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Mineralogy and Geochemistry of sediments on the far northern Great Barrier Reef shelf

by

Nuzhat Patail

A thesis submitted in partial fulfillment of

the requirements for the degree of

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Statement on the Contributions of Others

Nature of Assistance	***Contribution***	***Names***
Intellectual Support	1- Proposal Writing	i-Bob Carter (Ex-Co-supervisor) ii-Ken Woolfe (Ex- supervisor)
	2- Data Analysis	i-Guidance from supervisor R.A. Eggleton ii-Guidance from Ex-co-supervisor Bob Carter (seismic only)
	3- Statistical Support	Guidance from supervisor i-R.A. Eggleton ii-Chris Cuff (Ex- supervisor)
	4- Cartography & GIS	Adella Edward
	5- Editorial assistance	R A Eggleton
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Abstract

The sea-floor sediments of the Far North Section of the Great Barrier Reef Lagoon have been investigated by seismic traverse, and by detailed analysis of surface grab-samples and short (3-5m) cores. Sample collection was along three transects; two from coast to reef, the third parallel to and near the shore from Cape York to Weymouth Bay. In total, 195 samples have been investigated, using binocular microscopy, size analysis, X-ray diffraction, bulk and trace geochemistry, scanning electron microscopy and electron microprobe analysis.

The seismic data reveal an erosional unconformity ranging from at the sea bed to ~12 m below the sediment surface, interpreted as the Holocene-Pleistocene unconformity, resulting from lowering of sea-level during the Pleistocene. Marine transgression since the last glacial maximum has allowed the deposition of terrigenous and marine sediment across the Lagoon. The sediment character differs above and below the unconformity. Above, the sediments are seismically transparent, dominated by *Halimeda* bioherms, whereas those below are almost seismically opaque, non-marine sediments. Areas of the lagoon north of Raine Island are devoid of Halimeda because of poor nutrient supply. From the reef to shore, the *Halimeda* bioherms decrease in thickness and character, forming thick mounds in the east, but becoming flatter and thinner westward, and eventually disappearing toward the inner shelf.

The land bordering this section of the GBR Lagoon provides a narrow catchment between the Great Dividing Range and the coast. The area is subdued, erosion is minor, and both sediment and fresh water inputs to the lagoon are low. The source rocks for sedimentation into the Lagoon include quartzose sand dunes, lateritic regolith, Jurassic sediments and volcanics. Facies analysis shows the near shore inner shelf sediments are dominantly terrigenous, made up of quartz and clays with minor carbonate. Their detailed composition closely reflects the local sources. The clays include both kaolinite and smectite, derived from different sources; the kaolinite from the lower, more deeply weathered parts of the landscape, and smectite from the less mature high-lands and coastal volcanics. Sediments of the mangrove swamps are more clay-rich than others, and show the effects of post-depositional change as a result of changing physico-chemical conditions (redox) . These changes include quartz grain fragmentation, growth of pyrite framboids, precipitation of secondary magnesian calcite and the conversion of kaolinite to smectite.

Geochemical analysis allowed four factors to be developed from which a classification of the sediments of the lagoon was erected:

Factor 1: samples dominated by terrigenous sediment, Ga, Zn, Ni, Mn, Cr, Ti, Ba, Rb, Y, Nb, Al, NaO, $SiO_{2,}$ K_2O and V.

Factor 2: carbonate factor: Ca, Mg, Sr, P_2O_5, Pb, Cr, Ni and Zn.

Factor 3: transition elements Ti, Fe, Ga, Mn, V, As,Y and Nb.

Factor 4: S and Fe

These factors, plus the mineralogy, were used to establish sedimentary facies for the area and to map their distribution. Facies analysis delineate five facies:

Facies 1: Near shore terrigenous sandy mud facies, characteristic of swamp and mangrove intertidal zones.

Facies 2: Inner shelf shore sand, consisting largely of coastal dune sand.

Facies 3: Shelly beach sand, derived from both Pleistocene and Holocene
beach ridges, mostly found in Newcastle Bay.

Facies 4: Halimeda generated carbonate Facies, occupying the mid-outer shelf.

Facies 5: Pure carbonate coral reef Facies, characteristically occurring in the outer shelf and parts of the middle shelf.

Beyond the terrigenous dominated near shore region, carbonate sediments gradually increase in proportion, becoming very dominant as *Halimeda* and coralline algae Facies toward the outer shelf. The *Halimeda* Facies is shown by increased aragonite and higher Fe and Sr values. Coralline algae Facies has higher Mg-calcite. The distribution of these facies results from variations in nutrient supply for the *Halimeda*, and position relative to the reef itself and to the shore.

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CHAPTER 1 INTRODUCTION

1.0 Introduction:

The Great Barrier Reef of Australia (GBR) is the largest reef system growing on a continental shelf in the world. The continental shelf reefs form a line roughly parallel to the northeastern coast line of Australia 1900 km long, extending from approximately 153-154^{o} E at 24 ^{0} S to 143-144^{0} at 10^{0} S (Figure 1). Deep narrow passages and entrances separate the individual reef systems (eg Pandora approximately 144^{0} 2$^{'}$ E at 11^{0} 21$^{'}$ S and Raine Island entrances 144^{0} E at 11^{0}38$^{'}$ S) . On the eastern side of the GBR lies the Coral Sea, which is part of the Southwest Pacific Ocean. To the west of the GBR lies the Queensland coast line stretching from approximately Bundaburg in the south to Thursday Island in the north. The northern part of the reef is adjacent to Cape York Peninsula with the outer reef ranging from 25 km offshore at Weymouth Bay (a little to the south of this study area) to 200 km offshore at Cape York (Newcastle Bay). To the North of Cape York lies Torres Strait.

To understand the processes that have provided the environment for the development of the GBR and to appreciate the effects that anthropogenic activity or sea-level change might have on the reef, requires knowledge of the relationship of the reef to the composition and distribution of the sediments across the continental shelf. Although there have been studies of the shelf region for the southern sections of the GBR, most of this region has been affected by 200 years of run-off from the land by farming activity. The northern section of the GBR fringes a coastline that is virtually pristine, therefore study of the sediments across the shelf in this part of the GBR can provide valuable baseline information. The major objectives of this study were framed within this overall concept.

1.1 Major objectives:

To elucidate the Holocene history of the GBR shelf (continental shelf under the GBR), this thesis will:

1) *Assess the sediment provenance and the different processes of sedimentation*

- Facies analysis will be used to establish a model of sediment distribution in the area.
- The geochemistry of major and trace elements will provide diagnostic signals, characteristic of sediment sources or of diagenetic effects.
- Together, these data will provide information about the provenance of the sediments and the changes in sedimentary processes, and allow post depositional effects to be evaluated.

2) *Relate the distribution pattern of sediment facies to the palaeoenvironment.*

- The depositional history of sediments in this section of the GBR will provide information on palaeoclimatic and sea level changes.

- Current distribution of terrigenous and carbonate (marine) sediments will provide information about sediment inputs.

- The distribution of sediment type down core will provide a history of sediment change.

- Seismic stratigraphy will be used to provide information about postglacial change and the relationship between terrigenous and non-terrigenous sediment, and also provide a cross-section of the distribution of sediments of the GBR Shelf.

- The identification of oceanographic features such as terrigenous wedge-outs, reef bio-herms, channels and disconformities can provide constraints on models of past environments.

3) Look for trends in the weathering style over time as shown by changes in the terrigenous input.

- Elemental geochemistry will provide insights into the weathering in the hinterland, because in tropical weathering regions the mineralogy of weathering products is different between wet tropics and seasonal tropics.

- Geochemistry provides empirical information on elemental mobilities, which will provide an index against which to access other chemical and mineralogical changes. Such an index is necessary if interpretation of processes (e.g. weathering) is to be made.

- Trace element analysis combined with mineralogy will provide information on the ability of the sediments to act as a source or sink for elements in the environment. Clay minerals and colloids have the potential to adsorb and release ions into the environment. These adsorption processes are quantitatively and qualitatively dependent on mineralogy.

1.2 Criteria for selection of the study area:

The criteria for the selection of the study area were:

1) There is a limited amount of previous work in the far north section on the GBR. (See 1.6).

2) The fact that the GBR is a world heritage listed site and consequently of international significance, hence it is important to understand the processes of sediment transport from the land into the GBR Lagoon - the region between the shoreline and the reef itself.

3) The GBR is the largest reef system in the world but is distant from rivers of major significance on a worldwide scale. This is significant in limiting the amounts of detrital terrigenous sediment and fresh water input to the system.

4) The far north section of GBR has a very low human population density adjacent to it and Cape York Peninsula itself is considered to be a wilderness area. Thus the Far North section of the reef suffers minimal environmental degradation with possibly only increased runoff due to cattle grazing. Therefore the geochemistry of the sediments adjacent to the coast have not been impacted by anthropogenic activities.

1.3 Location:

The study area is a part of the reef adjacent to Cape York Peninsula. It extends from Weymouth Bay approximately (10^{0} $48^{'}$S to 12^{0} $32^{'}$ S) to Newcastle Bay at (143^{0} $15^{'}$ E to 144^{0} $25^{'}$ E). This area includes Newcastle Bay, Orford Bay, Shelburne Bay, and Temple Bay. The study extends across the shelf and covers the Great Detached reefs, Yule detached reef, Raine Island, and other small neighbouring reefs (Fig-1).

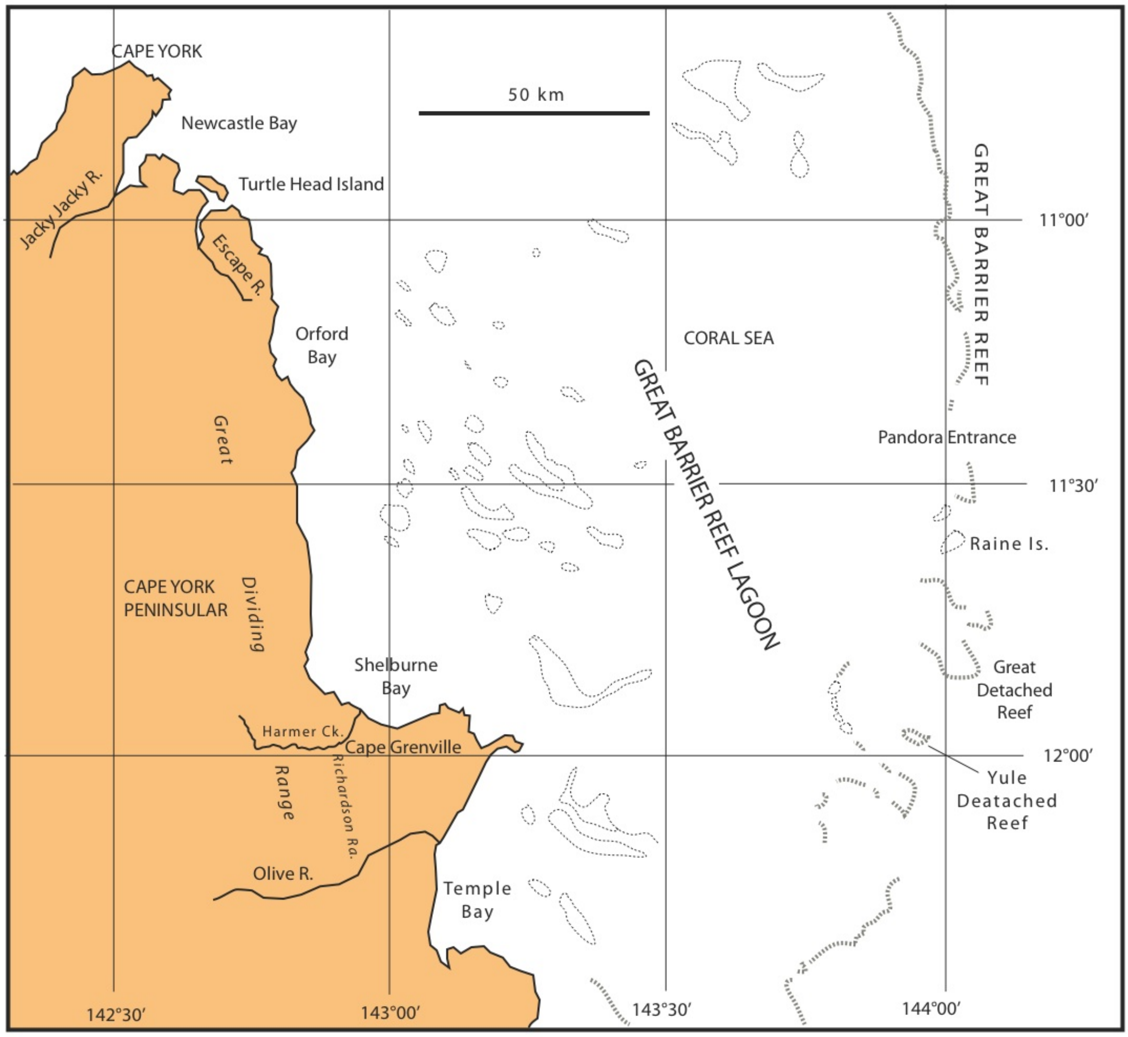

Figure 1.1. Locality map.

1.4 Physiography.

A major feature of Cape York Peninsula is the Great Dividing Range. This range extends down the whole east coast of Australia, and in far north Cape York it is generally within 50 km of the east coast. The range forms the western limit to all the catchments that shed sediments to this northern section of the GBR Lagoon. Small ranges occur to the east of Great Dividing Range including Jacky the Jacky Range (approximately 143^0 E at 12^0 $40^{'}$ S), and the Nelson Range (approximately 143^0 E at 12^0 $40^{'}$ S). Through these ranges the Pascoe River drains into Weymouth Bay, a little to south of the study area. Further north the Richardson Range is drained by the Olive River into Temple Bay and by Harmer Creek (approximately 142^o $58^{'}$ E at 11^0 $58^{'}$ S) into Shelburne Bay. The northernmost streams are the Escape River (approximately 142^0 $40^{'}$ E at $11^{'}$

S) and the Jacky Jacky Creek (approximately 142^0 30, E at 11, S), draining from the Great Dividing Range into Newcastle Bay.

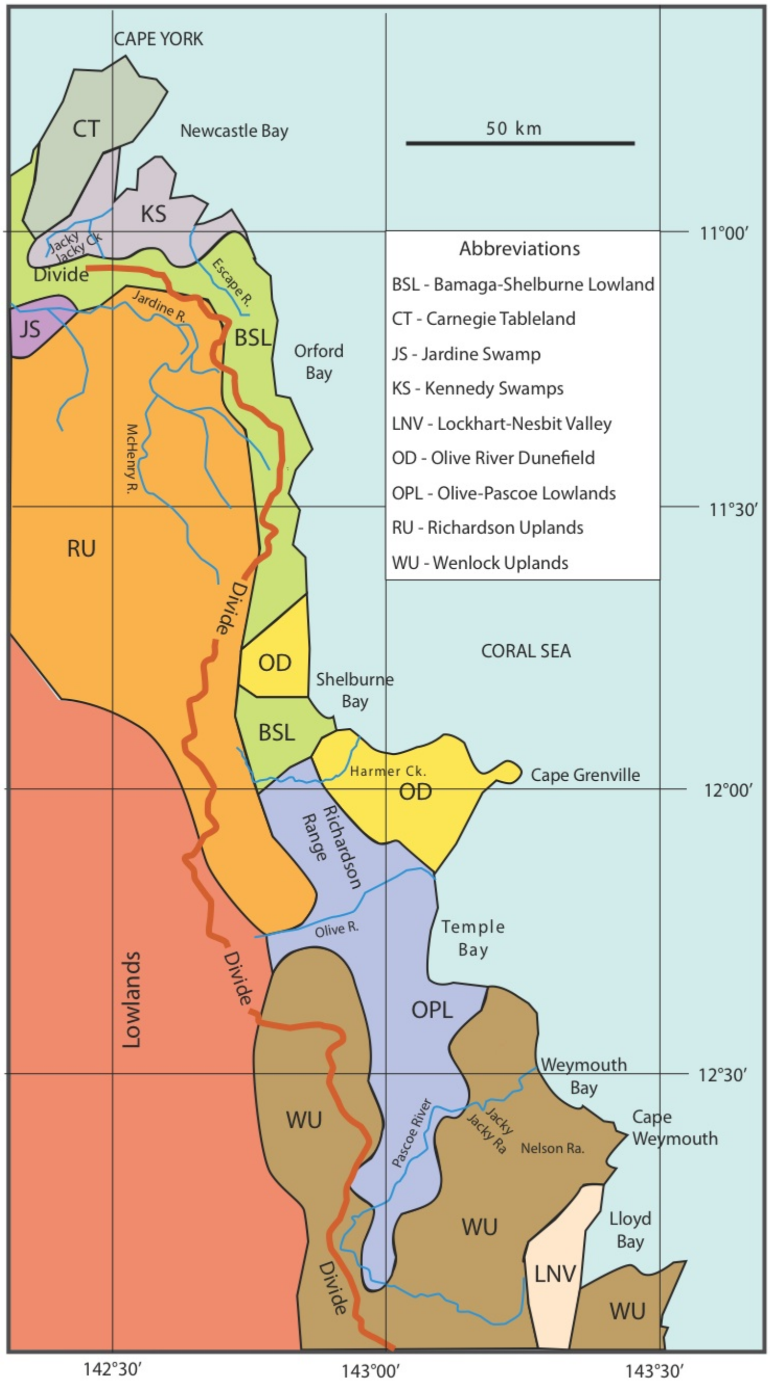

Figure 1.2. Physiographic Units of the eastern side of Cape York Peninsular (after Smart *et al*. 1980).

Smart et al. (1980) present a map of the physiographic units, from which Figure 1.2 is taken. To the north the Richardson Uplands, (also referred to as the McHenry Uplands by Smart *et al*. 1977) are a dissected area of Mesozoic sandstone, bounded on the southeast by steep escarpments, but merging to the north with the Bamaga-Shelburne Lowlands.

The Bamaga-Shelburne Lowlands consist of undulating sandstone bounded by the Jardine and Kennedy Swamps to the north, the Weipa Plateau to the west and the Merluna Plain to the south (shown as "Lowlands" in Figure 1.2). Towards the east, coastal dune fields are present at Shelburne Bay and farther to the north. The age of the dunes ranges from Pleistocene to Holocene. These silica sand dunes are parallel to the prevailing southeast wind direction. North of Bamaga – Shelburne Lowland, the Carnegie Tableland marks the tip of Cape York Peninsula.

The Jardine Swamps are drained by the Jardine River and its tributaries which deposit quartzose sands interbedded with clay and silt eroded from the Jurassic Helby Beds and Cretaceous Bulimba Formation sediments (see section 1.6)

A broad area of coastal alluvium and salt pans on the south side of Newcastle Bay is recognized as the Kennedy Swamps. The alluvium, which continues southward into the estuary of the Escape River and Jacky Jacky Creek, was deposited there during a period of slightly higher sea level in Holocene times.

Spark *et al*. (1977) describe the Olive River and Orford Bay Dune fields as extensive areas of northwest trending longitudinal and parabolic sand dunes along the east coast of the Cape York Peninsula. These active dunes originated from old stabilized dunes due to erosion on their windward slope. The sand bodies are largely derived from residual sand and rest on Mesozoic sandstones. Some sand may have been sourced by landward transport of offshore sands during low stands of sea.

Most of the large dune fields are present on the leeward side of fluvial outlets; suggesting Mesozoic sandstones as their provenance. These sand bodies were left there by headward erosion of the Olive River. Other than that, parabolic dunes in the beach zone formed by winds blowing inland during low tides. Landward movement of sediment is also the result of wave action.

The Olive-Pascoe Lowland lies to the east of the Great Dividing Range and merges into the swampland of Temple Bay. Erosion by the Olive River separated the Glennie Tableland to the south from the Richardson Uplands. The Richardson uplands are developed on the Mesozoic sandstone. A dissected scarp separates the Uplands from Olive River Dune field in the east and the Olive-Pascoe lowland in the south east; northward the Richardson Uplands gradually merge into the Bamaga-Shelburne Lowlands and Merluna Plain in the west.

The western side of the Cape York is represented by a low plateau and undulating plains adjacent to the Gulf of Carpentaria. These plains have a complex network of rivers that flow into the Gulf.

1.5 Climate:

Cape York Peninsula (far north section) is located within the tropics and has a southeast to northwest monsoonal climate. Average daily temperature ranges are 30-28^0 C in summer and 22-19^0 C in winter. The mean annual rainfall in most areas is >1000 mm. Rainfall is attributed to the following primary classes: (Bureau of Meteorology 1992).

1) Moisture bearing southeasterly winds contracting on the coast and causing the uplift of cloud, generating rainfall and showers. These winds bring showery weather even in the colder winter months of May-August. The months of September and October are notably dry;

2) thunderstorms, moving from west to east. Convection cells from September- December may bring up to 200 mm of rain in 3 hrs;

3) cyclones coming from the Gulf of Carpentaria (west to east) and from the Coral Sea (east to west). Rainfall may be either intense or restricted and is usually most intense in the SW-SE region of the system. Cyclones may give up to 1m of rainfall in 3 days e.g. cyclone Charlie 1988. (Bureau of Meteorology 1992);

4) rainfall associated with intertropical convergence fronts (i.e.-northwestern monsoon, wet season). The zone of convergence moves southward from Papua New Guinea in December, leaving Cape York again in April. Within the zone of convergence heavy daily rainfall occurs. In most years, the minimum southerly extent of the monsoonal influence is to the Cooktown region. In some years it may be much further South (eg 1974 Newcastle in New South Wales). This type of rainfall can produce from 10-50 mm/day and may occur for up to 30 days in succession.

This climatic pattern affects the sediment distribution. Flushing of sediments from hill slopes into drainages is dependant on several factors including grain size, intensity and duration of rainfall, mineralogy and the ability of that mineralogy to form either chemical or physical surface crusts. If a high intensity rainfall event occurs after a period of aridity, flushing may be small until the surface crust is expanded and loosened, allowing erosion to increase. If a high intensity rainfall event follows a period of gentle wetting during which clay minerals have had time to expand and break the crust, flushing may be more extensive.

1.6 Regional Geology / Geological History:

The geological history of North Queensland has been summarized by Bain & Draper (1997). Because this study addresses sedimentation into the GBR lagoon, here, only those aspects of Cape York Geology that have a bearing on the supply of terrigenous material are summarized. These are the rocks of the Iron Range Province as defined by Bain and Draper (1997), covering the region of Cape York north of 13°S. From Temple Bay, the Coen Inlier of Proterozoic metasedimentary and meta-igneous rocks extends some 300 km to the south. In the northern section of the Coen Inlier, rocks of the Carboniferous to Permian igneous Kennedy Province form Cape Weymouth and the margin of Waymouth Bay. North of the Coen Inlier the outcropping rocks are Jurassic terrestrial and shallow marine sediments of the Carpentaria Basin, including the Weipa Sub-basin and the small Olive River Basin (Figure 1.3).

The oldest rocks outcropping north of 13°S are small patches of the late Mesoproterozoic Sefton Metamorphics (Figure 1.4). These include fine-grained muscovite-quartz schists, quartzites, slates, phyllites, quartz-hematite schists, marbles and calc-silicates (Blewett *et al*. 1998). To the south of this region, Silurian and Middle Devonian deposition produced a mixed carbonate/siliciclastic shelf sequence, and during this time the granites and adamellites of the Cape York Peninsula Batholith were intruded, including the Siluro-Devonian Kintore Adamellite (Knutson *et al*. 1994). In the early Carboniferous, igneous activity in the Kennedy Province produced rhyolites and welded tuffs of the Kangaroo River and Janet Range Volcanics, which form the western edge of the Coen inlier in this region. These were intruded in the Permian by the Weymouth Granite.

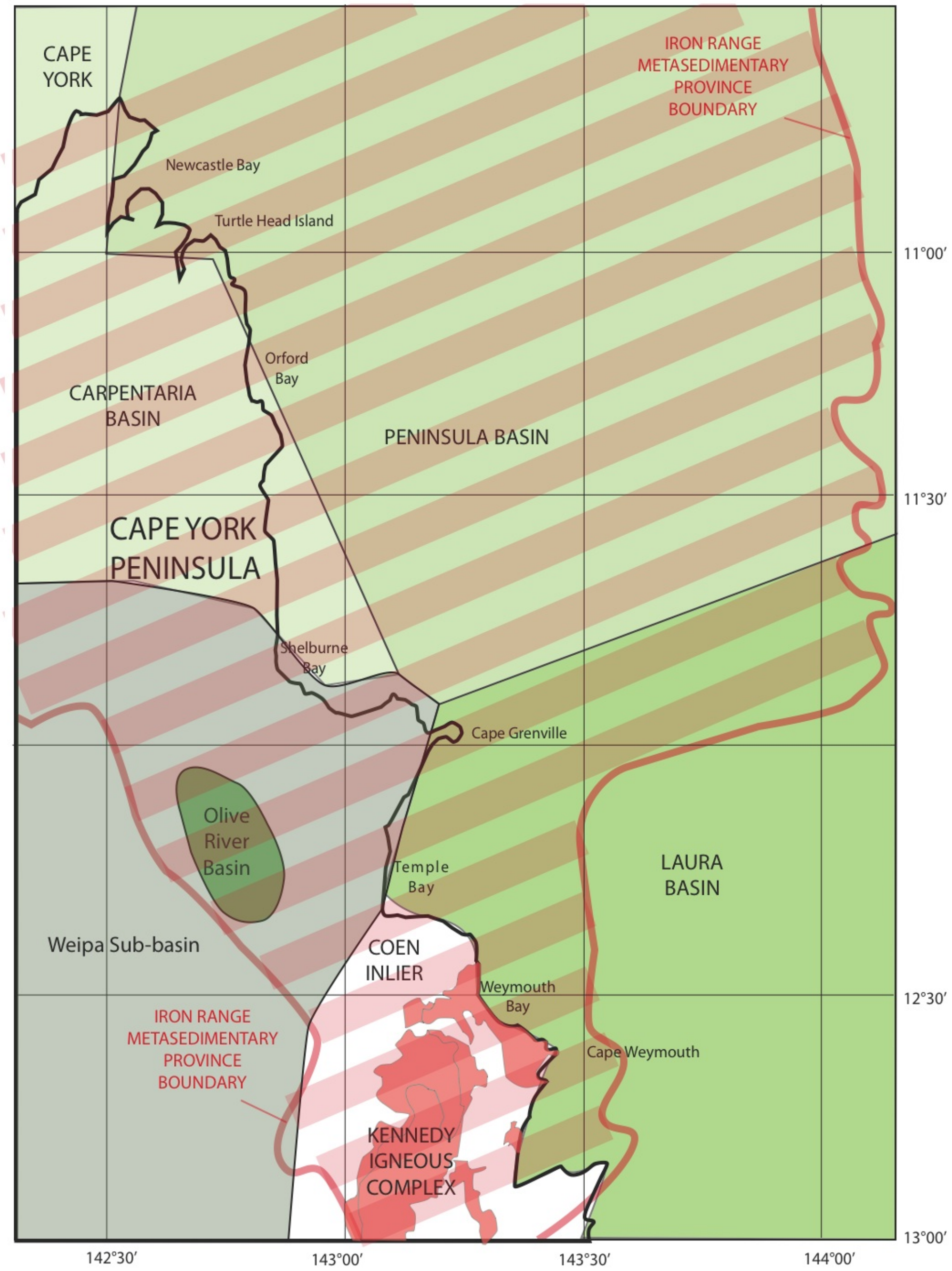

Figure 1.3. Geological Provinces and Basins of Cape York Peninsula (after Jell (2013) and Bain & Draper (1997)). Rocks of the Iron Range Metasedimentary Province underlie the study area but only outcrop in the Coen Inlier.

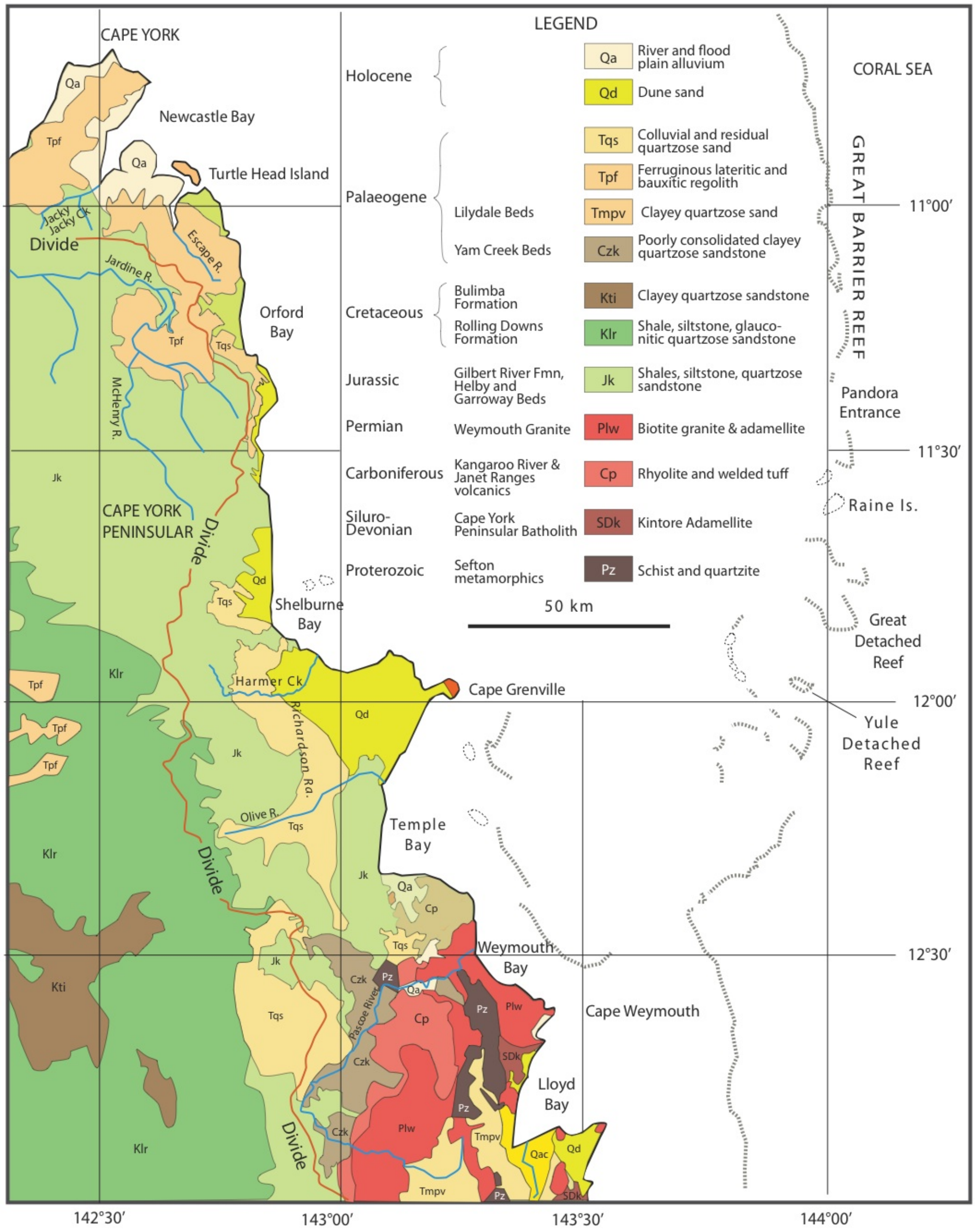

Figure 1.4. Geological map of northern Cape York Peninsula, based on the 1:250,000 geological maps Weymouth Bay (Willmott *et al*. 1977), Jardine River & Orford Bay (Spark *et al*. 1977), Weipa (Smart & Hellier 1976), Torres Strait-Boigu-Daru (Palfreyman *et al*. 1976).

There was depositional hiatus between the middle Triassic to middle Jurassic in North Queensland. Fluvial deposition started in the Jurassic period in the Carpentaria and Laura Basins (Figure 1.3), and further south in the Eromanga Basin. According to Spark *et al*. (1977), from the Late Jurassic to early Cretaceous deposition of transgressive shoreline and near-shore sediments occurred in all these basins, forming the fluvial to marginal marine Gilbert River Formation south of Cape Grenville, the Helby beds to the north, the fluvial to shallow marine Garroway Beds (Burger 1980) and the open marine Cretaceous Rolling Downs Formation (Figure 1.4).

In the Temple-Weymouth Bay region the Jurassic Garraway Beds lie at the base of the Mesozoic sequence and are confined to the Weipa Sub-basin (Figure 1.3) (Spark *et al*. 1977). They outcrop along the Temple Bay coast, in a north-south band about 40 km long and 10 km wide, extending as far south as the Coen Inlier. They are fluvial clayey quartzose sandstones, resting unconformably on Paleozoic or older rocks.

Spark *et al*. (1977) suggest that Triassic sediments may lie beneath the Garraway Beds in the small Olive River Basin within the Weipa Sub-basin. The Garraway Beds are succeeded conformably by the Late Jurassic to Early Cretaceous Gilbert River Formation, a widespread sandstone unit outcropping west of the Garraway Beds and extending well south of Cape Weymouth. Further north, interfingering with both these units are the Helby Beds, a thick sequence of marine and paralic clayey sandstones (Figure 1.4). These beds extend from about the Richardson Range, where the facies boundary has been placed, to the tip of Cape York.

The marine volcanogenic Cretaceous Rolling Downs Group sediments conformably overlie the Gilbert River Formation in the south and the Helby Beds in the north (Figures 1.4, 1.5). They include mudstones, siltstones, shales and labile glauconitic sandstones (Powell & Smart , 1977). The Jurassic-Cretaceous geological history of the region shows several marine regressions and transgressions, with the sediments becoming increasingly marine upward. Deposition ceased in the early Cretaceous and was followed by uplift.

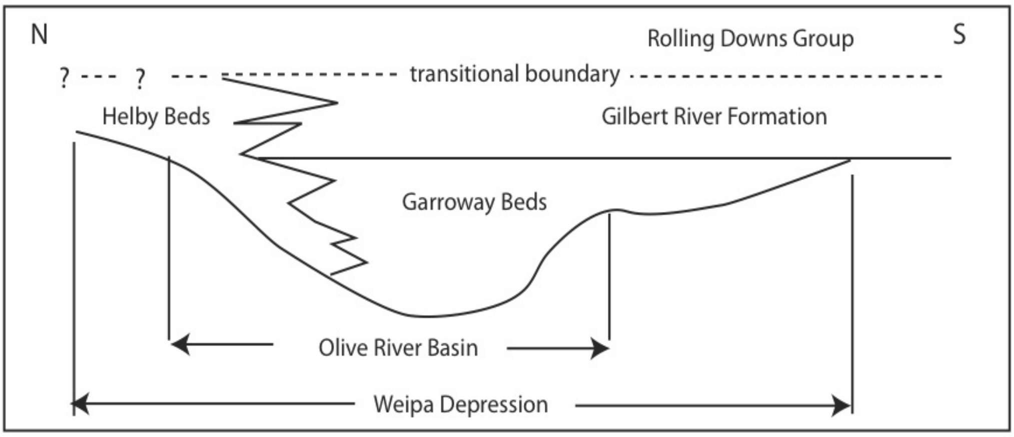

Figure 1.5 Schematic N-S section showing the relationship between the Jurassic-Cretaceous sediments of the Temple-Weymouth Bay regions (after Spark *et al*. 1977).

The Cainzoic in northern Cape York was characterized by widespread fluvial deposits of the Bulimba Formation to the west of the Great Divide (Taylor *et al.* 2008), whereas east of the Divide sedimentation was limited to fluvial and coastal localities, leading to river and flood-plain alluvium and sand deposits (Powell & Smart 1977). During the later Paleogene, intensive weathering of the Mesozoic and early Paleogene sediments resulted in widespread lateritic and bauxitic regolth profiles west of the Divide (Taylor *et al* 2008) and thick saprolite on the eastern side (Pain *et al*. 1997) (Figure 1.6).

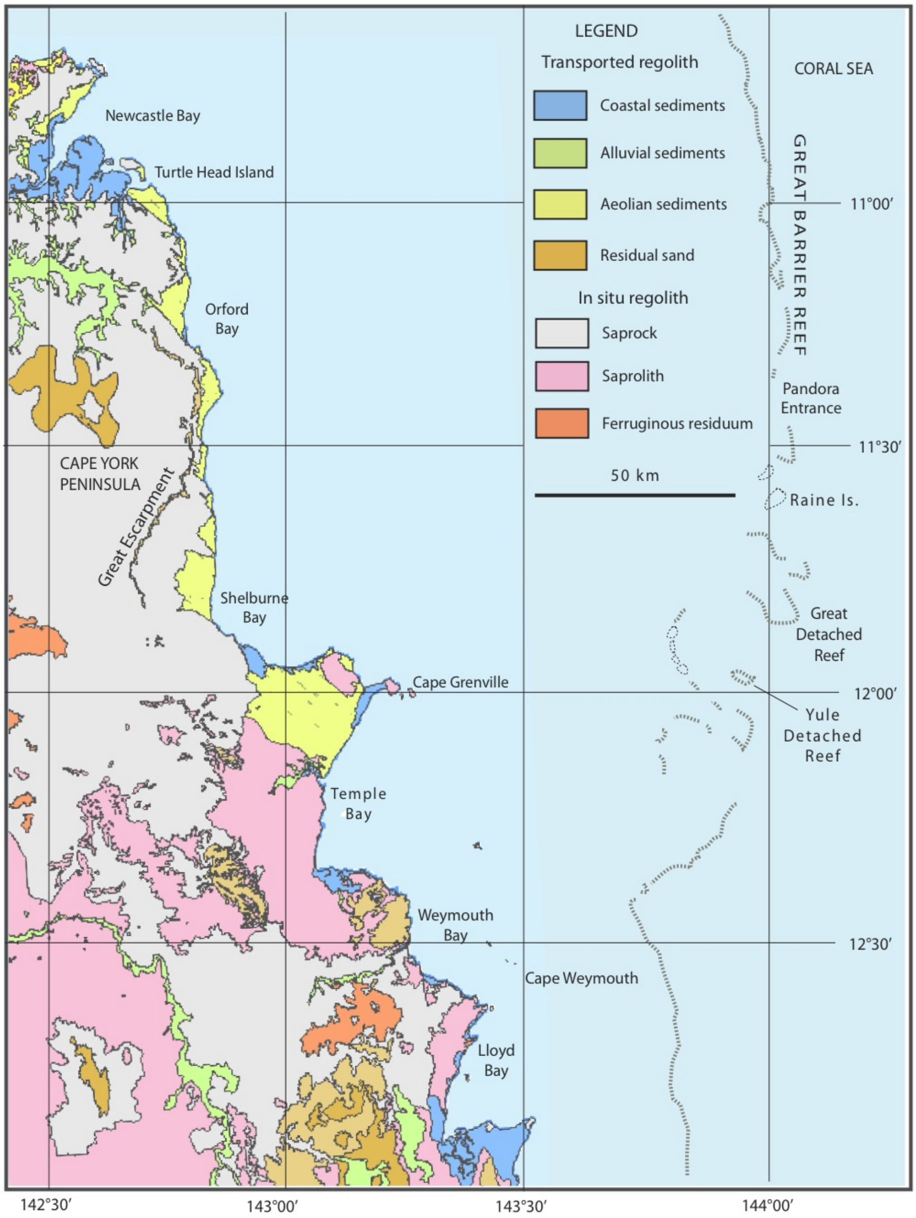

Figure 1.6. Regolith map of the east side of Cape York Peninsula. (From Raymond 2012)

Investigations for the Commonwealth Aluminium Corporation Pty Ltd by P.G. Miller (1957) found bauxite between the Escape River and the coast, and on Turtle Head Island. Later exploration by Comalco Ltd (White 1976) showed these bauxites to be associated with more ferruginous lateritic regolith. The mineralogy of the bauxite deposits is largely gibbsite, quartz, kaolinite and goethite. In places the bauxite is overlain by up to 8 m of brown weakly consolidated sandstone, itself overlain by as blanket of clean quartz sand (White 1976).

The original geological mapping of the 1:250,000 sheets used to construct Figure 1.4 interpreted the surficial materials of the headwaters of the Jardine and Escape Rivers as bauxitic and lateritic regolith. Later regolith mapping by Geoscience Australia led by C.F.Pain led to a revision of most of the regolith east of the Divide as saprolite; that is, deeply weathered Mesozoic Helby Beds (Fig 1.7), and this interpretation is used in Figure 1.6.

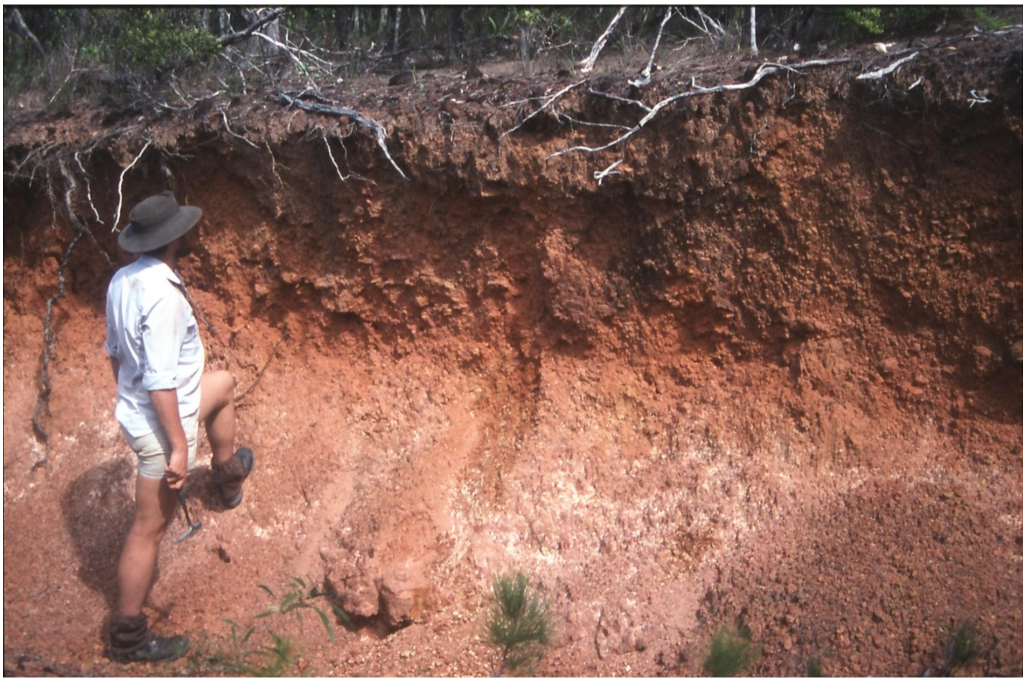

Figure 1.7. Regolith on deeply weathered Helby Beds showing thick surface ferruginization. (Photo C.F.Pain)

In his field notes, Pain describes these materials as (2013 pers. com.): “*Ferruginous pisoliths, ferricrete in valley floors and around melon holes (Pain and Ollier 1992). Also lumps of cemented ferruginous nodules etc. in stream channels. Along the Great Divide areas of residual sand containing buckshot ferruginous nodules. Dominantly the regolith consists of thin residual sand over bedrock.*”

Figure 1.8. Ferruginized edge of the Great Escarpment (Photo C.F.Pain)

Pain further notes that:

1. *The Great Divide is very close to the east coast in this area, so the source of materials is small.*
2. *The Great Escarpment (Fig 1.8) is the steepest part of this landscape by far, and is therefore the most likely source of sediments from inland. (The Great Escarpment is shown in Figure 1.6 as a sinuous band northward from 12°S).*
3. *There are cliffs along some of the coast, and the rest is dominated by quartz sand dunes.*

The sediments shed from these weathering profiles will be dominated by the composition of the weathered bedrocks. There are no detailed studies of weathering east of the Great Divide, but the Gilbert River, Helby and Garroway beds are quartz-glauconite-kaolinite assemblages, and these weather to quartz-illite-kaolinite-goethite, as evidenced by the detailed study of comparable Cretaceous Rolling Downs sediments at Weipa (Eggleton *et al*. 2008). Gingele & De Deckker (2004) found that the Normanby and Jardine Rivers, south and north of the study area respectively, carry kaolinite and illite as the dominant suspended sediment.

Extensive areas of sand dunes occur along the whole coastal strip from Cape Grenville to north. (Figure1.6). Lees (2006) concluded that those at Shelburne Bay have formed as a result of deflation of the exposed sediments on the Australian shelf during times of low sea-level during the last glaciation. They range in age from about 30,000 years to essentially modern. Pye (1983) studied the northerly coastal dune sands and suggested that large coastal dune fields of Queensland indicate a longer time period of sand accumulation during the late Quaternary. In early Holocene marine transgression the dunes become active in parts of north eastern Queensland. At that time a rapid shoreface erosion and destruction of littoral vegetation provided conditions for sand-blowing. He further suggested that in mid and late Holocene there were several episodes of dune activity, and the dune fields of north eastern Queensland reflect a large supply of sand from Precambrian and Paleozoic granites and metamorphic rocks, from Mesozoic sandstones and residual and alluvial deposits of Cainozoic. The riverine sands transported to short distances by littoral drifts and accumulated near headland and offshore islands. The beaches with southeasterly wind have moderate wave energy and medium to fine grain sand suitable for aeolian transport.

In Eastern Queensland nearly all the sediments deposited in the cainozoic time are related to weathering and erosion, or simply the concentration by fluvial and aeolian processes. Jell (2013) described three broad cycles of activity and several subsidiary cycles of geological activity. Each cycle has an active phase including uplift, erosion and deposition separated by (stable phase) deep weathering profiles with little or no sediment deposition. Eastern Australia uplifted in the middle late Cretaceous time which cause block faulting in the east, till Eocene time the erosion and deposition continued. The late Eocene – Oligocene was stable periods with deep weathering.

The second cycle starts with uplift in the eastern Australia in Oligocene time. Erosion continued in Miocene, interrupted by deep weathering in the middle Miocene. The third cycle commenced with upwarping in Pliocene which continued till Pleistocene.

Sea level variation also controlled the type of facies deposited in the eastern Australia as rise in sea level favoured the carbonate sedimentation and lowering of sea level increases the terrigenous input along the shelf and marked as an unconformity.

The correlation between onshore and offshore is hindered by the lack of direct evidence of sequences in seismic and other geophysical offshore profiles.

Symonds *et al*., (1983) developed a model for shelf evolution on the basis of seismic stratigraphy, structure, and plate tectonics. This model described the evolution of the shelf in six stages, which may be applicable to the entire eastern Australian margins.

Late Cretaceous-Paleocene has two stages

1. Pre-rift stage.
2. Rifting and rift fill stage.

Palaeocene-late Eocene

3. Marine transgressive stage (onlap), indicated by change of environment from shallow-water marine fans to open water turbidites.

Late Oligocene-early Pleistocene Shelf

4. Shelf progradational stage (offlap) marked by fluvial-deltaic-wave dominated marginal shelf sedimentation during low sea level.

Pleistocene

5. Shelf aggradational and post- progradational stage

Pleistocene-recent

6. Reef development stage

Draper & Bain (1997) explained the geological history of the northern region and indicated a transgressive sequence during the Palaeocene – Eocene. Wellman *et al*., (1997) explained that towards the end of the late Eocene and in post early Oligocene erosion took place and since then pelagic ooze, turbidities and slump deposits, in part derived from the flourishing carbonate platforms, have been major components of sedimentation. In the middle Oligocene a minor reactivation event occurred due to collisional tectonism along the northern Australian margin and was enhanced by global fall in sea level and marked as a regional unconformity. The sediments vary from marginal marine to open marine, followed by progradation in the late Oligocene and onlap in the early Miocene and progradation in the late Miocene. In the late Oligocene, sea level rise resulted in the gradual flooding of adjacent basement platforms, so establishing carbonate platforms and reef growth. Thus the Miocene was a period of reef formation. Progradation occurred again in the late Pliocene – early Pleistocene.

Feary *et al*., (1993), from the data acquired on the ODP leg 133, interpreted the Pleistocene seismic stratigraphy of the northern Great Barrier Reef. The sequence has three types of seismic geometry: a prograding lower sequence unconformably overlain by an aggradational outer shelf sequence, in turn unconformably overlain by a transitional sequence. In the middle of the succession small reefal mounds occur. The relief of these mounds ranges from 7-20 m.

CHAPTER 2 THE GREAT BARRIER REEF SHELF DURING THE HOLOCENE

2.0 Introduction

To understand the Holocene history of sedimentation on a continental shelf, the nature, distribution and sources of the sediment must be understood. This chapter summarises the available information relating to the mineralogy and geochemistry of postglacial sedimentation of mixed carbonate silicic-clastic sediments on GBRS sediments. It is not the intention here to provide a detailed and complete review of the wider literature; however important aspects of the subject that are pertinent to this study are included.

The initial work in the area was carried out by Jukes (1847) and Rattary (1869). Their work described raised reef and beach rocks on Raine Island and neighbouring reefs. According to Phipps (1967) Shepard (1948) stated that during low stands of sea level of the Pleistocene period intensive erosion and deposition resulted in the formation of sedimentary basins; initially a depression along the continental margin was formed and extended seaward across the continental shelf.

Phipps (1967) described the evolution and character of the continental shelf and related this to the geology of the hinterland, character of continental slope, continental rise and features of the ocean basin. This discussion included only that part of continental shelf which is susceptible to tectonic change; that is, the transitional areas between the thick continental and thin oceanic crust. He suggested that the variation in the depth of outer shelf margin is due to Pleistocene or Holocene tectonic movement. Phipps (1967) work explains that shelf rises are dominant features and that they extend across the continental shelf. These features are broad swells trending at right angles to the coast and which may result from faulting, because distinct tectonic trends are present parallel to the shelf margin. These rises are considered as the seaward extension of the shelf margin, and are recognized by Fairbridge (1952) in Northern Australia and by Maxwell (1967) in Queensland.

Hopley (1974) concluded that identification of raised reefs is useful as evidence in the investigations of sea level change. He suggested that the Holocene sea level history in north Queensland is similar to the rest of eastern Australia and that modern sea level was first achieved prior to 6000 B.P.

Hopley (2006) and Hopley *et al.* (2007) described the unconformable surface beneath the postglacial sediments and explained the Pleistocene surface as oxidized clay with calcareous nodules which is similar to the surface of adjacent coastal plains (Davies *et al.* 1983; and Graham, 1993). This surface marked as “Reflector A” (distinct seismic reflection surface first described by Orme *et al.*1978a, b) and at many places has very little or no sediment cover (Orme *et al*, 1978a). The thickness of postglacial cover is more on the northern shelf (maximum 20 m Searle *et al.* 1982) than elsewhere (< 2.5 m Johnson & Searle, 1984; Heap *et al.* 2002) except in the channel fills. The channel fill sediments are seismically transparent and interpreted as graded bedded fluvial sediments deposited during lowering of the sea level. They overlie fine grain estuarine sediments deposited during transgression. Some of the channels are overlain by mounds, comprised of delta-front sediments with weak parallel bedding (Johnson *et al.*., 1982; and Johnson & Searle, 1984).

Hopley (1982) discussed the development of soil horizons during erosion in Pleistocene times. Mid-shelf core collected from the centre of the reef contained red clay within the cavities at the top of Pleistocene profiles. Other minerals included quartz, illite, kaolinite and hydrated kaolinite (totalling > 80% non-carbonate material). Marshall (1983) also reports soil comprised of quartz sand with humate cement as a cavity filling between the corals. Marshall (1983) studied the diagenesis of Pleistocene material and found alteration of aragonite and high-magnesium calcite into low-magnesium calcite, some calcite cement filling was also found.

Frankel (1974) assessed the concentration of ferruginous and iron stained abraded carbonate and quartz sediments in the central Great Barrier Reef and identified these as dune or beach deposits of lower sea level period.

2.0.1 Reef classifications

Fairbridge (1968) classified the reefs into two broad classes, based on reef morphology:

• Ribbon reefs (linear reefs) have unvegetated cays and are present at the edge of the continental shelf, at the 100-fathom (183 m) line, only north of 14^{o} S;

• Platform reefs (patch/ barrier) sand cays are rare, they occur several kilometers shoreward from 100-fathom (183 m) line starting from south of about latitude 16^{o} S. They are broad, flat and tabular.

A more descriptive nomenclature and detailed classification of reefs was given by Maxwell (1968). The basis for classification is the shapes of reefs, their central structure, and their morphological zonation. Maxwell's major reef classes are platform reefs (which are further divided on the basis of the size and shape of their lagoons and linear /wall reef (further classified as varieties of ring reefs which may be closed or open

Maxwell and Swinchatt (1970) carried out a study of the terrigenous carbonate province of the Great Barrier Reef shelf. The study categorised the province on the basis of shallowing and width of the shelf (shelf geometry) and reef morphology:

a) Southern Region maximum depth >35 fathoms (> 64 m), lagoonal reefs, ring reefs and

elongated platform reefs.

b) Central Region maximum depth 20-35 fathoms (**37**-64 m), platform and resorbed reefs.

c) Northern Region maximum depth 20 fathoms (**37** m), linear shelf edge reefs.

Maxwell & Swinchatt (1970) distinguished the Great Barrier Reef Province from other carbonate areas including the Florida-Bahamas Carbonate Province by:

a) extensive development of shelf reefs due to variation in bathymetric and hydrological conditions;

b) wide-spread terrigenous facies; and,

c) relatively deeper shelf with free water circulation.

Hopley (1978) explained that the prominent features of the GBR province are due to the shelf geometry and bathymetry. He recognized six zones of reef and island development across the shelf.

Shelf	Zone	Type of Reef	Result from	Sea Level
Inner shelf	1	Island & small reefs with sand cays	Shallow pre-Holocene platforms	Long period of sea level close to or slightly higher than present level
	2	Larger Reefs with reef flats & reefs with vegetated and un-vegetated sand cays	Shallow pre-Holocene platforms	As above
Mid shelf	3	Massive reefs up to 25 km long & 125 km^2 in area with isolated patches of reef flat	Deeper pre-Holocene platforms	Rise in sea level (Transgression)
Outer shelf	4	Karst Surface No reefs only weathered limestone surface between 20 to 40 m depth	High turbidity so no development of reefs	As above
	5	Ribbon reefs with narrow passages in between at the outer edge of the continental shelf	Pre-Holocene rim Stable sea level creates an equilibrium with prevailing conditions and reef growth takes place	Longer period of stable sea level (more than 5000 years)
	6	Detached reefs beyond shelf edge	As above	As above

Table 2.1 Zones of reef development across the Great Barrier Reef Shelf (generated from Hopley 1978)

A model for the evaluation of the Far Northern barrier reefs was introduced by Veron (1978) in which he suggested that the northern Barrier Reef has a Miocene basement, underlain by Mesozoic sedimentary rocks. He considered that the present morphology resulted from tectonic subsidence which limited the northern extension of the reef and determined the position of ribbon reefs at the edge of the Queensland Trench, and sea-level changes during the Holocene leading to planated wave-resistant outer flat reefs. During sea level change transgression favours reef growth and during regression severe erosion and sedimentation occurred. The lowering of sea level in Quaternary led the erosion of older reefs. During the last glaciation period the sea retreated entirely from the northern Great Barrier Reef. Since then, reef building has created the present day barrier between the continental shelf and ocean.

2.0.2 Sedimentation on the Shelf

Important factors that influence the sedimentary, geochemical and mineralogical aspects of a shelf include the clay mineral species, the carbonate mineral composition, the sedimentary and post-depositional processes and the physico-chemical parameters, including Eh, pH and salinity (Berner 1981). Thomson & Wolanski (1984) further suggested that coral reef growth and distribution on the outer shelf may be linked to upwelling at the continental shelf.

The major investigations of the post glacial sediments of the Far North Section of the Great Barrier Reef Shelf (GBRS) have been confined to the inner shelf; the region between the coastline and the reef. No work has been conducted on the outer GBRS sediments of this area. Most of the existing works examined the inner-shelf and the Queensland Plateau (Belperio, 1983; Johnson, Cuff & Rhodes, 1984; Davies & Marshall, 1985; Alan *et al.* 1996; Larcombe & Woolfe, 1999 b; Bryce *et al.* 2000, Lambeck & Woolfe, 2000). These papers have addressed the hydrodynamics, geochemistry, mineralogy and the sediment type and their distribution patterns.

The studies by Johnson, Cuff & Rhodes (1984), Pomery (1987) and Dunbar & Dickens (2003) give combined models of sedimentation, mineralogy and geochemistry of shelf sediments. According to Dunbar & Dickens (2003) shelf sediments consist of two main components terrigenous clastics (clays, quartz and feldspar) and biogenic carbonates (aragonite and calcite).

Short (2010) studied the Holocene beach-barrier system and divided Australia into 3 broad provinces and 17 sub-provinces based on provenance, size and shape of barrier. The eastern province includes the eastern side of Cape York, characterized by tropical climate, terrigenous quartz sediments, northward transport of sediment, with significant onshore transport where shoreline orientation, wave and wind energy produces the coastal dunes.

In 1997 the Australian Geological Survey Organisation and The Geological Survey of Queensland compiled the geology of North Queensland and divided the region into nine sub-regions on the basis of unique and contrasting geological histories. The easterly parts of Cape York provide the terrigenous component to the sediments of the shelf, and the next section is largely taken from that compilation.

2.1 Source of shelf sediments

The composition of both intra-shelf and inter-shelf sediments is variable and is dependent upon the geomorphology of the area and source rock (Chamley, 1989). There are three components to the shelf fraction: terrigenous, marine, and diagenetic.

Terrigenous sediment is essentially derived from the regolith, which includes weathered rock in place, alluvium, colluvium and aeolian deposits. Regolith results initially from *in situ* chemical alteration of bedrock leading to mineralogical change, primarily the formation of clay minerals. Erosion and transport of both fragmented parent and its alteration products leads to terrestrial regolith deposits (colluvium, alluvium, aeolian deposits). Deposition of dissolved salts in ground water such as silica or carbonates may cement regolith in the form of ferricrete, calcrete, silcrete and other indurated regolith.

The global geo-chemical cycle is basically controlled by chemical weathering, which involves hydration, oxidation, and hydrolysis, as well as congruent and incongruent dissolution. By these processes primary alumino-silicate minerals are weathered to clays, mafic minerals to clays and iron oxyhydroxides, and resistate minerals such as quartz, rutile, zircon and ilmenite are released from the bedrock as discrete grains (Taylor & Eggleton, 2001).

Chesworth (1992) concluded that regardless of the parent rock, the end product of weathering in the humid tropical environment is a ferralsol. The major chemical differences that distinguished different parents are lost but physical differences may still be present. Since a ferralsol is composed largely of hematite kaolinite and gibbsite, these minerals contribute to the source materials for down-stream and ultimately marine sediments.

Draper & Bain (1997) described the geological history of the North Queensland; of major concern to this study is the Cainozoic history of the east coast of Northern Cape York Peninsula. This period was dominated by fluvial sedimentation, intensive weathering and marine transgression, followed by progradation in the early Pleistocene. Detrital sediments brought to the Great Barrier Reef Lagoon from Cape York Peninsula were derived from the erosion of the rocks and regolith of the Cape. As noted in the section on physiography, the Great Divide runs the length of Cape York. In the southern region of the study area, around Weymouth Bay, the Divide is about 30 km from the coastline. Further north the distance to the Divide decreases until at Orford and Newcastle Bays it is little more than 10 km inland. Rivers draining the east coast of Cape York thus are very short and only carry sediment from the immediate area.

The major terrigenous sources of material to the northern section of the GBR shelf sediments are the rocks of eastern Cape York Peninsula. Northward from Shelburne Bay, the bed rocks are Mesozoic shallow marine sediments of the Rolling Downs Formation, composed mainly of quartz, feldspar and glauconitic mica (Draper & Bain, 1997). Weathering of these rocks, in some places very deep weathering, has produced a variety of regolith materials which become the main source of sediment to the rivers. Chemical weathering of feldspars and micas leads to the formation of the 2:1 clay minerals illite, smectite, and interstratified clays which by further weathering yield as end products kaolinite, gibbsite and Fe-, Mn- and Al-oxyhydroxides. After the formation of these phases the ion exchange and ion-retention capacities for clay minerals are reduced which affects the elemental mobilities (Evans, 1992). Bauxite and lateritic regolith are widespread in the most northerly section of the Cape, while further south soils and sands covering saprolite constitute the major regolith materials (Pain *et al*. 1997). The erosion products of the Mesozoic sediments in this tropical environment include some weathered mica and feldspars, but are mainly quartz, kaolinite, gibbsite and hematite (R. A. Eggleton pers com).

Lees (2006) wrote about sand dunes Australia-wide. The easterly oriented sections of the north-east Queensland coast are dominated by strong and persistent southeast trades, which also dominated during the last glacial. Dune emplacement dates listed by Lees range from 170,000 to 800 years ago, with many being post the last glacial maximum. Dune sediment is regarded as being derived from the deflation of fluvial deltas on the continental shelf during periods of low sea-level.

Coastal quartz-sand dunes are present along the Queensland coast from the tip of Cape York Peninsula to Fraser Island and the Islands in Moreton Bay. They include beach sand and foredunes. The type and composition of the sand varies, depending on the inland geology and river which carried it. The dunes have an episodic history and their age ranges from Pleistocene-Holocene (Pye, 1982, Lees 2006). Older Pleistocene beach ridges are made of leached quartzose sand. Soils on these deposits are grey-brown organic stained. The younger beach ridges (Holocene) are made up of quartz, mica and shells; their soils are weakly organic stained. Estuarine deposits include mangrove swamp sediments and organic mud.

Pye (1982 & 1983) studied the sand dunes of north Queensland Australia. He concluded that dunes were stabilised in the last few hundred years, and only local remobilisation of these dunes occurs. Small blowouts remove some of the silt-size fraction (produced by weathering of quartz) and deposit this as a thin sheet in more protected areas downwind.

2.1.1 Terrigenous Component of the shelf

This refers to sediments derived from the land, though they may undergo a change in the sea as a result of change in their chemical environment. They may change morphology or chemistry during the course of transportation or as the result of interaction with the marine environment, which is a cation-rich environment with different Eh, pH and salinities from those at their source.

The rate of sediment input by rivers varies from year to year and place to place. Such input depends on climate, source and type of terrain (as described in Chapter 1). Riverine sediment input usually varies in size from sand to clay size particles. Brown, Harrison & Jacobson (1983) estimated the discharges of the Jacky-Jacky Creek as 2,110x10^6 m^3/a and Olive-Pascoe Rivers as 5,440x10^6 m^3/a.

Furnas (2003) calculated the average annual runoff for Jacky Jacky Creek to be 1.56 km^3 and 3.71 km^3 for the Olive-Pascoe Rivers. Fumas (1997) suggested that the total annual discharge occurs in catchments of all the rivers between November and April (wet season), regardless of size, and there is very little or no flow during May- October (dry season). Factors which control the flow are local catchments area, rainfall dynamics, monsoonal and cyclonic activity.

Lambeck & Woolfe (2000) suggested that sediments are transported northward along the inner shelf of the GBR rather than across the shelf, and that only limited cross shelf transport of the sediments takes place, restricted to the inner shelf. They further suggested that sediment inputs from the individual rivers may be retained relatively close to the source.

Larcombe & Woolfe (1999b) explained that in the mid- and late Holocene on the central GBR coast the sediment transport is mainly northwards as evidenced by the clastic sedimentation along the coastline. Terrigenous deposits include minor deposition in chenier ridges and inter-chenier plains and larger muddy intertidal and subtidal deposits. They further suggested that these deposits form an inner-shelf sediment wedge (< 5 m thick), which extends out to the 20 m isobath. These marine wedges may be shore-attached or shore-detached (separated from the coastline by a narrow band of erosion or non-deposition) depending upon their exposure to the wind and swell waves. Although this study concerned deposits well to the south of the study area, the general principles may be applied northward, since there is much evidence for similar directions of coastal sediment transport as far north as Newcastle Bay (Lambeck & Woolfe, 2000 and Luick *et al.*, 2007).

Gingele & De Deckker (2004) studied Australian riverine clay mineral assemblages and found that clay mineral fingerprints are not associated with the present climate of the drainage area but show a relation with bedrock. They conclude that clay mineral suites are formed after prolonged weathering of bedrock and that they do not follow latitudinal patterns and have no global latitudinal zonation on the sea floor surrounding Australia. Clay assemblages of sea floor sediments indicate that the considerable amount of terrigenous component contributed by river suspension can be traced for long distances. They consider that episodic flood events control the input of clay by rivers. Both the rivers they examined on Northern Cape York, the Jardine and the Normanby, flow west, but they are sourced in the same kind of bedrocks and regolith as the streams flowing east into the study area of this thesis. The clay mineral assemblages reported are kaolinite, chlorite and illite in the Jardine river area and in the Normanby River sediments again kaolinite dominates over other clay minerals including illlite, chlorite and smectite.

In the light of above studies it is expected that clay-sized sediments carried by the rivers flowing east from the divide are mainly kaolinite, less illite and chlorite, some hematite or goethite, and possibly gibbsite. Some smectite may also be produced from the saprolite. Studies of the Weipa bauxite (e.g. Loughnan & Bayliss, 1961) reveal that weathering of the Mesozoic sediments has continued probably since the mid Paleogene, thus it is likely that the same suite of terrigenous sediments has been deposited in the GBR Shelf since well before the Pleistocene.

John *et al.* (2006) worked on the clay mineral assemblages from the ODP sites located on the northeast Australian margin and found that there was a decrease in the smectite with an increase in kaolinite accumulation on two occasions at about 15.6 Ma and 13.2 Ma respectively, and these increases correlate with an increase in the calcite to detritus ratio. They further explained that both events were influenced by lowering of sea level along with aridity and subsequent erosion of older lacustrine sediments bearing kaolinite. They concluded that clay accumulation and weathering was controlled by climate during middle Miocene time.

Alongi & McKinnon (2005) suggested that in the near shore zone geophysical dynamics of the coastal boundary layer are vital in restricting and concentrating the biological and biogeochemical activity. Further to this the mangroves and tidal flats also trap and store sediments and organic matter within the Great Barrier Reef World Heritage Area. As the result of this relatively much less terrigenous sediments and organic matter leaves the coastal zone.

Brodie (2003) calculated the sediment input to the Great Barrier Reef from accumulation of sediments in the coastal zone or weighted discharge-export relationship from rivers. Brodie used simple models of run-off, land use and sediment discharge and suggested a several-fold increase in the sediment and nutrient fluxes to the Great Barrier Reef World Heritage Area. An estimated load of 14 Mt of sediments is exported to the Great Barrier Reef coast each year, less than 10 % of the total amount of erosion in the catchment area. The rest of the eroded sediment does not reach the coast but is deposited on foot slopes, river beds, floodplains and in reservoirs, but most of the nutrients are delivered to the coast and some of them are deposited with sediments.

Devlin & Brodie (2005) did aerial plume mapping of river discharges entering into the Great Barrier Reef World Heritage Area, and observed an increased sediment runoff during floods or cyclones which dispersed to near shore regions.

Sediments entering into the Great Barrier Reef Lagoon studied by McCulloch *et al.* (2003), essentially only happened during seasonal events like cyclones or occasional intense monsoonal depressions in which huge masses of fresh water and suspended sediments discharge into the near shore of Great Barrier Reef Lagoon. Apart from this there is not much terrestrial input in the inner shore. They found that the near shore environment is dominated by coarse grained granitic derived fluvial sediments, away from the coast near coral reefs basalt derived sediments become more important and they are the source of terrestrial phosphorus (P). Sediments act as a carrier for nutrients and pollutants and their enhanced levels are one of the major causes of coral reef degradation. However they looked at a region well to the south of the present study area; basaltic rocks do not outcrop in the catchments considered in this thesis.

Overall, these studies show that terrigenous sediments from Cape York Rivers discharge in the catchment during the wet season. Sediments are deposited near the river mouths and are moved north by long - shore currents. Sedimentation is restricted to the inner shelf and there is very little movement across the shelf. The mangroves and tidal-flats act as a sponge to hold the sediments so they stay near the coast, with much deposited near source. Over the last hundred and fifty years there has been an increase in the sediment load due to increased soil erosion from grazing land. These sediments along with high levels of nutrients are discharged to the coastal waters during floods or cyclones.

2.1.2 Aeolian component of the shelf

Wind sourced sediments may be derived from the Australian mainland, volcanic dust, and anthropogenic dust. The dust is transported by winds as suspended load and its size ranges from 100 µm diameter particles and aggregates to sub-micron sized particles (Chartres, 1998).

Okubo & Woolfe (1995) reported that in the Great Detached Reef of the Far North section of Great Barrier Reef Lagoon there was aeolian input of volcanic dust, transported by atmospheric and oceanic currents from Kuawe caldera in Vanuatu or from the Pacific-Indonesian region. In the dry season, trade winds blow from the east. These are capable of carrying volcanic dust from Pacific Rim volcanoes such as those of eastern New Guinea, the Solomon Islands, Bouganville and Fiji.

Studies of aeolian dust trajectories (Hesse & McTainsh 2003) suggest that there is very little dust from the Australian continent deposited onto the GBR shelf. Maher *et al*. (2010) (their Figure 1) show that the main dust paths in Australia do not pass over the northern GBR, so Australian aeolian deposition is probably minor. The modal size is silt and the mineralogy of Australian dust is essentially quartz > clay minerals> carbonate. McTainsh & Strong (2007) suggest that Fe is important for marine algae, that Fe arrives in aeolian dust, and that the reef is Fe deficient, suggesting there is not much aeolian input.

2.1.3 Marine Component of the shelf

Previous knowledge of the marine component is restricted to studies made south of Shelburne Bay and latitude 12^{o} S. Most of the existing works examined the inner-shelf ribbon reefs and the Queensland Plateau. This project is the first study conducted on the outer GBR shelf sediments of this area including the Great Detached Reef. Additionally it includes further data on the inner and middle GBR shelf sediments.

Autochthonous sediments (intrabasinal carbonates) are generally produced by corals, algae, diatoms, forams and molluscs. One of the most important biogenetic sources of sediment is *Halimeda*, algae generated carbonate sediments, identified on the mid-outer Great Barrier Reef shelf by Maxwell (1968), Orme *et al.* (1978), Drew & Abel (1986**)** in the region from 11° S to 15° S. The *Halimeda* dominated gravel fraction in the mid-outer shelf is 20-25 % with a total carbonate component of 75 % (Davis & Marshall 1985).

Maxwell (1968) categorized the carbonate sediments of Great Barrier Reef shelf into three categories on the basis of carbonate content.

a) Transitional facies (40-60 %) carbonate content

b) Impure carbonate facies (60-80 %) carbonate content

c) High carbonate facies (>80 %) carbonate content

The marine sediments are in-situ sediments. In the Great Barrier Reef Lagoon mostly skeletal and biogenic carbonate sediments are present and only minor amounts of inorganically-precipitated sediments are present. This is different from sediments reported from the Florida-Bahamas carbonate province (Maxwell & Swinchatt 1970). A simple reason for that is the extensive development of reef in the GBR generates more biogeneic sediments (coral algal, *Halimeda* etc). The GBR sediments have both allochthonous (formed due to the erosion of pre-existing reefs and transported by currents) and autochthonous carbonate sediments (formed within the marine environment and which may be or may not be transported). The Florida-Bahamas carbonate province has a vast variety of sediments but dominantly it has more inorganically formed sediments such as pisolitic and oolitic carbonate sediments. Skeletal and biogeneic sediments are also present, including *Halimeda*. The GBR Lagoon does not have pisolitic and oolitic sediments; rather skeletal and algal sediments dominate. These biogenic sediments of GBR Shelf vary from one section of the reef to another depending upon type of colony present in the area. Similarly the mineralogical and geochemical composition of the sediments also depends on the biological groups.

Milliman (1974) described the mineralogy and chemistry of both soft and stony corals and others in Atlantic Ocean. Mackenzie *et al.* (1983) also discussed the chemical and mineralogical composition of marine organisms (Table2.2). The corals are largely made up of aragonite, though some species are formed of calcite. The chemical composition of aragonite shows higher percentages of Sr and calcite has higher percentages of Mg.

	Carbonate skeletons	***Mineralogy***
Milliman (1974)	Soft and stony corals	Aragonite & Magnesia calcite
	Articulate & crustose coralline algae	Magnesia calcite
	Green algae *(Halimeda)*	Aragonite
Mackenzie (1983)	Corals	Aragonite (mostly) Calcite(rarely)
	Calcareous algae	Aragonite and Calcite
	Foraminifera	Calcite
	Molluscs & Bryozoa	Calcite and Aragonite

Table 2.2 Mineralogical composition of carbonate skeletons (modified from Milliman1974 & Mackenzie 1983)

The inner shelf sediments (Halifax Bay to Burdekin River) of the Great Barrier Reef shelf contain only 20-30 % average carbonate component, increasing up to 50 % between the 150-200 isobath (Belperio, 1978). Belperio (1978) attributes the increase to the survival of suspension feeders and the dominance of calcareous algae and foraminifera.

Mathews et al. (2007) carried out a comprehensive study of the inter-reefal environments of the GBR, providing an extensive regional synthesis of the surface sedimentology and geomorphology. They described the sediment facies of the inner shelf as dominantly terrigenous sand and mud of fluvial origin, forming a sediment wedge (Lambeck & Woolfe, 2000) about 5 m to 10 m thick extending only up to a water depth of 20-22 m (Belperio & Searle, 1988; Woolfe & Larcombe, 1998; Orpin *et al.* 2004). The concentration of mud varies and higher concentrations (> 60 %) occur within 50 km of coast and near northward opening embayments. Mathews *et al.* (2007) follow the Folk (1954) scheme to classify the sediments and give a wide variety of facies, being different proportions of gravel, sand and mud. The most abundant, covering almost 11 % of the area of the Inner Shelf is gravelly sandy mud. This and generally similar facies are exposed near headlands and in the open shelf. Gravel occurs near reef shoals and exposed tidal areas which have high carbonate and low sand concentration. Sand occurs in coastal and intertidal areas, mud near river mouths**.**

Less than 2 m thick mixed siliciclastic-carbonate sediments (terrigenous clays and shallow marine carbonate) comprise the middle shelf facies of Great Barrier Reef Lagoon, shore facing areas contain relatively higher amounts of terrigenous sediments (> 80 % offshore Cape York) while areas away from the shore have higher carbonate concentration. Three facies are recognized in the middle shelf, grading from slightly muddy sand to slightly gravelly sand and occur on open shelf and in inter-reefal areas. High gravel areas are offshore Temple Bay in the far north section, next to outer barrier reefs and protected shoals. Sand concentrates occur seaward of the ribbon reefs in the far north section whereas low concentrations of sand occur offshore Cape Weymouth. Mud dominated areas are offshore from Cooktown, north of Cape Grenville and offshore from Lockhart River.

The outer shelf facies basically consists of higher percentages of calcareous sediments, accumulated on inter-reefal seabed areas, where they are less than 1 m thick. Two facies are recognized, gravelly sand occurs in inter reefal areas around Swain Reef and slightly gravelly muddy sand occur on the open shelf. Gravel concentrates near the reef tract and at the shelf edge, while high sand concentrations occur on outer shelf near Swain Reef.

Mathews *et al.* (2007) found the gravel size fraction is derived from reefs and is composed of carbonate grains. A coarse lag of gravel forms due to winnowing of finer sediments by tidal current in the narrow passages between the reefs. Sand distribution and abundance are inversely proportional to the mud concentration, they found the distribution of sand is heterogeneous and consistent with the carbonate sand size fraction derived from the reef having undergone little dispersal, Apart from that sand is also generated from skeletal foraminifer, molluscs and *in-situ Halimeda*. Sand concentration in general is low on the inner and middle shelf in the central and northern Great Barrier Reef except in the far north section where high concentrations are found across the shelf, maybe due to the input of relict sands during seasonal flood input. Overall the offshore increase in sand is consistent with an increase in bulk carbonate.

Compared with sand, the mud concentrations are more or less uniform across the shelf except the lowest is in the outer shelf, while the highest mud concentrations occur in north facing embayment in the inner shelf.

Mathews *et al.* (2007) further explained that across the shelf there is shelf-parallel zonation of carbonate concentration in the sediments which varies from lowest (40 %) in the inner shelf to greatest in the outer shelf (60 %).

The outer shelf Carbonate *Halimeda* (green alga) sediments of the GBR shelf were studied by Maxwell (1973), Orme *et al.* (1978), Davies & Marshall (1985), and Drew & Abel (1986). *Halimeda* is a calcareous algae having significance for both the coral reef and coral sediments. *Halimeda* covered surface found behind the Great Detached Reef and formed the hummocky relief called the bioherms or banks or meadows (Hopley, 1978b & 1982). The full extent of the *Halimeda* bioherms is still unknown but they are more common on the northern Great Barrier Reef between 11° 50' to 15° 35' S from Raine Island in the north and up to southern limit of ribbon reefs, covered an area about 2000 km^2 behind the ribbon reef (Drew & Abel, 1985). The *Halimeda* banks are very thick and occur in a water depth of 60-100 m, with bedded structure extending down to the prominent seismic reflector A, recognized as Holocene–Pleistocene unconformity. The *Halimeda* banks are made up of packstone or wackestone along with gravel size unbroken plates of *Halimeda* in a mud matrix of carbonate and clay minerals (Orme *et al.* 1978b; Orme, 1985; Orme & Salma, 1988; Davies & Marshall, 1985; Marshall & Davies, 1988; and Searle & Flood, 1988). Davies & Hughes (1983) reported the presence of mud matrix on the northern Great Barrier Reef, consisting of both carbonate and terrigenous clay minerals, and they explained the clay as having been derived from major flooding with a recurrence interval of 5 – 10 years. Very little sign of movement was found in *Halimeda* sediments (Orme & Salama, 1988) consistent with Drew & Abel's conclusion (1983) that they were not derived from the reef itself.

The Pleistocene subsurface slopes gently underneath the *Halimeda* banks rising towards the reef structure. Searle & Flood (1988) explained that *Halimeda* bioherms do not need any antecedent surface for their growth which is different from the finding of (Orme & Salma, 1988). They found the upper parts of the Pleistocene sediments consist of cemented *Halimeda* sediments. The Australian Institute of Marine Sciences (2001) has confirmed the presence of cemented *Halimeda*.

The earliest known age of northern GBR *Halimeda* banks is 4750± 80 years BP (with an accumulation rate of 1.7 m Ka^{-1}) provided by Orme (1985) and Marshall & Davies (1988) from a thin layer of peat present on Pleistocene surface which is overlain by *Halimeda* gravels and carbonate sands.

2.2 Provenance of sediments

There are two major sources of sediments identified for the GBR Shelf with modern and relict origin. The terrigenous input may be riverine or remobilised relict deposits, carbonate sediments may be reworked or *in-situ* production of carbonate sediments (Mathews *et al.* 2007 and references therein).

Only a small percentage of terrigenous gravel carried by the rivers is transported to the shelf as most is deposited in the coastal and estuarine environments (Nakayama *et al.* 2002). The large amount of sand with minor mud transported to the coast during flood events (Bryce *et al.* 1998), usually restricted to the inner shelf and near river mouths. In the far north the sand derived from coastal dunes and catchments (Lambeck & Woolfe, 2000), from granite headlands Orme *et al.* (1978b) and relict bedforms on the sea bed Marshall (1977).

Luick *et al.* (2007) studied the residence time of the tracer sediments released at 320 places between Cape York and Hervey Bay and found that most of them encounter the outer-shelf reef matrix within 20 to 330 days. They also observed most of the tracers remain near shore for the longer period of time.

Wolanski (1994) found a large amount of the sediments is deposited in the subtidal and inter tidal deposits and forms a wedge of less than 5 m thickness extending up to water depth of 20 m. The finer sediment fraction of the wedge is resuspended in the shallow waters in low to moderate energy conditions and in deeper waters during cyclones (Gagan *et al.* 1987 & 1988, Wolanski & Ridd 1990 and Neil *et al.* 2002). Orpin *et al.* (1999) found at 20 m the sediments are resuspended only a few days in a year. In water depth less than 10 m the sediments are resuspended much more frequently, about 110 days in a year.

The inner shelf sediment wedge is made up of modern Holocene sediments including clay, silt and fine to coarse-sand. *Mathews et al.* (2007) found extensive areas of mud on the middle shelf and they explained that large river flood plumes are responsible for the distribution of mud in the middle and outer shelf or alternatively they represent the relict deposits of latest post glacial marine transgression, which form the present sea bed sediments.

The inter-reefal carbonate sediments of Great Barrier Reef middle and outer shelf are composed of modern and relict grains of skeletal remains of carbonate organisms usually molluscs, foraminifers, corals and *Halimeda* (Marshall & Davies, 1978; Brunskill *et al.* 2012). The concentration of each constituent varies across the shelf depending upon water depth, nutrient availability, temperature, salinity, turbidity and substrate type (Lees, 1975).

Flood & Orme (1988) suggested that wave action produces the carbonate sand on the outer shelf in large amounts especially around the reef. Relict *Halimeda* debris contributes a high proportion of the surface sediments in the middle and outer shelf of the northern Great Barrier Reef (Flood & Orme, 1988). Mathews *et al.* (2007) found areas of low carbonate concentration near the coast due to dilution of carbonate by locally sourced terrigenous sediment.

2.3 Facies

Marshall & Davies (1982) and Davies & Hopley (1983) suggested six Holocene bio-lithofacies, of which three are framework facies, two are detrital and one is a terrigenous facies. The terrigenous facies is siliciclastic sand with clay infills (inner shelf) forming the foundation of inner fringing reefs.

In some contrast to the previous facies models, Mathews *et al.* (2007) found more spatial variation in the concentration of mud in the inner shelf, with low concentration near river mouths and high concentration in north facing embayments. Regionally the concentration of mud is not continuous along the inner shelf and sand grains replace the mud as the dominant fraction in the far north. The sandy sediments form contiguous areas in the north Great Barrier Reef, which may be due to the northward transport and storage of sediments near the shore (Lambeck & Woolfe, 2000). Mathews *et al.* (2007) found large areas of the inner and middle shelves with spatial variation in carbonate concentration, and because of the extent of this distribution they consider it as a prominent feature of the facies distribution. Compositional changes in the surficial sediments makes their distribution patchy which reflects the presence of relict sediments and may cause abrupt changes in sediment facies.

2.4 Age of the Great Barrier Reef

Hopley *et al.* (2007) discuss the detailed structure and evolution of shelf edge reefs including the Great Detached Reef. The core collected from Raine Island comprises sand and shingle with occasional corals. A thick bed of cemented *Halimeda* was encountered at the top of the Pleistocene sequence. Radiocarbon dates of samples from the core indicate reef colonization 7 Ka ago. The dominance of *Halimeda* found on the submerged part of Great Detached Reef suggests that the environmental conditions during the last interglacial were similar to present day condition and favoured the upwelling of the nutrients, suitable for the growth of *Halimeda* (Young et al. 1994). The *Halimeda* banks have accumulated behind the ribbon reef. The highly variable Pleistocene surface with Holocene reef colonization is extensively iron stained.

Hopley *et al.* (2007) discussed the mangrove peats as highly organic units with macrofossils and considered they are good indicators of sea level change as they grow in the intertidal zones, and can be used for radio carbon dating. On the GBR, the mangrove peat is reported more than 0.15 m thick in the cores from the mainland. The radio carbon dates indicate a phase of mangrove accumulation between about 6 – 5 Ka which correlates with a big swamp phase in Northern Australia towards the end of transgression (Woodroffe *et al.* 1985).

The development of the GBR was influenced by the change in the sea level during the late Quaternary, growth of GBR started 450 Ka ago, but only episodic growth occurred when sea level rose and submerged the shelf, entire shelf submerged about 40-50 Ka only and for long periods the continental shelf was exposed and reef growth was restricted to the shelf edge and slope. These differences in the shelf's isostatic response to water load resulting from the different sea level histories have influenced the reef growth, geomorphological characters and the nature of reefs, so places where no emergences occurred, such as outer central shelf reefs, have different geomorphological characters compared to the reefs of the inner shelf where emergence occurred (Hopley *et al.* 2007).

Dubois *et al.* (2008) concluded that commencement of the Great Barrier Reef represents a major paleoceanographic change preserved in the sediments of north eastern Australia, and this commencement affects the environmental proxies (decrease in org-P and δ^{18}O with an increase in the abundance of large grains) which caused a non-reversible modification of the mean value of the proxy or frequency of its signal. They found an increased concentration of carbonate sediments (high magnesian calcite), aragonite and bioclasts) and a decrease in terrigenous material and organic matter. These are the mark of the beginning of Great Barrier Reef, which acted as a topographic barrier and trapped the material inshore. This is further confirmed by the decreased percentages of quartz and clay minerals in their XRD analysis. They proposed initiation of Northeastern Great Barrier Reef to have occurred between 560 and 670 Ka ago.

2.5 Summary The pre-reef landscape extended to the edge of the shelf, and a Pleistocene weathering profile formed on that landscape which is now the substrate for GRB shelf sedimentation. The Reef started growing about 600 Ka with an episodic growth history resulting from successive advances and regressions of the ocean throughout the Quaternary glaciations, with alternating episodes of marine deposition and erosion.

Latest sedimentation was initiated at the end of the last glacial maximum as the ocean covered the shelf, complete by 8Ka. Current terrigenous sediments, derived from Cape York east of the Great Divide, are mostly deposited after storms and floods. The *in situ* calcareous sediments are derived from the reefs or *Halimeda,* and also reworked from earlier post-Pleistocene shelf sediment.

Three zones are delineated across the Shelf: Inner, middle and outer having differing sediment styles and distribution patterns, mainly a gradation from terrigenous dominated muds and sands in the inner shelf to *Halimeda* and coral dominated carbonate sediments of the outer shelf and mixed silisiclastic carbonate sediments of middle shelf. Several lithofacies have been recognized across the shelf, marked by patchy distribution and complex variation.

Overall these studies did not include both along the shore and across the shelf transects. Detailed seismic survey, mineralogical and geo-chemical analyses of the shelf sediments is also not available. Most of the studies were carried out on the central Great Barrier Reef and concentrate on particle size variations across the shelf, hydrodynamics, geomorphology and sealevel change. Very little work has been conducted in the far north section and outer shelf of the Great Barrier Reef.

CHAPTER 3 METHODOLOGY

3.0 Introduction:

Both field and laboratory work were undertaken in this study. The fieldwork included collection of seismic data, vibrocores and sand surface bottom grab samples. The data were collected along transects parallel to and across the Great Barrier Reef Lagoon The laboratory studies included logging of cores and the textural, mineralogical and geochemical analyses of the samples.

3.1 Field Techniques:

3.1.1 Collection of seismic data:

Seismic data were collected along approximately W-E transects across the continental shelf (Fig 3.1). The positions of these transects were based upon factors including geomorphology, bathymetry, site accessibility and preconceptions (after Maxwell 1968) according to water depth sub-division across the shelf. Consequent to its very nature, the position of transects were biased by previous knowledge and practicalities. It was considered that more valuable regional information could be cost effectively obtained by several non-repeated lines over a considerable latitudinal range rather than fewer repeated lines over the same range.

This study is based upon the data collected during cruise number KG 9407 in 1994 aboard the James Cook University research vessel “R.V James Kirby”. The equipment used to collect the 375 km seismic record were a high resolution ORE uniboom and a 3.5 KHz PDR (Precision Depth Recorder) triggered at a rate of 0.25 seconds. In both cases data were recorded using thermal and carbon paper Epson EPC printer recorders. Other equipment utilised during the cruise included a Magellan 5000 GPS satellite navigator logger and a hand-held Magellan GPS. The PDR was mounted on the side of the vessel and was operated using a pulse length of 0.5 m. The uniboom worked at 380 J pulses, in connection with TTS TVG and annotator. A hifi VHS video recorder was used to record the raw signals.

The seismic data collected in 1994 consists of seven lines, both open and semi closed transects, this complexity is because of the morphology of the reef and the presence of a small narrow passage between the reefs in the outer shelf. The aim was to collect the data from different types of geomorphic features such as open reefs, closed reefs (Maxwell 1968) and the Great Detached Reef.

3.1.2. Collection of surface and sub-surface samples

In general the location of the samples was based on the position of seismic lines and therefore to the sampling factors that govern these lines. The total number of cores that could be taken was limited.

The sediment samples were collected by using Vibrocores with a 5 m long aluminium barrel and a frame supported Van Veen Grab Sampler from which one foot short cores were acquired using an aluminium barrel. For shallow water sediment samples a hand operated Van Veen Grab was used.

Fifteen vibrocores, twenty-eight short cores and eighty surface grab samples were collected during the two cruises (Figure 3.1)

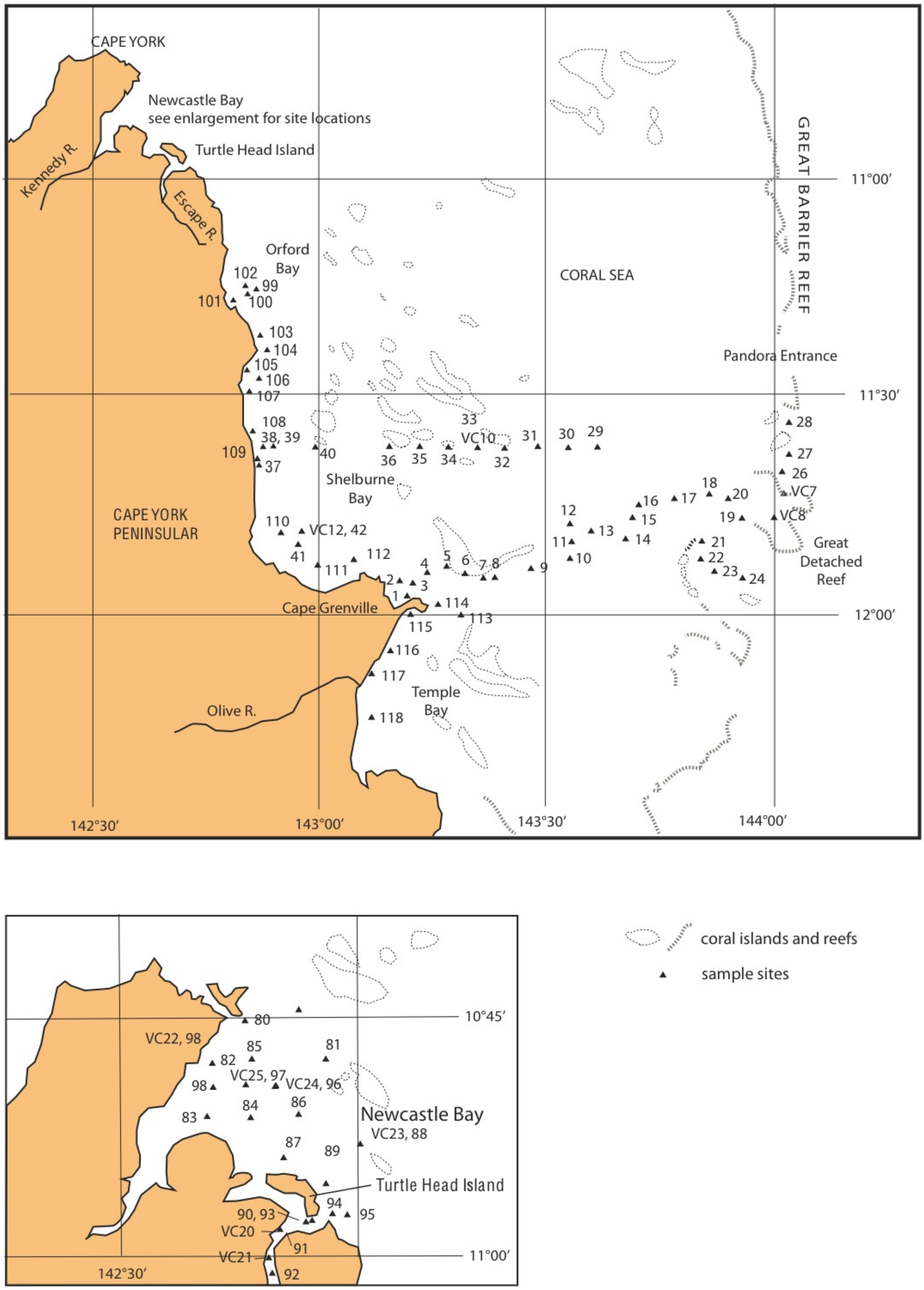

Figure 3.1 Location map showing sample sites and numbers

3.2. Laboratory Techniques:

3.2.1 Cutting and Logging of cores:

Vibrocores were cut into one-meter sections and split longitudinally to allow their logging and analysis. All short cores were also split longitudinally. Both the vibrocores and short cores were logged petrographically and stratigraphically, photographed and sampled. Both types of cores were then sealed, labeled, arranged systematically and stored in core boxes in a centrally air condition laboratory until they were logged and then in a cold storage room. For both long and short cores detailed logs were prepared (Appendix 1).

3.2.2 Grain size analysis:

Sub-samples were collected from all vibrocores, short cores and surface grab samples. Samples from vibrocores were collected at points reflecting different depths. These samples were passed as slurries through a 2mm sieve to remove the coarser debris. After sieving; the slurry was placed in tap water and dispersed ultrasonically for 30 seconds. Grain size abundances were determined for 32 size classes, over a range of 4-2000 microns using a Laser diffraction Malvern Mastersizer X at the JCU Geology Department. Two different magnification lenses were used for analyses, a fine detail lens of 300 mm focal length covering the size range 1.2-600 µm and a coarse detail lens of 1000 mm focal length covering the size range 4.2-2000 µm.

3.2.3 X-Ray Diffraction Analysis (XRD):

Approximately 10 g of sieved samples were required to perform both the general and clay mineral analyses. The 10 g of sample material was split into two 5 g portions. To perform the analysis of the general mineralogy one of the 5 g portions were gently crushed with a pestle and mortar to powder. It was then packed into a plastic cavity mount.

The other 5 g portion was used for clay mineral analysis. Oriented mounts were prepared for clay mineralogy. A pipette analysis was carried out and sub-samples were taken out at specific times and depths as described below (Lewis & McConchie, 1994). The sample was placed in a 500 ml beaker and then distilled water and a pinch of peptizer, Calagon (Sodium hexametaphosphate), was added. The slurry was then dispersed, using an ultrasonic bath for 5 minutes. The suspension was left for 3 hr and 37 minutes (time calculated from Stokes Law at 25 ^{0}C). Temperature plays an important role in pipette analysis as it effects the viscosity of water which in turn effects the settling velocity (Lewis & McConchie, 1994). The upper 5 cm of the fluid suspension was withdrawn using a pipette and filtered through a 4-5 micron-G/F-C paper using a vacuum filtration system. Then filter paper was air dried in an isolated (dust free) room and then mounted onto a glass disc.

XRD was carried out on the samples by using a Siemens D5000 diffractometer operating at 40 kV and 30 mA at the James Cook University Advanced Analytical Centre (JCU-AAC).The bulk samples were run from 4 to 70^0 2θ. For the clay extracts, five XRD traces were run for each sample following the technique of Moore & Reynolds (1989). Each treatment (i.e. simple air-dried, glycolated, glycerated, heated up to 350 ^{o} C and at 550^o C overnight). The treatment allows the determination of specific type of clay mineral present. Each variety of clay has its own specific reaction to each process as shown in Table 3.1

Table 3.1 Types of clay minerals and treatment required for their identification (JCU laorartory protocol).

Type of Treatment	**Types of Clay minerals**				
	Kaolinite	**Illite**	**Smectite**	**Chlorite**	**Mixed Layers**
Air dried	7 Å	10 Å	14 - 15 Å	~14 Å	14 – 32 Å
Glycolation	7 Å	10 Å	17 Å	~14 Å	Behaviour depends upon mixed layer type (Starkey 1984)
Glyceration	7 Å	10 Å	17 Å	~14 Å	
Heated to 350 ^{0}C	7 Å	10 Å	10 Å	~14 Å	
Heated to 550 ^{0}C	Destroyed	10 Å	10 Å	~14 Å (increases in intensity)	

Air-dried samples were scanned from 1.2^o 2θ to 30^o 2θ, with steps of 0.02^o at a rate of 0.5^o/min. However, due to the thickness of the sample or filter paper an error of ± 0.2 ^{o}(2θ) was introduced, recognized by displacement of peak position. Quartz peak positions are invariant because the quartz structure tolerates no significant atomic substitutions. Thus, the quartz pattern is a built-in internal standard against which can be estimated the accuracy and precision of peak positions for the other phases present.

The error value was added or deducted from every data value to give the true peak position. From the 2θ values of the peaks the *d*-spacing between the crystal lattice places were then computed using the Bragg Equation $n\lambda = 2d \sin\theta$ ($\lambda = 1.54178$ A for $Cu_{K\alpha}$) or by using Fang and Bloss (1966) X-ray diffraction tables for Cu $K\alpha$.

For glycolation the samples were arranged over a bath of ethylene glycol at 60^{o} C overnight. If smectite is present then the interlayer water is displaced by the larger ethylene glycol molecule. This results in expansion of the smectite structure and displacement from 15 Å to 17 Å. The glycerol treatment was followed by glycolation, which has a similar effect as to that of ethylene glycol except that vermiculite is expanded which does not occur on glycolation. After glyceration the samples were re-run. The samples were heated then at 350 ^{o}C overnight and then re-run in the XRD machine. They were then heated at 550 ^{o} C overnight. Heating to 550 ^{o} C brings about the collapse (10 Å) of the vermiculite and smectite structure. Illite shows no change upon glyceration and glycolation (Deer *et al.* 1983) nor does kaolinite. However, kaolinite is totally collapsed by heating up to 550^{o} C. Chlorite is not affected by any of these treatments.

After identification of various types of clay mineral from the XRD traces, a semi-quantitative estimation of the abundances of clay mineral, was made, on the basis of surface area and peak height for each type.

Some of the samples were re-run for both bulk and clay mineralogy in the XRD lab of the Geology department of Australian National University. The procedure for those samples is as follows.

For bulk analyses, raw samples were dried first, coarsely crushed in the tungsten carbide mill and then fine ground in mortar and pestle with acetone until the sample was no longer gritty then allowed to dry. Dried sample was then put randomly into a U-shape sample holder to be loaded into the Seimens D500 X-ray diffractometer.

For clay mineral analysis, 33 g of sodium hexa-metaphosphate and 7 g of anhydrous sodium carbonate were dissolved in distilled water to make a litre of solution. The sample was reduced by sieving and crushing to grains averaging a few millimetres in size. The sample was then ultrasonically disaggregated for 3 minutes in distilled water, suspended solids were decanted, and the process repeated until the supernatant was clear and the electron conductivity was < 0.4 mS. Then the dispersing solution was added and the sample was tumbled end over end for 16 hours. The suspended sediment was transferred to a settling cylinder and sub-samples were taken according to the Stokes law. Each sub-sample sample was extracted to filter paper by vacuum filtration. Magnesium chloride (0.1 M) was sucked through sample and then the sample was washed with deionised water and dried. The sample was inverted onto a glass slide, ready for XRD (Moore. and Reynolds 1989). The Mg-saturated sample was then treated with ethylene glycol vapour for ~24 hours at 60 ^{o}C and run through XRD again. Then sample was heated to 350 ^{o}C for 3 hours.

3.2.4 X-Ray Fluorescence Analysis (XRF)

Samples were dried at 60^{o}C overnight. Ten grams of dried samples were pulverised with a "Rock Lab" Minimill using a partially stabilised zirconium bowl and lid. These heads are very efficient and the polished surface of the components reduces sticking and jamming effects when clays and hydrated minerals are being ground for 5-15 mins, depending upon the nature of the sample. This mill may contaminate the sample with Zr, Mg, Hf and possible traces of some rare earth elements and Th and U. Each pulverised fraction was split into 6 g and 4 g portions for minor trace elements and major elements analysis respectively.

For major element analysis by XRF fusion discs were made up. The powdered sediment samples were fused with a Norrish-Hutton mixture (47% lithium tetraborate, 36.7% lithium carbonate borate, and 16.3% Lanthium oxide), and the melt cast into a mould. Platinum 5% gold alloy crucibles were used for fusion. The samples were fused in a furnace at a temperature of 1100^{o} C for 10-12 min with swirling of the molten mixture to homogenise the sample. Molten samples were poured into a graphite mould held on a hot plate at 200^{o} C. An aluminium plunger also heated up to the same temperature was then lowered into on the mould to press the bead into a flat disc (Potts 1996). The glass disc was annealed at 200 °C for 10 minutes on its mould before cooling to room temperature. The top surface/side of disc were used to analyse the major elements. Synthetic standards were also prepared in the same manner.

Minor elements were determined by XRF following sample preparation as boric acid backed pressed pellets. The five grams of finely milled sediment were pressed to 20,000 psi (1400-kg cm^{-2}) or more to form a pellet. Standards were prepared in the same manner so as to achieve the same packing density. For both major elements and minor trace elements, the samples were analysed against a calibration consisting of approximately 50 CRM's (certified reference material). Siemens SRS 3000 and Siemens SRS 303 XRF's were used to run samples at the JCU Advanced Analytical Centre. Overlap and other calculations were carried out by the Advanced Analytical Centre to refine the results to give the correct concentration of all-major elements and minor trace elements.

3.2.5 Carbon analysis:

The total carbon content of the sediments was determined using a Leco SC-444 DR which is a non-dispersive infrared, digitally controlled instrument at the JCU Advanced Analytical Centre. The samples were dried at 60^{o}C in an oven overnight and 5 g of sample was pulverised in a Rocklab minimill with a partially stabilised zirconium bowl and lid. Three one-gram samples were taken from the powdered material for analysis.

3.2.6 Microprobe analysis:

The core sub-samples and grab samples were air dried before mounting. The alumunium mounting stubs were first coated with a thin layer of carbon paste. The dried individual grain and aggregates were then mounted on the stubs by dropping or pressing them onto the paste. The layer of carbon paste was thin enough to prevent the grains sinking into it. When the paste was fully dried the sample was coated with a conductive layer of gold. The thickness of the coating varied from sample to sample. This is necessary as carbonate sediments and *Halimeda* type sediments are porous and need a thicker coat than more compact geological samples. However, there are several disadvantages when using a gold coating when performing energy dispersive analysis. Firstly, the presence of Au L lines may obscure the presence of elements such as Si, S and P if present at lower concentrations (<0.1 - 2 wt %). Secondly, preferential absorption of the lower energy X-rays (Na, Mg, Al, Si) contributes to unreliable results when attempting quantitative analysis.

The core sub samples were prepared for thin sectioning by solvent exchange and polyester resin impregnation (Camuti and McGuire 1998). Samples were placed over an acetone bath in a sealed container for about four weeks, until acetone had replaced the water in samples. The "Dried" samples were then impregnated with a slow curing polyester resin mix comprising clear casting resin, methyl methacrylate monomer, and cumene hydroperoxide. To ensure complete impregnation, the samples with resin were placed under vacuum (at –80 k Pa) for four hours. They were then allowed to cure for a period of about four weeks, until the resin was colourless and hard. The hardened impregnated blocks were sliced and prepared as polished thin sections.

A total of approximately 150 samples from cores and grabs were analysed under the JEOL JXA-840 Microprobe at the JCU Advanced Analytical Centre operating at 15 kV. The samples were collected from all cores representing different depths and from all surface grab samples. Energy Dispersive Spectroscopy was used to obtain qualitative chemical analysis of selected grains and minerals and the output was displayed as a spectrum showing the different intensities of element present. Photomicrographs were also taken at the same time by a Mamiya 120 camera with Kodak technical Pan film. Both photomicrographs and analysis were taken and done on selected grains, pore minerals and cement and matrix, both in secondary electron (SEI-Surface Topology contrast) and Back scattered electron (Atomic Number Contrast) modes.

3.2.7 Mass spectrometry:

Analyses for scandium were conducted using a Varian Ultramass Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) in the JCU Advanced Analytical Centre. This technique was used because in XRF analyses the peaks from the major element calcium interfere with those from the trace element scandium.

Sediment samples were digested with boiling in 10 M concentrated Hydrofluoric acid, then dried to incipient dryness. Two ml of concentrated nitric acid was then added to the dried sample. The volume was made up to 100 ml (volumetric flask) with Milli-Q water before analysis. The instrument was calibrated with the standard reference material AGV-1. The AGV-1 certified values were 12.1 ppm Sc and the values determined were 12.30 -+ 0.27ppm Sc.

CHAPTER 4 SEISMOLOGY

4.0 Introduction:

In this chapter, the details of seismic facies both regional and local are explained. This study is preliminary seismic work on the far north section of the Great Barrier Reef.

4.1 Collection of Seismic Data

This investigation has been conducted using a high-resolution ORE uniboom and 3.5 kHz precision depth recorder. Data were recorded in both cases using thermal and carbon paper EPC (two)-printer recorders. For navigation a Magellan 5000 global positioning system (GPS) satellite navigator logger and handheld Magellan (GPS) were used. A hifi video recorder was used to record the raw signals acquired by the uniboom. Transects lines are shown in (Fig 4.1). The acoustic velocity in the seawater varies from 1450-1570 m/sec and depends upon temperature, salinity and pressure (depth) (Fairbridge 1966). In the case of shallow seismic work, the salinity of the open ocean (*ca* 35 ‰) is assumed to be constant. The temperature of shallow water (*ca* 25^{o} C) is also taken as a constant. Depth has no significant influence on velocity down to 200 m, therefore the seismic velocity in the sediments is taken as 1500 m/sec (the same as through seawater) and this value was used to calculate depth and the sediment thickness from the primary reflector A in this study. Consequently, a slight, though negligible error is expected. Calculation based on the figure 1500 m/sec shows each timing line is equal to 25 ms (0.025 s) interval which corresponds to an interpreted depth of 18.75 m per timing line. Unfortunately the seismic data set for KG 9407 is now missing, although results presented here were generated before data were lost. Lines 1, 2 and 5 were fully recorded, however although lines 3, 4 and 6 were recorded, there were gaps in the previously available hard copy traces. This means that the profiles of lines 3, 4 and-6 could not be accurately located to their cruise track.

4.2 General Aspects of Acoustic Survey

In a continuous seismic reflection system the acoustic pulse reflects from the sediment water interface and also penetrates into sea floor sediments. The signal therefore, images shallow sub-surface layers and structure. The configuration of the seismic reflection relates to the geometric pattern of the reflectors, which are interpreted to explain the configuration of the beds producing the reflections.

The geological interpretation of seismic reflection patterns depends upon the reflection, continuity, amplitude frequency and velocity. Once the reflection pattern and other parameters are delineated, that seismic unit is interpreted in terms of lithology, environmental and depositional processes (Bates & Jackson 1987).

The variability of sub-surface reflection patterns depends upon the composition of the sediments, topography, roughness and sub-surface structure. Usually hard surfaces give good reflections whilst muddy bottoms give poor reflections (Fairbridge 1966).

4.3 Regional Seismic Stratigraphy

Prior to this work, some detailed seismic investigations were carried out in the Great Barrier Reef Lagoon north of Cooktown. (Orme *et al*., 1978, Orme1985; Belperio 1983; Davies & Marshall 1985; Marshall & Davies 1988; Orme & Salama 1988).

Orme *et al*., (1978) and Orme & Salama (1988) explain the seismic stratigraphy of the northern Great Barrier Reef on the basis of Holocene sediments overlying a pre-Holocene erosional surface. The middle-outer shelf Holocene sediments show three seismic facies.

1. Seismically opaque reef rock.

2. Semi-opaque homogenous back-reef coralgal facies.

3. Bedded mounded algal *Halimeda*[1] banks lithofacies. This facies is further sub-divided into three units on the basis of seismic response:

3.1 weakly parallel, discontinuous, discordant internal reflector, mounded upper surface, low – medium amplitude, average 7.5 m thick;

3.2 parallel, continuous, internal reflector with an upper mounded surface, medium

amplitude, overlying unit 3.3 or the pre-Holocene surface where unit 3.3 is absent; and,

3.3 transparent-semitransparent, thinly developed, discontinuous unit overlying the pre-Holocene surface.

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[1] *Halimeda* is green algae and is the primary producer of calcareous sand-mud size sediments in the reefal environment. *Halimeda* forms bioherms and bank type morphology.

4.4 Seismic Stratigraphy of Far North Section Of the Great Barrier Reef

4.4.1 Introduction

Seismic lines during cruise KG 9407 were run in 1994, named L1-L7 and these comprise two sampling transects (T1 & T2). T1 includes lines 3-7and T2 includes lines 1& 2 which were made from reef to shore (Figure 4.1). A third transect, T3, was run parallel to the coast during cruise KG 9305 in 1993, and only sediment samples of that cruise were analyzed and included in this thesis.

Reflector A is an unconformity which occurs between Holocene and Pleistocene sediments (Figure 4.2 and Figure 4.3). This surface was interpreted as the pre-Holocene erosional surface described by Orme *et al*., (1978) and named as “Reflector A”. This terminology is used throughout the thesis. The seismic trace has a different response above and below which shows change in sediment type and this change is very distinct.

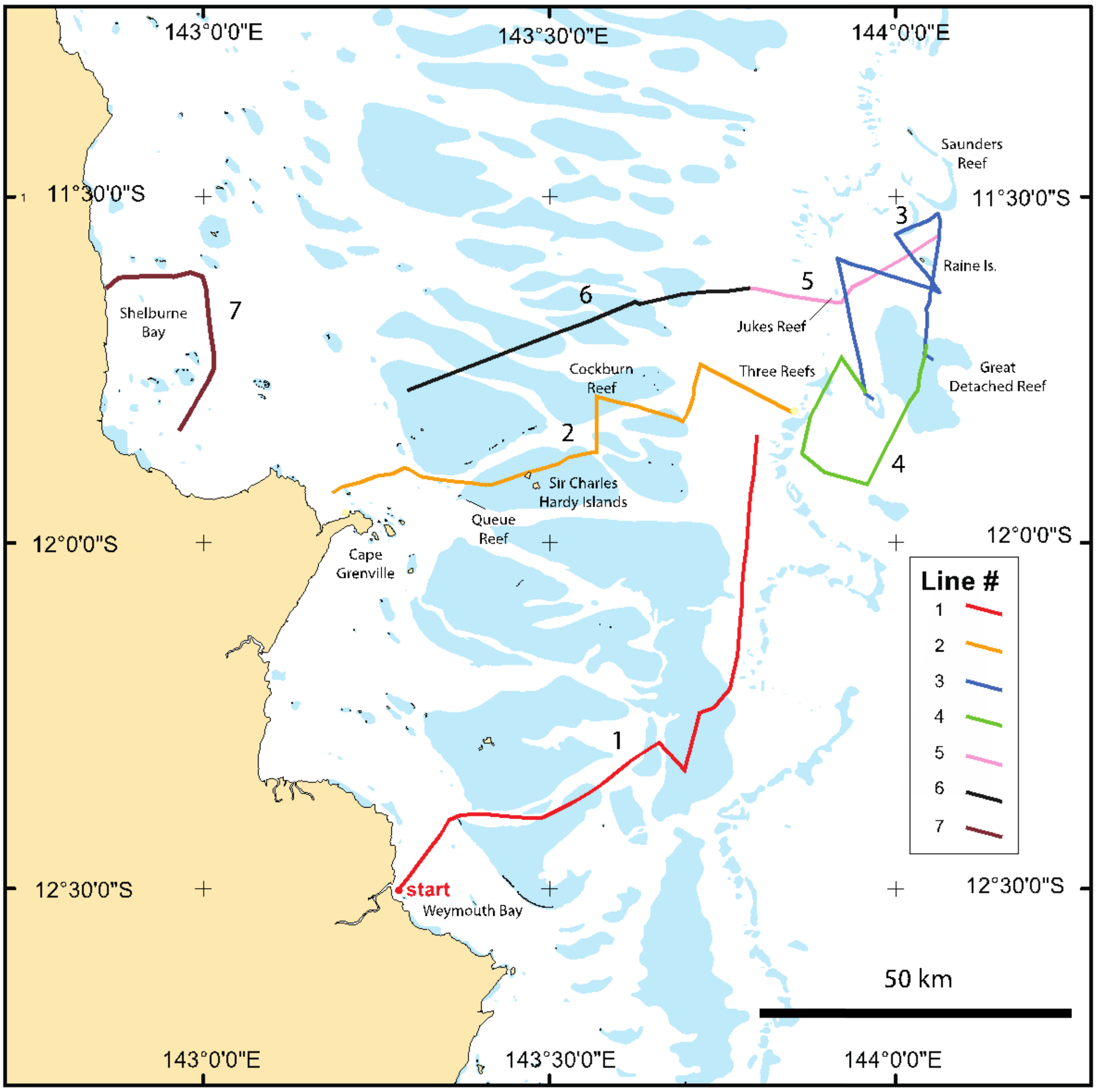


Fig 4.1 Map showing the seven seismic lines

4.4.2 Results and Description

4.4.2.1 Line-1 and Line 2

Line 1 in transect T2 is approximately 105 km long, starting from Weymouth Bay and finishing near the Three Reefs. Reflector A occurs as a horizontal continuous, distinct reflector both in PDR and uni-boom traces. The sea-bed morphology along the line includes channels, mounds, reef islands, a terrestrial wedge out near shore and *Halimeda* bioherms (Figure 4.2). Throughout the line seaward, broad and deep, symmetric to asymmetric (2-18 m) channels were mapped. Between the channels, single (4 – 23 m high) and double mounds (15 m high) are present. About 20 km offshore from Weymouth Bay a single sediment wedge out >3 m thick occurs which thins seaward, finishing where the reef starts. Farther seaward, more channels and mounds occur. Twelve to fifteen km farther along this line (NE), this surface is overlain by mounds of *Halimeda* bioherms. The thickness of the *Halimeda* banks (bioherm) varies from 3–12 m, and between these bioherms there is a very broad depression ~50 m deep. Here the sub-bottom Reflector A occurs very near to the seabed or at the seabed. Farther along the seismic line low amplitude *Halimeda* banks occur with small one or two coralgal mounds. *Halimeda* bioherms are bedded and acoustically transparent.

Line 2 is in transect (T2), 72 km long, being the return to shore continuation of line 1. *Halimeda* banks along this line vary in thickness from 2 m to 11 m. Similar to Line 1, deep depressions (~30 m) occurs between the *Halimeda* bioherms. Reflector A, at the edge of the depression, is only ca 2 m below the sea floor. Further westward *Halimeda* bioherms become thinner and mounds become flat with a sheet-like structure and overlie the reef.

Further west is the reef platform of Sir Charles Hardy Island. Reflector A is continuous and delineates more reefs and the platforms including Cockburn reef and Queue reef and platforms. Further shoreward, a few small mounds occur where the reflector is ~ 4 m below the sea floor.

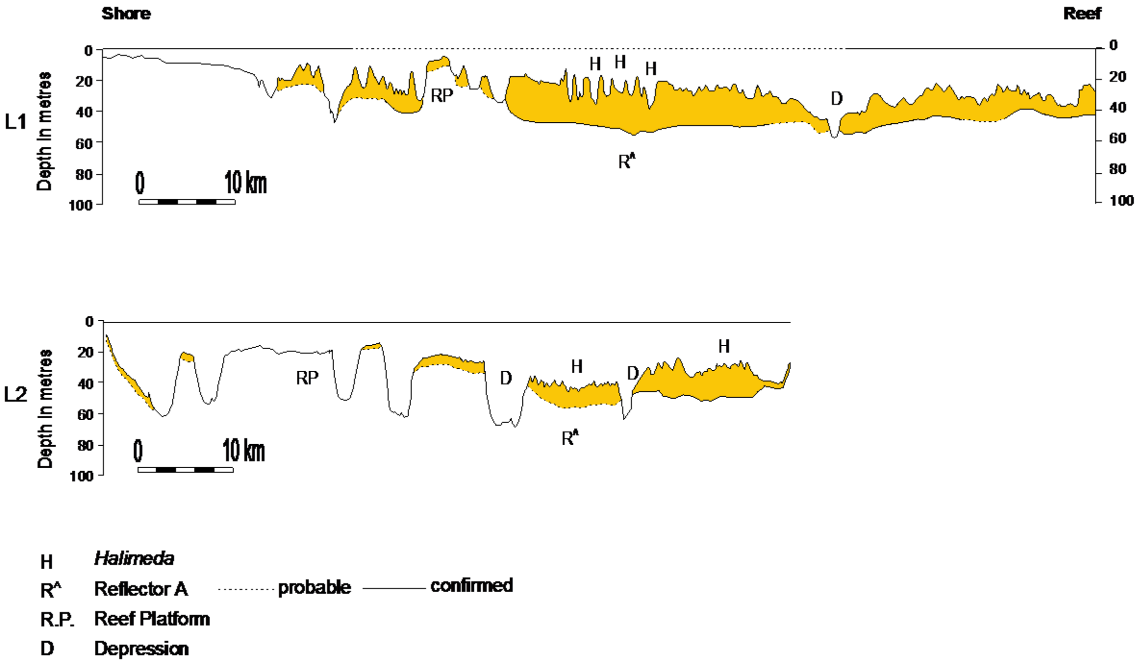


Figure 4.2 shows the interpretation of the seismic profiles Line 1 and Line 2 along Transect T2. Yellow shading indicates Halimeda sediment.4.4.2.2 Line-3 and Line-4

Both seismic lines 3 and 4 are complex closed transects of T1. Line 3 extends north of the Great Detached Reef and covers Raine Island. It continues farther west near Jukes Reef and then south to cover the Great Detached Reef. Line 4 is the continuation of line 3. It runs SW-NE from the lower inner end of the reef to its upper inner end. Only uniboom data were recorded, as there is very little or no penetration of the 3.5 kHz signals in the mid-outer shelf.

Throughout Line 3 high relief semi-opaque reef features occur. The tops of the reefs are covered by coral algal and *Halimeda* growth. The sub-bottom Reflector A occurs at 20-25 m below the sea floor.

Line 4 is a small line showing small coralgal pinnacles (mounds) on and around reefs and low amplitude growth of *Halimeda*, probably on the reef flank.

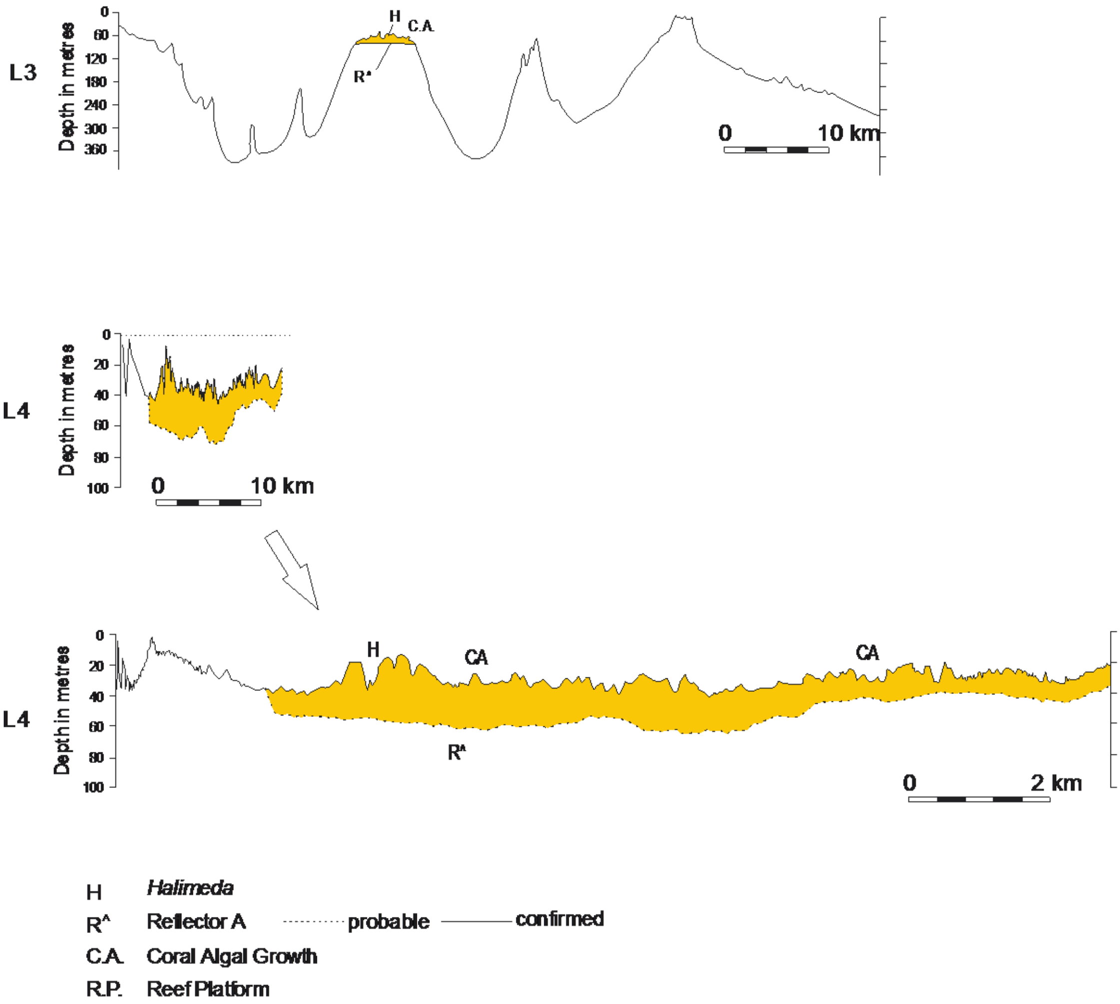


Figure 4.3 Interpretation and profile section of seismic lines 3 and 4 along transect T1. These two profiles cannot be accurately located to their cruise tracks due to technical reasons however they show important evidence about the sediments deduced from the seismic results in that region.

4.4.2.3 Line-5 and Line-6

Seismic Lines 5 and 6 are part of transect (T1). Line 5 extends from north of Raine Island towards the shore, and Line 6 is the continuation of Line 5 farther westward. The seismic traces along Line 5 show a reef connected carbonate wedge-out ~70 –80 m thick, thinning towards the shore. The top of the seismically semi-opaque reef shows coral algal growth only and no traces of *Halimeda* were observed.

Line 6 extends 47 km from shelf to shore. The Reflector A is more or less horizontal and continuous. It occurs very near or at the seabed where reef and reef platform occur. A few small mounds are present nearly in the middle and towards the end of the line.

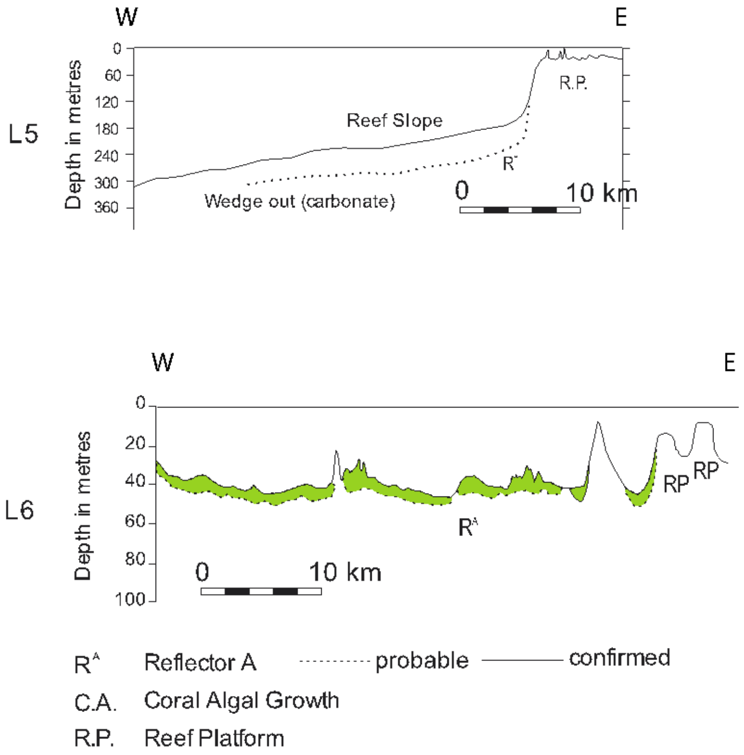


Figure 4.4. Interpretation and section of the seismic profile along transect T1. This profile consists of two seismic lines L5 & L6. Both lines were well recorded but for L6 the start & end points are not known for technical reasons. Green shading indicates coral algal sediment.

4.4.2.4 LINE-7

Line 7 runs parallel to the shore in Shelburne Bay. Reflector A is indistinct, horizontal, discontinuous and only 2 –3 m below the sea floor. The whole trace is very noisy and shows very poor reflections over a muddy bottom, compared with the good reflections of the hard bottom in the outer shelf. It is marked by the presence of fine suspended sediments, and the sediment samples confirm the presence of sandy-mud (see chapter 5). This seismic trace is not very clear and this type of appearance is common in the case of suspended fine sediments.

4.5. DISCUSSION:

The Holocene seismic stratigraphy reported in this study of the Far North Section of the Great Barrier Reef Lagoon is consistent with the previous studies carried out in the northern, central and southern parts of the Great Barrier Reef lagoon, and with lagoons in the Java Sea (Indonesia) and Caribbean Sea.

The interpretation of the seismic data indicates an inner shelf wedge-out of terrigenous sediments that thins seaward. This Holocene wedge-out overlies a regional seismic reflector (Reflector A) which represents the subaerialy exposed land surface produced by marine regression during the shelf emergence of the last glaciation maximum and subsequent erosional activity triggered by lowering of the sea level and fluvial erosion cutting channels. These channels later filled during the Holocene transgression as recognized further south (Orme *et al*., 1978, Searle 1983, Salama 1990, and Harris 1994). Following the interpretation of these authors, the subbottom Reflector A thus marks an unconformity between Pleistocene and Holocene sediments. The Holocene sediment wedge thins seaward from the present shoreline as a result of distance from the sediment source, dispersion pattern and the morphology of the seabed. The variable thickness of the sediments is seen in the cross sections (Figure 4.2). In these sections the thickness varies from a few metres to more than 30 m. At some places, there is no sediment accumulation, that is, Reflector A reaches the present day seabed.

The mid-outer shelf is characterised by *Halimeda* bioherms, which form banks on the shelf, ranging in thickness from 3-12 m. The outer shelf is dominated by a continuous barrier of reefs, reefal mounds and platforms. Deep depressions (20-50 m deep) and channels are present between and around *Halimeda* bioherms and reef platforms.

The seismic profiles suggest the maximum thickness of *Halimeda* bioherms in the Far North section of the Great Barrier Reef is *ca* 12 m. In other parts of the northern Great Barrier Reef it ranges up to 20 m (Davies & Marshall 1985; Orme 1985). In the southern Great Barrier Reef the maximum thickness is 14 m. Phipps & Roberts (1988) studied *Halimeda* banks in the Java Sea Indonesia, where they found that in the northern banks the maximum thickness is 20 m and in the southern banks it is 50 m. Hine *et al*., (1988) report more or less the same type of bioherms in the SW Caribbean Sea and found the maximum thickness is 30 m. This may suggest a relatively slow rate of growth in the far north section of the Great Barrier Reef.

Generally in the whole Great Barrier Reef the *Halimeda* bioherms occur at a depth of 20 – 50 m but in the Southern Great Barrier Reef small patches occur at 100 m depth.

Searle & Flood (1988) think the *Halimeda* banks in the southern Great Barrier Reef complex are not spatially related to banks of the northern Great Barrier Reef. The growth of the Southern complex depends upon the topography of the surface (flat lying surface) and not the upwelling of nutrient rich water as in the northern Great Barrier Reef. Drew & Abel (1985) suggest that in the northern Great Barrier Reef the upwelling and the availability of nutrients are the responsible reason for the growth of *Halimeda* banks. Phipps & Roberts (1988) suggest the same reason for the growth of the K-banks in the Java Sea Indonesia.

In previous studies of the Great Barrier Reef lagoon, the *Halimeda* bioherms were found to decrease in size (low amplitude banks) towards the west or (landward) and finally become flat. Seismically they are transparent zones (Davies & Marshall 1985). The results of the present work are consistent with this.

Davies & Marshall (1985) calculated the growth rate for *Halimeda* banks as 1-3 m / 1000 yrs with the oldest age around 5000 yrs in the Northern banks. The growth rate is 2-3.5 m / 1000 yrs for Swain Reefs *Halimeda* bioherms in the Southern Great Barrier Reef with an age of 5000 yrs. Phipps & Roberts (1988) calculated the growth rate for eastern Java *Halimeda* banks at 0.30 m - 0.60 m /100 yrs. From the observed thickness of the *Halimeda* bioherms (3 to 12 m) and assuming an age of 5000 years, their growth rate in the far north section of the GBR Lagoon is of the order of 1 to 2 m/1000 years.

The analysis of the grab samples taken from the *Halimeda* bioherm (Ch. 5) confirms that the bioherms are made up of *Halimeda* sediments and its debris in a lime mud matrix. The previous work of Davies & Marshall (1985) suggests that the *Halimeda* banks have a sedimentological composition of 20-25% terrestrial material (clays) and 75% carbonate material including *Halimeda* plates, Molluscs and Foramanifera segments. From the southern Great Barrier Reef *Halimeda* banks no clay minerals are reported. The Java Sea *Halimeda* bioherms are composed of *Halimeda* plates in a lime mud matrix with a reasonable amount of calcareous foramanifera tests (Phipps & Roberts 1988; Roberts *et al.*, 1988).

The outer shelf has high relief reef rocks. These reefs are seismically semi-opaque. The reflector A is present at the tip of these reef rocks. The top-most part of the reef is covered by coralgal and

Halimeda growth but beyond the shelf edge there is no trace of *Halimeda* in seismic traces, consistent with the work of Drew & Abel (1985). According to Davies & Marshall (1985) in the northern Great Barrier Reef near Cooktown the eastern edge of the bioherms is 1-2 km behind shelf edge reefs. The part of the shelf shoreward from Raine Island shows no growth of *Halimeda*. Drew & Abel (1985) explain the presence and absence of *Halimeda* in the Great Barrier Reef Lagoon on the basis of nutrient supply from the Coral Sea. Tidal jets cause upwelling but cannot lift the nutrient-rich water from below the thermocline or in shallow channels which are less deep than 50-60 m. The passage near Raine Island is no more than 40 m deep, so a tidal jet cannot lift nutrient-rich water. This explains the absence of *Halimeda* in that part of Great Barrier Reef lagoon.

Further discussion of the interpretation of seismic results will be deferred until after description of the sedimentology, mineralogy and geochemistry of the sediments.

CHAPTER 5 SEDIMENTOLOGY

5.0 Introduction:

The Great Barrier Reef lagoon has an enormous areal extent and its geological conditions are diverse from one place to another. Different geological settings contribute sediments having different size distributions and different chemical and mineralogical compositions. The nature of these sediments provides insight into processes that occur on the mainland, weathering and erosion and in the depositional environment of the ocean across the lagoon.

Grain size analysis is used widely to elucidate transportation and depositional processes, and post-depositional modification of sediments. The integration and interpretation of size analysis is also useful for the correlation of geologic units and depositional environments (Bradshaw *et al* 1994; Woolfe 1995). The aim of size analysis is to produce data to help establish a facies analysis of the area.

XRD and microprobe analyses are used to determine the mineralogy, allowing inferences about the provenance of the sediments. Quantitative mineralogy and SEM have been used to help interpret the depositional environment. Geo chemistry is reported in Chapter 6; conclusion drawn from all the results of this thesis are therefore deferred until Chapter 7.

5.1 High Resolution Grain Size Analysis

Size data obtained from the Malvern sizer showed a complex pattern of sedimentary textural characteristics in the study area, varying between uni-modal, bi-modal and poly-modal in a few samples. Such a variety of modes indicate differences in the processes of transportation, re-suspension, mixing, sediment modification and deposition, and so indicate the presence of different environments in this section of the Great Barrier Reef shelf.

5.2 Regional sedimentary and Mineralogical framework

The regional sedimentary cover in the study area varies widely and shows diversity of sediment type. The coastal and beach area includes white fine quartzose sand, coarse mixed shelly quartz sand, sand-flats and intertidal mud-flats. The mid-outer shelf is marked by the presence of *Halimeda* generated sediments. The outer shelf shows extensive reef growth and is dominated by reef-generated sediments. Such sediments show a variety of sizes from gravel to mud. Transition between sediment types adds to the complexity of the sedimentology of the Great Barrier Reef Lagoon.

From north of Weymouth Bay to the tip of Cape York Peninsula the inland geology is diverse. In the Temple Bay region, the main source of terrigenous sediments is the Olive River, which cuts the Quaternary (river and flood) plain alluvium (silty-clayey quartzose sand) and drains into Temple Bay. Further north of the Olive River an extensive coastal area is marked by the presence of northwest trending parabolic dune fields. A thick white residual sand cover~~s~~ overlies Mesozoic and Cainozoic sandstone that crops out to the west of the dune field. The sand dunes unit merges with alluvial sediments, transported dune sediments and coastal mud.

The explanatory notes for the Cape Weymouth 1:250,000 geologic map (Willmott & Powell 1977), and "The Regolith of Cape York Peninsula" (Pain *et al*. 1997) provide details of the coastal geology and near shore sediment. Near the mouth of the Olive River coastal alluvium (mud) forms mangrove swamps of estuaries. The platform reefs across Temple Bay show the formation of sand cays (foram, coral and shelly sand and shingle) on the leeward side. In intertidal zones sandy cays are cemented to form beach rock. To the north of the Olive River, the dune fields of Shelburne Bay merge with coastal alluvium (mud) deposited by rivers in the inter-tidal zone in mangrove swamps. In between the swamps a few beach ridges are present, made up of foram, coral and shelly sandy shingle cemented in the intertidal zone. The rest of the Shelburne Bay area has dune sand and thick white residual sand. About 3 km north of Harmer Creek near Double Point some ferruginous deposits occur on the side of mangrove swamps along with quartzose sandstone and micaceous-carbonaceous bioturbated siltstone of the Helby beds.

Further north of Shelburne Bay, there is a dune field of small parabolic dunes called the Orford Bay Dune Field. In the False Orford Ness area (at the southern end of Orford Bay) thick white residual quartzose sand forms a belt parallel to the dunes. Further north from the tip of Orford Ness, ferricrete deposits are present. Sandy cay deposits are present on the leeward side of the platform reefs across Shelburne Bay and Orford Bay (Powell & Smart 1977).

In the Newcastle Bay area the Kennedy Swamps cover a broad area with coastal alluvium and salt pans between the mouths of the Escape and Jacky Jacky Rivers (Pain *et al* 1997) To the north, on the west side of Newcastle Bay, is a field of northwest trending parabolic dunes~~.~~

In the Newcastle Bay area the Kennedy Swamps cover a broad area of coastal alluvium and salt pans between the mouths of the Escape and Jacky Jacky Rivers (Pain *et al* 1997). To the north, on the west side of Newcastle Bay, is a field of northwest trending parabolic dunes. Marine sands are present in the beach ridge and shoreward of the fringing reef, composed of quartz and appreciable amounts of calcareous detritus. Sandy cays are also present on the leeward end of some platform reefs.

There is very little known about the composition of the sediments in the northern part of the Great Barrier Reef lagoon. Such studies as have been made show there is great diversity in the mineralogy. Intermixing, burial and reworking of sediments makes the mineralogy very complex. Maxwell (1968) described the variation of mineralogy in the Great Barrier Reef lagoon. He found an average of 20 % kaolinite, 60 % montmorillonite and 20 % illite in inner shelf near-shore sediments of the Great Barrier Reef lagoon. He also explained the mineral distribution trends for the southern Great Barrier Reef and anticipated the same broad trends for the central and northern sections of the Great Barrier Reef lagoon. He found quartz is present out to 16 fathoms (30 m) depth, beyond that its occurrence is rare. The low magnesian calcite percentage increases with the distance from both reef and land; this is the reverse of aragonite and high magnesian calcite trends. The trends for both aragonite and high magnesian calcite are similar and show higher percentages close to *Halimeda* and Corals.

5.3 Sedimentology and Mineralogy of Far North Section of the Great Barrier Reef

To develop a grain-size based facies analysis the grain size distribution was grouped into three categories: <5 µm (clay), 5-60 µm (silt) and 60-1600 µm (sand) fraction (Table 5.1). Mineralogical analysis showed that the entire suite is dominated by quartz, aragonite, calcite and high magnesium calcite, with clay minerals, largely smectite and kaolinite, significant (> 5 %) in 43 of the 134 samples analysed (Appendix no 2 & 3).

Clay percentage was not able to be quantified in the bulk mineralogical analysis because they yielded a poor XRD signal. For this study the abundance of clay minerals is estimated from the size analysis,

X-ray diffraction of oriented aggregates of clay showed smectite, illite and kaolinite to be present. Using a simple algorithm to convert 001 peak areas to approximate weight percentage (Eggleton, pers com) semi-quantitative clay mineral analysis was obtained (Table 5.1 & refer Appendix no 1 for details).

5.3.1. Results and Description

5.3.1.1. Variation across the shelf Transects

The shore to reef transect T1 is dominated by quartz sand near the shore (~ 95 %). With increasing distance from the shore the quartz content falls, and is replaced by carbonate minerals and the proportion of silt and clay-sized material increases (Figure 5.1). At a distance of about 45 Km from the shore the surface sediment has a size distribution of about 50 % sand, 45 % silt and 5 % clay (samples 35, 36). Compositionally this part of the lagoon sediment is about 10 % quartz, 40 % aragonite, 50 % (calcite + high-magnesian calcite). Hereafter these two minerals are grouped as calcite.

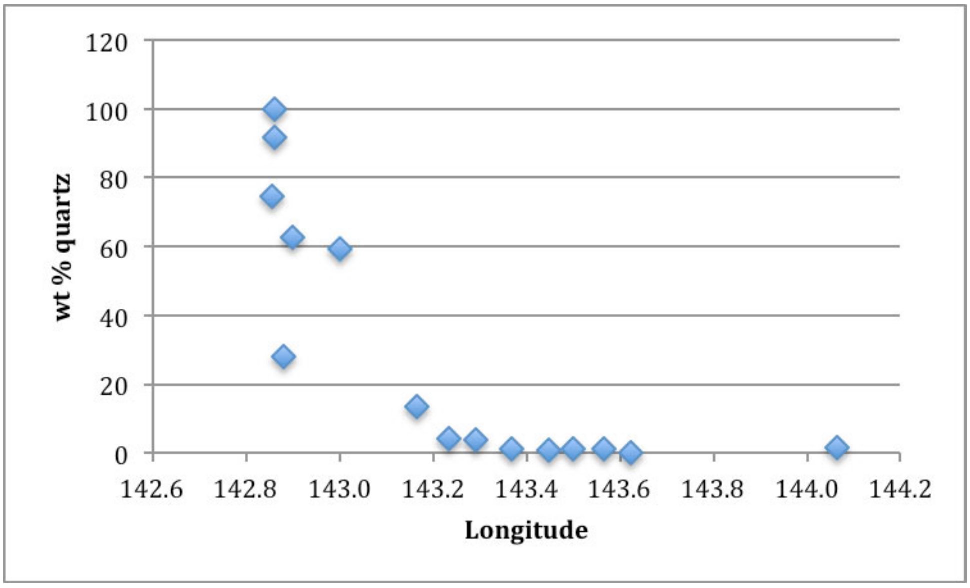


Figure 5.1. Quartz content from shore to reef (left to right) in surface samples from transect T1. Longitude proxies for distance from the shore because the transect is E-W.

Beyond 60km, quartz is minor (1 to 2 %) and the sediment is composed of aragonite and calcite in sub-equal quantities. Some of the sediment grab samples from the middle shelf have grain size fractions coarser than 2 mm, composed of shell fragments and coarse coral fragments and whole and broken *Halimeda* plates so no grain size analysis was carried out.

A few near shore samples showed the presence of kaolinite < 10 %. Calcite is < 15 % near shore, but increases from the inner to the outer shelf where it reaches over 50%. Aragonite also increases from shore to reef and reaches up to 50 %. High magnesium calcite shows a decrease from middle shelf to reef.

The transect T1 (cross shelf transect) shows the presence of clay minerals only up to the middle shelf samples. The sediment samples have more smectite (average 52 %) than kaolinite and illite except in G 40 and G 33 which shows the dominance of illite 53 % and kaolinite ~ 50 %

Transect T2 shows much the same variation from shore to reef as T1, with quartz varying between 60 % and 20 % in a dominant sand fraction for about 30 km, while beyond that distance quartz decreases to less than 1 % and aragonite and calcite, in sub-equal proportions, comprise over 90 % of these silt-dominated samples (Figure 5.2). In both the shore to reef transects the surface bottom grab samples of the outer shelf have a maximum of 65 % - 75 % sand size carbonate fraction. The silt size fraction varies from 20-70 % and the clay-size fraction, composed entirely of carbonate minerals, varies from 2 % - 15 %.

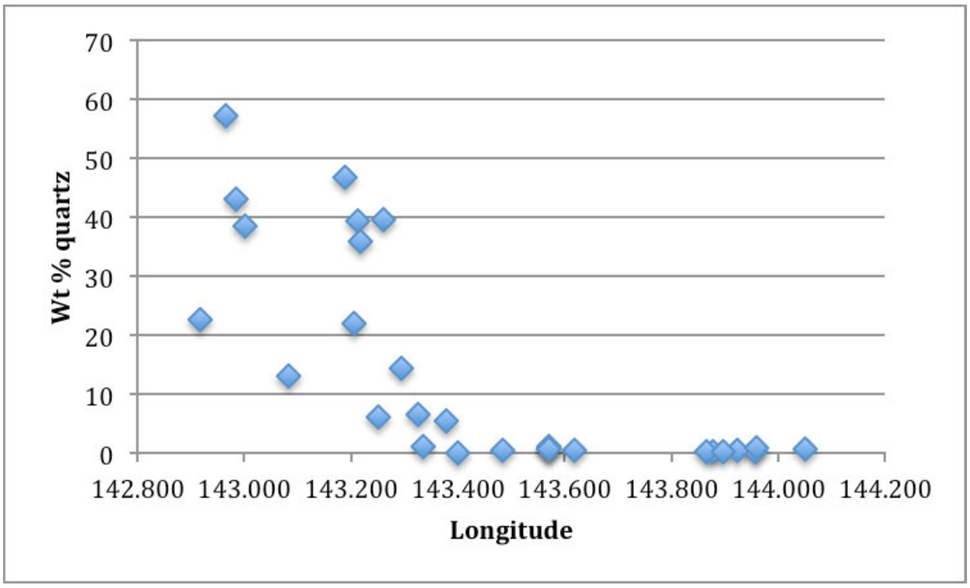


Figure 5.2. Quartz content from shore to reef (left to right) in surface samples from transect T2. Longitude proxies for distance from the shore because the transect is E-W.

The transect T2 samples from inner shelf are quite variable in the clay proportion, smectite ranging from zero in many samples to as much as 76 %. Other samples are 100 % kaolinite, while others have no clay at all. The middle shelf samples of this transect do not show the presence of any clay mineral except in a few samples, where smectite is the dominant clay mineral. All samples from outer shelf show no clay minerals in the XRD analysis

Transect T3 is parallel to the shore transect and covered two different parts of the reef, a near-shore transect from the north of Shelburne Bay to Orford Bay, and both vibro-core and grab sampling in Newcastle Bay. Considering only the near-shore part of this transect, and including the near-shore sections of T1 and T2, there is a clear predominance of quartz (~ 50%) over carbonate (aragonite and calcite both about 25%) in sediment dominated by the sand-size fraction (average ~ 66%). Kaolinite has only been seen in seven of the near-shore grab samples, where it ranges from 3 to 26 %.

Like T2, two extremes of clay minerals are observed, one with higher percentages of kaolinite (G30, G100, G96, and G104) and other with dominance of smectite (G92 and G97). The rest of the samples have no clay minerals.

Table 5.1 shows the results of grain size analysis, mineralogical composition of the sediment samples (including clays minerals) from the far north section of the Great Barrier Reef lagoon along the transects T1, T2 and T3 respectively (for details see appendix no 2 & 3).

Transect1

Sample no	Long	Lat	Grain size analysis			Sample	Quartz	Aragonite	Calcite	Gypsum	Kaolinite	Clay fraction		
			Sand%	Silt%	Clay%	No	%	%	%	%	%	Smc %	Illite %	Kao %
FG 28	144.06	-11.53	74	25	1	28	2	40	57	0	0	0	0	0
FG 29	143.62	-11.62	18	71	11	29	0	50	46	0	0	0	0	0
FG 30	143.57	-11.62	12	87	1	30	1	43	56	0	0	48	20	32
FG 31	143.5	-11.62	97	3	1	31	1	49	49	0	0	0	0	0
FG 32	143.45	-11.62	82	16	2	32	1	36	64	0	0	0	0	0
FG 33	143.37	-11.62	94	5	1	33	1	38	58	0	0	13	36	51
FG 34	143.29	-11.62	81	17	2	34	4	40	56	0	0	no clays		
FG 35	143.23	-11.62	56	39	5	35	4	36	56	0	0	58	8	34
FG 36	143.17	-11.62	40	52	8	36	14	40	46	0	0	46	34	20
FG 37	142.86	-11.63	99	1	0	37	100	0	0	0	0	54	18	28
FG 38	142.88	-11.62	76	21	3	38	28	25	38	0	8	44	12	44
FG 39	142.9	-11.62	41	52	7	39	63	15	22	0	0	57	16	27
FG 40	143	-11.62	61	34	5	40	59	15	26	0	0	12	53	35
G 108	142.86	-11.58	96	3	0	108	74	13	12	0	0	no clays		
G 109	142.86	-11.65	97	2	0	109	92	8	0	0	0	no clays		
VC-10-10			65	31	3									
						vc-10-15	2	40	58	0	0	no clays		
						vc-10-20	2	41	57	0	0	0	0	100
						vc-10-36	3	41	56	0	0	0	0	0

Transect 2

Sample no	long	lat	Grain size analysis			Quartz	Aragonite	Calcite	Gypsum	Kaolinite	Mineralogy of the clay fraction		
			Sand%	Silt%	Clay%	%	%	%	%	%	Sm %	Illite %	Kaolinite %
1	143.21	-11.96	45	50	5	22	26	26	0	26	33	26	41
2	143.19	-11.92	77	20	3	47	28	25	0	0	60	6	34
3	143.22	-11.93	60	33	7	36	27	38	0	0	76	1	23
4	143.25	-11.91	89	10	2	6	65	29	0	0	0	0	0
5	143.29	-11.89	7	80	13	15	30	55	0	0	46	13	41
6	143.33	-11.91	12	79	10	1	48	51	0	0	50	9	41
7	143.38	-11.92	10	78	12	5	44	45	0	6	0	0	0
8	143.40	-11.92				0	63	38	0	0	0	0	0
9	143.48	-11.90	14	76	11	0	46	53	0	0	39	33	28
10	143.57	-11.87	5	83	12	1	45	55	0	0	0	0	0
11	143.57	-11.83	18	71	11	1	44	55	0	0	68	5	26
12	143.57	-11.79	17	75	8	1	48	52	0	0	0	0	0
13	143.62	-11.81	7	84	10	1	41	59	0	0	0	0	0
14	143.70	-11.83	coarser than sand			4	69	27	0	0	0	0	0
15	143.71	-11.78	coarser than sand			2	67	31	0	0	0	0	0
16	143.73	-11.75	coarser than sand			1	65	34	0	0	0	0	0
17	143.80	-11.73	coarser than sand			1	52	48	0	0	0	0	0
18	143.88	-11.72	coarser than sand			0	38	62	0	0	0	0	0
19	143.96	-11.78	21	65	14	0	34	66	0	0	0	0	0
20	143.92	-11.73	21	68	10	1	37	62	0	0	0	0	0
21	143.88	-11.82	19	72	9	0	39	61	0	0	0	0	0
22	143.87	-11.87	31	64	6	0	43	56	0	0	48	21	31
23	143.90	-11.90	75	23	2	0	33	67	0	0	0	0	0
24	143.96	-11.91	54	39	6	1	36	63	0	0	0	0	0
26	144.05	-11.65	75	25	1	1	36	63	0	0	0	0	0
41	142.96	-11.84	11	77	12	57	20	23	0	0	0	0	0
42	142.98	-11.80	52	42	6	43	18	39	0	0	53	11	36
110	142.92	-11.81	94	6	1	23	28	39	0	10	75	3	22
111	143.00	-11.90	32	60	7	39	31	28	0	3	0	0	100
112	143.08	-11.88	86	12	2	13	34	53	0	0	43	21	36
113	143.33	-12.00	61	34	5	7	30	64	0	0	72	8	20
114	143.26	-12.02	43	47	10	40	22	21	2	16	58	11	31
115	143.21	-12.00	65	30	5	39	21	23	2	16	37	14	50
VC-7-30			coarser than sand			0.1	61.7	38.2	0	0			
VC-7-90			coarser than sand			1	59.5	39.5	0	0			
Vc-7-140			coarser than sand			0.9	57.3	41.8	0	0			
VC- 8-30			coarser than sand			0.3	76.6	23.1	0	0			
VC-8-90			coarser than sand			0.6	61.3	38.1	0	0			
VC-12-15			72	25	4	63.8	18.4	17.8	0	0	0	0	100
VC-12-108						70.6	14.4	15.1	0	0	2	47	51
VC-12-120			86	13	2	85.3	11.9	2.7	0	0	0	0	100

Transect 3

Sample no	Depth (m)	Lat	Long	Grain size analysis			Quartz	Aragonite	Calcite	Gypsum	Kaolinite	Mineralogy of the clay fraction		
				Sand%	Silt%	Clay%	%	%	%	%	%	Smectite %	Illite %	Kaolinite %
80	3	-10.69	142.52	all coarser than sand			67	12	21	0	0			
81	11	-10.79	142.72	99	0	0	20	24	56	0	0	0	0	0
82	10	-10.80	142.60	98	2	0	79	14	8	0	0	0	0	0
83	6	-10.86	142.59	98	2	0	100	0	0	0	0	0	0	0
84	7	-10.86	142.64	94	5	1	47	29	24	0	0	0	0	0
85	8	-10.80	142.64	99	1	0	100	0	0	0	0	0	0	0
86	15	-10.85	142.69	97	3	0	83	8	9	0	0	0	0	0
87	5	-10.90	142.67	98	2	0	100	0	0	0	0	0	0	0
89	7	-10.93	142.72	100	0	0	87	10	3	0	0	0	0	0
90	15	-10.96	142.69	98	2	0	85	9	6	0	0	0	0	0
91	7	-10.98	142.67	95	4	1	73	27	0	0	0	0	0	0
92	1	-11.01	142.65	81	17	2	73	12	3	4	8	69	3	29
93	12	-10.96	142.70	99	1	0	84	12	4	0	0	0	0	0
94	8	-10.96	142.72	98	2	0	81	15	3	0	0	0	0	0
95	10	-10.96	142.74	28	63	9	84	8	7	0	0	0	0	0
96	14	-10.82	142.66	91	8	1	63	8	29	0	0	0	35	65
97	11	-10.82	142.63	90	8	2	71	12	17	0	0	37	34	29
98	5	-10.82	142.59	96	3	1	100	0	0	0	0	0	0	100
99	7	-11.25	142.86	73	24	3	21	32	41	0	6	0	0	0
100	8	-11.26	142.84	72	25	4	63	15	22	0	0	0	0	100
101	4	-11.28	142.81	98	2	0	100	0	0	0	0	0	0	0
102	5	-11.25	142.84	97	3	0	90	7	2	0	0	0	0	0
103	4	-11.36	142.87	98	2	0	93	4	2	0	0	0	0	0
104	17	-11.39	142.89	70	26	4	50	29	20	0	0	0	22	78
105	4	-11.43	142.84	94	5	1	80	13	7	0	0	0	0	0
106	12	-11.46	142.87	64	31	5	21	29	50	0	0	0	0	0
107	4	-11.49	142.85	97	3	0	75	19	6	0	0	0	0	0
116	9	-12.07	143.17	36	54	10	38	15	19	7	21	49	17	34
117	8	-12.14	143.12	69	26	5	64	22	14	0	0	0	46	54
118	10	-12.23	143.13	24	66	9	15	33	51	0	0	73	3	24
VC-20-10	10	142.67	-10.98	71	25	4	100	0	0	0	0	0	0	100
VC-20-20	20			64	31	5	77	0	0	0	0	0	0	100
VC-20-30	30			68	28	4	100	0	0	0	0	0	0	100
VC-20-50	50			85	13	3	79	4	2	5	10	0	0	100
VC-20-63	63			74	21	5	93	0	0	1	6	0	0	100
VC-21-10	10	142.65	-11.01	68	28	4	95	5	0	0	0	0	0	0
VC-21-20	20			63	32	5	100	0	0	0	0	0	0	0
VC-21-35	35			76	21	3	100	0	0	0	0	0	0	100

Sample no	Depth (m)	Lat	Long	Grain size analysis			Quartz	Aragonite	Calcite	Gypsum	Kaolinite	Mineralogy of the clay fraction		
				Sand %	Silt %	Clay %	%	%	%	%	%	Smectite %	Illite %	Kaolinite %
VC-21-50	50			78	19	3	0	0	0	0	0	0	0	0
VC-21-55	55			89	10	1	100	0	0	0	0	0	0	0
VC-22-10	10	142.74	-10.96	56	37	7	56	14	15	0	16	0	0	100
VC-22-20	20			1	85	14	59	23	18	0	0	23	4	74
VC-22-30	30			17	69	14	75	17	8	0	0	0	0	100
VC-22-40	40			12	69	19	67	8	15	0	10	33	26	41
VC-22-50	50			0	78	22	64	11	19	1	5	7	20	74
VC-22-60	60			86	12	2	80	12	4	5	0	50	12	38
VC-22-70	70			91	8	2	78	13	9	0	0	37	42	21
VC-22-80	80			91	7	2	93	0	7	0	0	78	0	22
VC-22-90	90			91	7	2	94	0	6	0	0	0	0	100
VC-22-100	100			93	6	1	90	0	10	0	0	0	0	100
VC-22-110	110			Gravels size fraction			78	0	11	3	7	0	0	0
VC-22-120	120			17	57	26	86	0	9	1	4	0	0	0
VC-22-130	130			4	56	40	65	19	16	0	0	0	0	0
VC-22-140	140			0	74	26	41	34	25	0	0	0	0	0
VC-22-150	150			0	56	44	78	13	9	0	0	74	1	25
VC-22-160	160			15	64	22	74	6	20	0	0	61	8	31
VC-22-170	170			6	76	17	62	7	32	0	0	0	0	0
VC-23-10	10	142.75	-10.89	82	15	3	33	29	38	0	0	64	13	23
VC-23-30	30			84	14	2	39	25	36	0	0	0	0	100
VC-23-50	50			79	18	3	21	30	41	0	6	0	0	0
VC-23-65	65			83	15	3	67	17	17	0	0	no plain trace only treated trace		
VC-23-86	86			95	5	1	70	15	15	0	0			
VC-23-110	110			11	70	20	95	0	5	0	0	0	0	100
												0	35	65
VC-24-10	10	142.66	-10.82	89	9	1	75	14	12	0	0	0	30	70
VC-24-30	30			89	10	2	59	24	16	0	0	63	7	30
VC-24-60	60			0	84	16	43	17	40	0	0	65	7	28
VC-24-80	80			13	74	13	62	15	23	0	0	30	8	62
												37	34	29
VC-25-10	10	142.63	-10.82	83	14	3	74	10	16	0	0	79	4	17
VC-25-20	20			80	18	3	61	17	21	0	0	63	4	32
VC-25-40	40			82	16	2	60	17	23	0	0	0	0	100
VC-25-60	60			81	17	2	50	36	14	0	0	0	0	100
VC-25-80	80			76	21	4	47	25	27	0	0	86	0	14

5.3.1.2 Regions

a) Newcastle Bay

Newcastle Bay was sampled during Transect 3. Grab samples yield high percentages of quartz sand, similar to the values obtained in the near shore samples of Transects 1 and 2. Some samples are 100 % coarse to medium sand. The rest of the samples contain more than 90 % sand, composed on average of 80% quartz and 10% each of aragonite and calcite.

The vibro-core samples from Newcastle Bay allowed information to be obtained about the variation in the sediment with depth, although limited at best to 170 cm. All the core samples are dominated by sand and silt, with clay never reaching more than 15 %. The cores (VC 20 and VC 21) collected from the estuary of Escape River both have more than 80 % sand throughout the cores, except in the centre of the core where sediments have up to 60 % sand size fraction. Both cores contain > 95 % quartz with minor amounts of aragonite except for VC 20 which contains about 15 % goethite and 8 % siderite in the upper parts and in the lower parts of the core it contains up to 10% clay minerals (kaolinite) and < 5 % Gypsum.

Other cores from Newcastle Bay (VC-23, VC-24 and VC-25) display more or less same sort of results as VC 20 and VC 21 except that sand decreases towards the bottom with corresponding increase in the silt and clay size fractions.

The mineralogical composition of VC 23 shows about equal percentages of quartz, aragonite and calcite almost throughout the entire core except a little above the bottom where quartz is > 90 %. The middle portion of the core has > 5 % of clay minerals mostly kaolinite and smectite).

In case of VC-24 and VC-25 the quartz is the dominant mineral, averaging 60 %, with approximately equal proportion of aragonite and calcite. The lower parts of core VC-24 contain about 15% clay with smectite dominant at 60 cm and kaolinite dominant at 80 cm.

The core VC-22 collected near Turtle Head Island and Sharp Point, possesses 70-80 % silt and clay size sediments at the top 50 cm with 50 cm of sand-dominated sediment below, underlain by a narrow gravel layer at 110 cm. Below this the remaining 50 cm of sediment is ~60% silt-sized and 30% clay-sized. Quartz is the dominant mineral, averaging 70 %, with aragonite and calcite in approximately equal proportions making up most of the balance. The upper parts of VC-22 also have about 10 % clay minerals with varying proportions of smectite, illite and kaolinite.

Although the grain size analyses do not make the specific distinction, observations at the time showed that samples collected from Newcastle Bay have a higher percentage of coarse sand than fine sand, silt and clay.

b) Shelburne Bay

The core from the Shelburne Bay core VC-12 shows an increase in the quartz percentage from the top sediments to the bottom of the core. The top sediments have ~64% quartz with aragonite 18 %, high magnesian calcite 14 % and calcite 3.5 %. Down the core sediments have ~ 86 % quartz, 12 % aragonite, ~ 2 % high magnesian calcite and < 1 % low magnesian calcite. Clays from this core show the dominance of kaolinite over other clay minerals. Kaolinite is the only clay mineral present in both top and bottom sediments. Illite and smectite comprises about 50 % of clay minerals composition in the middle of the core.

c) Temple Bay

In the Temple Bay area all the samples have more smectite than kaolinite except in G114 and G117 where kaolinite is the dominant clay mineral.

d) Middle shelf

The core VC 10 (transect T1) collected from middle shelf across Shelburne Bay has only < 5 % of quartz with 40-45 % each of aragonite and high magnesian calcite. Low magnesian calcite ranges from 11-13 %. The core shows no clay minerals at the top and bottom sediments, only in the middle of the core is some kaolinite present.

e) Outer Shelf

The cores VC-7 and VC-8 (transect T2) collected from outer shelf of the Great Barrier Reef shows only traces of quartz (~ 1 %) throughout the cores. The dominant carbonate minerals are aragonite ~ 60-75 % followed by high magnesian calcite 17-34 % while calcite is < 10 %. The cores VC 7 and VC 8 do not show any clay mineral at any depth throughout the cores.

5.4 Scanning Electron microscopy and Microprobe Analysis.

These two techniques provide observation of morphology, texture and composition of the mineral phases. A large number of mineral grains have been imaged during this research; here are presented typical examples that show features important for mineral identification or for documentation of process.

5.4.1 Quartz

Fig 5.3 – 5.6 show~~s~~ highly fractured and etched quartz grains. The quartz grains are mostly subangular, but subrounded grains are also found with etched surfaces. Etch pits are developed along the cracks and fractures, which themselves show no pattern.

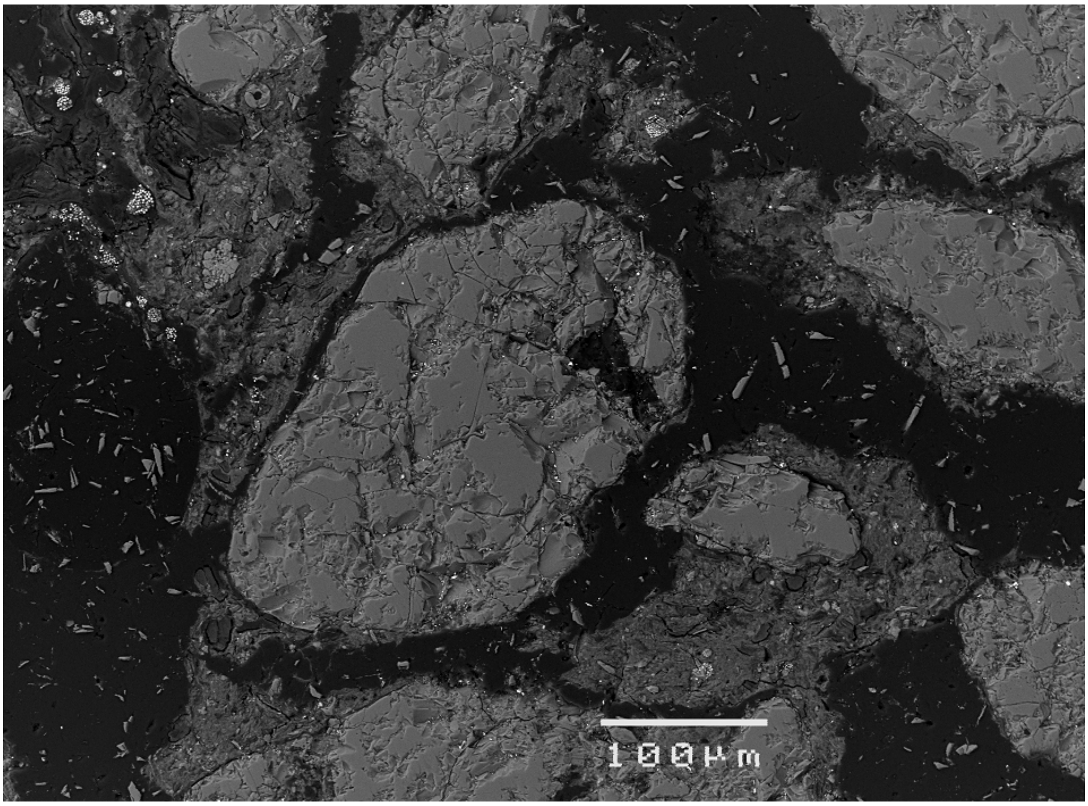


Figure 5.3 Back-scatter SEM photomicrograph of quartz grains in sample VC 21- 10 cm showing sub-angular to sub-rounded grains with fractures and etching.

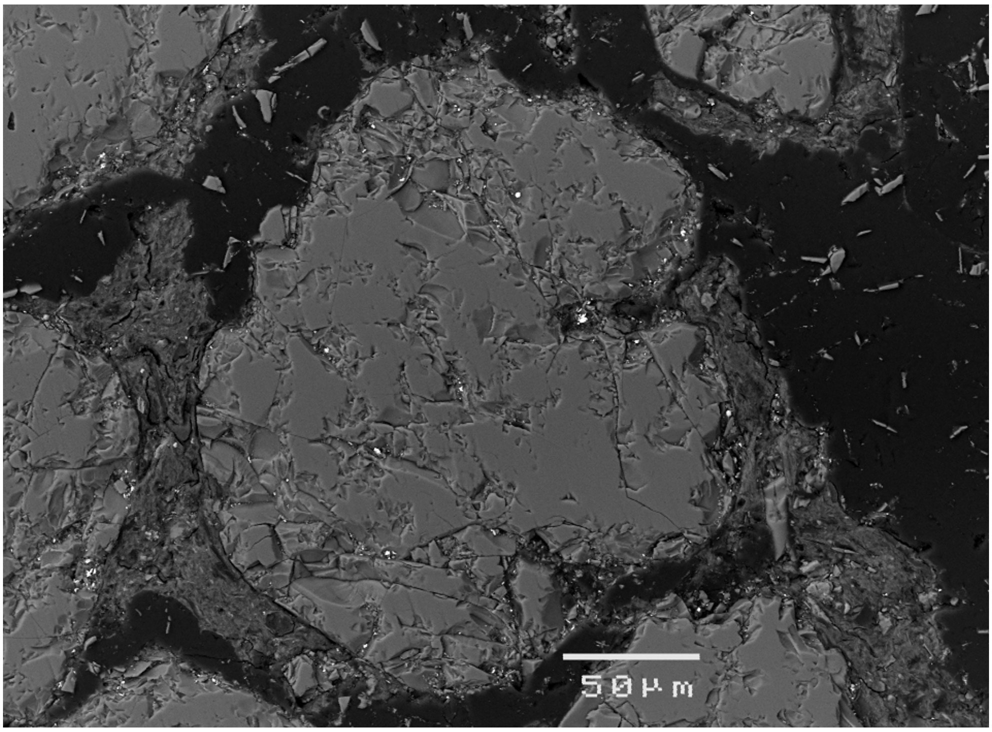


Figure 5.4 Back-scatter SEM photomicrograph of a sub-rounded quartz grain in sample VC 21- 10 cm showing fractures and etch pits.

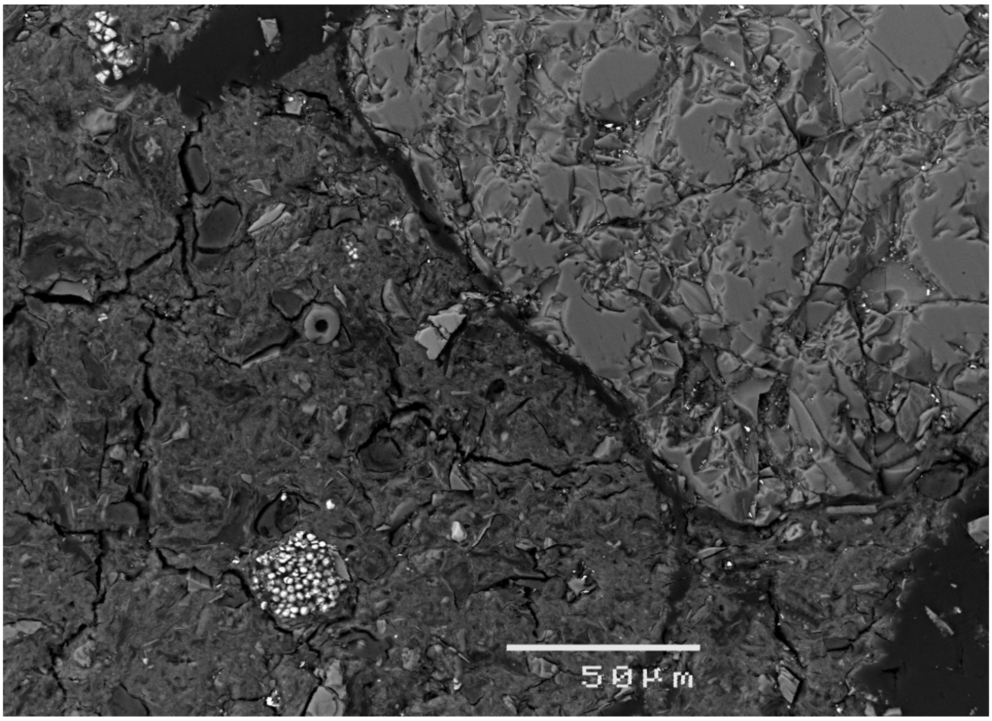


Figure 5.5 Back-scatter SEM photomicrograph from sample VC 21- 10 cm of a quartz grain in a mud matrix (darkest grey) containing shell fragments (brighter) and a small pyrite framboid (bright). Etching of the quartz is very evident.

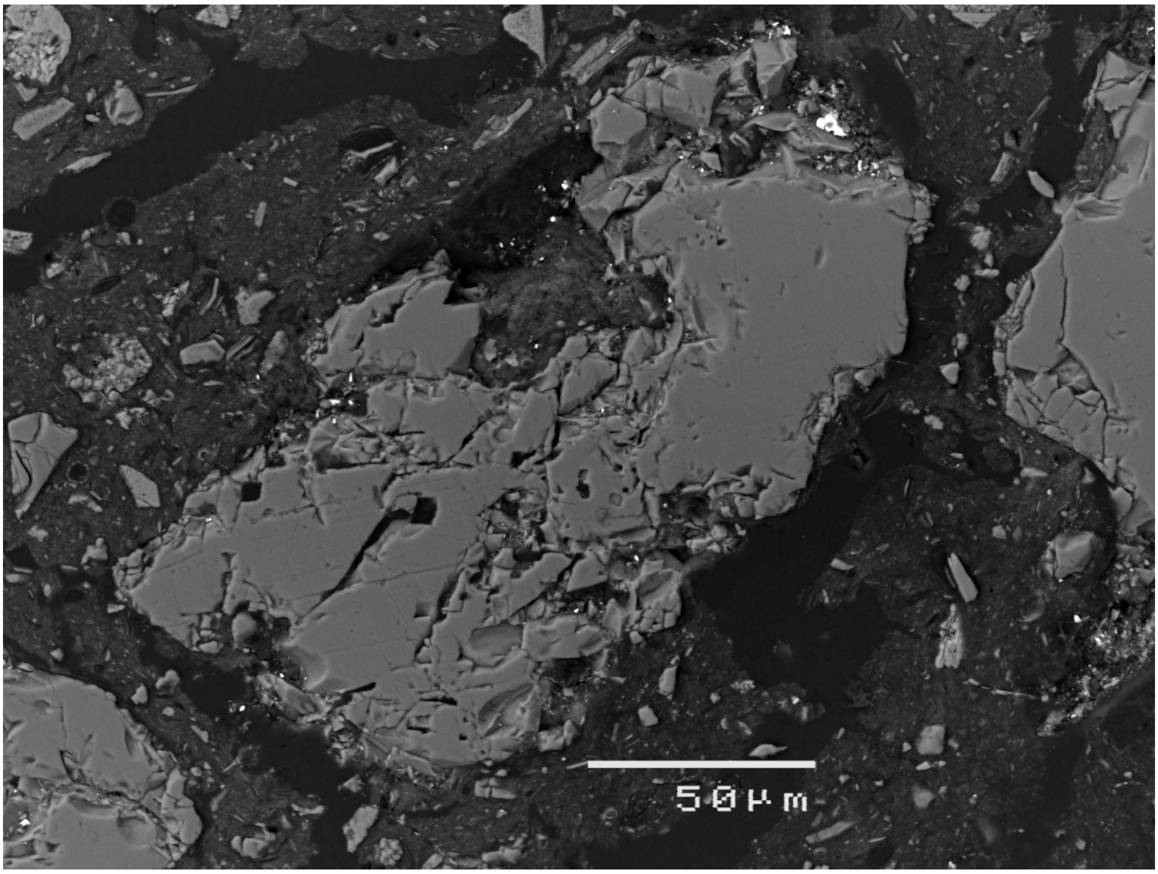


Figure 5.6 Back-scatter SEM photomicrograph from sample VC 12- 5cm of a heavily etched and partially dissolved quartz grain in mud matrix.

5.4.2 Pyrite

Fig 5.7- 5.8 shows different morphologies of iron sulfide (pyrite framboids).

a) Euhedral crystals. These are individual microcrystals of pyrite (in a loose aggregate). Their size is not uniform and varies from ~ 2 µm to 10 µm.

b) Welded spheres. The internal structure of these spheres is disordered but sometimes the individual crystals of pyrite follow radial or polygonal patterns. The size of framboids is about 5 um - 25 um. The welded spheres occur both isolated and in clusters.

c) The distribution of pyrite framboids is random in the sample.

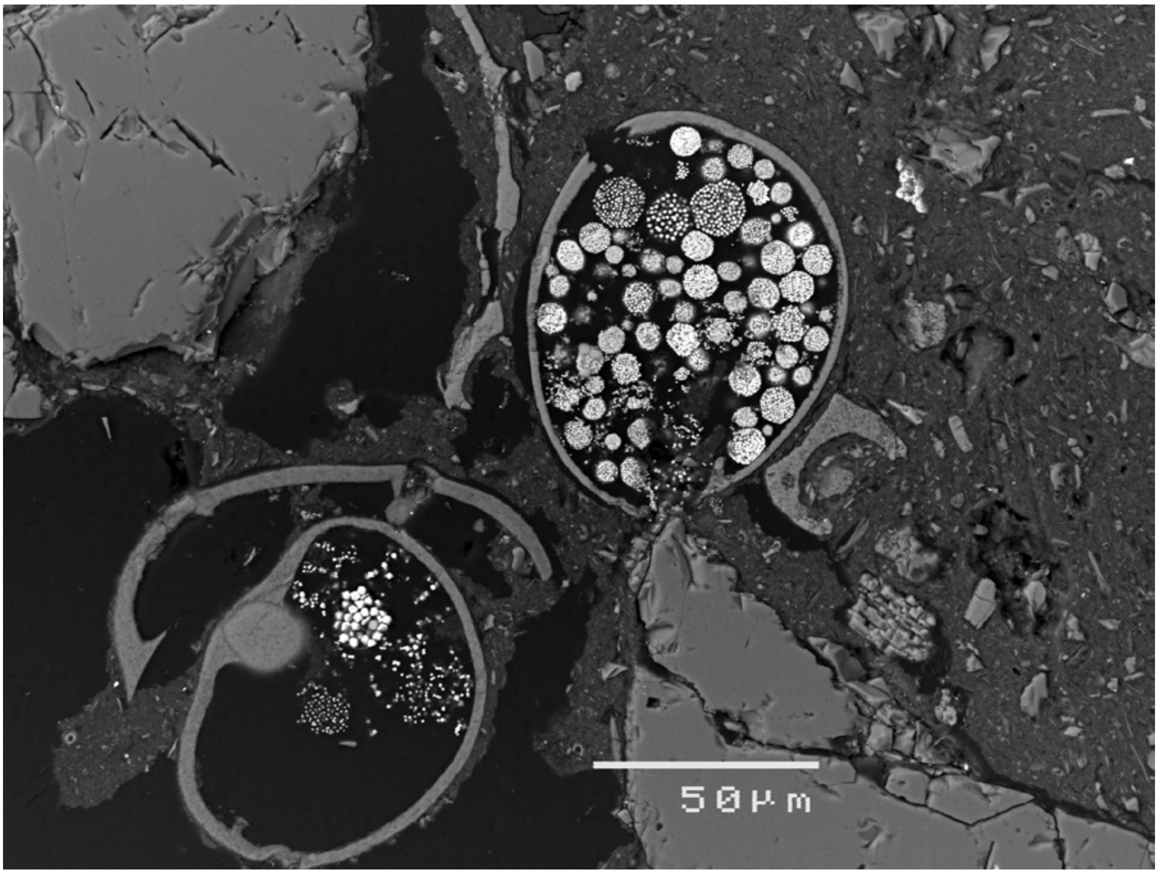


Figure 5.7 Back-scatter SEM photomicrograph from sample VC-12 at 18 cm, of pyrite framboids (bright) inside shells in a mud matrix with quartz grains showing sub-angular to sub-rounded grains with fractures and etching.

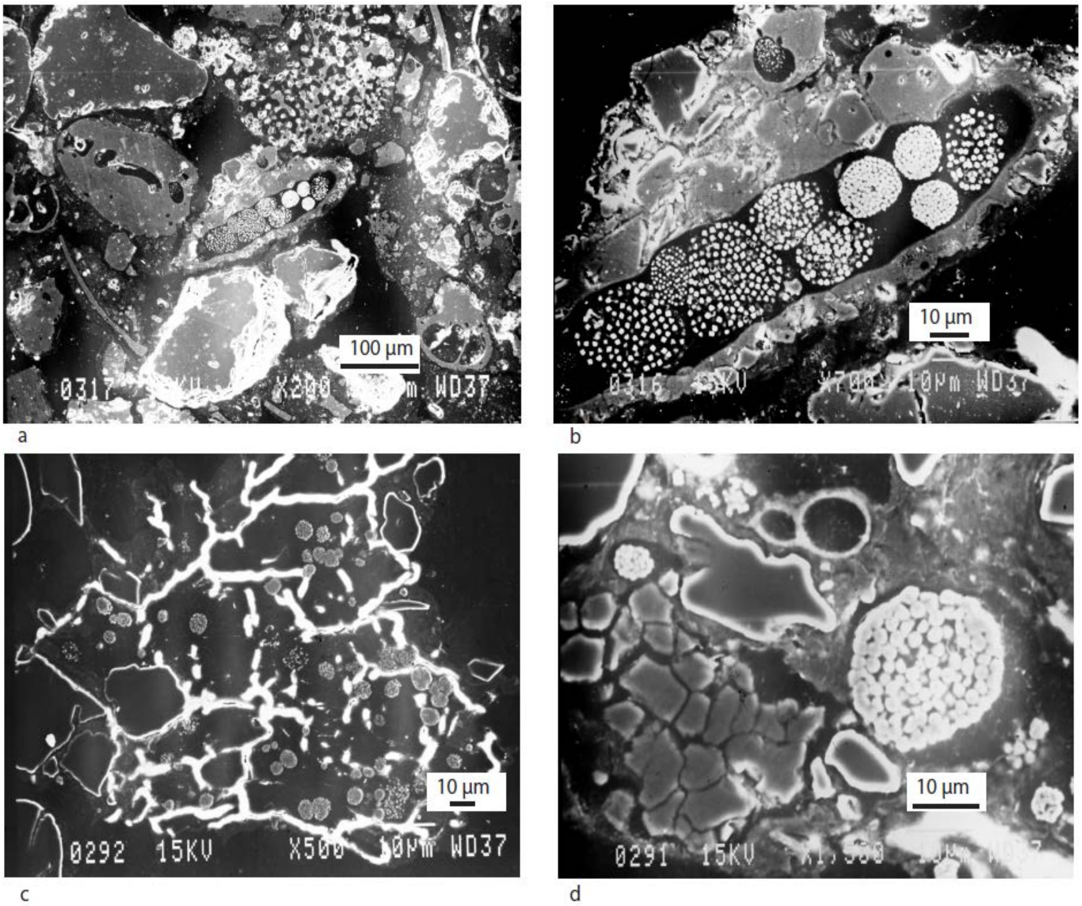


Figure 5.8 Back-scatter SEM photomicrographs (a – d) of pyrite framboids (bright) inside shells (a & b) in sample VC 12 – 55 cm, (c & d) of pyrite framboids (bright) in a mud quartz grains in sample VC 22– 35 cm showing sub-angular to sub-rounded grains with fractures and etching.

5.4.3 Zinc

Figure 5.9 shows an unidentified phase of zinc in carbonate sediments at a depth of 1.5 m at the Great Detached Reef in the core VC-7. The individual zinc rich crystals at 10,000 magnification look like a star. The average size of these crystals is 1 µm. Their identity is unknown; no other element is present on the X-ray spectrum, suggesting an oxide or carbonate.

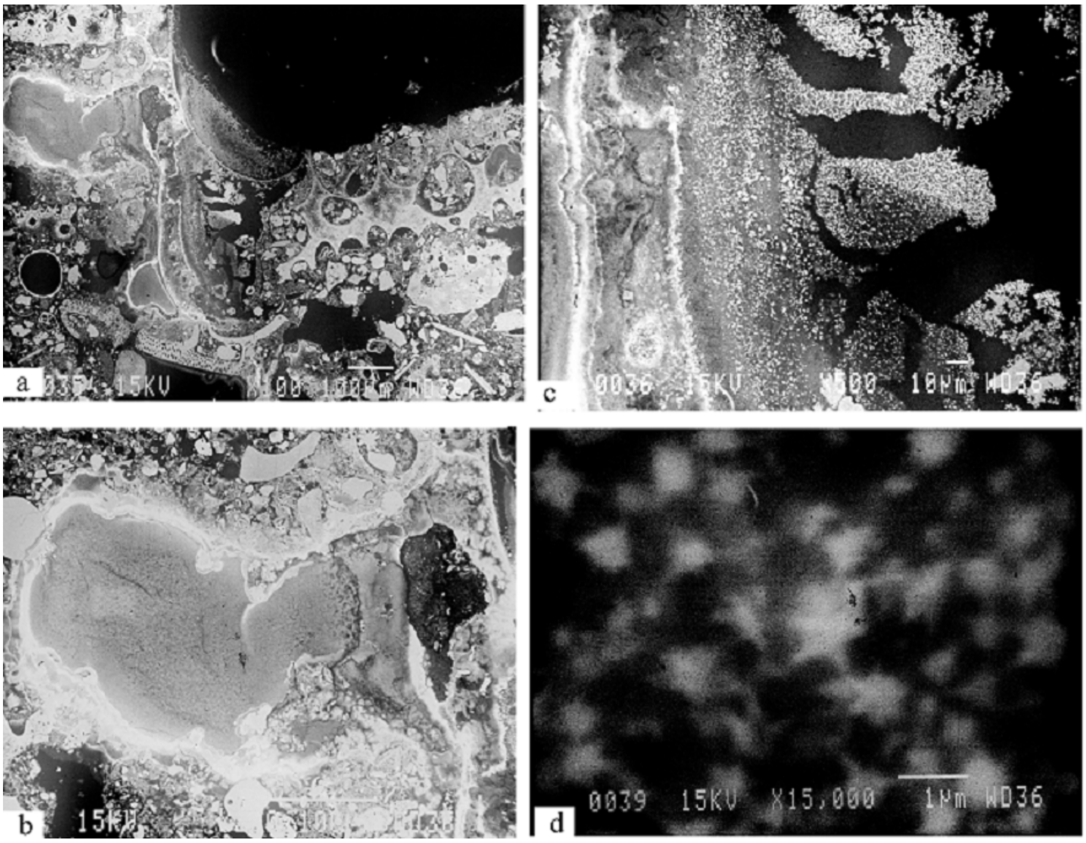


Figure 5.9 Back-scatter SEM photomicrograph of sediments (Zn stars) from outer shelf core VC 7 (a & b, shell debri along with Zn (c & d, shows zinc rich crystals).

5.4.4 Secondary Carbonates

Fig 5.10 – 5.11 shows development of secondary carbonate in a pore space > 100 µm. Several different morphologies of the same mineralogical and chemical composition are identified including;

a) Rosettes of high magnesian calcite (Fig 5.12)

b) Hexagonal, prismatic crystals (Fig 5.13) of high magnesian calcite with well-developed faces. The whole surface of such crystals is covered by cracks, dissolution grooves and small borings (possibly formed by organisms such as sponges, worms, bryozoans and barnacles which bore shells, or produced by plants, fungi or algae).

c) A spike shaped grain of high magnesian calcite with borings on the surface. The tip of the grain is broken and all the edges are rounded.

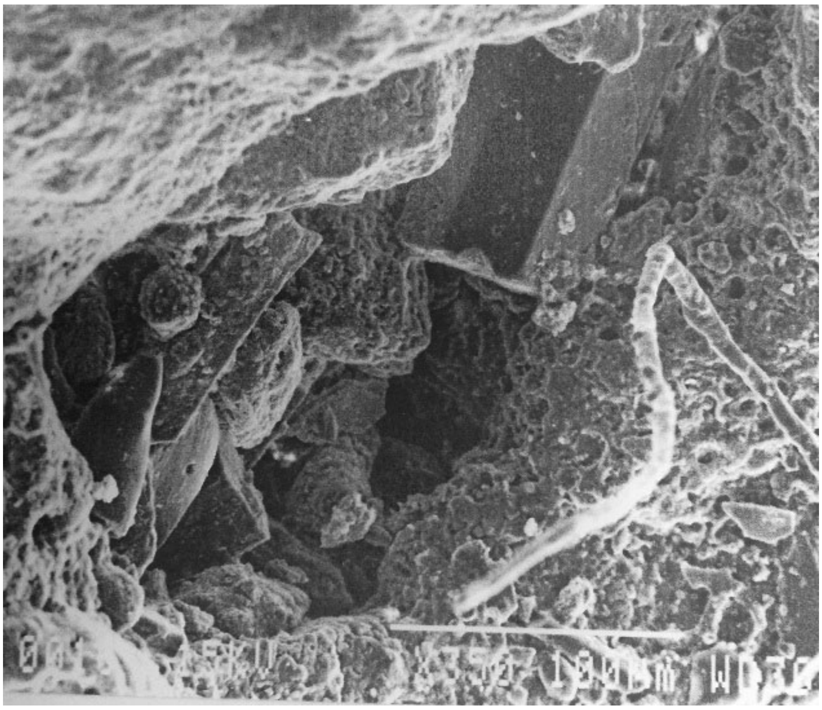


Figure 5.10 Back-scatter SEM photomicrograph from grab sample of a cavity with *in situ* growth of carbonate crystals.

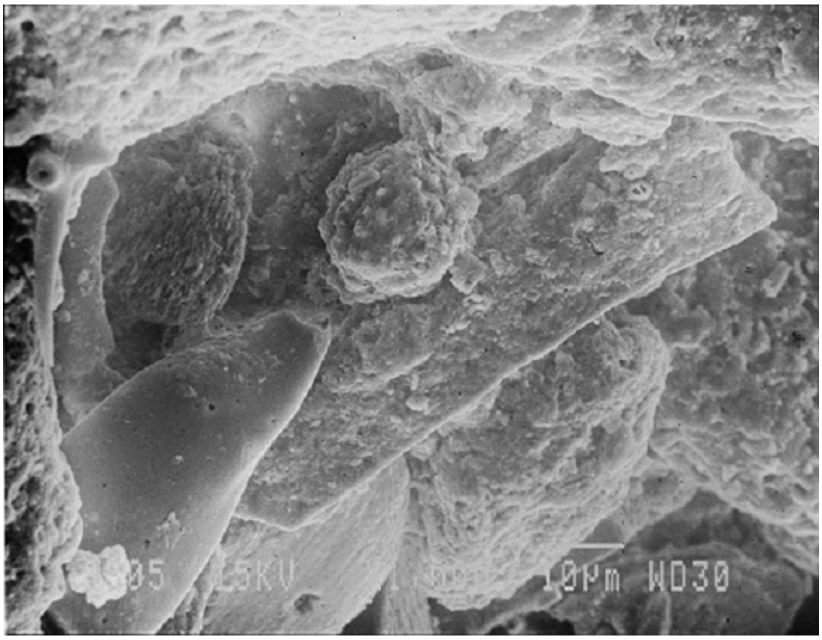


Figure 5.11 Back-scatter SEM photomicrograph from grab sample of a cavity with *insitu* growth of secondary carbonate

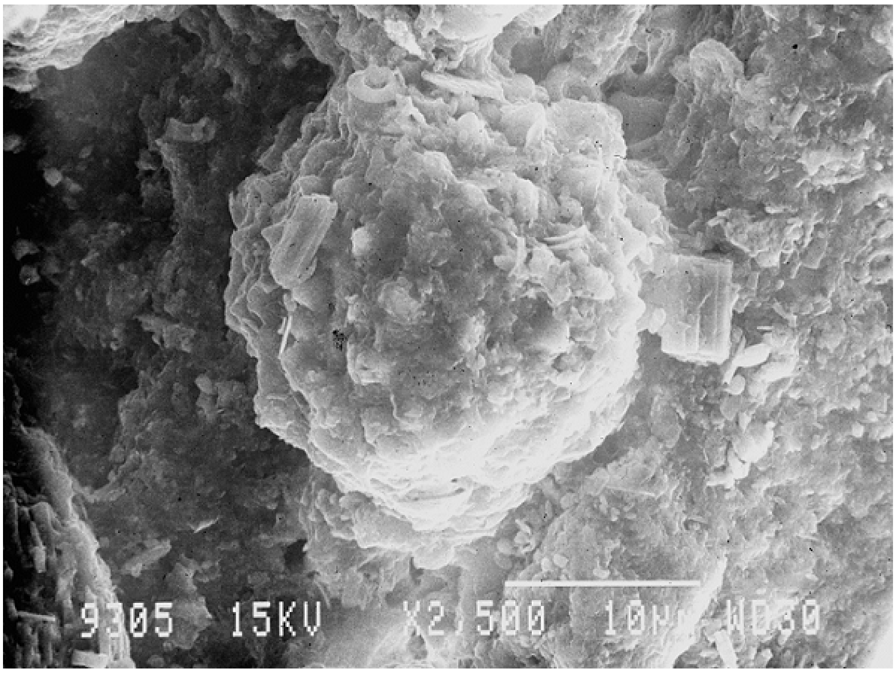


Figure 5.12 Back-scatter SEM photomicrograph from grab sample of a cavity with *in situ* growth of rosettes of high magnesian calcite

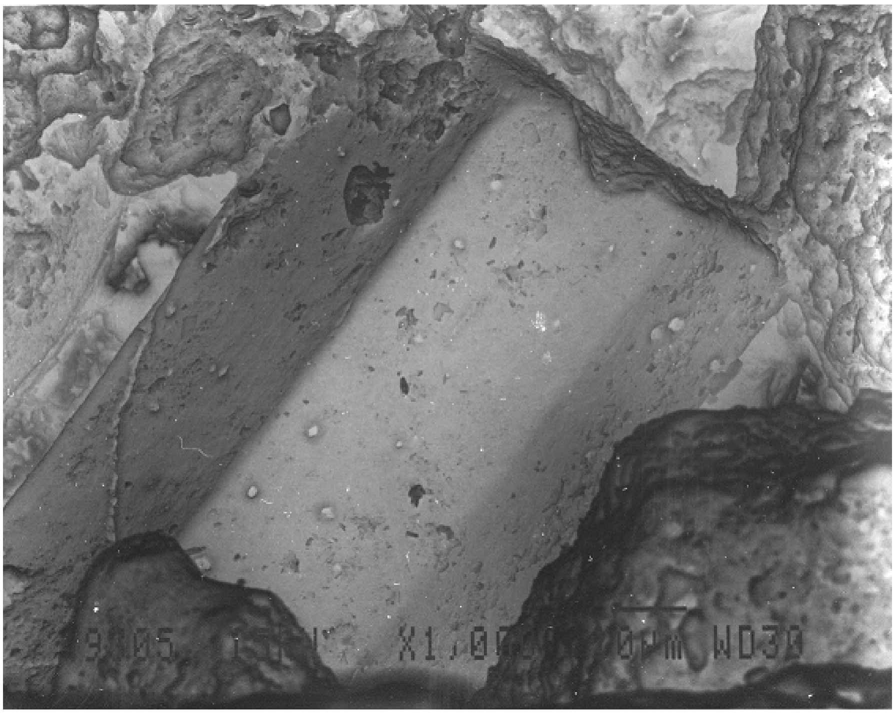


Figure 5.13 Back-scatter SEM photomicrograph from grab sample of a cavity with *in situ* growth of a hexagonal crystal of magnesian Calcite

5.5 Discussion

The cores and surface bottom grab samples of the far north section of the Great Barrier Reef shelf consist of three components:

a) terrigenous clastic (quartzose sand); b) carbonate fraction (including *Halimeda*, corals, molluscs and fragments); and c) mixed carbonate and siliciclastic producing a variety of sediment types. The sedimentary characteristics of the sediments of the Great Barrier Reef lagoon vary greatly and ~~the~~ facies changes occur widely throughout the study area. Such variations in sedimentary character can be explained on the basis of sediment source and type, (provenance), composition, hydrodynamics, shelf geometry and transportation processes. These factors are considered and explained in the following discussion.

The sediments of the far north section of the Great Barrier Reef lagoon are derived from a number of sources. One of the sources is land derived detrital sediment supplied by rivers including the Olive, Kennedy and Escape Rivers. The mouths of the Kennedy and Escape Rivers have extensive mangrove swamps, which trap much of the sediments carried by these streams.

The southeast trade winds prevail for more or less nine months and are responsible for generating south easterly waves, which travel in a north westerly direction, running parallel to the coast, rather than across the shelf. As the result of this, terrestrial sediments stay close to the shoreline and are not carried out to sea. Woolfe *et al* (1998) suggested that sediment contributed by the rivers into the Shelburne Bay of the Great Barrier Reef lagoon are relatively minor in amount, and riverine sediments reaching to the coast amount to 1 Mt y^{-1} in total. Compared to Woolfe's estimate, evidence gathered here suggests in the New Castle Bay area less sediments has been contribution by Jacky Jacky and Escape Rivers due to low landscape in their catchments and consequently less erosion than in the Shelburne Bay area. The sediment in New Castle Bay averages about 1 m in thickness over an area of 250 km^2 which amounts to 500 MT at a depositional rate of 60,000 tonnes of sediments per year since the last low stand (8,000 years).

Figure 5.14 Correlation of cores from New Castle Bay.Unit 1 (yellow) is granular medium – fine grained sand with shells and is found in all cores except VC-24. The (green) unit above (VC 22 & VC 23) and below unit 1(VC 23 & VC 24) is silty – sandy mud, the sand is coarse to medium grained with a few shelly fragments only at places in VC- 23. Underneath Unit 1. In VC 22 is a clayey silt unit (orange) with no shells or shelly debris**.** Black dash and solid lines indicate different types of beddings (refer core logs annexure 1 for details)

Correlation of the cores from Newcastle Bay (Fig. 5.14) shows a good correlation of the lowest Unit 1 (granular sand, medium- to fine-grained with shells and their debris). The unit can be and identified in all the cores from New Castle Bay except in VC-24. Unit 1 occurs at different depths in different cores, but is generally overlain by finer sediments, except at VC 25 where it occurs at the top of the section.

The occurrence of the unit at different depth is interpreted as local variation in bathymetry, palaeotopography and local variation in currents affecting the depositional processes. Variation in palaeotopographic surface and elevation during the time of deposition is the possible explanation of the absence of Unit 1 in VC 24 as well as variation in thickness of the unit and depth of occurrence. The seismic results presented in Chapter 4 clearly show that the palaeotopographic surface (Reflector A) has many such variations. Such correlation indicates relatively stable sea level conditions during the time of deposition.

The second source of the sediments to be considered is the large coastal dune complexes. Submerged dunes occur along the present and former coastline and have a history of episodic activity with phases of re-working (Pye 1982 & 1983; Lees 2006) sediments reach to the inner shelf by the erosional activity of waves, wind and streams. The waves and winds carry the sand and silt, depositing them as a thin surfacial sheet in more sheltered areas. The quantity of the sediments contributed by dunes is small as compared to the dimensions of the Great Barrier Reef shelf (Maxwell 1968). These dune sands consist of quartz with a minor amount of feldspars. The inner shelf shore sand facies is most probably derived from these sand dunes.

A third source of shelf sediments is in-situ carbonate production by fauna and flora and their re-working (coral, *Halimeda*, molluscs, forams). These sediments show a large variety of size, shape and degree of sorting. Generation of in-situ sediments depends upon biology and hydrodynamics. They are restricted in aereal extent until the detritus is spread into the lagoon by waves, currents and tides.

The sediments are so dominated by sand and silt that the sand isolith in (Fig 5.15) is sufficient to show the sediment size distribution. The full facies analysis including mineralogy shows a marked decrease in the terrigenous sediments progressing from Cape York (Newcastle Bay) to Shelburne Bay. The percentage of terrigenous sand is (> 90 %) from Escape River Swamps to Orford Ness Bay and some parts of Shelburne Bay. The lower part of Shelburne Bay is occupied by mangrove swamp and dominated by fine muddy sediments. Furthermore in the Shelburne Bay area near the tip of Cape Greenville, volcanic tuff and breccia is exposed, which may contribute sediments.

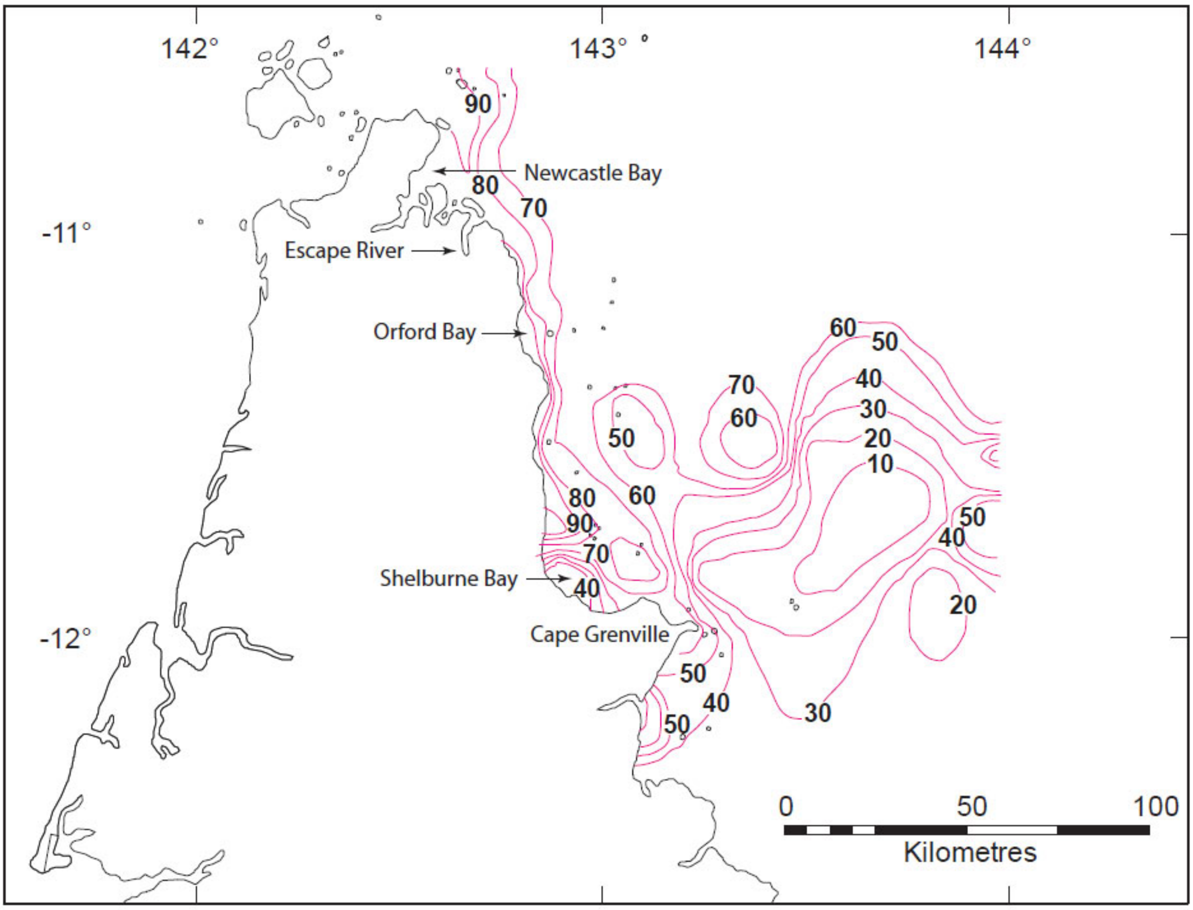


Figure 5.15 Sand Isolith map.

The percentage of the terrigenous sand decreases across the shelf with an increase in the percentage of the carbonate sand. This is interpreted as the result of the reduced competency of the fluvial-derived sediments, except in cyclones and flood. This result in the wedging out of the terrigenous material and a relative narrowing of the terrigenous shelf sediment belt in the northern section of the Great Barrier Reef lagoon. Maxwell (1968) describes the nearness of the reef (patches) to the shore in the northern region of the Great Barrier Reef as compared to the southern region. This provides the detritus (allochem) which mixes with and dilutes the terrigenous facies. Mineralogical analyses in this work show that the sediments near the coast are dominantly terrigenous, with carbonate marine sourced sediments becoming dominant as close as 20 km from the shore (Figures 5.1 & 5.2).

The wedge of the riverine sediments extends about 15 meters into the water depth. The seismic trace shows the presence of fine suspended sediments in the wedge-out area indicated by a very noisy signal.

The interpretation of the seismic traces of the Shelburne Bay area marks the presence of suspended sediments. Some of the suspended material settles down on the ocean floor but during storms it is disturbed and re- suspended in the water column. The sediments settle in the bay due to relatively low energy conditions in this sheltered environment.

The core log of VC-12, indicate the top one metre of core is dominated by fine muddy sediments. The evidence of the presence of muddy wave-suspended sediments in the seismic trace shows resuspension and redistribution of finer sediments in the area.

The mixing of terrigenous and carbonate sediments generates a variety of transitional facies. The facies analysis (details discussed in section 5.6) shows a change, which is interpreted as being due to the mixing of two different components. The VC-10 core sediments show mixed silic clastic carbonate sediments. The sandy-silty sediment grains have shells and shell detritus

Broadly speaking there are two types of carbonate facies. One is dominated by reef generated sediments and other by *Halimeda* generated sediments. At places, mixing of two different types of carbonate facies (*Halimeda* and reef generated sediments) produced the detritus. It is impossible to differentiate the two in the lime mud fraction. Cores VC 7 and VC 8 were collected from the Great Detached Reef and it is evident from both cores and seismic traces (line 4 and line 5) that both *Halimeda* and reef generated sediments are mixed together. The *Halimeda* plates dominate in both cores and show preferred orientation in core VC 7. The detritus comes from the reef due to the activity of waves, and accumulates *Halimeda* plates and their debris.

The mid-outer shelf of the far north section of the Great Barrier Reef Lagoon is dominated by *Halimeda* meadows. This facies is found on reef flats, reef lagoons and inter-reef floors (see seismic results in chapter 4). The flora supplies the sediments. The absence of this facies near Raine Island and north of it can be explained, following Drew & Abel (1985) due to poor circulation and up welling of nutrients with rich water coming from the Coral Sea. The *Halimeda* detritus is very coarse grained and therefore its transportation is limited because tidal currents cannot lift it from the floor. But in areas where both wave and current action is active, dispersal of the detritus occurs (Maxwell 1968). The *Halimeda* detritus is commonly available in the study area. In some places it is mixed with other sediments including debris of corals, molluscs and foraminifera. In places where *Halimeda* forms banks and bioherms, the facies almost entirely consists of *Halimeda* generated sediments, varying from granules to lime-mud. The disintegration of *Halimeda* does not require any wave or current activity and it thus provides an abundant supply of carbonate sediments. Thus *Halimeda* are considered to be a major supplier of carbonate sediments in the Great Barrier Reef lagoon.

Searle and Flood (1988) suggested that the *Halimeda* meadows also probably act as a trap for carbonate detritus. The result of the present study shows *Halimeda* facies are composed of < 10 %

of quartz and clay minerals (terrigenous) while > 90 % is aragonite and other allochems. This suggests that terrestrial sediments may also be trapped in the *Halimeda* meadows along with carbonate sediments.

The outer shelf reefal facies belongs to the high-energy zone, which favours disintegration. The sediments show less heterogeneity of grain size and a comparatively better degree of sorting. The waves not only disintegrate the reefal sediments but also favour transportation and deposition in the other areas of the lagoon.

In general there is low sediment input from the land which may be due to the subduded relief and tectonically stable position of the area. The present pattern of the sedimentation has continued at least since current sea levels were established after the last glacial period (at about 8,000 ka) and can be expected to continue unless the present stable conditions are disturbed tectonically or a change in the sea level occurs. This discussion, together with a general synthesis of seismic, mineralogical and geochemical aspects of this work, will be continued in the final chapter of discussion.

The mineralogical proportions in the sediments of the study area are extremely variable from coast to reef. Two types of terrigenous minerals dominate in the sediments; quartz and clays. The in-situ marine sediments have three minerals: aragonite, high magnesian calcite, and low magnesian calcite (Table 5.1).

The Newcastle Bay area is the most quartz dominated part of the study area. Most of the core sub-samples and bottom grab samples are entirely made up of quartz. The sediment mineralogy of this area is highly controlled by the provenance of the sediments, which are derived from Pleistocene-Holocene coastal dunes made up of quartzose sand. These dune sands contain some organic matter and only traces of heavy minerals (Pye and Mazzullo, 1994). The other source of sediments is the sand with subordinate clays of the riverine and flood plain Pleistocene-Holocene alluvial deposits.

The shelly sand of the Newcastle Bay sediment samples are probably derived from Pleistocene and Holocene beach rocks. The recent beach rock consists of shelly sand with calcarenite (Coquina beds). The older beach rocks mostly consist of quartzose sand (Willmott & Powell, 1977); they are not drained by any river or local drainage. The recent beach ridges are drained by small channels and creeks, which merge into the Kennedy River. Therefore it is interpreted that the source of shelly sands are recent (Holocene) beach ridges. The silty-clay with minor sand coastal alluvial deposits and swamps of the local Kennedy and Escape rivers are the source of clays in the area. There are two variations occurring in the clay minerals and described in the section 5.3.1. First, the relative percentage of the clay minerals varies from top to the bottom of the cores and also from one grab sample to other. Secondly the dominance of a type of clay mineral varies at short intervals in the core sub-samples and also in the surface bottom grab samples. These are interpreted as local, resulting from variation along the coast and due to differences in the sediment source. The smectite is derived from a less mature weathering profile Chamley (1989) or from deeper parts of a more mature profile (Taylor & Eggleton 2001). The Tertiary period marked an extensive weathering period in the Escape River and the Turtle Head Island area due to the withdrawal of the sea towards the end of Mesozoic era. At that time the land was reduced to low relief with the formation of Pliocene Laterite and Ferricrete (Willmott & Powell 1977).

The Helby beds of Jurassic to Cretaceous times weathered and developed a more mature weathering profile. These quartzose clayey sandstone pebbles – conglomerates with high bioturbation are shallow marine – estuarine deposits (Powell *et al* 1976). They are interpreted as the possible source of kaolinite in the Newcastle Bay area sediments.

The microprobe analysis shows the presence of iron sulphide (pyrite framboids) in the sediments of Newcastle Bay (Fig 5.8). The Pliocene lateritic and ferruginous products of weathering are the main source of iron in the area which ultimately produces the iron framboids. (The origin of framboids is discussed in detail in the chapter of general discussion). The framboids occupy different places, including shell chambers, cracks in the quartz grains and in the clay mineral cement. They grow and accommodate according to the space available.

XRD analysis does not show any pyrite. The pyrite framboids and crystals are reported only in polished slides. They are very common in Newcastle Bay and Shelburne Bay samples but none-the-less their concentration is below the level of detection by XRD.

Weathering in the Newcastle Bay area affects the morphology of the quartz grains. The microprobe studies of the sediments shows the quartz grains have a highly fractured surface. This is due to the instability of quartz in that environment and results in the disintegration and dissolution of quartz grains. The humid tropical weathering, pedogenesis and post-depositional changes all modify the shape and morphology of quartz grains (Pye & Mazzullo 1994). The results of the present studies are consistent with the previous work of Pye & Mazzullo (1994). The severe chemical etching and disintegration of quartz grain is so strong that only the grain's outline is left. This framework is later occupied by clay minerals and pyrite framboids (see Figures 5.3-5.6).

The study of impregnated and polished slides of the sediment containing quartz shows that the shape of the grains varies from angular to sub-angular, sub-rounded grains are less common. The angularity of the grains is due to etching and dissolution. These processes result in the fracturing and break- down of the quartz grains along planes of weakness. The degree of angularity is directly proportional to the intensity and time of exposure of quartz grains to surface etching and dissolution. The angular grains have been exposed more to chemical weathering and this may indicate they are derived from older Pleistocene dunes. The less angular or sub-rounded grains of quartz exhibit less exposure to these processes and are probably derived from younger Holocene dunes. The dissolution of quartz in the study area is observed in a reducing environment along with the formation of pyrite and secondary carbonates. (See the General Discussion in Chapter 7 for details.) The SEM observations show clear evidence of quartz surface disintegration and dissolution. Some silica has dissolved from quartz grains along cracks and edges~~,~~ with the space then occupied by clay and iron sulfide as cement.

The sediments of Orford Ness Bay also show the dominance of quartz over carbonate minerals except in few samples which are collected near to the inner-middle shelf boundary and which have higher percentages of carbonate minerals (aragonite and high magnesian calcite). This is the result of intermixing of the terrigenous and marine (*in-situ*) sediments by waves and currents and other coastal processes. These marine sediments are derived from local isolated patch reefs near Hunter Point (Hunter Reef) and further north of it in the False Orford Ness Bay.

The sediments of Orford Bay with higher percentages of quartz were derived from the coastal dune belt along the coast. These dunes were formed in the Quaternary period (Pleistocene-Holocene) (Powell & Smart 1977).

In Shelburne Bay there are multiple sources to generate the sediments including dune fields (Pleistocene-Holocene), quartzose sandstone, micaceous carbonaceous siltstone (Jurassic-Cretaceous), ferruginous lateritic bauxite and ferricrete residual weathering products (Pliocene), coastal alluvial swamp deposits of clay with sand (Pleistocene-Holocene) and volcanic breccia and tuff (Permian-Carboniferous) at Cape Greenvile.

In the Shelburne Bay area there is only a creek (Harmer Creek) draining the swamp area and mangroves are growing in that swamp. The mangrove mud of the swamp is interpreted as derived from coastal alluvial deposits mixed with dune sands. The quantitative mineralogical results of the sediment sample from this part of Shelburne Bay indicate a relatively higher percentage of sand (quartz). These are probably wind blown sand derived from sand dunes and trapped in the mud. The Shelburne Bay swamps also have pyrite framboids. The source of iron is once again identified as residual weathering products (laterite and ferruginous deposits).

The clay mineralogy shows a difference in the proportion of clay minerals between the core sub-samples and surface bottom grab samples. The surface grab samples of Shelburne Bay show dominance of smectite over kaolinite, but the opposite is true in the core sub-samples. This change of clay mineralogy is interpreted as a change at the source from Pleistocene to recent times. A deeply weathered landscape such as evolved on Cape York during the Tertiary (Pain *et al.* 1997), is kaolinite rich in its upper profile (pallid or plasmic horizon, (Butt & Smith 1992) and smectite-rich in the lower parts of the profile (saprock, saprolite). Dismantling of such a landscape yields kaolinite sediment at first, followed later by more illite-smectite-rich material.

In VC 12 collected from Shelburne Bay area there is sharp change of facies observed towards the bottom of the core where mangrove mud grades into sandy facies (see details in Chapter 5). This change indicates a different depositional environment and sediment source. The source of kaolinite in the core sub samples is interpreted to be from mature weathering deposits. The increase in illite (mica) to nearly 50 % at one meter depth may be explained as local variation of source from more weathered deposits to micaceous carbonaceous siltstone.

Another possibility is the conversion of one type of clay mineral into another in the reducing mangrove environment. (This will be discussed in detail along with origin of pyrite framboids and dissolution of quartz grains later in the discussion).

In the Cape Greenville area the surface sediments are enriched in smectite as the source in that area is volcanic breccia and tuff and not the terrigenous inland source. Smectites are common first weathering products of such volcanic rocks (Taylor & Eggleton, 2001)

Temple Bay area grab samples have relatively higher percentages of quartz. Their source is interpreted as the Temple Bay dune field. Sample no G118 has higher percentages of carbonate minerals over quartz, due to its proximity to a reef patch (Tyrell Reefs).

Clay minerals in the Temple Bay samples are quite variable in proportion; sample G117, close to the mouth of the Olive River, has much illite whereas samples 116 and 118, further from that sediment source, are richer in the finer-grained, more widely dispersed, smectite.

The mineralogy of the sediments changes across the shelf, which is as expected. The relative percentage of the terrigenous minerals decreases with a concomitant increase in carbonate minerals. The relative percentage of quartz in the middle shelf is < 5 % and further towards the reef it decreases to 1%. This is largely in agreement with the previous studies of Bryce et al (1998) & Woolfe (1998) who concluded that there is no oceanographic process able to transport the terrigenous material out to the reef or outer shelf. The presence of iron pyrites framboids is also marked in the outer shelf sediments.

Clay minerals are reported out to middle shelf sediment samples and are dominated by smectite except in FG 33 which has 50 % kaolinite, 35 % illite and 15 % smectite. It is difficult to explain why only this sample shows dominance of kaolinite. The bulk XRD analysis shows an absence of clays minerals in the outer shelf sediment samples. The probe analysis identified minor clay in the reef sediments, but at a concentration lower than the detection limit of XRD.

A possible explanation of how the terrigenous material reaches as the outer shelf in the absence of any major marine process to transport the material from coast to reef is that air-borne dust may be carried from the mainland.

The carbonate mineralogy of this section of the Great Barrier Reef shelf mostly represents the local biological colonies. The dominant group of flora and fauna are coral and calcareous algae. In calcareous algae there are two main sub-groups; *Halimeda* (green algae) and *Lithothamnioid* algae (red algae). Other important groups controlling the mineralogy are molluscs, bryozoans and forams, while echinoderms and crustaceans are subordinate. Some of the above mentioned species are destructive and they penetrate the coral and algal structure and break them down to produce reef detritus (Maxwell 1968). The other source of reef detritus is the erosion of the older reefs (dead reefs). These are lithified reefs and have been subject to erosion since the last sea level change.

The carbonate sediments of this section of the Great Barrier Reef lagoon are mostly skeletal, bio-clastic, while chemically or inorganically precipitated material is not observed. This differentiates the carbonates of Great Barrier Reef of Australia from those of the Bahamas in America (diverse grain type not only skeletal).

Of the carbonate minerals, aragonite is dominant, followed by high magnesian calcite and low magnesian calcite. The main source of aragonite is coral, *Halimeda* and molluscs. The Lithothamnioid algae and benthic forams provide the high magnesian calcite. The low magnesian calcite is derived from bryozoans, pelagic forams and lithified reefs (Maxwell 1968).

In transect T1 the values of aragonite are depressed at some sample sites. This is explained as due to the absence of *Halimeda* at those sites (see details in chapter 4). The value of aragonite is elevated at sample sites closer to small patch reefs.

Transect T2 compared to T1 show higher percentages of aragonite, and along that transect line very thick growth of *Halimeda* is present (see chapter 4). The higher percentage of the high magnesian calcite is noticed in those sample sites nearer to the Great Barrier Reef or in its surroundings.

The low magnesian calcite has a maximum value in the middle shelf samples where the absence of *Halimeda* depresses the value of aragonite. The second highest concentration of the low magnesian calcite is reported from the outer shelf near to the Great Detached Reef. This is interpreted as resulting from the availability of more detritus due to the erosion of the reef. The one other possible explanation is the conversion of high magnesian calcite into low magnesian calcite upon sub-aerial exposure and subsequent erosion (Maxwell 1968) in the past. The relatively low concentration of low magnesian calcite in the near shore samples indicates the lower concentration of land derived calcite in the study area.

5.6 Facies analysis

5.6.1 Introduction

The following facies groups are delineated on the basis of grain size, mineralogy, total carbonate content, and the physical & biotic characteristics of the sediments.

5.6.1.1. Near shore terrigenous sandy mud facies.

This facies comprises grey coloured, sandy, bioturbated mud. The primary mode occurs in the finer fraction. The modal grain size is finer than 15 µm. Some samples show a secondary mode in the medium sand size fraction. The average carbonate content reaches 50 %, consisting of intact and fragmmentary forams, corals, molluscs and bryozoans. A few samples are marked by the presence of mangrove plant remains. These sediments are widespread on the boundary between the inner and middle shelf and in the sub tidal – inter tidal zones, a wave and current-influenced area. The facies indicates a strong degree of transport (the larger particle or grains are well rounded). The mineralogical composition of sediments is quartz, calcite, aragonite; magnesium calcite, kaolinite, illite, smectite. The sediments are mainly derived from local streams and coastal alluvium (that is spread along the coastline)

5.6.1.2. Inner shelf shore sand.

The facies comprises white to creamy fine – medium grained quartz sand with minor feldspar. The sediments are moderately well sorted uni-modal sand (150 and 600 µm). Some sediment is iron stained and a few shell fragments are present in some samples. The carbonate content is very low at < 5%. The sediments are evidently derived from coastal sand dunes. Their mineralogy is quartz and rare feldspars.

5.6.1.3. Shelly beach sand

These sediments are coarse to medium grained shelly sands. Brown poorly sorted sand has a modal grain size of between 300 – 700 µm. The average carbonate reaches 45 %. Mineralogically, the sediments are made up of quartz, calcite, aragonite, and magnesium calcite. The sediments are interpreted as largely derived from the beach ridges due to wave activity.

5.6.1.4 Halimeda generated carbonate facies.

These sediments are *Halimeda* rich and consist of whole and broken *Halimeda* plates. Within the Great Barrier Reef lagoon, this facies occur characteristically in the mid-outer shelf (see transects 1 and 2) and forms bioherms and bank morphology, generally at a depth of 30 – 50 m. From the seismic data the average thickness of this facies in the study area is about 15 m. The grain-size varies widely from gravel to lime mud. Apart from *Halimeda* other minor constituents are forams, molluscs and bryozoans. The total carbonate content is > 90 % and has a mineralogical composition of calcite, aragonite and magnesium calcite. The facies incorporates < 10 % terrestrial sediments in the form quartz and clay silicates.

5.6.1.5. Pure carbonate coral reefs.

This facies consists of well-sorted medium to fine grain carbonate rich sand and lime mud, characteristically occurring in middle and outer shelf. The total carbonate is high at > 95%. The terrestrial sediments are < 5%, largely quartz. The modal grain size is variable and occurs in the fine fraction. Carbonate minerals are aragonite, calcite, and magnesium calcite. The carbonate grains are reef generated and include both allochthonous and autochthonous types.

The results of mineral quantification showed multiple sources contributing to the sediments in this section of the Great Barrier Reef Lagoon. Changing proportion of the sediments from these sources are known by the observed facies variation. The microprobe analysis shows the modification of the sediments, due to post depositional processes. These processes indicate the control of physical and chemical parameters on the mineralogy of the sediments.

Though Maxwell (1968) mentioned that the broad mineralogical trends are the same for both the southern and northern Great Barrier Reef, the present work indicates that certain factors make the mineralogy of the far north section of the Great Barrier Reef different from that of the Southern Great Barrier Reef. These include post-depositional changes and distribution of the sediments due to the shelf geometry, reef distribution, bathymetry, lithology, riverine discharges, climate, coastal variation and different geological settings. Such variations may also exist more in the southern section of the Great Barrier Reef Lagoon, but it would require detailed study of the kind reported here to establish this.

CHAPTER 6 GEOCHEMISTRY

6.0 Introduction

The chemistry of sediment plays an important role in determining the nature and type of changes (if any) observed in the geochemistry and mineralogy of the sediments. Sediments may serve as a sink or a source for elements (Forstner & Salomons 1991). The sediments formed during weathering processes may be modified by post-depositional processes such as adsorption and desorption of elements (Chapman 1992). In this chapter the geochemistry of the sediments is used as an indication of change in the depositional environment, and of the chemistry and mobility of the sediments from surface to subsurface. Geochemistry along with mineralogy also provides information about the source of the sediments.

Both bulk and trace elements were analysed by XRF. These results together with mineralogy were used to investigate the changes that occur in the sediments. Such investigations ultimately provide useful information to elucidate the type of depositional sequence present in the study area. The sediments may be unchanged since deposition as detritus from a terrestrial weathering profile. Alternatively, the sediments may have undergone post-depositional changes, as part of early diagenesis. Thus trace elements may be an indicator of the depositional environment.

6.1 Regional Geochemistry

No previous geochemical study of the study area has been published. Most of the studies in the Great Barrier Reef have emphasised growth rates of reefs, type of basement and age rather than reef sequence and geochemistry. Johnson *et al* (1984) document the geochemistry of Britomart Reef in the central Great Barrier Reef. They found magnesian calcite and aragonite were converted into low Mg - calcite below the Holocene and Pleistocene disconformity. They showed that the concentration of Sr varied from 7500-8500 ppm above the disconformity in corals to 1650-1500 ppm below it and decreased further downwards in the core samples to 400-800 ppm. They suggested the intermediate values of Sr indicate partial replacement of aragonite into calcite. Their work showed three units in the Holocene sequence at Britomart Reef:

a) An algal bound coral rubble unit formed the top 5 m, this is similar to the present reef top.

b) A coral frame-stone unit consisting of massive head corals belonging to *Diploastrea Heliopora and Porites presently* forms patch reefs in lagoons and the reef front.

c) A Coral rudstone unit composed of coral rudstone and float-stone with unabraded and unbound coral clasts in a muddy matrix. This matrix is made up of about 30 % sponge chips.

Cook and Mayo (1980) studied the geochemistry of the Broad Sound tropical estuary in Queensland and its catchment. They describe a two component system consisting of carbonate and terrigenous material. These components vary considerably in the depositional environment from pure calcareous to least calcareous. They attempted to use the abundance of Cr to distinguish between mangrove channel and swamp sediments. Similarly they used Ba at the 95 percent confidence level to distinguish between shallow marine and intertidal sediments. They explained that these differences are statistically significant but geologically meaningless in most cases and they reflect the gross changes in $CaCO_3$ or mud content and mean grain size. Therefore they suggested the concentration of trace elements in the Broad Sound sediment give no real indication of depositional environment. They conclude that environmental changes cause concentration and leaching of elemental ions, so therefore it is better to use elemental ratios than the absolute concentrations of trace metals to distinguish between the depositional environments.

Tye (1992) worked on the geochemistry of Southern Halifax Bay, central Great Barrier Reef. He found relative immobility of the metals including V, Cr, Ga, Sc, Y and Ni. Mineralogically these sediments are clay rich (smectite and interstratified clays) which have an ability to retain cations. Fe and Mn oxyhydroxides and organic matter are also present in the Halifax Bay sediments and they also adsorb cations. Tye concluded that consequently these cations are relatively immobile and stay in the intertidal sediments.

6.2 Results and Description

The major and minor element composition of the sediments of the Far North section of the Great Barrier Reef Lagoon is summarised in table 6 .1 & 6.2. These sediments basically consist of three components; a) terrigenous quartz b) terrigenous alumino-silicates c) carbonate (biogenic). To understand the relationship between the elements and their probable associations with the components of the geochemical system, different regressions were carried out

All possible element pairs were examined using regression and scatter plots to identify possible relationships between elements. Only those which have an evident mineralogical association are discussed in this chapter. They divide into four groups a) carbonate b) silicate c) oxides d) organic. From the carbonates, Mg/Ca (calcite) and Sr/Ca (aragonite) are selected because on the basis of their ionic radii, Mg is favoured over aragonite in the calcite lattice, and Sr over Mg in aragonite. The silicate element pairs include the feldspar elements Ba/K (as K_2O), Ba/Rb, and Al/Si in both clay and feldspar. In oxides the transition metals Mn, Co, Ni and Zn associate with iron and manganese oxides, largely hematite (Taylor & Eggleton 2001). For these the elemental ratios examined are Mn/Fe, V/Fe, and Ni/Fe.

Table 6.1 shows the *major element* composition of the sediments of the Far North section of the Great Barrier Reef Lagoon

Sample no	SiO_2%	TiO_2%	Al_2O_3%	Fe_2O_3%	MnO%	Mgo%	CaO%	SrO%	Na_2O%	K_2O%	P_2O_5%	SO_3%	S%
G-98	92.4	0.17	0.6	0.33	0	0.31	2.44	0.01	0.34	0.14	0.02	0.03	0.01
FG-36	13.3	0.17	3.4	1.27	0	1.95	37.7	0.25	0.34	0.1	0.09	0.7	0.29
FG-29	0.4	0.01	0.1	0.07	0	2.05	49.5	0.44	0	0.02	0.07	0.8	0.33
FG-28	1.8	0.02	0.6	0.58	0	2.43	47.7	0.36	0	0.03	0.25	0.83	0.34
FG-26	2.8	0.04	0.9	0.62	0	1.56	47.8	0.34	0	0.03	0.17	0.66	0.27
VC 7-5	0.2	0	0.3	0.01	0	1.02	50.1	0.68	0.14	0.01	0.05	0.64	0.26
VC 8-5	0.1	0	0.4	0.01	0	0.91	50.2	0.66	0	0.02	0.05	0.74	0.30
FG-20	1.7	0.02	0.8	0.51	0	2.05	48.3	0.37	0	0.03	0.3	0.74	0.30
FG-18	0.3	0	0.1	0.04	0	2.73	48.2	0.41	0	0.02	0.07	1.18	0.48
VC 10-5	3.3	0.05	1.2	0.68	0	2.5	46.5	0.31	0.29	0.05	0.1	0.85	0.35
G-37	95.2	0.05	0.1	0.04	0	0.12	2.33		0.01	0.11	0.01		0
G-38	55.2	0.14	2.6	1.06	0.01	1.39	19.1		0.16	0.1	0.07		0.21
G-40	46.2	0.13	2.8	1.1	0.01	1.46	23.58		0.19	0.12	0.07		0.15
G-42	59.2	0.14	2.5	0.87	0.01	1.31	17.23		0.2	0.12	0.05		0.11
G-100	67.1	0.08	1	0.37	0	1.02	14.62		0.23	0.07	0.05		0
G-104	56.4	0.13	2.6	1.06	0.01	1.3	18.57		0.2	0.12	0.05		0.14
G-107	96.4	0.05	0.1	0.01	0	0.12	1.55		0	0.09	0.01		0
G-111	37.4	0.2	4	1.38	0.01	1.59	25.81		0.3	0.25	0.06		0.24
G-112	62	0.14	2.6	1.14	0.01	1.11	15.6		0.21	0.13	0.05		0.02
G-113	20.2	0.14	3.4	1.27	0.01	2.17	36.16		0.17	0.15	0.09		0.28
G-115	56.7	0.19	2.6	1.25	0.01	1.4	18.33		0.23	0.18	0.06		0.15
G-116	63.2	0.2	3.7	1.35	0.01	1.26	13.85		0.44	0.21	0.05		0.05
G-118	24.5	0.33	7.5	2.47	0.02	2.36	27.53		0.69	0.33	0.08		0.37
VC 12-5	56.4	0.16	2.7	0.93	0.01	1.41	18.07		0.15	0.12	0.05		0.21
VC 12-10	59.4	0.11	2.2	0.73	0.01	1.2	18.12		0.12	0.1	0.05		0.13
VC 12-15	53.7	0.16	2.9	1	0.01	1.43	19.72		0.32	0.22	0.05		0.2
VC 12-45	52.2	0.14	2.6	0.88	0.01	1.42	21.36		0.24	0.17	0.05		0.21
VC 12-75	59.7	0.18	3	1.03	0.01	1.38	16.9		0.26	0.2	0.05		0.22
VC 12-110	74.4	0.16	2.4	0.8	0.01	0.82	10.36		0.38	0.15	0.04		.
FG-18	36.9	0.17	2.69	1	0.01	1.78	27.6		0.15	0.09	0.05		0.16
FG- 2	40.8	0.21	4.19	1.59	0.01	1.84	24.3		0.27	0.24	0.07		0.17
FG- 3	40.2	0.15	3.39	1.5	0.01	1.8	24.7		0.35	0.3	0.07		0.19
FG- 7	12.6	0.07	1.94	0.77	0	1.99	43.1		0.1	0.06	0.09		0.29
FG- 9	3.4	0.01	0.88	0.24	0	2.02	49.2		0.06	0.06	0.09		0.23
FG- 13	1.6	0.01	0.63	0.33	0	2.11	50.9		0.09	0.05	0.09		0.34
FG- 17	0.1	0.01	0.04	0.01	0	1.43	53.1		0.02	0.02	0.07		0.19
G-81	17.3	0.01	0.49	0.54	0.01	2.77	41.3		0.08	0.05	0.09		0.22
G-82	95	0.11	0.27	0.24	0	0.24	2.2		0.05	0.1	0.01		0
G-83	91.2	0.06	0.22	0.42	0	0.19	3.9		0.09	0.09	0.02		0

Sample no	SiO_2%	TiO_2%	Al_2O_3%	Fe_2O_3%	MnO%	Mgo%	CaO%	SrO%	Na_2O%	K_2O%	P_2O_5%	SO_3%	S%
G-93	82.4	0.03	0.36	0.46	0	0.25	8.3		0.07	0.11	0.02		0
G-94	98.1	0.08	0.17	0.06	0	0	0.5		0.02	0.08	0.01		0
G-96	78.7	0.07	0.94	0.63	0	0.79	9.2		0.09	0.07	0.03		0
G-97	68.6	0.09	1.07	0.84	0.01	0.96	14.1		0.1	0.07	0.04		0
VC-20-18	68.7	0.53	3.11	16.66	0.02	0.29	0.9		0.37	0.1	0.04		0.16
VC-20-63	92.2	0.2	3.98	0.61	0	0.01	0.1		0.02	0.07	0.02		0
VC-21-10	90.4	0.15	2.39	0.62	0	0.26	1.3		0.18	0.19	0.01		0
VC-21-20	91.9	0.16	1.75	0.54	0	0.22	1.3		0.15	0.18	0.01		0
VC 22-20	91.6	0.07	0.64	0.27	0	0.22	3.9		0	0.08	0.01		0
VC 22-100	92.3	0.07	0.9	0.32	0	0.3	3.1		0	0.1	0.01		0
VC 22-290	80.7	0.14	1.64	0.58	0	0.58	7.7		0.3	0.15	0.01		0
VC 23-86	88	0.04	0.43	0.35	0.01	0.43	5.72		0.08	0.07	0		0
VC 24-10	77.9	0.09	1.28	0.73	0.01	0.86	9.5		0.16	0.07	0.01		0
VC 24-80	66.7	0.1	1.55	0.8	0.01	1.22	14.57		0.21	0.08	0.02		0.09
VC 25-10	66.1	0.14	1.77	1.03	0.01	1.09	14.36		0.23	0.11	0.02		0.05
VC 25-60	62	0.15	2.23	1.21	0.01	1.29	16.04		0.36	0.13	0.03		0.08

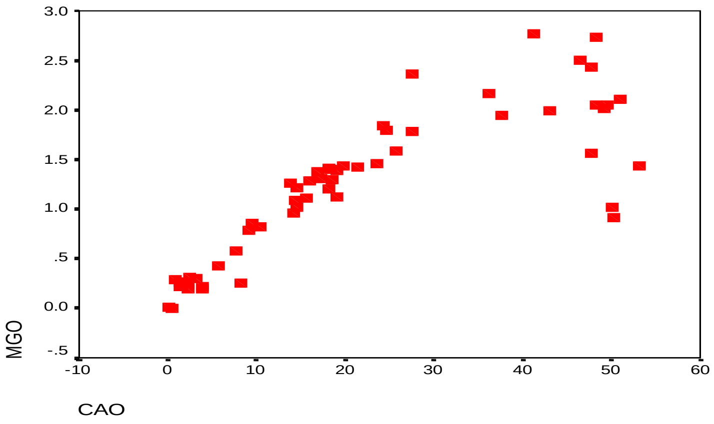
Table 6.2 shows the *Trace element* composition of the sediments of the Far North section of the Great Barrier Reef Lagoon

Sample no	**Sc (ug/g)**	**Ba (ug/g)**	**Ti (ug/g)**	**V (ug/g)**	**Cr (ug/g)**	**Mn (ug/g)**	**Co (ug/g)**	**Ni (ug/g)**	**Zn (ug/g)**	**Ga (ug/g)**	**As (ug/g)**	**Pb (ug/g)**	**Rb (ug/g)**	**Sr (ug/g)**	**Y g/g)**	**Zr (ug/g)**	**Nb (ug/g)**
G-98	0	15	938	9	23	36	2	3	16	0	13	8	0	117	15	1707	0
FG-36	8	50	699	27	30	127	0	12	30	6	0	18	23	2088	2	0	0
FG-29	9	33	38	0	22	27	0	6	17	0	0	21	0	3737	0	0	0
FG-28	10	32	116	15	27	64	0	9	23	0	0	20	0	3014	0	0	0
FG-26	7	30	223	26	24	69	0	10	22	0	0	19	0	2915	0	0	0
VC 7-5	11	27	0	0	17	21	0	10	17	0	0	27	0	5779	0	0	0
VC 8-5	11	33	0	0	14	19	0	9	17	0	0	25	0	5612	0	0	0
FG-20	11	11	135	19	24	55	0	9	32	0	0	20	0	3097	0	0	0
FG-18	10	23	0	15	32	53	0	8	17	0	0	22	0	3428	0	0	0
VC 10-5	10	39	341	23	22	107	0	8	30	0	0	21	0	2613	0	0	0
G-37	2	26	300	7	9	14	1	1	7	1	1	6	4	120	5	1164	2
G-38	11	62	1060	24	25	124	2	5	16	4	2	6	23	946	8	161	3
G-40	11	51	940	20	25	133	2	7	17	4	2	6	25	1243	7	207	3
G-42	10	57	1027	20	18	126	2	5	15	4	2	6	23	866	8	184	4
G-100	6	24	488	12	9	67	1	4	9	2	1	4	11	740	7	306	2
G-104	8	61	999	15	24	120	2	8	16	4	2	6	23	830	8	159	4
G-107	1	22	395	5	4	15	1	0	5	1	1	4	4	122	4	1195	3
G-111	14	88	1481	24	37	185	3	7	28	5	3	8	36	1337	11	216	4
G-112	7	71	1087	21	24	112	2	6	16	4	2	6	23	773	7	196	4
G-113	29	58	1164	29	29	163	5	9	22	6	1	5	29	2701	8	68	0
G-115	12	67	1299	19	26	124	2	5	15	4	3	6	23	835	11	300	4
G-116	12	92	1720	33	35	145	3	7	21	6	3	8	34	630	11	223	5
G-118	18	151	1971	46	38	226	7	13	36	11	6	16	63	1686	14	171	6
VC 12-5	11	83	1243	20	22	146	2	5	17	4	2	5	24	879	9	180	4
VC 12-10	11	56	982	17	20	125	2	4	17	3	1	6	20	829	9	206	3
VC 12-15	14	72	1318	26	25	153	3	5	18	4	1	6	26	968	9	161	4
VC 12-45	16	67	1107	21	21	132	1	5	17	4	1	5	22	928	9	147	3
VC 12-75	11	72	1408	22	27	148	2	6	17	5	1	5	26	812	9	150	4
VC 12-110	7	65	1451	23	30	111	1	4	14	3	1	7	22	569	8	275	5
FG- 2	14	77	1409	34	36	165	4	8	24	7	2	2	9	1352	11	182	4
FG- 3	16	78	1220	27	30	209	4	8	25	6	2	2	7	1648	9	187	3
FG- 7	33	35	624	22	22	110	2	7	15	4	2	2	4	3256	6	17	0
FG- 9	46	27	195	13	12	52	2	4	11	3	0	0	4	4019	4	0	0
FG- 13	50	28	135	12	14	53	2	7	6	3	1	1	2	3868	3	0	0
FG- 17	55	7	24	6	12	23	2	4	3	1	0	0	1	6636	1	0	0
G-80	7	32	342	12	11	85	0	3	10	4	3	2	7	1029	6	158	1
G-81	30	24	134	14	21	217	1	4	6	2	9	4	5	2045	6	75	0
G-83	1	21	379	8	4	35	0	1	5	1	5	3	4	163	4	1549	3
G-93	0	23	219	13	2	22	0	1	6	1	5	3	4	318	4	879	2
G-94	2	28	461	6	1	17	0	0	5	0	2	2	3	41	5	2489	3
G-96	2	31	462	21	12	139	0	2	11	2	3	3	9	396	5	246	3
G-97	7	24	584	10	23	133	0	3	10	3	4	4	9	642	8	283	3
VC-20-18	6	37	3245	65	27	216	0	8	9	9	15	6	7	30	12	936	9
VC-20-63	6	25	1684	31	21	30	0	1	7	5	3	8	6	20	7	481	5
VC-21-10	4	40	1332	23	17	29	0	2	19	3	2	4	13	74	7	600	5
VC-21-20	4	46	1197	19	15	26	0	2	20	2	2	5	11	68	7	832	5
VC 22-20	2	36	533	12	9	46	0	1	6	1	1	4	6	98	6	459	4

sample no	Sc (ug/g)	Ba (ug/g)	Ti (ug/g)	V (ug/g)	Cr (ug/g)	Mn (ug/g)	Co (ug/g)	Ni (ug/g)	Zn (ug/g)	Ga (ug/g)	As (ug/g)	Pb (ug/g)	Rb (ug/g)	Sr (ug/g)	Y g/g)	Zr (ug/g)	Nb (ug/g)
VC 23-86	2	12	238	10	8	119	0	1	6	1	2	3	5	283	5	327	3
VC 24-10	5	40	692	17	17	137	0	3	10	3	4	3	11	490	7	190	3
VC 24-80	6	32	714	16	19	157	1	4	11	4	4	4	14	776	7	206	3
VC 25-10	5	37	848	18	21	118	1	4	11	3	4	4	13	654	8	303	4
VC 25-60	6	44	990	17	21	142	2	6	13	4	5	6	17	810	9	279	4

Figures 6.1 - 6.7 shows plots of these elemental pairs, the linear regression equation between element pairs, as well as their Pearson correlation coefficient.

Figure 6.1 Shows regression pattern of Cao and MgO



Regression

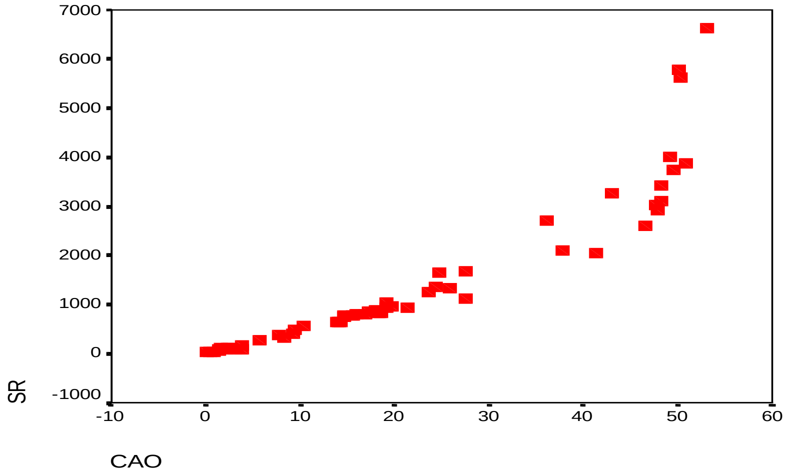
Descriptive Statistics

	Mean	Std. Deviation	N
MGO	1.2146	.7477	56
CAO	21.7365	17.0500	56

Correlations

		MGO	CAO
Pearson Correlation	MGO	1.000	.821
	CAO	.821	1.000
Sig. (1-tailed)	MGO	.	.000
	CAO	.000	.
N	MGO	56	56
	CAO	56	56

Figure 6.2 Shows regression pattern of Cao and Sr.



Regression

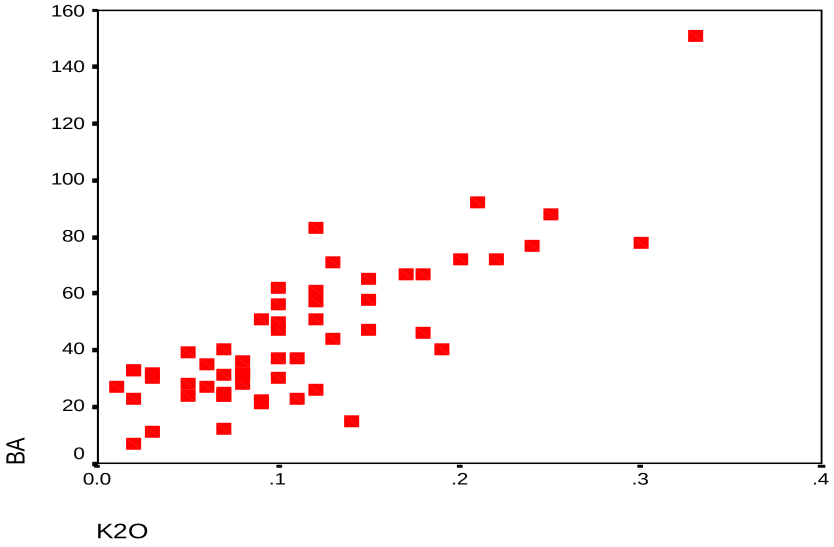
Descriptive Statistics

	Mean	Std. Deviation	N
SR	1439.6786	1566.2074	56
CAO	21.7365	17.0500	56

Correlations

		SR	CAO
Pearson Correlation	SR	1.000	.920
	CAO	.920	1.000
Sig. (1-tailed)	SR	.	.000
	CAO	.000	.
N	SR	56	56
	CAO	56	56

Figure 6.3 Shows regression pattern of Ba and K_2O.



Regression

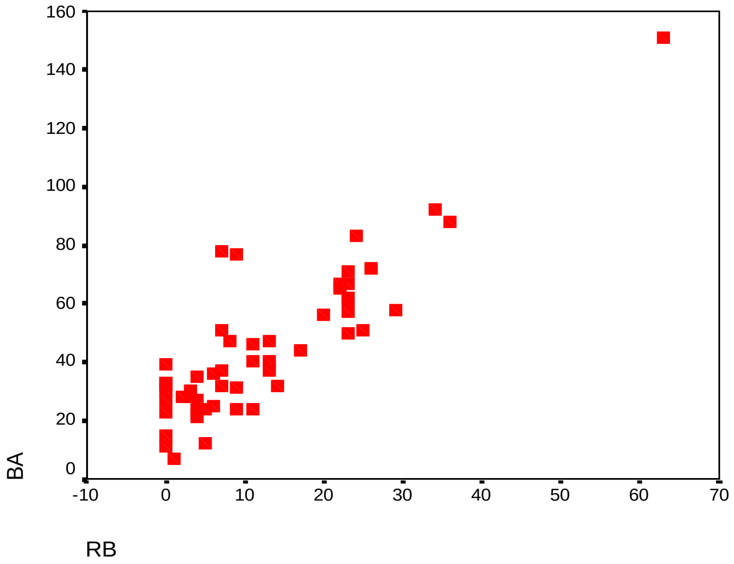
Descriptive Statistics

	Mean	Std. Deviation	N
K2O	.1107	7.011E-02	56
BA	44.5893	25.3117	56

Correlations

		K2O	BA
Pearson Correlation	K2O	1.000	.811
	BA	.811	1.000
Sig. (1-tailed)	K2O	.	.000
	BA	.000	.
N	K2O	56	56
	BA	56	56

Figure 6.4 Shows regression pattern of Rb and Ba.



Regression

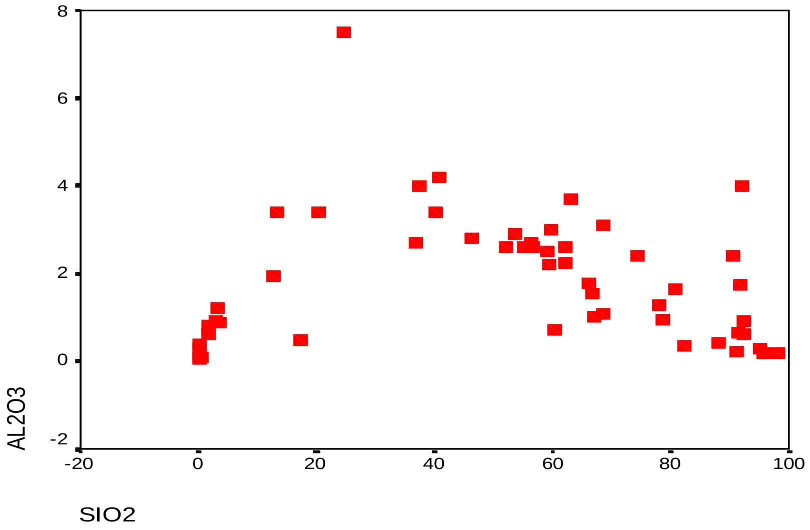
Descriptive Statistics

	Mean	Std. Deviation	N
RB	12.2500	12.1000	56
BA	44.5893	25.3117	56

Correlations

		RB	BA
Pearson Correlation	RB	1.000	.877
	BA	.877	1.000
Sig. (1-tailed)	RB	.	.000
	BA	.000	.
N	RB	56	56
	BA	56	56

Figure 6.5 Shows regression pattern of SiO_2 and Al_2O_3.



Regression

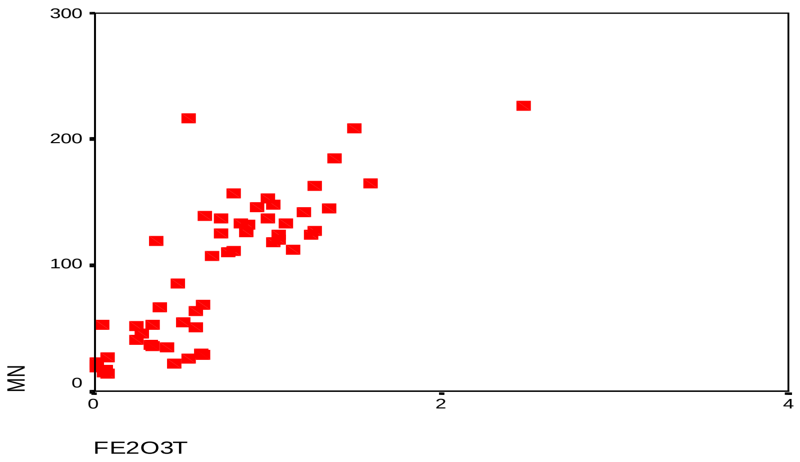
Descriptive Statistics

	Mean	Std. Deviation	N
AL2O3	1.7779	1.4460	56
SIO2	51.9393	33.2004	56

Correlations

		AL2O3	SIO2
Pearson Correlation	AL2O3	1.000	-.022
	SIO2	-.022	1.000
Sig. (1-tailed)	AL2O3	.	.436
	SIO2	.436	.
N	AL2O3	56	56
	SIO2	56	56

Figure 6.6 Shows regression pattern of $Fe_2O_3$and Mn



Regression

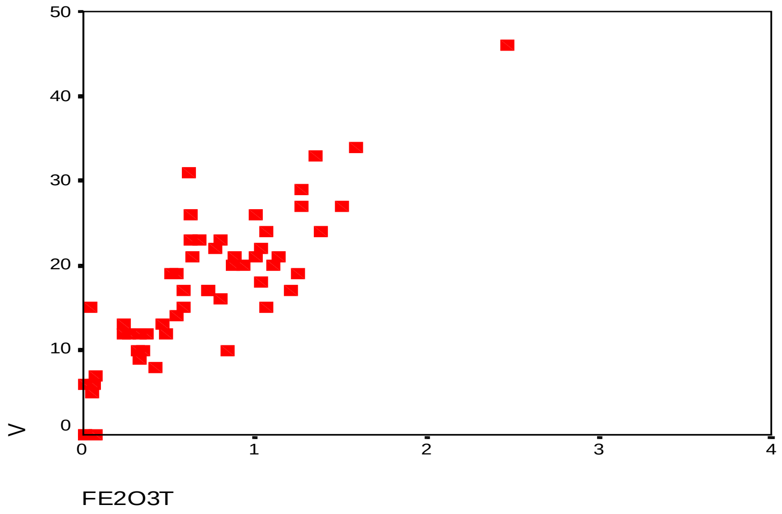
Descriptive Statistics

	Mean	Std. Deviation	N
MN	98.0893	59.8487	56
FE2O3T	.9957	2.1856	56

Correlations

		MN	FE2O3T
Pearson Correlation	MN	1.000	.438
	FE2O3T	.438	1.000
Sig. (1-tailed)	MN	.	.000
	FE2O3T	.000	.
N	MN	56	56
	FE2O3T	56	56

Figure 6.7 Shows regression pattern of Fe_2O_3 and V



Regression

Descriptive Statistics

	Mean	Std. Deviation	N
V	18.2857	10.8573	56
FE2O3T	.9957	2.1856	56

Correlations

		V	FE2O3T
Pearson Correlation	V	1.000	.724
	FE2O3T	.724	1.000
Sig. (1-tailed)	V	.	.000
	FE2O3T	.000	.
N	V	56	56
	FE2O3T	56	56

To understand the association and distribution of different elements and oxides in the study area, several ratios are plotted against distance from coast to Reef (T1 Fig 6.8 and T2 Fig 6.9) and in a north – south transect (T3 Fig 6.10) and these are interpreted in the discussion. Values below the detection limit for elements in all cases are taken as *ca* half of the detection limit. In the rest of the work values below detection limit are taken as zero.

6.2.1 Grab Samples

Fig 6.8 shows the elemental ratio distribution of surface bottom grab samples and core surface samples against distance from coast to reef along transect T1. Note that there is a difference of 10,000 between the units used for major elements (wt %) and trace elements (ppm). The ratios of the carbonate group elements (Sr/Ca and Mg/Ca) have a steady pattern. Al_2O_3/SiO_2 ratio rises toward the outer shelf. Mn/Fe exhibit similar trends with an increase in the ratio near shore.

Figure 6.8 Distribution of elemental ratios across the shelf T1 (~135 km long).

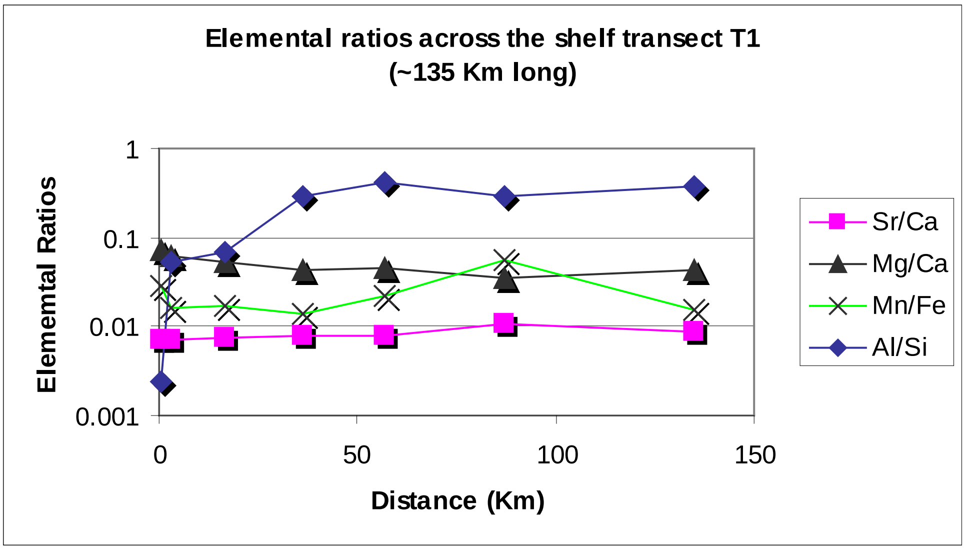


Fig 6.9 shows elemental ratios and their distribution across the shelf for the core surface samples and bottom grab samples belonging to transect T2. The Sr/Ca and Mg/Ca ratio have steady trends except near the end of transect near the reef in the outer shelf where the Sr/Ca ratio decreases and Mg/Ca ratio increases. The Mn/Fe at first decreases and after 80 km the pattern is very irregular. Once again like T1, in this transect the Al_2O_3/SiO_2 ratio increases across the transect towards the outer shelf near the Reef.

Figure 6.9 Shows the distribution of elemental ratios across the shelf Transect T2 (~135 km long)

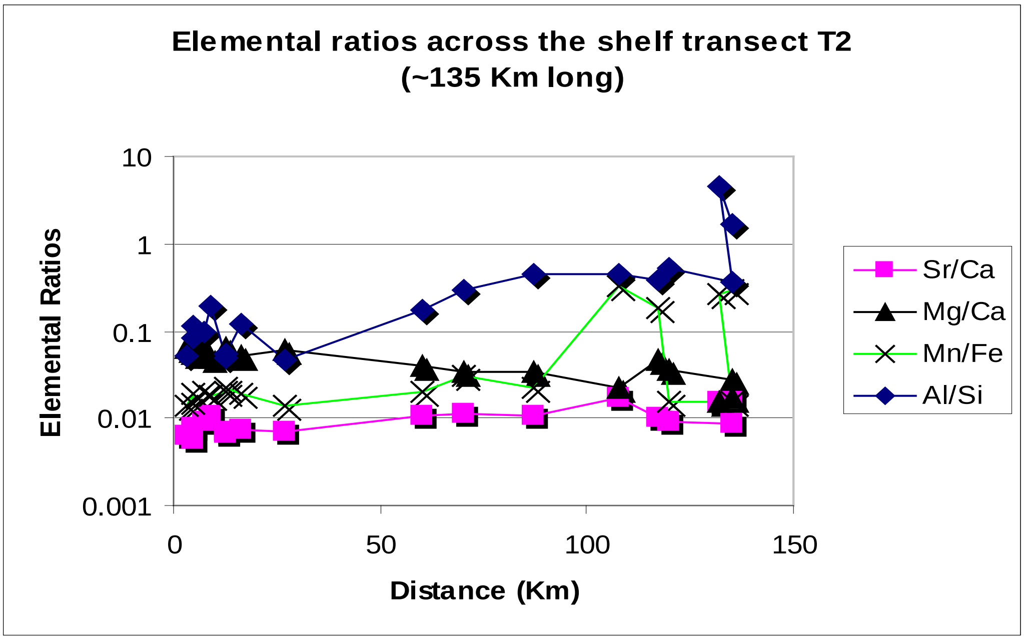
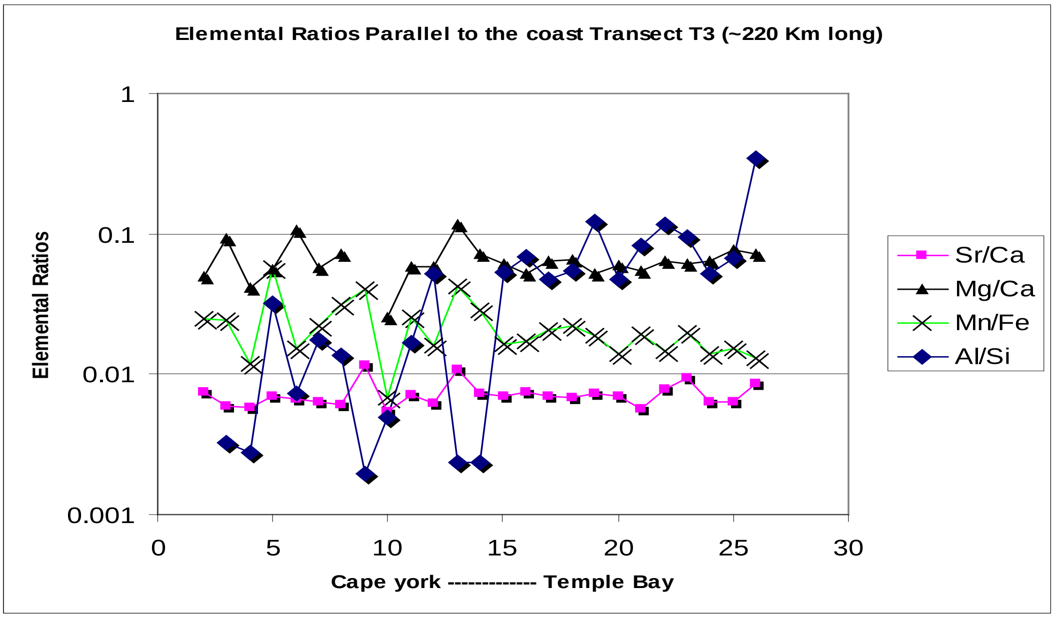


Fig 6.10 shows the elemental ratio distribution along the coast from the tip of Cape York to the Temple Bay area. These belong to core surface samples and bottom grab samples collected parallel to the coast. The ratio Al/Si shows irregular pattern. The Sr/Ca and Mg/Ca ratios showed little variation. The trend of Mn/Fe shows no definite pattern.

Figure 6.10 Shows the distribution of elemental ratios along the coast transect T3 (~220 km long)

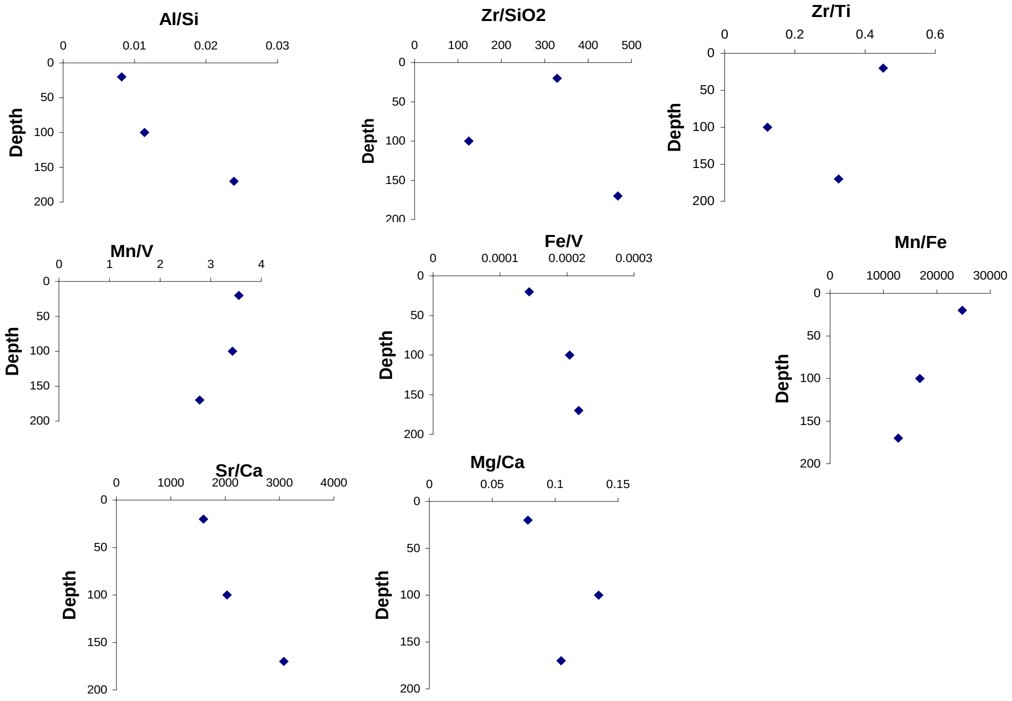


6.2.2 Cores.

Ten sediment Vibro core were collected (VC location shown in Figure 3.1). Two cores were studied in greater detail and it is these two cores which will be discussed in this section.

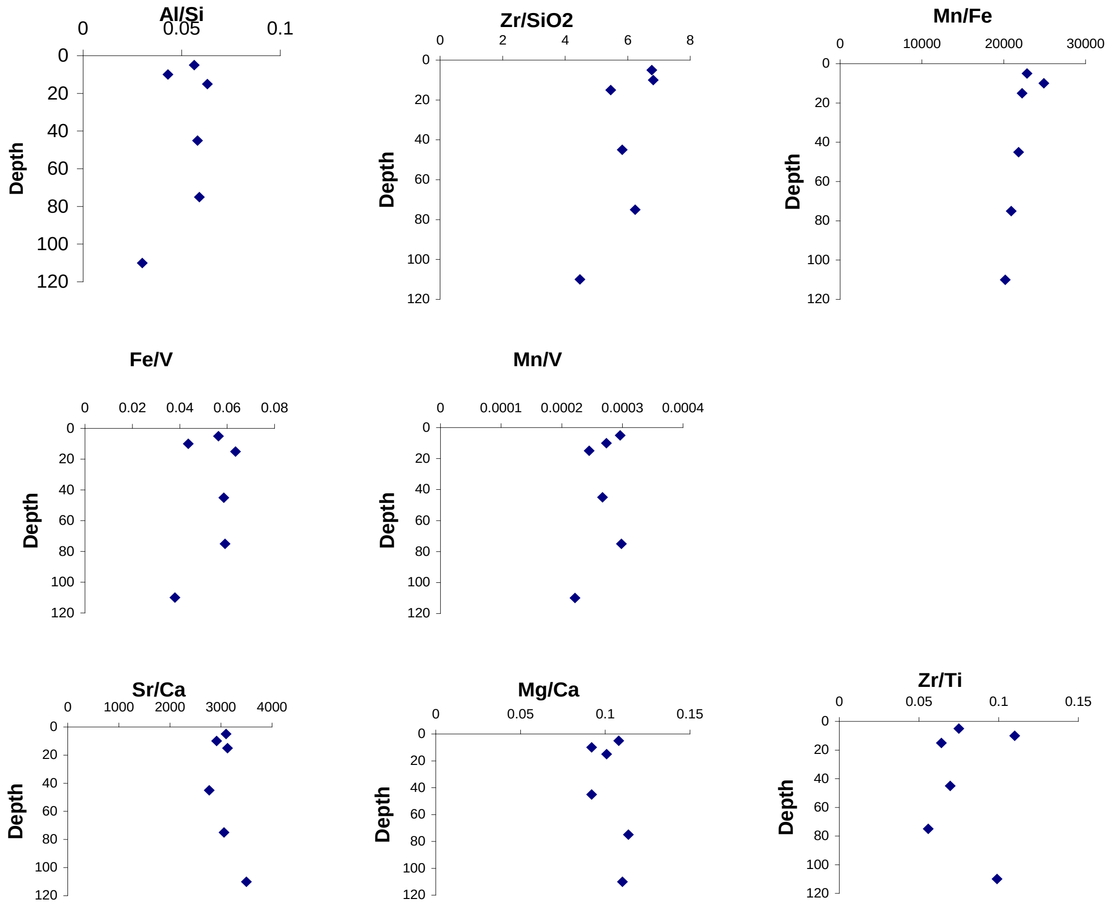
The same element pairs examined for grabs were considered for the cores also. Fig 6.11 shows the concentration of elemental ratios of VC-22 collected from Newcastle Bay. The elemental ratios Al/Si and Zr/SiO_2 show a gradual increase down the core and Zr/Ti have an erratic pattern. The ratio relating to carbonate minerals (Sr/Ca) also increases down the core. The Mg/Ca ratio indicates a decrease in the bottom core sediments. Mn with V and Fe also have a decreasing trend from top to bottom sediments. The ratio of Fe and V increases downward.

Figure 6.11 shows the distribution of elemental ratios down the core VC-22



The detailed XRF study of the core samples from Shelburne Bay (VC 12 Fig 6.12) indicates a decrease in Al/Si and Zr/Si ratio with an increase in the Zr/Ti ratio vertically down the core. Mg/Ca ratio decreases down to 50 cm depth than increases and continues this trend to the lowest sample bottom sediments. Sr/Ca shows an erratic pattern. Fe/V has a general decrease from top to the bottom of the core except at 20 cm depth where it increases slightly. Mn/V ratio has a straight line decrease up to 20 cm then this ratio increases up to 100 cm, but further down it decreases again. Mn/Fe also has a straight line decreasing trend from top to the bottom of the core. At 15 cm depth a slight increase in the ratio is observed.

Figure 6.12 shows the distribution of elemental ratios down the core VC-12



6.3. Principal Component Analyses (PCA)

The principal component analysis was carried out to understand more about the distribution and pattern of association of different elements and oxides. PCA basically extracts a component which describes the maximum variation in the data set. Further components are then extracted which accounts for variability not captured by the preceding components (Kreamer *et al* 1996).

Elements (Co and F) for which a significant number of analyses were below the instrument detection limit (see XRF results) were excluded from the variables of the PCA analysis.

Each consecutive component is independent and not correlated to others. The results of this analysis are presented as a *Scores matrix* and a *loading matrix*. In this study, the scores represent the different surface bottom grab samples and core sub samples. The loading scores represent the concentration of each of the major and minor trace elements in each of the samples. Table 6.3 summarises each variable element or oxide's contribution to each of the factor.

Table 6.3 Rotated component matrix[a]

Elements	Components			
	1	2	3	4
Ga	0.748	0.031	0.500	0.313
Zn	0.630	0.552	0.011	-0.451
Ni	0.390	0.810	0.234	-0.208
Cr	0.687	0.499	0.285	-0.132
V	0.565	0.070	0.749	0.003
Ba	0.939	0.055	0.056	0.034
As	0.063	-0.250	0.561	0.162
Pb	-0.056	0.570	-0.014	-0.744
Rb	0.893	-0.045	0.048	0.109
Sr	-0.286	0.826	-0.157	0.023
Y	0.686	-0.402	0.249	0.305
Zr	-0.188	-0.643	-0.044	-0.133
Nb	0.081	-0.638	0.493	0.018
SiO_2	0.484	-0.981	0.027	0.000
TiO_2	0.616	-0.246	0.703	-0.011
Al_2O_3	0.900	0.058	0.319	0.051
Fe_2O_3T	0.243	-0.025	0.950	0.030
MgO	-0.151	0.893	-0.067	0.158
CaO	-0.051	0.961	-0.141	0.020
Na_2O	0.811	-0.036	0.235	-0.025
K_2O	0.887	-0.239	0.013	0.074
P_2O_5	0.050	0.764	0.046	-0.233
S	0.474	0.398	0.123	0.692
Mn	0.645	0.220	0.415	0.344

EXTRACTION METHOD PCA
ROTATION METHOD VARIMAX WITH KAISER NORMALIZATION
[A]ROTATION CONVERGED IN 6 ITERATIONS

Table 6.4 shows the results of PCA (total variance).

Total Variance Explained

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	9.473	39.472	39.472	7.779	32.414	32.414
2	7.211	30.047	69.519	6.869	28.623	61.036
3	1.900	7.919	77.437	3.365	14.022	75.058
4	1.539	6.413	83.850	1.754	7.308	82.367
5	.790	3.291	87.141	1.146	4.774	87.141
6	.656	2.732	89.873			
7	.584	2.434	92.307			
8	.311	1.296	93.602			
9	.287	1.197	94.800			
10	.237	.987	95.787			
11	.202	.841	96.628			
12	.151	.628	97.256			
13	.140	.585	97.841			
14	.104	.432	98.273			
15	9.580E-02	.399	98.672			
16	8.875E-02	.370	99.042			
17	6.079E-02	.253	99.295			
18	5.893E-02	.246	99.541			
19	4.482E-02	.187	99.728			
20	3.053E-02	.127	99.855			
21	1.681E-02	7.006E-02	99.925			
22	1.092E-02	4.551E-02	99.970			
23	6.981E-03	2.909E-02	99.999			
24	1.389E-04	5.788E-04	100.000			

Extraction Method: Principal Component Analysis.

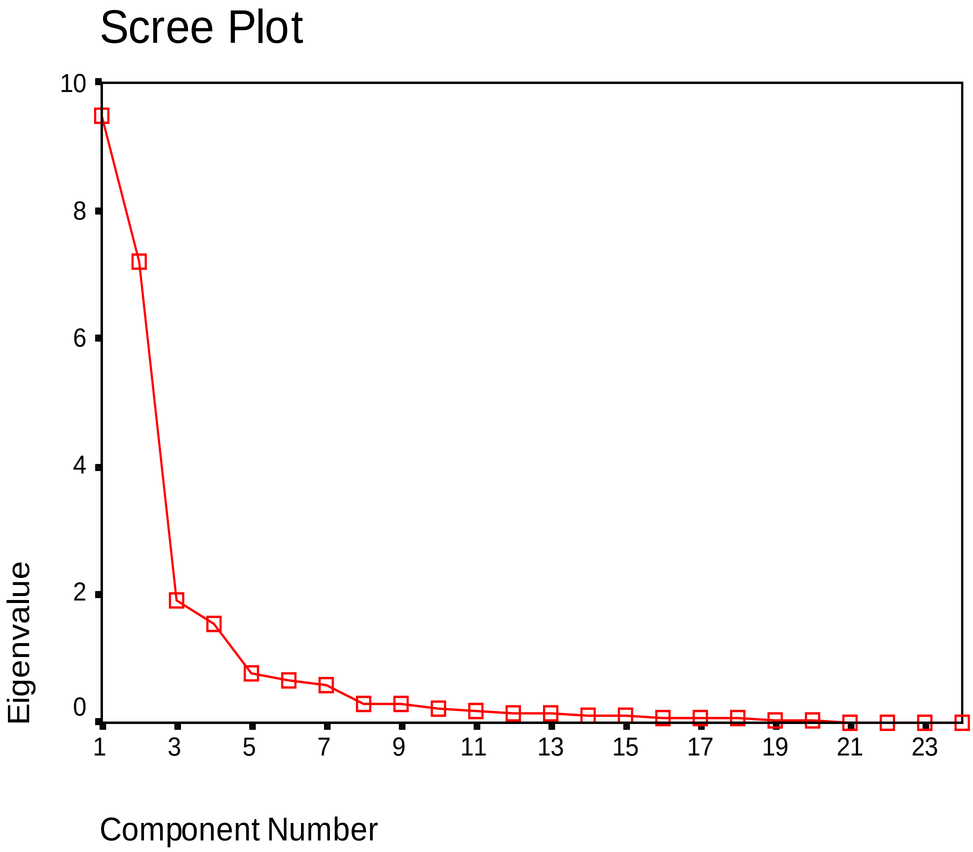


Figure 6.13 shows the PCA result (scree Plot)

A scree plot is one which shows the total variation in the samples and on the basis of the break in slope of the plot it can be decided how many groups are suitable for a given data set (Cattell 1966). In these data, 4 factors are enough to represent the data set, because after that little change in the slope is observed.

Variables belonging to each component are shown in Table 6.4 and scree plot (Figure 6.13). The cumulative variance shows that the first four components account for nearly 84 % of the variance in the data set.

The calculated D.F (differential factor to calculate the level of confidence for that data set) value for the data set is 0.335. The values lower than 0.335 are considered to be insignificant for that group. The elements that have values more than 0.335 are considered as loading for that group. A negative contour means confidence level is < 0.335 and positive contours indicate a statistical significance of 95 % or more with confidence level 0.335 or higher.

6.3.1 Component or Factor 1 'Alumino-Silicate' group (F1) accounted for 40 % of the total variance in the data set Table 7.3. The variables that have high loadings in Factor 1 is Ga, Zn, Ni, Mn, Cr, Ti, V, Ba, Rb, Y, Nb, SiO_2, Al_2O_3, Na_2O, K_20 and S. This group consists of elements that are associated with silicate minerals.

6***.3.2 Component or Factor 2 'Carbonate' group (F2)*** accounts for 30 % of the variance in the total data set. Elements associated with carbonate minerals are strongly grouped in factor 2: CaO, MgO, Sr, P_2O_5, Pb, Cr, Ni and Zn.

6.3.3 Component or Factor 3 'Oxide' group (F3) accounts for 8 % of the variance in the total data set. Significantly high loading elements were Fe, Ga, Mn, Ti, V, As, Y and Nb. This component includes the elements commonly found as or associated with oxides.

6***.3.4 Component or Factor 4 'Sulphur' (F4)*** Account for 6 % of the total variance in the data set. This component shows a strong grouping of elements occurring in a reducing environment. The elements with high loading for component 4 were Fe, Mn and S.

6.4. Contour maps of factors

The individual factor scores were used to draw a contour map for that factor. Each contour map represents a specific factor and its distribution in the area. A negative contour means confidence level is < 0.335 and positive contours indicate a statistical significance of 95 % or more with confidence level 0.335 or higher.

6.4.1. Factor 1 (F1) Alumino-Silicate group Map

The F1 Silicate contour Map 1 shows a relatively high concentration of the alumino-silicate group in the Shelburne Bay area and the highest concentration in the Temple Bay area, with the maximum value being 5.5. Across the shelf in the mid-shelf region this factor shows closed positive value contours followed by a lesser concentration of negative contours towards the outer shelf.

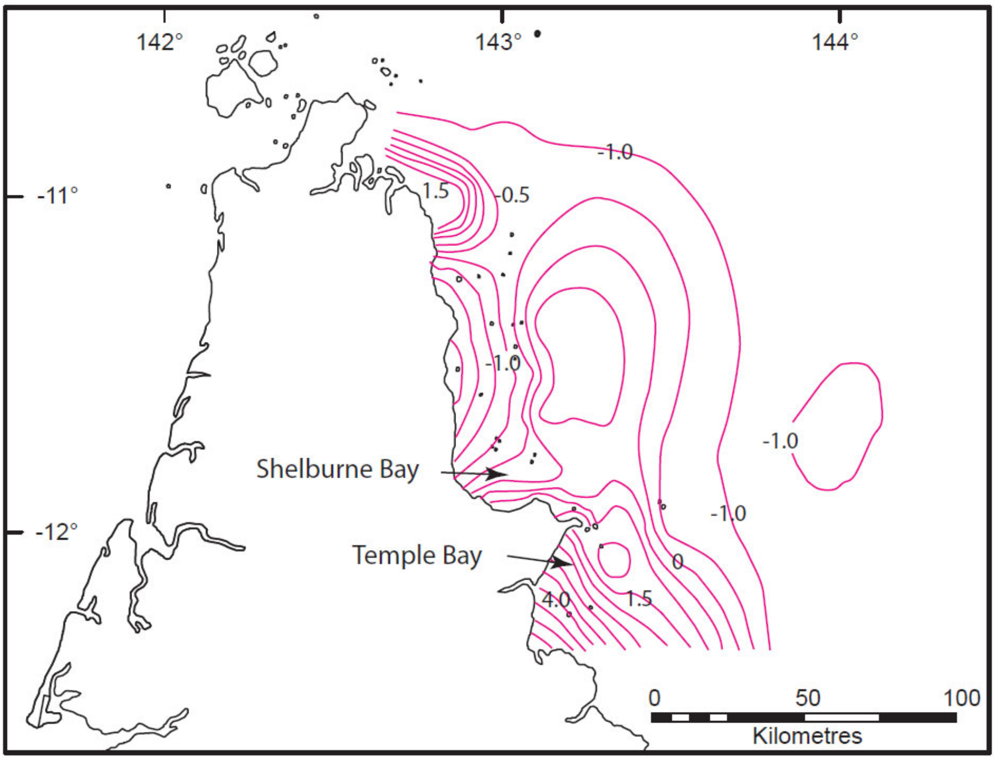


Figure 6.14 Map shows distribution pattern (contours) of silicate in the Far North Section of the Great Barrier Reef Lagoon.

6.4.2. Factor 2 (F2) Carbonate group Map

The F2 Carbonate contour map is nearly the opposite of the F1 silicate contour map. As expected the contour values increase from shore to reef. Parallel to the shore carbonate distribution contours are mostly negative from Newcastle Bay almost to the end of Shelburne bay. The map shows the values for the carbonate factor in and around Cape Grenville and in the Temple bay region. The maximum inshore value is 1 in the Temple Bay region as compared to it the value is 2 near reef in outer shelf.

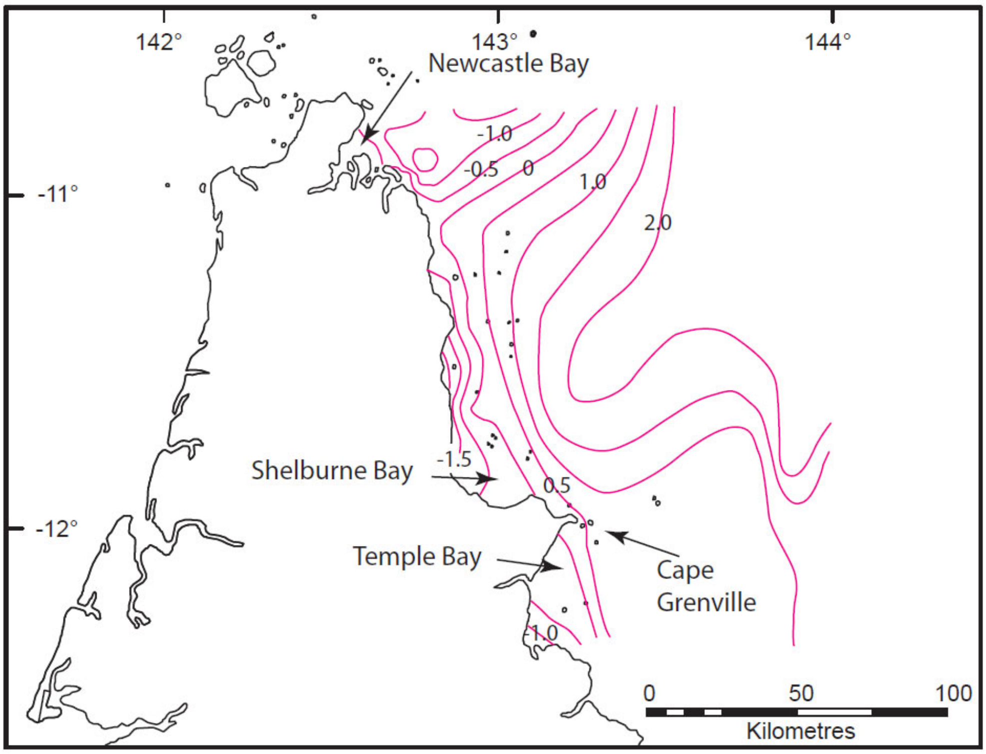


Figure 6.15 Map shows the distribution pattern of carbonate in the Far North Section of the Great Barrier Reef Lagoon.

6.4.3. Factor 3 (F3) Oxide group Map

The F3 of oxide contour map shows maximum concentration in Newcastle Bay with the highest value of 3.5 near to Turtle Island. In Shelburne and Temple Bays only a few samples have high oxide concentrations. In the middle-outer shelf a few samples have minor oxides.

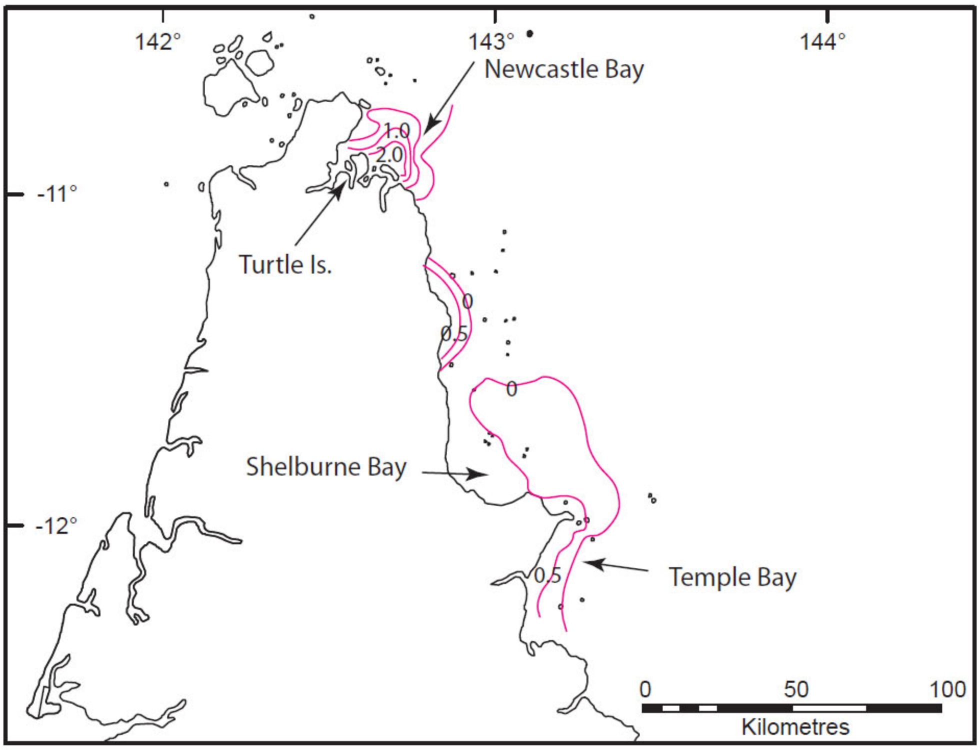


Figure 6.16 Map shows distribution pattern (contours) of oxides in the Far North Section of the Great Barrier Reef Lagoon.

6.4.4. Factor 4 (F4) Sulphur Map

The factor F4 dominated by S and contour map shows that the Shelburne and Temple bay have a reasonable concentration of sulphur in both the surface bottom grabs and core sub-samples. Newcastle Bay has only a few grabs and core sub-samples that have a considerable amount of sulphur.

The mid-outer shelf samples across Temple Bay have the highest concentration of sulphur with a maximum value of 4. Both Shelburne and Temple Bays have moderate sulfur levels, whereas Newcastle Bay and the Reef region have the lowest amounts.

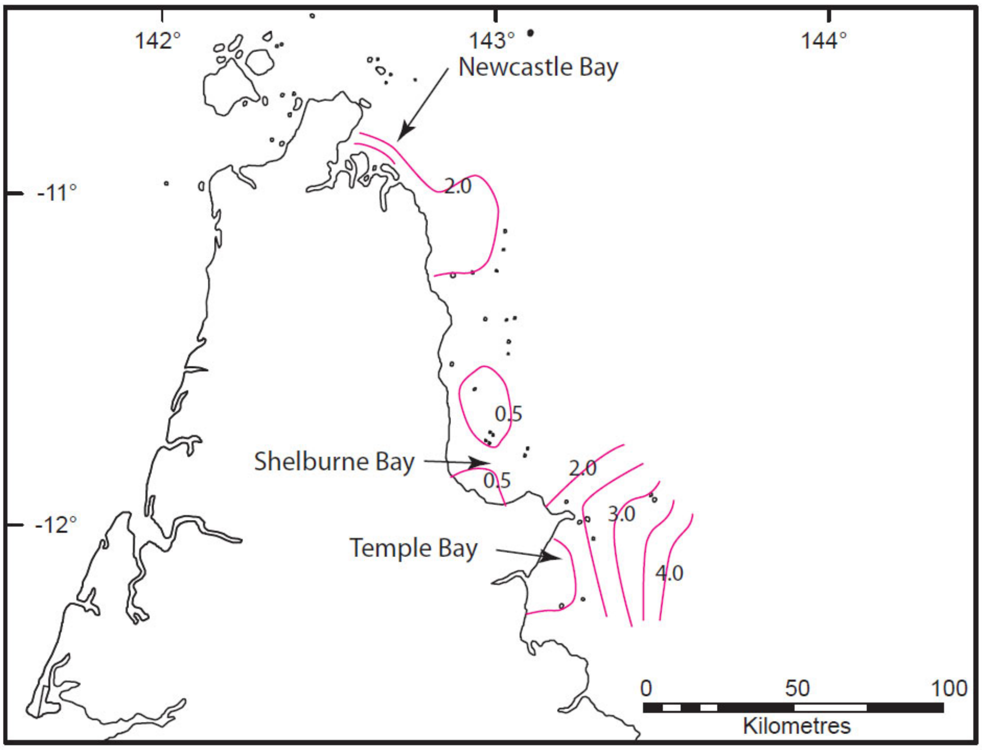


Figure 6.17 Map shows distribution pattern (contours) of Sulphur in the Far North Section of the Great Barrier Reef Lagoon.

6.5. Discussion

6.5.1 Inter-element relationship

The regressions for Sr/Ca (Fig 6.2) and Mg/Ca (Fig 6.1) are strongly significant and exhibit high correlation coefficients, which indicate they exist in the same phase, interpreted as their presence in the carbonate minerals aragonite and calcite respectively. Barium has a positive relationship with K_2O and Rb (Fig 6.3 and 6.4 respectively) and does not have strong association with CaO. K, Ba and Rb co-exist in K-feldspar and muscovite; their correlation in the sediment indicates they are derived from a terrestrial source. Zr has moderate to poor correlation with Si and Ti. This means Zr and Ti do not coexist in the same mineral phase which is hardly surprising as there are few Zr Ti minerals. The Zr in sediments almost only occurs in zircon, whereas Ti may be in ilmenite, rutile or anatase. Where weathering is releasing primary minerals that are quickly carried to sediments, correlation between unweathered heavy minerals such as zircon and ilmenite might be expected. Where the hinterland is deeply weathered, zircon remains in the sand and silt fraction, whereas titanium occurs in clay-sized anatase (Taylor & Eggleton 2001).

Aluminium has a positive correlation with Ti. Most of the Al in sediments comes from clays (Al-rich) thus Ti and Al would be expected to correlate if derived from a weathered (clay rich) terrain. Such a sediment source would not yield a high Zr/Ti correlation. The results obtained here indicate these sediments have been derived from a well-weathered terrestrial source.

Aluminium has zero correlation with Si. This low correlation of Al and SiO_2 is due to the presence of silicon in all the minerals of the silicate group.

There is a strong positive correlation (> 0.6) between Fe_2O_3, and the other transition metals Mn and V, Cr, Co, Ni and Zn, elements which commonly occur in Fe-oxyhydroxides (Taylor & Eggleton 2001) (Figures 6.6 - 6.7). High correlations also exist between Fe_2O_3 and TiO_2, Na_2O, and K_2O. This is interpreted as a physical association of the detrital minerals in the sediments, hematite, rutile, ilmenite, micas and feldspars.

The spatial distribution of the elemental ratios reveals changes in the sediment mineralogy. The cross shelf distribution in (Fig 6.8 and 6.9) shows that in T1 and T2 the Sr/Ca ratio increases with distance, which is interpreted as being due to the increased abundance of high Sr aragonite in *Halimeda* generated sediment (Milliman 1974). In parallel there is a decrease in the Mg/Ca ratio consistent with an increase in aragonite over calcite. (Refer Chapter-6 Mineralogy for details).

The Al_2O_3/SiO_2 ratio, after initial fluctuation near the coast probably because of local differences in clay and sand quantities, is consistent across the shelf (Fig 6.8 - 6.9), reflecting a trivial amount of clay.

Both the Fe_2O_3 & Mn content of the sediments steadily decreases across the shelf (Fig 6.8 and 6.9) reflecting both reduction in the amount of terriginous sediment and its dilution by carbonate. It is observed that a few species of *Halimeda* generated sediments have low concentrations of Fe while other species of *Halimeda* generated sediments have high Fe.

For the N-S transect from Cape York down to Temple bay (Fig 6.10), detailed examination of the results shows the higher values of Al/Si ratio in the sample sites near to dunes or swamps. Al is higher in the swamp sediment samples due to the presence of clay minerals.

For the N-S transect from Cape York down to Temple Bay (Fig 6.10), the results show the higher values of Al/Si ratio are in the sample sites near to dunes or swamps, the higher Al_2O_3 being interpreted as due to the presence of clay minerals. There is some correlation between Si, Ti and Zr in that all three tend to be high in the same samples. Quartz, rutile and zircon are abundant in the dune sands and move together into the near shore sediments. As already discussed in last chapter, quartz has more than one provenance in the study area. Any change of source effects the association of Si with different elements. The association of Si may be strong with one element in one bay but be poor with the same element in another bay.

The elemental ratios belonging to the carbonate mineral group do not change much from north to south. This is an important finding, for it gives confidence in extending a shore-reef facies distribution beyond the two cross-shelf transects. These transects show a steady increase in carbonate minerals towards the reef, and the parallel to the coast transect is consistent with this model.

The elemental ratios change vertically down the cores indicating a change in mineralogy as is discussed in the above paragraphs. The composition of the core VC-12 from Shelburne Bay is more or less constant until the bottom sample, where the proportion of silica, Zr and Ti increase at the expense of Ca and Mg, possibly reflecting a nearer shore environment (rise in the sea level).

6.5.2. *Factor analysis*

Factor 1 (alumino-silicates, Figure 6.14) has maximum value of 5.5 in Temple Bay, and then decreases towards the outer shelf. This group is also present in the intertidal zone of the Shelburne Bay area drained by Harmer Creek, which drains through colluvium, sand dunes and mangrove swamps. The windblown sand was deposited in the Shelburne bay area (see Ch. 5 for details). The reworking of sediments occurs due to wind, wave and tidal activity.

In the Temple Bay region the Olive River drains the coastal and alluvial plain deposits and clayey micaceous quartzose sandstone, which is the main source of alumino-silicates in the area.

Further north in the Cape York region, are the Jacky Jacky Creek and Escape River. The Escape River drains through deeply weathered regolith (laterite, ferricrete, minor bauxite and ferruginous laterite) as well as quartzose sandstone and micaceous siltstone. The Jacky Jacky Creek drains through coastal alluvium and weathering products. Coastal dunes, laterite and ferricrete deposits are present along this coast of Cape York and on Turtle Head and Trochus Island (Willmott & Powell 1977).

Most of the surface bottom grab samples consist of quartzose sands and weathering products. The core sub-samples (see core diagram in Chapter 4) show a change in chemistry and have a considerable amount of alumino-silicate in the sample (see Chapter 4). This may be due to the change in sea level, with consequent transgression and regression of the sea. The other possibility is a change of provenance in the past, also a result of sea-level change. Lower base-levels for these streams would have led to incised valleys, with eroded sediment being sourced from deeper in the weathering profile.

In the middle shelf there is a closed positive value contour surrounded by negative contours inshore (west) and in the outer shelf (east). The outer negative values are expected, consistent with the lack of alumino-silicate minerals (terrestrial sediments) on the outer shelf (see Sedimentology and Mineralogy chapter). On the western side near Orford Bay the negative value contours are due to the presence of the Orford Bay dune field, which contributed the quartzose facies rather than clays and other silicates. Some of the samples show a minor concentration of silicates, which may be due to the presence of feldspars or clays coming from coastal alluvial deposits.

Factor 2 (carbonate group) consists of elements associated with calcite and aragonite and is mapped in (Fig 6.15). Superposition of Map 1 over Map 2 demonstrates the negative value contour of the silicate coinciding with the positive value contours of carbonate, which clearly confirms the distribution of silicate in the area. As expected, the carbonate contour values increase away from the shore. Such a gradation from silicate-rich to carbonate-rich sediments in the lagoon has also been observed by (Doherty 2001). In the Temple Bay area positive contours are present, presumably due to the proximity of the reef in the area. The reef contributes carbonate shells, coral and debris that mix with the terrigenous sediments. In the intertidal zone of the Shelburne Bay area mostly mangrove shelly muds are present.

The weather pattern, current and the geomorphology of the Bay favours reworking and landward movement of the sediments (Bryce *et al* 1998). This pattern does not allow sediments to settle and consequently mud stays in suspension and tidal currents in the dry seasons drive it landward. In the wet season, the flood and cyclone events are not strong enough to reverse the transport direction of the suspended load.

Newcastle Bay is a freshwater swamp area and is dominated by colluvial and coastal alluvium sediments and sand dunes.

Factor 3 (Oxide Group) the elements included in this group are associated with terrigenous sediments. The contour distribution map of F3 (Figure 6.16) is made up of oxide elements showing positive contours in Newcastle Bay and in in-shore parts of Orford and Temple Bay. As already discussed above, the Newcastle area and Orford Bay areas have more terrigenous and less carbonate sediments which explains the presence of oxides in that area.

In the Shelburne bay area no positive value contour for oxides F3 is present. Further towards Cape Grenville, which is made up of volcanic tuffs and breccia (Powell & Smart 1977), some surface bottom grabs have elevated concentrations of elements belonging to the oxide group. The Temple Bay samples have oxides which were probably contributed by the coastal ferruginous laterite deposits.

Factor 4 (Sulfur) The distribution of sulfur in the area shows equally spaced contours in the Shelburne-Temple Bay area (Figure 6.17). The contour value increases towards the outer part of Temple Bay and continues until the beginning of the reef. The reef sample does not contribute to this factor. Compared to this transect, the other cross-shelf transect, across Shelburne Bay, shows distribution of this factor only up to the inner-middle shelf. There is no *Halimeda* reported in the mid-outer shelf across Orford Bay (see Chapter 4 for details). *Halimeda* is a known source of sulfur in carbonate sediments (see for example Lyons *et al*. 2004) and in general from this study it is evident that whenever *Halimeda* is abundant sulfur levels are higher.

The distribution of this factor in the Newcastle Bay region shows a higher concentration and contour values increase~~s~~ towards the land and decrease towards the reef. High contour values are present near the mouth of the Jacky Jacky Creek and Escape rivers, which is expected because of the nearby swamps.

The higher concentration of sulfur in Shelburne and New Castle bays is due to the presence of mangroves in these areas, and when sediments disperse across the shelf the sulfur is concentrated in the *Halimeda* sediments but not in reef sediments. In all factor contour maps only the values of surface core samples and the bottom grab samples were taken. Therefore contour patterns do not show the sub-surface distribution of these factors. This sometimes makes it difficult to understand the distribution pattern of the factor unless the whole set of factor scores are viewed together with these maps.

The geology of the study area is diverse and such changes are reflected in the elemental geochemistry. Both geochemistry and statistical analysis indicate the dominance of provenance control on changes in sedimentation in the study area.

CHAPTER 7 GENERAL DISCUSSION

7.0 Introduction

This chapter summarises all results and provides the geological details and interpretation about the Far North Section of the Great Barrier Reef Lagoon.

The study area has a geologically diverse adjacent landmass, with a wide variation in the character of the outcropping geology. This variability is reflected in the influence it has on the source on the sedimentation and their mineralogy and geochemistry. The near shore zone of the Lagoon includes fine sandy facies, quartzose sand, intertidal mud and carbonate sediments. The quartzose sands of the near shore (inner shelf) area have signatures of land processes (fluvial and aeolian) as well as marine processes. These sands have a hinterland source drained by the local rivers, from both Pleistocene and Holocene sand dunes and beach ridges. The clay minerals vary from kaolinite-illite-smectite, depending both upon the source and postdepositional changes. Additionally the mixing of sediments forms the transitional facies which makes sedimentation more diverse.

The sedimentology, chemistry and mineralogy of the sediments varies with depth. The surface sediments are generally dominated by kaolinite, but down the core sediments show increasing dominance of smectite. In Shelburne Bay, however the sediments are kaolinitic throughout the core. The cores from Newcastle Bay show graded bedding and facies change over short intervals. In Shelburne Bay core sub-samples show a facies change from bioturbated mud to sand facies in the bottom sediments only.

Across the shelf terrigenous sediments decrease considerably with an increase in the carbonate sediments so that in the outer shelf sediments only a little terrigenous quartz is present. The grain-size of carbonate sediments varies from lime-mud size fraction to pebble size *Halimeda* plates and coral fragments. The chemistry and mineralogy of the carbonate sediments changes as a result of change in fauna and flora.

The middle shelf is dominanted by *Halimeda* sediments. The seismic traces show the presence of *Halimeda* in the mid-outer shelf up to Raine Island, but further north there is no *Halimeda* present and the dominant sediments are formed from coral and reef detritus. The outer shelf sediments are derived from the erosion of older reef as well as the detritus from the present reef. Other organisms which generate sediments are forams, molluscs and bryozoa.

7.1 Influence of the hinterland on near shore sedimentation

In the study area there are four major bays. The northernmost, Newcastle Bay, is sourced by Jacky Jacky Creek and the estuary of the Escape Rivers. The shore of the Bay has a quite complex and irregular coast-line, bounded to the north by Cape York itself, and to the south by Turtle Head Island and Sharp Point. Between these are extensive regions of swamps and smaller islands. The reef is ~25 km away from the Bay. The shelf is sloping gently with a depth of ~7-15 m. The hinterland geology of Newcastle Bay varies from dune sands to swamps of the Jacky Jacky Creek and Escape Rivers, beach ridges and residual products of weathering. The swamp deposits of the Jacky Jacky and Escape Rivers are coastal alluvium, deposited in the Holocene at a time of higher sea level (Willmott & Powell 1977). Pain *et al* (1997) described swamp deposits as older fluvial deposits of the Kennedy and Escape Rivers, consisting of alluvial sand, grading down to well-rounded quartz gravels and cobbles. Their lower contact is sharp and the alluvium is sitting on saprolite. These alluvial terrace deposits are encountered in the core VC-22 at one-meter depth. This core was collected from Newcastle Bay near Jacky Jacky Creek and Turtle Head Island (refer location map for exact position). Older beach deposits are beach ridges of Pleistocene and younger beach ridges are of Holocene times. These beach ridges are the source of shelly beach facies in the study area due to wave activity. Mineralogically the sediments are quartz, calcite (both low and high magnesian calcite) and aragonite and this facies dominates in the Newcastle Bay area. The landscape marginal to the Bay has a regolith mapped as bauxite and ferricrete. There were two events of laterite weathering in the Bay area. Tertiary (Pliocene) weathering produced extensive areas of ferricrete. These deposits are present in the Turtle Head Island (Willmott & Powell 1977) and these are the source of iron for the pyrite framboids and of the clay minerals in the marine sediments of the area.

To the south of Newcastle Bay is Orford Bay. It is a fairly small elongate bay, bounded by coastal dunes on the shore and reef patches sea-ward. Its southern margin is Orford Ness. The distance of the reef from Orford Bay is ~20 km.

The Bay has a steep shore sloping down to a depth of ~7-18 m. The regolith on shore consists of beach ridges formed during high sea level in the Pleistocene-Holocene period. The Orford Bay dune field is an extensive northwest-trending field of longitudinal and parabolic sand dunes along the coast of the Bay. Both mobile and fossil dunes are present. The sands of these are derived from deflation of beach ridges and also from landward transport of offshore sand during lowering of sea level (Powell & Smart 1977).

To the south of Orford Bay is the much larger Shelburne Bay. It is a wide and broad bay, its sediment supplied by many small streams draining the eastern side of the Great Dividing Range. Where the streams enter the sea there are abundant intertidal mangrove swamps. The distance to reef from the upper section of the Bay is ~18 km and only ~10 km from the tip of Cape Greenville. The swamps have a very gentle slope with a depth near the shore of ~4 m only, increaseing seaward, to ~33 m. The Tip of Cape Greenville has a steep slope and there the shelf is ~20 fathom (37 m) deep. The inland geology of the Bay is complex. The dune field surrounding the Bay is formed by the reworking of the low sea level delta deposits of the Olive River and formed in the same way as that of Olive River dune field (Lees 1992a). The residual deposits of weathering in the area are bauxite and ferricrete and these are the source of clay and iron in the Bay area. Other regolith materials are residual sands mostly consisting of quartz, and iron nodules. White sands form the inner shore terrigenous sandy facies in the Bay. Sandy muds sourced from the surrounding deeply weathered regolith form estuarine sediments which underlie the mangrove swamps and broad flats of the coast (Pain *et al* 1997). The tip of Cape Greenville is made up of volcanic tuffs and breccia and is also a source of sediment in the Shelburne Bay area.

The last of the four Bays studied in this thesis is Temple Bay. It is almost as big as Shelburne Bay, and is bounded on the north by Cape Grenville and to the South by Mosquito Point. The Olive River is the main source of detritus to Temple Bay. The reef is only ~18 km away from the Bay. The shelf slopes gently into the Bay with depth varying from ~4-22 m. The surrounding regolith consists of a dune field, volcanics of Cape Grenville and residual sands. The residual sands are drained by the Olive River in to the Temple Bay area. The dune field is formed in the same way as that of Selburne Bay dune field except the Olive River brings a lot of quartz from Jurassic sandstones in its catchment. The modern catchment appears to be underlain entirely by sedimentary rocks (Lees 1992a).

7.2 General discussion

In this discussion all aspects of the data are brought together and used to document the changes in the study area since the last glacial period and sea level change. This work is an original initiative in a previously unstudied unique environment.

The sediments of Newcastle Bay are mostly riverine and dune sediments, although beach sediments and marine shells are also present. The Kennedy and Escape River which shed detritus to the Bay are seasonal rivers and their swamps trap the sediments. The sands of this bay are therefore mostly mud free and show the signatures of marine, aeolian and fluviatile processes. The sand derived from the submerged beach ridges; submerged in the transgression of Quaternary times (Maxwell 1968) is clean coarse grain sand. The sand derived from dunes is fine-grained white sand with negligible amounts of heavy minerals.

The Zr in sediments occurs as zircon, whereas Ti may be in ilmenite, rutile or anatase. Where weathering is releasing primary minerals that are quickly carried to sediments, correlation between unweathered heavy minerals such as zircon and ilmenite might be expected. Where the hinterland is deeply weathered, zircon remains in the sand and silt fraction, whereas titanium occurs in clay-sized anatase. Most of the Al in sediments comes from clays (Al-rich) thus Ti and Al would be expected to correlate if derived from a weathered (clay rich) terrain. Such a sediment source would not yield a high Zr/Ti correlation. The factor analysis of the geochemical data shows exactly this pattern, a strong correlation between Ti and Al and not between Ti and Zr. The results obtained here indicate these sediments have been derived from a well-weathered terrestrial source (Taylor & Eggleton 2001).

The sand brought by the river has a fine to medium grain-size with some silt-size fraction. The sediments have a mineralogical make-up of quartz, minor feldspar and clay minerals. Minor amounts of gypsum, siderite and goethite are also reported.

7.2.1 Iron-bearing minerals and oxidation-reduction (redox).

The presence of pyrite, siderite and goethite in the sediments indicate both oxidized and reduced phases of iron and indicate that sediments are collected from a region at the boundary of oxidation-reduction reactions. This implies mobility and redistribution of iron.

The main elements susceptible to changing redox conditions are S, Fe and Mn. Sulphur in marine sediments is derived by organisms from seawater, whereas Fe and Mn are provided by terrigenous sediments. In the swamps and mangroves the top layer of sediments is oxidized as a result of resuspension and bioturbation, which makes the upper few centimetres oxic due to the circulation of oxygen and water. Below about 15-20 cm depth in the sediments there is lack of oxygen as it is consumed by organisms and an anaerobic environment is created. Where the rate of sedimentation is high enough to provide a rapid cover (blanket) of sediment, less oxidation or degradation of organic matter occurs and formation of H_2S takes place. The Fe reacts with hydrogen sulphide and pyrite is formed (Berner 1982 and Raiswell &Berner 1985) (refer Figure 5.7 & 5.8). At the same time CO_2 reacts with water and carbonic acid ($CO_2 + H_2O = H_2CO_3 = H^+ + HCO_3^+$) is formed. The formation of carbonic acid triggers the dissolution of carbonates ($CaCO_3 + H^+ = Ca^{2+} + HCO^{3-}$) which buffers the media until all the carbonate is dissolved (Curtis 1987). The bicarbonate ion diffuses upward in pore spaces once away from the biologically acidified sediments, and then in pore spaces to form secondary carbonates (refer Figure 5.10 & 5.11).

After the dissolution of all the carbonate the environment becomes more acidic, the proton (H^+) released reacts with silicates establishing equilibrium, H_4SiO_4 is formed. At this stage the elements become mobile and movement of metals may also occur (Curtis 1987). In this environment the pyrite is stable, due to pH condition ~8, sufficiently high to dissolve silica and convert kaolinite to smectite. So in the presence of quartz at pH 7.5-8 the conditions are favourable for the conversion of kaolinite in to smectite and dissolution of quartz (detailas are discussed in ch 5) (Drever 1988). Presence of pyrite framboids in the sediments indicates a reducing environment and at the same depth dissolution of silica indicates instability of quartz in the environment (as shown by the SEM results). This change in the environment and physico-chemical condition favour the conversion of one type of clay mineral into other including transformation of smectite into kaolinite or illite-smectite (as discussed in the graphs)

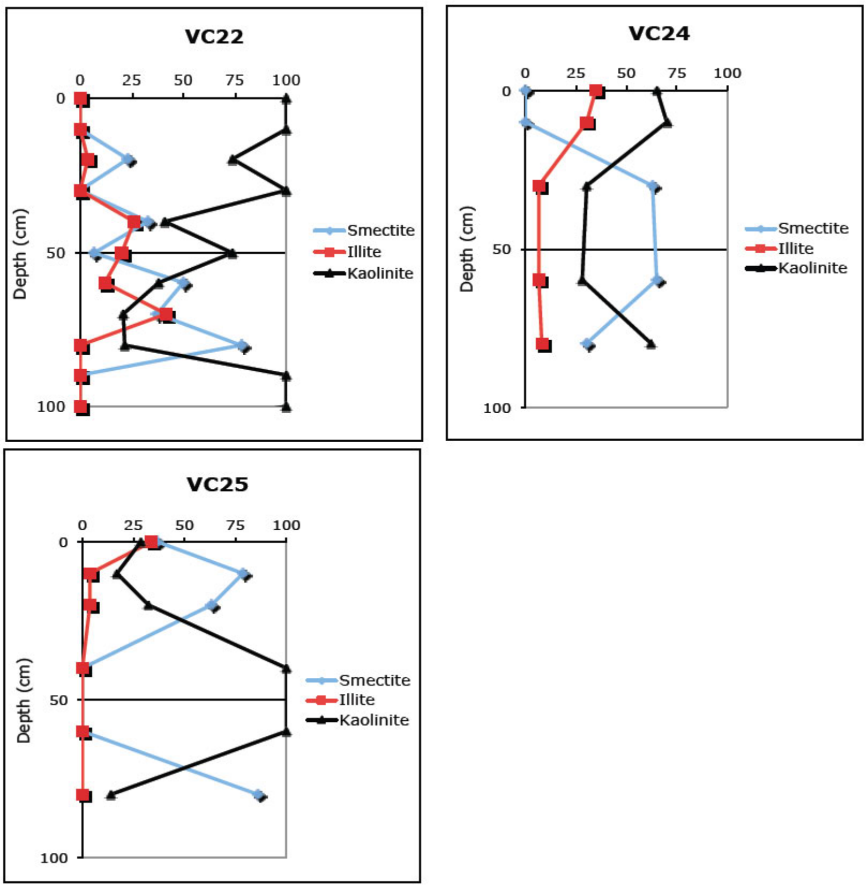


Figure 7.1 variation of clay minerals down the cores (VC 22, VC 24 & VC 25) collected from New Castle Bay.

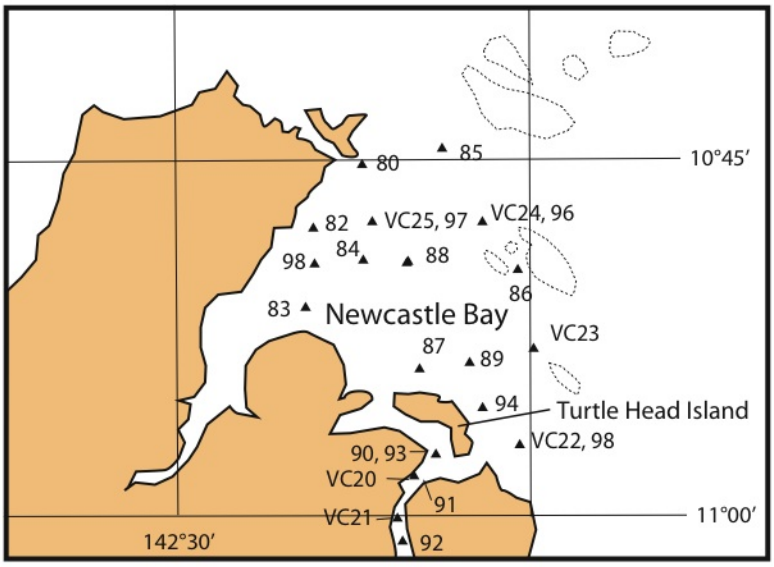


Figure 7.2 Location of the cores collected from New Castle Bay

The percentage of kaolinite decreases down the core and smectite percentage increases in the core samples from Newcastle Bay (see Table 5.1). Both Fe and Mn have been recycled between oxic and anoxic zones as shown by the variation in the mineralogy from pyrite to goethite and siderite. Fe sulphide is reactive under these conditions, dissolving and re-precipitating as carbonates and sulphates in the varying micro environments.

The cores from Newcastle Bay show change in sediment size, mineralogy and geochemistry vertically down the core, due to local variation, change of source and also due to post-depositional processes. This change in the environment and physico-chemical conditions favour the conversion of one type of clay into other including transformation of kaolinite into smectite and illite-smectite.

The percentage of kaolinite decreases down the core and smectite percentage increases in the core samples from Newcastle Bay (see Table 5.1). Both Fe and Mn have been recycled between oxic and anoxic zones as shown by the variation in the mineralogy from pyrite to goethite and siderite. The Fe sulphide is more soluble so it is dissolving and re-precipitating as carbonates and sulphates

The cores from Newcastle Bay show change in sediment size, mineralogy and geochemistry vertically down the core, due to local variation, change of source and also due to post-depositional processes. This change in the environment and physico-chemical conditions favour the conversion of one type of clay into other including transformation of kaolinite into smectite and illite-smectite.

The mineralogy of the Broad Sound tropical estuary in Queensland was studied by Cook & Mayo (1980). They found equal amounts of low magnesian calcite and high magnesian calcite in the sediments. Aragonite is less abundant and decreases seaward. The clay fraction of the estuary has equal amounts of kaolinite, illite, montmorillonite, and mixed layered clays. They found transformation of montmorillonite into illite and also mixed layer illite-montmorillonite as a result of the high salinity of the supratidal flats.

Davies & Marshall (1985) studied the mineralogy of *Halimeda* bank sediments. They found them to be made up of 75 % carbonate and 25 % clays (kaolinite, illite and smectite).

7.2.1.1 Pyrite

Pyrite framboids are formed (aggregate) in four stages as described by Taylor (1982) and Wilkin & Barnes (1997b), a) Nucleation and growth of monosulphide. b) Reaction of initial monosulphide to greigite. c) Aggregate of greigite micro-crystal. d) Replacement of greigite by pyrite. All stages are linked to redox-interfaces that separate water containing dissolved oxygen and sulphide respectively. The amount of pyrite precipitate in the sediments depends upon the concentration of sulphate, concentration and reactivity of the organic matter, iron minerals and type and availability of oxidant (Wilkin & Barnes, 1997a).

Scheihing *et al* (1978) reported kaolinite with pyrite in a coal bed in Ohio. In the study area pyrite framboids and euhedral crystals are found associated with carbonates and clay minerals. As mentioned above, in the mangrove and swamp environment, anoxic conditions existed below an oxic (surface) layer leading to the formation of pyrite.

The probe analysis and images shows that clay surrounds some individual crystals of pyrite as well as spherical pyrite aggregates and both minerals occupy fractures in the disintegrated quartz grains. Only euhedral crystals are found in the fractures.

Framboids are common inside shells (Figs 5.7, 5.8). The morpholgy and positions of the pyrite crystals and aggregates is clear evidence that their formation follows, or is contemporaneous with the dissolution and fracturing of the quartz. The size of welded spheres depends upon the microenvironment in which they grow (Frizzo *et al* 1991). They found smaller size spheres in restricted spaces, including plant cell and foraminifera tests and bigger spheres are found in the organic matter. The present work is consistent with their work as smaller framboids are present in the shells, and are accommodated in size according the space available. The single- and poly-framboid aggregates are found in the sediments.

7.2.1.2 QUARTZ

The microprobe study of the core samples shows (Figures 5.3 to 5.6) a mixture of subrounded and angular grains. Pye 1983 and Pye & Mazzullo 1994 studied dune sand and concluded that postdepositional weathering and pedogenesis results in the chemical etching and disintegration of quartz grains and production of *in situ* silt takes place. The shape of quartz grains is changed due to such processes. The present work finds similar features but in a different environment. Quartz dissolution and disintegration is observed in the intertidal and mangrove swamps and not in dune sediments. The dissolution of quartz occurred in a reducing environment, along with the formation of pyrite, smectite and secondary carbonates. The other difference is the presence of less sub-rounded and more angular grains of quartz in the study area.

The texture of the quartz grain is changed during dissolution and etching. Figure 5.6 shows a heavily etched and fractured quartz grain with clays filling the cavities. When disintegration starts the fractures develope along planes of weakness and along these fractures the dissolution starts and the size of grain become reduced. Later on the cavities are by occupied by clays and pyrite framboids (both the welded spheres and euhedral crystals). In some cases the fractures developed in the quartz grains are occupied by clays and pyrite crystals before the complete disintegration and dissolution of the grains takes place. The dissolution of quartz produced some of the quartz silt fraction and also contributes silica in the solution.

Pye & Mazzullo (1994) suggested the angular shaped grains are found in older dunes than in the younger dunes while subrounded grains are common in the younger dunes. The reason for that is angular grains are exposed to a longer period of post-depositional weathering in a humid tropical climate. In this study more angular grains are observed. Therefore it is interpreted the source of these sands is older Pleistocene dunes. The subrounded grains in the study areas are less common and belongs to the Holocene sand dunes. This confirms more than one source of this sand in the area.

7.2.2 Regional variation near shore

The sediments of Newcastle Bay have been described and interpreted in the previous section, because they are the most diverse and provided the most complete data sets in the form of core samples. These sediments range from mangrove-dominated muds to dune sourced sands.

The Orford Bay area is dominated by sand-size quartzose sand derived from the Orford Bay dune field. The geomorphology of the bay and absence of any streams and channels in the area is the reason for the absence of fluvial deposits in the area. The factor map shows negative contours of the silicates factor, which also indicate the absence of other silicate mineral phases.

Shelburne Bay area has diverse inland geology and geomorphology, which shows different sediment type in the area. The sedimentology of the Shelburne Bay dune field is complex. Lees (1992b) found the size and shape of coarse poorly sorted angular white sand present underlying the dune field is different from the fine well-sorted sands of modern dunes. He suggested the source of these dunes are Olive River sediments, erosion of thick, white residual sands of the Olive-Pascoe Lowland (resulted from the weathering of Mesozoic sandstone) and erosion of the Coen Inlier granite. The fluvial processes transported and deposited these to the coast and the inner shelf in both present and past time (lower sea level). Further, these sediments mixed with marine sediments by marine processes, followed by deflation of winds during last glacial period to emplace the dunes.

The other dune fields present in the study area also have episodic history of weathering and formation of palaeosols (Pye 1984, Lees 1992 b). This may explain the presence of some organic matter in the sediment samples of the study area; the other source of organic matter is marine organisms.

The mangrove swamps of the southern part Shelburne Bay have black mud rich in organic matter and have a considerable amount of fine sands. The swamp gets fresh water input through Harmer Creek.

The core from Shelburne Bay (VC 12) shows a striking change in the facies below one-meter depth. The top sediments are black mud with fine sand and are highly bioturbated, coarse-grained sands with very little clay in them occurs from 100 to 120 cm depth. This is most likely due to the local variation of source in the area; the mud being derived from alluvium, the sands from dune fields.

The coastal rocks at the eastern end of Shelburne Bay are the Cape Greenville Volcanics, which generate sediments different from the dune fields and mangrove swamps. These volcanics are considered as another provenance for the sediments. The sediment samples near and around the Cape Greenville headland are more complex and different as they mix with marine sediments by marine processes. The reef islands (Sir Charles Hardy Island) generate sediments due to erosion of reef. These sediments mix with terrigenous and volcanic sediments and thus dilute the facies. This is observed in the sedimentological results (Table 5.1); the sediment samples near to Reef Island have relatively higher percentages of carbonate minerals. The clay mineral fraction is dominated by smectites, which is as expected from the weathering of volcanic breccia and tuff.

Pyrite framboids are present in the Shelburne Bay sediments and their presence indicates an anaerobic-reducing environment, which is very common in the mangrove environment. The source of iron for the pyrite is the residual deposits of laterite and ferruginous material.

The Olive River drains through dune sands and ferruginous laterite deposits into the Temple Bay area. The other source of sediments include recent beach ridges present along the coast at the lower part of the bay, volcanics of Cape Greenville and patch reefs present near shore. The samples collected near the mouth of the Olive River have a higher percentage of sand, as the river is draining the dune sands. Relatively high levels of zirconium (200 ppm) are consistent with a dune sand source.

The sediment samples are kaolinite dominant in the clay mineral fraction, which indicate a deeply weathered mature source. This can be explained as the Olive River also drains Pliocene ferruginous laterite deposits, which are the source of kaolinite in the area. The samples collected near the tip of Temple Bay are smectite-rich; their source is volcanic breccia and tuff of Cape Greenville.

Overall, the geology of the study area is diverse and is reflected in the near shore sediment chemistry and mineralogy. In Newcastle Bay sediments sourced mainly from sand dunes have higher values of Si and Zr which is followed by Al, Fe and Ti. Dominant minerals are quartz, clay and pyrite. Orford Bay also has higher concentration of Si and Zr with quartz as a dominant mineral, here sourced from dunes also. Shelburne Bay shows two sets of values; sediments sourced from ferruginized sand dunes showing higher values of Si with Fe whereas those from Harmer Creek have Si with Al, Ti and Fe. These belong to quartz and pyrite and quartz, clay and pyrite respectively. The Temple Bay sediments have higher values of Si, Ti, Al, Fe, Zr and Ba indicative of quartz and silicate minerals sourced from the Olive River

All the above-mentioned concentrations basically reflect the source rocks. Elements and their concentration correspond to the mineralogy and provenance of the sediments present in the study area.

7.2.3 Regional variations - mid-outer shelf

The geology of the mid-outer shelf is different from the inner shelf. Mineralogically carbonate dominates over terrigenous fraction. Carbonate sediments of the Great Barrier Reef are dominantly skeletal bioclasts and their debris. Inorganically precipitated oolite and other types are not found. The Bahamas, shelf in contrast, has a variety of sediments including oolite and other inorganically precipitated sediments (dominantly) and some bioclastic sediments. Other main differences as explained by Maxwell & Swinchatt (1970) are massive development of reef, a continental source of sediments and relatively deeper shelf with open circulation in the Great Barrier Reef shelf.

Shelf geometry and bathymetry of the Northern Section of the Great Barrier Reef is different from the Southern Section. The shelf in Northern Section is narrower and shallower (<36m) than the southern Section. The reefs in the Northern Section are continuous and linear in shape and occupy the entire shelf edge (Maxwell 1968, Maxwell & Swinchatt 1970).

The carbonate sediments of the Great Barrier Reef are derived from three main groups 1) Reef generated sediments 2) *Halimeda* generated sediments 3) sediments derived from foram, bryozoa and molluscs etc.

The reef, mollusc (other groups also) and coral generated sediments and their debris is not very wide spread in the Great Barrier Reef lagoon. Strong wave action produces detritus of coral, molluscs and *lithoamnioid algae,* then transports and deposits them into other parts of lagoon. In the case of low competency waves and currents, the transportation of the detritus is limited and their distribution depends upon duration and competency of the wave and current action. The reef margins and reef surface are under strong wave action which sweeps the detritus across the lagoon. The inter-reef fauna is less subject to wave action and this region produces poorly sorted sediments (Maxwell 1968).

The disintegration of *Halimeda* does not require any wave action for them to, break up into pieces and accumulate on the seafloor. *Halimeda* have a natural disintegration process which favours the formation of detritus, more commonly found in the carbonate sediments of the study area. *Halimeda* is a primary and main producer of carbonate in the study area. *Halimeda* forms bioherms (banks) and gently dipping sheet-like morphology (refer Chapter 4 for details). The extent of *Halimeda* bioherms are comparable with that of coral reef, as both belong to the same ecosystem. *Halimeda* growth is found (seismic evidence) on the surface and floor of coral reefs.

As compared to the *Halimeda* bioherms of the Far North Section of the Great Barrier Reef the *Halimeda* banks of the Java Sea in Indonesia are huge, thick and extensive. The maximum thickness of the *Halimeda* bioherms in the study area is *ca* 12 m, while those in the Java Sea reach 50 m. In the Far North section of the Great Barrier Reef the *Halimeda* is found at a depth of 20-50 m whereas in the Java Sea they are present at 30m-100m depth. The Java Sea *Halimeda* deposits do not have the same morphology as of Australian *Halimeda* bioherms; they are in the form of elongated ridges to symmetrical broad mounds. Phipps & Robert (1988) calculate the accumulation rates for Java Sea deposits are 0.30-0.60 m/100 yrs. The growth rate of *Halimeda* bioherms in the study area is *ca* 0.6 m – 2.4 m/1000 yrs. This rate is calculated considering the age of 5000 yrs calculated by Davies & Marshall (1985) for the northern Great Barrier Reef. This is a relatively slow rate of accumulation for *Halimeda* in the study area, which may be due to availability of nutrients, light, and rate of upwelling, bathymetry, topography and oceanographic conditions in the study area as compared to the Java Sea deposits. This study suggest the main factors for the slow rate of accumulation of *Halimeda* in the Far North Section of the Great Barrier Reef are the narrowness of the shelf, nearness of the reef and reef development over entire outer shelf. These factors link with the amount of the nutrient that can reach to the mid-outer shelf and extent of shelf where *Halimeda* grows.

Drew & Abel (1985) and Wolanski et al (1988) suggest that in the Northern Great Barrier Reef the upwelling and the availability of the nutrients are the factors responsible for the *Halimeda* growth. Phipps & Robert (1988) suggest the same reasons for the Java Sea deposits. Drew & Abel (1985) further explained the presence and absence of the *Halimeda* deposits in the Northern Great Barrier Reef on the basis of depth of the channel through which upwelling nutrient rich water from the Coral Sea jets into the Great Barrier Reef Lagoon and allow *Halimeda* to flourish (Refer Chapter 4 for details).

Searle & Flood (1988) suggested that the *Halimeda* bioherms of the Northern and Southern Great Barrier Reef Lagoon are not spatially correlated. The growth of the Southern complex depends upon the topography of the sub-surface and not the upwelling of the nutrient rich water. They found *Halimeda* growing on the flat-lying surface and coral reefs growing on the substrate with positive topographic relief. They further suggest that *Halimeda* meadows probably act as a trap for the carbonate detritus. As carbonate mud is derived by bioturbation and near the surface it is winnowed out, and the vertical growth incorporated with mud into bioherms as the base level of bioturbation rises.

As is evident from the seismic traces (lines 1 and 2) the *Halimeda* deposits have two different morphologies, bioherms (high amplitude form) and sheet-like flat structures (low amplitude form). From the coast eastward along line 1 the high amplitude form is present up to the shelf edge (after that there is no *Halimeda* reported). Westward along line 2 *Halimeda* deposits start thinning and mounds become flat sheet-like structures and overlie the reef platform top; and further westward there is no trace of *Halimeda.*

Orme (1985) explains the spatial and temporal variation in the carbonate sediments of the Northern Great Barrier Reef Lagoon. *Halimeda* sediments occur over fine-grained sediments which are different from *Halimeda* sediments in texture and composition. This indicates a rapid change from mangrove to shelf water environment. In the study area the same change is observed (see line 1 section 1 Chapter 4). The seismic trace shows clearly the *Halimeda* deposits (acoustically transparent bioherm) overlying sediments with different morphology and character. This change in the seismic character indicates different types of sediments. The boundary between these sediments is interpreted as an erosional surface and break in sedimentation. This also infers a change in the depositional environment and is marked as disconformity (between Holocene and Pleistocene times) and called Reflector A (refer Chapter 4 for details of Reflector A).

In seismic traces (line 1 and 2) deep depressions between the *Halimeda* bioherms are 50 m deep and reflector A is very near to the sea bed or at the sea bed (thickness of sediments is zero), indicating no deposition and a breakin sedimentation. This surface is marked as the post glacial surface and the depressions in it are a result of deep cutting by the rivers in the last glacial period followed by marine regression during the shelf emergence. At that time erosional activity was triggered by lowering of the sea level (Orme *et al* 1978, Searle 1983 & Harris 1994).

The outer shelf of Far North section of the Great Barrier Reef Lagoon is marked by the presence of shelf edge reefs. Seismic profiles show the presence of a reef connected carbonate wedge up to (line 5) *ca* 70 m thick, thinning towards shore. There is no trace of *Halimeda*. The core sediments of the outer shelf near the Great Detached Reef have *Halimeda* plates mixed with coral algal reef debris. The *Halimeda* plates in one of the cores collected from Great Detached reef show preferred orientation. This may indicate current movement in that direction in which the plates are oriented. The presence of *Halimeda* near the Great Detached Reef is interpreted as due to the availability of nutrient rich upwelling water through the channel near to the reef. Further north of Raine Island as described above there are no traces of Halimeda as the channel is shallow and tidal jets can not lift the nutrient-rich water below the thermocline (refer to Chapter 4 for details).

The core and grab samples of the outer shelf have *Halimeda* plates and coral fragments in a lime mud matrix. The coarse–medium sand-sized coral material is derived from the nearby reef community and *Halimeda* plates and is transported by the currents, thus this facies is interpreted as the result of more than one process.

XRD quantitative mineralogy shows that aragonite is the dominant carbonate mineral. *Halimeda* is mineralogically aragonite. For crystal chemical reasons Sr is more strongly associated with Ca in aragonite and Mg is associated with Ca in calcite

It is observed in some samples the concentration of Sr increases as the value of Ca increases. The regression analysis shows good correlation between these two elements. This interpreted as *Halimeda* as the source of aragonite. The carbonate factor map shows higher value contours at places where seismic profile confirmed the presence of *Halimeda*.

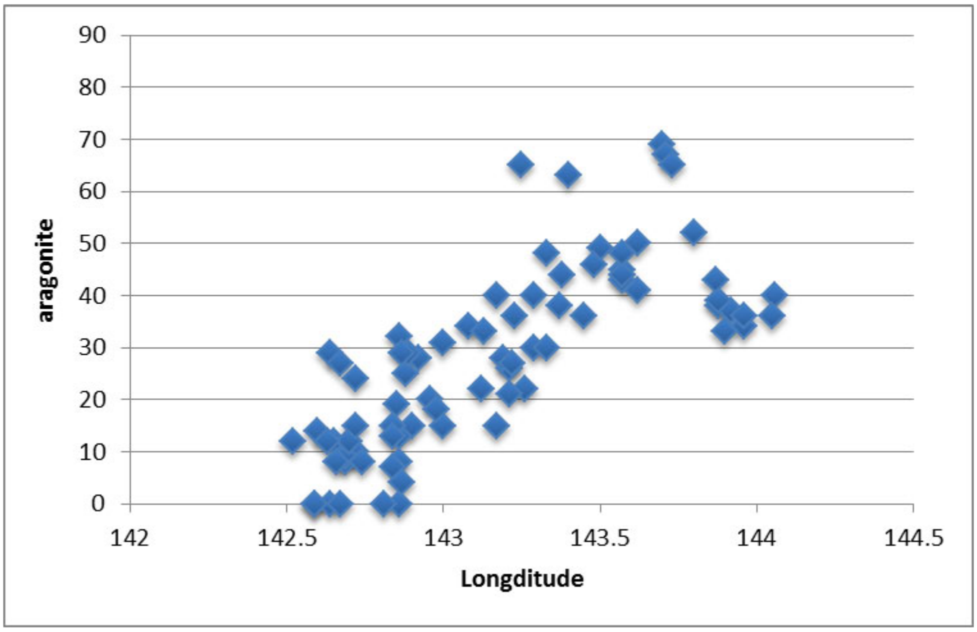


Figure 7.3 (a) Distribution of aragonite across the Great Barrier Reef Shelf

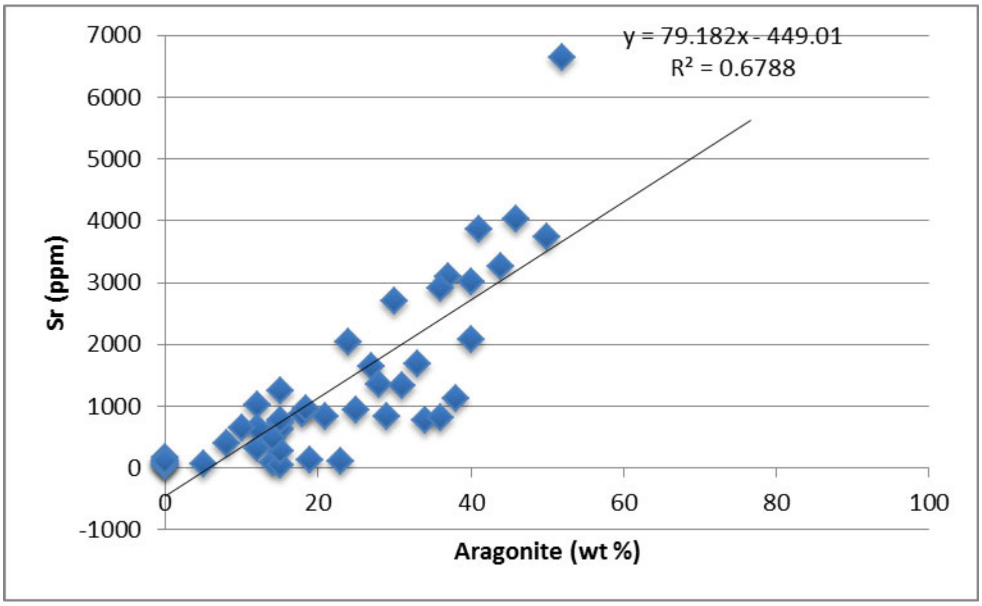


Figure 7.3 (b) Plot of Sr vs aragonite across the Great Barrier Reef Shelf

Mineralogically the outer shelf sediments have <5 % quartz and clays. The XRD result shows the presence of quartz but the concentration of the clay minerals is below the detection limit. The microprobe analyses show minor amounts of clay in the samples. High magnesian calcite is dominant in the grab samples while core samples show the dominance of aragonite. The aragonite is dominated in the core samples as the sediments mostly consist of *Halimeda* plates and its debris rather than coral algal and reef sediments. The higher percentages of high magnesian calcite in the grab samples may be due to the presence of lithoamnioid algae and benthonic forams. This is interpreted as dominance of different biological colonies in the last 6000 yrs or since the last sea level changed. This may be due to variation in conditions including light, wave energy, currents and availability of nutrients for the growth of biological colonies, transportation and deposition of the detritus.

The chemistry of the mid-outer shelf is mostly the chemistry of the *Halimeda.* Sediments have high value of CaO and Sr, which is followed by MgO. The outer shelf coral reef sediments have higher concentrations of CaO and Mg, made up of calcite. The chemistry of the Great Barrier Reef shelf thus reflects the signatures of biota present in the study area.

Milliman (1974) summarized his and others' work about the chemical composition of green algae *(Halimeda).* The concentration of Fe is high (160-7700 ppm) in *Halimeda*. The Present study is consistent with the previous work in finding 100-6200 ppm Fe in the *Halimeda* sediments. The variation in the Fe concentration is due to a biological factor which favours the concentration of Fe in certain species while other species have low concentration of Fe. The microprobe analysis shows the presence of pyrite framboids in the mid-outer shelf sediments; this can be explained as Fe from *Halimeda* and sulphur from sea water and *Halimeda* is combining to form pyrite framboids. The factor map 4 of sulphur shows positive value contours in the mid-outer shelf area where the seismic data gives evidence of the presence of *Halimeda.*

Okubo & Woolfe (1995) suggest much of the sediments that reach to the outer shelf are volcanic in origin. The present study has not observed any shards of volcanic glass or morphological evidence to suggest the quartz grains of the outer Great Barrier Reef shelf are of volcanic origin. The present work found minor amount of terrigenous sediments present in the outer shelf including quartz and clay. They may be the result of aeolian input. The post glacial period was very dry and windy but the present distribution of winds over the study area shows equatorial monsoon northwestlies, the equatorial monsoon blowing from land to sea in the Far North Section. They are sourced in the maritime area to the north and west of Australia, this very warm, moist (dew-temperature 21^o - 24^o C) and unstable airmass only affects north and north-western Australia in summer in association with the monsoon. It brings extremely heavy rainfall and high humidity to this area (Tapper & Hurry 1993). As the air is very humid it is not likely to pick up dust and blow it towards the outer shelf of the Great Barrier Reef at the present time.

Bryce *et al* (1998) and Woolfe *et al* (1998) suggest that there is no oceanographic process at present to transport the sediments across the Great Barrier Reef shelf. The sediments are moving backward from the shelf to land (Bryce *et al* 1998).

Another possibility that is these sediments were transported by fluvial processes in the last glacial time after lowering of the sea level. At that time erosion followed emergence and rivers cut deep channels which remained unfilled in the outer shelf were but filled in the inner-middle shelf by estuarine sediments in the transgression period or possibly were over filled during high supply of sediments in the still-stand period.

Searle (1983) also describes the Quaternary as alternate periods of emergence and submergence, emergence being for longer periods than sub-mergence, allowing subaerial erosion and down cutting of channels 25 m deep, thus the sea floor is incised at various places. This is marked as the Reflector A (unconformity), and shows a change from non-marine (past riverine) to marine (present).

Purdy (1974) and Maxwell (1968)–suggested different models for the Great Barrier Reef shelf. Purdy (1974) suggested the present shelf morphology reflects Pleistocene topography. Modern open and closed depressions are evidence of karst drowned topography of limestone. Searle *et al* (1981) discussed the Purdy (1974) model and provided seismic evidence from the central Great Barrier Reef lagoon, which does not support Purdy's model. The seismic section across the shelf shows past emergence, subaerial erosion, surface drainage and fluvial, alluvial and marine sedimentation. These suggest fluctuation in the sea level.

Maxwell (1968) suggested the present bathymetry follows the past antecedent drainage. Searle *et al* (1981) found reefs grow on the antecedent highs and are exposed to karst processes. Seismic data suggests that in the Cainozoic the sub-aerial weathering and fluvial processes during lower sea level and emergence modified the reef province. This supports Maxwell's (1968) model.

7.3 SUMMARY

In the study area the presence of sediment filled channels shown in the seismic results reveals the past drainage during the low sea level. The presence of huge and deep depressions (up to 50 m) in between the bioherms of *Halimeda* are also interpreted as a result of extensive cutting by fluvial processes during emergence time. These are unfilled and only a thin layer of sediment is deposited at the edges. This is evident from seismic trace (line 1 and 2) where reflector A is present very near to the seabed or at the seabed, indicating the sediment veneer is thin or absent. This surface of erosion and non-deposition is identified as the unconformity between the Pleistocene and Holocene and is called reflector A. The unfilled depressions indicate longer exposure of the surface to subaerial erosion and very deep cutting of the sea bed, followed by submergence. During the last emergence period the older reefs were also subject of erosion until submerged again, afterwards the reef and *Halimeda* florish again.

The northern shelf is narrow and shallow compared to the southern shelf so it was exposed longer and would have had more subaerial exposure. This may be why Reflector A is stronger in the northern shelf of the Great Barrier Reef than the southern shelf. In the seismic traces Reflector A has a high amplitude and frequency near shore and is followed by high frequency and low amplitude in the reef area, thus indicating a change from antecedent surface (terrigenous) to carbonate sequence (Searle 1983). Searle (1983) also further described the low and high stand facies as follows;

The low stand (transgressional) occurred from late Pleistocene-early Holocene times. The low stand transgressional facies are fluvial, estuarine-channel fill, relict delta front, palaeo channels and relict re-working facies of existing shelf deposit by transgressive surf zone.

The high stand (modern) Holocene facies are restricted to the near shore from where the terrigenous sediments progrades seawards. They consist of thick embayment deposits (close to modern rivers with high sediment yield), coarse high energy deposits, fine sediments and a little modern terrigenous sediment.

Symonds, Davies & Parisi (1983) describe three periods of low sea level. 1) Late Oligocene 2) late Miocene 3) late Pliocene to Pleistocene. During low sea level, alluvial sediments deposited across the shelf, with fluvial, wave dominated, deltaic progradation at the shelf edge. Some 10-40 Km of shelf out-building occurred during the low stands. In high sea level times sedimentation occurred as coastal deltaic progradation on the inner shelf and onlap of the of continental slope by sub-marine fans.

In this study the main emphasis is on Pleistocene – Recent sediments. The lowering of sea level in Pliocene-Pleistocene times as described by Symonds, Davies & Parisi (1983) is the last glacial period in the area. Further onlap (transgression) continued up to recent time though in the mostrecent time the conditions are stable (changes in the sea level are now minimal).

The sequence of sediments observed and studied in this section of Far North Great Barrier Reef Shelf is a transgressive sequence. The terrigenous sediments are mixed with marine shelf sediments which dilute the fraction, forming new facies. Inner shelf facies are dominantly terrigenous but in the sample sites nearby to the patch reef and reef islands are dominated by marine carbonates.

Broadly speaking there is low sediment input from the land at present. This may be due to the subduded relief and tectonically more stable position of the area. The present pattern of the sedimentation has continued since the last glacial period (8000 yrs) and can be expected to continue unless the present stable conditions are disturbed tectonically or a change in the sea level occurs. As explained above, due to longer period of emergence extensive erosion of the shelf sediments takes place. At present the study area does not have very high relief to provide a high sediment input, the fluvial processes are not very active, only seasonal rivers are present and they carry heavy loads only during floods and cyclones. Longshore currents favour sediment movement further north rather than across the shelf. The waves, currents and other oceanographic processes move sediments up to the inner shelf but not further across the shelf. The fine sediments are suspended in the near shore water where only partial settling will take place before they move land-ward (Bryce *et al* 1998). The swamps act as a trap for sediments those of both Newcastle Bay and Shelburne Bay have fine to medium grained sandy to muddy sediments. These sands are a combination of riverine and wind blown sand.

Maxwell (1968) mentioned the broad geological trends are the same for the entire Great Barrier Reef lagoon. The present study indicates that many factors (shelf geometry, reef distribution, bathymetry, lithology riverine discharges, climate, palaeotopography, coastal variation and different geological settings) make the mineralogy, sedimentology, seismic and geochemistry of the northern section of the Great Barrier Reef different from the southern section. Davies (1988) differentiated between the northern and southern section in that the reefs are narrowest (23 km) in north and widest (260 km) in the south, and reefs occupy the whole shelf in the northern section and only mid-outer shelf in the south. He concluded that the carbonate province is older in the north and younger to the south.

The differences between the southern and northern section of the Great Barrier Reef are continuous band of reefs in the northern section while in the southern section there is a break at Gladstone. The reefs are linear and elongated in the northern section while in the southern section the reefs are lagoonal elongate platform reefs and ring reefs.

Halimeda forms bioherms in the northern section and in the southern section mound and sheet structures are present. The main factor responsible for the growth of the *Halimeda* in the Far North Section is upwelling of nutrient rich water from the Coral Sea. In the southern section the subsurface geometry and topography are the factors responsible for the growth of *Halimeda*.

The present work found this section of the Great Barrier Reef shelf to be unique and to have its own characteristics and identity compared to the other sections of the Great Barrier Reef Shelf. This is a result of shelf geometry, longer periods of erosion and down cutting and extensive development of reefs. The diverse hinterland geology and geomorphology is reflected in the varying sediment chemistry and mineralogy near shore. Mixing of these sediments with marine sediments in the inner-middle shelf zone dilutes the terrigenous fraction leading to development the development of the variety of sedimetary facies described in this thesis.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.0. Introduction

This study is an original initiative in a previously unstudied, unique environment. The work is focused on post glacial sedimentation, mineralogy and geochemistry of the Far North Section of the Great Barrier Reef Lagoon.

8.1. Conclusions

1) The marine sediments have bimodal to multi-modal distribution which indicates more than one process was involved in the formation. The fine-medium grained sand in the mangrove and swamp sediment is derived from coastal sand dunes by wind and wave activity. The mud is composed of silt-clay-size fraction brought by local rivers and channels.

2) Facies analysis delineates five facies, the near shore terrigenous sandy facies, inner shelf shore sand, shelly beach sand, *Halimeda* generated carbonate facies and coral reef facies. Of these the first two have a terrestrial source, shelly beach sand is a mixed terrestrial-marine facies and the last two consist of marine sediments.

3) The study area is distant from any river of major significance and only seasonal rivers drain the hinterland. Sediment input is low except in cyclone and flood events.

4) Cape York Peninsula has a maximum relief < 300 m, the conditions are stable (changes in the sea level are now minimal). These factors limit the availability of terrigenous sediments to the study area.

5) In the reducing environment of the mangrove swamp sediments pyrite framboids and single crystals were formed

6) Microprobe study provides evidence for dissolution of carbonate in an acidic anaerobic environment, upward diffusion of Ca^{2+} and formation of secondary–high magnesian calcite with varying morphologies in pore spaces.

7) The dissolution and disintegration of quartz in humid tropical weathering, pedogenesis and post depositional processes changes the morphology and texture of the grains. Both angular and sub-angular quartz grains are present in swamps and intertidal zones. The more angular

grains were subjected to longer weathering and were derived from older Pleistocene sand dunes, while sub-rounded grains were derived from younger Holocene dunes.

8) At pH 8 in the swamp environment increased solubility of quartz leads to dissolution and etching, resulting in fracturing and break-down of grains along planes of weaknesses. In the swamp environment at pH 8, Si in solution transforms kaolinite into smectite. In the rest of study area the smectite is derived from less mature weathering sources and kaolinite from more mature and deeply weathered profiles.

9) There is only one terrigenous wedge found in the study area (Shelburne Bay). This extends from land and thins seaward, finishing where the reef starts. The narrow and thin wedge-out indicates limited sediment dispersal and input of terrestrial sediments in the study area.

10) Seismic traces from the outer shelf shows the presence of a carbonate wedge *ca* 70-80 m thick near the reef and thinning west ward.

11) Small channels are present across the shelf. These are filled with sediments on the inner shelf but remained unfilled in the middle-outer shelf.

12) The channels are asymmetrical due to unequal cutting on either side by fluvial processes.

13) Seismic stratigraphy indicates an erosional unconformity between Pleistocene and Holocene sediments. The marine and terrestrial sediments have different composition as revealed by change in the seismic character and confirmed by sampling. The sediments above the unconformity are marine (*Halimeda*) and seismically transparent while the underlying sediments are almost seismically opaque (non-marine terrigenous sediments deposited in channels).

14) The large depressions in between *Halimeda* bioherms indicate past antecedent drainage and deep cutting by fluvial processes during a time of lowering of the sea level and emergence. The Reflector A is at the sea bed on these depressions, indicating very little or no deposition on these area.

15) Halimeda bioherms have internal bedding concordant with the edge of the bioherm.

16) *Halimeda* sedimentation forms two different morphologies. They form bioherms and also gently dipping sheet like deposits.

17) The absence of *Halimeda* north of Raine Island is due to lack of nutrients in this area.

18) Mineralogically the *Halimeda* sediments are aragonite, trace element chemistry shows higher concentration of Sr. The coral reef sediments are mineralogically aragonite but lithified reef sediments are made up of calcite with higher concentration of Mg than Sr. The coralline algae are made up of high magnesian calcite.

19) The chemistry of *Halimeda* sediments shows relatively higher concentration of iron and sulphur. The concentration of Fe in the *Halimeda* varies from 100-6200 ppm.

20) The maximum thickness of *Halimeda* bioherms in the study area is *ca* 12 meters and the accumulation rate is 0.6 – 2.4 m/1000 yrs. The accumulation rate of *Halimeda* deposits in the study area is relatively less than that in Java Sea deposits. This may be due to availability of nutrients, light, rate of upwelling, bathymetry, topography and other oceanographic conditions in the area.

21) The geology of the adjacent land in the study area is diverse and is reflected in the mineralogy and geochemistry of the sediments. The sedimentation in the Far North Section of the Great Barrier Reef Lagoon is provenance controlled and further modified by post-depositional processes in the swamp environment.

8.2. Recommendations

For future work in the Far North Section of the Great Barrier Reef these suggestion are strongly recommended:

1) A seismic survey should be completed with more closely spaced lines (Newcastle Bay not covered in this study) to draw an isopach map of the post glacial sedments.

2) Vibro and drilled cores from reefs and islands should be collected to allow more detailed relationships between sediment source, input, distribution pattern and depositional environment to be established.

3) Sediment age dating (e g C-14) is the key for relating sedimentation events with sea level changes in the past and present.

4) Detailed XRF of the core samples from middle-outer shelf samples to asses the causes of variation in the elemental ratios and to know their association with minerals and to link this variation with provenance.

5) Identification of biota (fauna and flora) at least down to genus level to find out if there is any change in the reef ecosystem.

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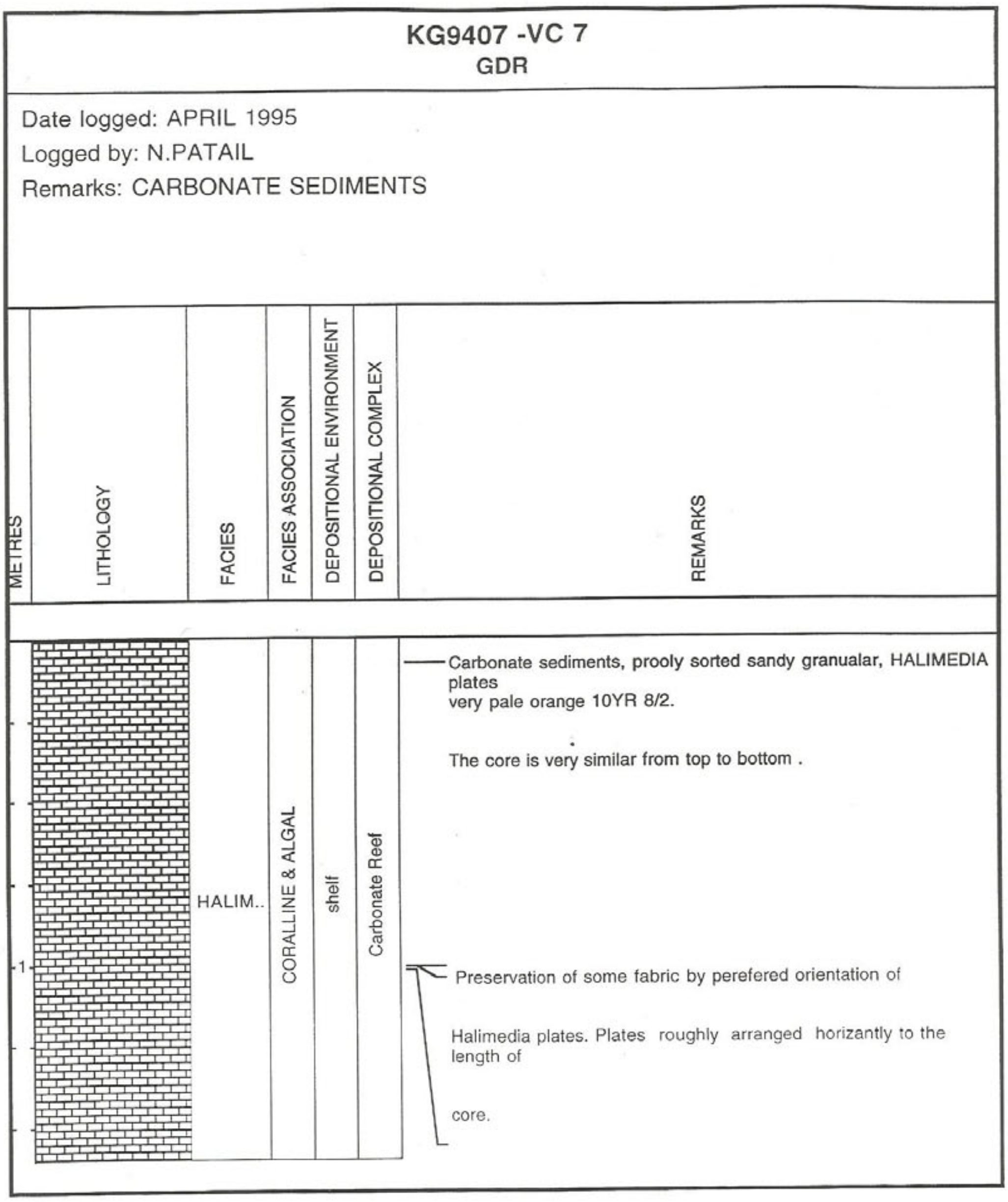
Appendix

Core Logs



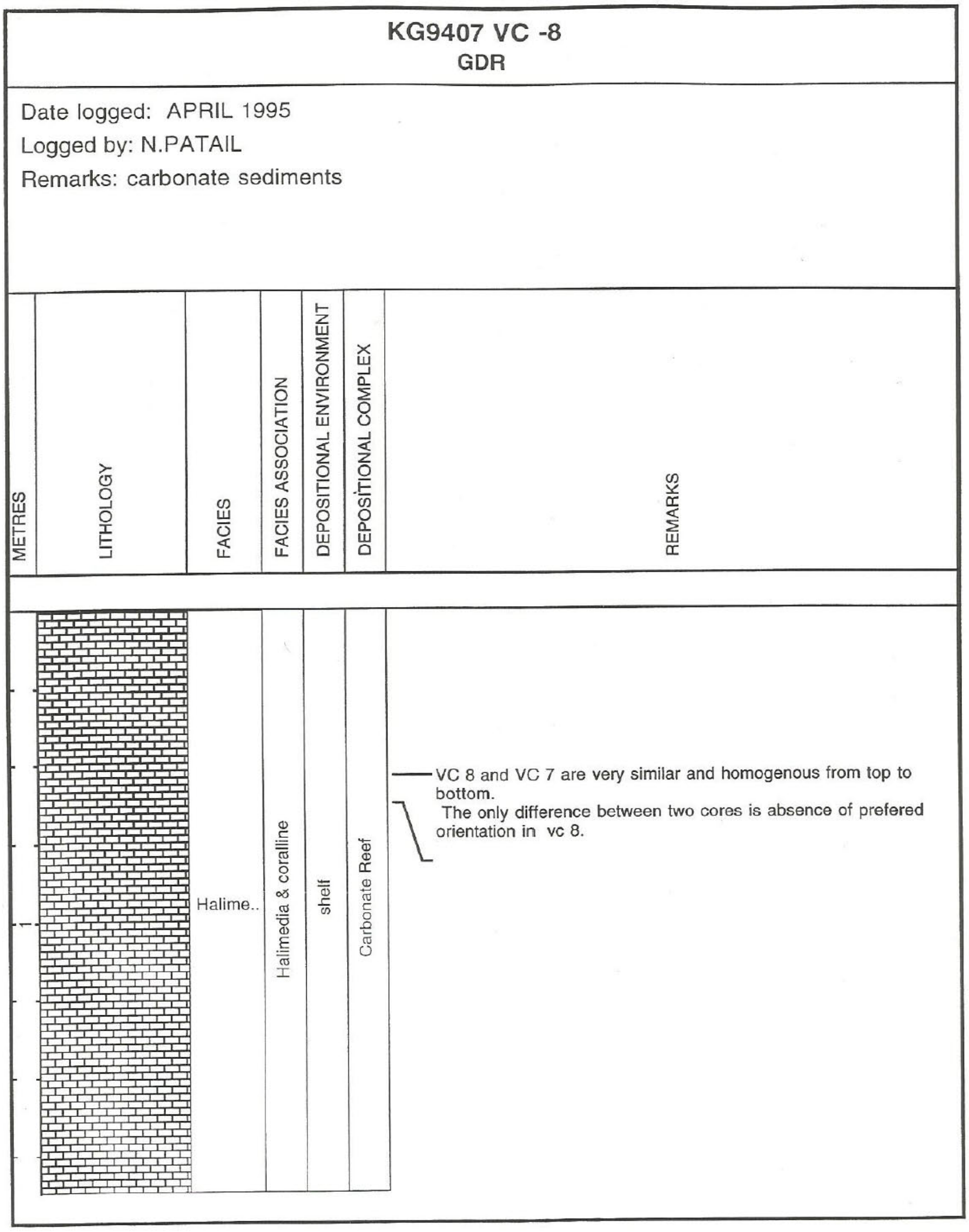
KG9407 -VC 7
GDR

Date logged: APRIL 1995
Logged by: N.PATAIL
Remarks: CARBONATE SEDIMENTS

Carbonate sediments, prooly sorted sandy granualar, HALIMEDIA plates
very pale orange 10YR 8/2.

The core is very similar from top to bottom .

Preservation of some fabric by perefered orientation of Halimedia plates. Plates roughly arranged horizantly to the length of core.



KG9407 VC -8

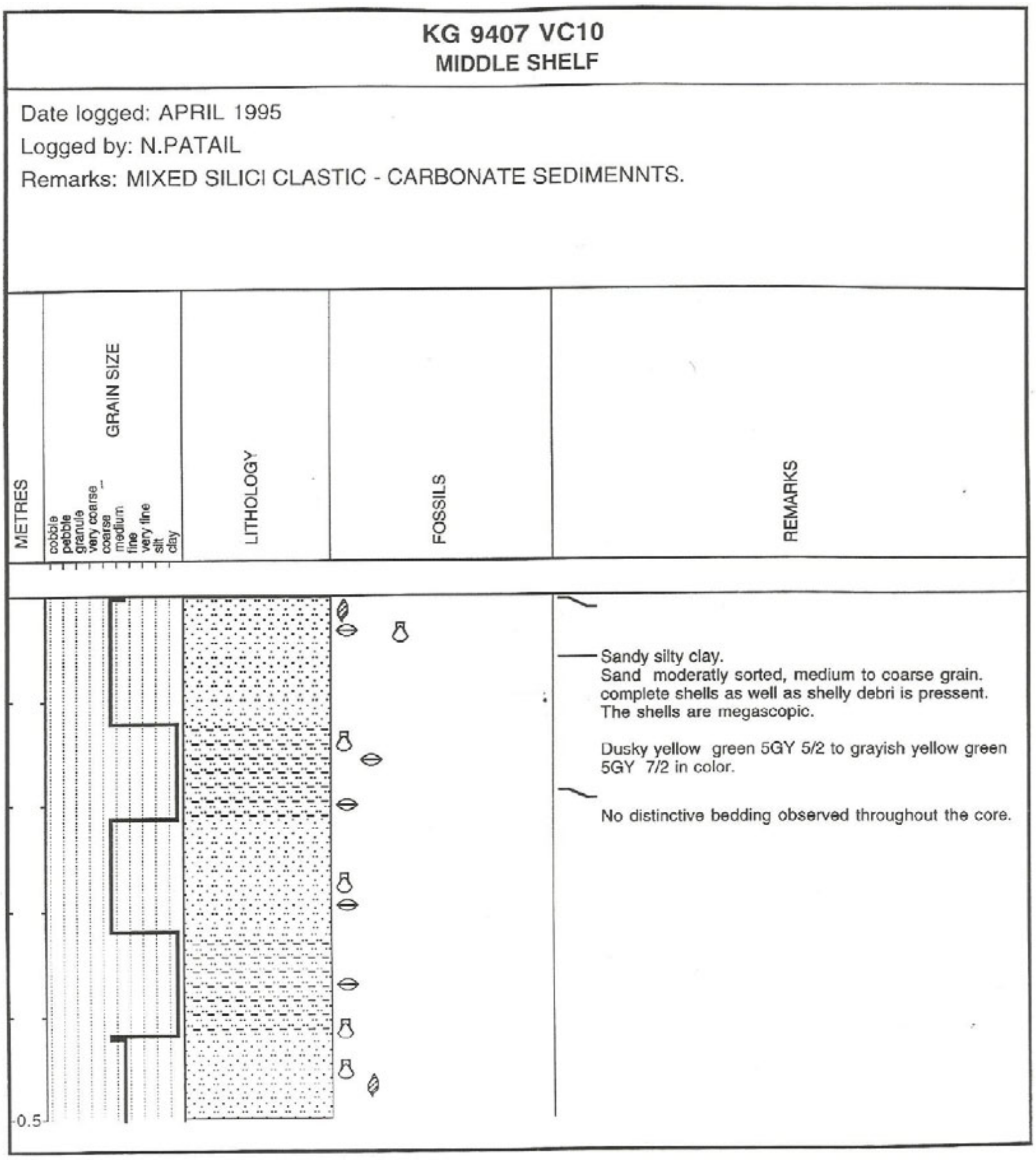
GDR

Date logged: APRIL 1995

Logged by: N.PATAIL

Remarks: carbonate sediments

METRES	LITHOLOGY	FACIES	FACIES ASSOCIATION	DEPOSITIONAL ENVIRONMENT	DEPOSITIONAL COMPLEX	REMARKS
1		Halime..	Halimedia & coralline	shelf	Carbonate Reef	VC 8 and VC 7 are very similar and homogenous from top to bottom. The only difference between two cores is absence of prefered orientation in vc 8.



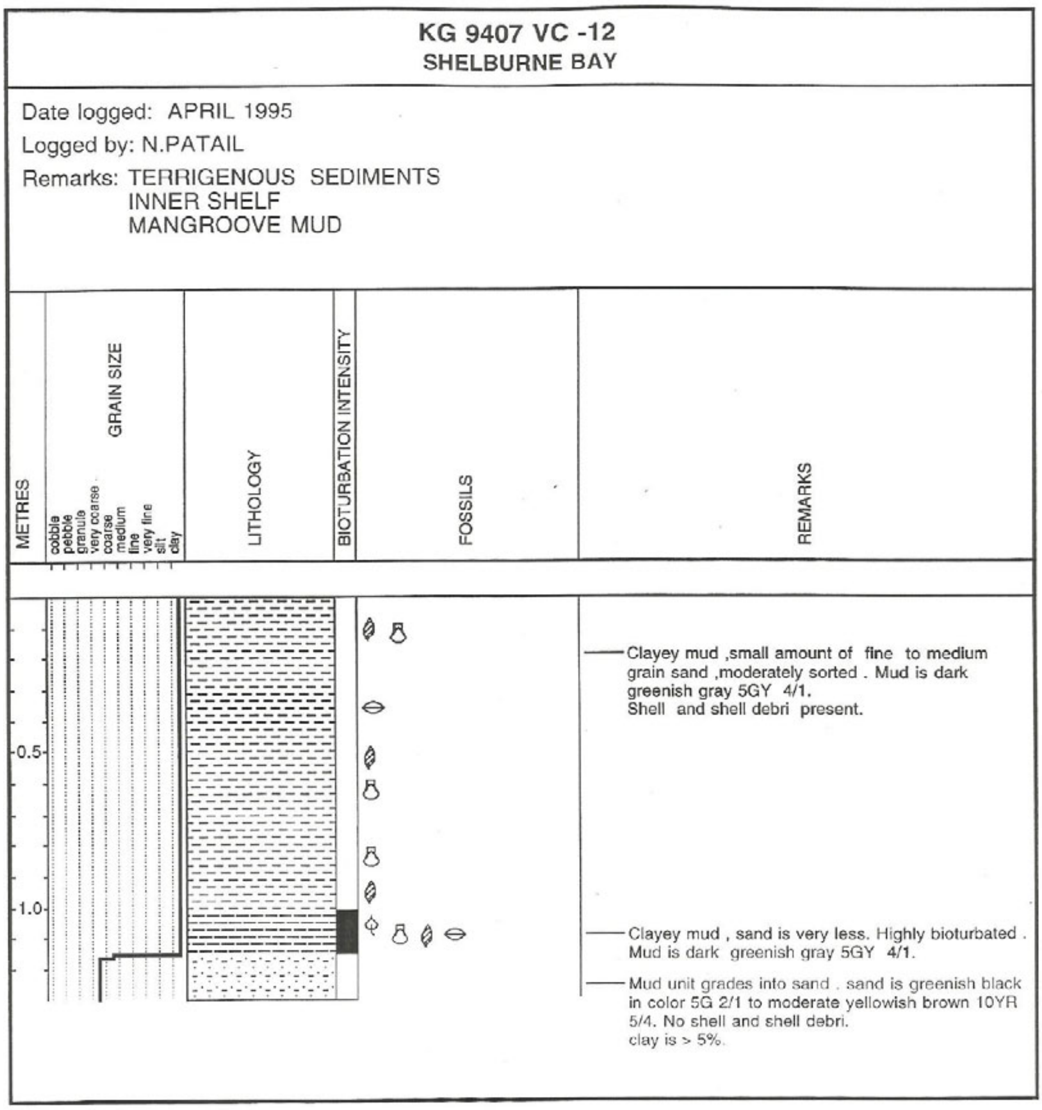
KG 9407 VC10
MIDDLE SHELF

Date logged: APRIL 1995
Logged by: N.PATAIL
Remarks: MIXED SILICI CLASTIC - CARBONATE SEDIMENNTS.

Sandy silty clay.
Sand moderatly sorted, medium to coarse grain.
complete shells as well as shelly debri is pressent.
The shells are megascopic.

Dusky yellow green 5GY 5/2 to grayish yellow green 5GY 7/2 in color.

No distinctive bedding observed throughout the core.



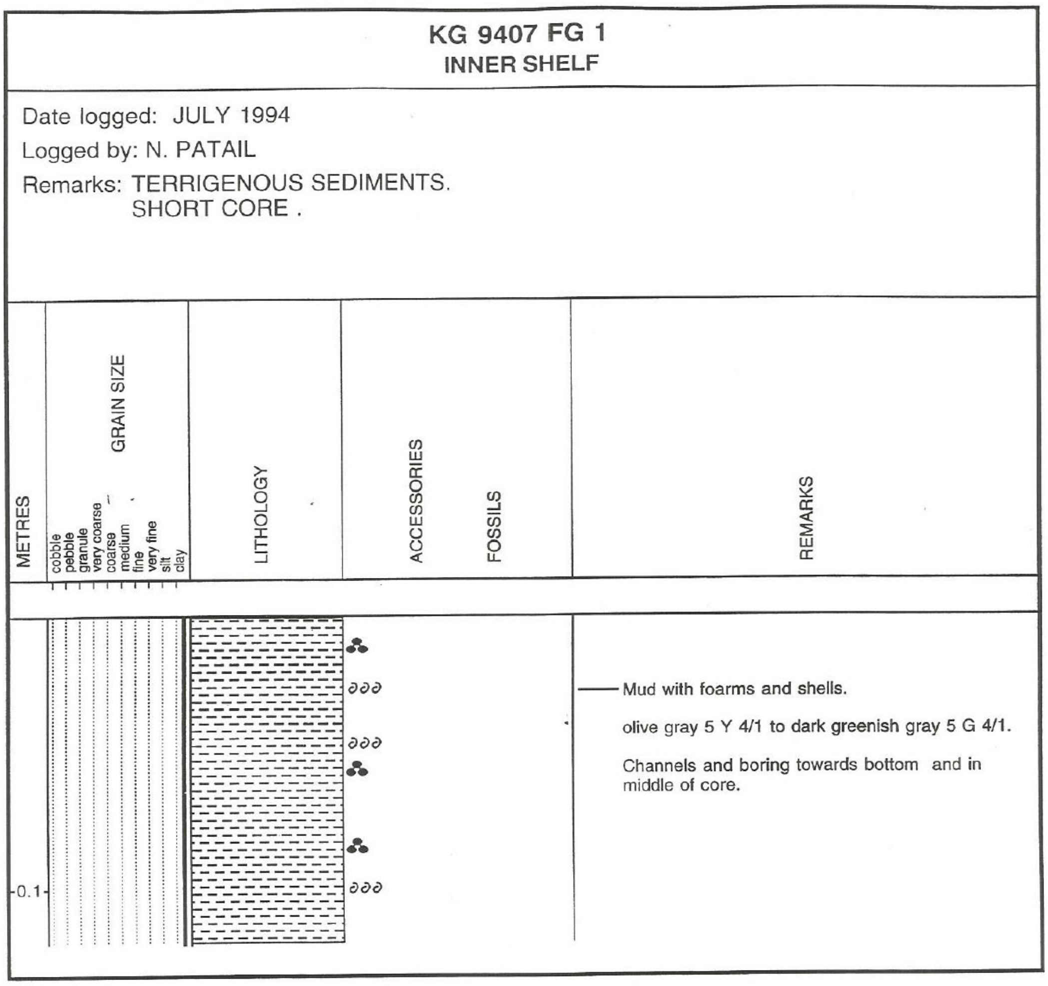
KG 9407 VC -12
SHELBURNE BAY

Date logged: APRIL 1995
Logged by: N.PATAIL
Remarks: TERRIGENOUS SEDIMENTS
INNER SHELF
MANGROOVE MUD

Clayey mud ,small amount of fine to medium grain sand ,moderately sorted . Mud is dark greenish gray 5GY 4/1.
Shell and shell debri present.

Clayey mud , sand is very less. Highly bioturbated . Mud is dark greenish gray 5GY 4/1.

Mud unit grades into sand . sand is greenish black in color 5G 2/1 to moderate yellowish brown 10YR 5/4. No shell and shell debri.
clay is > 5%.



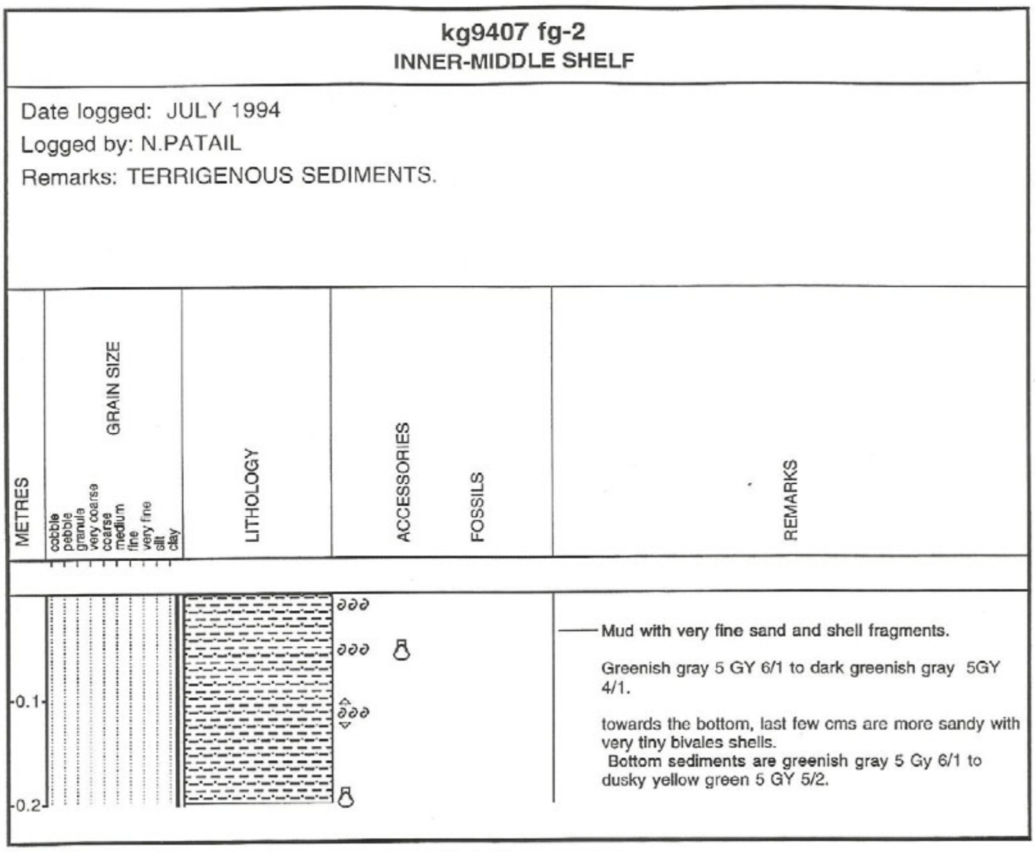
KG 9407 FG 1
INNER SHELF

Date logged: JULY 1994
Logged by: N. PATAIL
Remarks: TERRIGENOUS SEDIMENTS.
SHORT CORE .

Mud with foarms and shells.

olive gray 5 Y 4/1 to dark greenish gray 5 G 4/1.

Channels and boring towards bottom and in middle of core.



kg9407 fg-2

INNER-MIDDLE SHELF

Date logged: JULY 1994

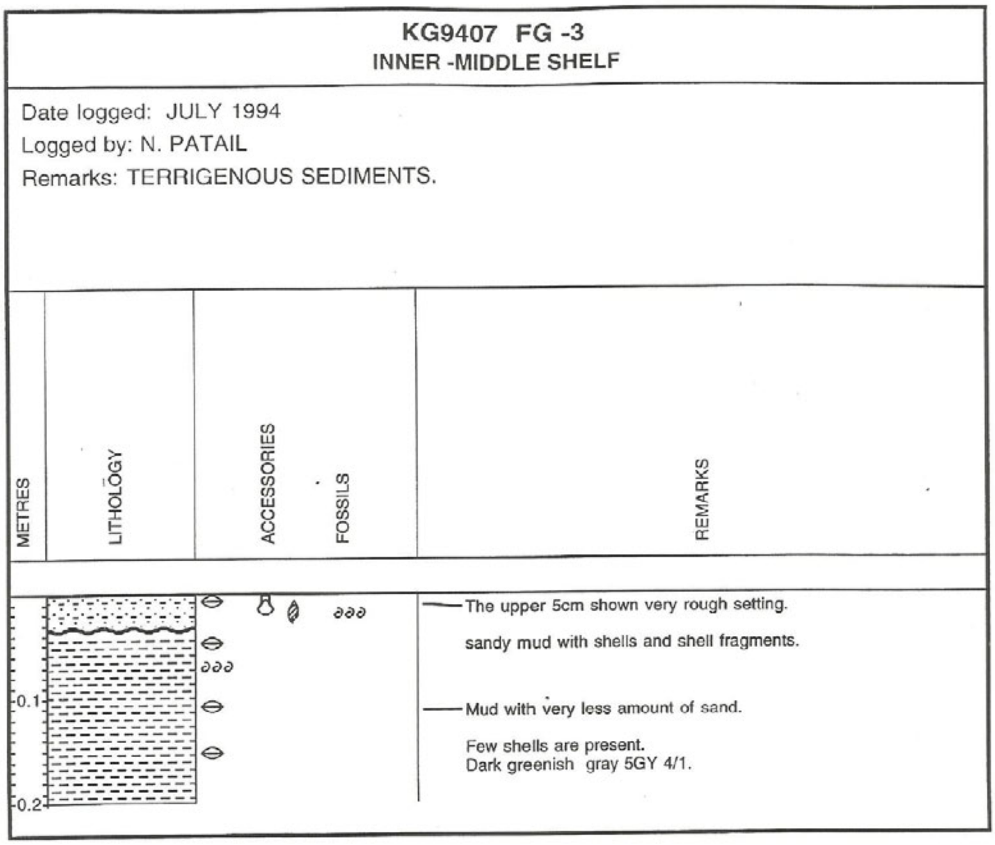
Logged by: N.PATAIL

Remarks: TERRIGENOUS SEDIMENTS.

Mud with very fine sand and shell fragments.

Greenish gray 5 GY 6/1 to dark greenish gray 5GY 4/1.

towards the bottom, last few cms are more sandy with very tiny bivales shells.
Bottom sediments are greenish gray 5 Gy 6/1 to dusky yellow green 5 GY 5/2.



KG9407 FG -3
INNER -MIDDLE SHELF

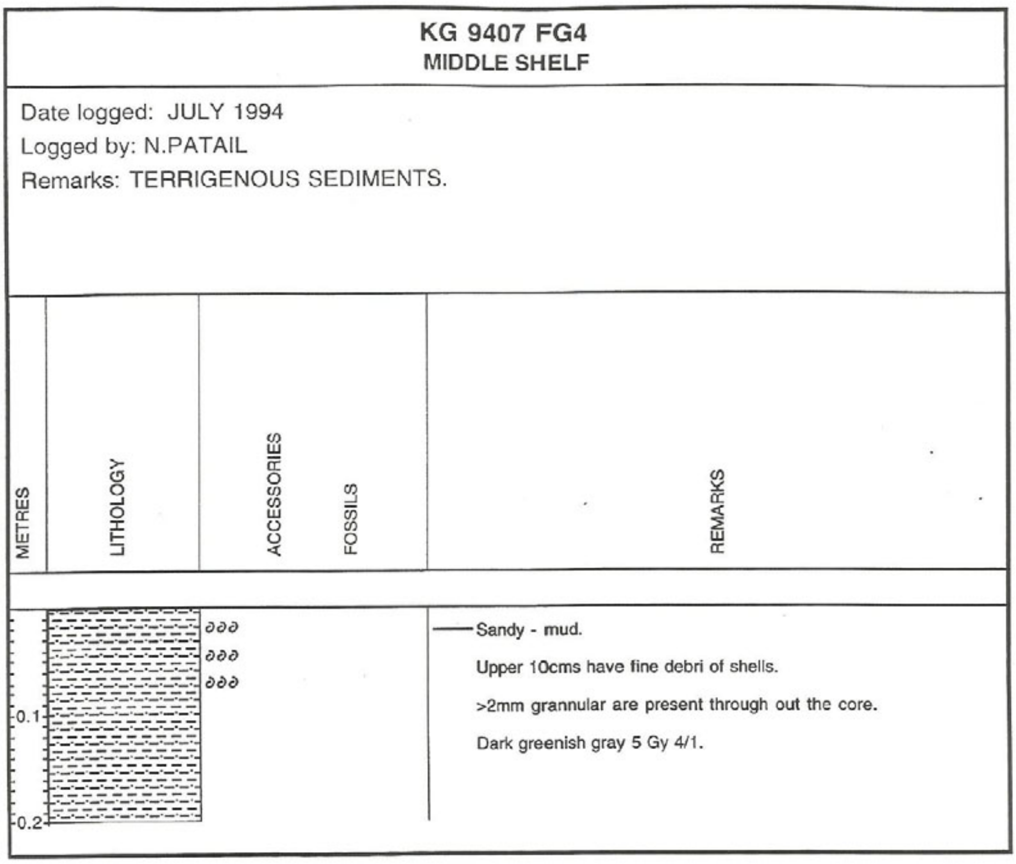
Date logged: JULY 1994
Logged by: N. PATAIL
Remarks: TERRIGENOUS SEDIMENTS.

The upper 5cm shown very rough setting.

sandy mud with shells and shell fragments.

Mud with very less amount of sand.

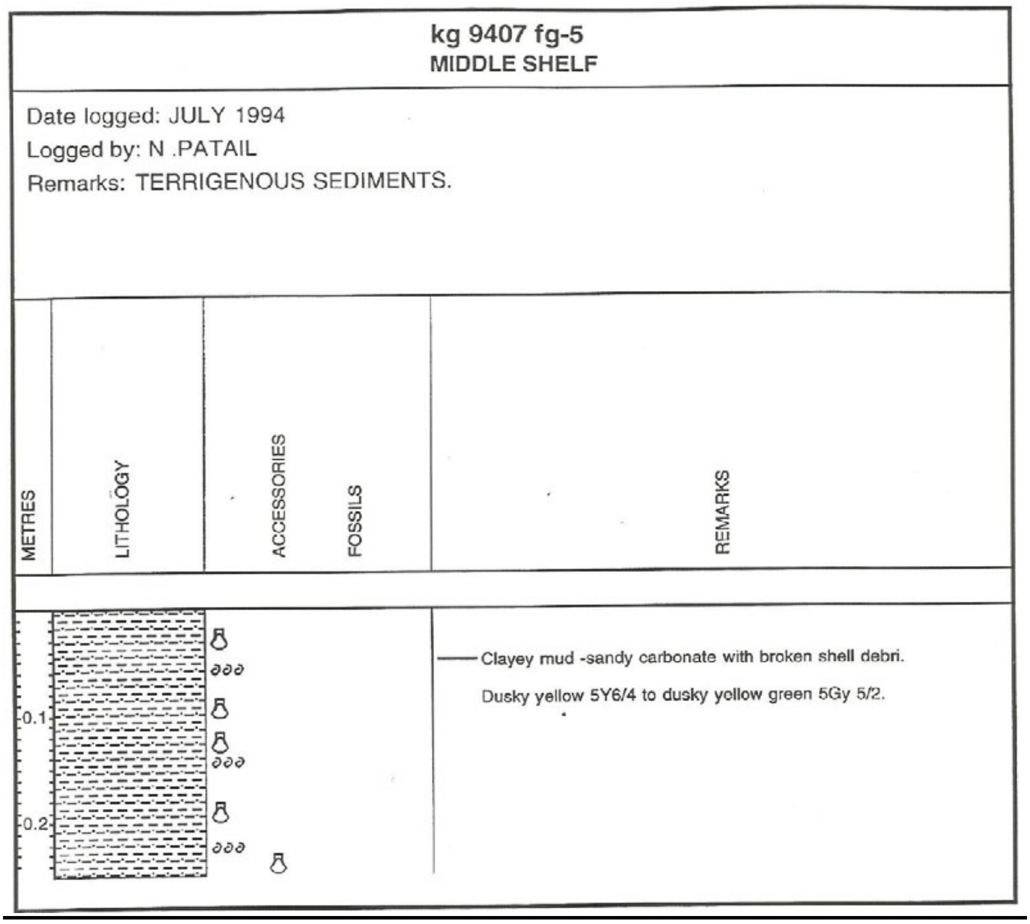
Few shells are present.
Dark greenish gray 5GY 4/1.



KG 9407 FG4
MIDDLE SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRIGENOUS SEDIMENTS.

METRES	LITHOLOGY	ACCESSORIES	FOSSILS	REMARKS
		∂∂∂ ∂∂∂ ∂∂∂		Sandy - mud. Upper 10cms have fine debri of shells. >2mm grannular are present through out the core. Dark greenish gray 5 Gy 4/1.
0.1				
0.2				



kg 9407 fg-5

MIDDLE SHELF

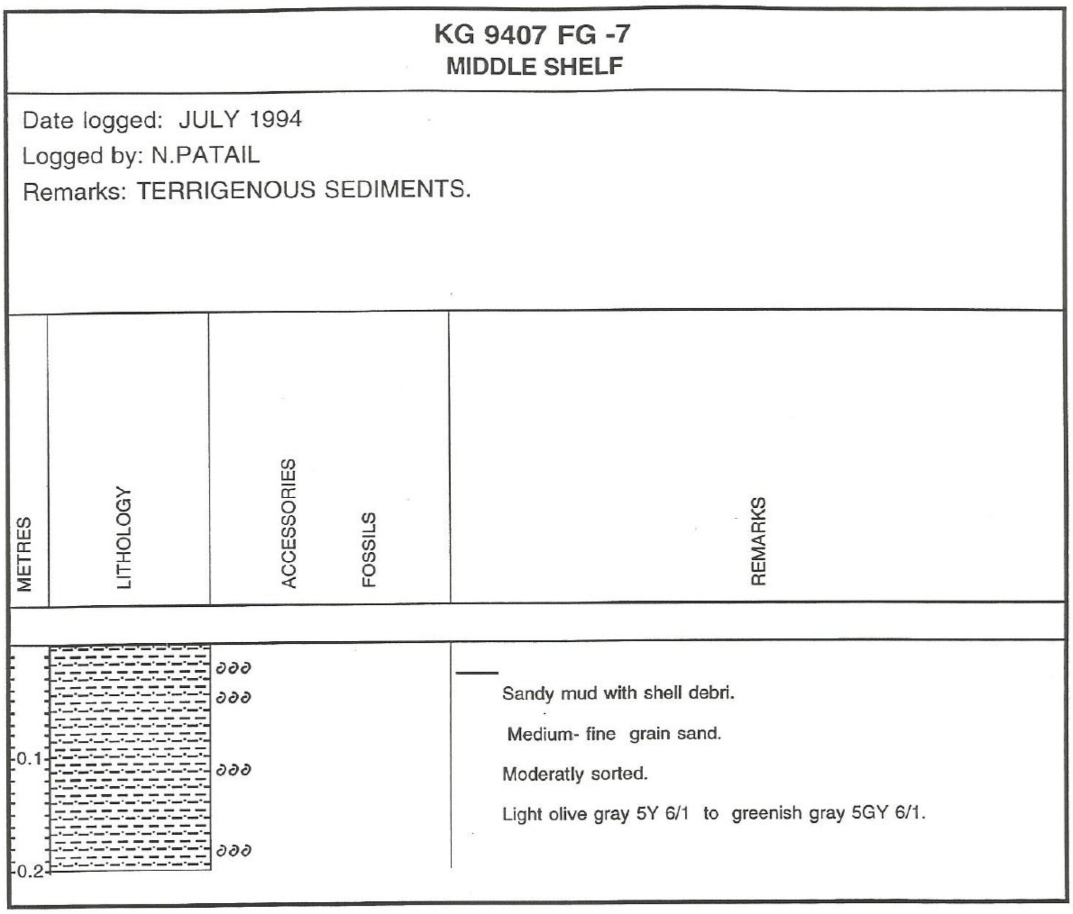
Date logged: JULY 1994

Logged by: N .PATAIL

Remarks: TERRIGENOUS SEDIMENTS.

Clayey mud -sandy carbonate with broken shell debri.

Dusky yellow 5Y6/4 to dusky yellow green 5Gy 5/2.



KG 9407 FG -7
MIDDLE SHELF

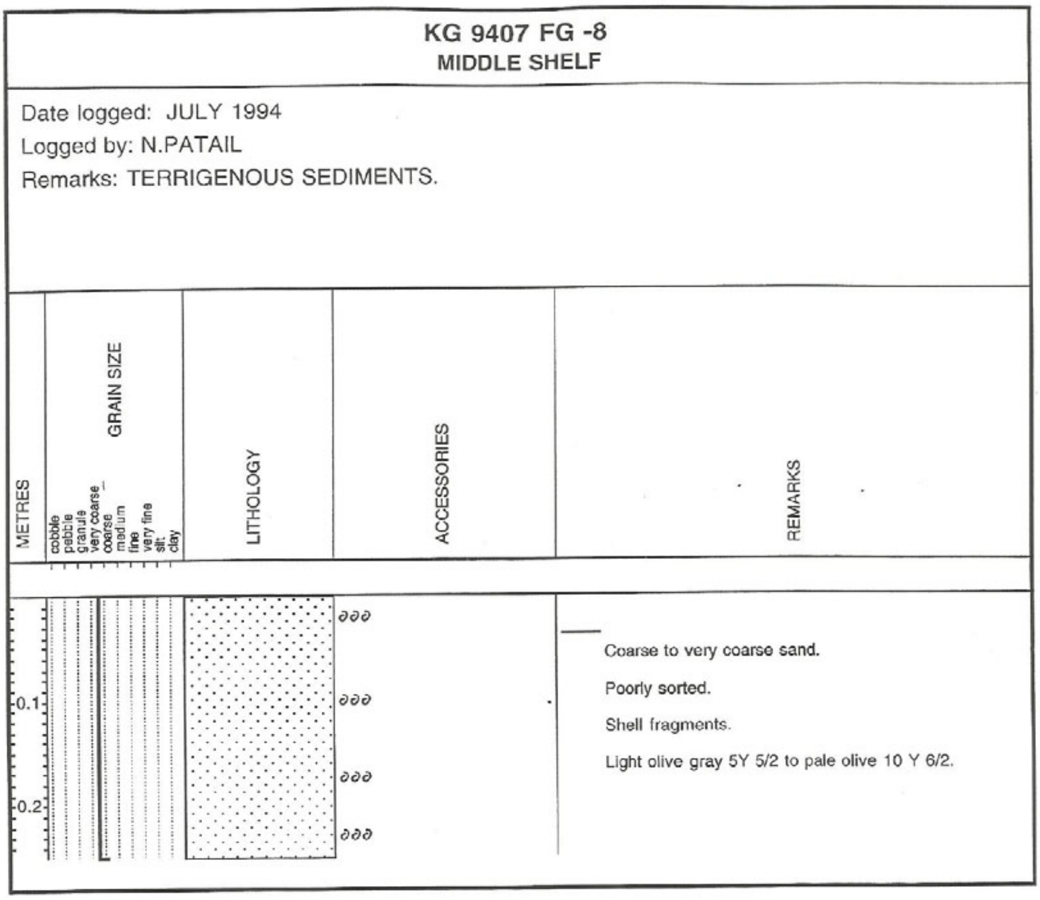
Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRIGENOUS SEDIMENTS.

Sandy mud with shell debri.

Medium- fine grain sand.

Moderatly sorted.

Light olive gray 5Y 6/1 to greenish gray 5GY 6/1.



KG 9407 FG -8

MIDDLE SHELF

Date logged: JULY 1994

Logged by: N.PATAIL

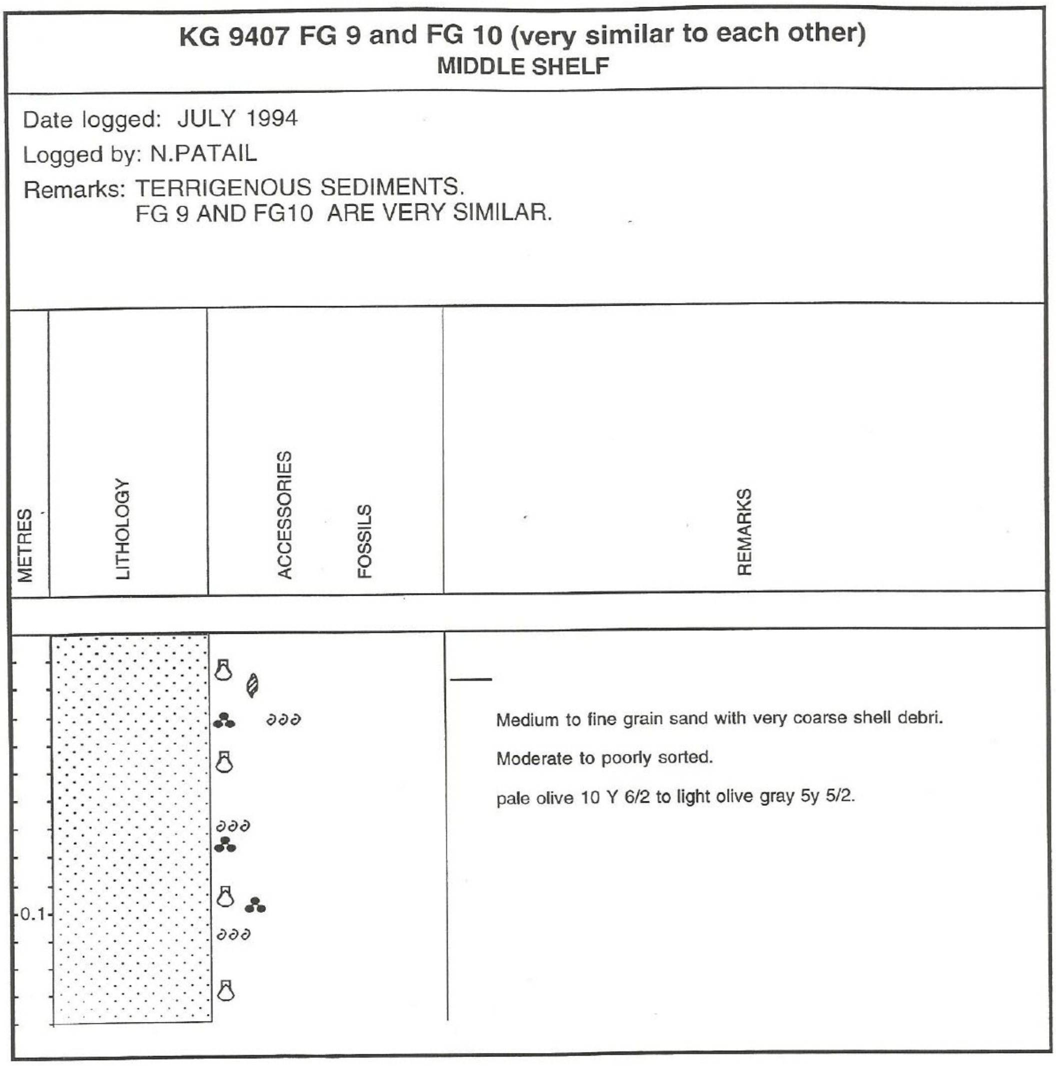
Remarks: TERRIGENOUS SEDIMENTS.

Coarse to very coarse sand.

Poorly sorted.

Shell fragments.

Light olive gray 5Y 5/2 to pale olive 10 Y 6/2.

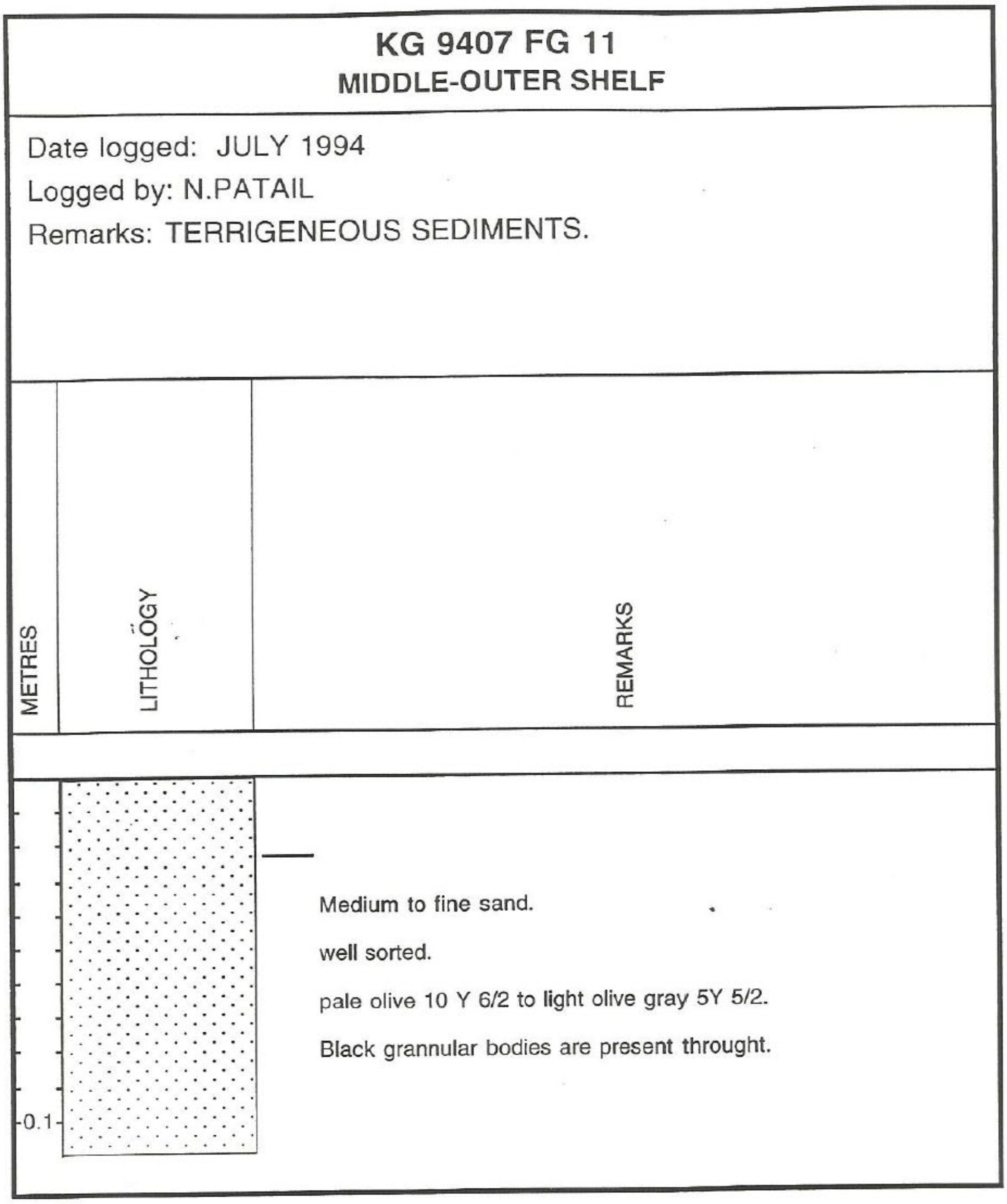


KG 9407 FG 9 and FG 10 (very similar to each other)

MIDDLE SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRIGENOUS SEDIMENTS.
FG 9 AND FG10 ARE VERY SIMILAR.

METRES	LITHOLOGY	ACCESSORIES FOSSILS	REMARKS
0.1			Medium to fine grain sand with very coarse shell debri. Moderate to poorly sorted. pale olive 10 Y 6/2 to light olive gray 5y 5/2.



KG 9407 FG 11

MIDDLE-OUTER SHELF

Date logged: JULY 1994

Logged by: N.PATAIL

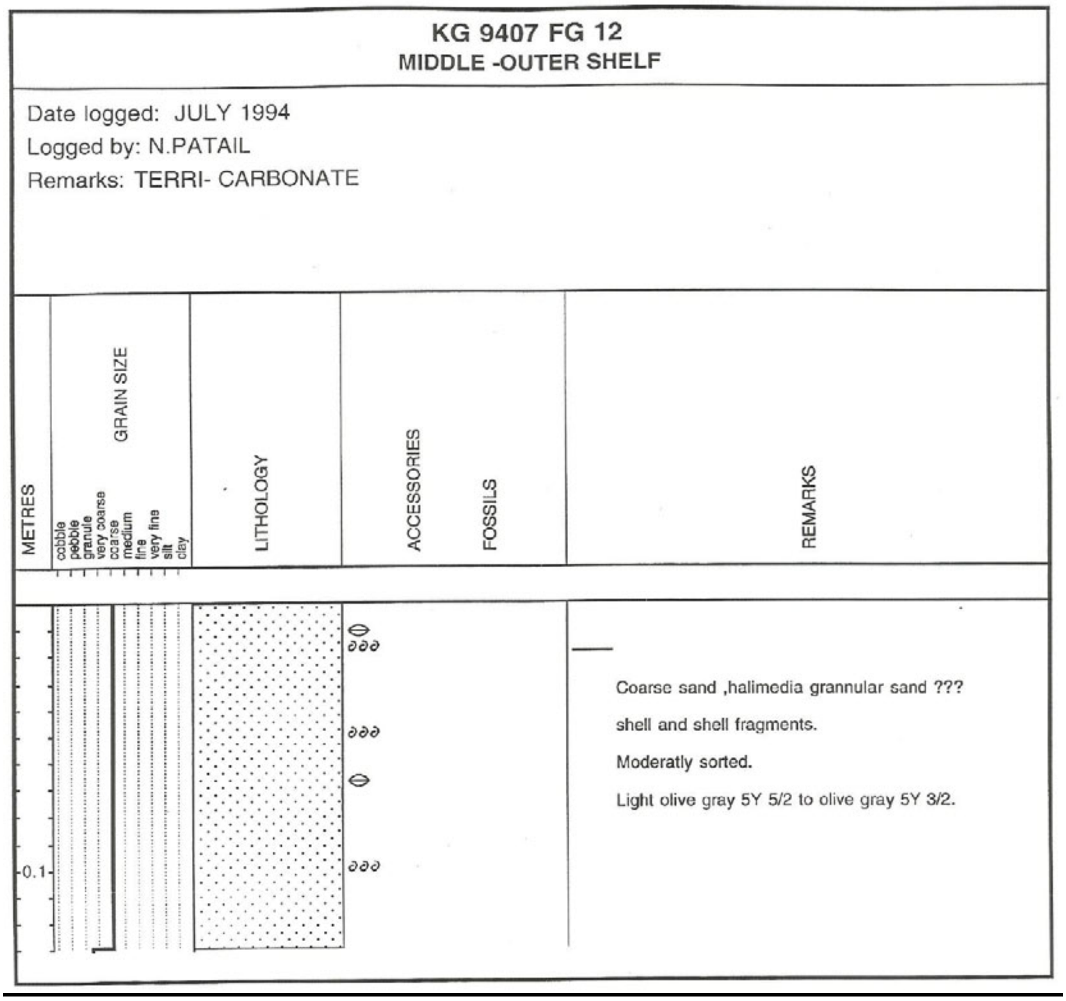
Remarks: TERRIGENEOUS SEDIMENTS.

Medium to fine sand.

well sorted.

pale olive 10 Y 6/2 to light olive gray 5Y 5/2.

Black grannular bodies are present throught.



KG 9407 FG 12
MIDDLE -OUTER SHELF

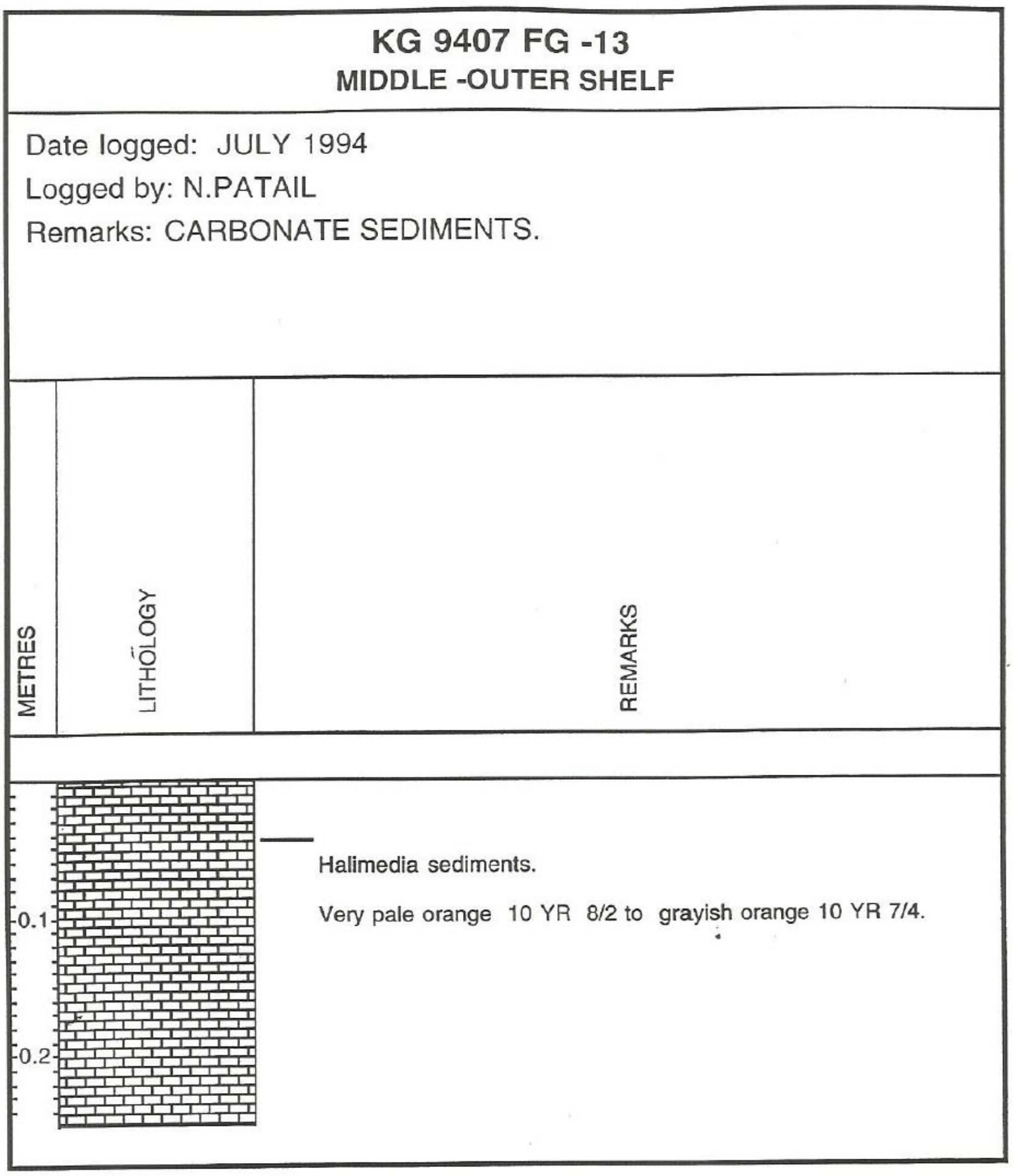
Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRI- CARBONATE

Coarse sand ,halimedia grannular sand ???

shell and shell fragments.

Moderatly sorted.

Light olive gray 5Y 5/2 to olive gray 5Y 3/2.



KG 9407 FG -13

MIDDLE -OUTER SHELF

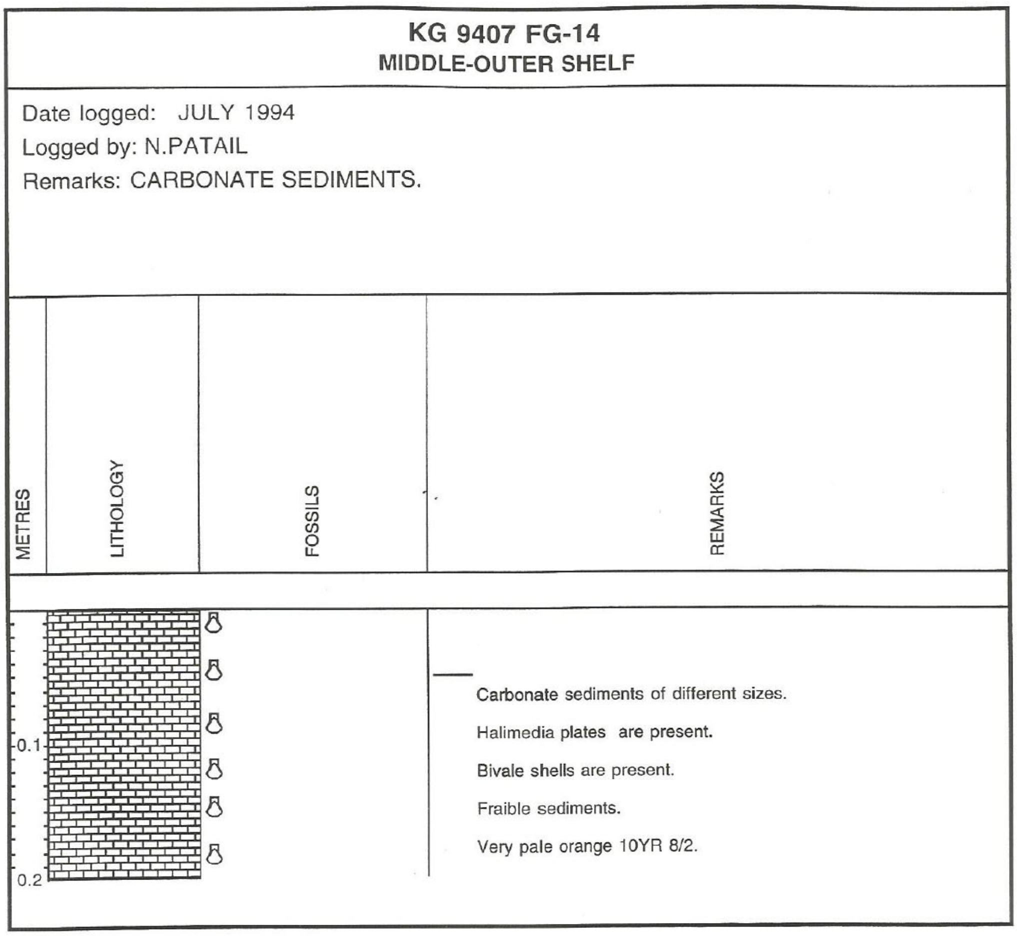
Date logged: JULY 1994

Logged by: N.PATAIL

Remarks: CARBONATE SEDIMENTS.

Halimedia sediments.

Very pale orange 10 YR 8/2 to grayish orange 10 YR 7/4.



KG 9407 FG-14
MIDDLE-OUTER SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: CARBONATE SEDIMENTS.

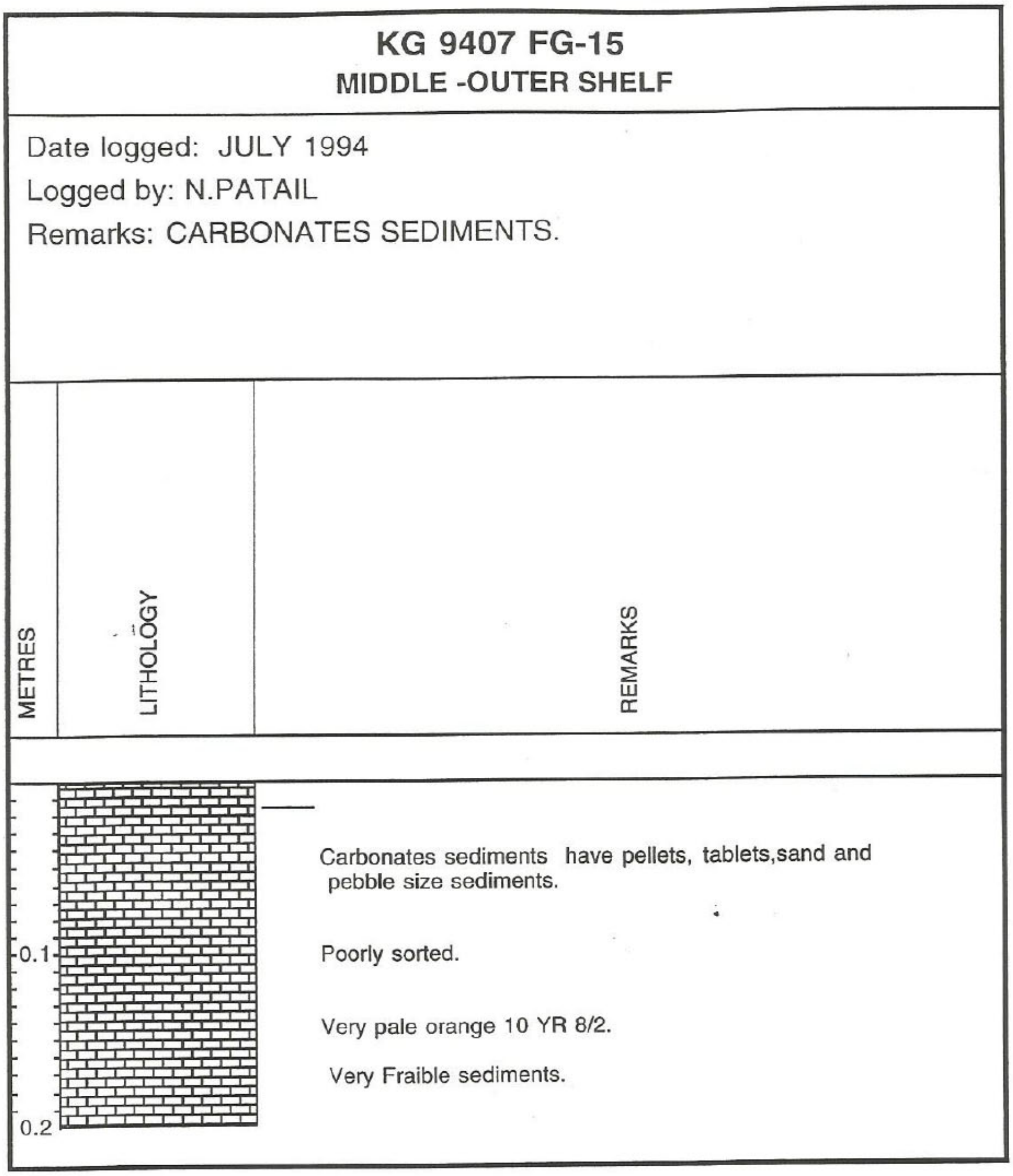
Carbonate sediments of different sizes.

Halimedia plates are present.

Bivale shells are present.

Fraible sediments.

Very pale orange 10YR 8/2.



KG 9407 FG-15
MIDDLE -OUTER SHELF

Date logged: JULY 1994

Logged by: N.PATAIL

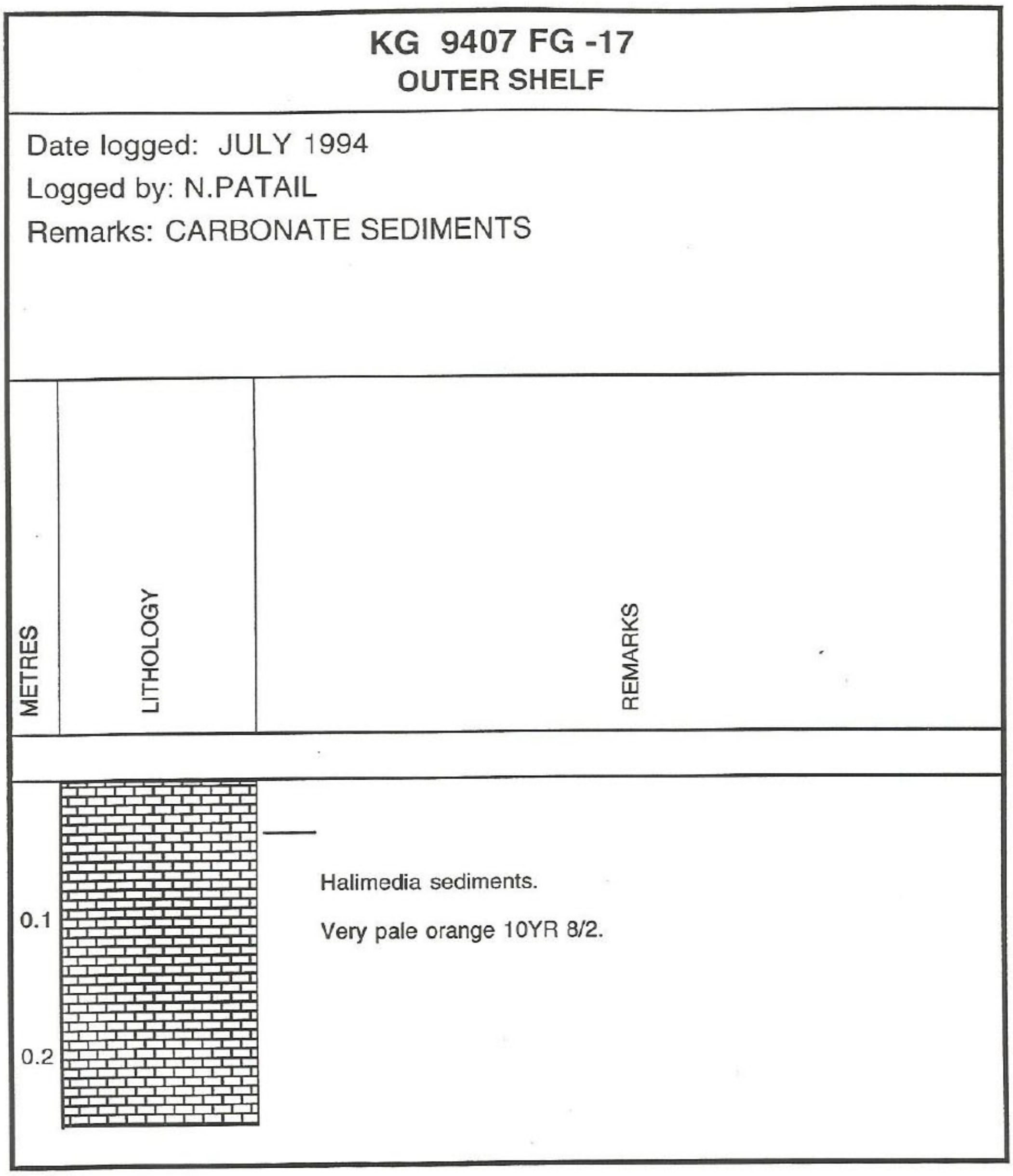
Remarks: CARBONATES SEDIMENTS.

Carbonates sediments have pellets, tablets,sand and pebble size sediments.

Poorly sorted.

Very pale orange 10 YR 8/2.

Very Fraible sediments.



KG 9407 FG -17

OUTER SHELF

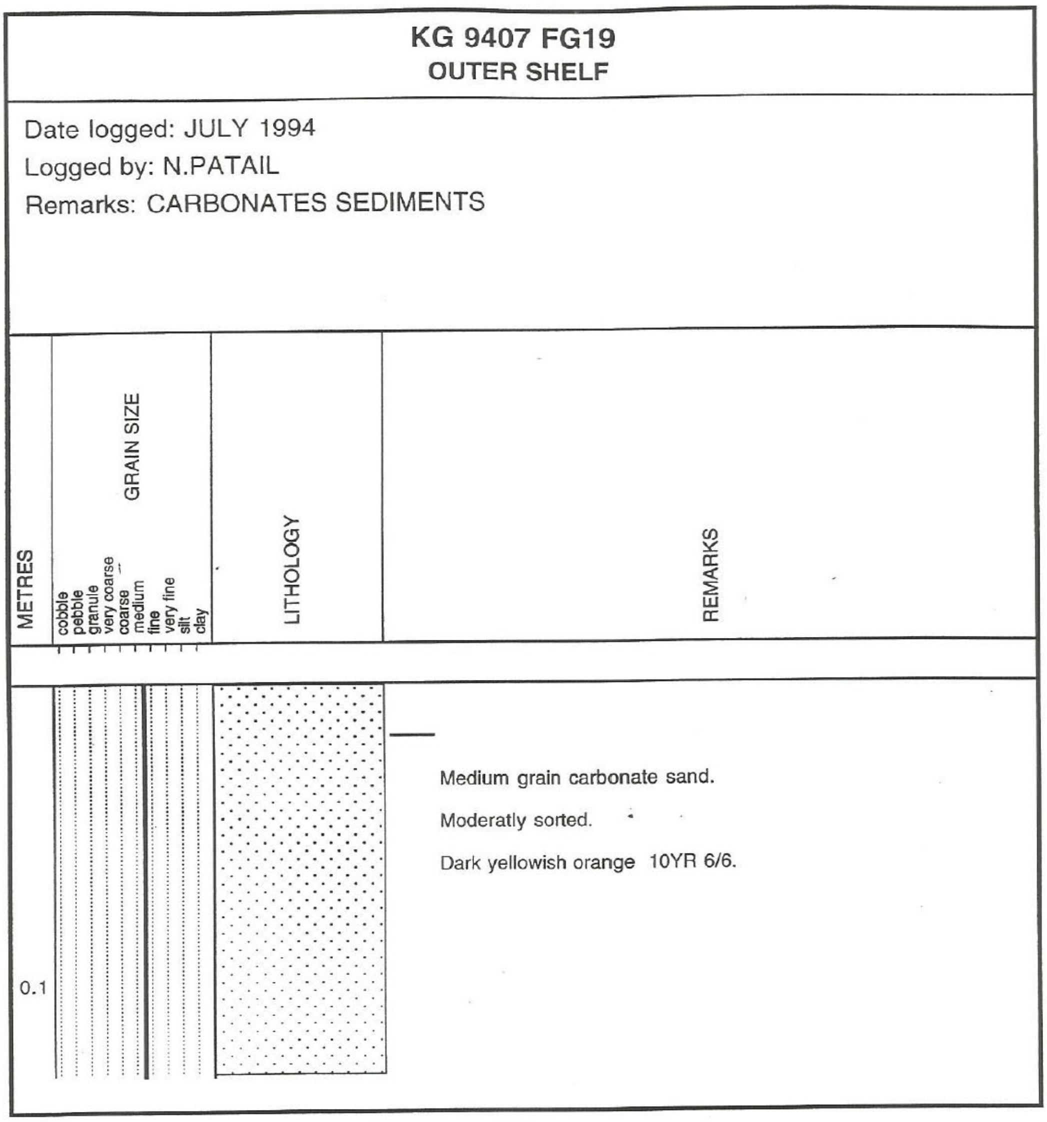
Date logged: JULY 1994

Logged by: N.PATAIL

Remarks: CARBONATE SEDIMENTS

Halimedia sediments.

Very pale orange 10YR 8/2.



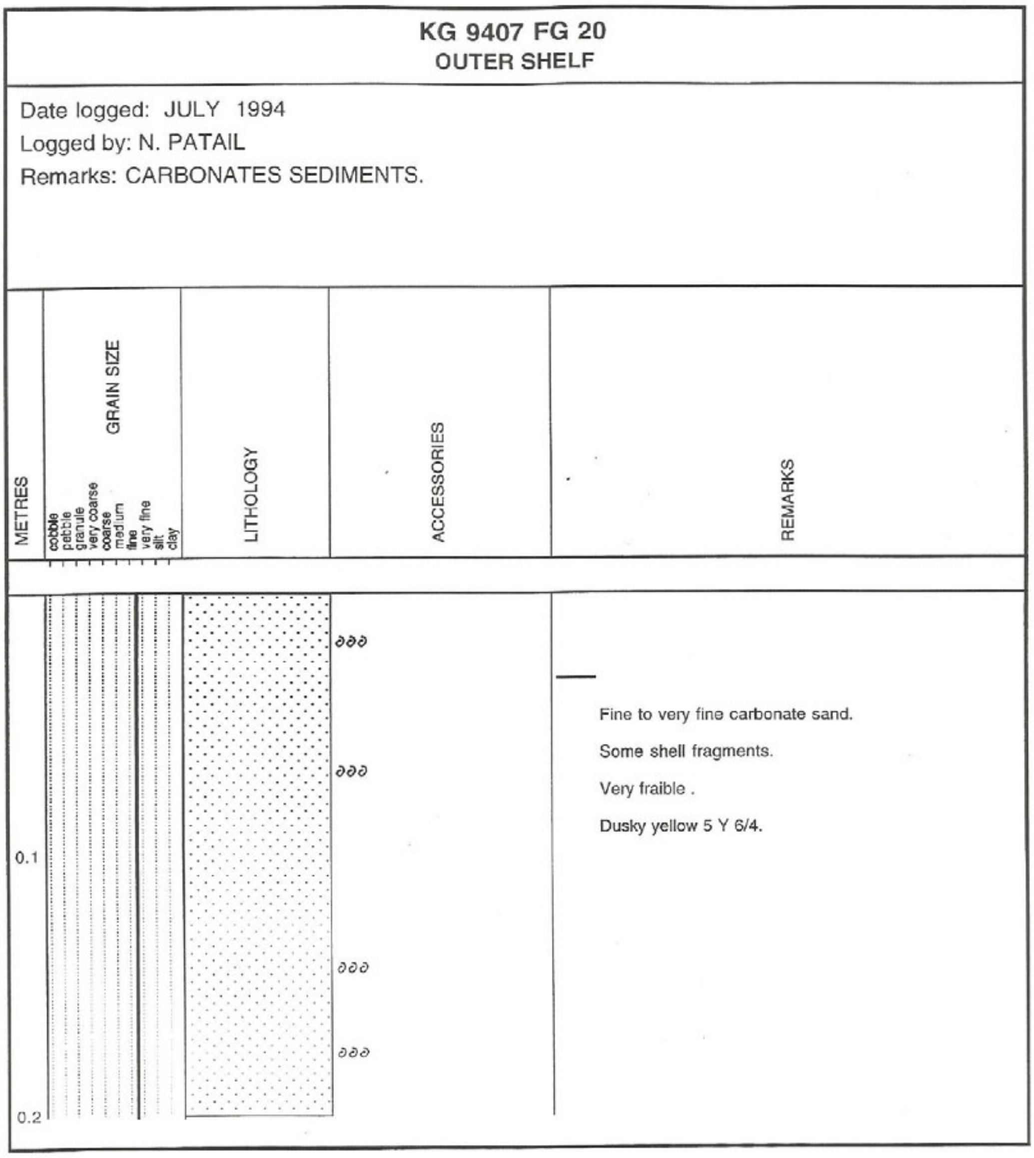
KG 9407 FG19
OUTER SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: CARBONATES SEDIMENTS

Medium grain carbonate sand.

Moderatly sorted.

Dark yellowish orange 10YR 6/6.



KG 9407 FG 20
OUTER SHELF

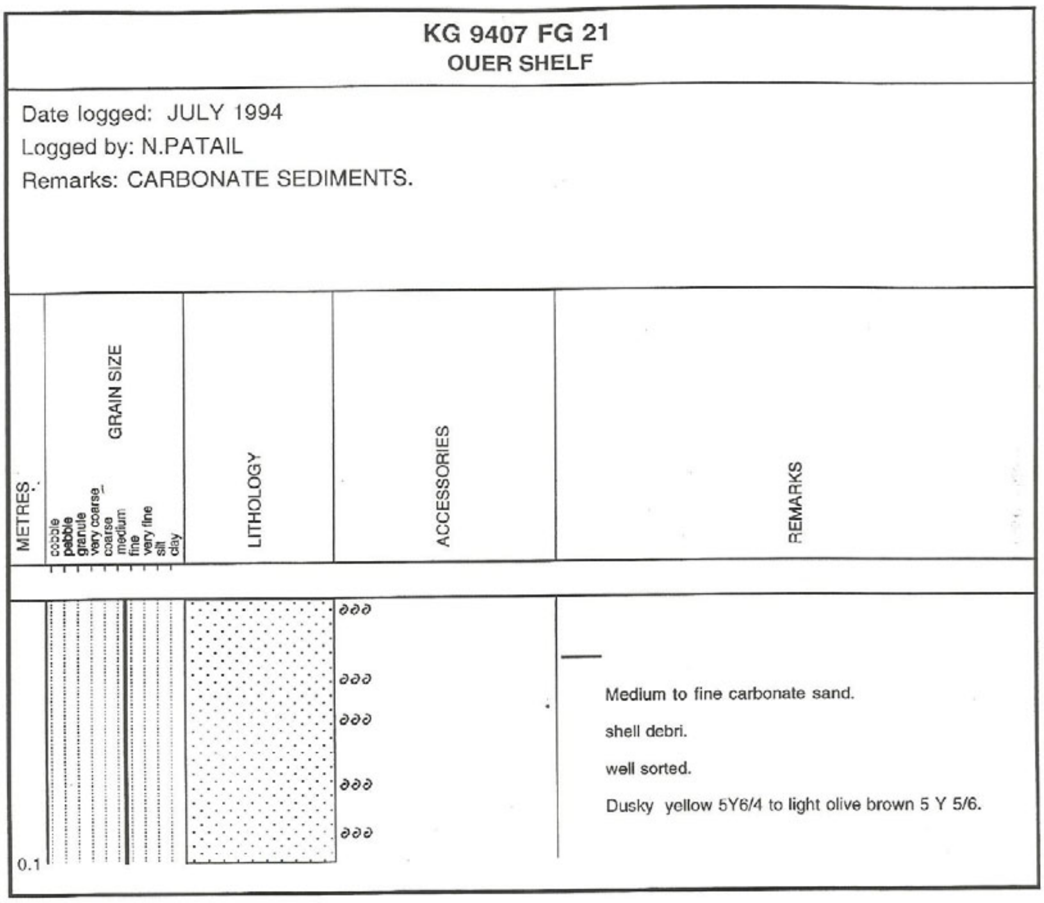
Date logged: JULY 1994
Logged by: N. PATAIL
Remarks: CARBONATES SEDIMENTS.

Fine to very fine carbonate sand.

Some shell fragments.

Very fraible .

Dusky yellow 5 Y 6/4.



KG 9407 FG 21
OUER SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: CARBONATE SEDIMENTS.

METRES
GRAIN SIZE
cobble
pebble
granule
very coarse
coarse
medium
fine
very fine
silt
clay
LITHOLOGY
ACCESSORIES
REMARKS

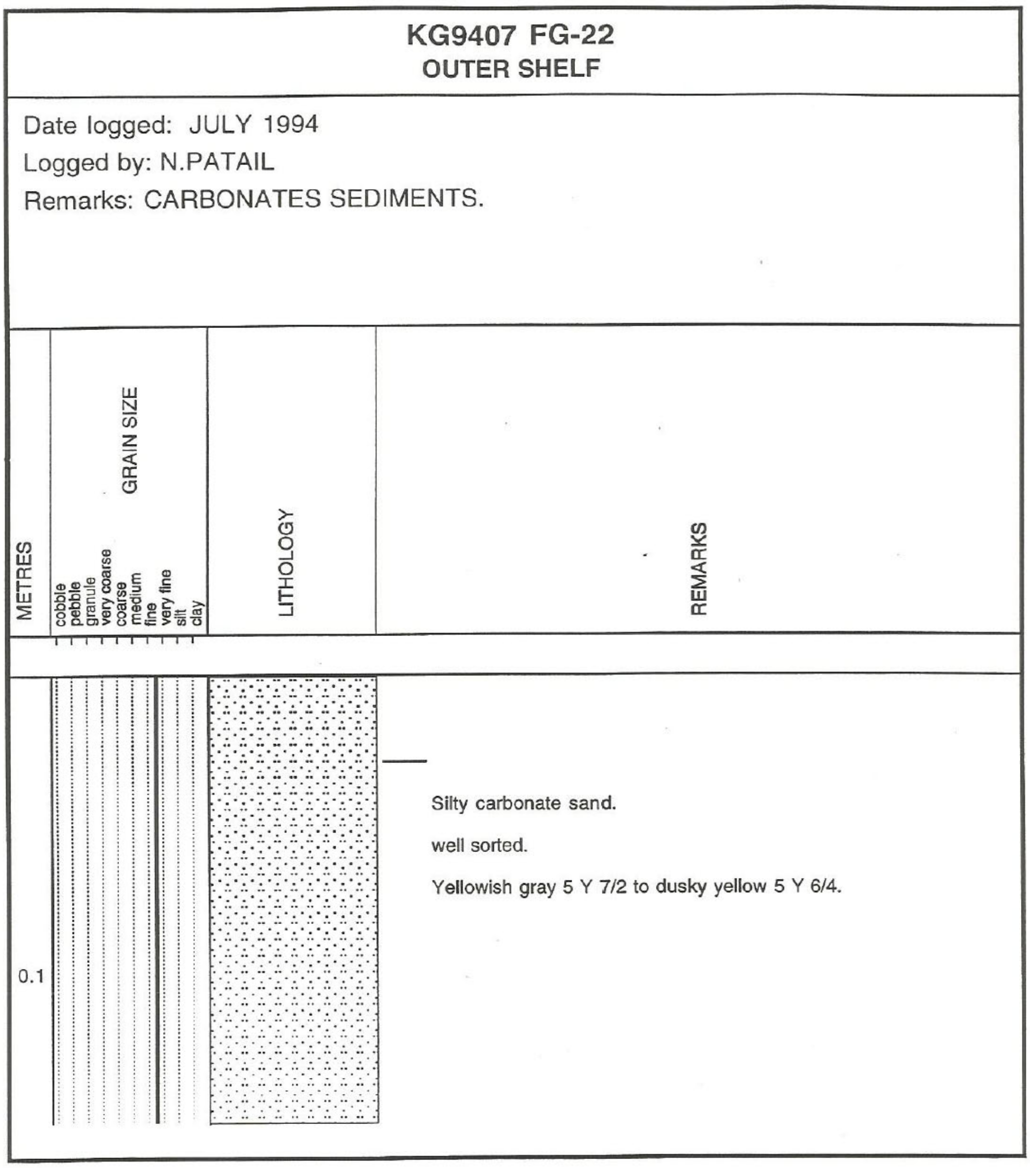
Medium to fine carbonate sand.

shell debri.

well sorted.

Dusky yellow 5Y6/4 to light olive brown 5 Y 5/6.

0.1



KG9407 FG-22
OUTER SHELF

Date logged: JULY 1994

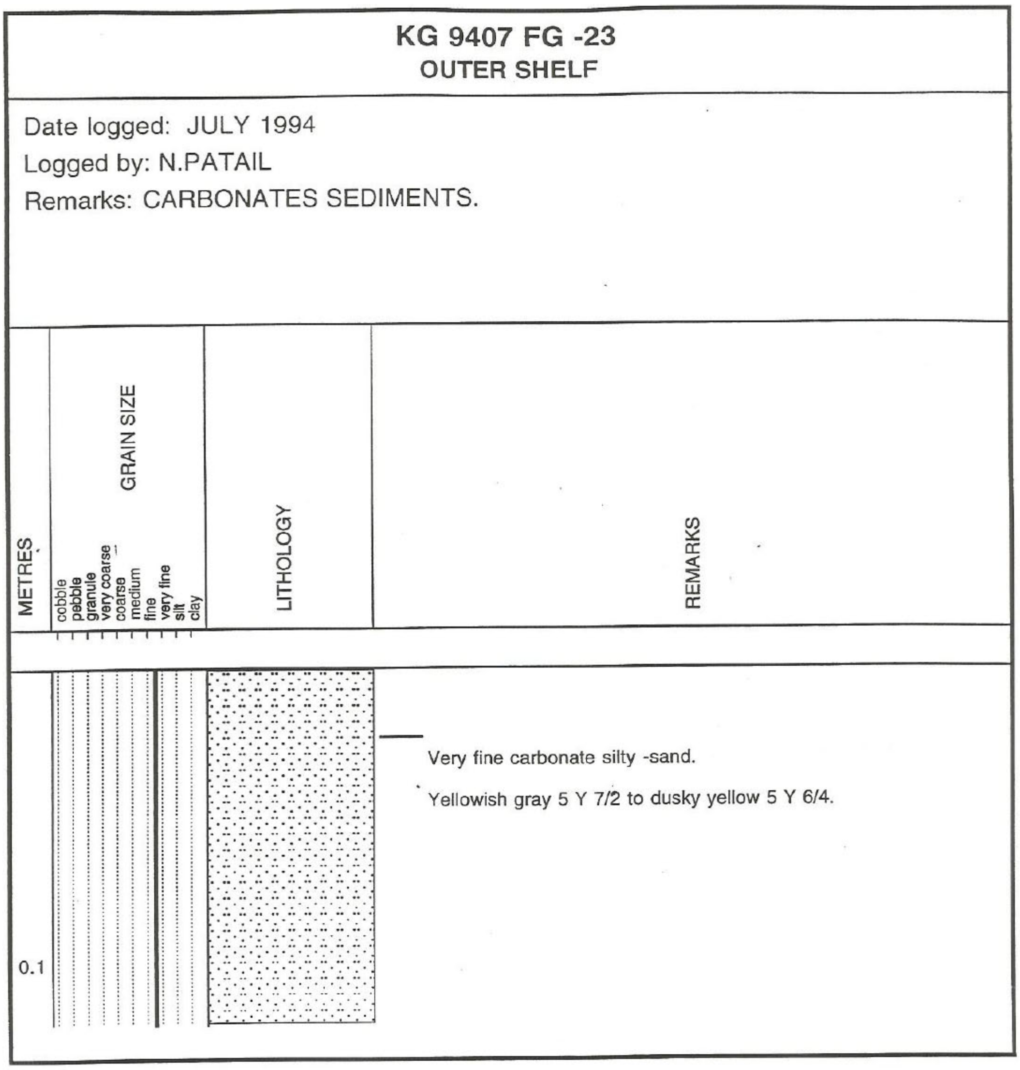
Logged by: N.PATAIL

Remarks: CARBONATES SEDIMENTS.

Silty carbonate sand.

well sorted.

Yellowish gray 5 Y 7/2 to dusky yellow 5 Y 6/4.

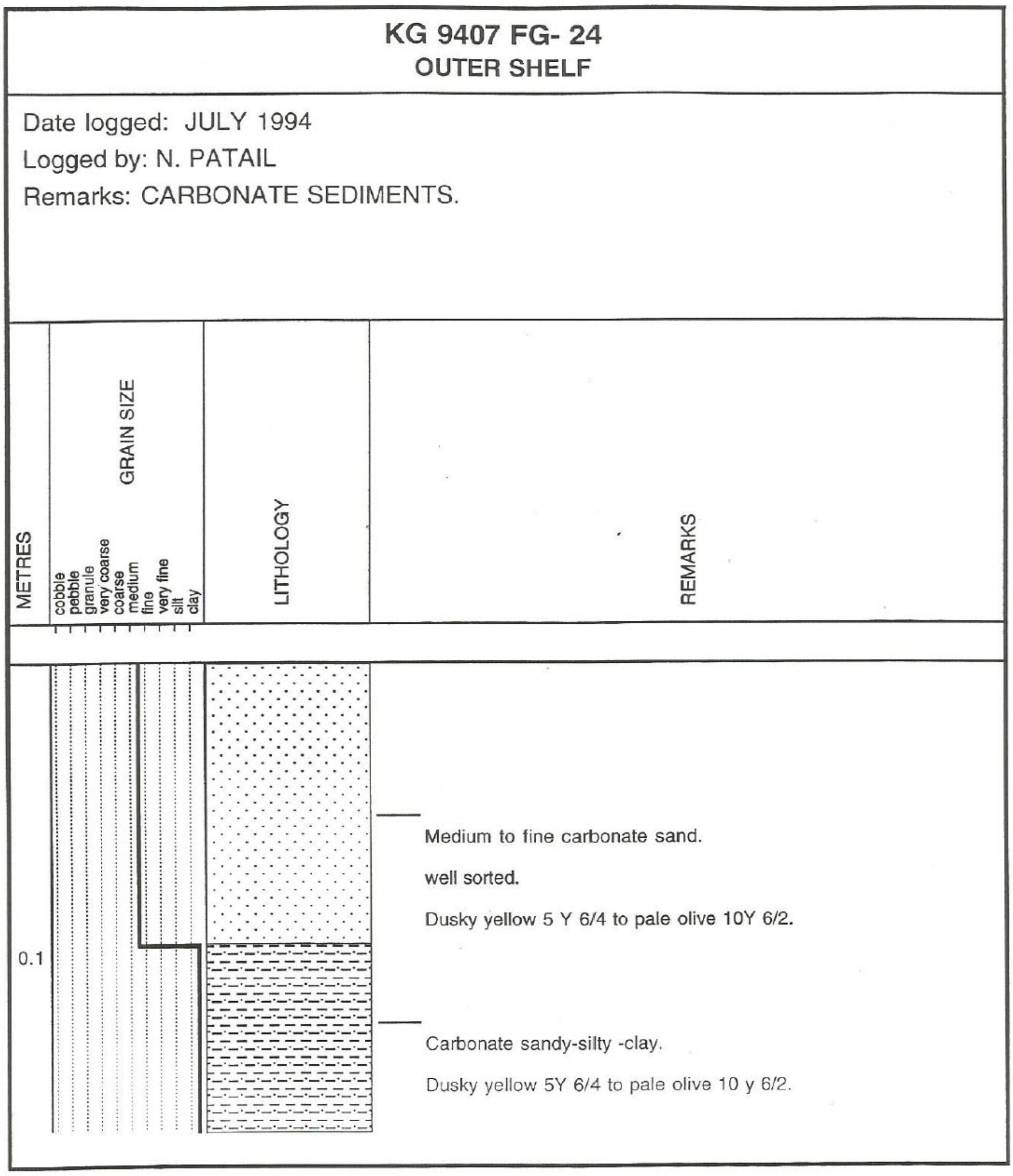


KG 9407 FG -23
OUTER SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: CARBONATES SEDIMENTS.

Very fine carbonate silty -sand.

Yellowish gray 5 Y 7/2 to dusky yellow 5 Y 6/4.



KG 9407 FG- 24
OUTER SHELF

Date logged: JULY 1994

Logged by: N. PATAIL

Remarks: CARBONATE SEDIMENTS.

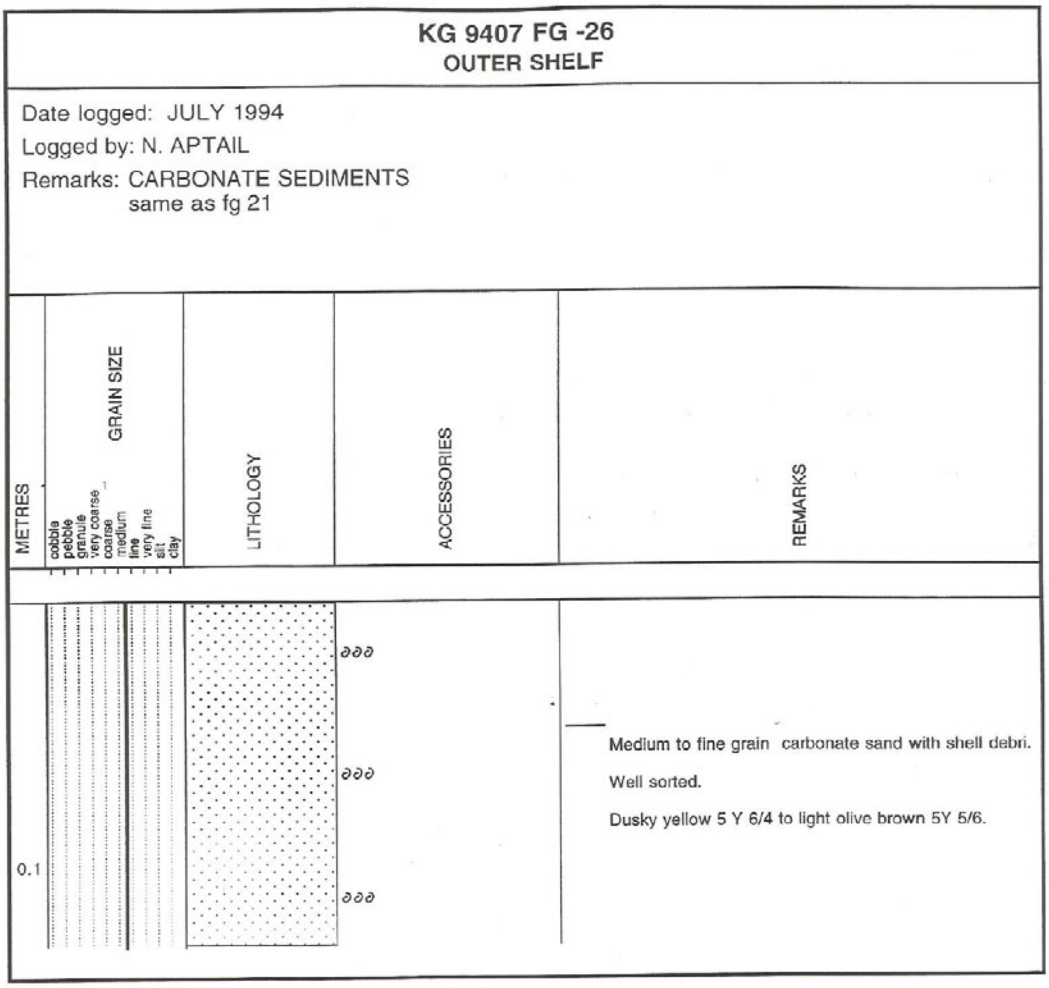
Medium to fine carbonate sand.

well sorted.

Dusky yellow 5 Y 6/4 to pale olive 10Y 6/2.

Carbonate sandy-silty -clay.

Dusky yellow 5Y 6/4 to pale olive 10 y 6/2.



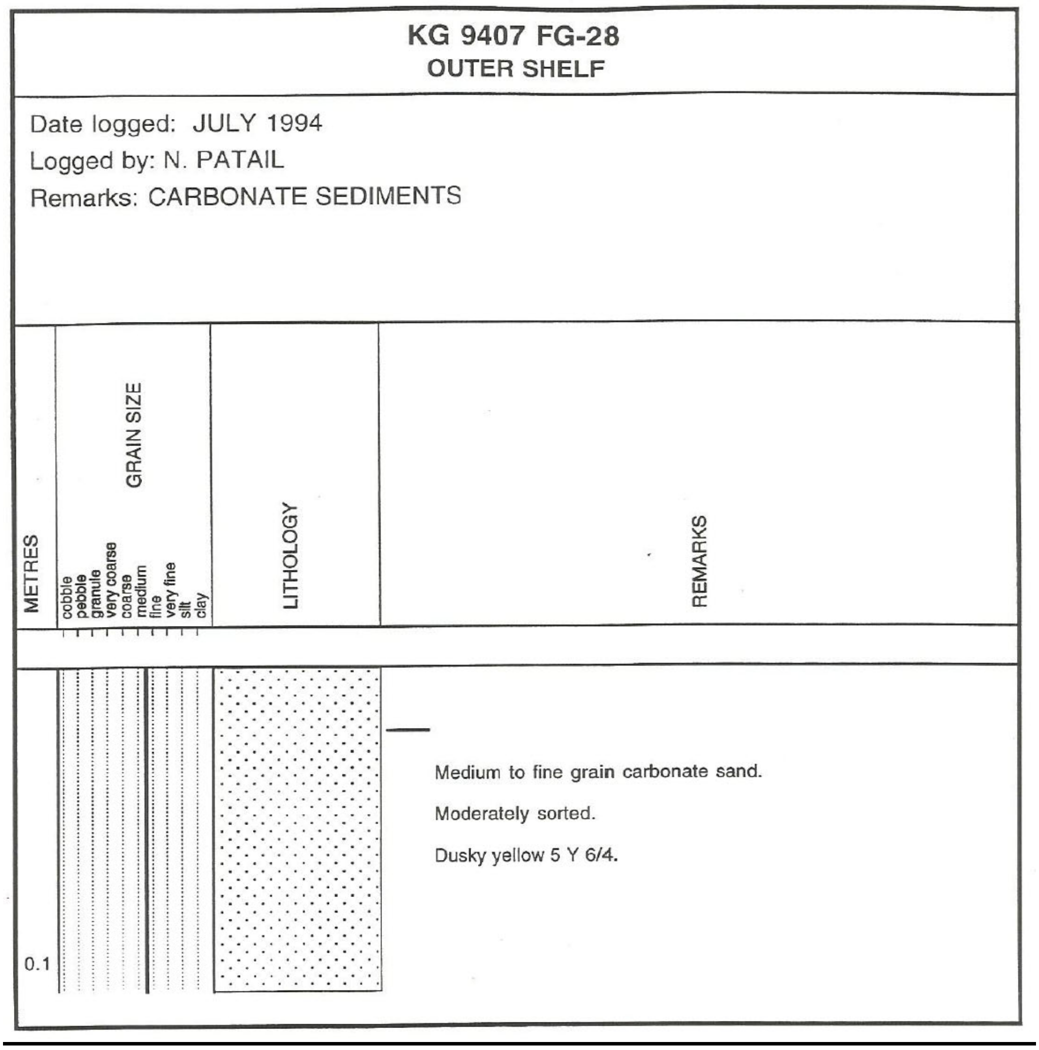
KG 9407 FG -26
OUTER SHELF

Date logged: JULY 1994
Logged by: N. APTAIL
Remarks: CARBONATE SEDIMENTS
same as fg 21

Medium to fine grain carbonate sand with shell debri.

Well sorted.

Dusky yellow 5 Y 6/4 to light olive brown 5Y 5/6.



KG 9407 FG-28

OUTER SHELF

Date logged: JULY 1994

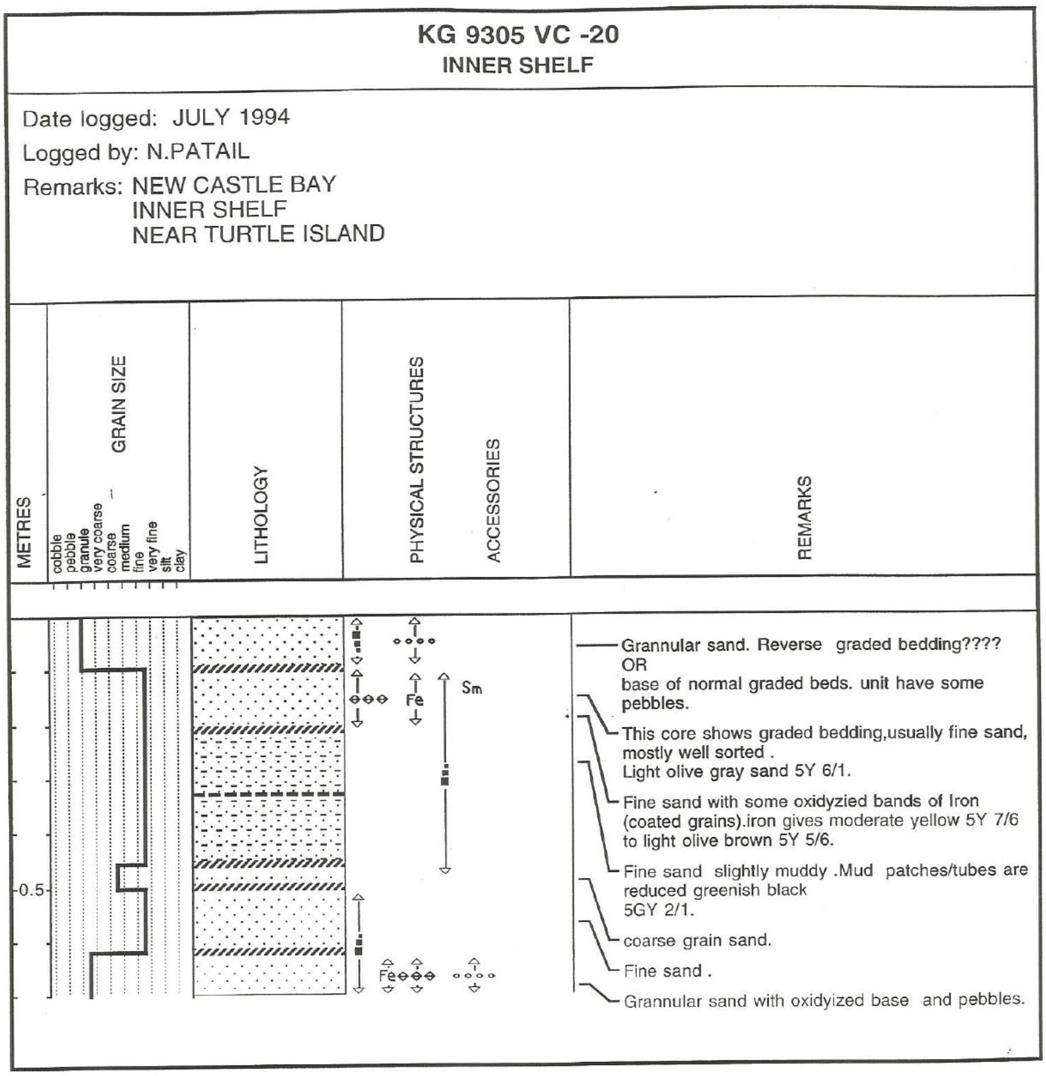
Logged by: N. PATAIL

Remarks: CARBONATE SEDIMENTS

Medium to fine grain carbonate sand.

Moderately sorted.

Dusky yellow 5 Y 6/4.



KG 9305 VC -20
INNER SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: NEW CASTLE BAY
INNER SHELF
NEAR TURTLE ISLAND

Grannular sand. Reverse graded bedding????
OR
base of normal graded beds. unit have some pebbles.

This core shows graded bedding,usually fine sand, mostly well sorted .
Light olive gray sand 5Y 6/1.

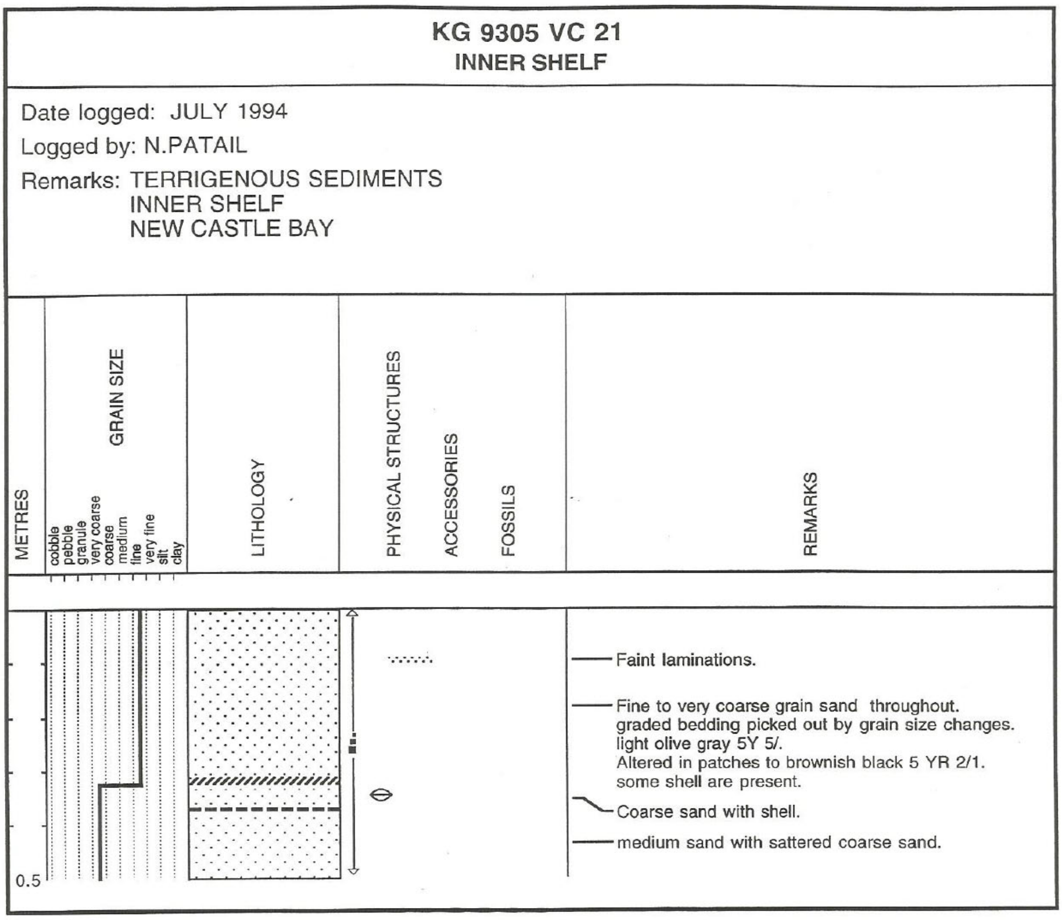
Fine sand with some oxidyzied bands of Iron (coated grains).iron gives moderate yellow 5Y 7/6 to light olive brown 5Y 5/6.

Fine sand slightly muddy .Mud patches/tubes are reduced greenish black 5GY 2/1.

coarse grain sand.

Fine sand .

Grannular sand with oxidyized base and pebbles.



KG 9305 VC 21
INNER SHELF

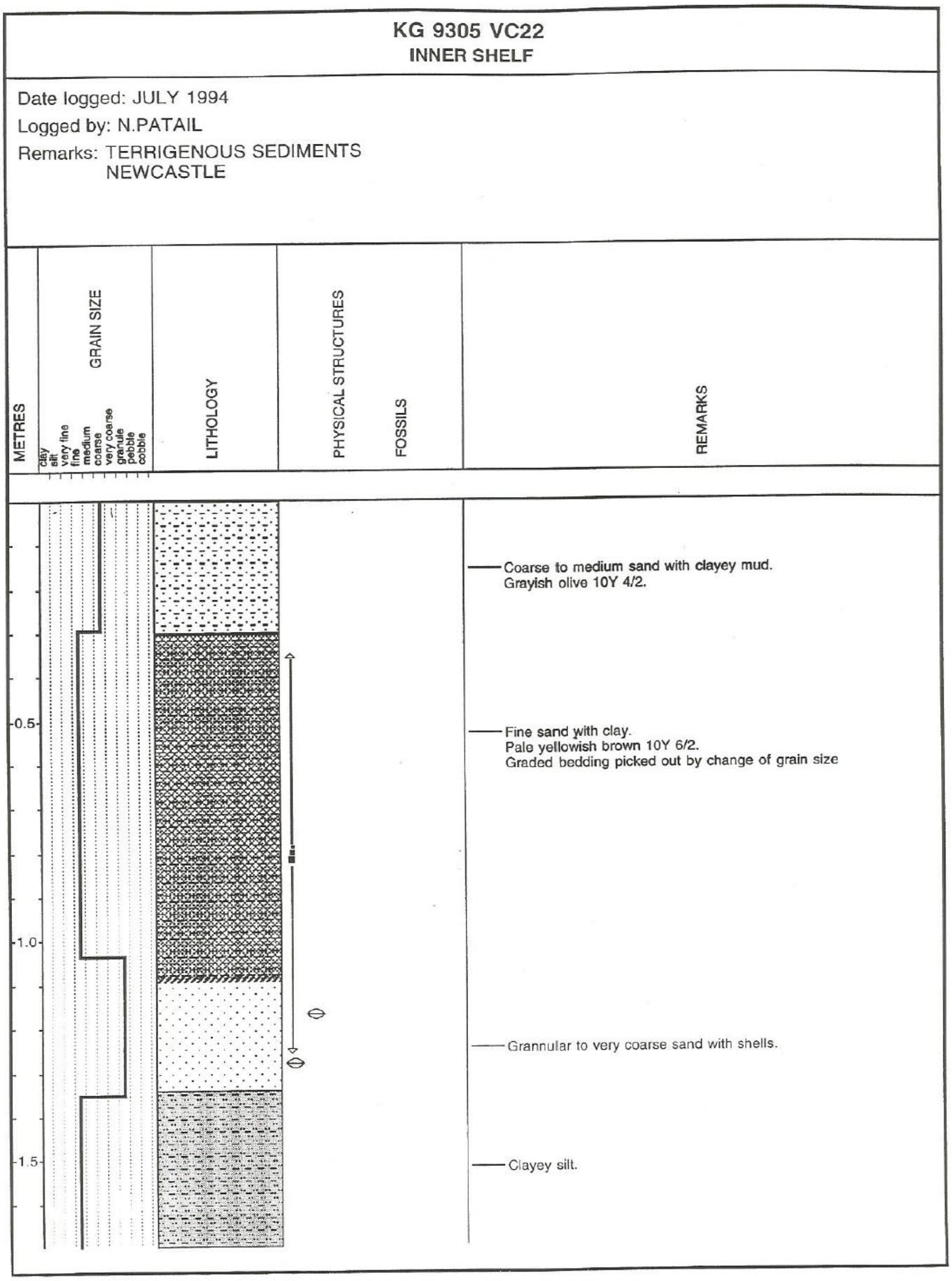
Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRIGENOUS SEDIMENTS
INNER SHELF
NEW CASTLE BAY

Faint laminations.

Fine to very coarse grain sand throughout.
graded bedding picked out by grain size changes.
light olive gray 5Y 5/.
Altered in patches to brownish black 5 YR 2/1.
some shell are present.

Coarse sand with shell.

medium sand with sattered coarse sand.



KG 9305 VC22
INNER SHELF

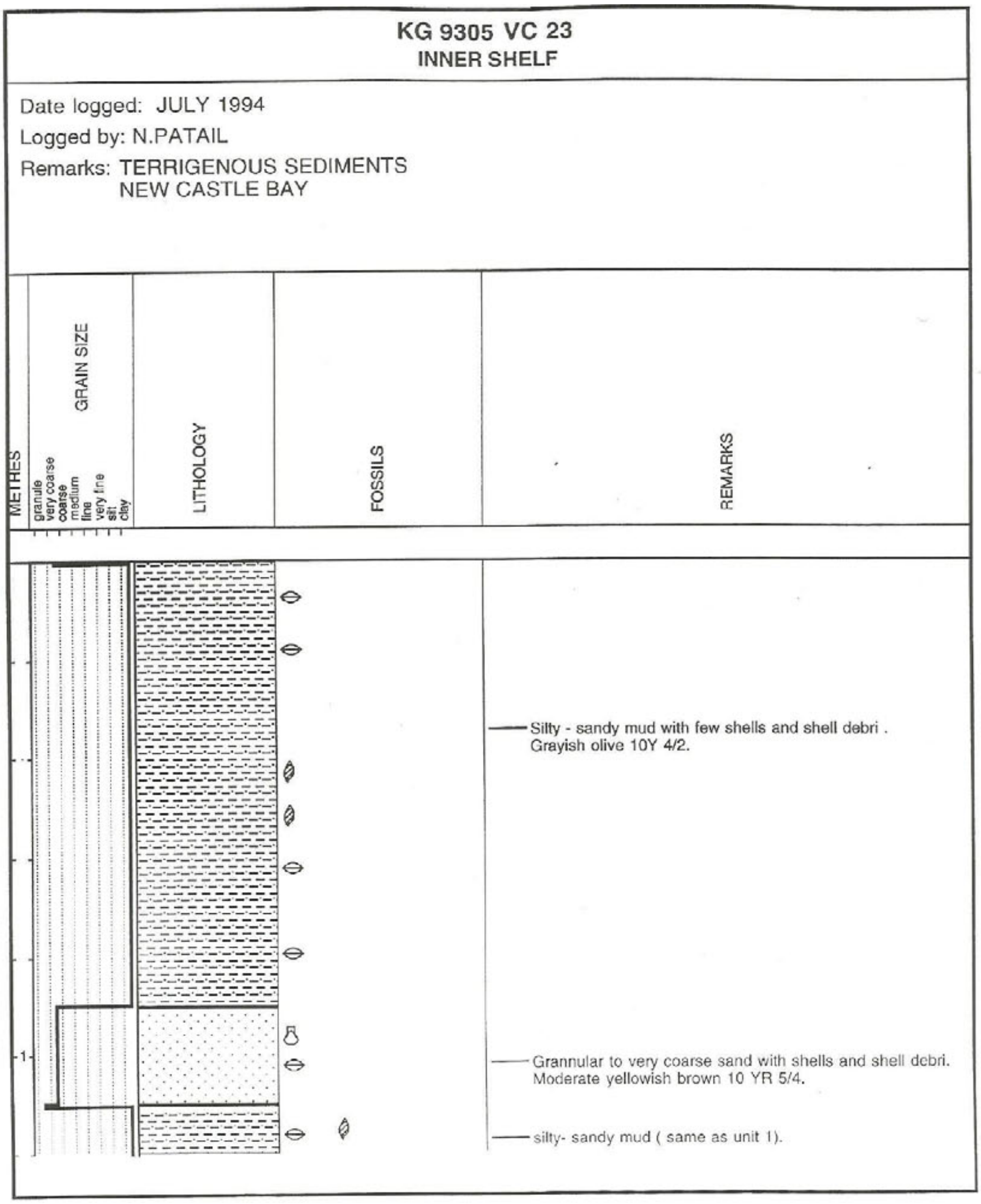
Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRIGENOUS SEDIMENTS
NEWCASTLE

Coarse to medium sand with clayey mud.
Grayish olive 10Y 4/2.

Fine sand with clay.
Pale yellowish brown 10Y 6/2.
Graded bedding picked out by change of grain size

Grannular to very coarse sand with shells.

Clayey silt.



KG 9305 VC 23

INNER SHELF

Date logged: JULY 1994

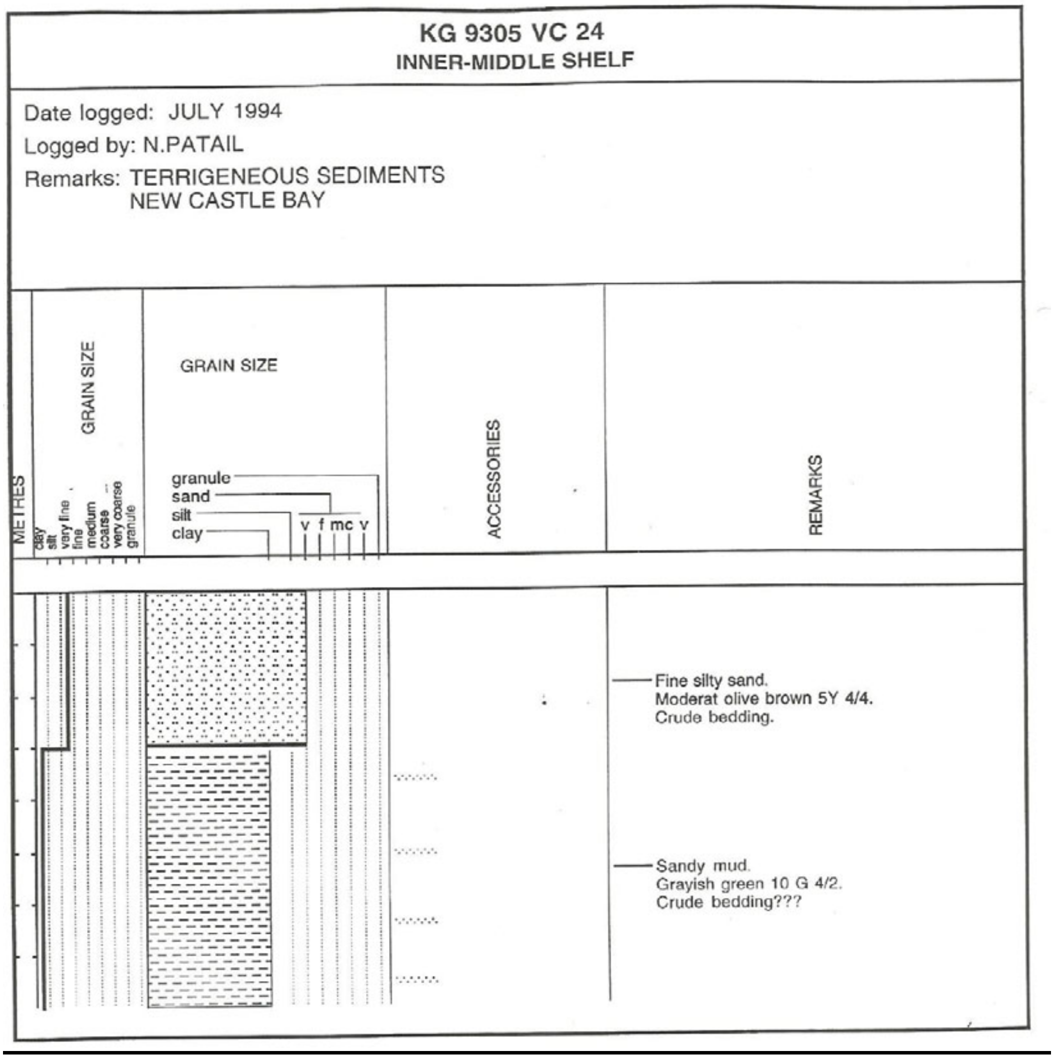
Logged by: N.PATAIL

Remarks: TERRIGENOUS SEDIMENTS
NEW CASTLE BAY

Silty - sandy mud with few shells and shell debri . Grayish olive 10Y 4/2.

Grannular to very coarse sand with shells and shell debri. Moderate yellowish brown 10 YR 5/4.

silty- sandy mud (same as unit 1).

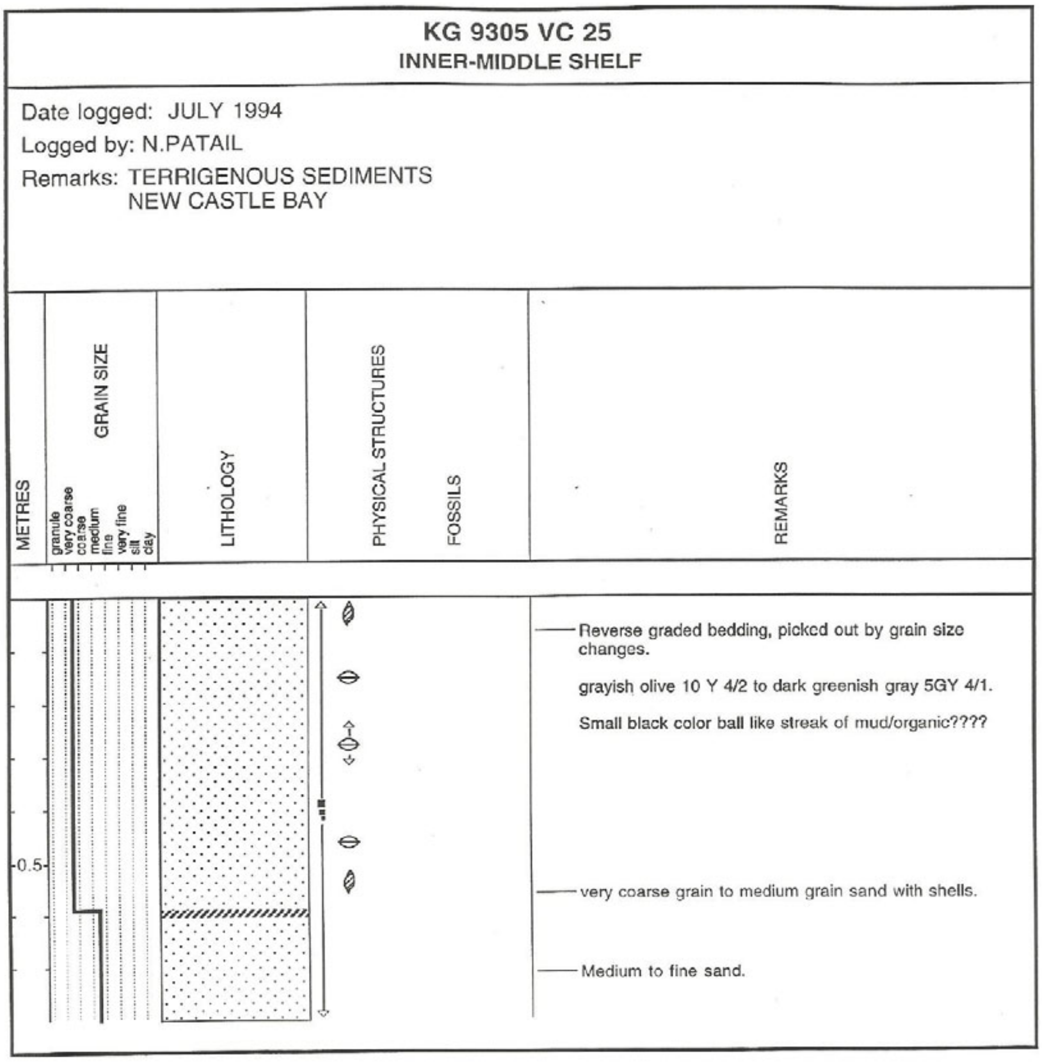


KG 9305 VC 24
INNER-MIDDLE SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRIGENEOUS SEDIMENTS
NEW CASTLE BAY

Fine silty sand.
Moderat olive brown 5Y 4/4.
Crude bedding.

Sandy mud.
Grayish green 10 G 4/2.
Crude bedding???



KG 9305 VC 25
INNER-MIDDLE SHELF

Date logged: JULY 1994
Logged by: N.PATAIL
Remarks: TERRIGENOUS SEDIMENTS
NEW CASTLE BAY

Reverse graded bedding, picked out by grain size changes.

grayish olive 10 Y 4/2 to dark greenish gray 5GY 4/1.

Small black color ball like streak of mud/organic????

very coarse grain to medium grain sand with shells.

Medium to fine sand.