Heavy minerals in marine and fluvial sediments: provenance indicators and distributions in the tropical southeastern shelf of the Gulf of Carpentaria and its hinterland North Australia

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Haredy, Rabea A, Heavy minerals in marine and fluvial sediments: provenance indicators and distributions in the tropical southeastern shelf of the Gulf of Carpentaria and its hinterland North Australia, PhD thesis, School of Earth and Environmental Sciences, University of Wollongong, 2008. http://ro.uow.edu.au/theses/263

Chapter One – Introduction

The study area includes the southeastern shelf of the Gulf of Carpentaria and its major surrounding river systems. It is located on the northeastern corner of Australia (Figure 1.1). The current research represents the first investigation of heavy minerals across the gulf region. It discusses the provenance and distribution of heavy mineral facies in the Holocene sediments within the southeastern shelf of the gulf and its surrounding river systems. This research forms part of the Geosciences Australia Survey No. 238 that studied the sedimentary environments in the southern Gulf of Carpentaria through the sedimentlogical, ^{14}C dating and geophysical analyses recorded in Heap *et al.* (2006).

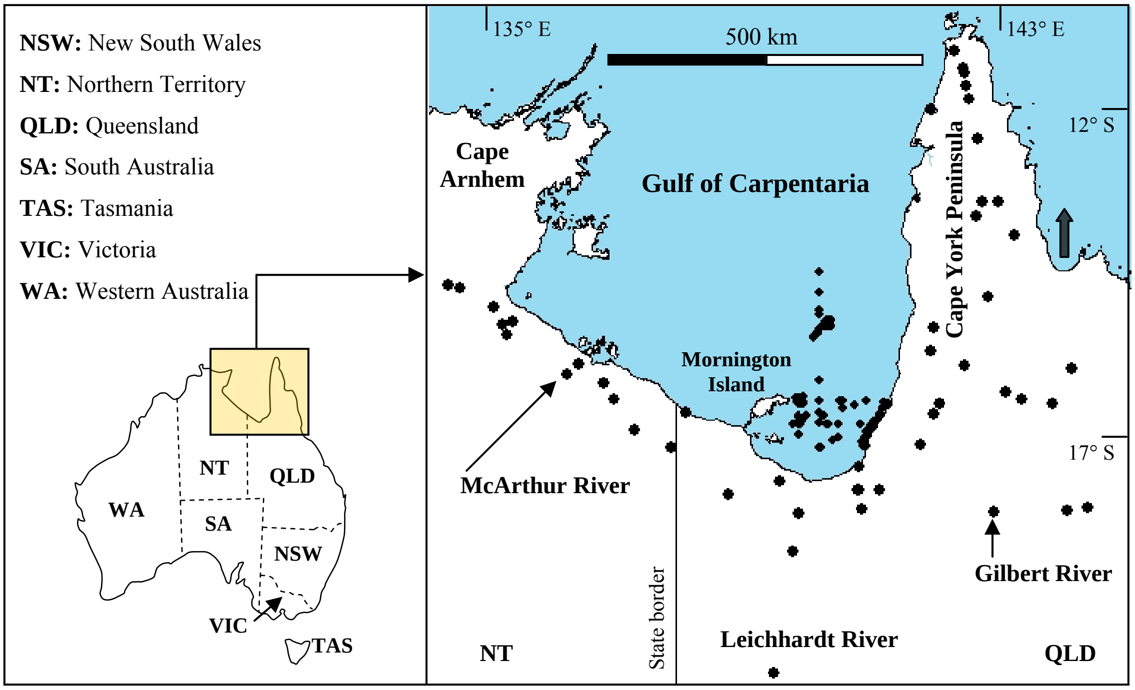

Figure 1.1 – Location of the study area and samples. See Figure 8.1 for detail hinterland lithologies and geological divisions and Appendix A (maps; pages 346-351) for detail sample locations and geographical extents.

1. 1 – Gulf of Carpentaria region: overview

The Gulf of Carpentaria is a very large shallow (< 70 m; Figure 1.2) epicontinental sea between Australia and Papua New Guinea (Torgersen *et al*., 1985; Heap *et al*., 2006; Playà *et al*., 2007; Reeves *et al*., 2007). It is a U-shaped basin lying in a tropical region between latitude 11° to 17.5° S and longitude 136° to 142° E (Othman *et al*., 1990; Burford *et al*., 1994). The greatest length of the gulf is 800 km along longitude 140° E and its greatest width is 650 km at latitude 14° 45´S (Othman *et al*., 1990), covering an area of about 500 000 km^2 (Somers and Long, 1994). However, the total area of the gulf has varied between several authors according to their definition of the northern boundary dimensions (e.g. Othman *et al*., 1990; Wolanski, 1993; Burford *et al*., 1994; Burford and Rothlisberg, 1999; Cox and Preda, 2003; Reeves *et al*., 2008). The surrounding coastline of the Gulf of Carpentaria is around 2500 km (Burford and Rothlisberg, 1999) or 1900 km, excluding shores of islands and bays (Othman *et al*., 1990).

The Gulf of Carpentaria developed, as a result of changing sea levels during the Quaternary, from a shallow land-locked basin (Lake Carpentaria) to an embayment with a northwest opening (between -40-20 m sea level) and thence to the present Gulf of Carpentaria (Jones and Torgersen, 1988). It has an entrance around 500 km wide (Jones and Torgersen, 1988; McCulloch *et al*., 1989) and is connected to the Coral Sea by the shallow, 12 m deep, Torres Strait (100 km in width) in the northeast and with the Arafura Sea by the 53 m deep Arafura Sill (200 km in width) in the northwest (Wolanski, 1993; Cox and Preda, 2003).

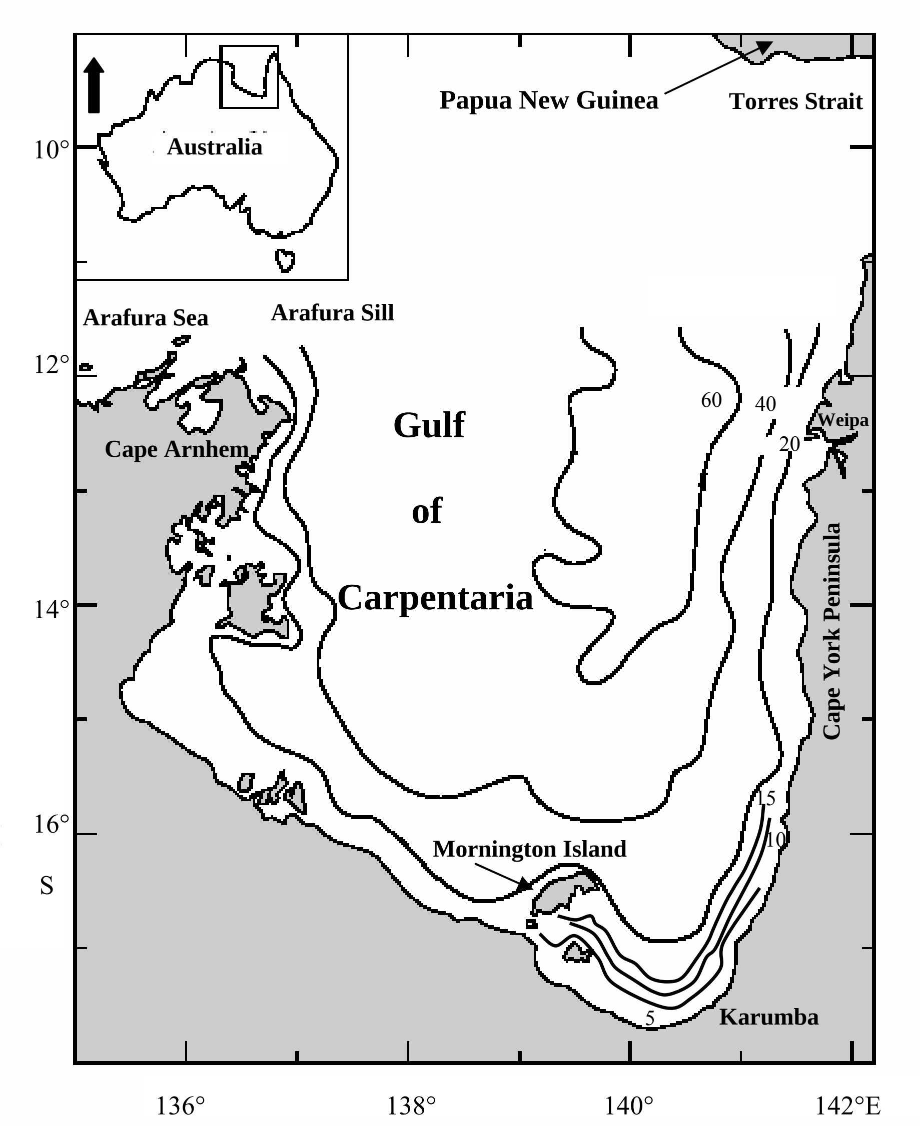

Figure 1.2 – Map showing the bathymetry of the Gulf of Carpentaria.

A total of 33 river systems drain into the Gulf of Carpentaria, transporting a large amount of terrigenous sediment to the coastal environment of the gulf, especially during the summer monsoon period (Figure 1.3; Jones *et al.*, 2003; Cendón *et al.*, 2003, 2004; Heap *et al.*, 2006; Playà *et al.*, 2007). As a result of the large fluvial input from the surrounding rivers, associated with the reworking of terrigenous sediments across the gulf floor, the southern Gulf of Carpentaria contains Australia's largest shelf province of terrigenous-dominated sediment with an average of terrigenous content of more than 50% of the surficial sediment (Figure 1.4; Heap *et al*., 2006; Harris *et al*., 2008).

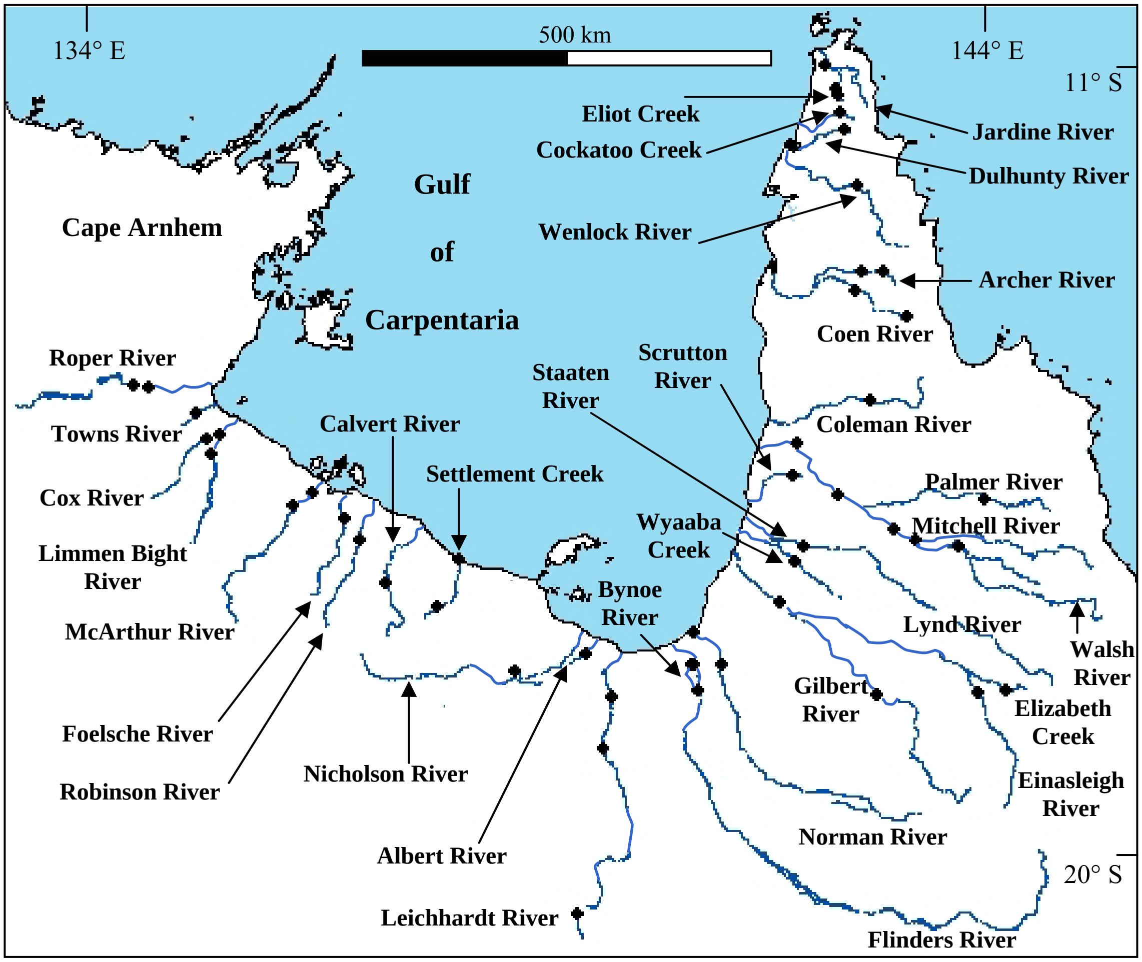

Figure 1.3 – Map shows the major water rivers around the Gulf of Carpentaria.

Please see print copy for figure 1.4

Figure 1.4 – Map showing the concentration of carbonate in the Gulf of Carpentaria, north Australia (Harris *et al*., 2008).

1. 2 – Climate

The Gulf of Carpentaria region covers three climatic zones. The northeastern part of the gulf is an equatorial savannah and most of the south and west are considered tropical savannah, with a small section of hot climate in the southern catchment area (Playà *et al*., 2007). The tropical climate in the Gulf of Carpentaria is dominated by the summer-winter monsoon cycle (Somers and Long, 1994; Burford and Rothlisberg, 1999). During the summer months (December through March) winds are predominantly rain-bearing, north-westerlies whilst their strengths increase and switch to drier south-easterlies during the winter time (May through October; Somers and Long, 1994; Burford *et al.*, 1995; Burford and Rothlisberg, 1999; Munksgaard and Parry, 2000). According to the National Climate Centre 12 months record map (May 1, 2007 – April 30, 2008; Australia Bureau of Meteorology, 2008), the general annual rainfall rate over the gulf region varies between 1200 mm and 1800 mm. However, a lower rainfall rate (600 mm – 900 mm) was recorded in the southern and southwestern coast of the gulf and a higher rainfall rate (1800 mm – 2400 mm) was recorded along the western side of the Cape York Peninsula. Tank evaporation rate is approximately 750-1000 mm per annum (Rhodes, 1982).

The maximum mean temperature varies between 30 and 36 °C whereas the minimum mean temperature varies between 18 and 24 °C with a slightly higher record (27 °C) at Cape York (values are based on a 12 month record, May 1, 2007 – April 30, 2008; Australia Bureau of Metrology, 2008). Finally, the Gulf of Carpentaria is subject to strong cyclone activities, which cause both widespread destruction (loss of seagrass and mangroves) and construction with run-off from heavy rains transporting large quantities of sediment into southern gulf coastal habitats and recharging aquifers (Royal Geographical Society of Queensland, 2008).

1. 3 – Physical oceanography

The Gulf of Carpentaria is located adjacent to the Western Pacific Warm Pool and the northern part of the gulf acts as a large high heat transfer system from the Pacific Ocean into the Indian Ocean. This generates El Niño/La Niña phases of the Southern Oscillation over the gulf region (Chivas *et al.*, 2001). During the winter time, convective overturn due to heat loss from the surface water ensures well-mixed conditions across the gulf (Church and Forbes, 1981, 1983; Forbes, 1984). Shallow coastal waters (< 30 m) are generally well mixed throughout the year with the exception of short periods after heavy rainfall and runoff, which cause significant late summer and autumn vertical stratification (Church and Forbes, 1981; Forbes, 1984; Wolanski, 1993; Somers and Long, 1994). In addition, the northern part of the gulf is well mixed and shows no vertical stratification with little or no difference between surface and bottom temperatures due to the strong influence by Torres Strait tidal flow (Figure 1.5; Forbes, 1984; Somers and Long, 1994). During the summer a significant vertical stratification of water temperature occurs in the central part of the gulf (deeper than 35 m) with a strong thermocline representing a difference between surface and bottom water of more than 5 °C (Figure 1.5; Forbes, 1984; Somers and Long, 1994).

Tides in the Gulf of Carpentaria are forced by both the Arafura Sea and the Coral Sea, and vary from semi-diurnal to fully diurnal with a remarkable response to meteorological condition fluctuations (Rhodes, 1982; Wolanski, 1993). The general tidal range observed in the gulf is 2 m (Church and Forbes, 1981), however, it reaches a high range in some coastal areas of 3.2 m at the southern end of the gulf (Karumba) and 2.4 m along the northeastern side of the gulf (Weipa; Rhodes, 1982). The semi-diurnal tides decrease rapidly as they enter the gulf, generating a first-mode Poincaré wave and trapping the energy in the northern half of the gulf (Church and Forbes, 1981; Wolanski, 1993. However, diurnal tides, consisting of a Kelvin wave, enter into the gulf from the north-west and propagate clockwise around the gulf with one central amphidromic point (Church and Forbes, 1981; Wolanski, 1993).

Please see print copy for figure 1.5

Figure 1.5 – (A) Gulf of Carpentaria temperature profile shows the differences between surface and bottom water, (B) Isotherms along a north-south transect at 139° 12 E (shading represents sea floor; November-December 1990; Somers and Long, 1994).

Significant seasonal fluctuations in sea level occur in some areas around the gulf (Forbes and Church, 1983; Wolanski, 1993). These fluctuations are controlled by the annual variations of wind, atmospheric pressure, density, river runoff and mean sea level in the Arafura Sea (Forbes and Church, 1983). The largest vertical variation range in sea level occurs at Karumba (0.5-0.75 m) in the southeastern end of the gulf (Forbes and Church, 1983; Wolanski, 1993). High values also appear along Weipa Peninsula (0.61 m) on the northeastern side and to the west (0.62 m) at Centre Island (Forbes and Church, 1983).

1. 4 – Regional Geology

The continental region surrounding the Gulf of Carpentaria consists mainly of sedimentary rocks deposited in three basins: Mesoproterozoic McArthur Basin, Mesozoic Carpentaria Basin and Cainozoic Karumba Basin (Figures 1.6 and 1.7). These basins are bordered by two major geological structures: Mt Isa Inlier to the southwest and Georgetown Inlier to the southeast. Also, the Laura Basin and Coen Inlier border the eastern margin of the Carpentaria Basin (Figure 1.6).

The Palaeoproterozoic to Mesoproterozoic McArthur Basin is exposed over an area of about 180 000 km^2 along the west and northwest coast of the Gulf of Carpentaria and is separated from the Mount Isa region by the Murphy Inlier to the southeast (Figure 1.8; Plumb *et al.*, 1980; Rawlings and Page, 1999; Rawlings, 1999; Glikson, 2001). To the north and the northwest, the McArthur Basin is bordered by older Palaeoproterozoic rocks of the Arnhem Inlier and the Pine Creek Inlier respectively (Rawlings and Page, 1999; Rawlings, 1999). Generally, the sedimentary rocks of McArthur Basin (*ca* 1815-1450 Ma) are an unmetamorphosed mixed carbonate-siliciclastic succession with minor volcanic rocks close to the base (Rawlings, 1999). Rock types in the McArthur Basin include quartz arenites, micaceous lutites, dolostone and minor mafic and felsic volcanic rocks (Logan *et al.*, 1990; Rawlings, 1999).

Please see print copy for figure 1.6

Figure 1.6 – Geological features surrounding the Gulf of Carpentaria and the sub-basins classification of the Carpentaria Basin (McConachie *et al.*, 1997a).

Please see print copy for figure 1.7

Figure 1.7 – Areal extent of Karumba Basin (McConachie *et al.*, 1997a).

The Mount Isa Block (Mt Isa-Cloncurry Province, Mt Isa Inlier or Mt Isa Geosyncline; Henderson, 1980) is defined as a polydeformed and metamorphosed block, which occurs as a result of Palaeoproterozoic and Mesoproterozoic intracontinental rifting (Giles and Nutman, 2002; Hatton and Davidson, 2004). It is exposed diagonally in a southeasterly direction in northwest Queensland (Figure 1.9). Variations in lithology, metamorphic grade, bounding faults and deformation type divide the Mt Isa block into three broad tectonic units (Figure 1.9): (1) the relatively low-grade metamorphic rocks of the Western Succession (Western Fold Belt, Lawn Hill Platform), (2) Kalkadoon-Leichhardt Belt, and (3) the deformed high-grade metamorphic rocks of the Eastern Succession (Eastern Fold Belt, Mary Kathleen Shelf; Figure 1.9; Carter *et al.*, 1961; Henderson, 1980; Blake, 1987; Blake *et al.*, 1990; Domagala *et al.*, 2000; Betts and Lister, 2002; Giles and Nutman, 2002; Hatton and Davidson, 2004). Blake *et al.* (1990) described the stratigraphy and rock types, and they subdivided the major units (Figure 1.9). The Western Fold Belt is subdivided into the Lawn Hill Platform, Leichhardt River Fault Trough, Ewen Block and Myally Shelf. The Eastern Fold Belt is subdivided into the Mary Kathleen, Quamby-Malbon and Cloncurry-Selwyn zones. A summary of the geological features and their rock types for each tectonic unit of Mt Isa Block is recorded in Table 1.1.

Please see print copy for figure 1.8

Figure 1.8 – Geological divisions of McArthur Basin (Rawlings, 1999).

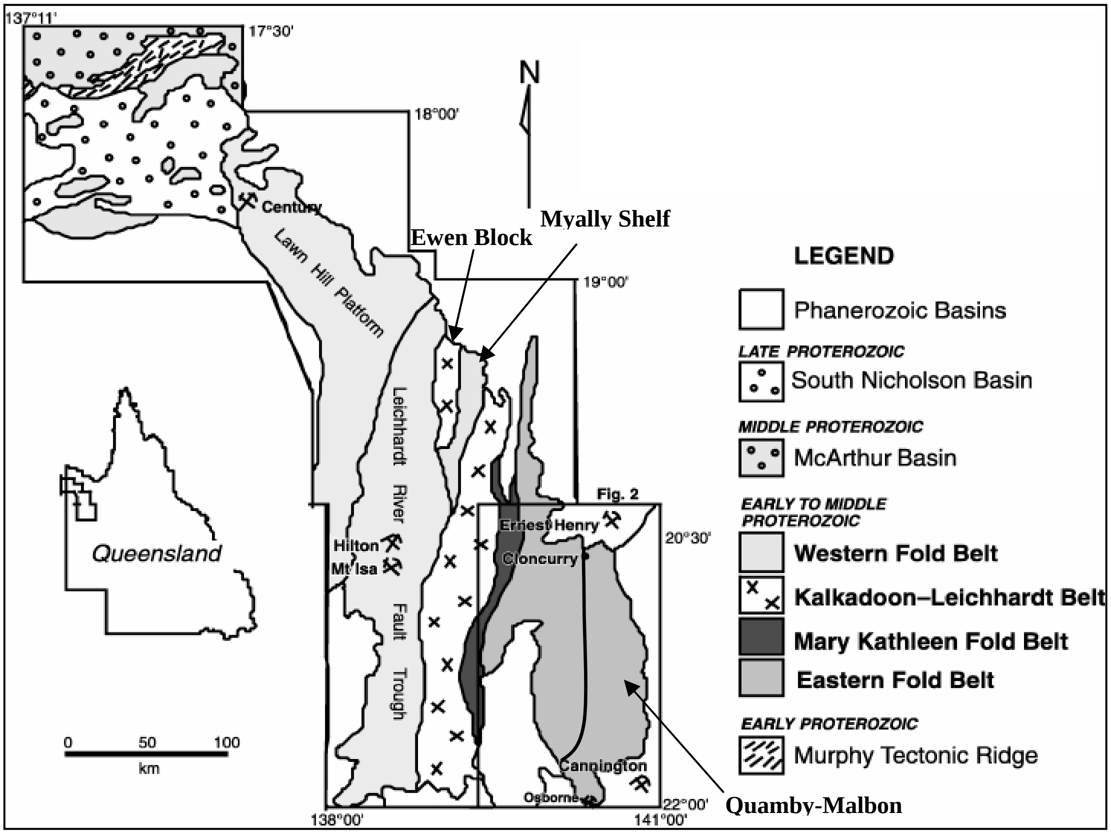

Figure 1.9 – Tectonic units of Mt Isa Block (modified from Giles and Nutman, 2002).

The Georgetown Inlier is a Palaeoproterozoic-Mesoproterozoic block, covering an area of about 25 000 km^2. It is located in the northeastern Precambrian Australian Shield and is considered to be the largest of the four main units of Precambrian rocks in north Queensland (Withnall, 1996; Withnall *et al.*, 1997, 1980; Spikings *et al.*, 2001). On the basis of stratigraphical, structural and metamorphic variations, as well as the intrusive history, Withnall *et al.* (1980) divided the Precambrian rocks of the Georgetown Inlier into three tectonic subprovinces (Figure 1.10). These units from east to west are the Greenvale, Forsayth and Croydon Subprovinces. The lithology of the Greenvale Subprovince consists of metasedimentary and felsic to mafic metavolcanic rocks, and mafic-ultramafic complexes. Rock types of this subprovince include mylonitized schist, muscovite schist, chlorite schist, actinolite schist (hornblende), amphibolite, quartzite pegmatite, phyllite and quartz-rich phyllite (Withnall *et al.*, 1980; Withnall, 1996). The Forsayth Subprovince includes strongly and multiply folded metasedimentary and metavolcanic rocks, which range in metamorphic grade from lower greenschist to granulite facies. These facies are intruded by Proterozoic and Siluro-Devonian granitoid batholiths (Withnall, 1996). Rocks of the Croydon Subprovince include mainly felsic Proterozoic volcanic rocks that are intruded by comagmatic granite and overlain by fluviatile sandstone (Withnall, 1996).

The Coen Inlier is a Proterozoic to Late Palaeozoic metamorphic and igneous rock sequence that is exposed along the northeastern side of Cape York Peninsula (Figure 1.6; Blewett *et al.*, 1997). It is bordered by the Mesozoic-Cainozoic Carpentaria and Karumba Basins to the west and the Mesozoic Laura Basin to the east (Figure 1.6). It includes six Precambrian metamorphic groups, and is intruded and overlain by mid to Late Palaeozoic igneous and sedimentary rocks (Blewett *et al.*, 1997). A summary of these groups and their rock types is recorded in Table 1.2.

Tectonic Unit	Geological units	Rock types
Western Fold Belt	McNamara Group, Mt Isa Group, Myally Subgroup, Surprise Creek Formation, Bigi Formation, Quilalar Formation, Bottletree Formation, Weberra Granite, Yeldham Granite, Big Toby Granite, Kamarga Volcanics, Fiery Creek Volcanics, Leichhardt Volcanics, Eastern Creek Volcanics, Jayah Creek and Oroopo Metabasalts, Sybella Batholith, Ewen Batholith, Mt Guide and Leander Quartzites and the basement rocks of Yaringa metamorphics	sandstone, siltstone, shale, chert, greywacke, conglomerate, carbonate, dolomite, rhyolite, porphyritic rhyolite, rhyolitic to dacitic ignimbrite, basalt, trachybasalt, tuff and felsic tuff, mafic and felsic volcanics, granodiorite, aplite, pegmatite, migmatite, feldspar phenocrysts or augen in biotite granite, porphyritic biotite, muscovite granite, hornblende granite, leucogranite, microgranite, xenoliths, greisen, quartizite, gneiss and schist
Kalkadoon-Leichhardt Belt	Mt Albert Group, Corella Formation, Argylla Formation, Makbat and Stanbroke Sandstones, Ballara Quartzite, Magna Lynn Metabasalt, Wonga Batholith, Kalkadoon Batholith, Leichhardt Vocanics, and the basement rocks of Kurbayia Migmatite and Plum Mountain Gneiss.	sandstone, siltstone, limestone, shale, greywacke, conglomerate, evaportic sedimentary rocks, carbonate, dolomite, felsic and mafic tuff, basalt, felsic volcanics, rhyolitic to dacitic ignimbrite, feldspar phenocrysts or augen, biotite and hornblende in foliated granite, porphyritic, and xenolithic granite , microgranite, leucogranite, aplite, porphyritic rhyolite, gabbro, biotite granodiorite, tonalite, monzonite, diorite, banded migmatite (metasedimentary), migmatite metadacite, metarhyolite and felsic gneiss
Eastern Fold Belt	Mt Albert Group, Mary Kathleen Group, Soldiers Cap Group, Corella Formation, Argylla Formation, Ballara Quartzite, Mitakoodi Quartzite, Marraba Volcanics, Williams and Naraku Batholiths, Wonga Batholith, and the basement rocks of Double Crossing Metamorphics.	sandstone, siltstone, limestone, shale, chert, greywacke, rhyolitic to dacitic ignimbrite, conglomerate, carbonate, calcareous breccia, banded iron formation, evaportic sedimentary rocks, mafic and felsic volcanics, basalt, tuff, non-foliated granite containing biotite, hornblende, clinopyroxene, sphene, magnetite, foliated leucocratic granite, microgranite, aplite, pegmatite, gabbro, greisen, granodiorite, tonalite, gneiss, schist, migmatite and quartzite.

Table 1.1 – Geological units and their rock types in the Mt Isa Block (based on Blake *et al.*, 1990).

Please see print copy for figure 1.10

Figure 1.10 – Tectonic units of Georgetown Inlier (Withnall, 1996).

Geological units	Rock types
Yambo Metamorphic Group	Schist, quartzite, orth- and paragneiss, amphibolite, and mafic granulite.
Newberry Metamorphic Group	Quartzite, orth- and paragneiss, amphibolite, some schist and mafic granulite.
Holroyd Metamorphic Group	Variably deformed and metamorphosed metasiltstone/sandstone, slate, phyllite, quartzite, schist, gneiss, metadolerite (greenstone) and amphibolite.
Edward River Metamorphic Group	Metasiltstone and metasandstone
Coen Metamorphic Group	Sillimanite-andalusite and sillimanite-garnet schist, quartzite, biotite-muscovite gneiss, sillimanite-garnet gneiss (rarely kyanite) and amphibolite.
Sefton Metamorphic Group	Muscovite-quartz schist, quartzite, slate/phyllite, quartz-haematite schist, magnetite, greenstone, schistose limestone, marble and calc-silicate rock.

Table 1.2 – Metamorphic groups of Coen Inlier and their rock types (based on Blewett *et al.*, 1997).

The Laura Basin is an elongate intracratonic basin of non-marine Middle Jurassic rocks that pass up into marine Early Cretaceous strata, lying on the eastern side of Cape York Peninsula (Figures 1.6 and 1.10; Henderson, 1980; McConachie *et al.*, 1997b; Marshallsea *et al.*, 2000). It was probably continuous with the Carpentaria Basin to the southwest during much of the time of basin fill and at present it is contiguous with the Carpentaria Basin across the Kimba Arch (McConachie *et al.*, 1997b; Marshallsea *et al.*, 2000). To the west, the Laura Basin overlies igneous rocks of Coen Inlier. The lithology of the Laura Basin is represented by three main units: the basal unit fluvial and deltaic Dalrymple Sandstone, the Gilbert River Formation and the uppermost marine Rolling Downs Group (McConachie *et al.*, 1997b; Marshallsea *et al.*, 2000). A summary of the rock types within these units is presented in Table 1.3.

Geological units	Rock types
Dalrymple Sandstone	Quartzose to lithic sandstone, feldspathic to quartz sandstone, claystone, siltstone, conglomerate, tuff, coal.
Gilbert River Formation	Quartz to sublabile sandstone, quartz to feldspathic clay-rich sandstone that is locally glauconitic, oolitic and calcareous, claystone, siltstone, conglomerate.
Rolling Downs Group	Shale, calcareous and glauconitic shale, siltstone, claystone, conglomerate bands.

Table 1.3 – Geological units of the Laura Basin and their rock types (based on McConachie *et al.*, 1997b).

The Carpentaria Basin is located between northern Queensland and the Northern Territory and lies beneath the Gulf of Carpentaria in offshore northern Australia (McConachie *et al.*, 1997a). It extends approximately 1000 km north to south and 650 km east to west, covering an area of 560 000 km^2 (Burgess, 1984; McConachie *et al.*, 1997a). The maximum thickness (≈ 1700 m) of the basin occurs offshore to the west of Weipa (Henderson, 1980; Burgess, 1984; McConachie *et al.*, 1997a). Differences in lithology, provenance, thicknesses and diachronism divided the Carpentaria Basin into four sub-basins (McConachie *et al.*, 1990, 1997a). The classification of these sub-basins and their lithologies are shown in Figures 1.6 and 1.11.

The intracratonic Carpentaria Basin is a Mesozoic sequence that ranges between Middle Jurassic to Early Cretaceous (Figure 1.11; Smart *et al.*, 1980; Henderson, 1980; Burgess, 1984; Passmore *et al.*, 1993; McConachie *et al.*, 1997a; Cox and Preda, 2003). Most of the basin rests on an erosional surface cut into deformed Proterozoic rocks but a small portion of the northeastern offshore part overlies pre-Jurassic sedimentary rocks (Bamaga Basin; Geosciences Australia, 2008). Much of the Carpentaria Basin succession includes both marine and fluvial sediments represented mainly by sandstones, which are interbedded with mudstone, shale and some limestone (Day *et al*., 1983; Cox and Preda, 2003). Precambrian igneous rocks of the Coen, Yambo and Georgetown Inliers occur along the eastern and southeastern border of the basin respectively (Burgess, 1984). To the west and southwest, the onshore margin of the basin is bordered by Precambrian rocks of Arnhem Block, Mount Isa Block and Proterozoic sediments of McArthur Basin (Burgess, 1984; McConachie *et al*., 1997a).

Please see print copy for figure 1.11

Figure 1.11 – Lithostratigraphy, ages and sub-basins classification of the Carpentaria Basin (McConachie *et al*., 1997a).

The Karumba Basin (Figure 1.7) is a Cenozoic sequence that ranges between Miocene to Recent and unconformably overlies most of the Carpentaria Basin (Smart *et al.*, 1980; McConachie *et al.*, 1997a; Geosciences Australia, 2008). This basin is mostly thin, recording its maximum thickness (600 m) offshore in the central part of the gulf (McConachie *et al.*, 1997a).

1. 5 – Previous research in the Gulf of Carpentaria

The Gulf of Carpentaria hosts important commercial fisheries and, therefore, numerous ecological studies (e.g. Somers, 1987; Othman *et al.*, 1990; Grant, 1994; Burford *et al.*, 1995; Burford and Rothlisberg, 1999; Salini *et al.*, 2000, 2001; Crocos *et al.*, 2001) have been undertaken in the gulf. The most recent research in the gulf investigates the discovery of the early Holocene coral reefs within the southern shelf of the gulf (Harris *et al.*, 2004, 2008). However, this section will focus on sedimentlogical, mineralogical and geochemical studies that have been conducted in the Gulf of Carpentaria.

The surficial sediments in the Gulf of Carpentaria are a mixture of mud, sand and minor gravel. Therefore, sediments were classified according to their mud content (Figure 1.12): mud (>80% mud), sandy mud (50-80% mud), muddy sand (20-50% mud) and sand (<20% mud; Somers and Long, 1994). Mud content in the surficial sediments shows an increasing pattern from southeast to northwest. High mud contents are also present in shallow (<20 m) sheltered embayments and/or around rivers in the eastern coastal area as well as all the Arnhemland coast and across the Arafura Sill (Somers and Long, 1994).

Please see print copy for figure 1.12

Figure 1.12 – Mud content as percentages in the surficial sediments of the Gulf of Carpentaria (Somers and Long, 1994).

Jones (1986) characterised the surficial sediments in the southeastern Gulf of Carpentaria. Sediments in this area are variable, ranging from gravelly sand to mud. According to the sand contents, surficial sediments were categorised into three groups: sand (>80% sand), muddy sand (50-80% sand), and sandy mud (<50% sand). Sediments with high sand contents (80%) occur adjacent to the coastal fringe in the deltaic mouth bar deposits of river systems (e.g. Gilbert and Archer Rivers). Sediments with low sand contents (<50%) occur most extensively in the Karumba region. On the basis of grain size and microscopic examination of the sand fractions, three sedimentary sand facies were identified in the southeastern Gulf of Carpentaria. (I) Fluvial delta sand; (II) fluvial prodelta sandy mud; and (III) nearshore relict sand and muddy sand. These facies are mainly controlled by the terrigenous supply, sea level fluctuations, the physical setting of the gulf and its hydrology system, biogenic productivity and substrate.

Furthermore, Jones (1986; 1987) also characterised the surficial sediments in the western Gulf of Carpentaria. The surficial sediments in this part of the gulf are quite variable in grain size and composition. According to mud contents, sediments were classified into four groups: sand (0-20% mud), muddy sand (20-50% mud), sandy mud (50-80% mud), and mud (>80% mud). Mud content in the sediments increases with increasing water depth and distance offshore. Also, similar to the southeastern part of the gulf, three sedimentary facies were identified in this area. (I) Delta and prodelta deposits fringing the coastline; (II) nearshore relict deposits (10-20 m water depth); and (III) Carpentaria continental shelf. These facies are mainly controlled by the same factors mention for the southeastern part of the gulf.

In addition, Jones and Torgersen (1988) studied the surficial sediments and the stratigraphy of subsurface sediments in the central part of the gulf. The surficial sediments in the central part of the gulf range in age between 4580-6850 ± 100 a BP. These mid-Holocene ages for the surficial sediments suggest low rates of sedimentation in the central part of the gulf. In terms of subsurface stratigraphy, Torgersen *et al.* (1985) and Jones and Torgersen (1988) reported five sedimentary facies within 25 short piston cores. The sedimentary facies in order of increasing depth in each core are: (I) marine soft green-grey sandy mud with a diverse marine fauna; (II) lacustrine dark grey mud with minor biogenic carbonate fragments; (III) lacustrine firm laminated dark grey mud to sandy mud with fine pale grey laminations; (IV) lacustrine shelly mud; and (V) subaerially weathered marine cohesive blue-grey clay to sandy clay (mottled orange). The C^{14} ages of the core facies reflect at least 35 ka of sedimentary record. The differences between the lacustrine facies indicate variations in environmental conditions during the evolution of Lake Carpentaria. Facies IV reflects a high rate of biological productivity in comparison with other units. In facies III the relative short-term monospecific foraminiferal blooms were associated with the precipitation of calcite to form the fine laminae. In addition, variations in lake levels and chemistry contribute to the formation of the laminae. The occurrence of pinpoint mottling in facies II suggests occasional short-term exposure. In summary, Lake Carpentaria developed in response to sea level changes, erosion and shallow water deposition of sediments influenced by the height of the Arafura Sill (Jones and Torgersen, 1988).

In terms of geochemical analyses of fossils, McCulloch *et al.* (1989) studied the same cores mention earlier in Jones and Torgersen (1988). This study involved the analysis of Sr ratios in ostracods preserved in the Gulf of Carpentaria sediments. Variations in $^{87}Sr/^{86}Sr$ ratios show a rapid decrease between 56 cm and 25.5 cm depths in the cores (facies II and I). This rapidly decreasing pattern corresponds with the transition from a lacustrine to a marine environment and confirmed the earlier works of Torgersen *et al.* (1985, 1988). The highest $^{87}Sr/^{86}Sr$ ratio ($\Delta Sr = 18$) was recorded at 56 cm (facies II), this value contrasted with the relatively constant ratios within the rest of facies II ($\Delta Sr = 14$; 80-140 cm). This high Sr ratio suggests an increase in the Sr isotopic composition of the continental runoff water (from northern Australia) draining into ancient Lake Carpentaria. On the basis of ΔSr values within the five sedimentary facies, McCulloch *et al.* (1989) concluded that the Arafura Sill had established a permanent marine connection with Lake Carpentaria at about

12, 000 years BP as a result of rising sea level. The highest ∆Sr value reflects a large quantity of runoff from northern Australia draining into Lake Carpentaria that may have been the result of a southward migration of monsoonal rainfall (McCulloch *et al.*, 1989).

A study by Chivas *et al.* (2001) investigated environmental changes within the ancient Lake Carpentaria using various methods of dating, biostratigraphical, geochemical and palynological analysis on six cores (4-15 m in length). Two distinctive stratigraphical facies, marine and non-marine (lacustrine) are defined by the differences in microfossil assemblages. These facies recorded radiocarbon ages of 6910 ± 80 yr (core MD-31) and 9520 ± 80 yr (core MD-28) in the fully marine facies and 10,350 ± 90 yr (core MD-31) and 14,350 ± 90 yr (core MD-28) in the upper parts of the non-marine facies. These radiocarbon ages for the cores show that the last marine transgression flooded the region at about 9700 yr BP. This value is not much different from the early estimation of 8500 yr BP for core GC-2 by Torgersen *et al.* (1988) for the same transition between the two facies. The palynological analysis indicates a very shallow lake on the western side of the gulf during the non-marine phase associated with open grasslands and swamps with sedges. Deep lake conditions on the eastern side are associated with swamps, grasses, sedges and *Typha* (Chivas *et al.*, 2001).

De Deckker (2001) evaluated the extent and timing of maximum aridity in the Gulf of Carpentaria. He reported that the maximum aridity in the Carpentaria region occurred around 21,500 cal yr BP through the recovery of aeolian quartz grains in core GC-2 (located in central eastern part of the Gulf of Carpentaria), which encompasses 40,000 cal yr BP of sedimentation. De Deckker (2001) identified that arid events occurred every

~ 2,600 cal yr between 12,000 and 25,000 yr BP in the gulf region. In an attempt to relate the Carpentaria arid events with other global climate phenomena, De Deckker (2001) found no synchroneity between the Carpentaria arid events and the last three Heinrich events in the north Atlantic, nor with southern hemisphere Chilean glacier events. However, the most arid event (21,500 yr BP) in the Carpentaria area is coeval with the maximum extent of New Zealand Taramaku 2_2 glacier. He concluded that dry and cold phases in northern Australia coincide with the New Zealand glaciations but are not related to north Atlantic climate changes.

Cox and Preda (2003) studied the relationship between surficial trace metal distribution and sediment mineralogy within the Gulf of Carpentaria. This study shows a strong affinity between the concentration of Cr, Co and Ni trace metals and the occurrence of smectite-rich mixed layer clay, which has a larger surface area, allowing higher metal adsorbent capacity than other clay species. A wide range of trace metals is found in the central and northwestern section of the gulf corresponding to the occurrence of fine-grained Fe-rich sediments. Despite the low concentration of trace metals, they present a significant regional distribution, which is most likely influenced by the geological source rocks surrounding the gulf and providing the terrigenous component of the gulf sediments (cf. Preda and Cox, 2005).

In terms of provenance studies, Munksgaard and Parry (2000) measured the Pb isotope ratios and element concentrations in the offshore sediments from the southeastern Gulf of Carpentaria (Roadstead trans-shipment area 45 km offshore between the Bynoe and Norman Rivers). They reported strong correlations between the Pb isotope ratio and Th, U and light rare-earth element concentrations, which suggest that the high $^{208}Pb/^{206}Pb$ and low $^{207}Pb/^{206}Pb$ component is monazite occurring as a detrital heavy mineral grains in the sediments. Ilmenite and zircon also are common in the heavy mineral assemblage. Differences in catchment lithologies of both the Norman and Bynoe Rivers show chemical and/or mineralogical variations, which appear in the Pb isotope ratios of the monazite. These variations of Pb isotope ratios make a clear distinction between the sediments from the two river systems. Although the monazite Pb isotope ratios of both rivers (Bynoe and Norman) are recorded in the offshore sediments, the main source of monazite in the Roadstead offshore sediments is thought to be Proterozoic S-type granitic rocks from the Georgetown Inlier in the Norman River catchment.

Also, Munksgaard *et al.* (2003) used the REE compositions of estuarine and coastal sediments as provenance indicators in north Australia (Bynoe and Norman Rivers in Gulf of Carpentaria and Adelaide and Daly Rivers west and south of Darwin respectively). High $La/Yb_{(PAAS)}$ ratios in both the Norman and Adelaide River's sediments reflect high abundance of felsic rocks in the source area (Georgetown Inlier) of the Norman River and abundant $LREE_{(PAAS)}$ enriched granitic rocks in the source area (Pine Creek Geosyncline) of the Adelaide River. In contrast, low $La/Yb_{(PAAS)}$ ratios in the Bynoe River sediments reflect the common mafic rocks in the Bynoe River catchment area (Mt Isa Inlier). Also, mineralogical data, high smectite/kaolinite ratios and low quartz content in Bynoe River sediments reflect the same source rocks.

Jones *et al.* (2003) studied the formation of two deltas (McArthur and Gilbert) around the coast of the Gulf of Carpentaria. Both deltas are located in a similar mesotidal area, but their morphologies are influenced by two main factors: the presence of bedrock and a high wave energy action. The Gilbert delta is subject to high wave action and, therefore, elongated beach ridges and cheniers were built up, restricting fluvial and tidal access to the nearshore area. On the other hand, the morphology of the McArthur delta was controlled by bedrock, which restricted the width of the delta. Also, it is protected from wave action by offshore islands, which resulted in the absence of major beach-ridge systems.

Playà *et al*. (2007) compared the geochemistry of river waters in the northern part of Cape York Peninsula (Jardine, Dulhunty and Wenlock Rivers; Figure 1.3) with the gypsum laminas in the sub-surface sediments of the ancient Lake Carpentaria within the northeastern shelf of the gulf (core MD-32). They reported significant continental influence on marine-derived precipitates (gypsum laminae) within the offshore core sediments in the northeastern shelf of the gulf. The Sr concentrations in the modern northern Cape York river waters are low ranging from 2 to 15 ppb, recording an average ^{87}Sr/^{86}Sr ratios of 0.7148 (Cendón et al., 2003, 2004). This value is more radiogenic than the world average riverine inputs (0.7119; Palmer and Edmond, 1989) and that of modern marine values (0.7092; Elderfield, 1986 cited in Playà *et al*., 2007). The low Sr concentration in the northern Cape York rivers is attributed to a high continental fluvial supply that likely produces the ^{87}Sr/^{86}Sr ratio values (0.7093-0.7098) observed in the gypsum within the northeastern shelf of the gulf.

Finally, the previous studies in the Gulf of Carpentaria cover a wide range of different scientific disciplines (e.g. Cox and Preda, 2003; Reeves, 2004; Holt, 2005; Preda and Cox, 2005; Reeves *et al*., 2007, 2008). However, little is known about the mineralogical composition of the marine and riverine sediments in relation to their provenance, especially the heavy minerals that have never been discussed in previous research. Therefore, the present study presents a detailed mineralogical investigation of sediment in the southeastern shelf of the Gulf of Carpentaria and its surrounding river systems.

In this thesis the integration of sediment textural analyses and geochronology with high resolution heavy mineral analyses, including their spatial distribution, petrography and geochemistry, provide essential information on the mineralogical composition of marine and fluvial sediments in the southeastern shelf of the Gulf of Carpentaria and its surrounding river systems. This research leads to an important understanding of the Holocene sources and sinks of terrigenous sediments in the southeastern shelf of the gulf. As a result, it increases knowledge on the geological evolution of the Gulf of Carpentaria as the largest modern example of a tropical shallow epicontinental sea and broadly helps in understanding the evolution of the northern Australian margin as one of the largest tropical shallow shelf regions on Earth.

1. 6 – Thesis objectives

(I) To characterise the mineralogical components of the surface and sub-surface sediments of the southeastern shelf of the Gulf of Carpentaria and its surrounding main river systems, in order to understand the distribution pattern of the mineralogical facies.

(II) To trace the provenance of the heavy minerals.

(III) To discuss the spatial heavy mineral distributions in relation to sediment sources, and physical riverine and marine processes during the Holocene.