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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Chapter Nine – Spatial distribution of heavy minerals

In total 17 different translucent heavy mineral types were identified in the southeastern shelf of the Gulf of Carpentaria and its surrounding river sediments. Although, several authors have previously discussed the sedimentology, stratigraphy, geochemistry and geomorphology of the Gulf of Carpentaria region (e.g. Torgersen *et al.*, 1985, 1988; Jones, 1986, 1987; Jones and Torgersen, 1988; McCulloch *et al.*, 1989; Nanson *et al.*, 1991. 1993, 2005; Jones *et al.*, 1993, 2003; Somers and Long, 1994; Jackson *et al.*, 2000; Page *et al.*, 2000; Chivas *et al.*, 2001; Forsyth and Nott, 2003; Heap *et al.*, 2006; Reeves *et al.*, 2007; Jones *et al.*, 2008), no previous investigation of the heavy mineral distributions and facies were addressed.

This chapter discusses the spatial distribution of the common translucent heavy minerals including zircon, tourmaline, epidote, hornblende, sillimanite and garnet in the four surficial sedimentary areas of the southeastern shelf of the Gulf of Carpentaria and its surrounding river sediments within the six geological divisions. Other translucent heavy minerals including rutile, andalusite, staurolite, kyanite, titanite (sphene), spinel, augite, titanaugite, chlorite, biotite and glauconite will not be discussed due to their non-significant minor and/or very rare occurrence (see Chapter Five and Appendix B).

Although, the sub-surface concentrations of heavy minerals were determined, the spatial distribution of these heavy minerals in core sediments is complicated by the intermixing of individual heavy minerals from the broad range of lithologies in the gulf hinterland, associated with other factors mentioned below. However, the concentrations of heavy minerals show a reasonable distribution within the sub-surface heavy mineral facies (see Chapter Ten).

The ultrastable minerals (zircon and tourmaline) show very high average contents in the heavy mineral assemblages of the modern river sediments derived from the Helby Beds and McArthur Basin divisions (95% and 92%, respectively; Figures 5.5 and 5.12; Tables 5.9, 5.13 and 9.1). This very high average abundance is attributed to the provenance. River sediments in these two divisions drain a wide range of sedimentary successions (Figure 8.1; Tables 8.1 and 8.6). The denudation of these sedimentary rocks under the monsoonal climate conditions contributes sediments and reworked ultrastable heavy minerals to river systems in the Helby Beds and McArthur Basin divisions. In general, the common occurrence of zircon and tourmaline in sedimentary successions is associated with their high stability level (Tables 2.3 and 2.4) and explains the overwhelming dominance of ultrastable minerals in river sediments within the above divisions (Morton, 1985; Mange and Maurer, 1992; Li *et al.*, 2004; Link *et al.*, 2005; Mange and Otvos, 2005; Morton *et al.*, 2005; Morton and Hallsworth, 2007; Nascimento *et al.*, 2007; Kutterolf *et al.*, 2008).

In contrast, the total average concentrations of ultrastable minerals (zircon and tourmaline) display very low concentrations in river sediments derived from the Georgetown Inlier (13%; Table 9.1), they are moderate in river sediments derived from the Coen Inlier-Carpentaria Basin and the mixed source division of the Georgetown-Mt Isa Inliers-Great Australia Basin (45% and 39% respectively; Table 9.1) and moderate to high in the Mt Isa Inlier division (53%; Table 9.1). The significant lithological changes in river catchments around the gulf hinterland is the main factor influencing the heavy mineral assemblages between river systems within the six geological divisions (Figure 8.1; Tables 8.1, 8.2, 8.3, 8.4, 8.5 and 8.6).

Although the average concentrations of zircon and tourmaline decreased in the above four divisions in comparison with the Helby Beds and McArthur Basin divisions, they are concentrated in some river systems (Appendix B). The occurrence of sedimentary strata around the sample locations and their upstream river catchments in the Wenlock River, Staaten River and Wyaaba Creek from the Coen Inlier-Carpentaria Basin division, the Norman River-upstream from the mixed source division of the Georgetown-Mt Isa Inliers-Great Australia Basin, and the Albert and Nicholson Rivers from the Mt Isa Inlier division, increases the concentration of zircon and tourmaline in these samples in comparison with other rivers in the same division (Figure 8.1; Tables 8.2, 8.3, 8.4, 8.5 and 9.2; Appendix B).

In addition to the provenance-induced variability, the differences in heavy mineral assemblages between river sediments could be explained by hydraulic sorting associated with grain properties and sample location, whereby the smaller dense grains (e.g. zircon) remain as lag material in areas of low current velocity (e.g. channel margins; Figure 9.1A; Appendix B; cf. Padmalal *et al.*, 1998; Haredy, 2003). Also, the behaviour of fine grains of greater densities is to hide in voids between larger grains where they are shielded from stream flow (Fletcher and Loh, 1996). Further, the heavy minerals of higher density are difficult to entrain and transport by wave and current action. Hence they also form lag deposits within the delta and beach sands. As a result, the Wenlock River delta sample is characterised by a very high ultrastable minerals content, low sillimanite and a subordinate amount of hornblende and epidote (We2 in the delta of Wenlock River; Figure 9.1B; cf. Frihy *et al.*, 1995; Frihy, 2007).

	Geological divisions of river systems around the Gulf of Carpentaria					
Common translucent heavy minerals	**Division A** (Helby Beds) **(n=5)**	**Division B** (Coen Inlier-Carpentaria Basin) **(n=16)**	**Division C** (Georgetown Inlier) **(n=4)**	**Division D** (Georgetown-Mt Isa Inliers-Great Australia Basin) **(n=6)**	**Division E** (Mt Isa Inlier) **(n=5)**	**Division F** (McArthur Basin) **(n=13)**
Zircon	67.1	26.9	2.1	21.6	18.3	53.4
Tourmaline	27.4	18.4	11.2	17.7	34.4	37.4
Epidote	0.8	16.7	26.9	31.4	19.1	3.5
Hornblende	0.3	17.9	27.9	10.1	22.2	3.1
Sillimanite	0	7.6	0.3	1.3	0.2	0.5
Garnet	0.1	2.8	4.2	8.1	0.4	0

Table 9.1 – Average concentrations as number percentages of the common heavy minerals in the translucent heavy mineral fraction within the six geological divisions around the Gulf of Carpentaria.

River/Creek Name	Sample Number	Total concentration of zircon and tourmaline
Wenlock River	We1	78
	We2	93
Staaten River	St1	66
Wyaaba Creek	Wy1	59
Norman River	No1	68
Albert River	Al1	77
Nicholson River	Ni 1	92

Table 9.2 – Total zircon and tourmaline concentrations as number percentages of the translucent heavy mineral fractions in Wyaaba Creek and the Wenlock, Staaten, Norman, Albert and Nicholson Rivers around the Gulf of Carpentaria.

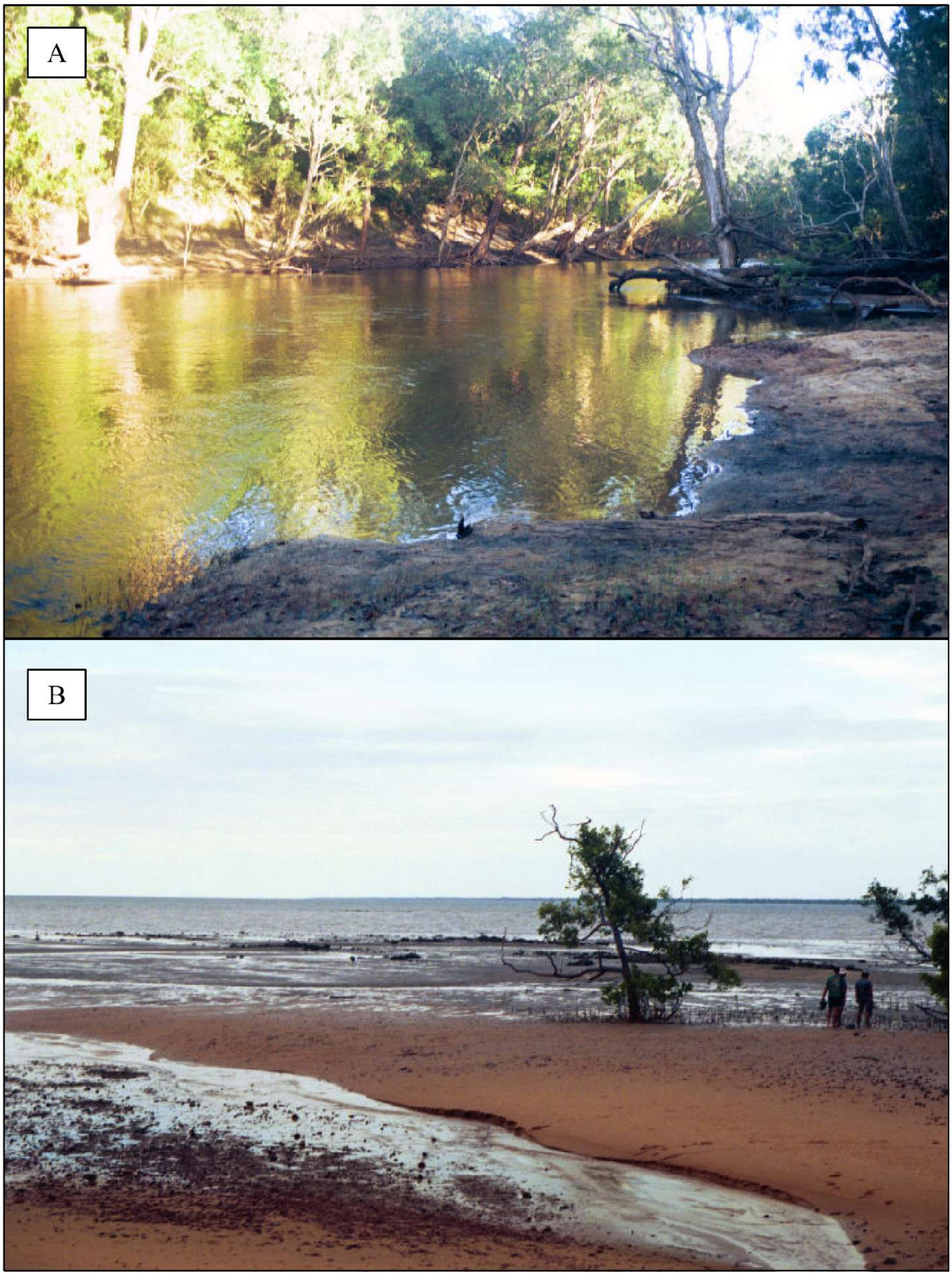

Figure 9.1 – River photographs show the general sample locations of (A) Wenlock River-upstream (at Moreton Telegraph Station, We1 collected from the channel margin) and (B) Wenlock River-downstream (We2 collected from the delta at port Musgrave). Photos were taken in April-May, 2004.

The uncommon occurrence of epidote, hornblende, sillimanite and garnet in the sedimentary source rocks of the Helby Beds and McArthur Basin divisions resulted in very minor abundance of these minerals in their river sediments (Figures 5.24, 5.32, 5.38 and 5.42; Tables 5.25, 5.29, 5.33 and 5.37 and 9.1). The scarcity of epidote, hornblende, sillimanite and garnet in the sedimentary deposits of the Helby Beds and McArthur Basin indicates low abundance in the adjacent parent rocks associated with their low stability level, especially hornblende and epidote, as they cannot survive reworking and weathering processes in comparison with zircon and tourmaline (Tables 2.3, 2.4).

The combined effect of tidal currents and wave action (relatively low hydrodynamic energy level) associated with the platy habit of hornblende and low density of both epidote and hornblende, means that these minerals were transported from the nearshore sand in the gulf into the estuary of Settlement Creek through Tully Inlet, increasing the concentration of hornblende and epidote in the estuarine sample (Se2; Figure 9.2; see Appendix B; cf. Minnamurra estuary in the south coast of New South Wales recorded in Haredy, 2003). As a result, the average concentration of hornblende and epidote in the McArthur Basin division is higher in comparison to the Helby Beds division (Table 9.1). A similar enrichment mechanism also occurs in the Norman River Estuary within the mixed source division of the Georgetown-Mt Isa Inliers-Great Australia Basin (sample No2 at Karumba Point; Appendix B).

Figure 9.2 – Photographs (A) Settlement Creek estuary at Tully Inlet and (B) the Wollogorang Beach 300 m east of Tully Inlet along the southwestern coast of the Gulf of Carpentaria. Photos were taken in April-May, 2004.

As hornblende and epidote are the least stable minerals within the common heavy mineral suite in the Gulf of Carpentaria, their concentration may decrease as a result of chemical weathering and physical abrasion. However, the effects of strong chemical weathering under the humid climate conditions over the gulf region (Nanson *et al.*, 2005) are suppressed and further diluted by the high rate of monsoonal river runoff that rapidly transports detritus and sediments into the gulf along these rivers (Erskine *et al.*, 2005; Hamilton and Gehrke, 2005; Jones *et al.*, 2008). Such a mechanism minimises the mineral residence time in the alluvial storage and thus reduces the effects of chemical weathering (Johnsson *et al.*, 1991; Morton and Hallsworth, 1999). The overall low feldspar weathering index supports the weathering-limited conditions, whereby the transportation processes are faster than the weathering rate (Appendix D).

In terms of physical abrasion during transportation associated with hydraulic sorting based on shape and density, hornblende concentrations are likely to decrease in some long river systems, such as the Mitchell River system (that incorporates the Lynd and Walsh Rivers) from the Coen Inlier-Carpentaria Basin division, Gilbert River from the Georgetown Inlier division, the Norman and Flinders Rivers from the mixed source division of the Georgetown-Mt Isa Inliers-Great Australia Basin and the Leichhardt River from the Mt Isa Inlier division (Figure 5.32; Appendix B; cf. Ladin *et al.*, 1978; Morton and Hallsworth, 1999; Rimington *et al.*, 2000; Komar, 2007). However, the common availability of hornblende-rich sources, especially igneous rocks, around the sample localities and in the upstream catchments of the Leichhardt, Gilbert and Mitchell River systems (Figure 8.1; Tables 8.2, 8.3 and 8.5) increases the average hornblende concentrations in their divisions. The Georgetown Inlier division shows the highest average hornblende content and the lowest average zircon and tourmaline contents around the Gulf of Carpentaria (Figures 5.5. 5.12 and 5.32; Tables 5.9, 5.13, 5.29 and 9.1; Appendix B; cf. Silva and Vital, 2000; Vital and Guedes, 2000; Mange and Otvos, 2005; Gonzalez *et al.*, 2007).

Similarly, the high average epidote contents in river sediments derived from the Georgetown Inlier, Mt Isa Inlier and the mixed source division located between the two inliers, is attributed to the provenance (Figure 5.24; Tables 5.25, 8.3, 8.4, 8.5 and 9.1). In general, epidote in river sediments derived from the Coen Inlier-Carpentaria Basin division shows a low concentration with no great variation within this division, pointing to low epidote in the source area. However, epidote displays a relatively high abundance in the Palmer River (38.8%; Appendix B) in comparison with other river sediments in this division. This high concentration indicates the presence of epidote-rich source rocks in the catchment of the Palmer River. A large exposure of gneiss occurring near the sample location along the bank of the Palmer River in the southern Coen Inlier confirms this deduction (Figures 8.1 and 8.2; Table 8.2).

Sillimanite and garnet show the lowest concentrations in comparison with zircon, tourmaline, epidote and hornblende in the gulf hinterland (Figures 5.38 and 5.42; Tables 5.33, 5.37 and 9.1). The abundance of these minerals is mainly controlled by the provenance. The highest average sillimanite concentration around the gulf occurs in the Coen Inlier-Carpentaria Basin division, especially in river sediments draining the northern Coen Inlier, including the Coen River-downstream and Coleman River, reflecting the presence of a high grade metamorphic source (Figure 5.38; Tables 5.33, 8.2 and 9.1; see Appendix B and Chapter Eight). Also, the highest average garnet content in the gulf hinterland appears in the mixed source division of the Georgetown-Mt Isa Inliers-Great

Australia Basin, followed by the Georgetown Inlier division (Figure 5.42; Tables 5.37 and 9.1). The significant garnet abundance in these two divisions indicates that their metamorphic source rocks are garnet-rich in comparison with other metamorphic rocks around the Gulf of Carpentaria (Tables 8.3 and 8.4; Appendix B).

In the southeastern shelf of the Gulf of Carpentaria, the heavy mineral assemblage in the nearshore area between Accident Inlet and the Gilbert River mouth shows the lowest average concentration of ultrastable minerals (zircon and tourmaline) and highest average contents of hornblende, epidote and garnet (Figures 5.5, 5.12, 5.24, 5.32 and 5.42; Tables 5.7, 5.11, 5.23, 5.27, 5.35 and 9.3). The formation of such a heavy mineral assemblage in the nearshore area is attributed to the provenance in association with the nature of the environment. Shallow marine areas act as sediment traps and deposition occurs in bands around river mouths (Preda and Cox, 2005). The nearshore zone in the study area is very shallow (< 7 m) and mainly receives terrigenous sediments from river systems that drain the Georgetown Inlier division (approximately 40% of the fluvial sediments are trapped in gulf coastal zones; Heap *et al.*, 2006; see figures 13 and 15 in Jones *et al.* (2003, pp.32-34) that illustrated the sediment accumulation in the nearshore areas of Accident Inlet and Gilbert River mouth. The heavy mineral assemblages of rivers draining the Georgetown Inlier division show the lowest average zircon and tourmaline contents in the gulf hinterland, but are rich in epidote and hornblende and have common garnet (Figures 5.5, 5.12, 5.24, 5.32 and 5.42; Tables 9.1 and 9.3; cf. Jones *et al.*, 2008).

In contrast, the increased zircon and tourmaline concentrations in the Bryomol Reef sediment (area C; Figures 5.5 and 5.12; Table 9.3) is accredited to the effect of several cycles of sea level change that likely formed the elevated rugged platform of the Bryomol Reef area (Figure 4.2C; see seismic data in Heap *et al.*, 2006) associated with differences in hydrodynamic behaviour and stability level of heavy minerals (see section *10.2.1.3* in Chapter Ten for details). During the last glacial sea level regression (Reeves, 2004; Holt, 2005; Reeves *et al.*, 2007), surface sediments on the southeastern shelf of the Gulf of Carpentaria were exposed to subaerial weathering processes (Heap *et al.*, 2006). Therefore, metastable minerals were gradually decreased or removed according to their level of stability (e.g. hornblende and epidote; Tables 2.3 and 2.4). Further, the post-glacial transgression reworked, abraded and redistributed sediments across the floor of the gulf (Chivas *et al.*, 2001; Reeves, 2004; Holt, 2005; Heap *et al.*, 2006). During sediment reworking, selective sorting processes concentrated ultrastable heavy minerals in the Bryomol Reef area (e.g. zircon and tourmaline).

In addition, ultrastable heavy minerals are often small dense grains, except for tourmaline, which is a larger and less dense grain in comparison with zircon and rutile (Mange and Maurer, 1992). Therefore, they are difficult to entrain and transport by wave and current actions in comparison with other less dense and larger platy heavy mineral grains (e.g. hornblende and epidote; Frihy *et al.*, 1995; Frihy, 2007). As a result of the clockwise circulation within the Gulf of Carpentaria, associated with the rugged seabed in the Bryomol Reef area, larger and less dense heavy mineral grains are entrained and transported away, leaving lag deposits of small dense grains along the troughs between the curved and linear ridges in the Bryomol Reef area (Figure 4.2C; see seismic charts in Heap *et al.*, 2006). Further, the increased overall gravel concentration in the Bryomol Reef area (Figure 4.3 C) enhanced the ability of high density fine grains to hide in voids between coarser grains and thus be sheltered from current transportation (Slingerland, 1984; Slingerland and Smith, 1986; Fletcher and Loh, 1996; Carling and Breakspear, 2006).

Common translucent heavy minerals	**Nearshore area between Accident Inlet and Gilbert River mouth (n=25)**	**Middle area of the southeastern shelf of the gulf (n=31)**	**Bryomol Reef area east of Mornington Island (n=36)**	**Northern reefs area of the southeastern shelf of the gulf (n=36)**
Zircon	11.4	17.2	26.0	17.3
Tourmaline	19.5	21.8	23.1	17.8
Epidote	36.8	33.0	30.1	21.7
Hornblende	18	6.3	4.9	5.2
Sillimanite	4	7.1	1.5	6.9
Garnet	2.4	3.2	1.5	1.7

Table 9.3 – Average concentrations as number percentages of the common heavy minerals in the translucent heavy mineral fraction within the four surficial sedimentary areas of the southeastern shelf of the Gulf of Carpentaria.

As tourmaline grains are less dense and typically coarser in comparison to zircon and rutile, they were more likely to be entrained within the shelf dispersal system, and thus tourmaline shows very minor concentration differences between the four sedimentary areas of the southeastern shelf of the Gulf of Carpentaria (Figure 5.12; Tables 5.11 and 9.3; Appendix B; cf. Riech *et al.* 1982; Haredy 2003). Further, hornblende as a platy mineral tends to be hydraulically equivalent to smaller quartz grains (Morton and Hallsworth, 1994) and thus, hornblende grains were easily entrained into the shelf dispersal system (Vital and Guedes, 2000). Therefore, they were transported from the high energy areas, including the Bryomol Reef area and the northern area (see the formation of heavy mineral facies for detail discussion in Chapter Ten).

Also, in addition to the hydrodynamic regime of the gulf that is characterised by clockwise tidal circulation and tropical cyclones, the selective chemical decomposition and hydraulic fractionation during the last glacial regression and subsequent transgression, mentioned earlier, decreased the concentrations of hornblende and epidote in the northern reef area and the middle area of the southeastern shelf of the gulf. However, epidote shows a slightly higher concentration in the western margin of the middle area of the SE shelf. The relatively high abundance of epidote in this area is attributed to the dominance of terrigenous sediments in fluvial palaeo-channels that were identified by Heap *et al.* (2006) in this part of the gulf, associated with hydrodynamic conditions and the relative stability of epidote in comparison to hornblende (Figure 5.24; Tables 5.23 and 9.3; Appendix B, see seismic data in Heap *et al.*, 2006 and the formation of heavy mineral facies in Chapter Ten).

The high abundance of garnet and sillimanite in the middle area of the southeastern shelf of the gulf is attributed to their relative high stability level in comparison to hornblende and epidote. Also, tropical cyclones and/or large storm events are likely to participate in concentrating sillimanite in the northern reef area (Figure 5.38; Tables 5.31 and 9.3). Nearshore terrigenous sediments rich in metamorphic aluminum silicates were probably suspended during cyclones or large storm events and transported southwest by clockwise tidal circulation pattern from the nearshore area between Archer Bay and Coleman River Inlet into the northern reef area. This nearshore area receives fluvial sediments from the Coen Inlier-Carpentaria Basin division where the heavy mineral assemblages show the highest average sillimanite content in the Gulf of Carpentaria hinterland (Figure 5.38;

Tables 5.33 and 9.1; Appendix B; see the formation of heavy mineral facies in Chapter Ten for more explanation).

In conclusion, the spatial distribution of heavy minerals in the southeastern shelf of the Gulf of Carpentaria and its surrounding river sediments is influenced by several factors including the provenance, rate of fluvial supply in relation to the monsoon cycles, embayments and river morphology, marine regressions and subsequent transgressions during the Quaternary period, littoral dynamics, longshore drift processes, current regime, cyclone activities and hydraulic sorting processes in relation to the physical properties of the minerals. The combined influence of the above factors forms distinct heavy mineral facies in the Gulf of Carpentaria hinterland and its southeastern shelf (see the following chapter).