



Geological and Exploration Models of Beach Placer Deposits, Integrated from Case-Studies of Southern Australia



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ABSTRACT

The processes leading to the formation of beach placer deposits generally begin inland and terminate at the coast, including source rocks being weathered, eroded and then transported by streams and rivers to the coast, where the sediments are deposited in a variety of coastal environments. The coastal sediments are reworked by the action of waves, tides, longshore currents and wind, which are effective processes for sorting the mineral grains based on differences in their size and density, resulting in laminated or lens-shaped packages of sediments up to tens of meters thick that are rich in heavy minerals. Detailed studies of sedimentary basins, as well as peripheral (paleo-)valleys that drained sediment source areas, are important tools in the exploration for heavy mineral resources. Knowledge of the (paleo-)basin, associated valley architecture and the source of heavy minerals concentrated in the shorelines and valleys are useful guides to the potential for, and location of, economic deposits. Evidence from sedimentology can be combined with that from other geological and geophysical characteristics to arrive at a general reconstruction of basin and paleovalley architecture and depositional environments. Complex paleogeography of the shorelines can influence or determine the sites of heavy mineral concentration. Heavy mineral sands tend to concentrate in certain shoreline settings during storm activity. Repeated storm erosion and reworking over centuries (e.g., the southeastern coast of Australia) or millennia (e.g., the Eucla and Murray Basins of Australia) can progressively enrich heavy mineral sand deposits. Preservation of these deposits over a geological timeframe of millions of years can ensue through subsidence of coastal sediments, and during sea-level change that results in either shorelines migrating inland (marine transgression) or seaward (marine regression), potentially burying or stranding earlier deposits or reworking them to form younger deposits. Refinements in remote sensing and geophysical techniques, data processing, sedimentology and computer-aided interpretations provide effective, economic and efficient methods for modeling coastal reconstructions and for exploring provinces and terrains prospective for heavy mineral sand deposits. Landscape topography analysis, combined with geophysical methods that can resolve physical property contrasts between the shoreline sediments and underlying sequences, are increasingly used in mineral exploration to locate and to reconstruct paleoshorelines and paleovalleys.

Australia has modern and ancient beach-placer deposits, both of which show many similar geologic features. The formation of these heavy mineral deposits provides one of the best examples of applying knowledge of modern systems (e.g., the west and east coasts of Australia) as an analogue to interpret and understand the geology and form of ancient deposits (e.g., the Eucla and Murray Basins of southern Australia). This study provides descriptive and exploration models of Australia's heavy mineral sand deposits formed in coastal environments, which can be applied to similar settings worldwide.

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1. Introduction

Heavy mineral (HM) deposits associated with sediments in basins and paleovalleys are known in many places around the world. HM sands have two main deposit styles: (paleo-)shoreline/marine placers

commonly associated with beach (including barrier and aeolian coastal dune) or shallow offshore deposits, and fluvial/alluvial (e.g., gold and diamond) deposits. Rivers and streams carry HM-bearing sediments sourced from weathered geological domains and deliver the detritus to marine basins. Deposition occurs in particular geological sites where the geological and hydrological conditions are suitable for concentrating the HM. The heavy (dense) minerals in the sediments, such as gold, diamond, rutile, ilmenite and zircon, can then be reworked by

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waves, tides, longshore currents and wind, and thereby concentrated in various fluvial and coastal depositional environments. Sedimentation can occur in channels, deltas, the beach face (foreshore), sand dunes

behind the shore, offshore barrier islands, and tidal lagoons, as well as in estuarine channels and floodplains of streams and rivers within a coastal plain (Fig. 1).

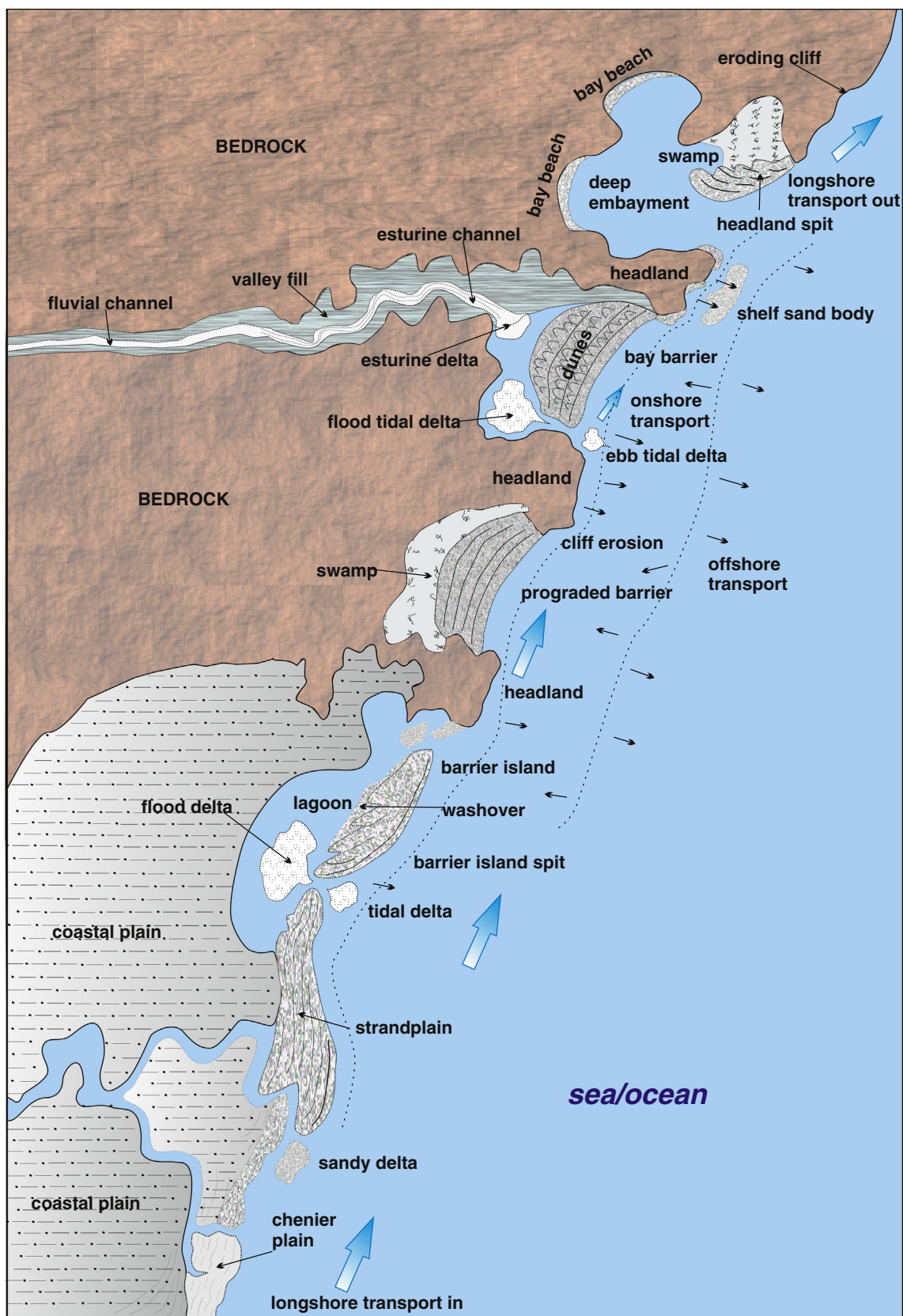


Fig. 1. Schematic of shoreline morphologies and deposits, showing distribution of coastal environments, including fluvial channels, estuaries, deltas, coastal barriers, strandplains, coastal plains, chenier plain, lagoons and cliffs; sources of sediments; and coastal sedimentation processes. After Hou et al. (2016).

The world's (paleo-)shorelines have a diverse range of mineral deposits of potential economic interest, including detrital minerals such as rutile, zircon, ilmenite and other HMs with similar density. These deposits have been, and continue to be, the principal global source of important industrial minerals, in particular titanium-bearing ore minerals (ilmenite, rutile, and leucoxene) and zircon. Intensive exploration for HM deposits is occurring in many countries, including Australia, Canada, China, India, Kenya, Madagascar, South Africa, Sri Lanka and the USA (Van Gosen et al., 2014). Australia is the world's leading producer of titanium and zircon minerals (Australia produced 53% of the world's rutile, 15% of ilmenite, and 50% of zircon in 2011; Geoscience Australia, 2013; Van Gosen et al., 2014). In Australia, the commercially important HMs occur almost entirely as beach placer, barrier/dune and offshore deposits that range in age from older inshore-nearshore deposits of Paleogene–Neogene age in the Eucla Basin (Hou et al., 2003b, 2011b), and inshore deposits of Pliocene–Pleistocene age in the Perth and Murray Basins (Shepherd, 1990; Roy et al., 2000; Hou et al., in press). Deposits of Pleistocene and Holocene (<120 000 years b.p.) age occur along the southeastern coast (Roy, 1999) (Fig. 2). The Eucla and Murray Basins in southern Australia, two of the largest Cenozoic basins in the world, contain large nearshore and onshore provinces of marine and coastal sediments. The basins, their margins (e.g., paleoshorelines) and peripheral paleovalleys present numerous exploration challenges and opportunities (e.g., within and beneath these sediments), and challenge traditional exploration techniques

(Hou et al., 2001a,b,c). The processes of paleoshoreline formation can, to some extent, highlight or even disguise exploration targets and, when understood, can be applied to advantage in mineral exploration. Thus, a systematic and detailed study of basins and adjacent paleovalleys can enhance the processes of modeling and exploring for HM deposits.

For much of the world, there is a lack of integrated geological and exploration models derived from representative descriptions of individual HM deposits in the literature. This study, based on the understanding of HM deposits and their formation, particularly those in southern Australia, provides an overview of the geological characteristics and exploration approaches for HM beach placers, and aims to develop new descriptive and exploration models, with a focus on HM deposits formed in coastal environments.

2. Overview of HM beach placers

As the world's principal source of titanium and zircon feedstocks, beach placer deposits play a significant role in the global mineral economy. These deposits have several characteristics that make them more prospective than other potential sources (Van Gosen et al., 2014; Hou et al., in press) including that they are 1) usually voluminous, covering large areas, with currently mined individual deposits typically comprising > 10 Mt of ore (the total size of the individual sand-silt body) and often contain > 2% HM; 2) usually located at shallow depth or near the



Fig. 2. a) Map of Australia showing major sedimentary basins and coastal regions that host HM deposits (modified from Geoscience Australia, 2013); b) SRTM DEM (Shuttle Radar Topography Mission digital elevation model) imagery of the Eucla Basin showing major paleodrainages, shorelines of various ages, and HM deposits/prospects; c) SRTM DEM imagery of the Murray Basin showing approximate extent of basin sediments and approximate extent of Late Miocene–Early Pliocene coastal strandlines of Loxton Sand.

surface, buried only by thin sedimentary/regolith covers; 3) generally easy to excavate (most HM deposits mined today vary in coherence from unconsolidated to poorly consolidated and thus are easily worked with heavy equipment); 4) benefit from well established, highly mechanized, and efficient mineral-separation techniques; and 5) produce several saleable minerals as co-products to the titanium minerals (e.g., staurolite, garnet and/or monazite).

Globally, economic HM deposits on (paleo-)coasts range in age from Cretaceous to Holocene (Recent) (Van Gosen et al., 2014). Modern and ancient deposits of HM display similar geologic features and thus their formation provides one of the best examples of applying knowledge from analogous modern systems (e.g., the southeastern coast of Australia; Fig. 2a) to interpret and understand the geology and form of ancient deposits (e.g., the Eucla and Murray Basins, southern Australia) (Fig. 2b, c).

2.1. Research history

The research history of HM from its infancy (starting in 1880) is best summarized in the works of Luepke (1984) and Van Gosen et al. (2014). During the first three decades of the 20th century, the research began to include analyses of direction of sediment transport and sources, quantitative mineral proportions, and relations that explain variations in HM content and possible bedrock sources (e.g., Mackie, 1923). Since the middle of the 20th century research on HM deposits has gone beyond local petrologic descriptions and extended to the study of regional- and global-scale factors that affect the formation and preservation of HM deposits, such as sea-level fluctuations due to climatic changes (e.g., McKellar, 1975; Chappell and Shackleton, 1986; Kotsonis, 1995, 1999; Hou et al., 2006, 2008); tectonics (e.g., Roy et al., 2000; Paine et al., 2004; Hou et al., 2008); extended periods of marine transgression, which move HMs from the shelf onto the shoreface (e.g., Roy, 1999); storm (e.g., Roy et al., 1994, 2000) and other events which drive energetic wave/swell action (e.g., Force, 1991); longshore drift (e.g., Hou and Warland, 2005; Hou et al., 2003b); and coastline morphology (e.g., Roy, 1984). Recent research has contributed reconstructions of the HM sources and paleocoasts that existed when significant HM ores were deposited (e.g., Carpenter and Carpenter, 1991; Force, 1991; Hou and Warland, 2005; Lees, 2006; Hou et al., 2011a,b, in press; Reid

and Hou, 2006; Reid et al., 2013). These reconstructions provide valuable exploration guides.

2.2. Commodities

The principal commodities in the majority of HM sand mining operations are zircon and the titanium minerals (ilmenite, rutile, leucoxene); other heavy minerals, such as sillimanite, staurolite, garnet, monazite and xenotime, are sometimes recovered as co-products (Table 1). Other titanium minerals occur between the end members of ilmenite and rutile, including pseudo-rutile and anatase that can form during weathering as iron is leached from ilmenite. Concentrations of co-product monazite in HM deposits represent potential sources of thorium and rare earth elements (Hoatson et al., 2011). Other constituents of the HM suite can include cassiterite, kyanite, corundum, topaz, and tourmaline. Heavy minerals are the primary source of titanium raw feedstock for the titanium dioxide (TiO_2) pigments industry (Gambogi, 2012), and also the principal source of zircon. In most coastal HM deposits, ilmenite is the most abundant of the HM assemblage and is overall the highest quantity of mineral product recovered and sold from HM deposits. Occasionally some deposits contain more zircon than ilmenite. Among these are the Jacinth and Ambrosia deposits in the eastern Eucla Basin, South Australia (Hou and Warland, 2005) and several deposits in the Murray Basin in Victoria, Australia (Geoscience Australia, 2012). Monazite is a principal product of HM deposits in places such as beach placer deposits in India.

2.3. Sources and deposition

HM-bearing materials derived from weathered and eroded bedrocks are transported by rivers to coastal areas. The HM-bearing sediments are then deposited along the shoreline with HM sands concentrated at particular shoreline sites (Fig. 1). Many studies identify inland complexes of high-grade metamorphic and igneous rocks as the primary sources of the heavy minerals deposited in a particular coastal basin (e.g., Force, 1976, 1991; Goldsmith and Force, 1978; Reid and Hou, 2006; Hou et al., 2011b; Reid et al., 2013; Keeling et al., 2015). High-grade metamorphic rocks are considered the predominant original source of the titanium oxide minerals found in HM sand deposits

Table 1
Common heavy minerals in HM deposits (listed in order of average specific gravity. Leucoxene – altered ilmenite). In nature, the specific gravity of a mineral varies from the mineral's pure form due to impurities and alteration.

Heavy Minerals	Ideal Composition	Specific Gravity	Hardness	Colour	Stability in weathering	Provenance
Magnetite	Fe_3O_4	5.2	5.5–6.5	black, dark grey	moderate	igneous & metamorphic rocks, hydrothermal veins
Monazite	$(\text{Ce}, \text{La}, \text{Y}, \text{Th})\text{PO}_4$	4.9 – 5.5	5–5.5	brownish red	high	igneous & metamorphic rocks
Ilmenite	FeTiO_3	4.5–5	5–6	black	moderate–high	igneous & metamorphic rocks
Zircon	$(\text{Zr}, \text{Hf}, \text{U})\text{SiO}_4$	4.2–4.9	7.5–8	many	high	igneous & metamorphic rocks
Xenotime	YPO_4	4.4 – 5.1	4–5	brown, yellow	high	igneous & metamorphic rocks
Rutile	TiO_2	4.2 – 4.3	6–6.5	brownish red	high	igneous & metamorphic rocks
Corundum	Al_2O_3	4.0	9	colourless, blue, red	low–moderate	igneous & metamorphic rocks
Leucoxene	FeTiO_3 to mostly TiO_2	3.5 – 4.5	4–4.5	white to yellow-brown	high	igneous & metamorphic rocks
Staurolite	$\text{Fe}_2\text{Al}_9\text{O}_6(\text{SiO}_4)_4(\text{OH})_2$	3.7 – 3.8	7–7.5	brown	high	metamorphic rocks
Garnet	$(\text{Mg}, \text{Fe}, \text{Mn}, \text{Ca})\text{Al}_2\text{Si}_2\text{O}_{12}$	3.1 – 4.3	7–7.5	colorless, all colors	moderate	mostly metamorphic but igneous also.
Kyanite	Al_2SiO_5	3.5 – 3.7	4–8	blue, white, gray, green, black	high	metamorphic rocks, rarely in igneous rocks.
Sillimanite	Al_2SiO_5	3.2	6.5–7.5	colorless, various colored	high	metamorphic rocks, sometimes granite.
Tourmaline	$(\text{Na}, \text{Ca})(\text{Li}, \text{Mg}, \text{Al})(\text{Al}, \text{Fe}, \text{Mn})_6(\text{BO}_3)_3(\text{Si}_6\text{O}_{18})(\text{OH})_4$	3.0 – 3.3	7	black, various colored	high	granitic pegmatites, some metamorphic rocks.

(Force, 1991). Igneous rocks commonly associated with and interspersed with metamorphic rocks are typically considered subordinate sources in comparison to metamorphic rocks (Table 1). Proposed igneous sources of HM must account also for high contents of ilmenite and rutile as well as zircon, which are often the dominant economic heavy minerals in HM deposits. In mafic intrusions, much of the TiO_2 is tied up in magnetite, which is inconsequential to economic HM. Thus, igneous rocks in which the high TiO_2 content is primarily due to ilmenite and (or) rutile are the desired rock types (discussed in detail by Force, 1991). Sillimanite-grade and higher metamorphic grade rocks are considered the primary source of ilmenite and rutile in coastal HM deposits, as well as of garnet, staurolite, sillimanite/kyanite, and xenotime (Table 1). In addition to the titanium oxide minerals, most of the co-product HM are typically derived from intermediate to high-grade metamorphic rocks of amphibolite to granulite facies (e.g., garnet, staurolite, monazite, xenotime, and kyanite or sillimanite) (Van Gosen et al., 2014).

Sedimentary rocks can be an intermediary host for HM, which are subsequently re-deposited. Sedimentary rocks (mostly sandstones and conglomerates) located within the drainage catchment of a basin can contain detrital grains of HM derived from past erosion of igneous and metamorphic rocks. Subsequent erosion of the sedimentary rocks by fluvial or coastal processes can remobilize the HMs, which are then re-deposited in coastal sands (Leonardos, 1974; Shepherd, 1990; Roy et al., 2000; Ali et al., 2001; Roy and Whitehouse, 2003). The sedimentary rocks of the Officer Basin, for example, have been shown to be a significant secondary source area for the HM sand deposits of the Eucla Basin of Australia (Fig. 2a; Hou et al., 2011b; Reid et al., 2013).

2.4. Weathering processes

Weathering processes are particularly important in the formation and beneficiation of HM deposits, as the final mineral assemblage of HM deposits can be influenced by the style of weathering (i.e., physical sorting, mechanical abrasion and dissolution) of source material before or during the formation of the HM deposits (Morton and Hallsworth, 1999). According to Force (1991), HM are subjected to weathering in four general settings during the processes of formation of HM deposits: 1) in the region where source igneous and metamorphic rocks are weathered to form sediment; 2) during fluvial transport; 3) within intermediate sedimentary host rocks; and 4) following the deposition of the minerals in coastal sediments. In the source regions, bed-rock weathering disaggregates the rocks, reduces the mass of the rocks by destroying the less stable minerals, and liberates the HM into the fluvial system as mainly mono-mineralic detrital grains. During transport to the depositional site, generally, most stable HMs are subjected more often to mechanical forces (tumbling, abrasion, rounding) than to chemical weathering. After deposition of HMs in sediments, weathering enhances the TiO_2 content of some Ti oxide minerals, i.e., iron is mostly leached from ilmenite ($\text{Fe}^{2+}\text{TiO}_3$) during weathering (Force, 1991; Paine, 2005). Thus, weathering of HM deposits may transform some or most of the ilmenite in situ into leucoxene, by the removal of iron from the ilmenite crystal lattice.

Most of the rich modern placer deposits of the world are in tropical regions, because weathering processes there play an important role in releasing HMs from their parent rocks (Pirkle et al., 1974). Tropical to subtropical climates especially promote chemical weathering, which disaggregates the crystalline bedrock at the source area, an important pre-concentration process in the development of placer deposits. Climate influences the weathering processes directly, first by decomposing the rock matrix and liberating the HM. Moisture is the key component in forming HM sands from beginning to end, from weathering of bed-rock to fluvial transport and to sediment deposition, as well as finally by influencing the weathering in-place at the coastal area. Force (1991) noted that Quaternary HM sand deposits occur at latitudes of 35° or less; this relationship also applies for older HM deposits hosted

by paleoshorelines (Hou et al., 2008). Macroclimates have a strong influence on the formation of HM sands and likewise influence the weathering of HM deposits. Major transgressions and regressions of sea level during the Cenozoic have been linked to cycles of global sea-level events (Chappell and Shackleton, 1986; Haq et al., 1987; Force, 1991; Roy and Whitehouse, 2003; Hou et al., 2006, 2008). These major sea level fluctuations, driven by climatic cycles, have a direct influence on the weathering regime of HM sands because: 1) during major transgressions earlier deposited sands are covered by the sea and subsequent transgressive deposits, lessening oxidizing conditions; and 2) during major regressions of the sea coastal deposits are exposed to erosion and oxidizing conditions.

2.5. Dimensions

HM sand deposits in a basin occur (1) discontinuously along the strike of a strandline (e.g., Murray Basin; Fig. 3), and (2) as stratigraphically stacked deposits, representing different sea level events over time (e.g., Eucla Basin; Hou et al., 2008). In plan view, HM deposits are elongate, oriented roughly parallel with the strike of the paleoshoreline (for fossil deposits; Fig. 3). In cross-section, the deposits have convex lens-shaped profiles (Fig. 4). Ore bodies are lens-shaped packages of HM-rich sediments that total several (3 to 45) meters in thickness. Along the length of the strandlines, these lens-shaped ores are stacked and offset in the sedimentary stratigraphy, separated by intervals with low HM content (Geoscience Australia, 2012). Subdued terraces associated with HM deposits are most likely to represent major sea level events of paleostrandlines rather than faulting or other structural features. Terraces formed during regional or local highstands of the sea were stranded as the sea retreated and are now manifested as ridges that are up to tens of meters high and located inland by up to several tens of kilometers. Multiple sets of shoreline terraces are documented in the southeastern United States (Force, 1991) and Australia (Geoscience Australia, 2012). Each terrace level is interpreted to represent a significant transgression or regression event, which can be associated with HM deposition (Baxter, 1977).

2.6. Host-rock facies

Beaches, strandlines/barriers, dunes and associated deposits are commonly the host sediments of HM (Fig. 4). Both the composition and grain size of these sediments are controlled directly by the nature of the rocks in the provenance area. Fine to medium grain-size sediments comprising HM deposits are common in coastal environments (Folk, 1968), such as those of the southeastern Australian coast (Roy, 1999), the Murray (e.g., Roy et al., 2000; Roy and Whitehouse, 2003) and Eucla (Hou et al., 2003b, 2011b) basins of Australia. The basal sediment in most of these HM deposits is either medium- or coarse-grained sand with minor gravel or grit (Fig. 4), the HM fraction often being contained in medium- to fine-grained quartz sand. The beach and/or barrier deposits are considered to have formed initially in moderate to high energy conditions, followed by a period of accretion and progradation during lower energy conditions when finer grained sands were laid over earlier deposits. Most economic HM deposits are found in unconsolidated to weakly consolidated layers of sediments (Fig. 5), although it is not unusual to see (non-economic) HM sands in consolidated layers of sediments (even in Precambrian and Paleozoic sedimentary rocks). Minor production of HM has occurred in the past from sandstones, and it appears there is no active mining operation that recovers HM from well lithified sandstone (Van Gosen et al., 2014).

2.7. HM strandlines

Heavy mineral strandlines are typically high grade with a proportion of valuable HM (VHM) and are well sorted. In the Eucla and Murray Basins, strandlines containing economic HM are typically 100 to 500 m

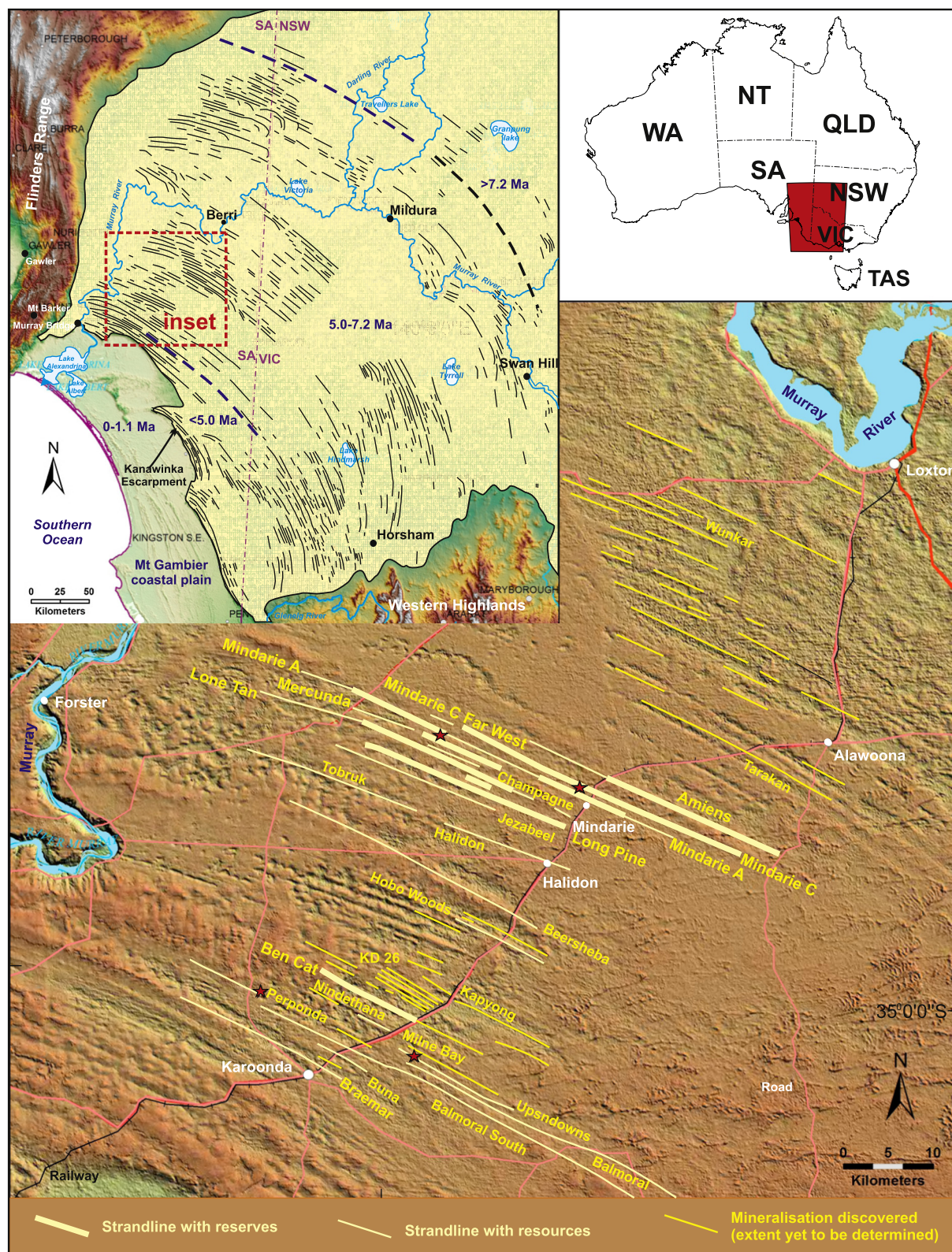


Fig. 3. Mindarie-Karoonda HM deposits, western Murray Basin (after Hou et al., *in press*); and distribution of the Loxton Sand strandplain with strandlines and corresponding strontium isotope ages (modified from Miranda et al., 2009) (ages for the Mt. Gambier coastal plain are from Huntley et al., 1993 and Murray-Wallace et al., 2001).

wide, 1 m to over 20 m thick, and from 500 m up to tens of kilometers long (Fig. 3) (e.g., Roy et al., 2000; Hou et al., 2011a,b). Strandline deposits range from composites of numerous individual strandlines related to a single depositional event, to multi-depositional 'stacked' strandlines. Within HM strandlines, HM grade is generally higher near

the base, which is generally erosional, and to the landward side of the strandline with the HM grade decreasing both offshore and vertically in shoreline deposits formed during marine regression (Fig. 6). Along strike, the HM grade generally shows greater continuity (Jones and O'Brien, 2014).

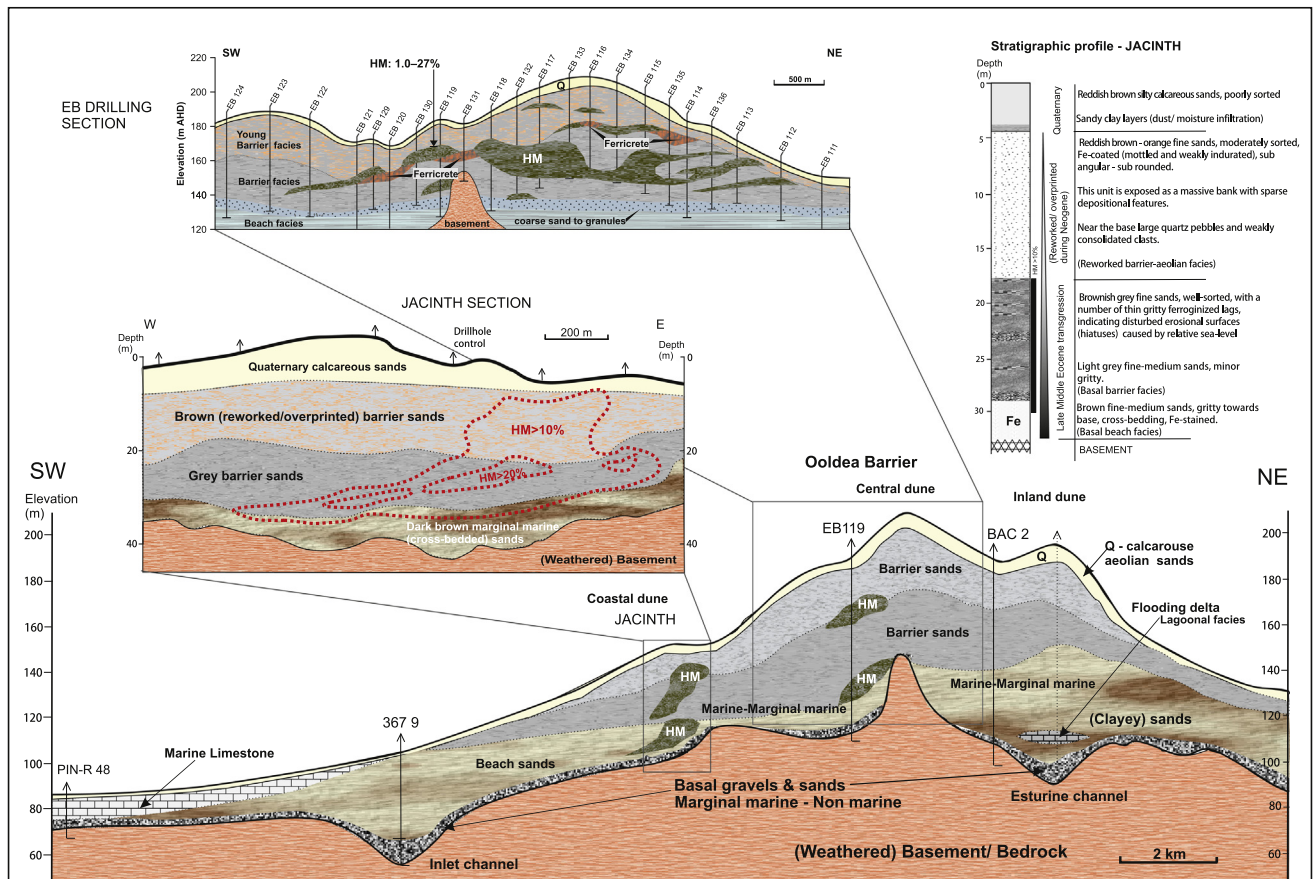


Fig. 4. Cross sections through the Ooldea barrier at Jacinth HM deposit of Eucla Basin, showing association of heavy mineral concentrations with host barrier facies and topographic features. See Fig. 2b for location of section A-A' (modified from Hou et al., 2011b).

2.8. HM aeolian dunes

Dunal HM deposits (Figs. 5 & 6) generally comprise lower grades compared to strandline HM deposits and the mineralization is typically more disseminated with poorly defined preferred grade orientations. In some situations, however, relatively higher HM grade is observed, often associated with erosional surfaces and potentially aligned with the prevailing wind direction as in the eastern Eucla Basin (Hou et al., 2003b). Generally, dunal deposits are more extensive than strandline HM deposits, and are from one to a few meters in thickness depending on the size and complexity of the deposit.

2.9. Fluvial HM deposits

Fluvial HM deposits associated with coastal environments (Fig. 1) (e.g., Allen and Posamentier, 1993; Dalrymple et al., 1994) are generally irregular in morphology, mostly comprising paleochannels but occasionally deltaic-hosted deposits and more rarely alluvial fans.

3. Geological and geographical implication of HM mineralization

3.1. (Paleo-)shorelines

HM-bearing shorelines are exposed to inputs of energy (e.g., wave, wind, and tides; Fig. 7) and materials (e.g., water and sediments), which interact within the geological framework to produce coastal landforms (Fig. 1). The genetic features of shoreline evolution (erosion or accretion of both consolidated and unconsolidated sediments) are extremely complex, involving diverse processes such as crustal movement, climatic change, eustatic change and energy imparted by waves,

tides and winds (Kraft, 1978; Kraft and Chrzastowski, 1985; Nummedal, 1983). Geological controls include: the rock types in the source area (which determine the composition of the HM fraction), and the controls on the drainage systems, which transport the materials to shoreline areas and can cause periodic inflow of sediment into the settling system. Also influential are marine wave and long-shore drift, which transport marginal marine sediments to the coast, and a persistent sorting medium such as wind or swell waves on a microtidal coast. A combination of these controls is necessary for forming HM deposits.

Fluctuating shorelines occur over a wide range of nested time and space scales, but can be broadly separated as short-, intermediate- and long-term scales (Fig. 8; Cowell and Thom, 1994). An obvious relationship exists between sea level rise, during which there is shoreline erosion and sea level fall, when shoreline preservation occurs. Therefore, the time scale underpinning models for sea level change and paleo-shoreline development needs to be taken into account when interpreting HM distribution in shoreline deposits of variable age. Some HM deposits accumulated over a relatively long geological period (e.g., deposits of the Perth, Murray and Eucla Basins, Australia), but others formed over a relatively short period (e.g., the HM deposition along the Australian eastern coast) (Fig. 2a). The paleoshorelines in the Eucla Basin and Murray Basin HM deposit areas are moderately mature paleobeaches, as these deposits appear to have formed by the long-term activity of currents, storm waves and swell as well as longshore drift, including reworking of previous beach deposits. Most shorelines flanking the coastal plains of the Eucla and Murray Basins are slightly curved to straight. In places, they are interrupted by rocky headlands giving rise to 'J-shaped' coastlines (e.g., Jacinth deposit, eastern Eucla Basin, Australia). Progradation in the 'J-shape' coastlines appears to be more favorable for the preservation of HM sands (Hou et al., 2003b,

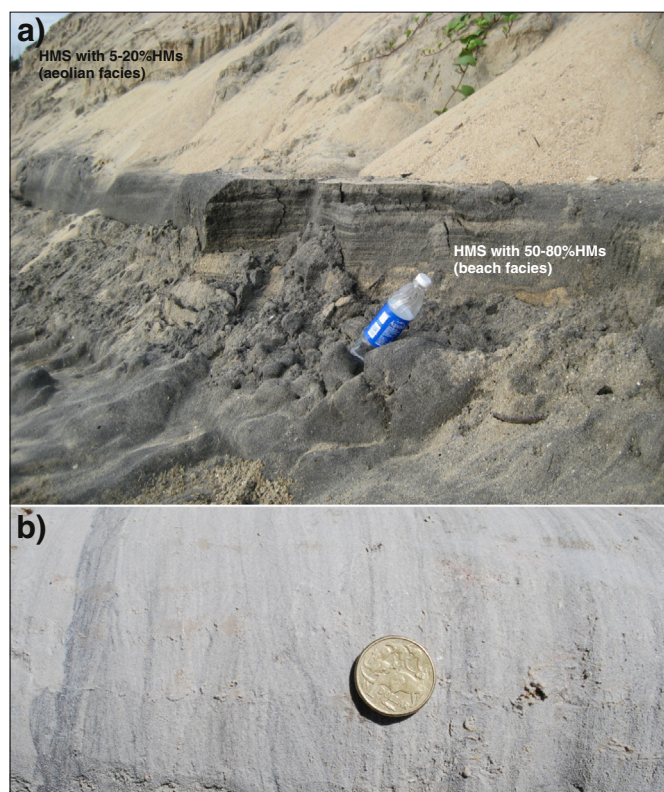


Fig. 5. Heavy mineral layers (‘black sand’) within quartz beach sand: a) beach and aeolian facies Trivandrum, India, water bottle is 20 cm in length; b) lower shoreface/shallow off-shore facies demonstrating the layering of the cross-bedded sediments, western Murray Basin, Australia (photograph by Darren Klingner of Australian Zircon NL).

2011a,b). Along the Ooldea barrier of the eastern Eucla Basin, several heavy mineral deposits have formed at similar elevations during different stages of progradation of a few ‘J-shape’ shoreline segments (Fig. 9; Hou et al., 2011b).

3.2. Eustasy

Study of sea-level change provides information that is essential for understanding shoreline history (Einsele, 1992), and is a useful tool in the prediction and extrapolation of (paleo-) shoreline position (e.g., Benbow, 1990a; Clarke et al., 2003; Hou et al., 2003c, 2006, 2008). This can be achieved by the combination of biological, biostratigraphic and geomorphological approaches. The various elevations at which paleoshorelines containing HM deposits occur in the Murray and Eucla Basins are commonly attributed to relative sea-level change (regionally related to third-order transgressions; world-wide variations in respective elevation of the land and sea). The shoreline deposits are usually more complex than predicted from Fig. 1, consisting of several wave-cut benches and associated beach deposits, indicating that transgression (as in the eastern Eucla Basin), and regression and progradation (as in the western Murray Basin) have, in detail, strongly modified the predictable effects of sea-level change. Preservation of HM deposits depends on the rate of transgression or regression of the shoreline after deposition, and the volume of sediment deposited at the time of sea-level fluctuation.

Estimates of the age of HM deposits on the Paleogene and Neogene coastal plains of the Eucla Basin are commonly compared to local, regional and international models of eustatic change (Clarke et al., 2003; Hou et al., 2003c, 2006). This approach needs to take account of the effects of Cenozoic tectonism (Sandiford, 2007; Hou et al., 2008) and, therefore, ages determined by eustatic correlation should be treated with caution (Hou et al., 2008). On the Cenozoic coastal plain of the

western Murray Basin, wave cut platforms of different elevations are correlated by their geomorphic associations (Hou et al., in press). Their varying elevations are due to marine regression towards the south but also are influenced locally by contemporaneous tectonism (Clark et al., 2012).

3.3. Currents, waves and longshore drift

Longshore currents and storm waves transport significant quantities of shoreline HM-bearing sediments to the beach (Figs. 1 & 7). For example, along the paleocoasts of the eastern Eucla Basin and western Murray Basin the currents oscillated between easterly and southeasterly drifts. Longshore currents on the west coast of the Eucla Basin do not appear to have been an important sorting agent, but the north coast of the basin experienced persistent eastwards longshore currents that flowed parallel to the coast and were the main sorting agent (Hou et al., in press). Also, swell and waves generated by the dominant westerly wind system were probably the main agent of sorting on the west and southwest coasts of the western Murray Basin (Kotsonis, 1999; Miranda et al., 2009; Keeling et al., 2015). Beach HM-bearing sediments were periodically removed by storm waves and redeposited in the littoral zone adjacent to the paleoshorelines of the Eucla and Murray Basins, as evidenced in the buried paleoshorelines at the Jacinth HM mine (eastern Eucla Basin; Fig. 4) and the Mindarie HM mine (western Murray Basin; Fig. 3). Destruction of a beach due to sea level changes is followed by re-deposition by swell, during which most of the sorting of the sediment occurs (Fig. 6). This type of reworking appears to have taken place on the Eocene beach in the Jacinth-Ambrosia deposits of the Eucla Basin. While swell is the principal sorting medium, storms may be essential for the formation of larger HM deposits as storms ensure complete reworking of the sediment.

Longshore sediment movements principally occur on linear coastal plains that are not strongly embayed (i.e., relatively ‘open’) and are exposed to waves with an oblique angle of approach (Fig. 9). Waves mainly move HM-bearing sand alongshore on the beachface and in the surf zone, and contribute significant amounts of sand to the upper shoreface zone, but much less to the lower shoreface and inner shelf (Fig. 7). Therefore, the width of the longshore sand transport pathway for a particular coast is primarily defined by these sediments. Zone widths vary with energy level between coastal sites and also vary at any one site as wave conditions change. Along the western, northern and eastern coasts of the Eucla Basin, for instance, the zone of longshore transport corresponded to the inner nearshore sand zone, which extended to depths of a few tens of meters and was up to a few tens of kilometers wide and as much as a thousand kilometers long (Hou et al., 2008). On coasts where point-source sand supplies can be identified, the direction of net littoral drift is indicated by the asymmetrical arrangement of strandplain deposits (e.g., northeastern margin of the Eucla Basin) adjacent to river mouths (e.g., paleoriver mouths along the western and northern coasts of the Eucla Basin), and the orientation of features such as headland spits (Fig. 9; e.g., Immarna and Jacinth areas of the Eucla Basin).

3.4. Shoreline Sedimentation

For a HM deposit of economic importance to form it appears there should be: (1) a settling environment adjacent to a shoreline fed by drainage from HM-bearing terrain, (2) a moderately consistent current and wave pattern, (3) an immature beach, (4) a moderate slope or gradient of the pre-existing land surface, and (5) a protected shoreline. Features of coastal environments are summarized in Table 2 together with the coastal processes associated with their formation and the implications for shoreline sedimentation. These features are described from modern and ancient shoreline environments (e.g., Fairbridge, 1968) and can be combined with studies of modern coasts (e.g., Roy et al.,

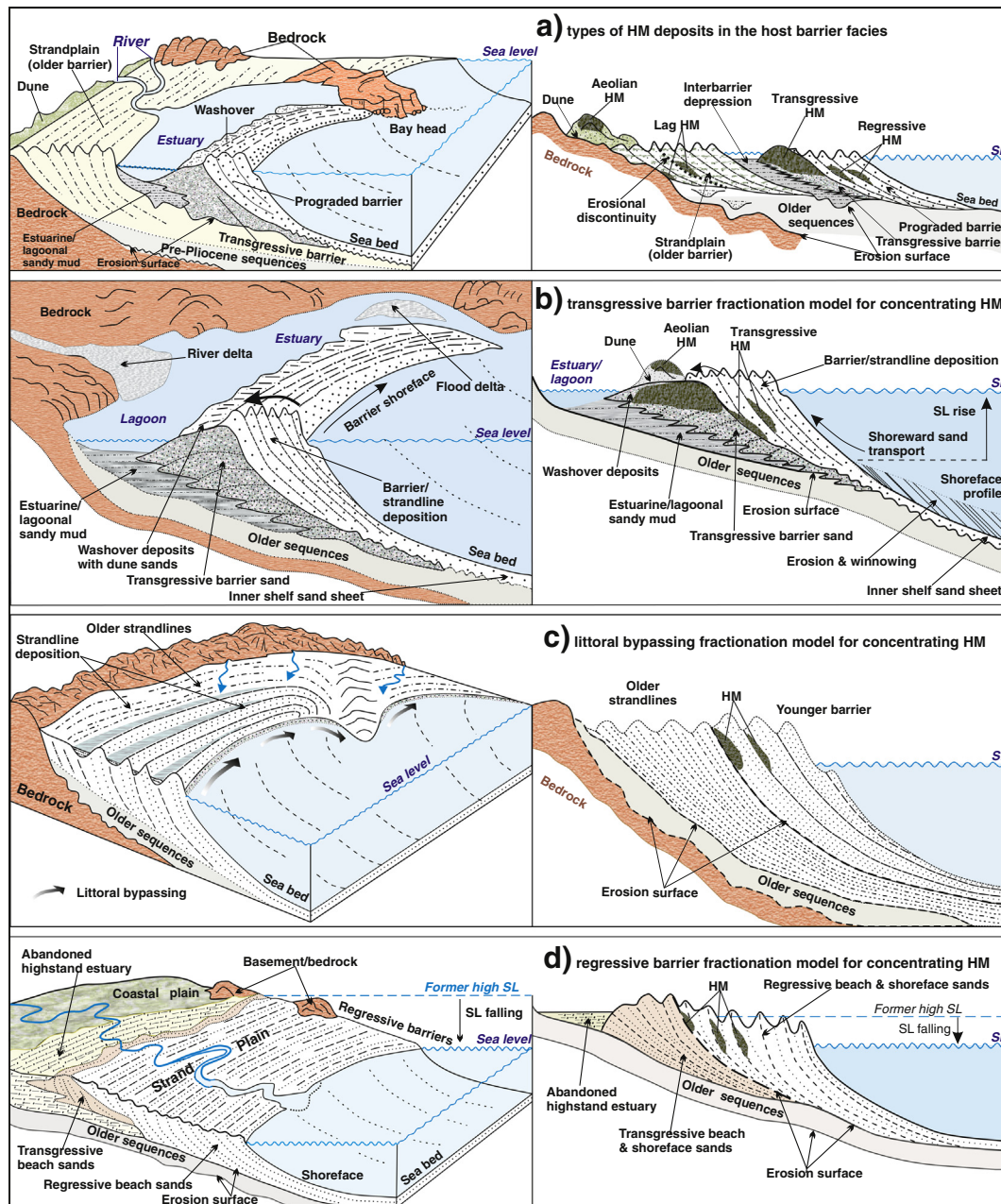


Fig. 6. Generalized models indicating genesis of South Australia's HM deposits based on HM studies of the Murray Basin and Eucla Basin (after Roy, 1999; Hou et al., 2003b, 2011b): **a)** four types of HM deposits defined by their location in the host barriers (lag deposits along erosional discontinuities at the contact between different-age barriers along drift-aligned coasts formed from bypassing and winnowing; transgressive deposits formed in swash-aligned, compartmented embayment at the rear of prograded barriers in their transgressive facies, immediately landward of the strandplain; regressive deposits located in compartmented embayments within prograded barriers of the strandplain; aeolian deposits, relatively low-grade, disseminated HM deposits in transgressive dunes downwind from HM-rich beaches.); **b)** transgressive barrier fractionation model for concentrating HM; **c)** littoral bypassing fractionation model for concentrating HM; **d)** regressive barrier model for concentrating HM.

1994) to understand sedimentation and the geomorphic processes leading to formation of HM deposits on shorelines of the past.

HM-bearing sand supplied to a wave-dominated coast is sorted and redistributed over the entire barrier shoreface. Sediment lost from the beachface into transgressive dunes or tidal deltas causes erosion and readjustments over the entire barrier shoreface profile; as a result, shoreline accretion or recession in turn controls the formation of the HM-bearing strandline plain (Figs. 1 & 6). For instance, drowning of (paleo-) rivers along the (paleo-) coasts of the Murray and Eucla Basins resulted in large estuaries and inlets. The drowning is attributed to several marine transgressions during the past 60 Ma. Inlets such as the Pidinga and Ifould inlets along the Ooldea barrier of the eastern Eucla

Basin (Fig. 9), and the Coorong inlet of the Murray Basin (Fig. 2c) are examples of such estuaries (Hou et al., 2012). In these situations areas where periodic flow from major rivers (e.g., the paleorivers into the Eucla Basin; Fig. 2b) enters into semi-closed or sheltered water prior to entering the ocean, efficient separation of silt and sand occurs, and the separated materials are flushed onto the coast during flooding.

In the Eucla and Murray Basins, some estuaries are linked to successive HM-bearing paleoshorelines/strandlines lying roughly parallel to one another (Figs. 3 & 9). These shoreline deposits commonly have intermixed swamp, lacustrine, fluvial and marine sediments. Barriers, one of the most important depositional environments for concentrating HMs, are defined as elongated, shore-parallel sand bodies that extend

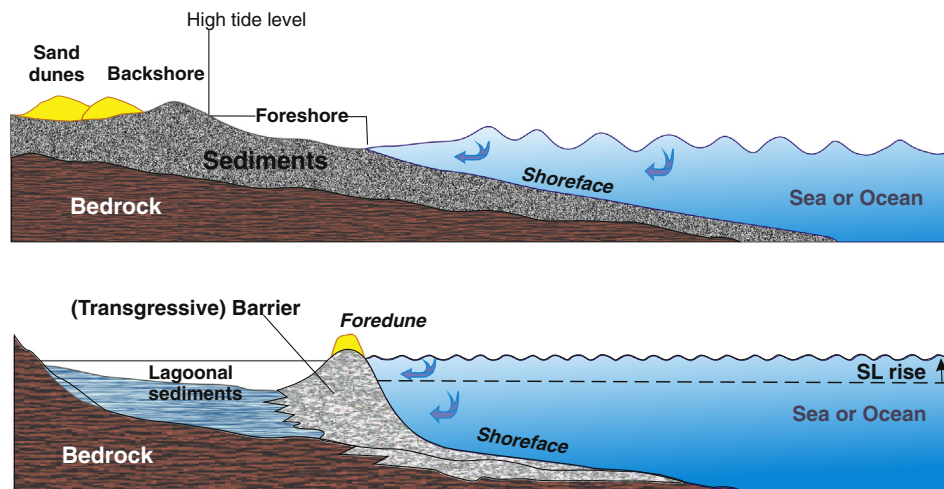


Fig. 7. Schematic cross-section showing the features commonly used to describe shoreline (strandline) depositional environments associated with HM deposits (after Hou et al., in press); a) mainland beach depositional environment; b) barrier-tidal lagoon shoreline depositional environment (after Roy et al., 1994).

above sea level and consist of sandy lithofacies including beach, dune, shoreface, tidal inlet and washover deposits (Fig. 6) (Curry, 1969; Boyd et al., 1992; Roy et al., 1994).

Estuaries or lagoons located behind transgressive barriers may receive sediment as sea level is rising, and act as long-term sediment sinks for marine sand during transgression, as in the Eucla Basin. They are spatially restricted during marine regression (e.g., the western Murray Basin) (Figs. 1 & 6). The physical character of the estuary mouth is controlled by a dynamic balance between littoral and tidal sediment movements on the open coast and in the tidal inlet, respectively (Roy, 1984; Nichols and Biggs, 1985; Dalrymple et al., 1992). By linking the deltas to contemporaneous depositional systems (i.e., lowstand, transgressive and highstand system tracts) Hou et al. (2001b, 2003c, 2008) developed a conceptual framework for long-term coastal or deltaic evolution in studies of the Eucla Basin. Relative sea-level (RSL) rise (transgressive system tracts) caused retrogradation into the incised valleys (Suter, 1994). On moderate to high wave-energy coasts, deltaic sediments are transported downdrift, possibly for hundreds of kilometers, such as along the Ooldea paleocoast of the eastern Eucla Basin (Hou et al., 2003b,c, 2008). A feature of both flood-tidal deltas and washover deposits is their formation under similar environmental conditions (Fig. 1). As shown in the Ooldea barrier system of the eastern Eucla Basin, the inlet channels could be maintained by tidal currents flooding through, but closed due to wave-induced longshore drift (Hou et al., 2006, 2008).

Sediment-starved sandy shelves that are exposed to a high energy wave regime are likely to transfer HM-bearing sand between the inner shelf and shoreface, thus influencing coastal sedimentation (Fig. 6). In the Wimmera district of the Murray Basin extensive deposits of fine-grained HM sands have formed offshore in this environment, possibly with significant reworking of older basin sandy sediments by wave action. These include the large sheet-like WIM 150 deposit, which spreads across 32 km² and is 4–8 m thick. It contains 3–4% HM, dominantly ilmenite (~30%) with rutile/leucoxene (~20%) and zircon (~13%) (Olshina and van Kann, 2012).

Morphology of beach ridges is produced by individual beach berms or foredunes that indicate former shoreline positions as the coast has prograded (Figs. 1 & 6). The studies of barriers by drilling and dating in southeast Australia show that barrier progradation extends from the barrier superstructure (beach and dune) to the shoreface zone, to depths of 20 m below sea level and for more than 1,000 m offshore (Thom, 1978; Roy et al., 1994). In higher wave energy environments such as the eastern Eucla margin, barrier sand bodies are thicker (up to 110 m) and extended a similar distance offshore (Benbow, 1990a,b; Hou et al., 2006, 2008). Here rates of Eocene shoreline progradation were higher and an abundant sand supply is inferred. A substantial proportion of this sand is thought to have come onshore from the adjacent continental shelf from water shallower than about 50 m, but a major proportion of this sand was supplied alongshore by littoral drift in an approximately east-southeast direction (Hou et al., 2003c, 2006, 2008).

The coastal sand barrier models related to relative sea-level changes include transgressive barrier, regressive barrier, and stillstand barrier models (Fig. 6) (e.g., Roy et al., 1994). These models address the broad aspects of sand barrier genesis and evolution over geological timespans, coastal geomorphology, and of sediment stratigraphy that result from barrier evolution, particularly barrier systems with HM deposits (Benbow, 1990a; Hou et al., 2011a). In the Eucla Basin, transgressive barriers migrate over the previous landscapes, such as marsh and scrub, or infill lagoons, lakes or estuarine channels (Hou et al., 2011b). The transitory features of transgressive barriers involve maintaining the barriers in dynamic equilibrium with rising sea-level by the landward transfer of sediments, which are eroded from the shoreface and transported to backbarrier settings (Fig. 6). Foredunes impede washover processes and decelerate the rate of shoreface recession. During the stillstand, the barrier progrades seaward, but the rate of progradation is slowed as the shoreface advances into deeper water. This effect is evident in the evolution of the Barton barrier system, eastern Eucla Basin (Hou et al., 2003a,c, 2006, 2008). Continuously falling RSL forces the barrier to prograde seaward into the excavated zone and thus reconstitute the former sea-bed morphology. As shown by

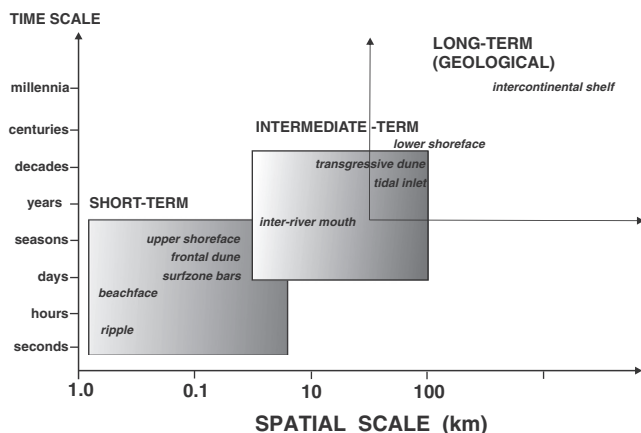


Fig. 8. Spatial and temporal scales of coastal change/evolution (modified from Cowell and Thom, 1994).

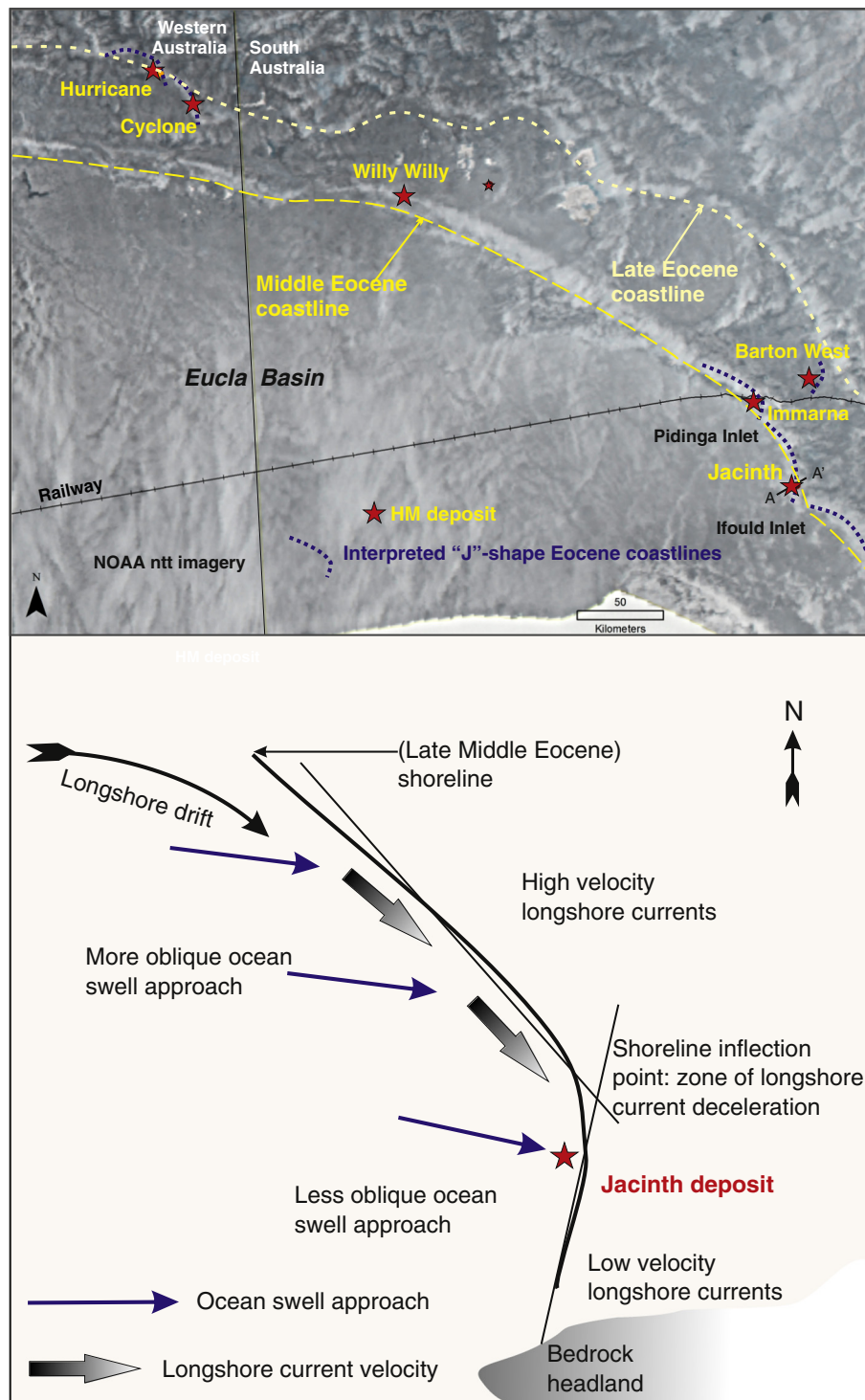


Fig. 9. Schematic model of longshore current impacts on the paleoshorelines, extracted from a case study of the Eucla Basin HM (interpreted subsurface features are shown on NOAA night-time thermal imagery). The longshore current velocity south of the inflection point is less than the longshore current velocity north of the inflection point due to relative differences in the angle of oblique wave approach (Komar, 1979) (modified from Hou et al., 2011b).

an example in the Murray Basin, the surface of the regressive barrier formed a wide strandplain (Fig. 6d) but was not backed by an estuary (Fig. 1), unlike barriers formed during rising or stable sea level. Regressive barriers are widespread globally on relatively energetic, low gradient, sand-rich shelves, typified by numerous examples in the Murray Basin (Fig. 3).

As a form of stillstand barriers that have principally grown along-shore in response to littoral drift (Allen, 1982), headland spits are commonly formed on rocky, embayed coasts (e.g., King, 1972) or adjacent to

sandy river mouths on drowned coastal plain coasts (e.g., Wright, 1985), such as those formed along the Ooldea barrier of the eastern Eucla Basin (Hou et al., 2011b). The morphological features of spit growth are characterized by successive beach and foredune ridges that are often recurved at their downdrift end (Fig. 1). The growth of a recurved spit often results in the formation of a series of beach ridges marking the paleoshorelines, (e.g., Willy Willy HM prospect of the Ooldea barrier system, eastern Eucla Basin; Hou et al., 2007, 2011a,b). Spits commonly occur on receding coasts (Allen, 1982), particularly

Table 2

Coastal environment and indicated processes, showing information of shoreline sedimentation.

Coastal environment	Indicated coastal processes
Beach rocks exposed on the shoreface	Erosion
Estuaries exposed on the shoreface	Erosion
Eroding cliffs, bluffs	Erosion and down drift sediment supply
Longshore drift/ movement	Theoretical sediment movements
Fluvial/estuarine deltas	Seaward sand loss and rate of sand supply
Flood-tidal deltas	Landward sand loss and rate of sand supply
Ebb-tidal deltas	Seaward sand loss and rate of sand supply
Fluvial/estuarine deltas	Accretion (and rate of sediment supply)
Beach/foredune ridge strandplains	Accretion and rate of sediment supply
Inner shelf sand sources & deposition	Theoretical sediment movements
Transgressive barriers/dunes	Landward sand loss and rate of sand supply
Regressive barriers/dunes	Seaward sand loss and rate of sand supply
Stillstand barriers/dunes	Slow seaward sand loss and rate of sand supply
Headland spits	Downdrift progradation and rate of sediment supply
Chenier ridge plains	Accretion and rate of fine-grained sediment supply

rocky embayed coasts because these provide more traps for HM-bearing sediments to accumulate (e.g., Jacinth HM deposit area of the eastern Eucla Basin; Hou et al., 2011a,b). Washover deposits are the result of barrier recycling (erosion of the seaward face and deposition at the backbarrier face), which mostly occurs under conditions of rising sea-level (Fig. 6). Studies of the Ooldea and Barton barrier systems of the eastern Eucla Basin indicate that washover played an important role in the formation of these HM-bearing systems (up to 50 km wide and 100 m thick in places) during Eocene time (Hou et al., 2006, 2008, 2011b).

Aeolian dune HM deposits are likely to develop on the shoreward side of beach concentrations of HM (Fig. 6). Aeolian sand dunes (up to 30 m in thickness), commonly containing HM, are widespread in the Ooldea and Barton ranges of the eastern Eucla Basin (Fig. 2b) (Benbow, 1990a,b) and the modern coast of the Murray Basin (Fig. 3; Mt Gambier coastal plain in South Australia) (Ferris and Hayball, 1993). HM concentrations commonly occur in the foredunes of the eastern Eucla Basin and all such dune deposits are found in transverse dunes, lying parallel to the coastline. Modification of fossil dunes by wind and sheet erosion produces wide, near-horizontal sheets of slightly re-sorted dune sands. These may contain areas where HM are concentrated sufficiently to approach ore grades, such as the HM mineral deposits/prospects of the eastern Eucla Basin. HM-bearing dunes may develop at considerable distances from the shoreline and on precipitous coasts if onshore winds are sufficiently strong. For example, at the Jacinth HM deposit, dune deposits occur up to 3 km inland from the late Middle Eocene (39 Ma) shoreline (Hou et al., 2003b, 2011b); and along the Ooldea Range, dunes are up to 70 m above sea level along the Eocene coastline (Hou et al., 2008).

3.5. Geotectonic Implications

Prior to the 1970s, depositional models for beach placers generally assumed that these deposits formed on stable platforms under little tectonic influence (Van Gosen et al., 2014). These geologic models of HM deposits in coastal settings (particularly the models proposed for older deposits) commonly state that the genesis of such deposits requires a stable tectonic environment. Economic deposits of coastal HM sands usually occur on the trailing margins of continents, which in general are less subject to large-scale tectonism. In contrast to many other ore deposits, HM deposits are not usually a consequence of active regional or large-scale tectonics involving major faulting, fracturing or folding.

Recent studies, however, have identified links between active tectonics within coastal basins and the clustering of HM deposits and/or their preservation (Roy et al., 2000; Sandiford, 2003; Paine et al., 2004; Hou et al., 2008, 2011b). Hou et al. (2008) determined that the Eucla Basin experienced differential vertical movements and tilting (west side up) since the Eocene, which appeared to have modified the pattern of sedimentation and reworking of HM during later Neogene transgression/regression of the coastal basin. Relative uplift of the Eucla Basin since Miocene time, and progressively drier climatic conditions, have preserved the extensive Eocene coastal deposits that contain the HM. Roy et al. (2000) considered that growth faulting during sedimentation in the Murray Basin was responsible for creating virtual headlands on uplifted blocks of an otherwise featureless sandy coastline. The concentration of high-grade HM strandlines on uplifted blocks was postulated to be due to increased supply of sand and HM from erosion of offshore older sandy sediments, with onshore transport concentrating HM in the prograding coastal barriers (Roy et al., 2000; Roy and Whitehouse, 2003). Winkler and Howard (1977) concluded that shorelines of the southern Atlantic coastal plain of the United States were deformed (warped) from the Pliocene to Pleistocene coinciding with periods of HM deposition along the coast. Tectonic influences on active coastal process therefore provide additional criteria that can be modeled when assessing prospective terrains for HM deposits.

4. Mineralization of HM beach placers

There are several variations in the mode of formation of beach placer deposits, which are controlled by many factors. However many ancient and modern examples have common features, such as: 1) the deposits lie on the trailing margins of continents; 2) the HM are sourced primarily from high grade metamorphic terrains; 3) HM-bearing sand body complexes are generally oriented parallel to the coast and the paleo-strandlines correspond to past fluctuations in local sea level; and 4) HM deposits occur at latitudes less than 35° (e.g., southeastern coast of Australia, the southwest and southeast coasts of India, southeast USA, Thailand, southern Africa etc.) (Force, 1991; Roy, 1999; Ali et al., 2001; Van Gosen et al., 2014; Hou et al., in press).

4.1. HM sand deposit formation

The basic processes involved in the formation of coastal HM deposits include source, transportation, deposition, erosion and re-deposition. All of the above steps apply to both ancient and modern HM deposits, with minor modifications. In addition to the general ore-forming processes, there are numerous regional and local factors that can influence the development of HM sands, such as: strong and sustained wave action (Komar and Wang, 1984), winds, coastal currents (longshore drift) combined with the geomorphology of the coast (Baxter, 1977) (Fig. 1), sea level changes (McKellar, 1975; Chappell and Shackleton, 1986; Hou et al., 2006, 2008) (Fig. 6), tectonic events, and post-deposition weathering (Force et al., 1982).

HM-bearing sediments are deposited and redistributed in a variety of shoreline environments (Fig. 1), including the beach face (foreshore), the shoreface, barriers/ridges/spits, dunes, tidal lagoons, and deltas (Frihy, 1994; Roy, 1999; Roy et al., 2000; Hou et al., 2003b, 2011b). Shorelines move landwards or seawards as sea level changes over geological time, so HM deposits on earlier shorelines are either covered by more sand, or eroded and re-deposited in the 'new' shoreline (Fig. 6). The result of this activity is that HM deposits are occasionally found far inland and sometimes buried up to 50 m below the surface. In the Eucla Basin, for example, the Eocene marine transgression moved the shoreline further inland by as much as 30 km between 39 Ma and 37 Ma (Hou et al., 2006, 2008, 2011b). The sorting processes, naturally segregating high density minerals from lower density materials, can result in discrete thin layers (and composite intervals) composed predominantly of heavy minerals (Fig. 5). The most significant sites of

HM accumulation are sediments deposited in barriers, dunes (aeolian sand), foreshore, shoreface, and lagoonal environments (Figs. 6 & 7) (e.g., Force, 1991; Roy, 1999; Hou et al., 2011b).

4.2. HM enrichment

In the vast majority of HM suites, ilmenite is the most abundant HM and the principal ore mineral, followed by zircon, rutile, and leucoxene (“altered ilmenite”), which together often comprise more than 80 percent of the HM suite. Other HMs sometimes recovered as co-products include garnet, sillimanite, staurolite, and monazite. Depending on various aspects, such as location, depth, scale of the deposit, and market price, economic deposits can contain less than 1% HMs, with composite grades usually >2% which locally can exceed 10%, or, on a small scale, may exceed 60% (Hou and Warland, 2005). The gangue minerals in HM deposits are generally dominated by quartz sand/silt, clay minerals, and iron-oxide minerals, with minor or rare feldspar and carbonate minerals.

Specific processes of HM enrichment occur mainly in the principal zone of mineral sorting, i.e., the upper part of the beach face, also known as the swash zone (the foreshore) (Force, 1991) (Fig. 7). The heaviest grains, which have the highest settling velocities, are deposited at the bottom of the swash zone. Coarse low density detritus is carried by backwash to the wave zone, while HM tend to settle out and accumulate on the upper beach face (Komar and Wang, 1984). Force (1991) described HM concentration as “a process involving lag enrichment on the swash face,” in which erosion dominates over deposition and “backwash efficiently sorts the available material, to produce a layer enriched in fine dense minerals” (Fig. 5). Economic deposits of HM represent innumerable thin layers of HM accumulations separated by mini-unconformities.

Mature development of a HM suite in the coastal environment can be enhanced by: 1) long periods of erosion; 2) relatively low rates of sediment supply; 3) strong sustained wave action that moves fluxes of sand onshore and along the shore; 4) relative sea-level changes; and 5) winds (Roy, 1999; Hou et al., 2003b). Important mechanisms for sorting and concentrating HM in the shore environment are interpreted to be: 1) surf wave action in the swash zone of a beach; 2) high energy surf and surge driven by turbulence during storm events; and 3) longshore drift (Baxter, 1977; Force, 1991). The forces of waves, tides, and longshore drift work the detritus, selectively carrying off lighter grains and leaving a fine-grained accumulation of heavy, dense mineral grains. Variation in particle settling velocities, due to differences in mineral densities (Table 1), work in combination with wave and tide actions in the swash zone to effectively segregate HM from light minerals. The resulting sands are typically well sorted, medium- to fine-grained, well rounded, and not indurated (Force, 1991).

Wind can be a very effective mechanism for sorting the heavy, dense minerals from the lighter grains of sand (quartz). After sands accumulate on the beach (particularly the backshore), wind can rework the sands to form sand dunes (Figs. 5 & 6). Some aeolian deposits contain substantial concentrations of HM. Aeolian processes created many of the world's largest fossil and recent heavy-mineral deposits, such as: 1) the Guaju HM (ilmenite-dominant) deposits on the eastern coastal area of Brazil (Sabedot and Sampaio, 2006); 2) Late Holocene aeolian HM backshore dune deposits on the southern coast of Brazil (Dillenburg et al., 2004); 3) the Grande Côte HM deposit, a mobile dune field about 100 km long bordering the Senegal coast (Mineral Deposits Limited, 2016); 4) the highly productive Richards Bay area HM deposits (zircon, rutile, and ilmenite hosted in dune sands) on the east coast of South Africa (Richards Bay Minerals, 2013); and 5) DuPont's Trail Ridge HM deposits hosted in a Pliocene dune field in north-central Florida (Force and Rich, 1989).

Four different types of HM deposit are recognized in both modern (e.g., the HM-bearing shorelines of the eastern Australian coast; Roy, 1999) and ancient shorelines (e.g., the paleoshorelines of the Murray

and Eucla Basins): lag deposits, transgressive deposits, regressive deposits, and aeolian deposits (Fig. 6a). The mechanisms for concentrating HM along (paleo-) coasts occur on drift-aligned coasts experiencing littoral bypassing (alongshore drift; Fig. 1) and/or in transgressive barriers with negative sediment balance (Figs. 1 & 6). Littoral bypassing fractionation operates during sea-level highstands on open drift or headland-bounded coasts (Figs. 1 & 6c), where repeated storm erosion and winnowing progressively enrich the lag of HM on the beach face, and new sands with fresh HM are added from updrift during beach-recovery phases between storms (Roy et al., 2000). Transgressive barrier fractionation, referring to the erosional reworking of the seabed, occurs during marine transgressions when there is a negative sediment budget (sand outputs exceed inputs) within a swash-aligned coastal sector (Roy et al., 2000). Landward migration of the transgressive barrier results in downdrift sand losses due to erosion of the pre-existing substrate. The HMs contained in the substrate tend to progressively accumulate in the barrier beach and washover facies, resulting in the emplacement of transgressive-type HM deposits along the transgressive/highstand coasts (Fig. 6b). As washover lithofacies make up virtually the entire transgressive barrier, the transgressive type HM placers are considerably thicker than either lag type (e.g., Ooldea barrier of the eastern Eucla Basin; Hou et al., 2003b; Hou et al., 2008, 2011b) or regressive type deposits (e.g., HM deposits of the Murray Basin; Roy et al., 2000).

5. HM exploration

The basis of HM exploration is recognition of suitable depositional environments, such as strandlines/beach ridges and embayments. This is followed by formulation of a geological and geomorphological model. The model must incorporate a number of factors including basin geometry, stratigraphy, (paleo-) shoreline evolution, (paleo-) climate, tectonics, provenance areas, prevailing wind and wave directions, and potential sites of deposition. HM exploration is based on knowing as fully as possible the geomorphological and geological processes resulting in the local and regional formation of HM deposits, as well as being aware of the properties of the valuable HM, which enables their detection using appropriate (e.g., geophysical) exploration methods. Exploration for HM sand deposits involves the positive identification of key criteria leading to the focus of exploration to locate shorelines or strandlines that host HM facies, to be followed by surface sampling, augering and drilling. It is critical to identify key (paleo-) shorelines and potential HM trap sites as well as favorable sedimentary facies within host sequences.

A complex interplay between Quaternary sedimentary cover, paleoshoreline sediments, and older (e.g. Paleozoic) sediments and deeply weathered basement rocks make paleostrandline/ beach ridge identification difficult in ancient sedimentary basins such as the Murray and Eucla Basins. There are considerable opportunities and challenges for exploration in such complex paleocoastal terrains, often masked by a cover of surficial regolith. Generally, because cover can conceal most of the paleo-features such as sand barriers and strandlines, there are few surface geologic indicators to guide exploration to favor one part of a tenement over another. Paleoshoreline and paleovalley identification can assist mineral exploration by providing HM exploration targets (Hou and Mauger, 2005). Mapping out paleoshorelines and associated paleochannels, and understanding their distribution and interrelationships, are critical to the choice of effective exploration methods (Table 3).

5.1. Methodology

The development of exploration techniques, especially techniques that can be applied at regional scales (Fig. 2b, c), will benefit ‘greenfield’ exploration for HMs. Ideally, the technique(s) can also be scaled down to local scales to identify and delineate individual HM deposits (Fig. 3).

Table 3

Methods for identification of paleofeatures and comparison of the effective features.

Techniques	Data	Feature	Sampling depth	Costing	Effective-ness
Geology	Field observation and sample	Surface geology	Surface	Low	Low-medium
	Geology GIS Dataset	Surface geology	Surface	Where available	Low-medium
	(Variable scale geological maps)				
	Solid geology & Geology Provinces GIS Dataset	Subsurface geology	0–1000 m plus	Where available	Low-medium
	Palynological/isotopic dating	Defining host unit	0–200 m plus	Medium -high	High
	HM dating	Predicting sources	Hosting strata	High	High
	Type sites of paleostrandline/ paleovalley formations	Buried paleogeography	0–100 m plus	Where available	High
	Deposit, associated with paleovalleys/ paleoshorelines	Economic significance	0–100 m plus	Where available	High
	Open pit	Subsurface geology	0–tens m plus	High	High
	Drillhole log or sample	Subsurface geology	0–200 m plus	High	High
Geochemistry	Geochemical survey	Surface geochemistry	0–0.1 m plus	Medium -high	Low
Topography/ landscape	Aerial photographs	Surface feature & elevation	Surface	Low	Medium -high
	Landscape reliefs				Medium -high
Remotely sensed data	NASA SRTM 3 s DEM	Elevation	Surface	Low	High
	Landsat multispectral image	Reflectance	Surface	Low	Low-medium
	NOAA ntt image	Thermal property	Near/surface	Low	High
	ASTER ntt image	Thermal property	Near-surface	Low	High
	Landsat 7 ETM + ntt image	Thermal property	Near-surface	Low	High
	Hymap	VNIR-SWIR	Surface	High	Low
Geophysics	magnetic	Magnetic	0 – 10,000 m plus	Medium	Medium
	gravity	Density	0 – 10,000 m plus	Medium	Low
	AEM/TEM images	Conductivity	0 – 300 m plus	Medium-high	Medium -high
	Shallow seismic	Seismic velocity	0 – 1,000 m plus	High	Medium -high
	Radar (ground, air & space)	Microwaves	1 – 40 m	High	Medium -high
	Radiometrics	Gamma rays	<1 m	Low- Medium	Low-medium
	Induced Polarization (IP)	Resistivity	0 – 1,000 m plus	Medium-high	Medium -high

Existing geological data (e.g., maps and drillholes) can be combined with field studies to improve what is known of the dimensions, trends and continuity of paleoshorelines and associated paleovalleys. Sampled materials should be examined to determine sedimentary type and facies, environment of deposition and conditions of weathering. This will usually require petrological, mineralogical and geochemical analysis on selected sediments and HM assemblages. For the Australian basins, the stratigraphic framework that underpins interpretations relies to a large extent on geochronological and paleontological age determinations from an extensive drillhole dataset (e.g., Smyth and Button, 1989; Waterhouse et al., 1994; Benbow et al., 1995; Hou et al., 2003b, 2006). Combining this with regional sea level history, sedimentological analysis is summarized for the interpretation of the formation of the basins that contain HM resources, including the paleoshorelines and paleovalleys. To understand the source of the HMs, which is importance for exploration, detrital HM (zircon, and possibly rutile and monazite) should be geochronologically dated (e.g., Reid and Hou, 2006; Reid et al., 2009, 2013; Hou et al., 2001a,b, 2003a,b,c, 2006, 2008; Keeling et al., 2015).

Difficulties arise in exploring for HM deposits buried beneath thick overburden over broad areas without resorting to close-spaced drilling to reconstruct paleocoastal features and to identify HM target areas. More precise delineation of paleoshorelines and paleovalleys allows for more targeted and effective drilling. In recent years, various geophysical techniques have been applied in projects to map the distribution of buried paleocoastal and paleochannel deposits or to directly detect HM concentrations; these include magnetics, seismic, gravity, electromagnetics, and down-hole gamma logs (e.g., Smyth and Barrett, 1994; Deen et al., 2000; Leslie et al., 2000; Mackey et al., 2000; Hou et al., 2001c, 2003a). Remote sensing and digital topography assisted by computer processing techniques have proven useful for delineation of paleoshorelines and paleochannels, where these continue to influence surface features (e.g., Tapley and Wilson, 1985; Tapley, 1988, 1989; Statham-Lee, 1994; Hou et al., 2000, 2011a,b, in press; Hou and Mauger, 2005).

The first step to identify (paleo-)shorelines involves the use of regional geological maps, Landsat imagery and/or aerial photography to compile geomorphological maps that outline and categorize geomorphological features. The second step includes the use of DEM and

night-time thermal images combined with geological and drillhole data to delineate strandlines/beach ridges/barriers/dunes to reveal coastal features, which form the basis of HM exploration. Geophysical methods, such as magnetic, gravity, radiometrics, induced polarization and resistivity, radar, electromagnetic, and shallow seismic may provide useful information for refining delineation of features (see below) (Webster, 1990). Although geophysics is not widely used in HM exploration, it provides relatively cheap and useful exploration tools, compared to close-spaced drilling.

5.2. Specialised mapping (GIS)

The distribution and the two and three-dimensional (2D or 3D) arrangement of sediments in paleoshoreline and associated paleovalley deposits are of significance for HM exploration. The paleoshorelines and associated paleovalleys in the HM-bearing sedimentary basins of South Australia have been shown to be broadly mappable using a variety of techniques (Table 3; Hou et al., 2007, 2012). However all methods have advantages and disadvantages due to complexities associated with variable resolution of images, and underlying regional and local geological controls, which may not be fully resolved (Hou and Mauger, 2005). The paleoshoreline- and paleodrainage-landform features outlined in GIS, when combined with other (e.g., geophysical) datasets, can often reveal patterns of sedimentation sufficient for some level of geomorphological and sedimentological analysis (Hou et al., 2001c). In terms of understanding a paleoshoreline and associated paleovalley areas, some of the difficulty arises from insufficient understanding of shoreline and channel behavior and of lateral and vertical lithofacies changes in shoreline- and channel-sediment profiles. Eventually, models of shoreline and channel behavior and associated lithofacies changes in the shoreline- and channel-sediment profiles should be tied to paleoshoreline and paleochannel maps of appropriate scale, to allow 3D mapping, where possible (Hou and Mauger, 2005; Hou et al., 2012). The application of remote sensing and geophysical data to paleoshoreline and associated paleovalley delineation is based on three important factors: 1) the spatial and genetic relationships between surface materials and underlying sediments; 2) the physical and spectral contrasts between sediments and surrounding terrains; and 3) the nature of paleocurrent and paleoriver dynamics.

5.3. Aerial photography and topography

The surface expression (e.g., topographic highs) of paleostrandlines/beach ridges is 'obvious' only in places where sedimentary cover and regolith is thin or lacking, such as in parts of the margin of the Eucla Basin and western Murray Basin. In such situations, analysis includes consideration of overall strandline/beach-ridge orientations and patterns, individual strandline/beach-ridge patterns, and strandline/beach-ridge irregularities. Parallel strandline/beach-ridge patterns and other pattern variations have gross characteristics that readily distinguish them from irregular patterns, i.e., there is a tendency toward parallelism of the larger tributaries in a topographic pattern. Pattern variations are characterized by internal details, but these are commonly obscure. Further investigation of pattern variations can provide insight into processes such as basement faulting or post-depositional reworking that may influence HM concentration or subsequent redistribution.

5.4. Remote sensing techniques

Satellite remote sensing techniques are generally useful for generating near surface geological data and facilitate the screening of large areas to identify target regions for geophysical acquisition during HM exploration. Sands that host HMs may show diagnostic absorption patterns in the visible (VIS) to mid-infrared (MIR) region of the electromagnetic spectrum that allow them to be discriminated from other sediments in a particular region, but, apart from their generally dark color, titanium minerals (e.g., ilmenite, rutile and leucosene) lack distinctive diagnostic features in the VIS to NIR spectral region. Spectra of zircon and monazite show fine structure in absorption features in the VIS to NIR that are caused by crystal field f-f transitions of rare earth ions present in the minerals. When these minerals occur in very high concentrations, the sharp spectral bands can be used for identification and can also help identify the rare earth elements within their structure (Van Gosen et al., 2014). However, zircon and monazite, occurring in low concentrations would be very difficult to detect directly using airborne or spaceborne remote sensing.

5.4.1. SRTM DEM

Digital elevation models (DEMs), which particularly used as overlays on photographic-style imagery provide nearly scale-independent 3D viewing capabilities, have become essential analytical tools for quantitative-process geomorphology. Their value lies in the ability to generate morphometric and hydrogeological attributes of the terrain, which in turn provide fundamental information on landscape processes and the geomorphological evolution of the region. DEMs can be very effective in revealing broad-scale patterns associated with paleoshorelines and paleochannels as linear or dendritic topographic highs and lows, which can be related to a coherent paleoland surface, even where only disconnected remnants of these remain in the current landscape. In areas, such as the eastern Eucla Basin and Murray Basin, where there are spatial and genetic relationships between the modern and fossil landscapes which are able to be discriminated, DEMs can be used as surrogates for mapping paleostrandlines/beach ridges and paleochannels and related features (Fig. 2b & c; Bowler et al., 2006; Hou et al., 2012).

5.4.2. Landsat TM (day-time) Data

Enhanced surficial geological features using the ratios of Landsat TM bands are useful for separating and identifying different materials, but are problematic for linking to subsurface paleoshoreline and paleovalley features (Hou and Mauger, 2005). The processed Landsat image can be draped over DEM/geological map/night-time thermal images to enhance the paleoshoreline and paleochannel interpretation when the models of shoreline and channel behaviors and lithofacies changes in the shoreline and channel sediments can be tied to appropriate scale

paleoshoreline and paleochannel maps (Hou et al., 2012). For example, paleodrainages are visible in parts of the eastern Eucla Basin and western Murray Basin on Landsat TM images as branching features made lighter than the surroundings by the presence of carbonate and gypsiferous clays within playa lakes and depressions, which are arranged along the lines of paleodrainage within broader paleovalleys. Landsat images are effectively photographs of the landsurface, which can be used in combination with DEMs to map paleodrainage and major paleostrandlines or ridges and to also identify spectrally anomalous zones or regions. In this way, Landsat TM imagery can provide reasonably acceptable maps of the major paleostrandline or barrier coastal dunes, but discrimination of minor paleostrandlines is less successful because of poor tonal contrasts, low resolution at 30 m pixel size, and/or inadequate ground response to the imaging system, due, in part, to vegetation and soil cover.

5.4.3. Night-time thermal data

Night-time thermal (NTT) images are preferred by the earth sciences for geological interpretation, as temperatures are stable and topographic effects are suppressed (Drury, 1987). Temperature inversions caused by the concentration of cold dense air in depressions in the landscape are more common at night than during the day (Gentili, 1972), and may contribute to significant changes in radiant temperature values recorded by the satellite sensors. A NTT image is a record of the stored heat being emitted from surface and subsurface features (Fig. 10). The dominant factors that affect these thermal properties are moisture content, soil/rock type, density, porosity, albedo and emissivity (Tapley, 1989), which control the appearance of individual features in thermal images.

NTT data are today inexpensive and readily available and provide a regional dataset useful for mapping paleostrandlines or ridges and paleovalleys, especially in areas where water-saturated clayey sediments occur, such as in depressions between paleostrandlines and along paleodrainage channels. Paleocoastal and paleovalley features evident in NTT imagery appear to be primarily caused by elevation contrasts. Strandline features are accentuated by the ponding of cool air in swales between the relatively higher strandlines (Fig. 10). In fact, many of the lineaments correlate well with elevation (fault scarps, basement outcrops and strandlines). A secondary effect results from the thermal inertia contrast between denser vegetation cover on the dune crests and open vegetation or grassland cover in the swales and surrounding areas. NTT imagery can show these features clearly, particularly at times of the year when there is a large diurnal temperature range, which accentuates the thermal contrast between channel sediments or moist sands and the surrounding terrain during the period of night-time cooling (Fig. 10).

5.4.4. Comparison of the remote sensing methods

The remote sensing methods outlined above have been used to identify paleostrandlines and paleovalleys to varying degrees (Table 3). Considerable differences in effectiveness are seen between Day-time (DT) and NTT imagery. The DT images primarily highlight the surficial/modern sand dunes, whereas the NTT images more clearly reveal features associated with buried coastal sand barriers and drainage of the paleo-landscape. The improvement in resolution of NTT data (ASTER cf. Landsat 7 ETM+ and NOAA) is evident in the detail of the Ooldea paleocoastal dunes and northwestern Murray Basin strandlines (Fig. 11). Landsat 7 ETM+ NTT imagery, particularly when combined with SRTM DEM, was found to be the most effective method for delineating paleovalley and paleocoastal features. In particular, high resolution Landsat 7 ETM+ NTT data, 60 m pixel compared to 90 m pixel for ASTER NTT data, and 1100 m pixel for National Oceanic and Atmospheric Administration (NOAA) NTT, have improved the discrimination and mapping of drainage channels within paleovalleys, and the pattern of partially buried paleocoastal dune complexes.

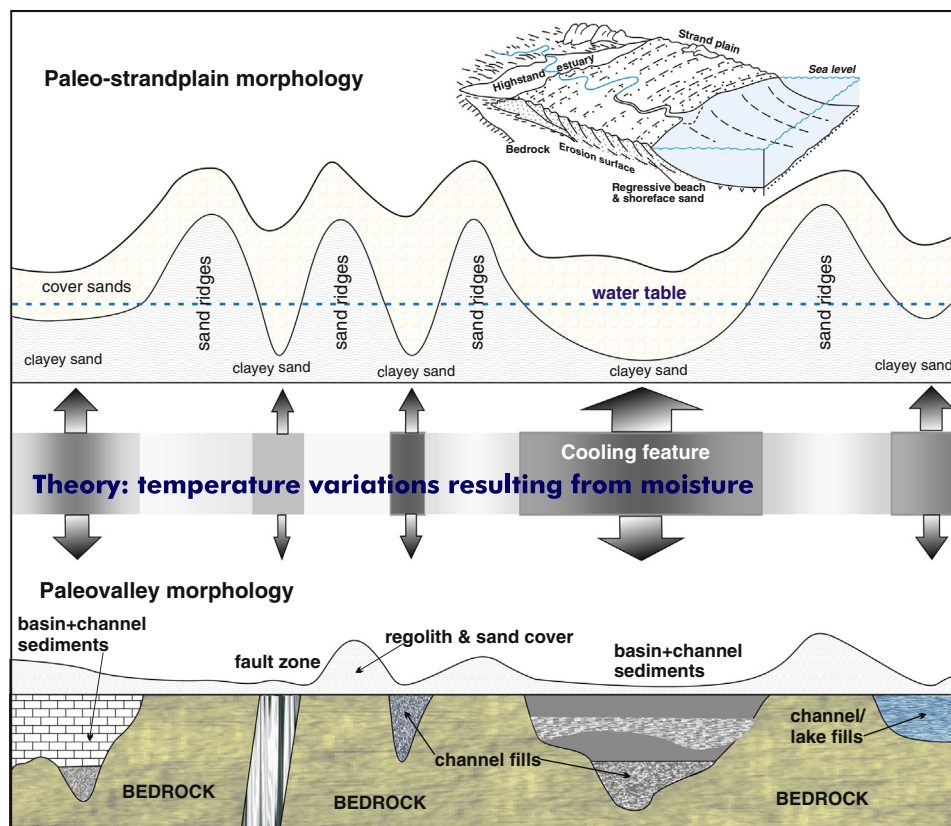


Fig. 10. Schematic night-time thermal (NTT) interpretation for a record of the stored heat being emitted from surface and subsurface features of paleovalleys and strandlines/beach-ridges/sand barriers and outcropping bedrock/basement (from Hou et al., in press).

A possible extension in the use of NTT imagery would be to directly detect paleostrandline and paleovalley features that host concentrations of HM. This would require resolution of subtle paleocoastal features partially buried by younger or reworked sediment. To achieve the best results for this type of study, the acquisition time of the data must correspond with maximum thermal contrast between paleostrandline and paleovalley sediments and surrounding lithology. To optimize results, a pre-dawn acquisition time of between 2.00 and 4.00 am following a period of extended solar heating may be necessary at a time of year specific to the region of interest (e.g., January–February in Western Australia; August–September in South Australia) (Hou and Mauger, 2005; Hou et al., 2001c). Features identified from high quality NTT imagery would need additional investigation, possibly using other geophysical methods, to interpret them in terms of sediment facies and shoreline/channel interactions, which could be used to refine HM targets for drill testing.

5.5. Geophysical methods

Geophysical methods used for HM exploration include radiometric (gamma-ray spectrometry), magnetic and induced polarity surveys, which are all based on the physical and/or chemical properties of particular HMs. Other methods such as gravity, radar, electromagnetic and shallow seismic may also be useful for mapping features of relevance.

5.5.1. Magnetic methods

The likelihood of success from magnetic methods is related to the presence of magnetic minerals in the HM suite (Force et al., 2001; Shah et al., 2012). Magnetic anomalies highlight lateral magnetic contrasts in coastal and channel sediments generated by minerals such as magnetite, titanomagnetite, maghemite, and hematite, integrated over depth. A HM assemblage may generate a measurable magnetic anomaly, depending specifically on the properties and quantity of magnetic

minerals in the sediment. Where magnetic anomalies are identified as associated with the HMs, then high-resolution airborne magnetics is a potentially useful exploration method to discriminate strandlines with high HM content.

Successful examples of using low level, high-resolution magnetic surveys for exploration of HM deposits include locating HM concentrations within a few hundred meters of linear aeromagnetic anomalies in the Russian Kolyma River Basin (Bronshiteyn and Karpova, 1969), and imaging strandlines with variable HM content in Murray Basin, which led to discovery of HM deposits at Kulwin, Woornack and Rownack near Ouyen, Victoria (Leandri, 1998), and additional strandlines near Mindarie, South Australia (Mudge and Teakle, 2003). The magnetic anomalies in Murray Basin strandlines are due mostly to iron oxides and possibly magnetite at Kulwin, and weakly magnetic ilmenite/hematite together with iron oxides at Mindarie.

The very weak magnetic anomalies (± 20 nT) are identified by using very low flight heights, 15–25 m above ground level, straight flight lines perpendicular to the strandline orientation and ~400 m apart, and post processing (involving filtering the data to enhance the near-surface signal then automated correlation of linear features across flight lines, so as to eliminate isolated cultural features; Mudge and Teakle, 2003). In off-shore settings, shipboard magnetic surveys have also detected magnetic anomalies that likely represent placer deposits rich in ilmenite and magnetite, as in offshore Maharashtra, Indian Ocean (Siddiquie et al., 1984). A drawback of the method is that deposits with high content of valuable HM (e.g., zircon, rutile), but containing few magnetic minerals or iron oxide weathering products, would not be detected in magnetic surveys and may therefore be overlooked.

5.5.2. Gravity signature

The fundamental principle governing the use of gravity as an exploration tool for coastal and channel deposits is that a sufficiently large density contrast exists to differentiate coastal and channel sediments

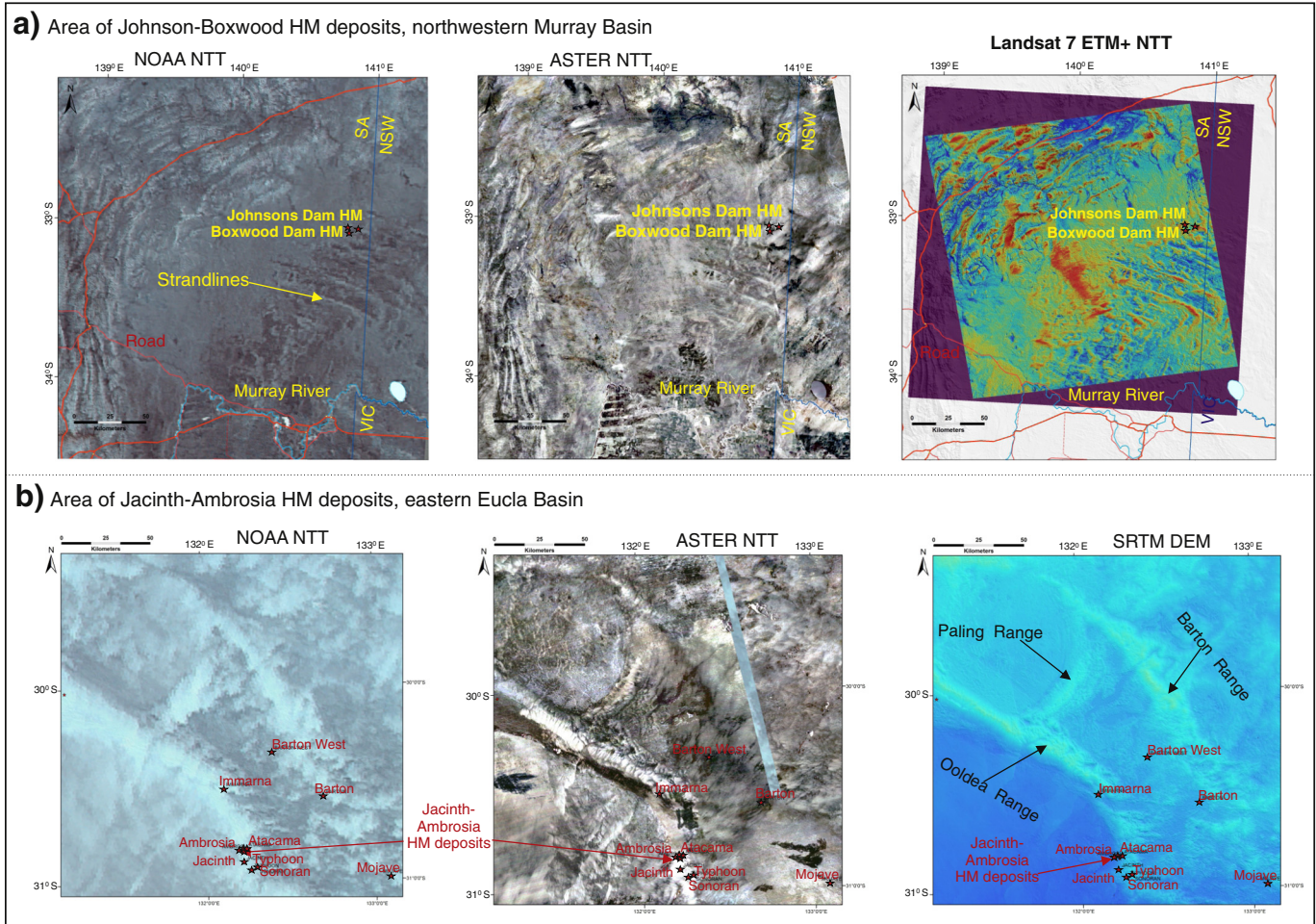


Fig. 11. Comparison of Landsat 7 ETM + NTT, ASTER NTT and NOAA NTT, and DEM images for mapping of paleovalleys and paleocoastal barriers (from Hou et al., in press).

from the underlying and surrounding materials. For example, for a 10 percent concentrate of HM having an average density of 4.5 g/cm^3 , and background sediments (such as quartz) with a bulk density of 2.6 g/cm^3 , the associated density contrast would be 0.19 g/cm^3 . Such contrasts are often measured for bodies that are several hundred meters thick and wide (Hou et al., in press). Placer deposits are often thinner (e.g., in the Eucla and Murray Basins), but basic calculations show that a body close to Earth's surface that is less than 100 m thick would produce an anomaly of as much as 0.7 mgal. Such an anomaly is small but certainly measurable with high-resolution modern instruments.

As ground gravity measurements at a single station typically take several minutes, the large number of measurements required to delineate HM concentrations in narrow strandlines might prove to be too labor-intensive. As with magnetic anomalies, it may also be difficult to separate placer source signals from background noise, i.e., to distinguish anomalies attributable to placer sources from those attributable to deeper density variations (Table 3). Consequently, gravity methods are not typically used to delineate paleostrandline/beach ridges and associated placer deposits, but might be considered for characterization of surrounding geologic features, which can also influence coastal development and control paleoshoreline features.

5.5.3. Radiometric signature

Airborne gamma-ray measurements record the radiometric decay of potassium, thorium and uranium, essentially from the top 50 cm of the earth surface (Table 3). Radiometric anomalies can be generated by various components of HM concentrates, in particular, monazite, which presents as a Th peak if spectral analysis of the data is provided (Force

et al., 1982; Grosz et al., 1989, 1992; Grosz and Schruben, 1994), zircon generates Th and U anomalies, uranium-rich phosphates also generate radiometric anomalies (Force et al., 1982; Grosz et al., 1989), and light minerals such as K feldspar and micas contribute to total count surveys but appear as K peaks in the gamma spectra. For HM concentration showing anomalous radiometric Th levels a high monazite content might be suspected and be of particular interest for the rare earth element potential from monazite. It is expected that areas showing high total count values can be identified as depositional zones, where the true radiometric response from the underlying HM-bearing sediments reflects a reasonable amount of accumulated radioactive elements. Radiometric methods, therefore, have been commonly used in exploring for HM sands worldwide, including the southeastern United States and southern Australia. The combination of airborne gamma-ray spectrometry and digital terrain models have been useful in the Murray Basin to assist with identification of paleo-strandlines for HM exploration (Fabris, 2002; Miranda, 2007). Wynn et al. (1990) reported an example of the effective use of radiometric methods in the exploration for monazite-rich HM deposits. Conversely, HM concentrations containing minor amounts of monazite, or those buried several meters below Earth's surface, are unlikely to produce a corresponding radiometric anomaly (e.g., Grosz and Schruben, 1994).

Results from radiometrics generally do not appear to lead to better identification of paleostrandlines/beach ridges and paleovalleys; numerous factors, such as the shallow effective depth of the method and variable behavior of the radioactive materials could interfere. The relative distribution of these radioactive elements in the surface materials around and in the near-surface sediments or in bedrock, as estimated

from the intensity of their emitted peaks, does not directly encourage the study of buried strandlines and channels and their related mineralization. In the case of the eastern Eucla Basin (Hou et al., 2001c), as well as in similar studies such as at Eneabba in Western Australia (Mudge, 1994) and the Olary block in South Australia (Curtis et al., 1990), the radiometric method for defining paleostrandlines and paleochannels did not prove to be successful, mainly because target materials are effectively limited to less than a half meter from the surface. As the interpretation of radiometric data is complex and does not allow it to be used independently, radiometric data are best interpreted in conjunction with other datasets, including Landsat, DEM, night-time thermal, and AEM images (Hou et al., 2001c).

5.5.4. Electromagnetic (AEM and TEM)

The conductivity of HM-bearing sediments is dependent on porosity, moisture content and the conductivity of the groundwater in the sediment. Electromagnetic (AEM and TEM) methods will give a very strong response in conductive highly saline brines in porous channel sediments and have very low signal strengths over fresh, dry dune/barrier sands and bedrock (Table 3). Both AEM and TEM are good guides to conductive variations in the subsurface and have proven to be very useful techniques for detecting buried conductive anomalies. Interpretation of the cause of conductivity and the depth to the anomaly is improved where there is additional information, against which the results can be correlated (e.g., gravity, seismic, ground magnetics, and drilling). Paleostrandlines and beach ridges are often difficult to delineate in electromagnetic data because there is rarely a significant conductivity contrast between the ridges and adjacent terraces. Buried paleodrainage channels with saline groundwater or water saturated clay sediments have been effectively mapped from AEM data, but complications arise where channel sediments are dry and where saline groundwater is present in deeply weathered bedrocks (Hou et al., 2001b,c).

5.5.5. Induced Polarization (electrical signature)

As a technique for measuring an induced potential field in the ground, Induced Polarizations (IP) can be used to map the geological subsurface (Table 3). IP measures the slow decay of voltage after pulsing an electrical signal into the ground, and is a useful tool to follow-up airborne magnetic targets prior to drilling, and to confirm the area and extent of deposits after the first stage of drilling (Webster, 1990). IP has been used to detect many types of deposits, including porphyry copper, gold-bearing sulphides, and manganese and titanium-bearing placers. The use of electrical methods for HM delineation has been explored most fully through the use of IP, which uses time-varying currents to measure how well charges are retained. IP has been used for identifying ilmenite-dominant deposits. Robson and Sampath (1977) found a strong IP response to ilmenite concentrates from Australia, but Lawton and Hochstein (1980) did not observe an IP response to New Zealand titanomagnetite sands. Successful application of IP in identifying HM in the marine environment was reported by Wynn et al. (1985, 1990) and Wynn (1988), who attributed the source of chargeability anomalies primarily to ilmenite, and to a lesser degree to leucoxene.

5.5.6. Radar methods

Radar methods are tools of increasing importance in the study of subsurface features (Table 3). Side-looking airborne radar (SLAR) can be used to identify geomorphological structures such as paleostrandlines/beachridges beneath cover/vegetation. Ground-penetrating radar (GPR) can also be used for delineating sand barrier sequences that contain HM. GPR measures changes in the electromagnetic properties of subsurface features that cause reflection of transmitted electromagnetic waves, and thus can image the shallow subsurface by measuring differences of electromagnetic properties in sediment. Water plays an important, sometimes complicating, role in the behavior of GPR waves in sediment because of its large electromagnetic contrast with both sediment grains and air. The GPR method is useful for

delineating the geometry, structure and thickness of sandy shoreline/channel deposits by providing a high-resolution image of subsurface features in the form of a cross-section view. This essentially shows the variation in ground electrical properties and the method is only suitable for shallow investigations (up to tens of meters in the best conditions). These variations can be correlated with physical changes such as the beach sand/bedrock interface, the boundary between different clay/sand types (including HM-bearing sands and sands) and the water table. Features in the GPR section will correlate with geological cross-sections if, for instance, stratigraphic boundaries represent different rock types and as a result correspond to significant variations in the electrical properties, but not necessarily to other physical properties such as density, grain size or chemical composition (Griffin and Pippett, 2002). The use of high-resolution GPR allows rapid mapping of lateral variations in bedding and lithology (best at 0–30 m depth, to date), and has been used to successfully delineate HMs within a sand barrier sequence (Baker, 1991).

5.5.7. Shallow seismic methods

The fundamentals of shallow seismic techniques, including refraction, reflection and borehole methods, can be applied in mapping of subsurface structures such as buried valleys and beach ridges, as well as determining the top of bedrock, the base of paleocoasts and paleovalleys, and for examining the sedimentology and stratigraphy of coastal and channel sediments (Table 3). Shallow seismic methods are useful tools for delineation of subsurface paleostrandline/ridge and paleovalley architectures. The seismic waves are reflected and refracted when they reach a boundary between different layers underground. Using the time required for the wave to come back to the surface and the velocity of travel, the depth of different geological boundaries can be determined. As the velocity value of the waves carries information on the type of sediment or rock, this method is important not only for structural information, e.g., in delineating faults or valley structures, but also for physical characterization of layers and thus is very useful in investigations of HM-bearing paleostrandlines/beach ridges. Some examples of the successful use of seismic refraction and reflection techniques for delineating paleovalleys in Australia were also reported in the Yilgarn craton of Western Australia (Smyth and Barrett, 1994), West Wyalong (Leslie et al., 2000) and Lachlan fold belt (Deen et al., 2000) of New South Wales and the Gawler craton of South Australia (Hou et al., 2001c).

5.6. Geological methods

Seven criteria/steps provide the foundation for identifying potential sites of HM sand deposits of significant size, prior to close-spaced drilling:

1. Paleogeographic mapping dedicated to show subsurface features.
2. Identification of HM-bearing strandplains and strandlines.
3. Identification of (paleo-)drainage, associated with the (paleo-)coasts, which drain from (cratonic) provenance areas.
4. Identification of bedrock terrains with abundant high-grade metamorphic rocks or igneous rocks, focused on rock types that are especially enriched in Zr and Ti oxide minerals, specifically zircon, ilmenite and rutile.
5. Identification of HM host units and facies.
6. Preparation of geological cross-sections and block diagrams that incorporate the interpreted geological history of the area.
7. Location of prospecting drill lines on identified HM targets with sufficient sampling to also test sediment facies models.

Paleogeographic maps that outline specific subsurface features, can show the aerial distribution of paleo-environments including barriers, littoral zone and associated strandlines/beach ridges, as well as geological and structural information sourced from standard geological maps. At the shoreline, arrangements of sediment packages represent the

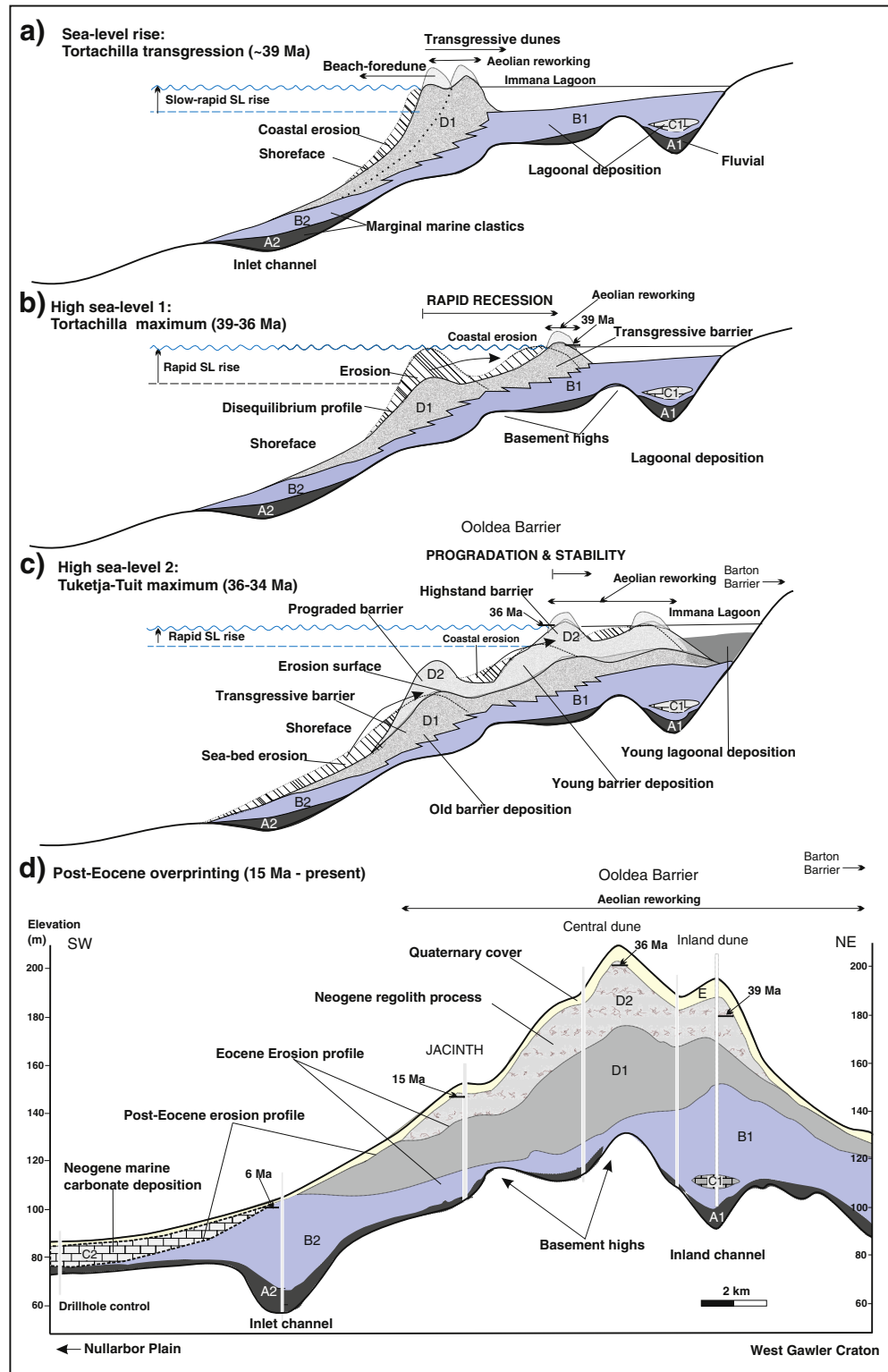


Fig. 12. Schematic evolutionary model for the Ooldea barrier and associated HM deposits, eastern Eucla Basin (from Hou et al., 2011b). The models A to D display the building events for the distinct shoreline facies shown in the SW–NE stratigraphic cross-section of Fig. 4. A) Sea-level curves for local cycles (McGowan et al., 2004) show the approximate age and sea-level for each facies building event and its change. Longshore drift, wave action or inlet bypassing that added sand to the downdrift sector (SW) of the (Ooldea) coast tends to stabilize the barrier and permitted foredunes to form on the barrier surface; foredunes impede washover processes and decelerate the rate of shoreface recession under slowly rising sea-level that may in place result in drowning of barrier superstructure, deepening the lagoon and shoreface profile. B) Rapidly rising sea-level resulted in washover processes – the barrier was overtopped and transferred inland while the shoreline moved landward. C) Continued rapidly rising sea-level resulted in sea-bed erosion and caused a disequilibrium profile offshore, which promotes nearshore (e.g., by longshore drift) and onshore sand transport (e.g., by paleorivers), building up new barriers on the old ones. D) Early Neogene weathering and erosion produced a steeper (Middle Miocene–Early Pliocene) coastline along the Eocene Ooldea barrier, and mottled the profile of the upper barriers. Erosion and aeolian reworking of each earlier stage deposition locally modified the morphology of the barrier coasts.

interplay between fluvial systems and shoreline dynamics (waves, long-shore currents, winds and tides). Thus, identifying areas where streams and rivers entered the coastal area may be helpful in indicating target zones most likely to contain HM deposits. Most major HM deposits can be interpreted in the context of such coastal settings and processes, and have been described for various HM deposits of the Murray and Eucla Basins and the southeastern coast of Australia (Roy et al., 2000; Hou et al., 2011b.). Knowledge that enables favorable zonation of permissive tracts plays an important role in recognizing zonation of HM concentrations (Figs. 9 & 12). Identification of (paleo-)drainages associated with (paleo-)coasts and the particular bedrock terrains, which are the source of HMs, is also within the scope of paleogeographic studies (Hou and Keeling, 2008; Hou et al., 2011a,b; Reid and Hou, 2006; Reid et al., 2009, 2013).

Identifying the existence and trends of paleo-strandlines is a key attribute in defining potential areas for undiscovered HM deposits. Multiple deposits of HM, each representing equivalent depositional events, can exist along the length of a strandline when viewed locally and regionally along a coastal sedimentary basin. In Australia, tens of known HM deposits occur along Pliocene strandlines in the coastal plain of the Murray Basin and more than ten are known to occur along Paleogene and Neogene beach barrier/strandlines in the coastal plain of the Eucla Basin (Fig. 2). The extent of (paleo-)strandlines/beach ridges can be indicated by recognizing (paleo-)geomorphology and time-equivalent sedimentary units and facies, which in turn predict the possible locations of related beach placer deposits. For identifying HM host units and facies, stratigraphic-sedimentological studies are essential for refining the genetic classification of sediment sequences. Evaluation of hydrographic-oceanographic data can also help to identify coastal dynamic and depositional conditions, such as coastal currents/waves and sedimentation processes.

In locating prospecting drill lines, it should be considered that several factors influence the 'footprint' of potential deposits (e.g., possible orientation of HM mineralization, deposit size and number of repetitions). HM deposits across a basin occur: 1) discontinuously along the strike of multiple strandlines (Fig. 3); and 2) are usually stacked at different stratigraphic horizons, representing different sea level events over time (Fig. 12). In plan view, concentrations of HM sands are commonly elongate but not thick; most deposits are less than 50 m thick. The areal extent of HM deposits can aid in their discovery due to their length, with individual deposits typically <1 to 2 km wide and extending for more than 5 km along strike, with a near-surface footprint of 5–10 km² (or greater) (Force, 1991). Thus, individual HM sand deposits generally cover large areas and are thereby amenable to reconnaissance exploration techniques, such as in the exploration of the Murray and Eucla Basins. In contrast to the relative ease of recognizing the orientation of HM concentrations, it is difficult to generalize about the typical density of occurrence of these deposits in a coastal sedimentary basin; the sedimentation dynamics vary considerably from basin to basin and even within a single basin (e.g., western versus eastern Eucla Basin; Hou et al., 2008).

5.7. Drilling and 3D modelling

Paleoshoreline and paleovalley mapping largely relies on extrapolating knowledge from sedimentology using a combination of geological and geophysical interpretation techniques. Information derived from the subsurface varies enormously depending on the complexity of the paleo-landscape history and local geological controls, which often complicate the responses evident in geoscientific datasets. As such, some information that is easily interpretable by one technology (e.g., night-time thermal imagery or AEM) may not be mappable or evident using other technologies (e.g., DEM or Landsat). Therefore it is important to integrate and then refine the information derived from a combination of technologies, and eventually to confirm the results by drilling. Hou (2008) carried out test drilling to validate the mapping of

paleoshoreline and paleovalley architecture interpreted from multi-source geoscientific data in the eastern Eucla Basin. Tens of drillholes intersected paleoshoreline or paleovalley sediments as well as underlying bedrock, indicating that the mapping was largely successful. The final GIS dataset and drillhole data with the interpreted results were used to create 3D models (Hou et al., 2001a; Hou, 2008; Hou and Mauger, 2005). The sediment architecture interpreted from the GIS datasets (and confirmed by drilling) can be viewed as 3D plume diagrams (Hou, 2008), mapped onto surfaces and/or visualized as block models of the paleoshoreline/valley and palaeolandscapes, in which paleosurfaces are separated to clearly illustrate change in the paleolandform over time (Hou and Mauger, 2005).

The 3D models of paleoshoreline and paleovalley landforms are very important to the understanding of landscape evolution and the major controls on the dynamics of paleorivers and paleocurrents (Hou, 2008). Details of the subsurface, from which the landscape history and paleoshoreline or paleovalley dynamics can be deduced, are revealed by linking the 3D models to knowledge of lithofacies relationships and to residual regolith and bedrock geology (Hou, 2008).

6. Conclusions

- Studies of Australia's Cenozoic HM sand deposits have provided extensive information about HM sands as to the geophysical/geological expressions of basins (and adjacent paleovalleys) containing HM resources hosted in (paleo-)coastal environments.
- HM-bearing sediments, sourced from weathered basement and bedrock, are transported via drainage systems and deposited in a variety of coastal environments, as shown in Fig. 1. Source rocks in the headwaters of rivers contribute sediment to the coast and largely determine the composition of the HM fraction in deposits.
- HM deposits occur in mostly unconsolidated sands and generally have a favorable ore thickness-to-overburden ratio. Many bodies of HM, such as those in the Murray and Eucla Basins, are typically <1 km wide and greater than a few kilometers long; their areal extent can be more than ten kilometers, and encompass several individual deposits.
- HM sand sedimentation in the coastal zone occurs in environments ranging from fluvial through estuarine to marginal marine, during marine transgressions and/or regressions. Around the peak of transgression and highstand, HM deposits form principally in beach or barrier island/dune sand complexes. Stillstand shorelines are likely associated with the formation of some of the largest and richest HM deposits.
- HMs are concentrated by the action of waves, longshore currents and wind, which are effective mechanisms for sorting the mineral grains based on differences in their size and density, resulting in laminated or lens-shaped packages of sediments. HM-rich sediment packages typically contain >2% total HM, but can locally exceed 10%, and can be up to tens of meters thick. When repeated many times over millions of years, these processes eventually create large deposits along certain paleo-shorelines.
- Complexity in the (paleo-)geography of shorelines and associated channels determine preferential sites of HM concentration. Their relative high density tends to concentrate HM components in lag and transgressive/regressive barriers/dunes or 'J-shape' bays, particularly during storms when lighter components, such as quartz, are carried offshore or along shore by strong littoral drift.
- Neotectonic movements along the margins of sedimentary basins may lead to HM-bearing strandlines being either preferentially developed on uplifted blocks or reworked and destroyed.
- HM sand deposit preservation takes place through subsidence of coastal sediments and changes in sea-level. These cause shorelines to migrate inland (marine transgression; e.g., HM accumulations of the Eucla Basin during late Eocene time) or seaward (e.g., HM accumulations of the Murray Basin during late Miocene-Pliocene). Marine

regression results in HM deposits being preserved many tens of kilometers inland of present-day coastlines.

- The greatest challenge for shoreline-related exploration is to develop practical models that explain where HMs should be concentrated and preserved in particular (paleo-)shorelines. Major refinements in remote sensing, geophysical techniques, data processing, sedimentology and computer-aided interpretations provide more effective, economic and efficient models for exploring highly prospective provinces and terrains.
- The basis for the geologic modelling of HM sand deposition relies on the integration of 1) paleogeography (particularly of paleoshorelines and paleovalleys), 2) regional and global evidence for relative sea-level change and major eustatic events, 3) the identification of HM source and dispersion, in combination with 4) tectonic activity, particularly during the time of deposition of the HM-bearing sediments.
- Regional exploration for HM deposits can initially utilize sediment sampling in conjunction with remote sensing and geophysical surveys. Physical property contrasts that exist between the basin/channel sediments and the underlying bedrock can be differentiated by various geophysical methods to locate the margins of paleoshorelines/paleovalleys, and to map sediment distribution. The geophysical signature associated with these is not represented by a simple quantifiable response from one geophysical method but instead derives from the application of several available tools. The most successful procedure for defining paleoshorelines and associated paleochannels is to combine remote sensing imagery with geological and geophysical methods to derive architectural and evolutionary models of shoreline development.
- Knowledge of the sedimentary basin and paleovalley architecture, including the sources of HM concentrations can be used as guides to the location of potential deposits, particularly in greenfield exploration areas.
- Any trace of other valuable HMs in the paleoshorelines and paleochannels (e.g., gold and diamond) is of interest as a guide to the location of bedrock mineralization.
- The descriptive and exploratory models, and methods of investigation that have been applied to Australia's HM deposits can be applied to other HM deposits across similar geologic environments worldwide.

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