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Heavy Mineral Sands in the Eucla Basin, Southern Australia: Deposition and Province-Scale Prospectivity*

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Abstract

The marine Eucla basin in southern Australia is emerging as a major new heavy minerals province in Australia. Beach placers are associated with a series of partially buried Cenozoic coastal barrier sands formed along an arcuate 2,000-km-long basin margin, the trace of which is up to 320 km inland of the present coastline. The presence of high-grade deposits with dominant zircon over ilmenite and lesser amounts of rutile and leucoxene was established with the discovery of the Jacinth and Ambrosia heavy mineral deposits in late 2004. An additional 10 heavy mineral prospects were subsequently identified and are at various stages of evaluation.

The Eucla basin and its adjacent paleovalley system have a large areal extent that contains a complicated succession of marine and nonmarine strata spanning a wide range of depositional environments. Four distinct constructional phases for the development of shorelines can be recognized and correlated with major third-order sea-level events, established by others from the marine depositional record as occurring during the middle Eocene (~42.5 Ma), late middle Eocene (39–36 Ma), late Eocene (36–34 Ma), and Miocene-Pliocene (15–2.6 Ma). Prevailing westerly winds built extensive dune systems by longshore drift. Sediment movement was from west to east. Detrital zircon grains from the Ooldea and Barton barriers show a distribution of zircon age that is consistent with the Proterozoic Musgrave province to the north of the basin as the dominant primary source area of the heavy minerals, with a contribution from the Albany Fraser orogen to the west. The likelihood is that these heavy minerals have been recycled via sedimentary basins that flank the Musgrave province and include the Neoproterozoic to Cambrian Officer basin and Permian to Mesozoic deposits of the Bight basin.

Our current depositional model is summarized as follows: (1) initial rapid transgression and deposition of a shallow marine sand sheet subsequently overlain by shallow marine limestone during middle Eocene; (2) a major Eocene transgression and deposition of a shelf, barrier, and lagoonal shoreface marine complex during the late middle Eocene; (3) further transgression and highstand deposition during the late Eocene; (4) renewed transgression of barrier, lagoonal, and possibly flooding deltaic sand blanket in the southeastern coastal plain with neotectonic uplift tilting in the western Eucla margin during Mio-Pliocene time. Each stage of reworking increased the potential for heavy mineral concentration in placer deposits.

Introduction

THE EUCLA basin, along the southern margin of Australia, owes its distinctive landscape to a unique set of interactions involving eustacy, climate, and tectonic processes over the last ~50 m.y. (Hou et al., 2008). The result is preservation of one of the largest onshore areas of Cenozoic marine sediments anywhere in the world (Benbow, 1990; Clarke et al., 2003). The 650-km-long paleoshoreline sequence along the northeastern margin of the basin exhibits a high degree of preservation and is highly prospective for heavy mineral placer deposits (Fig. 1). The extent and complexity of the paleoshoreline deposits hampered early heavy mineral exploration. A review of exploration drilling for heavy mineral sands in the region by Ferris (1994) highlighted the need for improved understanding of the evolution of the paleoshorelines in order to identify more highly prospective regions and provide a focus for exploration. A revision of stratigraphic correlations across the basin provided new correlations relating marine-coastal sediments to the stratigraphic record of offshore sediments (Clarke et al., 2003; Hou et al., 2003b). This included a reconstruction for sequences of coastal deposition in the context of well-constrained chronology of major sea-level events (e.g., McGowran et al., 1997). Previously established models for heavy mineral concentration (e.g., Roy, 1999; Roy et al., 2000) were incorporated into the stages of coastal barrier formation and used to predict new prospective sites (Hou et al., 2003b). Aided by this perspective and results of earlier drilling, renewed heavy mineral exploration by Iluka Resources Ltd. in June 2004 led to successful greenfield discoveries of the Jacinth (November 2004) and Ambrosia (December 2004) heavy mineral deposits (Hou and Warland, 2005). Ongoing exploration has identified 10 additional significant heavy mineral prospects along the eastern and northern margins of the

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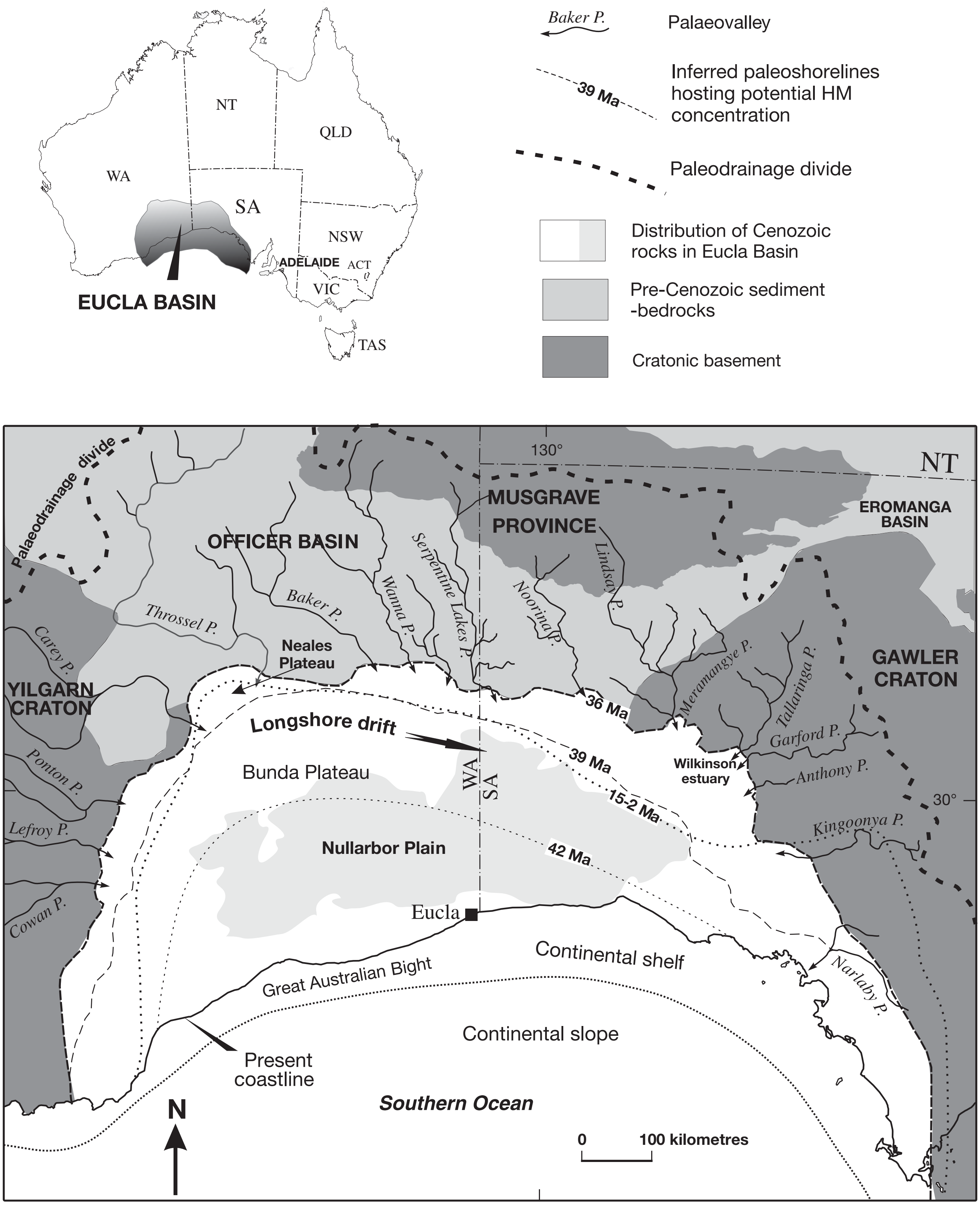

FIG. 1. Eucla basin of southern Australia showing geologic relationships with surrounding highlands (cratons and older basin) and major palaeovalleys, early Cenozoic coastlines and their approximate ages, and adjacent major features referred to in the text, modified after Hou et al. (2008), also based on GIS mapping of this study (see Fig. 2).

TABLE 1A. Eucla Basin Heavy Mineral Deposits with Resource Estimate

		Resource			Mineralogy		
Deposit	Overall dimensions	Tonnage (Mt)	Heavy mineral grade (%)	Contained heavy mineral (Mt)	Zircon (%)	Ilmenite[1] (%)	Rutile (%)
Jacinth	3.2 km length, up to 0.9 km wide, ore thickness avg 20 m, overburden thickness avg 7 m	124.3	5.2	6.5	47	30	5
Ambrosia	2.2 km length, up to 0.7 km wide, ore thickness avg 12 m, overburden thickness avg 8 m	114.8	2.7	3.0	50	21	5
Typhoon	3.0 km length, up to 0.4 km wide, ore thickness 1–21 m, overburden thickness 5–27 m	22.0	6.1	1.3	14	76	1
Atacama	7.0 km length, up to 3.0 km wide, ore thickness 1.5–18 m, overburden thickness 5–42 m	29.2	11.3	3.3	15	75	2
Tripitaka	3.7 km length, up to 1 km wide, ore thickness avg 10 m, overburden thickness avg 9 m	42.0	2.4	1.0	65	9	5
Cyclone	5.0 km length, up to 2.5 km wide, comprised of up to 5 coalescing beach-dune strandlines, ore thickness avg 18 m, overburden thickness avg 11 m	98.4	2.9	2.8	33	44	12
Total		430.7		17.9			

Notes: Number rounding may generate differences in the last decimal place; source: company information releases to the Australian Stock Exchange prior to January 2011

[1]Ilmenite includes altered ilmentite minerals - hydrated ilmenite (Ti/Ti+Fe = 0.5–0.6), pseudorutile (Ti/Ti+Fe = 0.6–0.7), and leucoxene (Ti/Ti+Fe = 0.7–0.9)

TABLE 1B. Eucla Basin Heavy Mineral Prospects

Prospect	Indicative size	Indicative grade and mineralogy
Barton West	Variable heavy mineral intersections over an area 25 km by up to 12 km	Discontinuous intersections, avg 1–3% heavy mineral over a max 16 m; heavy mineral content range 6–21% zircon, 2–10% rutile, 50–67% ilmenite, 6–24% leucoxene
Immarna	Three strandlines 4–8 km long and 150–500 m wide	Upper and lower heavy mineral intervals of avg 2 m thickness below 18 m overburden; upper zone grade 2.7% heavy mineral with 86% ilmenite/leucoxene,11% zircon
Willy Willy	At least 900 m long and ~300 m wide	Grades up to 4.9% heavy mineral over 6 m; zircon content high at 25–40% valuable heavy mineral[1] fraction
Mojave	~ 8 km long and 1–3.5 km wide	Grade range 1–22% heavy mineral over avg thickness 10 m, below avg 15 m thickness overburden; preliminary mineralogy 13% zircon, 30% leucoxene and rutile, 2% ilmenite
Dromedary	~ 1 km long by up to 500 m wide	Up to 4.5 m at 8.4% heavy mineral; indicative content 17% zircon, 57% ilmenite, 4% leucoxene; overburden avg 25 m thickness
Gulliver	~ 7 km long and up to 2.5 km wide	Avg 1–3% heavy mineral; indicative heavy mineral content 60% altered ilmenite, 21% zircon, 5% leucoxene, 2% rutile; thickness 3–7 m below avg 25 m thickness overburden
Cyclone Extended	2 km extension of Cyclone deposit that is up to 800 m wide; 2 narrower standlines to the east have been traced for 4.5 km	Grades up to 6.8% heavy mineral over 8 m; maximum thickness about 17 m, below avg 15 m overburden; zircon content above 40% valuable heavy mineral[1] fraction in some samples; fines content avg 4.2%
Balladonia	Lefroy palaeochannel outlet strandline ~1.5 km × 300 m wide	Grades to 5% heavy mineral; indicative heavy mineral content 82% ilmenite, 1.4% zircon, 3% leucoxene, 2% rutile; thickness 6–10 m below avg 10 m thickness overburden
Plumridge	Minor strandlines, preliminary test drilling only	Up to 4.2% heavy mineral of dominantly primary ilmenite with low rutile and zircon content

[1] Includes zircon, ilmenite, rutile, leucoxene

basin (see Table 1) and anomalous heavy mineral occurrences have been reported in Cenozoic sediments near Balladonia on the western margin. Exceptionally high concentrations of zircon at Tripitaka, Jacinth, Ambrosia, and Cyclone, together with the number and extent of new discoveries, establish the onshore margin of the Eucla basin as a new heavy mineral province of international significance (Hou and Warland, 2005; Hou and Keeling, 2008).

Models for the formation and reworking of paleostrandlines of the Eucla basin have continued to evolve. Earlier models that identified dominant sediment input from large paleovalley networks that drained across the Precambrian Gawler craton have been revised because the age distribution of detrital zircon from the heavy mineral deposits correlates with crystalline ages of the Musgrave province, identifying the latter as an important primary source area for the barrier sands (Reid and Hou, 2006). The significance of eastward longshore drift in building beach barriers was emphasized. This is consistent with Eocene climatic regime of dominantly westerly weather systems (e.g., Kemp, 1978) and the extensive development of lagoonal and estuarine facies at the terminal end of paleorivers draining from the Gawler craton.

It is suggested that continental-scale tilting during the late Cenozoic as a consequence of northward drift of the Australian continent (Veevers, 2000; Sandiford, 2007) is in agreement with apparent land movements noted in Eucla basin studies. These studies indicate that middle-late Eocene age shallow marine deposits on the western margin of the basin are approximately 130 m higher than chronostratigraphically equivalent shallow marine deposits on the eastern margin of the basin (Hou et al., 2008). This dynamic topography, as suggested by the changing pattern of sedimentation, provides an explanation of progressively deeper marine inundation on the eastern margin as well as a mechanism for discordant alignment of younger paleobarrier deposits formed during Mio-Pliocene sea-level highstands (Hou et al., 2008).

The unique combination of eustatic conditions, dynamic topography, and climatic and provenance factors provides a basis for proposing new integrated models for heavy mineral beach placer accommodation in the Eucla basin. This paper updates our previous interpretation of depositional events in the Eucla basin in the context of regional heavy mineral dispersion and deposition and includes a summary of data from recently discovered deposits. Exploration models can be derived from an understanding of the broader controls on sand movement and reworking across the basin that may assist in identifying additional heavy mineral targets.

Geologic Relationships of the Eucla Basin

Previous work

Early exploration for heavy mineral deposits in the eastern Eucla basin followed reconnaissance drilling for sandstone-hosted uranium and lignite during the 1970s to early 1980s, which produced samples with anomalous heavy mineral concentration (Ferris, 1994). The recognition that these anomalies were associated with a former coastal barrier system was a breakthrough (Benbow, 1990) but focused attention on the topographically elevated Ooldea, Barton, and Paling Ranges that have substantial components of reworked younger aeolian deposits with low heavy mineral content (see Fig. 2). The age, origin, and stratigraphic relationships of the sediments, particularly those containing heavy mineral deposits, and the role of sea level and neotectonics on paleoshoreline development were not well established. Geologic mapping of the eastern part of the basin (Benbow, 1990; Benbow et al., 1995a, 2000; Alley et al., 1999) identified the middle Eocene upper Hampton Sandstone and late Eocene Ooldea Sand, of (marginal) marine and barrier-dune origin, as sediment hosts for heavy mineral sands. Palynology, facies, and sequence-stratigraphy analyses were used to identify distinctive key surfaces corresponding to changes in relative sea level (e.g., Clarke et al., 2003; Hou et al., 2003a, b). The Ooldea Sand and then the Barton Sand were named for sands deposited on the respective shorelines (Hou et al., 2006, 2008). The correlation of sediments east to west across the basin and from offshore to onshore made use of many earlier studies, often on specific sites within and marginal to the basin (e.g., Lowry, 1970; Hocking, 1990; Jones, 1990; Cowley and Martin, 1991; Benbow, 1993; Clarke, 1993, 1994a, 1994b; Kern and Commander, 1993; Alley and Lindsay, 1995; Benbow et al., 1995b; Keeling et al., 1995; Clarke and Hou, 2000; Rogers, 2000; Hou et al., 2001a, b, 2003c, 2007; Johnson and McQueen, 2001; de Broekert, 2002; Hou and Alley, 2003; Li et al., 2003; Hou, 2004; de Broekert and Sandiford, 2005).

Basin setting

The Eucla basin extends 2,000 km from west to east, adjoins the Yilgarn and Gawler cratons and Albany Fraser province, and is separated from the Musgrave province to the north by the Officer basin (Fig. 1). Including offshore extensions to the platform edge, the basin is ~500 km wide from north to south. Around its northern margin, the basin contains remarkably preserved Cenozoic coastal barrier island features and peripheral paleovalley systems. The central part of the basin is characterized by a carbonate platform, named the Nullarbor Plain, a distinctive, remarkably flat, and treeless landscape extending some 1,400 km along the southern Australian margin. The large areal extent of the Eucla basin and adjacent paleovalley system, which together cover ~20 percent of the Australian continent, encompasses a complicated succession of marine and nonmarine strata, making correlation of stratigraphic, sedimentary, and tectonic events difficult. Paleogene to early Neogene landforms on the basin margin are largely covered by a veneer of aeolian dunes and sand plains, but their excellent preservation is evident from regional topographic data and from remotely sensed satellite imagery, including NOAA-AVHRR and ASTER (Fig. 2). ASTER nighttime thermal infrared imagery is especially useful in discriminating thick sand units from younger, thin aeolian sand cover. Features include large-scale paleovalleys, lagoons, estuaries, shoreline, and coastal barrier islands. These features represent Cenozoic coastal plains and paleovalleys located in large onshore margins (Figs. 1, 2). The pattern of paleovalleys in the onshore basin margin is dominantly subdendritic, reflecting both the preCenozoic land surface gradient and bedrock lithology and structure (Alley et al., 1999; Hou et al., 2001a, 2003a; de Broekert and Sandiford, 2005). On the eastern Yilgarn craton, many trunk paleovalleys are parallel to the northeast orientation of a regional fracture field (Johnson and McQueen, 2001), whereas on the western Gawler craton, paleovalleys preferentially cut into and follow weakly resistant, deeply weathered bedrock (Hou et al., 2003a).

The record of marine, marginal marine, estuarine, fluvial, and lacustrine environments is characterized by an extensive borehole dataset and spans five major depositional phases during the Paleocene-early Eocene, middle-late Eocene, Oligocene-early Miocene, middle Miocene-early Pliocene, and Pliocene-Quaternary. These phases identify the key role of eustatic change, during which highstands inundated the craton margins and flooded paleovalleys as far as 400 km landward of the present coastline. The extent of inundation was affected also by epeirogenic movement of the Eucla platform, expressed as a west-side up, east-side down tilting of ~100 to 200 m (Fig. 3; Hou et al., 2008). This differential

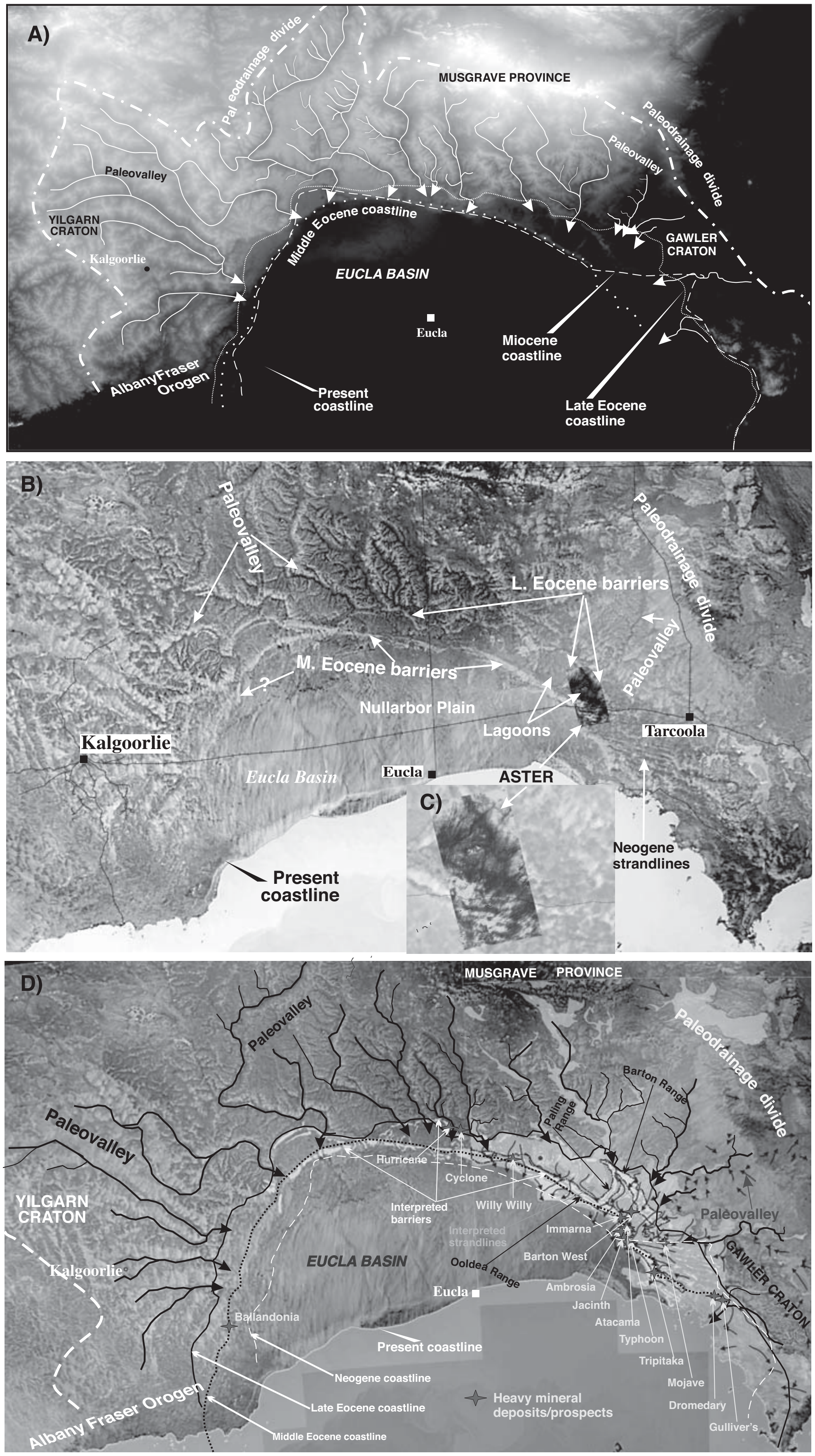

FIG. 2. GIS mapping and interpretation of the Eucla basin. A) SRTM DEM imagery, showing Eucla basin, major paleovalleys, and shorelines of varying age; B) NOAA-AVHRR and ASTER nighttime thermal images; the textural difference between paleovalleys and the sand barriers is apparent; C) comparison of enlarged NOAA-AVHRR (1.1 km pixel) and ASTER (90 m Pixel) nighttime thermal images; the latter showing much more detail of the textural features than the former; D) SRTM DEM imagery draped over NOAA-AVHRR nighttime thermal imagery; the textural difference between paleovalleys and the sand barriers and surrounding basement terrain is apparent; showing orientation of the barriers, strandlines, paleovalley systems, dune ranges, and adjacent major features, including heavy mineral deposits and prospects, different-age shorelines, and the relative high relief of the Musgrave province and the Yilgarn craton/Albany Fraser orogen when compared to the Gawler craton to the east.

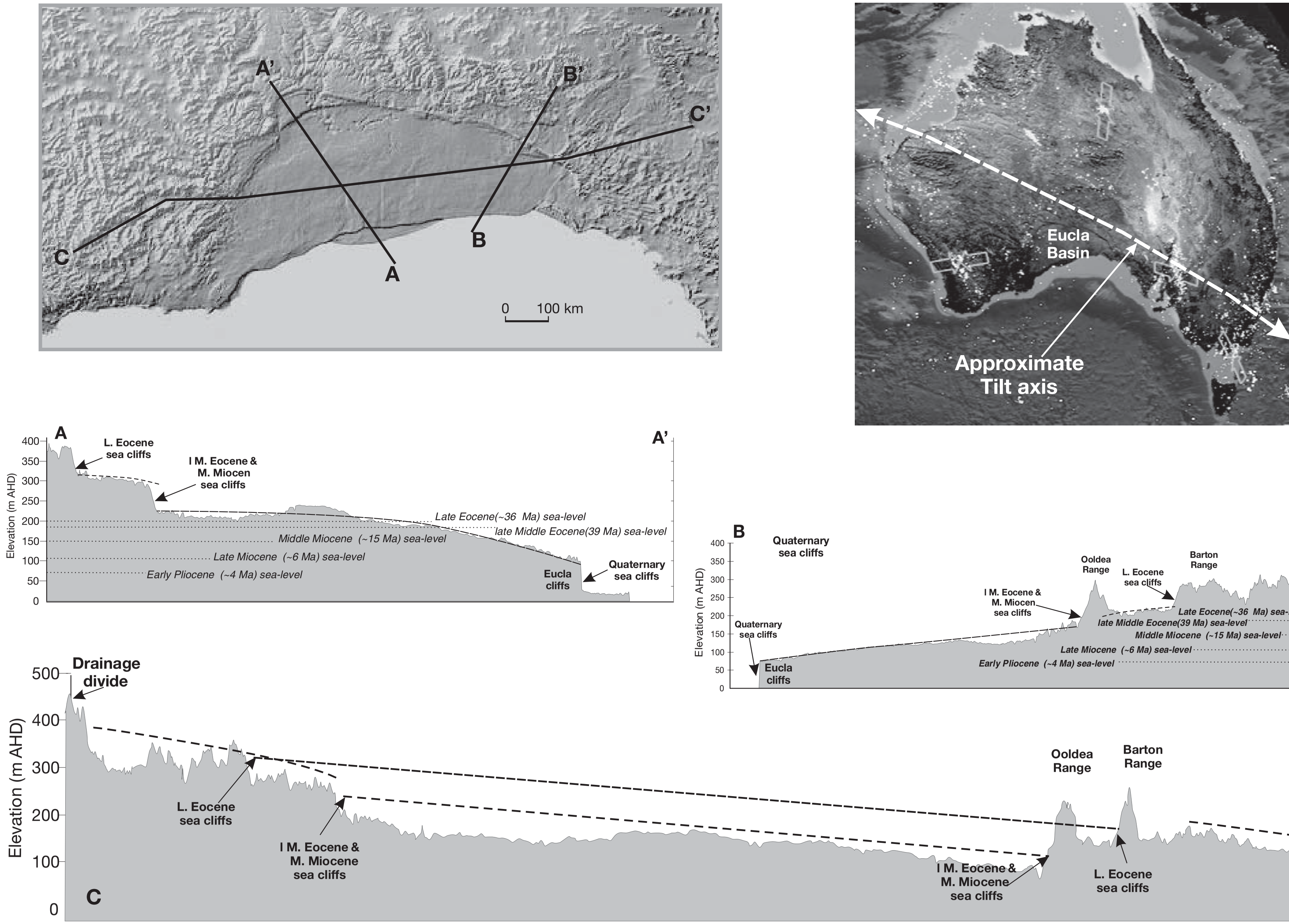

FIG. 3. The topographic difference between the western and eastern margins of the Eucla basin, showing the downtilting to the east and interpreted tilt axis across the continent. Modified from Hou et al (2008).

movement forms part of a broader north-down–southwest-up dynamic topographic tilting of the Australian continent associated with the latter stages of relatively fast (6–7 cm/yr) northward plate motion following separation from Antarctica at ~43 Ma (Sandiford, 2007). The evolving dynamic topography played a key role in facilitating development of placer deposits, largely through multistage, eastward reworking of near-shore sequences during highstand transgressive cycles, on a progressively tilting platform under the influence of dominant westerly prevailing weather systems (Hou et al., 2008).

Stratigraphic interpretation

Despite the large extent, the marine successions of the Eucla basin show a remarkably consistent stratigraphy across the entire basin (Smyth and Button, 1989; Waterhouse et al., 1994; Benbow et al., 1995a; James and Bone, 2000; Clarke et al., 2003; Hou et al., 2003a, 2006). Our focus here is mainly on the nearshore and coastal sequences, particularly in the eastern part of the basin, where the majority of heavy mineral discoveries have been made and where additional data have been obtained recently. The main sedimentary units identified throughout the basin are shown in Figure 4, which summarizes current knowledge of the stratigraphic relationships, age ranges, and depositional environments relative to regional geologic events. The age ranges and distribution of the heavy mineral-bearing units at various times throughout the Cenozoic and their correlation to the eustatic and regional depositional cycles are illustrated in Figure 5.

In the western and central parts of the basin, the basal unit, the Hampton Sandstone (zone P12, Fig. 4), comprises up to 30 m of shallow marine sands. This is overlain by up to 300 m of carbonates of the Wilson Bluff, Abrakurrie, and Nullarbor Limestones (Lowry, 1970; Hocking, 1990; Jones, 1990; Clarke et al., 2003). In the southwestern and central parts of the basin, Wilson Bluff Limestone is unconformably overlain by the Oligocene-early Miocene Abrakurrie Limestone (Lowry, 1970; James and Bone, 1994; Li et al., 1996), and farther to the north and northeast, by middle Miocene Nullarbor Limestone (Lowry, 1970). The sediment distribution over time suggests a northeasterly migration of the Eucla basin depocenter from Eocene to Miocene times (Fig. 4). The relatively thick and localized occurrence of Abrakurrie Limestone, compared with the overlying thinner but more aerially extensive Nullarbor Limestone, is consistent with local tectonic subsidence in the central part of the basin in the early Neogene (Hou et al., 2008). Farther inland (?50–100 km), post-Abrakurrie erosion prior to and during initial deposition of the Nullarbor Limestone has apparently removed any record of laterally equivalent late Oligocene-early Miocene terrigenous clastic facies on the Eucla margin and paleovalleys (Fig. 4; Benbow et al., 1995a; Alley et al., 1999; Hou et al., 2003a).

A veneer of Paleogene clastic-dominated sediments onlaps craton margins and older sedimentary deposits along the Eucla basin margin (Clarke, 1994a; Alley and Lindsay, 1995; Hou et al., 2003a). These are principally middle Eocene sediments (zone P10?–P14, Fig. 4) that in places unconformably overlie and onlap Cretaceous, Permian, and Neoproterozoic-Cambrian sedimentary rocks as well as Precambrian crystalline basement (Fig. 4). Locally, these intertongue with the basal Wilson Bluff Limestone (zones P14 and P15) and pass laterally into the sand equivalents of estuarine and paleovalley fills (Benbow et al., 1995a; Clarke et al., 2003) through tidal inlets along the Ooldea barrier (Hou et al., 2003a, 2006). Late Eocene sediments (zones P16 and P17) are overlain and intertongue with the sponge-spicule facies of the Khasta Formation and Princess Royal Member (Clarke et al., 2003; Hou et al., 2003a, b, c, 2006; Fig. 4).

The Yarle Sandstone and Colville Sandstone correlate basinward with the Nullarbor Limestone and landward with the youngest aeolian (?) facies of the Ooldea Sand (Benbow et al, 1995a; Clarke et al., 2003), and they were deposited along the middle Miocene shoreline. They consist mainly of sediment reworked from beach-barrier sands of the Eocene beach-barrier-dune complex (Figs. 1, 4). In the southeast Eucla margin, marginal marine and estuarine channel sediments of the Garford (Kingoonya Member; Hou et al., 2003a) and Narlaby (Benbow et al., 1995a) formations were deposited during the middle Miocene and early Pliocene as a thin sequence of laminated clay, silt, and sand. Locally, these are capped by a minor carbonate unit up to 5 m thick, (Ilkina Formation of Pliocene age; Benbow et al., 1995a). Along the western Eucla margin, however, this marginal marine and estuarine sequence is absent (Fig. 4), consistent with uplift on this side of the basin, which limited the extent of Miocene marine transgression and development of backshore lagoons (Hou et al., 2008).

Sea-level events

Cenozoic marine transgressions of the Eucla basin, established from regional carbonate biostratigraphic studies (e.g., McGowran, 1979; McGowran et al., 1997, 2004), make up at least five third-order transgressions (Fig. 4). The transgressive-regressive phases associated with relative sea-level change need to be taken into account when interpreting the vertical and lateral lithological variations observed in drill hole samples across the basin (Figs. 4, 5). Recent studies (Hou et al., 2001a, 2003c, 2006) show that Cenozoic sediments in the eastern Eucla basin are bounded by major erosion sequence boundaries corresponding to relative sea-level changes. This scenario is consistent with that suggested by Clarke et al. (2003) in correlating sedimentary sequences from the western and eastern margins of the Eucla basin. The sedimentary units recovered across the basin correspond to the established Cenozoic transgressions from neritic components of the chronostratigraphic record, i.e., Wilson Bluff, Tortachilla, Tuketja-Tuit, Bairsdale, and Jemmys Point-Hallett Cove (McGowran et al., 1997, 2004). A gradual increase in the energy of coastal deposition throughout Eocene time is reflected in terrace evolution of Eocene shoreline sediments (Li et al., 2003). Effective delivery of sand by westerly longshore drift was the transport agent instrumental in the formation of extensive coastal barriers. Analysis of the geomorphology of Cenozoic coastal deposits and sequences in selected drillholes across the eastern basin provide a record of Mio-Pliocene progressive coastal progradation, followed by a series of regressive strandlines. This pattern of sedimentation, reflecting Mio-Pliocene sea-level change, is not apparent along the western margin of the basin because of continental-scale tilting and relative uplift of the region (Figs. 2, 3).

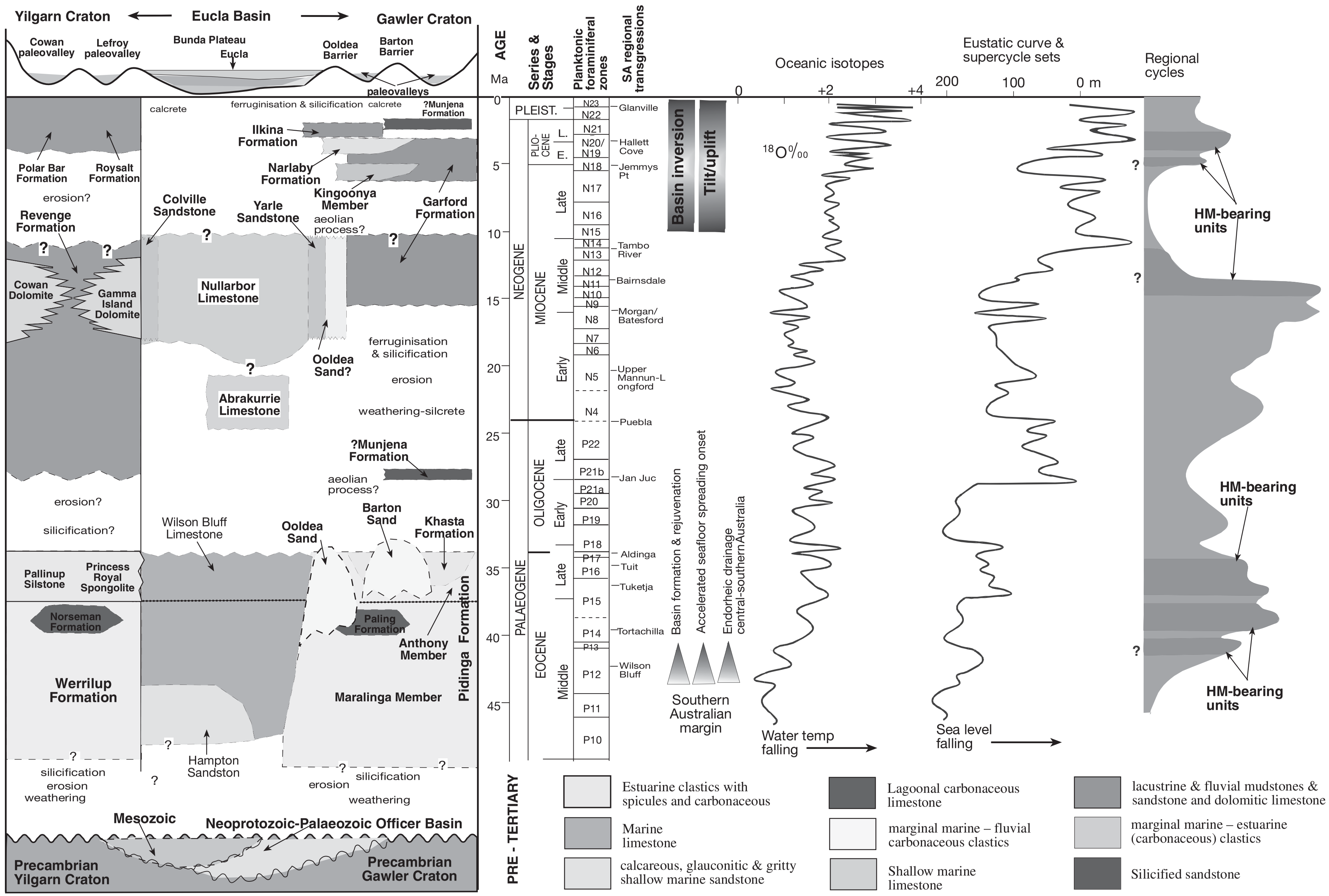

FIG. 4. Stratigraphic correlation chart and inferred depositional environments in the Eucla basin and paleovalleys (for localities see Fig. 3, section C; modified from Hou et al., 2008). Planktonic foraminiferal zones (McGowran et al.,1997); regional transgressions (McGowran et al.,1997), tectonic events in southern Australia (Li et al., 2004), oceanic oxygen-isotopic cycles (Abreu et al., 1998), eustatic supercycle sets (Haq et al., 1987, 1988), and local cycles (McGowran et al., 2004) in relation to age of HM-bearing units.

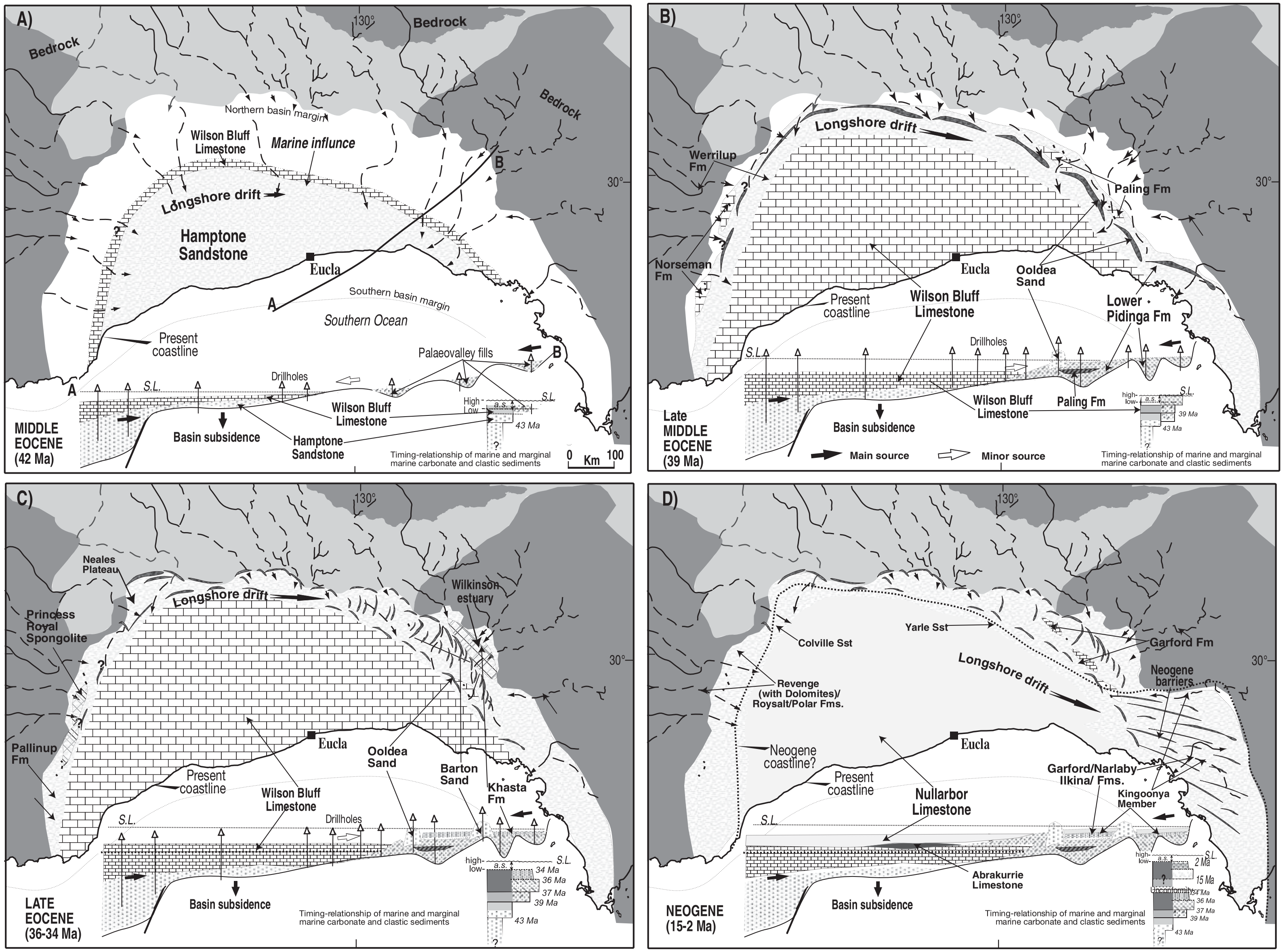

FIG. 5. Simplified maps and cross sections along line A-B, showing successive stages in the depositional history of the Eucla basin. A) Middle Eocene (Wilson Bluff transgression and lowstand); shallow marine Hampton Sandstone (overlain by lower Wilson Bluff Limestone), onshore lower Pidinga-Werrilup fluvial. B) Late middle Eocene (Tortachilla transgression and highstand); lower Wilson Bluff Limestone (shelf), nearshore Pidinga-Werrilup marginal marine and estuarine (including transgressive barriers and lagoonal Paling and Norseman limstones), and onshore Pidinga-Werrilup fluvial. C) Late Eocene (Tuketja-Tuit transgressions and highstand); upper Wilson Bluff Limestone (shelf), nearshore upper Pidinga-Pallinup marginal marine and estuarine (including transgressive-regressive barriers and estuarine spongolite or sponge-spicule facies), and onshore Pidinga-Pallinup fluvial. D) Neogene (transgression-regression); shelf Nullarbor Limestone, shoreface Yarle-Colville Sandstones, Garford-Revenge fluvial (including lacustrine dolomites); fluvial dominant in the western margin of the basin, fluvial and lacustrine in the northeastern margin of the basin (Garford Fm), and marginal-estuarine in the eastern margin of the basin (Kingoonya Member, Narlaby and Ilkina Fms).

Paleoshoreline records

The Cenozoic shorelines, defined as bodies of coastal sand, here make up beach, shoreface, barrier, dune, tidal inlet, washover, and lagoonal facies (Hou et al., 2003b), regionally representing third-order highstands (Clarke et al., 2003; Hou et al., 2003c). Along the Eucla margin, the paleoshorelines and paleoriver mouths are characterized by features that reflect a series of former estuaries (e.g., Neales, Wilkinson, and Anthony), lagoons, and coastal barrier islands (e.g., Ooldea and Barton; Figs. 1, 2). Along the eastern Eucla margin, Hou et al. (2003c, 2006, 2008) recognized four distinct constructional phases for shoreline formation. These can be correlated with the following major third-order sea-level events (Figs. 3, 4): (1) middle Eocene (~42.5 Ma), (2) late middle Eocene (39–36 Ma), (3) late Eocene (36–34 Ma), and (4) Mio-Pliocene (15–2 Ma).

Prior to the Wilson Bluff transgression in the middle Eocene (~42.5 Ma), paleovalleys probably delivered a substantial volume of siliciclastic sediment to a shoreline close to or beyond the present-day coastline (Quilty, 1994). The position of the shoreline at the beginning of the Wilson Bluff transgression is placed at the most landward position of Hampton Sandstone in the central Eucla basin (Figs. 3, 5A), now overlain by lower Wilson Bluff Limestone (Clarke & Hou, 2000; Hou et al., 2003b, 2006). Landward migration of the shoreline during the marine transgression between 42 and 41 Ma is uncertain but may be marked locally by the presence of sandy, sponge spicule facies (Hou et al, 2003b). Fluvial sediments were delivered to the shoreline but the distribution of paleoriver systems beneath the cover of marine carbonates is poorly known. Early middle Eocene paleovalley sediments beneath the Wilson Bluff Limestone, west of Jacinth (Fig. 5A), were identified from recent airborne electromagnetic surveys and confirmed by palynological analyses from drill cuttings (L. Stoian, unpub. data, 2007). The paleovalley is 3 to 5 km across with sandy sediment fill to as much as 65 m thick, overlain by 25 to 30 m of marine carbonates. At about 45 to 50 m below ground level the sediments are saturated with saline groundwater, which are used as the principal source of water for beneficiation of mineral sands at the new Jacinth-Ambrosia heavy mineral mine.

The influence of late middle Eocene Tortachilla and late Eocene Tuketja-Tuit transgressions extended some several hundred km up paleovalleys that drain into the Eucla basin (Figs. 4, 5B, C; e.g., Alley et al., 1999; Clarke et al., 2003). During these stages, input of terrigenous flux resulted in extensive aggradations, first as nonmarine to marginal marine sediments and then as highstand deposition of biogenic sediments (Alley et al., 1999). Initial development of the late middle Eocene shoreline during the Tortachilla transgression is expressed as marginal marine and estuarine (carbonaceous) sand, silt, and mud onlapping an erosional surface in the coastal plain and adjacent paleovalleys along the Eucla margin (Figs. 4, 5B). The highstand deposits of this sequence are locally intercalated with carbonaceous, calcareous, and glauconitic limestone (e.g., Paling and Norseman Formations), and with barrier sands (Benbow, 1990) of the Ooldea Sand (Hou et al., 2003a; zones P14 and P15, Fig. 4) in the eastern part of the basin. The Tortachilla shoreline is characterized by the Ooldea barrier along the northern and eastern margin of the basin. Shortly afterward, a yet higher sea level led to further marine transgression during the Tuketja-Tuit transgressions and resulted in the shoreline migrating farther inland (Fig. 5c). The shoreline position extended to the inland margin of the Neales Plateau in the northwest (Clarke and Hou, 2000) and to the Barton barrier-Wilkinson estuary in the northeast (Hou et al., 2003b, 2006; Figs. 1, 2), characterized by the Barton barrier in the eastern basin. The absence of Tortachilla and Tuketja-Tuit coastal barrier island sands in the western Eucla margin may reflect coastal processes of longshore drift toward the east under the influence of prevailing westerlies (Fig. 1; Kemp, 1978). A provenance study, based on zircon age distribution in heavy mineral concentrate from the Notrab prospect in the Barton barrier sands (Reid and Hou, 2006) indicated a dominant sand supply ultimately from the Musgrave province or Albany Fraser orogen via paleorivers to the west or north. The sand may have been through several generations of intermediate reworking in the late Neoproterozoic, earliest Cambrian, Permian, and/or early Cretaceous.

The Barton and Paling barrier systems are characterized by a series of late Eocene (36–34 Ma) coastal sand barriers, oriented southwest-northeast, whereas the Ooldea barrier was partly submerged to form a string of offshore barrier islands (Clarke and Hou, 2000; Hou et al., 2003a, c, 2006). In contrast to previous models (e.g., Benbow, 1990; Rogers, 2000), recent interpretations (Hou et al., 2006, 2008) suggest that the distribution pattern of the late Eocene coastal barrier islands is neither parallel to that of the Ooldea barrier nor aligned along the present Barton Range (Figs. 2, 5C). Thus, the "Ooldea and Barton barrier islands" (characterizing early Cenozoic geomorphological features) are not strictly equivalent to the present day "Ooldea and Barton Ranges," which reflect additional aeolian reworking following several marine regressions and later dry and windy conditions that accompanied cycles of southern hemisphere glacial maxima during the Quaternary (Sheard et al., 2006; see comparison in Fig. 2). Landward of the Ooldea barrier, parallel beach ridges developed in the late Eocene that reflect the interaction of localized sediment supply along paleodrainage networks and continuous, westerly longshore drift processes operating behind the Ooldea barrier "islands" (Fig. 5C). Sediments make up both lagoonal facies and barrier island facies with beach placer mineralization (Reid and Hou, 2006). Wave energy was likely much less than that for the seaward Ooldea barrier. The elevation of the Barton-Paling barrier-ridge feature decreases toward the southeast, following the direction of longshore drift, which reflects a decrease in sand supply from the northwest and a broader-scale, relative downward vertical movement toward the east (Hou et al., 2008). Paleoclimate modeling (Kemp, 1978) indicated westerly winds predominated across southern Australia at latitudes between 60° and 80°S in the Paleocene and Eocene. This is consistent with the preservation of coastal dune barriers along the northeastern Eucla basin margin and the apparent absence of substantial dunes along the western margin. "J-shape" barriers behind the Ooldea barrier islands that formed during the late Eocene may indicate a more northwesterly component to the prevailing winds at that time (Fig. 6).

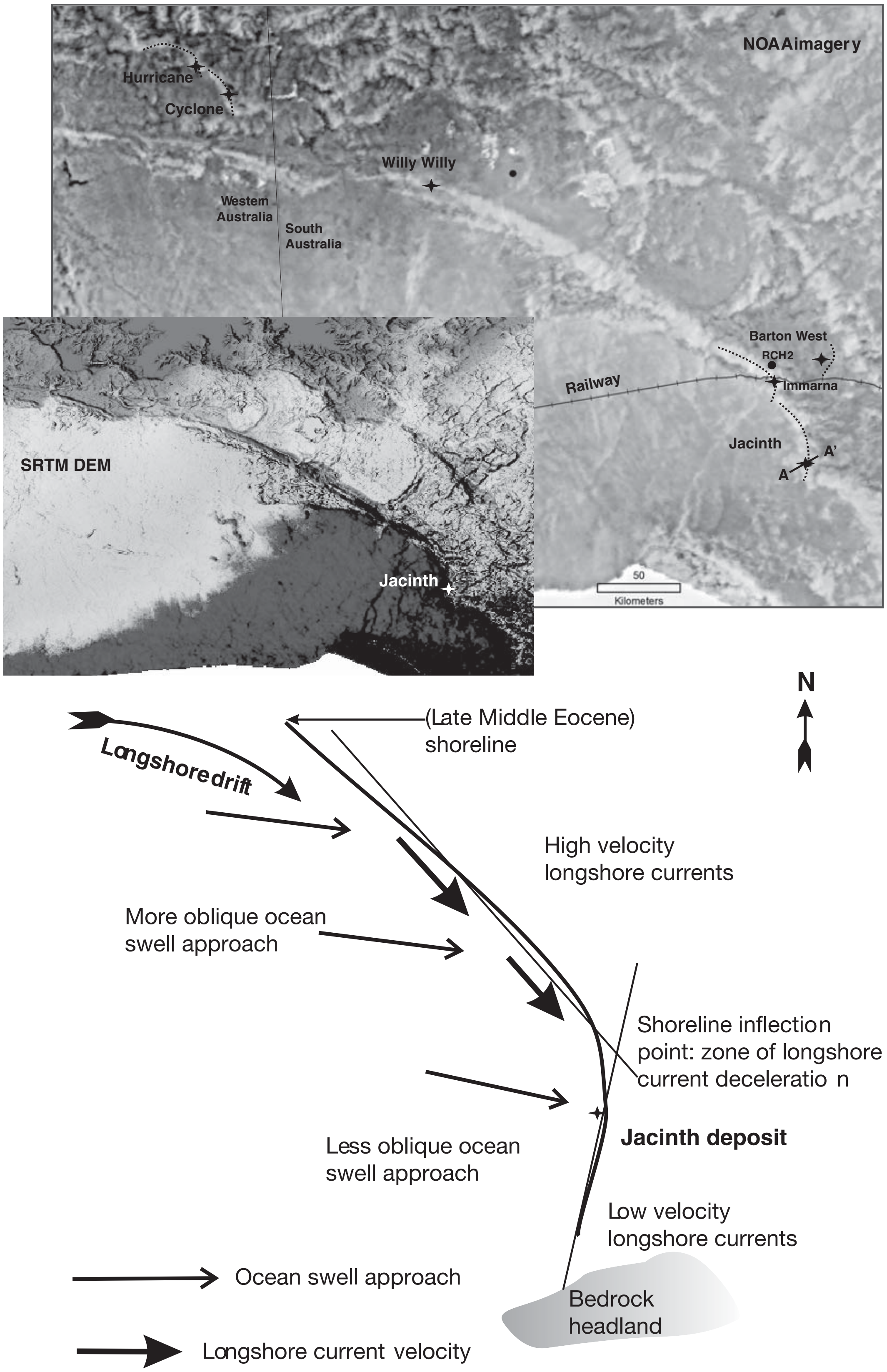

FIG. 6. Longshore current impact on the paleoshorelines; the longshore current velocity of south of the inflection point is less than that of north of the inflection point owing to relative differences in angle of oblique wave approach (Komar, 1979).

The Mio-Pliocene shorelines mainly followed those of the late middle Eocene in the western, northern and northeastern Eucla margins (Fig. 1). Relatively high cliffs developed along this margin during the Miocene, mimicking earlier, slightly more landward Eocene cliffs (Figs. 3, 5D). However, in the southeast Eucla margin, parallel linear ridges at an angle to the late Eocene Ooldea barrier represent Mio-Pliocene strandlines (A. Crooks, pers. commun., 2002) of the Narlaby and Ilkina Formations. These are fine- to medium-grained, moderately to well-sorted sandstone that formed from reworking of the middle Eocene Ooldea barrier sands (Benbow, 1990; Hou et al., 2003a, b, c, 2006). More extensive inundation of this area was due to downward tilting of the basin toward the east. The prolonged nature of the dynamic tilting is indicated by a relative northeastward decline in elevation of the key Eocene surfaces and "reverse flow" features in Mio-Pliocene valleys in the western Gawler craton (Fig. 3; Hou et al., 2008). Thus, the Mio-Pliocene shorelines that developed in the southwestern Gawler craton following maximum marine transgression extend farther inland than those of the Eocene (Hou, 2004). These shorelines may prove also to be prospective for heavy minerals.

Regional Mineralization of Heavy Mineral Sands

The middle-late Eocene paleoshorelines of the northern and eastern Eucla basin are highly prospective for beach sand-hosted heavy minerals related to sea-level changes (Hou and Warland, 2005; Hou and Keeling, 2008). Since late 2004, significant new heavy mineral deposits and prospects have been discovered along these paleoshorelines (Table 1). Some (e.g., Jacinth, Ambrosia, Tripitaka) are characterized by zircon-dominant heavy mineral assemblages throughout, and in this respect they differ from most heavy mineral deposits worldwide where the average production ratio of zircon to titania is about 0.21 compared to 2.6 for the Jacinth-Ambrosia deposits (Iluka Resources, unpub. data, 2009). Favorable sites for beach placer accumulation include a series of J-shaped segments along the Ooldea and Barton barriers (Fig. 6). These geomorphic features provide protected beaches where heavy minerals might be transported and concentrated via the combined interaction of westerly longshore drift and diffraction of waves around headland promontories. Development of the Jacinth-Ambrosia deposits began in 2008, with the first production of heavy mineral concentrate from Jacinth in December 2009. The prospectivity of the western paleoshoreline increased with the discovery of heavy mineral sands at Balladonia.

Ooldea and Barton barrier sands

Benbow (1990) recognized the Ooldea, Barton, and Paling Ranges as Eocene shoreline features and named this unit the Ooldea Sand (Fig. 4). Subsequently, the terms "lower" Ooldea Sand and "upper" Ooldea Sand were used informally to separate the Eocene sand units in different age dune systems, but no physical or boundary criteria are presently known (Clarke et al., 2003). More recently, the terms Ooldea and Barton Sands have been introduced. This classification allows different-age barrier systems to be independently characterized (Hou et al., 2006), but the distinction between barrier systems is not everywhere apparent. These marine-coastal barrier island sand complexes (including aeolian and lagoonal components) are recognized as the main heavy mineral-bearing units. They are extensive along the eastern and northern basin margin and cover an area that is up to 30 km wide and 1,000 km long (Fig. 2).

Description of Eucla basin heavy mineral deposits and prospects

The geologic setting and mineralogy of various heavy mineral deposits and prospects described below are based on our interpretation of data from various sources. In particular, wide use was made of data included with mandatory reporting by publicly listed mineral exploration companies operating in the region, data compilations from early company activity by Jurica and Rothnie (1990) and Ferris (1994), and results of mineralogical investigations by Ruperto et al. (2006) and Powcenby et al. (2008a, b).

Jacinth and Ambrosia deposits: Jacinth and Ambrosia formed on the western, basinward side of the Ooldea barrier island system with heavy mineral concentrated on a beach complex formed in a J-shaped bay (Fig. 6). A prominent headland at the southern end of the bay is the result of sand accumulation on shallow crystalline basement of Paleoproterozoic metagranite, part of the Fowler Domain of the western Gawler craton. Bedrock in the area is predominantly granitic intrusive rocks that are faulted and sheared by major structures trending northeast-southwest. A basement fault, apparent in regional magnetic data, shows close correspondence with the headland alignment. The Jacinth deposit is ~3.2 km long and 0.9 km wide. The orebody has an overall north-south orientation and is slightly curved in plan view (Hou and Warland, 2005). A high-grade core of >20 percent heavy mineral, between 2 and 10 m thick, is present at 5 to 10 m above the bedrock contact and extends across the full width of the deposit. This is interpreted as aggradations of beach swash zone deposits that extend basinward over surf zone sands and are partly reworked into overlying younger beach deposits or aeolian backshore dunes (Ruperto et al., 2006). Concentration of heavy minerals in the swash zone increases from north to south. Change in the relative level of the base of the high-grade zone indicates a slope of about 1 percent basinward, a drop of 10 m per km across the deposit. The top of the high-grade zone is marked by patchy and generally weak silicification and a narrow zone of bioturbation in the form of intensive burrowing. The high-grade core is overlain by up to 20 m thickness of iron-stained quartz sand that contains 3 to 5 percent heavy mineral. Average ore zone thickness is 20 m at 1.0 percent heavy mineral cutoff; overburden thickness averages 7 m. Contained heavy mineral is estimated at 6.4 Mt (Table 1).

Ambrosia deposit is 3 km to the north of Jacinth and is ~2.2 km long by 0.7 km wide. The orebody is elongated northwest-southeast. Heavy mineral distribution is less consistent than for Jacinth and overall grade is lower. High-grade zones of >10 percent heavy mineral are associated with beach swash zone aggradations, typically <3 m thick, with lower grades present in overlying sands that include backshore dunes and backshore wash-over sand facies. Ore zone thickness, at 1 percent heavy mineral cutoff, averages 12 m, and overburden thickness is an average of 8 m. Contained total heavy mineral content is estimated at 3 Mt (Table 1).

Both deposits are above the water table in unconsolidated, moderately to well-sorted fine sand of average grain size between 0.1 and 0.2 mm. Grain-size distribution is typically slightly skewed toward the coarser fractions. Grains are subrounded to well-rounded and rarely exceed 1 mm diameter. Silt and clay "fines" content (<53 μm fraction) averages 11 percent for Jacinth and 14 percent for Ambrosia. Fines content is lowest in the high-grade ore zones and increases to a maximum of about 30 percent in the upper portion of barrier-dune deposits, usually between 6 to 12 m below ground surface. The dune sands are typically orange-brown in color due to iron-oxide-stained clay coating on grain surfaces.

Heavy mineral concentrates average 82 percent valuable heavy minerals at Jacinth and 76 percent at Ambrosia. Zircon proportion is high for both deposits at about 50 percent of total heavy mineral, with a zircon to titanium dioxide ratio of ~2.6, which is about 10 times the industry production average. Zircon grains are mostly <120 μm diameter, are subrounded to well rounded (with minor needle-shaped grains), clear and translucent, typically showing oval outline with average length to width ratio of 1.5:1 (Fig. 7). Ilmenite content is about 30 percent for Jacinth and 20 percent for Ambrosia, mostly as altered ilmenite with a high average TiO_2 content of 64 percent and Ti/(Ti + Fe) equal to 0.66, equating to pseudorutile (Pownceby et al., 2008a). Rutile-anatase content is about 5 percent. Other minerals present in the heavy mineral fraction include tourmaline, spinel, staurolite, monazite, and chromite, with minor iron oxide-coated quartz contributed mainly from the upper ore zone. Monazite and chromite content in the heavy mineral concentrate is typically low at about 0.2 percent each.

Tripitaka prospect: Announcement of the discovery of Tripitaka in November 2005 was 12 months after the discovery of Jacinth. The deposit is ~90 km southeast of Jacinth-Ambrosia and is a smaller orebody with an inferred resource of 39.5 Mt at 2.3 percent heavy mineral, yielding ~0.9 Mt total contained heavy mineral (Table 1). Zircon content of the heavy mineral fraction is high at 65 percent, making this the most zircon-rich of the Eucla basin deposits discovered to date. Tripitaka is also in the Ooldea barrier system, and has a core zone of >3 percent heavy mineral, locally >10 percent heavy mineral, as a beach concentrate that accumulated along a northwest-facing, paleocoastal bay. Heavy minerals are present also in backshore dune deposits that form overlying, lower-grade ore zones with 1 to 2 percent heavy mineral. The deposit extends over 3.7 km by 1.0 km, elongated northeast-southwest. The ore zone shows variable thickness and can exceed 20 m, but is absent over a bedrock high that underlies a portion of the

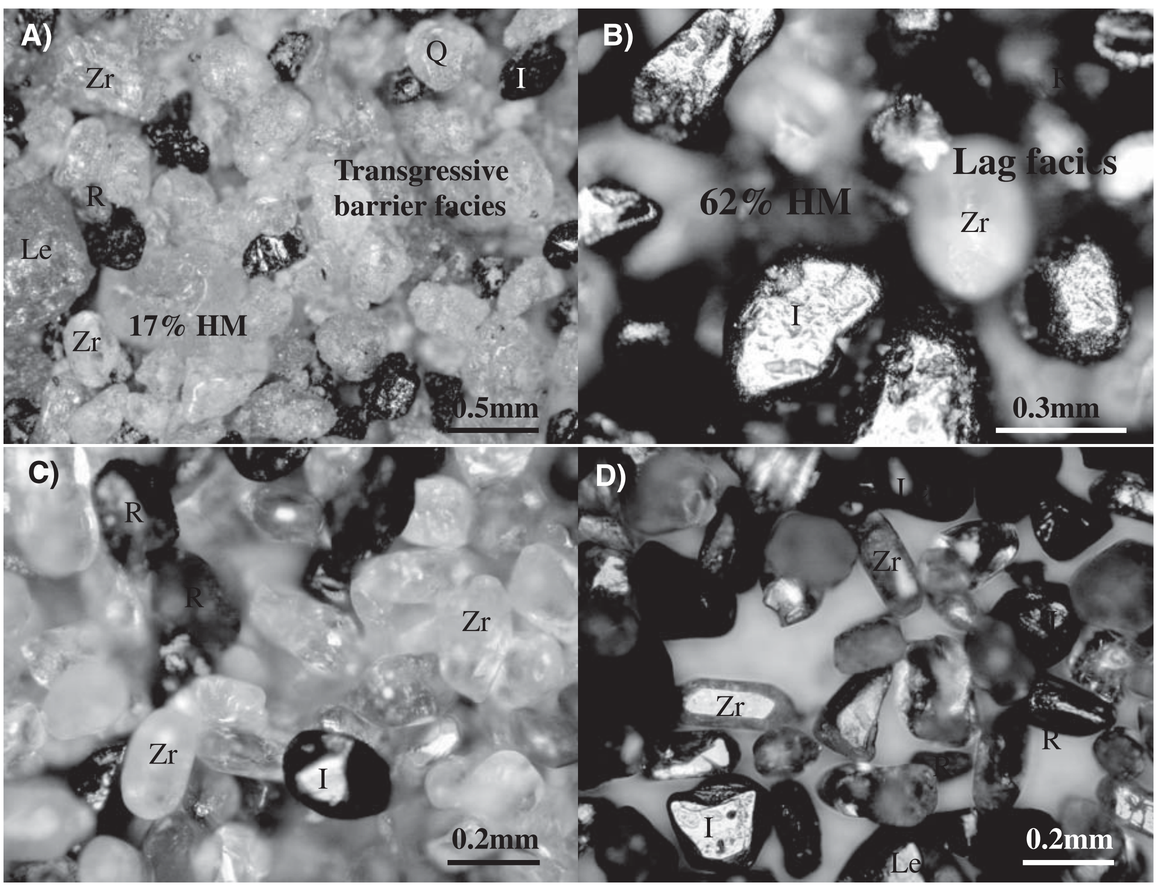

FIG. 7. Photography of heavy-mineral-bearing sand and heavy-mineral sands (I = ilmenite. Le = leucoxene, Q = quartz, R = rutile, Zr = zircon; reflection of polarization). A) Transgressive barrier facies of Ooldea Sand (17.6% heavy mineral, the bar equals 0.5 mm, drill hole EB115, see Fig. 9); B) Lag facies of Ooldea Sand (62% heavy mineral, the bar equals 0.3 mm, drill hole EB119, see Fig. 9); C) Zircon concentrated heavy mineral sands (>90% Zr) of Jacinth deposit (the bar equals 0.2 mm); D) Concentrated heavy mineral sands of Jacinth deposit (>95% heavy mineral, the bar equals 0.2 mm).

central part of the deposit. Overburden thickness ranges from 5 to 20 m. The deposit overlies weathered meta-igneous rocks of the Fowler Domain and also fluvial paleochannel sands of probable early Eocene age.

Tripitaka deposit is in fine-grained, unconsolidated sands above the water table. Fines content averages 14 percent and is greatest in the upper part of the deposit. Heavy mineral concentrate contains about 80 percent valuable heavy minerals with overall content 65 percent zircon, 9 percent ilmenite, predominantly as pseudorutile, and 5 percent rutile. The median grain size diameter (d50) of the heavy mineral separate is 100 μm for zircon and 115 μm for ilmenite; few grains exceed 1 mm diameter. Other mineral grains in the heavy mineral fraction include aluminosilicates, composite TiO_2-quartz and iron-oxide coated quartz, and trace amounts of monazite and chromite.

Typhoon and Atacama deposits: Brownfield exploration along the Ooldea barrier in the vicinity of the Jacinth-Ambrosia deposits has located additional heavy mineral resources at Typhoon and Atacama. These deposits are higher in ilmenite but are likely to be mined due to their proximity to mineral processing infrastructure recently established at the Jacinth mine. Typhoon was discovered in 2007 and is 4 km southeast of Jacinth-Ambrosia. The orebody is defined by a 3 percent heavy mineral cutoff and is approximately 3 km long, elongated northwest-southeast, and between 80 m and 400 m wide. The thickness of ore-grade, foreshore sands ranges from 1 to 21 m and is overlain by between 5 and 27 m of sandy overburden. The average grade is 6.1 percent heavy minerals and the fines content is 10 percent with an inferred resource of 1.3 million tonnes heavy mineral (Table 1). Composition of the heavy mineral separate is 76 percent combined ilmenite and leucoxene, 14 percent zircon, and 1 percent rutile. Heavy mineral grain size at d50 is 140 μm for zircon and 165 μm for ilmenite.

The Atacama deposit is 9 km northeast of Jacinth-Ambrosia and is approximately 7 km long, elongated north-south, and between 400 and 3,000 m wide, as defined using a 3 percent heavy mineral cutoff grade. Ore-grade heavy mineral sands are between 1.5 and 18 m thick and beneath 5 to 42 m of sandy overburden. Discovery of the deposit was reported in September 2010 and an inferred resource, based on a 5 percent heavy mineral cutoff, was released in January 2011. The estimated 3.3 million tonnes of heavy mineral contained within the high-grade ore zone has an average grade of 11.3 percent heavy mineral of composition 75 percent combined ilmenite and leucoxene, 15 percent zircon, and 2 percent rutile. The ore zone contains a low fines content of 7 percent. Average grain size of the heavy minerals is 100 μm.

Other Ooldea barrier heavy mineral prospects: Other heavy mineral prospects associated with the Ooldea barrier system include Immarna and Willy Willy. Immarna was located during early reconnaissance exploration for heavy minerals in the late 1980s to early 1990s. The prospect is ~9 km west-southwest of Immarna railway siding and consists of three strandlines from 4 to 8 km long and 150 to 500 m wide. These typically include two intervals of anomalous heavy mineral concentrations. Representative bulk samples show the upper interval as medium-grained sand grading 2.7 percent heavy mineral containing predominantly altered ilmenite and leucoxene (86%) with 11 percent zircon (avg heavy mineral grain size is 210 μm). The lower interval is fine grained and grading 1.9 percent heavy mineral with altered ilmenite and leucoxene (66%) and 26 percent zircon (avg heavy mineral grain size is 90 μm) (Jurica and Rothnie, 1990). Intersections of >10 m with heavy mineral grade above 2 percent are present but of limited extent, with intersections of ~2 m typical, below an average 18 m of overburden. The combination of high overburden to ore-stripping ratio and the limited lateral extent of high-grade zones makes the prospect uneconomic. The discovery was significant, however, in establishing the potential of strandlines in the region to contain heavy mineral accumulations with comparatively high zircon content. The Willy Willy prospect is ~300 m wide and at least 900 m long with up to 6 m thickness of anomalous heavy mineral grading up to ~5 percent heavy mineral. The heavy mineral assemblage is dominantly zircon, at 25 to 40 percent of valuable heavy minerals, together with rutile, ilmenite, and leucoxene. Grain size of the heavy mineral fraction ranges from 75 to 150 μm.

Cyclone prospect: The Cyclone heavy mineral prospect was discovered in June 2007 on the northern margin of the Eucla basin, 25 km west of the state border of Western and South Australia. A resource of 98.4 Mt at 2.88 percent heavy mineral using a cutoff grade of 1 percent heavy mineral has been determined, with a total 2.8 Mt of contained heavy minerals (Table 1). The deposit includes up to five partly coalescing beach and backshore dune strands that extend for ~5 km, trending north-northeast–south-southwest, which together are up to 2.5 km wide. The prospect is near the western end of the known extent of eastern Eucla barrier sands and to the east of the interpreted discharge zone of the Wanna paleodrainage system (Figs. 1, 2D). The host sands are equated to the Barton barrier complex formed during the late Eocene Tuketja-Tuit transgressions. Concentrations of heavy minerals occur in stacked zones of >5 percent heavy mineral that reflect a combination of aggradation and progradation of beach deposits with multiple strandlines formed during (late Eocene) marine transgression multiple stillstand events (Fig. 4). Heavy mineral intervals, which incorporate lower-grade dune deposits, are 16 to 25 m thick with barren cover sands averaging 12 m thickness. Strandlines of the Cyclone prospect continue to the south and southeast on an adjoining tenement where drilling shows continuity of heavy mineral intersections over a width of up to 800 m and 2 km in length. Two narrower strandlines, farther to the east, also contain anomalous heavy minerals and have been traced along strike for 4.5 km. The southerly prospect is known as Cyclone Extended.

The heavy mineral suite at Cyclone has a high zircon content of about 33 percent, together with 44 percent altered ilmenite and leucoxene, 12 percent rutile, and 11 percent nonvaluable heavy mineral sands (Table 1). Zircon proportion increases from 30 percent in the north to 40 percent in the south. The sands are clean and moderately to well sorted with about 4 percent fines content and 5 percent oversize grains (>2 mm). Average heavy mineral grain size is 120 μm.

Other Barton barrier heavy mineral prospects: Other heavy mineral prospects associated with the Barton barrier complex include Barton West and Mojave (Fig. 2D). Barton West includes the Notrab prospect and is a series of anomalous heavy mineral zones oriented north-northeast–south-southwest with drill intersections of >1 percent heavy mineral in 4- to 14-m-thick intervals that extend over an area some 25 km north-south and up to 12 km east-west. Grades are typically <3 percent heavy mineral but are locally up to 10 percent heavy mineral. Indicative mineralogy is 10 percent zircon, 20 percent rutile and leucoxene, and 60 percent ilmenite (mostly as pseudorutile). Mojave prospect, to the south of Barton West, is elongate north-northwest–south-southeast extending for ~8 km and varying between 1 and 3.5 km wide. Grades range from 1 to 22 percent heavy mineral (typically <5% heavy mineral) over intervals averaging 10 m, below barren sand cover of average 15 m thickness. Preliminary mineralogical investigations showed heavy mineral composition of 13 percent zircon, 30 percent leucoxene and rutile, and 2 percent ilmenite. Zircon grain size has an average d50 of 90 μm and the average d50 of ilmenite is 100 μm.

Miocene(?) heavy mineral prospects: On the southeastern margin of the Eucla basin, two heavy mineral prospects of probable Miocene age have been located: Dromedary and Gulliver's (Fig. 2D). Dromedary prospect is 45 km northeast of Ceduna and is ~1 km long by up to 500 m wide. Heavy mineral intersections, above 1 percent cutoff, have a maximum 4.5 m thickness with the highest-grade intersection of 1.5 m at 14.6 percent heavy mineral sands. Overburden thickness averages 25 m. Indicative mineralogy from the high-grade zone is 17 percent zircon, 4 percent rutile-leucoxene, and 57 percent ilmenite. Zircon grain size has an average d50 of 100 μm and ilmenite has an average d50 of 120 μm. Gulliver's prospect is ~60 km east of Ceduna and extends for ~7 km north-south and is up to 2.5 km wide. The heavy mineral interval, using 1 percent heavy mineral cutoff, is between 3 and 7 m thick below an average 25-m thickness of overburden. Heavy mineral content is mostly in the range of 1 to 3 percent. Mineralogy of a composite sample shows valuable heavy mineral sands of 60 percent altered ilmenite, 21 percent zircon, and 7 percent leucoxene-rutile. Grain size of the heavy mineral suite is finer than for other prospects in the area with an average d50 of ~70 μm. Fines content averages ~6 percent. The fine grain size and relatively homogeneous heavy mineral grade have been interpreted as reflecting an offshore sand deposit. Both deposits are in areas interpreted as having been extensively reworked during Miocene marine transgression (Hou et al., 2007).

Western Eucla heavy mineral prospects: Heavy minerals in strandlines along the western margin of the Eucla basin were reported from mineral exploration drilling during the 1980s and early 1990s. Follow-up drilling in 2007 confirmed widespread heavy mineral occurrences in the Balladonia area in unconsolidated beach sand deposits formed during the Eocene marine transgression associated with the Wilson Bluff Limestone. Drilling at the Lefroy prospect shows aggradations of heavy mineral-bearing sands, 6 to 10 m thick, deposited to the east of a paleoshoreline consisting of north-south oriented cliffs of crystalline basement. The thickest intersections are near the interpreted outlet of the Lefroy paleochannel. Heavy mineral content is mostly 1 to 3 percent and dominated by ilmenite (90–96%), together with 3 to 10 percent zircon and <3 percent rutile-leucoxene. The ilmenite fraction includes both primary and altered components, including highly altered ilmenite grains in which secondary, fine-grained rutile is evident (Pownceby et al., 2008b). Rutile and zircon contents are typically low; other heavy mineral phases include iron oxide-hydroxide, staurolite, tourmaline, and garnet, with minor sillimanite, monazite, and barite. Fines content averages ~25 percent and overburden is ~10 m thick. The high proportion of low-value ilmenite makes this prospect subeconomic, although intersections of heavy mineral sands in which zircon is as high as 42 percent of the heavy mineral suite were recorded. Farther north, at the Plumridge prospect, up to 4.2 percent heavy mineral content was reported in strandlines, including intersections with high zircon content. Examination of a heavy mineral composite by Pownceby et al. (2008b), taken from drill holes across the site, reported dominant primary ilmenite with low rutile and zircon content, along with accessory iron oxide, sillimanite, garnet, and tourmaline. Exploration of strandlines along the western Eucla paleocoastline has focused on identifying sites of preferential concentration of zircon that would upgrade the value of potential deposits.

Detrital Zircon U-Pb Dating from the Jacinth Deposit

The high zircon content of several heavy mineral deposits in the Eucla basin is a significant factor in the economics of their development, given that zircon is currently the more valuable of the heavy mineral suite and a higher percentage reduces the requirement for excess production of titanium dioxide. The ultimate source of the zircon is a factor in determining its dispersion history and in understanding how these high-grade deposits form. Results from dating populations of zircons from the Barton barrier (Reid and Hou, 2006) showed a dominant contribution from rocks of Musgrave province age, and work was done to compare these data with a sample from the Ooldea barrier.

Analytical methods

Zircons from representative sand from the Jacinth deposit were analyzed for their U-Pb age by laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) at Macquarie University, Sydney. Detailed description of the analytical techniques are presented elsewhere (Belousova et al., 2001; Griffin et al., 2006) and are only summarized here. The LA-ICPMS system utilizes a 213-nm laser ablation unit coupled with a quadrupole ICPMS. Isotopic data were processed using the software GLITTER (van Achterbergh, 1999) and calibrated for Pb-U fractionation using the GJ standard zircon (Jackson et al., 2004). A 3-D concordia correction routine (Andersen, 2002) was applied to account for any common Pb component; however, for the majority of analyses no common Pb was detected in the routine. Where the ^{207}Pb-^{206}Pb age was less than 1000 Ma, the ^{206}Pb-^{238}U age was used as the preferred crystallization age. Weighted mean ages have been calculated using Isoplot v3 (Ludwig, 2003).

Results

Fifty-five analyses were made on zircon grains from the Jacinth deposit (Table 2). The majority of data are concordant or near concordant and range in age from a maximum of ~2930 Ma to a minimum of ~616 Ma (Fig. 8). Three analyses have greater than 10 percent discordance and are

TABLE 2. Summary of LA-ICPMS Results from Zircons of the Jacinth Deposit

	Isotopic ratios						Ages (Ma)				
Analysis no.	$^{207}Pb/^{206}Pb$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	$^{206}Pb/^{238}U$	1σ	% Disc
3982-1	0.0788	0.0025	0.1956	0.0036	2.1249	0.0560	1167	66	1152	20	1
3982-2	0.0977	0.0021	0.2682	0.0050	3.6127	0.0706	1581	40	1532	26	3
3982-3	0.1040	0.0035	0.2964	0.0068	4.2503	0.1340	1697	64	1673	34	1
3982-4	0.0897	0.0020	0.2358	0.0042	2.9144	0.0566	1418	44	1365	22	4
3982-5	0.0746	0.0019	0.1764	0.0033	1.8134	0.0425	1056	54	1047	18	1
3982-6	0.0790	0.0019	0.1930	0.0036	2.1020	0.0457	1172	48	1138	20	3
3982-7	0.0780	0.0018	0.1890	0.0035	2.0325	0.0423	1147	46	1116	20	3
3982-8	0.0803	0.0021	0.1993	0.0041	2.2052	0.0555	1204	54	1171	22	3
3982-9	0.0942	0.0025	0.2586	0.0050	3.3575	0.0803	1512	50	1483	26	2
3982-10	0.0790	0.0016	0.1960	0.0035	2.1348	0.0380	1172	42	1154	18	2
3982-11	0.0755	0.0021	0.1791	0.0034	1.8647	0.0457	1083	56	1062	18	2
3982-12	0.0796	0.0021	0.2006	0.0038	2.2001	0.0524	1186	52	1179	20	1
3982-13	0.1017	0.0021	0.2879	0.0053	4.0358	0.0765	1655	40	1631	26	1
3982-14	0.0785	0.0019	0.1901	0.0036	2.0577	0.0452	1159	48	1122	20	3
3982-15	0.0744	0.0020	0.1751	0.0035	1.7950	0.0444	1051	54	1040	20	1
3982-16	0.0775	0.0020	0.1892	0.0034	2.0226	0.0467	1135	54	1117	18	2
3982-17	0.2131	0.0046	0.5282	0.0091	15.5201	0.2756	2929	36	2734	38	7
3982-19	0.0602	0.0014	0.1003	0.0018	0.8321	0.0169	610	50	616	10	–1
3982-20	0.0728	0.0018	0.1667	0.0031	1.6723	0.0367	1008	50	994	18	1
3982-21	0.0786	0.0017	0.1971	0.0036	2.1356	0.0414	1162	44	1160	20	0
3982-22	0.0795	0.0043	0.1994	0.0057	2.1874	0.1115	1184	108	1172	30	1
3982-23	0.0777	0.0021	0.1925	0.0037	2.0630	0.0502	1139	54	1135	20	0
3982-24	0.1789	0.0039	0.4916	0.0085	12.1260	0.2199	2643	36	2578	36	2
3982-25	0.0793	0.0018	0.1956	0.0034	2.1396	0.0425	1180	46	1152	18	2
3982-26	0.0796	0.0020	0.1990	0.0036	2.1841	0.0497	1188	52	1170	20	2
3982-27	0.0764	0.0018	0.1863	0.0034	1.9627	0.0407	1106	48	1101	18	0
3982-28	0.1013	0.0022	0.2801	0.0050	3.9145	0.0738	1649	40	1592	26	3
3982-29	0.1037	0.0028	0.2966	0.0057	4.2414	0.1030	1692	52	1674	28	1
3982-30	0.1007	0.0022	0.2701	0.0046	3.7497	0.0685	1637	40	1541	24	6
3982-31	0.0749	0.0022	0.1771	0.0036	1.8292	0.0495	1066	60	1051	20	1
3982-32	0.0791	0.0019	0.1954	0.0035	2.1312	0.0442	1175	48	1151	18	2
3982-33	0.1318	0.0028	0.3403	0.0062	6.1833	0.1186	2122	38	1888	30	11
3982-34	0.0801	0.0016	0.2038	0.0035	2.2494	0.0397	1198	42	1196	18	0
3982-35	0.0925	0.0031	0.2123	0.0042	2.7086	0.0804	1478	64	1241	22	16
3982-36	0.1801	0.0036	0.4959	0.0083	12.3105	0.2042	2654	34	2596	36	2
3982-37	0.1032	0.0025	0.2958	0.0059	4.2089	0.0962	1682	46	1671	30	1
3982-38	0.0816	0.0035	0.2053	0.0047	2.3100	0.0918	1237	86	1204	24	3
3982-39	0.0807	0.0017	0.1961	0.0036	2.1833	0.0409	1215	42	1154	20	5
3982-40	0.0725	0.0021	0.1618	0.0030	1.6169	0.0413	999	60	967	16	3
3982-42	0.0781	0.0026	0.1927	0.0039	2.0754	0.0623	1149	66	1136	20	1
3982-43	0.0768	0.0019	0.1725	0.0031	1.8267	0.0393	1116	50	1026	16	8
3982-44	0.0836	0.0033	0.1840	0.0040	2.1207	0.0769	1283	80	1089	22	15
3982-45	0.0958	0.0024	0.2659	0.0054	3.5112	0.0820	1543	48	1520	28	1
3982-46	0.1042	0.0022	0.2947	0.0052	4.2328	0.0778	1700	40	1665	26	2
3982-48	0.1637	0.0034	0.4708	0.0084	10.6226	0.1932	2494	36	2487	36	0
3982-49	0.1007	0.0024	0.2853	0.0054	3.9619	0.0866	1637	46	1618	28	1
3982-50	0.0797	0.0018	0.1964	0.0035	2.1589	0.0438	1191	46	1156	18	3
3982-51	0.0789	0.0020	0.1937	0.0037	2.1072	0.0503	1169	52	1142	20	2
3982-52	0.0779	0.0022	0.1832	0.0035	1.9661	0.0503	1144	58	1084	20	5
3982-53	0.1010	0.0021	0.2952	0.0051	4.1093	0.0731	1642	40	1668	26	–2
3982-54	0.0809	0.0025	0.2060	0.0042	2.2958	0.0653	1218	62	1207	22	1
3982-55	0.1768	0.0036	0.5041	0.0089	12.2840	0.2152	2623	34	2631	38	0

% Disc. = percent discordance

not considered further. The oldest group of zircons is Archaean, with ages ~2930 to ~2500 Ma, within which three analyses form a minor age cluster at ~2650 Ma. A second grouping occurs within Paleoproterozic to earliest Mesoproterozoic zircons that range from ~1700 to ~1510 Ma. Within this age range occurs the second largest age peak of the sample which can be described by a weighted mean ^{207}Pb-^{206}Pb age of 1662 ± 20 Ma (n = 9, MSWD = 1.4). Mesoproterozoic-aged zircons dominate the sample with the major age population of the sample occurring at 1172 ± 11 Ma (n = 22, MSWD = 1.1) derived from 40 percent of the total zircons analyzed. A second age peak occurs as a shoulder on the younger side of the main ~1180 Ma peak and can be characterized by a weighted mean age of 1074 ± 24 Ma (n = 5; MSWD = 0.8). The remaining three data points yield Neoproterozoic ages of ~990, ~970, and ~620 Ma (Table 2).

Provenance of zircons from the Jacinth deposit

The majority of zircons within the deposit are derived from a source terrain dominated by Grenvillian-aged, ~1180 Ma, crystalline rocks. This source and the slightly younger ~1080 Ma age peak are identical to those of the two Grenvillian belts of southern Australia—the Musgrave province and the Albany Fraser orogen (Clark et al., 2000; Edgoose et al., 2004; Spaggiari, 2009), both of which occur within the broader catchment of the Eucla basin and associated paleodrainage (Fig. 8).

The source of the ~1650 Ma population is more difficult to pinpoint. Within the Gawler craton, volumetrically minor, predominantly mafic magmatism is recorded at ~1650 Ma (Daly et al., 1998), which may have provided some of these zircons. However, in light of the abundance of zircon from Grenvillian rocks to the west and north of the paleocatchment, it is possible to probable that the ~1650 Ma age population is derived from either a western or central Australian source. Possible sources are large ~1750 to 1600 Ma magmatic deposits in the Arunta region of central Australia (Scrimgeour et al., 2005) or the Capricorn orogen to the north of the Yilgarn craton, which records ~1690 to 1600 Ma magmatism and associated orogenesis related to the Mangaroon orogeny (Sheppard et al., 2005). Invoking either of these as source terrains implies that the zircons have most likely been through at least one cycle of erosion, transport, and deposition, possibly into the Neoproterozoic to Cambrian Officer basin (Fig. 8A), prior to further reworking and transport into the Eucla basin because neither the Arunta Region nor the Capricorn orogen lie within the catchment of the Eucla basin. An alternative source for zircons with ages between ~1700 to ~1650 Ma is the Albany Fraser orogen. The Albany Fraser orogen comprises a number of different tectonic zones, including the 1,200-km-long Biranup zone (Spaggiari et al., 2009). Felsic and mafic gneisses from the Biranup zone were emplaced between ~1690 to ~1665 Ma (Nelson et al., 1995; Spaggiari et al., 2009). The timing of this late Paleoproterozic magmatism and associated deformation in the Albany Fraser orogen matches the distribution of zircons in the Jacinth deposit. Although it is uncertain exactly where zircons of this age were derived from, the identification of source rocks located thousands of kilometers away, in either central or western Australia, is indicative of long distance transport.

The Archean zircons within the Jacinth deposit, although relatively few in number, are more suggestive of a Yilgarn craton source than a Gawler craton source because the ages are identical to the extensive ~2990 to 2650 Ma volcanic sequences of the Yilgarn craton (Krapež and Hand, 2008), rather than the Late Archean to earliest Paleoproterozoic, ~2560 to 2440 Ma ages typical of the Gawler craton (Jagodzinski et al., 2009; Reid and Daly, 2009).

In summary, it appears that the dominant crystalline basement source rocks for the zircons within the eastern Eucla basin were likely from the Musgrave province and/or the Albany Fraser orogen, both of which occur to the west of the Jacinth deposit. This source and an Archean component, probably derived from the Yilgarn craton, are consistent with a dominantly westerly longshore drift across the Eucla basin. Importantly, the ages documented here from the Ooldea barrier are similar to the ages of zircons in the Barton West (Notrab) prospect about 100 km to the northwest of the Jacinth deposit and part of the Barton barrier complex (Reid and Hou, 2006). The similar ages suggest that the dominance of the Grenvillian source material may well be a regional pattern for detrital zircons within the Eucla basin mineral sands province (Fig. 8).

Models of Coastal Evolution and Implications for Heavy Mineral Exploration

Refinement of models of landscape evolution of the Eucla basin margin and associated shorelines assists mineral explorers in reviewing and modifying strategies in the search for paleobeach placers in the region. Information provided on deformation of the Eucla basin and heavy mineral provenance suggests that heavy mineral accumulations may be found farther to the west than the current batch of discoveries in the eastern Eucla basin because the dominant source of zircon was not in the immediate vicinity, but was significantly to the north and/or west of recent discoveries. Whereas the role of local control on sediment dynamics leading to localized heavy mineral concentrations in specific regions is still poorly understood owing to lack of detailed data, the predominant eastward longshore drift in the Eocene beach system makes knowledge of the cratonic provenance for the heavy mineral an important predictive exploration tool. For example, if a solely Gawler craton origin could be demonstrated, then high-grade zircon deposits, similar to Jacinth and Tripitaka, would be confined largely to the eastern Eucla margin. Fortunately, this is not supported by current models of landscape evolution, including source of supply, Eocene longshore drift, and epeirogenic deformation of the basin, or by detrital zircon ages of contained grains. In contrast, a source solely from the Yilgarn and Albany Fraser region would significantly extend the prospective area of the Eucla basin paleobeach placer province. Our studies indicate a predominantly Musgrave province or Albany Fraser orogen source for the zircon fraction, but multiple source regions for other heavy minerals remain a possibility. Future work must consider characterization and dating of other minerals in the heavy mineral fraction, including titanite, rutile, and monazite, to give a more comprehensive picture of the source regions and likely routes of dispersion.

Basis for model

The basis for the geologic model presented here is the integration of sequence stratigraphy with regional and global evidence for relative sea-level change and major eustatic events, heavy mineral source and dispersion, and neotectonic activity in the Cenozoic, particularly during the time of deposition of the heavy mineral-bearing sediments. Earlier studies (e.g., Benbow, 1990; Benbow et al., 1995a, b) proposed a regressive development of strandlines that followed marine transgression in the late middle Eocene. Regarding the extent of the Eocene transgression, Li et al. (2003) concluded that at approximately 39 Ma a shallow-shelf sea extended to the Eucla onshore record of the continental margin, more than 300 km inland of the present coast. This position equates with paleocoastal landforms that today exceed 180 m elevation (Fig. 3; Hou et al., 2008). Similar conclusions were drawn by Clarke et al. (2003) and Hou et al. (2006) in studies of Eocene

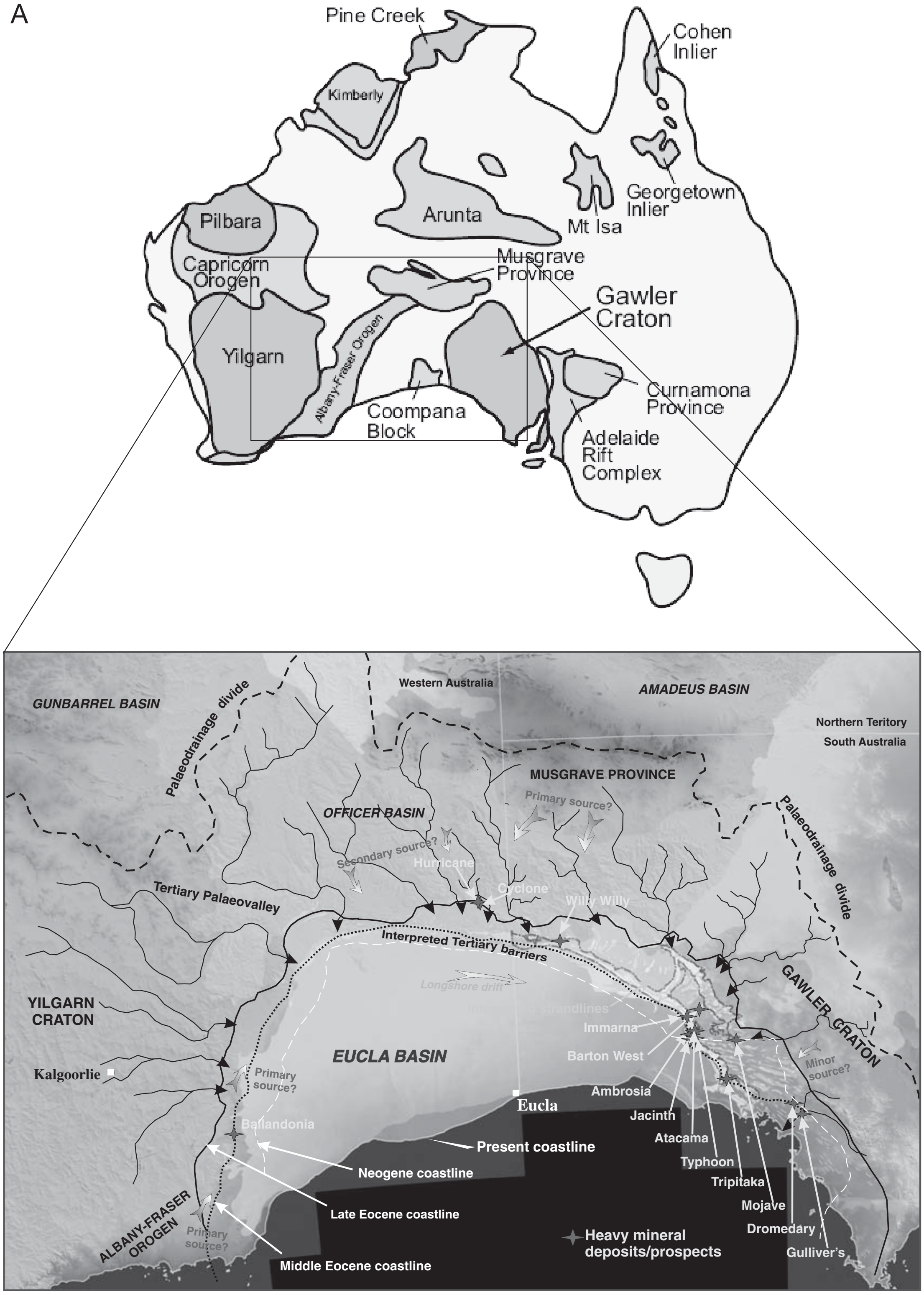

FIG. 8. Interpretation of heavy mineral sources. A) Relationship of Eucla basin and paleovalley network and heavy mineral deposits and prospects to the bedrock source areas for the sediments; B) U-Pb results and predicted detrital zircon signatures shown as probability plots for Precambrian basement terranes within the catchment for the Eucla basin, for comparison. The signatures for the Gawler and Yilgarn cratons and Musgrave province are modified from Pell et al. (1997). The distribution from the Albany Fraser orogen is taken from an age spectra from Cawood et al. (2003), who analyzed a sample of modern stream sediment within a river that drains over the southern Yilgarn craton and the Albany Fraser orogen. This distribution was interpreted by Cawood et al. to contain some component of detrital zircon from the Yilgarn craton in addition to zircons that have undergone reworking within the Albany Fraser orogen itself.

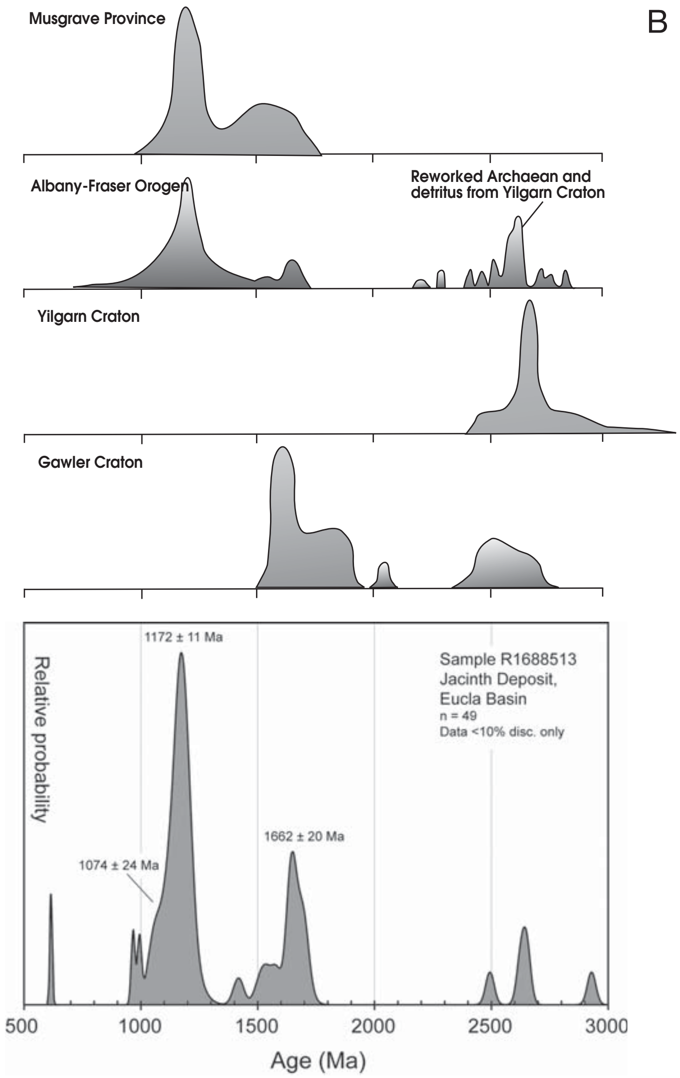

FIG. 8. *(Cont.)*

sedimentation in southern Australia. Using palynological and facies evidence, they concluded that two transgressive stages occurred at about 39 and 36 m.y. ago. During the peak of late Eocene marine transgression, eustatic sea level was estimated to be ~200 m higher than today (Fig. 3; Hou et al., 2008). Hou et al. (2008) also concluded that since mid-Miocene time, uplift of the western Eucla margin relative to the eastern margin was greater by approximately 130 m. These transgressive events were sufficiently extensive to incorporate the elevation range observed for all known heavy mineral-bearing strandlines.

For the Jacinth-Ambrosia deposits, geologic sections compiled from company exploration drilling results (Fig. 9) were evaluated, resulting in an interpretation indicating the presence of eight distinct facies that provide the basis for a model of the evolution of the Ooldea barrier system, shown in Figure 10. Units A1 and A2 are correlated with the >39 Ma lower Pidinga Formation (see Fig. 4), and are largely of marginal marine to beach origin with fluvial sediments preserved in the base of channels. These units are discontinuous across basement highs, possibly the result of erosion during later marine transgression. Alternatively, the basement highs may have remained emergent. Unit B formed during the Tortachilla transgression, as a marginal marine facies intertonguing with Unit C1, representing highstand flooding delta deposits. Unit D1 formed during the late middle Eocene Tortachilla highstands (39 Ma, ~180 m; Fig. 3) through deposition of (Ooldea) beach placers and overlying backshore dunes. The unit was exposed and, in part, weakly silicified as sea level dropped prior to renewed transgression during the Tuketja-Tuit transgression. Unit D2 includes partly reworked D1 from older barrier island and dune complexes. D2 most probably formed during stillstands and regression associated with the last marine transgression of late Eocene age (36 Ma, ~200 m, Figs. 3, 4), which also formed the Barton barrier farther to the east.

Rapid regression followed the Tuketja-Tuit highstand and caused the formation of steep Mio-Pliocene-aged cliffs along this part of the Ooldea barrier, which restricted later Mio-Pliocene transgressions to the Nullarbor Plain (limestone, C2), with marginal marine facies (e.g., Yarle Sandstone) probably reworked from Eocene barrier dunes. Units D1and D2 are correlated to the Eocene Ooldea Sand and Barton Sand (Fig. 4), but the variety of the barrier sands and interpreted ages are yet to be fully resolved. During the maximum Eocene transgression (Fig. 3), transgressive barrier island and dunes complexes migrated tens of kilometers across the eastern Eucla margin to produce extensive deposits of Unit D2. Regolith processes associated with gentle uplift and drying of the southern margin of the continent are apparent in mottles and indurations in the sand profile and in aeolian reworking (Fig. 9). Unit C2 was deposited during the middle Miocene to early Pliocene and deposition of Unit E, forming the surface dune features that were initiated in the early Quaternary. Unit C2 has been active during periods of glacial maxima, most recently at ~20 ka.

Depositional model and heavy mineral prospectivity in the Eucla basin

The revised depositional model for the Eucla basin provides a framework for the timing of individual heavy mineral-bearing units in the Eucla coastal plain. Whereas the series of shorelines along the basin margin extend over the entire ~2,000 km from east to west, concentrations of heavy mineral have not occurred continuously along these shorelines. In addition, regional spectral and elevation data combined with drilling data indicate that the area of the Eucla basin occupied by beach and/or barrier sands is many times bigger than was previously recognized, and the distribution of these sands along the shorelines is quite different from previous interpretations (Fig. 2). These interpretations present major challenges in devising cost-effective exploration strategies across the Eucla basin, where tenements for heavy mineral sands cumulatively cover thousands of square kilometers. Strategies need to consider the impacts of sea-level change, predominant wind and longshore drift directions, and the effect of dynamic deformation on reworking and realigning beach and barrier features during marine transgressions, particularly in the Mio-Pliocene. Our revised model consists of the following events: (1) initial rapid transgression and deposition of a

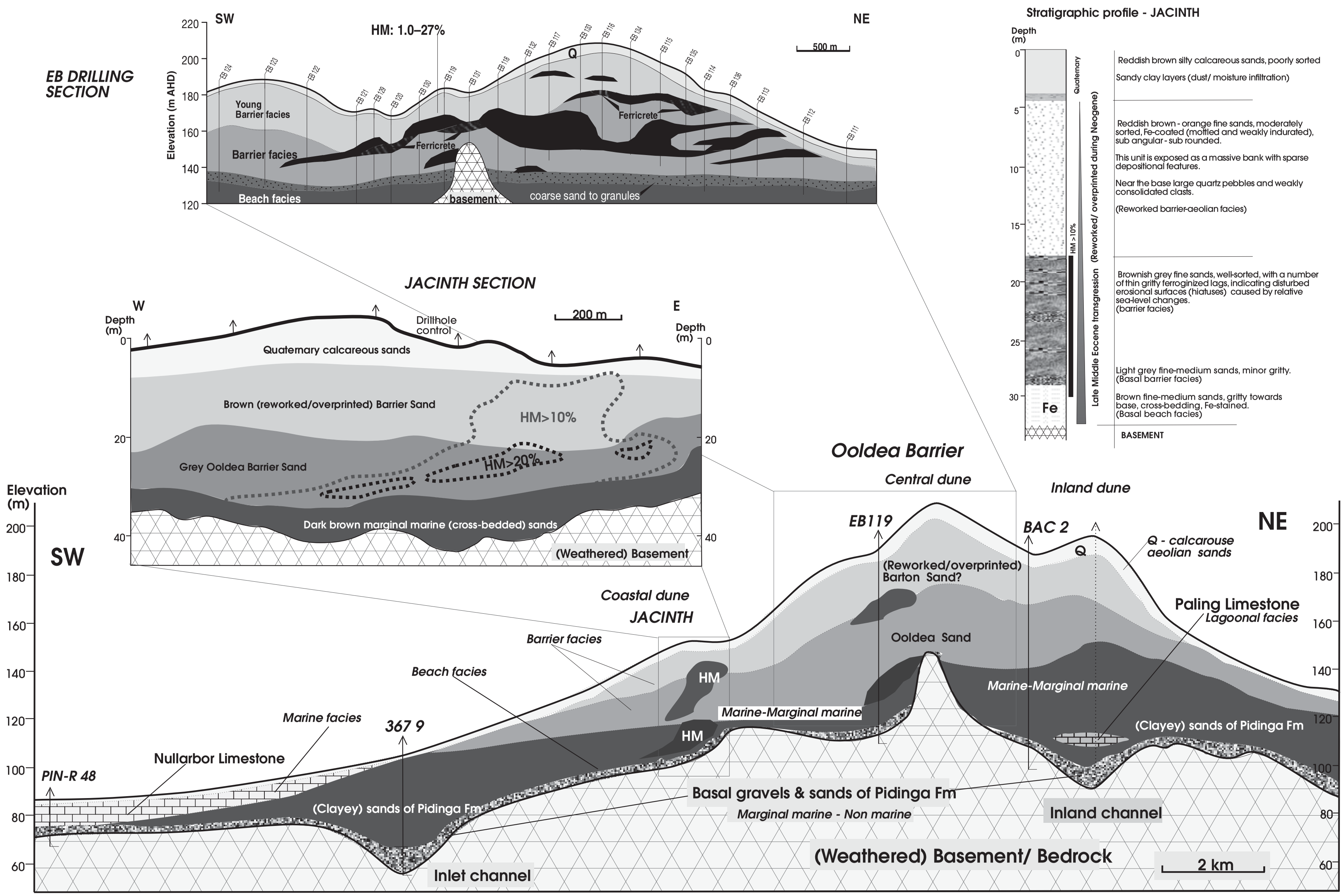

FIG. 9. Geologic cross sections through the Ooldea barrier and mineralized zones from representative drill hole data, showing association of heavy mineral anomalies with their host barrier facies and topographic features. See Fig. 6 for location of sections.

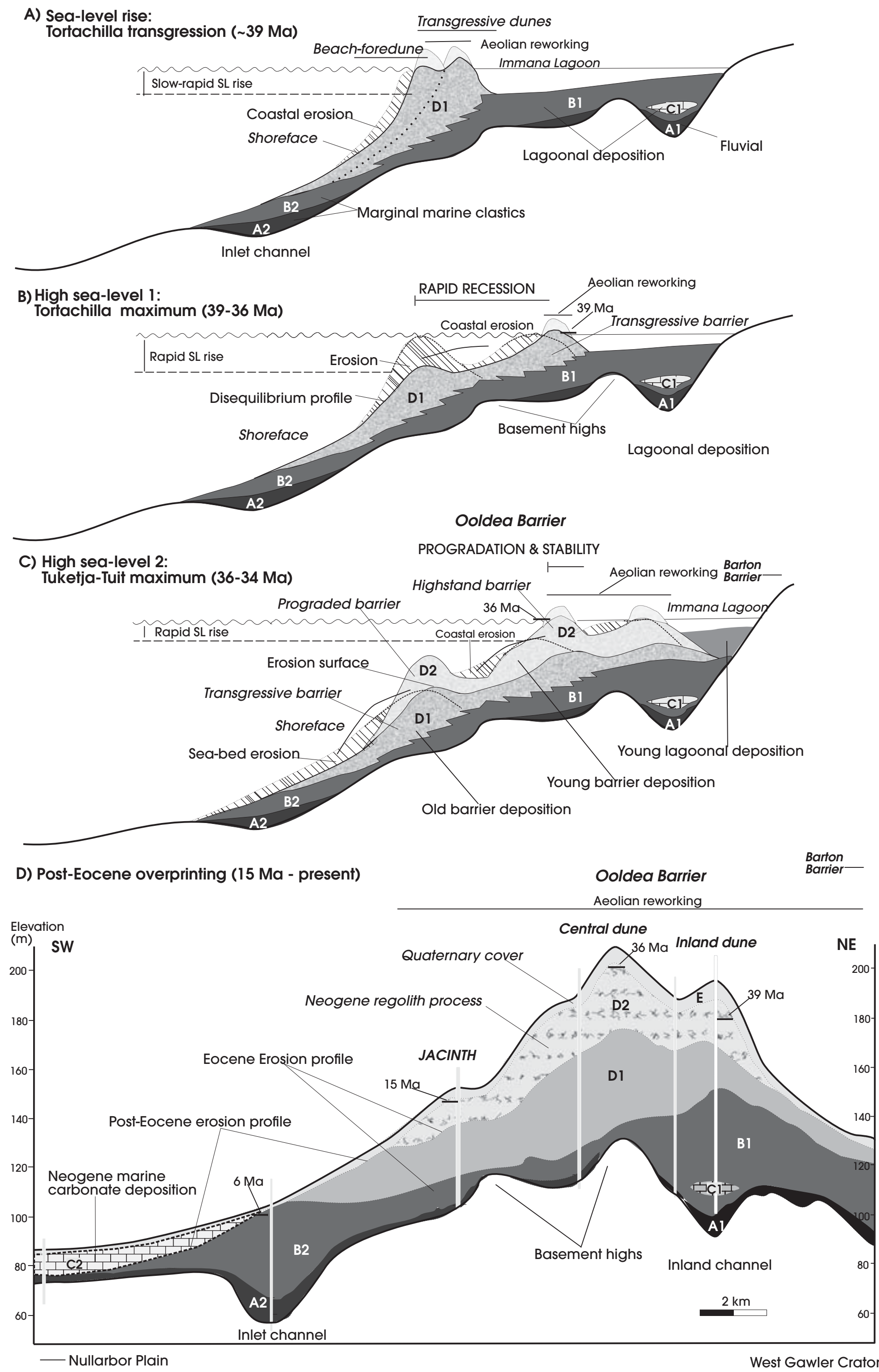

FIG. 10. Schematic evolutionary model for the Ooldea barrier and HM deposits, eastern Eucla basin. The models A to D show distinct shoreline facies-building events for the southwest-northeast stratigraphic cross section shown in Figure 9. A) Sea-level curves for local cycles (McGowran et al., 2004) show the approximate age and sea level for each facies-building event and its change. Longshore drift, wave action, or inlet bypassing that add sand to the downdrift (southwest) sector of the (Ooldea) coast tend to stabilize the barrier and permit foredunes to form on the barrier surface; foredunes impede washover processes and decelerate the rate of shoreface recession under slowly rising sea levels that may in turn result in drowning of barrier superstructure, deepening of lagoon, and shoreface profile. B) Rapidly rising sea level resulted in washover processes—barrier was overtopped and transferred inland while shoreline moved landward. C) Continued rapidly rising sea level resulted in seabed erosion and disequilibrium profile offshore, which promotes nearshore (eg., by longshore drift) and onshore (eg., by paleorivers) sand transport and build 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 profile of the upper barriers. Erosion and aeolian reworking of each stage locally modified the morphology of the barrier coasts.

shallow marine sand sheet subsequently overlain by the shallow marine limestone; (2) a major Eocene transgression and deposition of a shelf, barrier, lagoonal, and locally flooding deltaic carbonaceous limestone blanket; (3) further transgression and highstand; (4) renewed transgressive deposits of barrier, lagoonal, and possibly flooding deltaic sand blankets in the southeastern coastal plain with neotectonic deformation and progressively higher uplift of the western Eucla margin; and (5) postdepositional preservation.

Initial rapid transgression (middle Eocene): In the central Eucla basin, offshore marine sand and some of the terrigenous sand in the paleovalleys was recycled during the middle Eocene (Wilson Bluff) transgression and transported to the onshore margin where it was deposited as Hampton Sandstone, unconformably on cratonic basement or older sediments (e.g., Hocking, 1990; Benbow et al., 1995a). These early beach deposits were later buried by marine limestone. A poorly defined Wilson Bluff shoreline of inferred beach facies of the Hampton Sandstone (Fig. 5A; Hou et al., 2003b, c, 2006), may express placer characteristics in the thin beach sand sheet and basal lag (Fig. 10A), although limited drilling data indicate that this lithofacies contains no anomalous levels of heavy mineral sands. This shoreline remains prospective for middle Eocene beach placers (zones P12 and P13). The economics of exploring and mining such deposits beneath marine limestone has not been evaluated.

Major Eocene transgression (late middle Eocene): At present, the highest grade identified heavy mineral concentrations essentially follow the late middle Eocene shoreline and correspond to the beach deposits of the Tortachilla Transgression (Hou et al., 2003b). Marine transgression in the late middle Eocene (eastern) coastal plain is marked by deposition of shelf, barrier island, lagoonal, and locally flooding deltaic carbonaceous limestone sediments that in places blankets lower Pidinga Formation, Paling Formation and Ooldea Sands (Fig. 10). The fine-grained, well-sorted sands of the shoreface and barrier island units contain a mature assemblage of heavy minerals formed as waterlain beach sands or barrier-dune complex sands. Zircon, a very resistant and locally concentrated heavy mineral, is rounded, as are most of the other heavy minerals. The heavy mineral assemblage is probably of multicyclic origin. In the eastern basin, heavy mineral is hosted mainly by highstand beach-barrier sands of the Ooldea Sand and occur in zones ranging from tens to hundreds of meters wide and 2 to 20 m thick (Figs. 4, 5). The Tortachilla transgressive (Ooldea) beach was characteristically reflective, displaying a steep beach face composed of fine to medium sand with sediment sourced from erosion of (Musgrave) cratonic rocks transported down incised valleys and then by longshore drift toward the east (Figs. 5B, 6). Multiple swash-aligned foredune ridges within the Ooldea Range provide evidence of prolonged accumulation of coastal sediments during the Tortachilla transgression (Clarke and Hou, 2000). This paleoshoreline is highly prospective for late middle Eocene beach placers (zones P14 and P15).

Further transgression and highstand (late Eocene): The heavy mineral concentrations identified in the late Eocene (Barton) barrier in the eastern basin are hosted by highstand beach-barrier sands of the Barton Sand that were deposited along the late Eocene (Tuketja-Tuit) coast and on the top of Ooldea barrier (Fig. 10). As marine transgression progressed during the late Eocene reaching ~20 m higher sea level than the earlier marine transgression (Clarke and Hou, 2000), the deposition of the barrier island unit was deposited at successively higher elevations. This transgression was followed by a rapid regression that resulted in erosion of a wave cut tidal plain (between the Pidinga and Khasta formations; Fig. 4) (Hou et al., 2003c). This coast in the eastern basin was characterized by a series of coastal barrier island sands, oriented southwest-northeast (at an angle to the Ooldea barrier). The Ooldea barrier remained as a series of offshore barrier islands. Paleorivers cutting through the late Eocene (Barton) barrier island complex also contributed to placer deposition, particularly where local factors reduced stream velocity (Fig. 5C). The Tuketja-Tuit transgressive (Barton) beach was also typical of beach faces composed of fine-medium sand transported via incised valleys (Hou et al., 2003b). Protection afforded by offshore (Ooldea) islands in the late Eocene coast created a wave energy gradient decreasing to the northeast in this coastal sector (Fig. 5C). This shoreline is also highly prospective for late Eocene beach placers (zones P16 and P17).

Upgrading heavy mineral concentrations in some parts of the Ooldea and Barton barriers may have occurred during sea-level changes, by means of the transgressive barrier island and longshore current (littoral bypassing) fractionation model shown in Figure 6. Identification of the western extension of the Ooldea barrier and later beach-barrier island complex facies in the northern and western margins of the basin is important and essential to advance further exploration efforts to find heavy mineral deposits in these areas. High-resolution nighttime thermal imagery (e.g., ASTER) and detailed elevation data combined with geologic and drill hole data and interpreted in a GIS environment (Fig. 2) have been shown to combine as an effective approach for evaluating Cenozoic geomorphology. This method has allowed recognition of sequences of beach ridges interpreted as numerous strandlines <50 to 100 m apart within these coastal barrier island sands in the remarkably wide (up to 30 km) Ooldea and Barton barriers (Fig. 2). These indicate higher order influences on barrier accretion (Roy and Whitehouse, 2003). This strandline complex holds significant promise for defining economic concentrations of heavy mineral sands.

Renewed progradation (regression; Miocene-Pliocene): The Mio-Pliocene period of shoreline deposition is represented by reworked Eocene coastal sediments in the southeastern Eucla coastal plain. These sand units are typically heavy mineral bearing. They are fine-grained, moderately to well sorted, have a distinct enrichment in heavy mineral sands, and probably represent a period of beach, barrier, and/or dune complex deposition. Numerous low grade (>1%) heavy mineral were discovered from the middle Miocene-early Pliocene sediments in the coastal plain (Fig. 2). Information from this poorly defined Mio-Pliocene coastal plain around the Kingoonya and Narlaby paleoriver mouths has been updated by the recent study of the basin evolution, particularly the neotectonic impact on the heavy mineral-bearing strandlines (Hou et al., 2008). These Mio-Pliocene transgressive-regressive shorelines are very prospective for heavy mineral concentrations in the southeastern margin of the basin (Figs. 2, 5D).

Two interdependent mechanisms are likely to produce localized concentrations of heavy mineral sands in the southeastern Eucla basin during Mio-Pliocene time. The first involves transgressive-regressive barrier island fractionation processes operating in parts of the former Ooldea barrier where old (Eocene) barrier island sands containing concentrations of heavy mineral were exposed to marine reworking while the Mio-Pliocene barriers were forming. The second involves longshore current fractionation processes operating in an environment where downwarping was active. Reworking older heavy mineral-bearing strandlines is the most likely source of heavy mineral sands, as sediment supply from the flow in rivers draining the nearby Gawler craton was reduced during Mio-Pliocene time. Continued exploration for heavy mineral deposits in the Mio-Pliocene coastal zones of the eastern basin is an indication that results are encouraging and that discovery of further heavy mineral-bearing shorelines beneath relatively thin cover is likely. In contrast, the uplift and the condition of beach-sediment starvation that apparently existed in the western margin of the basin in late Miocene-early Pliocene times would have been less favorable for the formation of heavy mineral placers.

The role of regional deformation: Whereas a series of roughly parallel Mio-Pliocene barrier islands would have acted as a focus for heavy mineral concentration in the southeastern basin, along the western, northern, and northeastern margin of the basin, shorelines from this time are largely unknown (Fig. 2). However, the Mio-Pliocene basin shorelines were not completely featureless. That active downwarping would have influenced Mio-Pliocene shorelines is indicated by the depositional migration of the barriers (Hou et al., 2008). We believe a genetic relationship exists between downwarping and heavy mineral sand fractionation processes, at least in the southeastern basin. Under stable sea-level conditions, a tendency for the (epeirogenic uplift) to shift the shoreface seaward in the western basin is counteracted by reduced rates of deposition (or even erosion) on uplifted parts. This, together with eastward longshore drift, largely explains the apparent lack of dislocation of barrier alignments. In contrast, a tendency for the downwarping to shift shoreface deposition landward in the eastern basin is offset by increased rates of deposition in areas subjected to marine flooding.

Conclusions

The evolution of the Cenozoic shorelines of the Eucla basin is characterized by a landward stepwise migration of the coastline. There is evidence for at least four main phases of paleoshoreline sedimentation: middle Eocene, late middle Eocene, late Eocene, and middle Mio-Pliocene. Shorelines formed during these third-order sea-level rises contain beach placers, mostly formed during coastal sea-level change, at sites where there was supply of heavy mineral sands and conditions for concentration and preservation favorable for heavy mineral deposits. In aggregate, the accumulation of barrier island sands is up to 30 km wide and their complexity conceals numerous individual strandlines, deposited during high order events of sea-level rise that are mostly undocumented and remain highly prospective for heavy mineral sands. Around the peak of transgression and highstand, heavy mineral deposits formed in beach or barrier island and dune sand complexes. Stillstands were likely associated with late middle Eocene deposition as this shoreline includes some of the largest and richest deposits. The heavy mineral deposits are most likely to have arisen from multicyclic origin. The likely sources for heavy mineral-rich zircon sands are late Mesoproterozoic to Cambrian fluvial and shallow marine sandstones along the northern and western margins of the Eucla basin, with recycling of heavy mineral sands sourced primarily from cratonic basement rocks of the Musgrave province and the Albany Fraser orogen, (based on crystallization ages from those terranes) with lesser contribution from older terrains.

Apart from the relatively well known Ooldea and Barton barriers, other shorelines are prospective for hosting heavy mineral deposits. These include the middle Eocene Hampton Sandstone in the central part of the Eucla basin and Neogene strandlines in the eastern basin. Reconstructing early shorelines of the middle Eocene Wilson Bluff shoreline in the central basin is hampered by marine limestone cover and limited drill hole data. Similarly, tracing the extent of Neogene shorelines, especially in the more prospective areas near paleoriver outlets and across older coastal barrier islands, is difficult due to extensive surficial cover of younger aeolian dunes. Further research to delineate these systems may provide additional heavy mineral targets.

Many world-class heavy mineral deposits were formed during the late Miocene to early Pleistocene marine transgressive-regressive events. These include Eneabba in Western Australia (Lissiman and Oxenford, 1975; Baxter, 1977) and those of New Jersey (Puffer and Cousminer, 1982), Trail Ridge of Florida (Force and Rich, 1989), North Carolina and Virginia (Carpenter and Carpenter, 1991), the southeast coast of Australia (Roy, 1999), and the Murray basin of Australia (Roy et al., 2000; Roy and Whitehouse, 2003). Findings here have significance for worldwide exploration for older (Eocene) heavy mineral deposits in that concealed deposits of the type described here may exist in areas that have received little or no previous exploration for heavy mineral deposits, in particular where they lie adjacent to Precambrian shield areas. Given the example here, such deposits may be located over 120 km (Jacinth-Ambrosia deposits) and even 320 km (Cyclone) inland from modern shorelines (Fig. 2).

Major points arising from the present study are as follows.

1. The Eucla basin has potential to become a major new heavy mineral province in Australia, and probably a world-class zircon source. At the time of writing, over 12 separate heavy mineral prospects have been reported from paleobeach and barrier island sands in the Eucla basin, with mining at the Jacinth deposit commissioned in 2009.

2. The deposits are in mostly unconsolidated sands above the water table and generally have a favorable ore thickness to overburden ratio. Consequently, mining and processing appear relatively feasible. The remote location and general lack of infrastructure mean that large or high-grade deposits with a high content of the more valuable heavy minerals are more likely to be developed in the near future as driven by economic conditions.

3. Recent stratigraphic investigations and new data from mineral exploration suggest revision of earlier views that the

prospective coastal strandlines resulted from a single transgressive-regressive cycle across the basin. More than four generations of Cenozoic shorelines comprise many heavy mineral-bearing strandlines.

4. The regional distribution of the heavy mineral-bearing strata and the shoreline evolution is consistent with landward terrace migration of the shoreface complexes from the central basin to the onshore margin—by over 300 km—as a result of sea-level change. The predominance of zircon in high-grade heavy mineral deposits originating from the Musgrave province enhances the prospectivity of the northern and eastern margins of the Eucla basin.

5. The valuable heavy mineral assemblage consists mostly of zircon and altered ilmenite with lesser proportions of rutile and leucoxene. Zircon is the dominant heavy mineral in parts of the eastern basin, while ilmenite predominates in prospects along the northern and western basin. The highest concentration of zircon (up to 65% of the heavy mineral fraction) is found along the Ooldea barrier in the eastern Eucla margin.

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