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Cenozoic Eucla Basin and associated palaeovalleys, southern Australia — Climatic and tectonic influences on landscape evolution, sedimentation and heavy mineral accumulation

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Abstract

The Eucla Basin including the vast Nullarbor Plain lies on the margins of the Yilgarn, Musgrave and Gawler cratons in southern Australia and owes its distinctive landscape to a unique set of interactions between eustatic, climatic and tectonic processes over the last ~50 Ma. Understanding of the history of the basin and the palaeovalleys that drained from the surrounding cratons are important because they contain major mineral deposits, and the sediments derived from them contain remobilised gold, uranium, and heavy minerals. In particular, a remarkably preserved palaeoshoreline sequence along the north-eastern margin of the Eucla Basin is highly prospective for heavy mineral placer deposits. The record of marine, marginal marine, estuarine, fluvial and lacustrine environments, as constrained mainly by an extensive borehole dataset, reflects major depositional events during the Palaeocene–Early Eocene, Middle–Late Eocene, Oligocene–Early Miocene, Middle Miocene–Early Pliocene and Pliocene–Quaternary. These events reflect the key role of eustatic sea-level variation which, during highstands, inundated the craton margins, flooding palaeovalleys to up to 400 km inboard of the present coastline. However, a systematic eastward migration of the depocentre across the Eucla Basin during the Neogene, together with apparent flow reversals in a number of palaeovalley systems draining the Gawler Craton, suggest that the Eucla Basin has also been subject to differential vertical movements, expressed as a west-side up, east-side down tilting of ~100–200 m. This differential movement forms part of a broader north-down–southwest-up dynamic topographic tilting of the Australian continent associated with relatively fast (6–7 cm/yr) northward plate motion since fast spreading commenced in the Southern Ocean at ~43 Ma. We suggest that the evolving dynamic topography field has 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 persistent westerly weather systems.

Keywords: Eucla Basin; Palaeovalleys; Heavy minerals; Landscape evolution; Southern Australia

1. Introduction

The Eucla Basin in the southern interior of Australia contains remarkably preserved Cainozoic coastal barriers and palaeovalley systems inland of the vast Nullarbor Plain (Fig. 1). As well as flooring the Nullarbor Plain and offshore Eucla Basin, shallow marine sediments deposited in highstand events extend far onshore as sediment fill of palaeovalley systems. Geological mapping and exploration for economic resources of heavy mineral sands, uranium, coal, clay minerals and groundwater, have revealed a wealth of information on the sediments (e.g., Lowry, 1970; Benbow, 1990, 1993; Jones, 1990; Cowley and Martin, 1991; Clarke, 1993, 1994a, 1994b; Kern and Commander, 1993; Benbow et al., 1995a, b; Keeling et al., 1995; Alley and Lindsay, 1995; Alley et al., 1999; Benbow et al., 2000; Clarke and Hou,

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2000; Rogers, 2000; Hou et al., 2001a, b, 2003a, b, c; 2006; Johnson and McQueen, 2001; de Broekert, 2002; Hou and Alley, 2003; Li et al., 2003; Clarke et al., 2003; Hou, 2004; de Broekert and Sandiford, 2005). In this apparently stable tectonic environment, it is hardly surprising that the interpretation of the spatial and temporal distribution of sedimentation has been framed almost exclusively in terms of eustatic processes. However, recent studies have also demonstrated that differential vertical motions with an amplitude in excess of the eustatic sea-level variation affected the Australian continent in the Neogene (de Broekert and Sandiford, 2005, Sandiford, 2007). Our objective here is to analyse the contributions of eustatic, climatic and tectonic processes to the remarkable archive of near-shore environments across the Eucla Basin. The work extends previously published stratigraphic analyses by the authors (de Broekert and Sandiford, 2005, Hou et al., 2001a, b, 2003a, b, c; 2006) by explicitly incorporating the role of long-wavelength vertical motions due to dynamic topographic effects associated with Australia's rapid northward motion, as elucidated at the continental scale by Sandiford (2007). We will also build on the work of Benbow et al. (1995a) who concluded that epeirogenic movement of the Eucla Platform produced tilting with greatest uplift to the northwest. These authors, however, were unable to quantify the amount of tilting.

The large areal extent of the Eucla Basin and adjacent palaeovalley system, which together covers ~20% of the Australian continent, has resulted in a complex succession of marine and non-marine strata, making correlation of stratigraphic, sedimentary and tectonic events non-trivial. While the landscape of the Eucla Basin and the surrounding region contains remarkably well-preserved and varied palaeo-landforms of Cainozoic age (Benbow, 1990), pervasive aeolian sand and clay cover and widespread duricrusts in the present-day landscape hamper thorough mapping of the basin and associated palaeovalley sediment fills. Reconstructing the distribution, thickness and sedimentary facies of palaeovalley fills therefore challenges the application of geological, geophysical and geochemical exploration techniques and presents both difficulties and opportunities for mineral exploration (Hou et al., 2000). The stratigraphic framework for the basin that underpins our interpretations relies to large extent on palynological age determinations (e.g., Smyth and Button, 1989; Waterhouse et al., 1994; Benbow et al., 1995a; Hou et al., 2003a, 2003b) from an extensive drillhole dataset as discussed in detail elsewhere (Hou et al., 2001a, b, 2003a, b, c; 2006). We begin with a summary of the stratigraphic framework.

2. Stratigraphic framework for the Eucla Basin and related palaeovalley systems

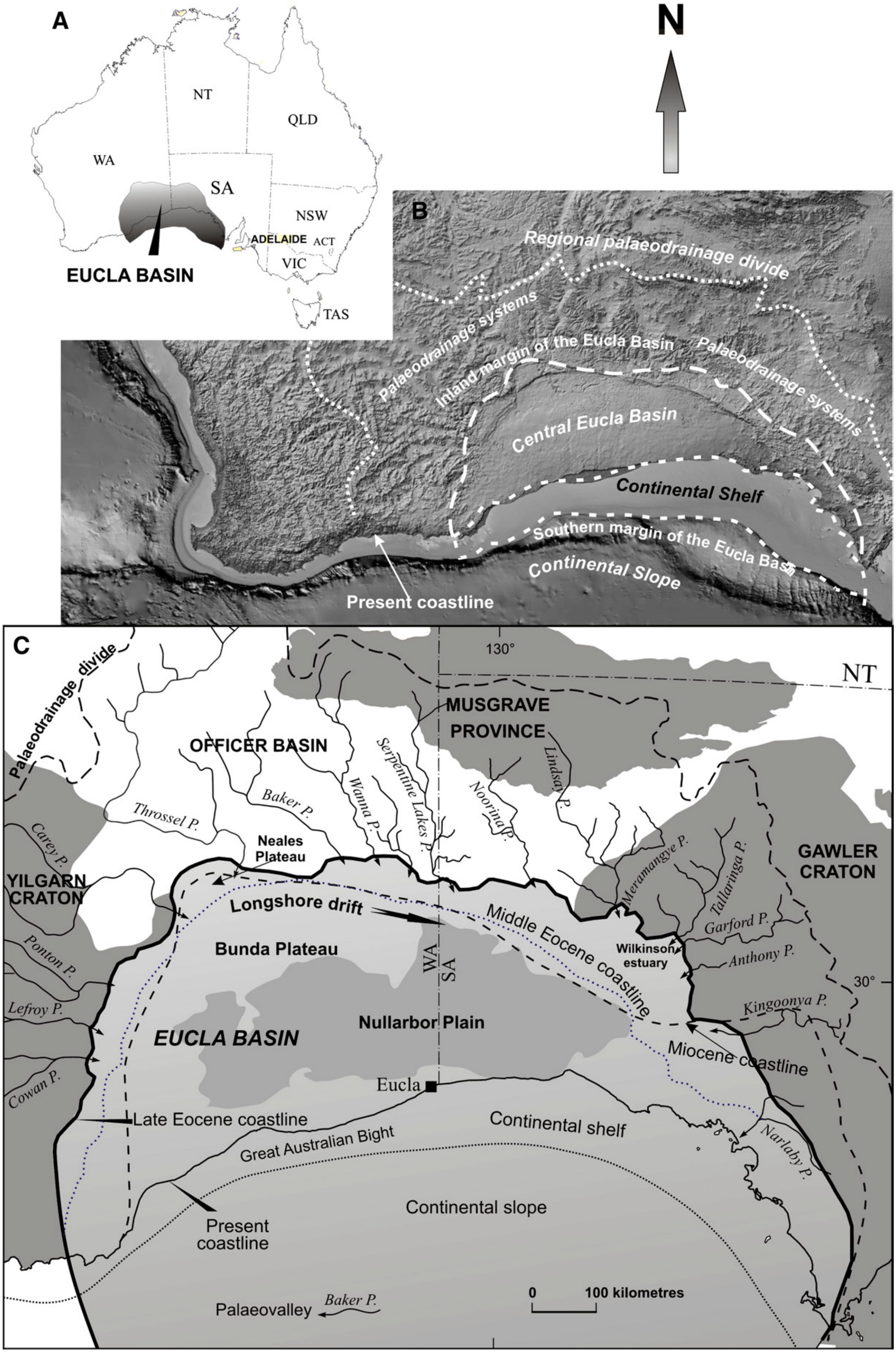
The Eucla Basin is a cratonic basin developed on the margin of the Yilgarn (e.g., Clarke, 1993, 1994a), Musgrave and Gawler cratons. The basin extends 2000 km from west to east and, including offshore extensions (platform edge), ~500 km from north to south (Fig. 1). Our focus here is mainly on the onshore sequences. These are evident in a number of distinct geomorphic units including the Nullarbor and Roe Plains, a series of coastal barrier ranges including the Ooldea, Barton and Paling Ranges and hinterland palaeodrainage systems now largely delineated by strings of playa lakes and lunettes developed in topographic lows on the adjacent cratons and extending inland as far as basin the Neoproterozoic–Paleozoic Officer Basin (e.g., Benbow, 1990; Benbow et al., 1995a; Clarke et al., 2003; de Broekert and Sandiford, 2005; Hou et al., 2003a, b, c; 2006; Reid and Hou, 2006). The present landscape is dominated by Quaternary sand plains and colluvial regolith, largely superimposed on and locally obscuring the older Tertiary landforms (Fig. 2).

Several major continental drainage networks dissect the Yilgarn, Musgrave and Gawler cratons into valleys that slope toward the Southern Ocean (e.g., Beard 1973, 1998; Benbow et al., 1995a; Figs. 1 and 2). The modern topography has been shown to largely reflect the pattern of early Tertiary palaeovalleys (Hou et al., 2003a; de Broekert and Sandiford, 2005; Figs. 1 and 2). The pattern of palaeovalleys in the onshore Eucla Basin is dominantly sub-dendritic (Fig. 1), reflecting both the pre-Tertiary land surface gradient and bedrock lithology and structure (Alley et al., 1999; Hou et al., 2001a; 2003a; de Broekert and Sandiford, 2005). In the eastern Yilgarn Craton, many trunk palaeovalleys parallel the northeast orientation of a regional fracture field (Johnson and McQueen, 2001) while in the western Gawler Craton palaeovalleys preferentially follow the topographic lows within weakly resistant, deeply weathered bedrocks (Hou et al., 2003a).

The marine Eucla Basin successions show a remarkably consistent stratigraphy across the entire basin (Clarke et al., 1996, James and Bone, 2000; Clarke et al., 2003; Hou et al., 2003a; 2006; Smyth and Button, 1989; Waterhouse et al., 1994; Benbow et al., 1995a; Hou et al., 2003a, 2003b) and are lithostratigraphically correlated in Fig. 3.

2.1. Central Eucla Basin stratigraphy

The central Eucla Basin is characterised by a carbonate platform and is famous for its distinctive remarkably flat and treeless landform, the Nullarbor Plain, extending some 1400 km along the southern Australian margin. In the western and central parts of the basin, the basal Hampton Sandstone (zone P12, Fig. 3) comprises up to 30 m of shallow marine sands overlain by up to 300 m of mostly cool-water carbonates of the Wilson Bluff, Abrakurrie and Nullarbor Limestones (Lowry, 1970; Hocking, 1990; Jones, 1990; Clarke et al., 2003; see Fig. 3). In the southwestern and central parts of the basin, Wilson Bluff Limestone is overlain unconformably by the Late 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), which suggests a northeast migration of the Eucla Basin depocentre from Eocene to Miocene times (Fig. 3). The relatively thick and localised occurrence of Abrakurrie Limestone compared with the overlying thinner but more aerially extensive Nullarbor Limestone suggests local tectonic subsidence in the central part of the basin in the Early Neogene. Further inland (?50–100 km), post-Abrakurrie erosion prior to and during initial deposition of the Nullarbor Limestone has


A
NT
QLD
WA
SA
NSW
ADELAIDE
ACT
VIC
TAS
EUCLA BASIN
N
B
Regional palaeodrainage divide
Palaeodrainage systems
Inland margin of the Eucla Basin
Palaeodrainage systems
Central Eucla Basin
Continental Shelf
Southern margin of the Eucla Basin
Continental Slope
Present coastline
C
Palaeodrainage divide
130°
NT
MUSGRAVE
PROVINCE
OFFICER BASIN
Serpentine Lakes P.
Lindsay P.
Baker P.
Wanna P.
Noorina P.
Throssel P.
Carey P.
Neales
Plateau
GAWLER
CRATON
YILGARN
CRATON
Meramangye P.
Tallaringa P.
Longshore drift
Middle Eocene coastline
Garford P.
Wilkinson
estuary
Bunda Plateau
Anthony P.
Ponton P.
WA
SA
30°
Kingoonya P.
Lefroy P.
EUCLA BASIN
Nullarbor Plain
Miocene coastline
Cowan P.
Eucla
Late Eocene coastline
Continental shelf
Great Australian Bight
Narlaby P.
Present
coastline
Continental slope
0
100 kilometres
Palaeovalley
Baker P.

removed any identifiable record of laterally equivalent Late Oligocene–Early Miocene terrigenous facies on the Eucla margin and palaeovalleys (Fig. 3; Benbow et al., 1995a; Alley et al., 1999; Hou et al., 2003a).

2.2. Eucla Basin margins and shoreline record

Over a distance of 100–150 km, the western Gawler Craton, southern Musgrave Block and eastern Yilgarn Craton are onlapped along the Eucla Basin margin by a veneer of Tertiary sediments, locally thicker in palaeovalleys (Clarke, 1994a; Alley and Lindsay, 1995; Hou et al., 2003a; Fig. 1). Along the eastern Eucla margin, the palaeochannel mouths are characterised by deposits that reflect a series of former estuaries (e.g., Neales, Wilkinson and Anthony) lagoons and coastal barriers (e.g., Ooldea and Barton) in which Middle–Late Eocene and Middle Miocene–Early Pliocene deposits dominate. Coastal beach and barrier deposits locally contain significant heavy mineral deposits (Benbow, 1990; Clarke and Hou, 2000; Hou et al., 2003b; Fig. 3). The Barton–Paling barrier/ridge elevation decreases toward the southeast, following the longshore drift direction, partly reflecting a decrease in sand supply from the northwest, but also a broader-scale, relative east-down vertical movement.

The lower Pidinga Formation and its correlative Maralinga Member along the eastern margin (Zone P14, Fig. 3) is the principal basal Tertiary sequence, unconformably overlying and onlapping Cretaceous and older sediments locally, and Precambrian crystalline basement (Fig. 3). At Tietkins Well, to the north of Maralinga, the lower Pidinga Formation intertongues with the basal part of the overlying Wilson Bluff Limestone (Zone P14/15) and passes laterally (northwards) into the basal sand equivalents of palaeovalley fills (Benbow et al., 1995a). The upper Pidinga Formation (Zone P16/17), and its correlative Anthony Member on the eastern margin, intertongues with the associated facies (Paling Formation) of the Wilson Bluff Limestone, and is overlain disconformably and may be interbedded with the Khasta Formation (Clarke et al., 2003; Hou et al., 2003a, b, c, 2006; Fig. 3).

The Yarle Sandstone, which correlates basinward with the Nullarbor Limestone and landward with the Ooldea Sand (Benbow et al., 1995a), was deposited along a northwest-trending Middle Miocene shoreline comprising mainly reworked Ooldea Sand of the Ooldea barrier/dune system (Figs. 1 and 3). In the southeast Eucla margin (e.g., Kingoonya and Narlaby palaeovalleys on the west and southwest margin of the Gawler Ranges), however, a marginal marine and estuarine channel sequence of the Garford (Kingoonya Member, Hou et al., 2003a) and Narlaby (Benbow et al., 1995a) Formations were deposited during the Middle Miocene–Pliocene. A thin sequence of laminated clays, silts, sands and minor carbonate up to 5 m thick (Ilkina Formation of Pliocene age; Benbow et al., 1995a), overlies the Garford Formation in the southeast Eucla margin.

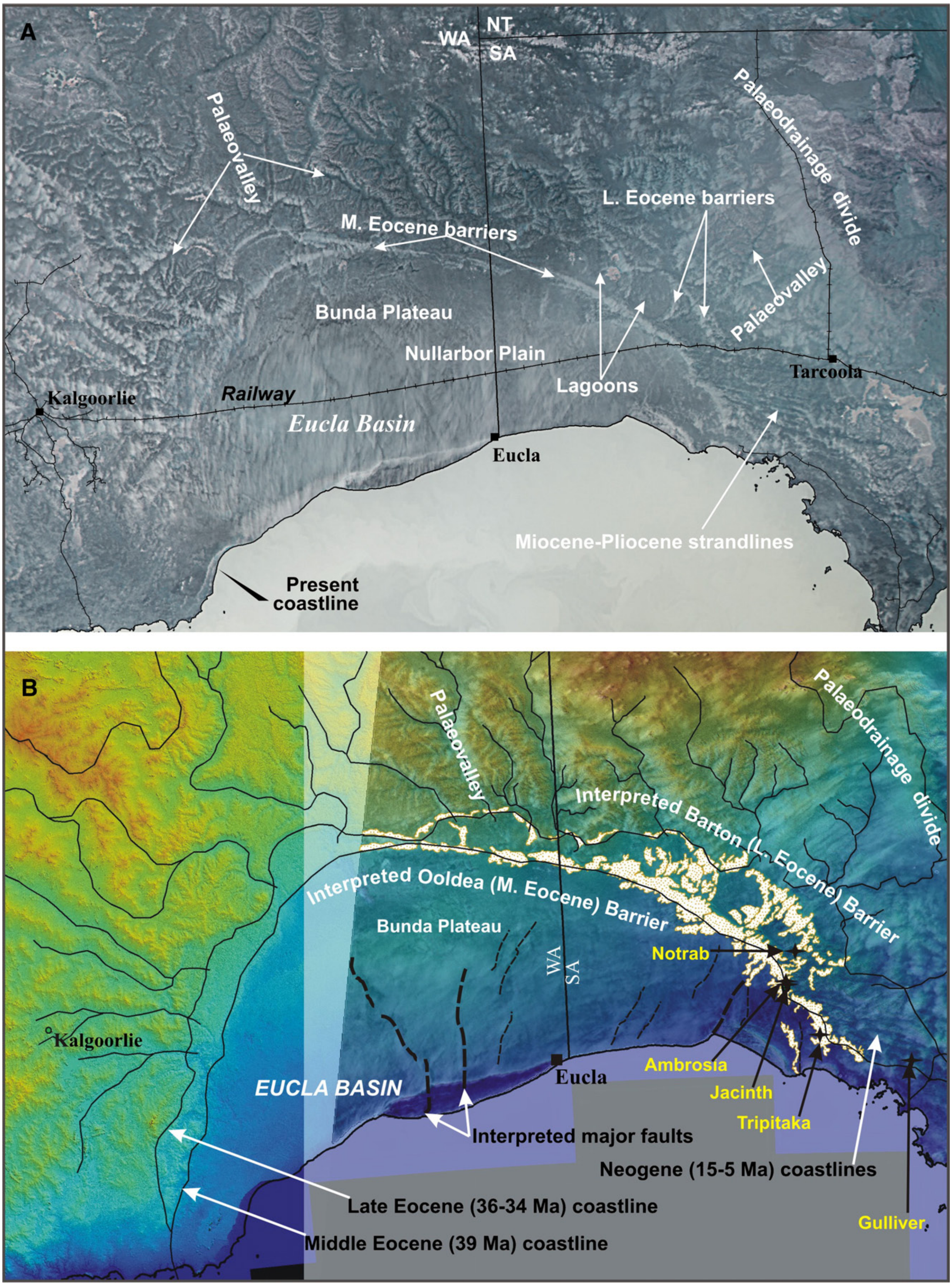
Along the eastern Eucla margin, Hou et al. (2003c; 2006) recognised four distinct constructional phases for coastal barrier and near-shore depositional sequences, that can be correlated with major third-order sea-level events (Figs. 3 and 4), in Middle Eocene (~42.5 Ma), late Middle Eocene (39–36 Ma), Late Eocene (36–34 Ma), and the Neogene (15–5 Ma), respectively. The Barton and Paling barriers are characterized by a series of Late Eocene (36–34 Ma) coastal sand barriers, oriented SW–NE, while the Ooldea barrier represents an offshore barrier (Clarke and Hou, 2000; Hou et al., 2003a, c; 2006). Importantly, the distribution pattern of these Late Eocene coastal barriers is neither parallel to that of the Ooldea Barrier, nor aligned along the present Barton Range (Fig. 2). Thus the 'Ooldea and Barton barriers' (characterizing Tertiary morphology) are not strictly equivalent to the "Ooldea and Barton Ranges", with the latter reflecting in part additional Quaternary aeolian reworking (see comparison in Fig. 2). Landward of the Ooldea Barrier, a series of parallel beach ridges reflects the interaction of localised sediment supply along palaeodrainage networks and continuous, westerly longshore drift processes operating behind the Ooldea Barrier 'islands' (Fig. 2).

The Barton–Paling barrier is a morphologically complex, topographically elevated area formed as part of a beach barrier–lagoon system (Fig. 3). Behind the Ooldea barrier, the lagoonal area is separated by the Paling barrier into two major lagoons termed the Immarna and Tietkens Lagoons (Fig. 1; Benbow et al., 1995a). Sediments comprise both lagoonal facies and barrier facies with beach placer potential (Reid and Hou, 2006).

Miocene–Pliocene shorelines mainly followed those of late Middle Eocene in the western, northern and north-eastern Eucla margins (Fig. 1), due to the constraint of relatively high cliffs developed along this margin during the Miocene (Fig. 4). However, in the southeast Eucla margin, a number of parallel linear ridges at an angle to the Ooldea Barrier represent Neogene strandlines of the Narlaby and Ilkina Formations formed from reworking of the Middle Eocene Ooldea Barrier sands (Benbow, 1990; see also Hou et al., 2003a, b, c, 2006).

The eastern parts of these shorelines are highly prospective for beach-sand hosted heavy minerals related to sea-level changes (Fig. 2; Hou and Warland, 2005). The Tertiary shorelines, defined as bodies of coastal sand comprising beach, shoreface, barrier, dune, tidal inlet, washover and lagoonal facies, are associated with numerous palaeodrainage systems that drained areas of cratonic basement and supplied sediment to the basin (Hou et al., 2001b). A series of 'J'-shaped segments along the Ooldea and Barton Barriers, which are favourable sites for beach placer accumulation, is inferred to have resulted from westerly longshore drift wave refraction around headland promontories (Benbow, 1990; Hou et al., 2003c; Fig. 2). It is arguable whether, or how far, the late Middle Eocene coastal sand barrier may have extended westwards. A westerly longshore drift model implies that beach placers may

Fig. 1. The Eucla Basin and major palaeovalleys, southern Australia (composite from Benbow, 1990; Langford et al., 1995; Alley et al., 1999; Clarke and Hou, 2000). (A) Location of the Eucla Basin. (B) Interpreted Eucla Basin frameworks draped over modern digital elevation model (Imagery courtesy of Geoscience Australia) for the region, showing the main palaeodrainage divide, onshore valleys, present coastline, continental shelf and platform margins in perspective view. (C) Detail of the Eucla Basin, Tertiary coastlines, palaeovalley systems and adjacent major features referred to in the text (see Figs. 2 and 3).


A
WA
NT
SA
Palaeovalley
Palaeodrainage divide
L. Eocene barriers
M. Eocene barriers
Palaeovalley
Bunda Plateau
Nullarbor Plain
Lagoons
Tarcoola
Kalgoorlie
Railway
Eucla Basin
Eucla
Miocene-Pliocene strandlines
Present coastline
B
Palaeovalley
Palaeodrainage divide
Interpreted Barton (L. Eocene) Barrier
Interpreted Ooldea (M. Eocene) Barrier
Bunda Plateau
WA
SA
Notrab
Kalgoorlie
Ambrosia
EUCLA BASIN
Eucla
Jacinth
Tripitaka
Interpreted major faults
Neogene (15-5 Ma) coastlines
Late Eocene (36-34 Ma) coastline
Gulliver
Middle Eocene (39 Ma) coastline

accumulate along the north-western Eucla margin, largely because the longshore drift might preferentially move finer sand away to the east or offshore.

Palaeodrainage systems. Eucla palaeodrainage systems are widely distributed around the basin margins, and their dimensions vary greatly, with river valley widths ranging from a few tens of meters to more than 30 km; depths of up to 100 m; and main channel lengths extending typically 100 to 700 km into the hinterland (Fig. 1). The principal direction of the palaeodrainage flow was directly towards the basin from the continent, but, locally, some palaeochannels feeding the eastern Eucla Basin show apparent reversed gradients at key stratigraphic horizons. The palaeovalleys form a well-integrated contributory pattern. They typically form "V-" (mostly upper reaches), "U-" (mostly middle reaches) or "W-shaped" (mostly lower reaches) cross-sections, and are of very low gradient (0.01%–0.008%) with total relief of 10–150 m (Hou et al., 2001b; de Broekert, 2002).

A comparison of the longitudinal gradient of palaeovalleys from western (e.g., the Roe Palaeovalley) to eastern (e.g., Garford Palaeovalley) margins of the basin is shown in Fig. 4. Although some irregularities in the valley floor are detected, these overall profiles of the palaeovalley floors are remarkably smooth but show significantly different gradients in places. Borehole-controlled transects in eastern Yilgarn (Mt. Morgan) and western Gawler cratons (Garford Palaeovalley) indicate that the irregularities along the paleovalley floors dominantly occur as bedrock highs with an elevation of about 10–20 m above the regional gradient (Hou et al., 2003a; de Broekert and Sandiford, 2005).

Changes in the basinward gradients of the western and eastern palaeovalleys are evident (Fig. 4), e.g., from about 0.33% between Zuleika Pit and borehole KRA8 to about 0.01% east of borehole J10 in the Roe Palaeovalley (de Broekert and Sandiford, 2005), but from about 0.1% between the drainage divide and borehole TPS3 to about 0.001% at borehole 5638-253, and to about 0.01% west of borehole WL55 in the Garford Palaeovalley (Hou et al., 2001a, 2003a). Changing sediment patterns and flow reversal observed within the eastern Eucla palaeovalley fills suggests that the palaeovalleys were affected by post-Eocene tectonic movements. A negative gradient in the lower reach of the Garford Palaeovalley (between boreholes P63 and west of borehole WL59:−0.16‰) is attributed to post-Eocene uplift along the north-eastern margin of the Eucla Basin (Hou et al., 2003a; see later discussion), as is 'reverse' flow observed in the pattern of Neogene valley fills in the Garford Palaeovalley (Hou et al., 2001a, 2003a). A similar progression of gradients occurs within the Kinygoonya Palaeodrainage system, which drained the western Gawler Craton. Here, marine influence in the Neogene channels was greater than that in the Paleogene channels (Hou, 2004), in contrast to the western and northern Eucla margins (see Tertiary shorelines in Fig. 1).

Although basal Early Cretaceous infills are present in some palaeovalleys in the western onshore basin (Alley et al., 1999, de Broekert and Sandiford, 2005), palaeovalley fills are dominated by Cainozoic sediments, with the major phases of deposition associated with the Middle Eocene Wilson Bluff and Tortachilla Transgressions and Late Eocene Tuketja–Tuit Transgression (Benbow et al., 1995b; Alley et al., 1999; Clarke et al., 2003; Hou et al., 2003a). Distinct phases occurred in the Early Eocene (fluvial sediments), Middle Eocene (lagoonal carbonaceous limestone, and estuarine–fluvial carbonaceous clastics), Late Eocene (marginal marine–fluvial carbonaceous clastics, and estuarine clastics), Middle Miocene–Early Pliocene (lacustrine mudstones and dolomitic limestone and marginal marine–estuarine clastics), and Quaternary (regolith, lake sediments, aeolian sands, calcrete, silcrete, ferricrete) (Clarke et al., 2003: Hou et al., 2003a, c, 2006). The Late Oligocene–Middle Miocene succession comprising the Revenge and Gamma Island Formations and Cowan Dolomite in the west, and the Garford and Narlaby Formations in the eastern basin (Fig. 3) thicken towards the east (e.g., from ~10 m to up to 80 m in the eastern palaeovalleys; Benbow et al., 1995a), indicating flow reversal at this time. Minor lignite, of similar age, occurs in the western margin of the basin (Frewster and Denman, 1984) together with thin carbonaceous lenses in Lake Cowan. In the eastern margin, the Yaninee, Narlaby and Kingooyna Palaeochannels contain a facies of carbonaceous grit, sand and clay (Kingoonya Member; Hou, 2004), typically 10–20 m thick, containing abundant marine dinoflagellates indicative of estuarine conditions (Alley, 1996; Hou, 2004; Hou et al., 2006), with Late Miocene–Early Pliocene palynology ages (Hou, 2004; Hou et al., 2006). Dolostone facies are extensive in the upper part of Miocene channels, e.g., Cowan Dolomite (western palaeovalleys) and dolomite facies of the Garford Formation (eastern palaeovalleys). Thin sediments (sand, clay and evaporites, mostly <10 m in thickness), of Pliocene–Quaternary age are found in both the eastern (Munjena and Ilkina Formations; Benbow et al., 1995a) and western (Polar Bar and Roysalt Formations, Clarke, 1993) palaeovalleys, overlying Miocene sediments along an erosional surface (Alley et al., 1999).

2.3. Sediment source and supply

Sediments deposited in the palaeovalleys were largely derived from associated palaeodrainages. Therefore, knowledge of where and what bedrocks the palaeovalleys have incised and drained provides a useful guide to related mineral resources. In the eastern Yilgarn Craton, for instance, the areas where the palaeo-rivers drained primary gold deposits have exploration potential for placer gold, as shown at Zulieka Pit and Lady Bountiful Extended

Fig. 2. NOAA-AVHRR night-time thermal imagery (A) and Radar Topography Mission (SRTM) imagery (90 m pixel) (B) of the Eucla Basin and palaeovalley area, overlain by interpreted Tertiary features, highlighting the Middle Eocene (39 Ma), Late Eocene (36 Ma) and Miocene (15–5 Ma) shorelines and palaeovalleys. (A) The textural difference between palaeovalleys (dark tones indicating cooler features) and the sand barriers and surrounding basement terrain (brighter tones indicating warmer regions) is apparent. (B) The distribution of the Ooldea and Barton (Tertiary) coastal barrier systems (note the locations of new beach placer discoveries: Jacinth and Ambrosia deposits, Notrab, Tripitaka and Gulliver prospects) and the neotectonic faults are highlighted when the NOAA-AVHRR night-time thermal imagery is draped over SRTM DEM imagery, and is supported by geological and drillhole data.

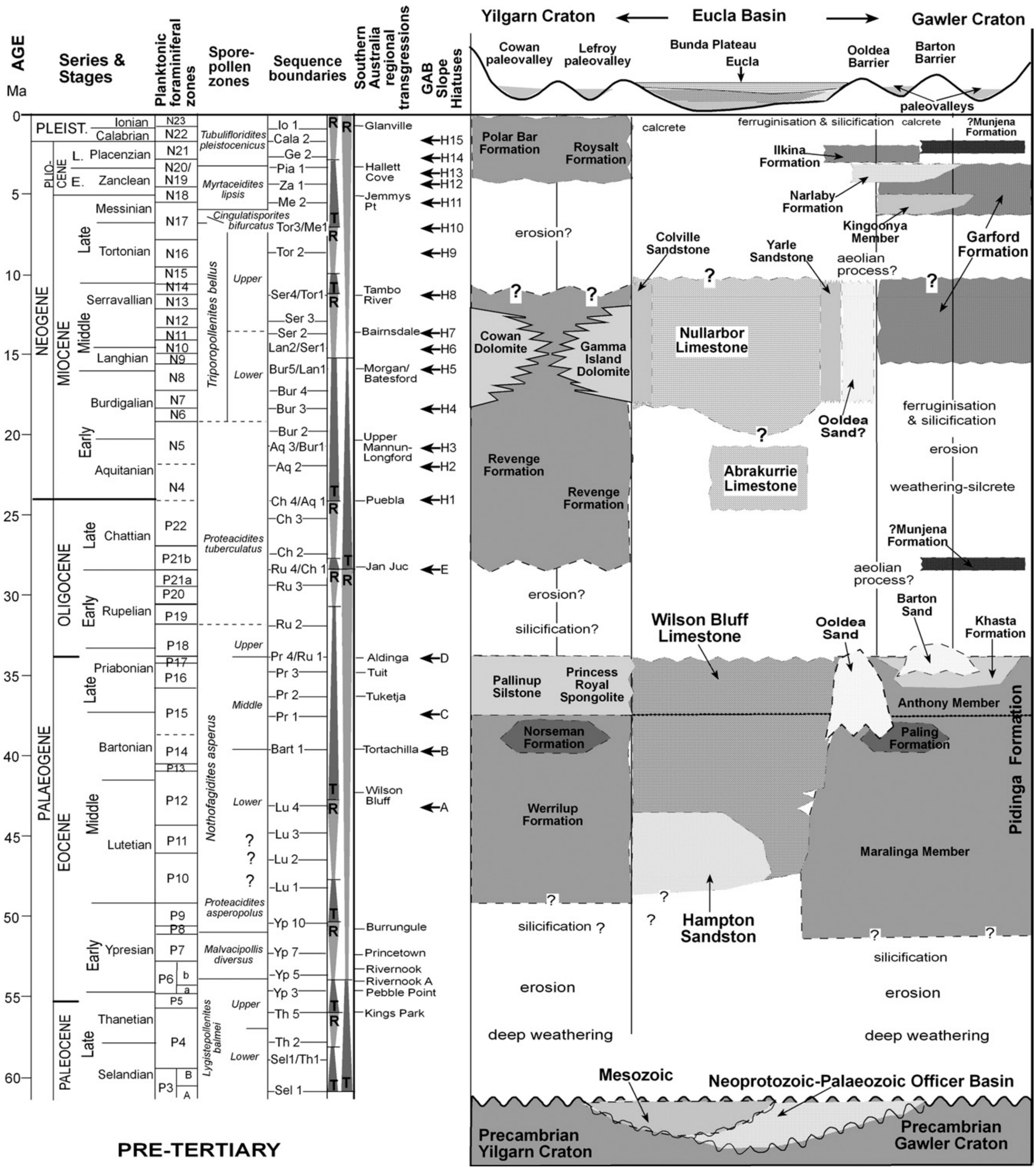


Fig. 3. Stratigraphic correlation chart for the Eucla Basin and palaeovalleys (for localities see Fig. 4, section C). Planktonic foraminiferal zones (Taylor, 1983, 1986; McGowran et al., 1997) are shown, together with; pollen zones (Stover and Partridge, 1973; Chaproniere et al., 1996); third-order sequences and their ages, and higher order transgressive/regressive cycles (T/R) (Hardenbol et al., 1998); regional transgressions (McGowran et al., 1997, 2004) and Great Australian Bight (GAB) continental slope hiatuses (Li et al., 2003, 2004). Correlations of stratigraphic boundaries of the GAB and Eucla Basin carbonates and fluvio-estuarine-marginal marine siliciclastics (Hou et al., 2003a, 2003c) are chronologically questionable due to lack of definitive age data available for Eucla Basin carbonates (Hou et al., 2006).

gold deposits in the upper reaches of the Roe Palaeovalley system (de Broekert, 2002). Similarly, anomalous uranium found in some of the eastern Eucla palaeovalleys was sourced most likely from the Gawler Craton 'hot' granites (e.g., Hiltaba Suite) with elevated concentration of heat-producing elements (Neumann et al., 2000).

Extensive Tertiary coastal barriers of the eastern Eucla margin must have formed where large volumes of sand were supplied by the nearby Eucla palaeo-rivers (e.g., western Gawler Craton) or were reworked shorewards from the platform by marine processes (e.g., Benbow, 1990). Sediment

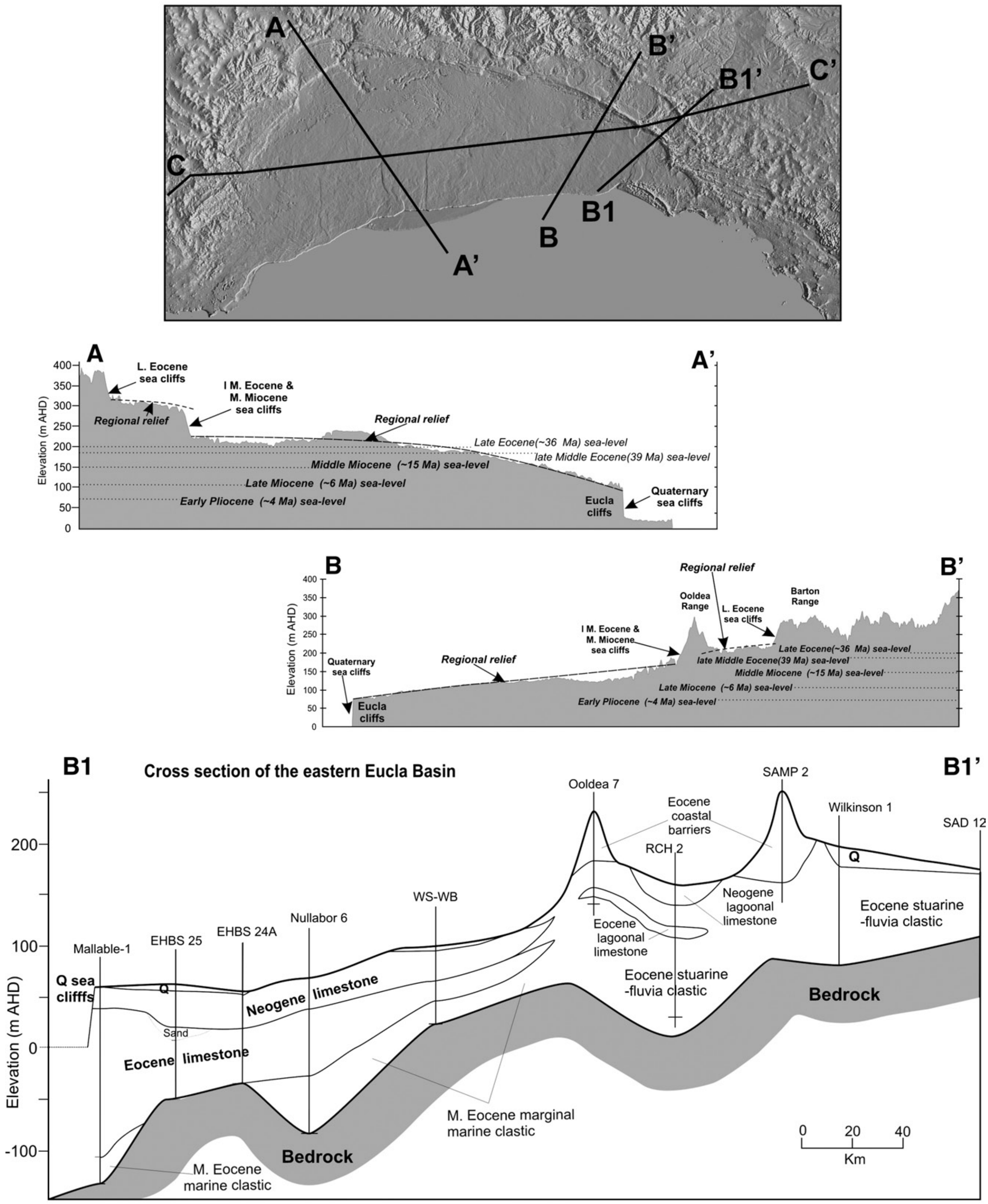


Fig. 4. Cross-sections through the Eucla Basin and marginal craton areas showing present-day topography and interpreted distribution of sediment fill and stratigraphic correlations, together with selected drill holes. Sections A–A' and B–B' show Cenozoic sea levels from dated, shallow marine facies. Quaternary and older sea cliffs/ beach barriers are evident in the topographic data and their ages are based on sea-level interpretation. Correlation across the basin, section C–C', clearly shows downtilting to the east and also highlights the Eocene coastal barriers (Ooldea and Barton ranges) developed along the eastern margin of the basin. Note that on the cross sections of sediment distribution, Quaternary sediments have not been included.

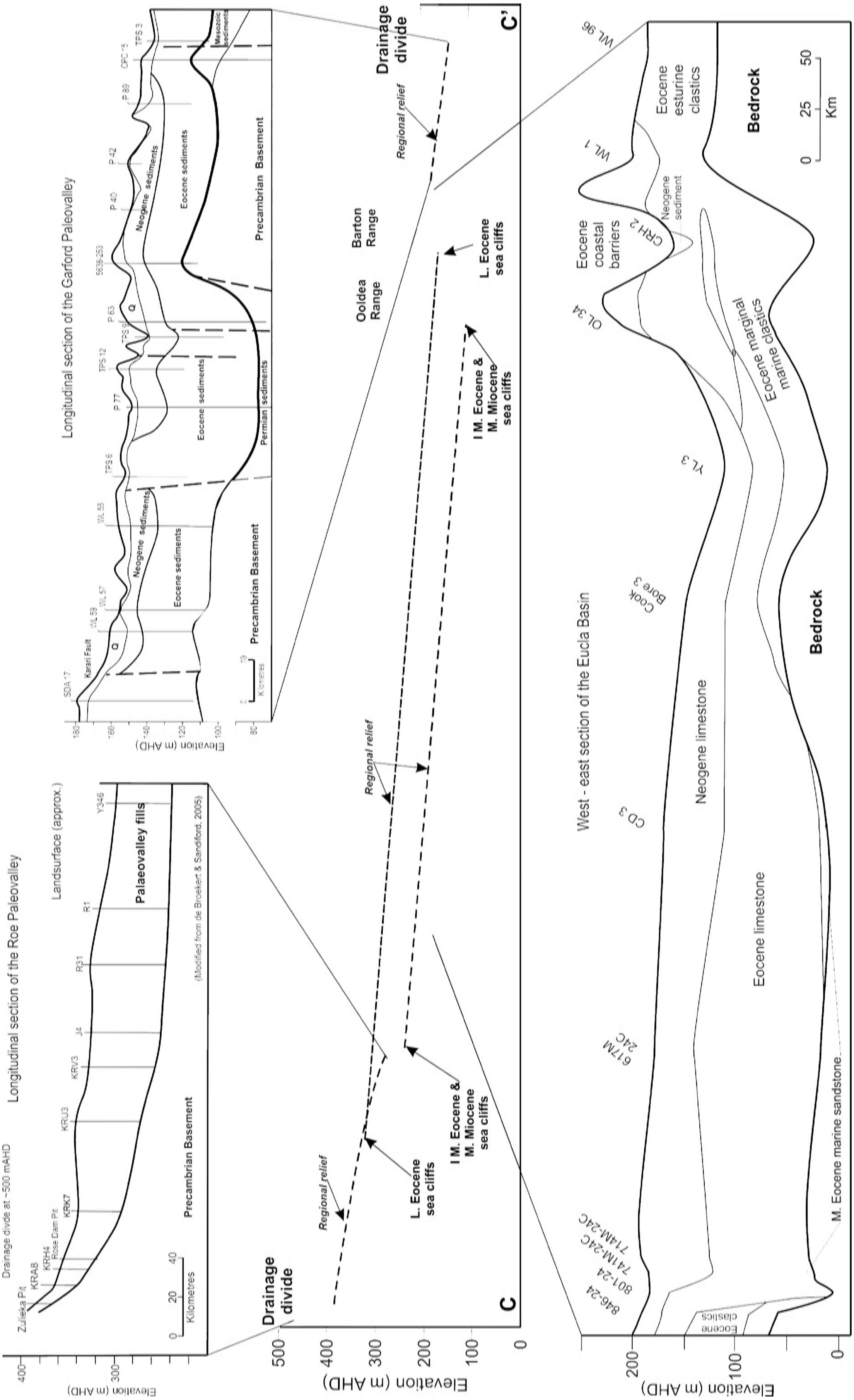


Fig. 4 (continued).

provenance studies of both the Ooldea barrier (e.g., Jacinth and Ambrosia HM deposits, Hou and Warland, 2005) and Barton barrier (e.g., Notrab HM prospect, Reid and Hou, 2006) heavy mineral deposits suggests that zircons and rutiles were derived mainly from the Musgrave Province and possibly the Albany-Fraser Orogen, with minor contribution from the eastern Gawler Craton. This is consistent with westerly longshore drift during the Tertiary. The absence of zircons with ages between c. 2800 and 2600 Ma, which are prominent within the Albany-Fraser Orogen, indicates that the Musgrave Province was the most likely, or dominant, source region (Reid and Hou, 2006).

3. Palaeoclimatic regimes

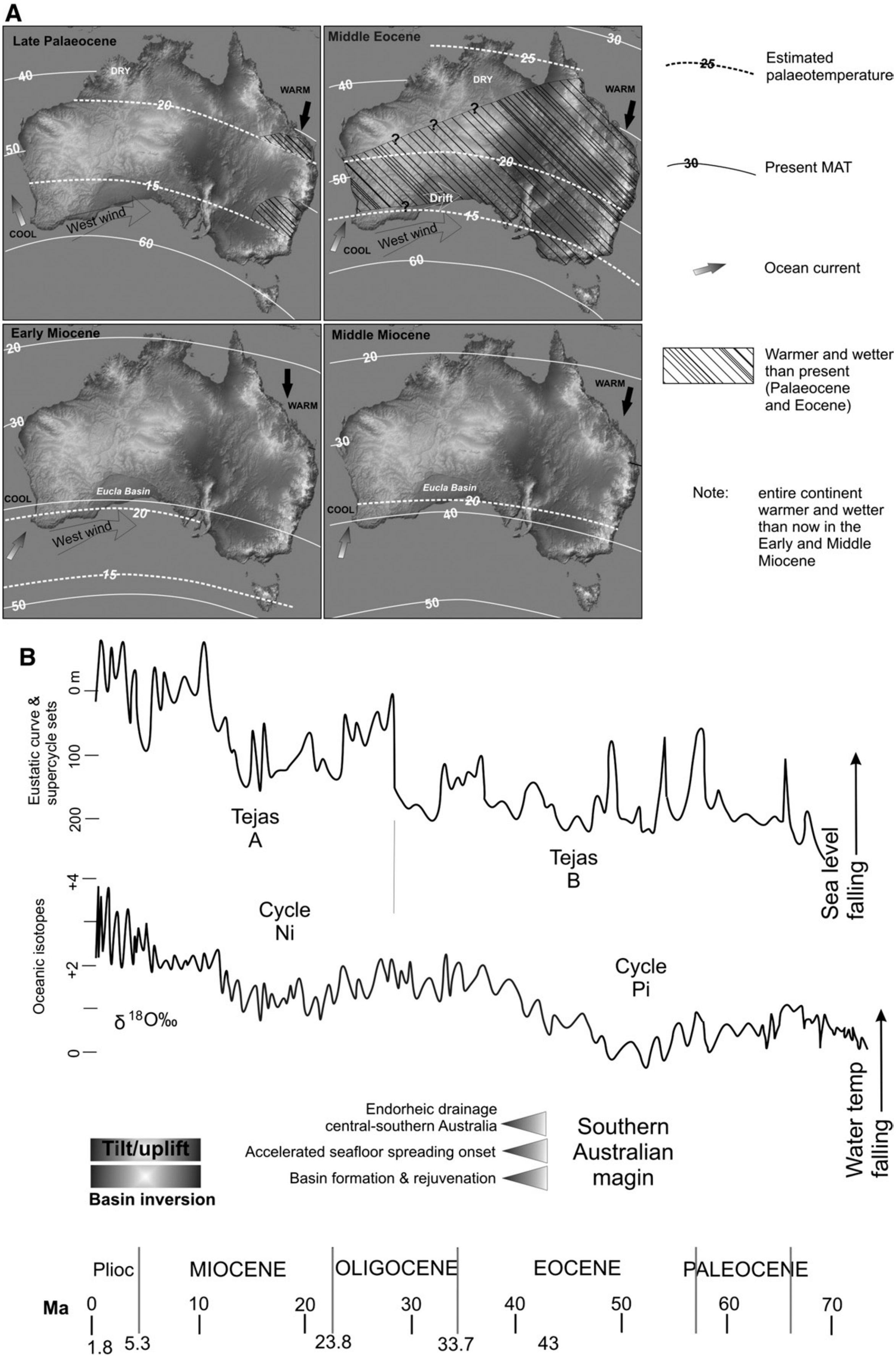
The distribution of palaeoshoreline features both informs and is informed by palaeoclimatic interpretations, which we briefly summarise here. In the last 43 Ma, since onset of fast spreading of the southern Ocean, Australia has drifted ~3000 km northward. The climatic effects of Australia's motion into lower latitudes and progressively warmer climate zones (Fig. 5) was countered to a significant extent by cooling on the global scale (Benbow et al., 1995b). On a continent-wide basis the balance of these opposed trends favoured slight warming (Frakes, 1999). For the post-Paleocene interval, the strongest warming seems to have taken place in the Middle Eocene; other warmings occurred in the Early Eocene and the Middle Oligocene. The evidence from Eocene megaflora and micro-flora, as well as widespread accumulation of lignites along the southern continental margin, suggests that at least local warm-temperate rainforest conditions prevailed during the Middle Eocene (Macphail et al., 1994; Quilty, 1994; Benbow et al., 1995b; Alley et al., 1999). Palaeoclimate modelling (Kemp, 1978) suggests westerly winds dominated the southern Australia at between 60°–80°S in the Paleocene and Eocene (Fig. 5) consistent with occurrence of coastal dune barriers in the north-eastern Eucla Basin margin but not along the western margin. Late Eocene 'J-shape' coastal barriers behind the Ooldea Barrier imply a more north-westerly component in the prevailing winds.

Prominent cooling took place in the earliest and the latest Eocene. Key events in the history of the Yilgarn and Gawler cratons and the Eucla Basin margin were the apparently episodic duricrust development in the Early and Late Eocene, the Middle Miocene and the Late Pliocene (McGowran, 1979). Variable and wetter conditions, which were coeval with a major cooling of oceanic waters (Frakes, 1997), occurred at the Early/Middle Eocene boundary This may therefore have temporarily resulted in a substantial decrease in evapo-transpiration and an increase in discharge, which would be expected to trigger deep and widespread fluvial incision evident in the 'inset valleys' of the palaeodrainage systems (de Broekert and Sandiford, 2005).

Aridity in the region increased markedly beginning in the Late Miocene. Indicators of warm and arid climates include dolomitic carbonates intercalated with gypsum, halite and sheet flood deposits in extensive palaeo-lakes and-channels. Palaeosol carbonates probably started forming during the early Pliocene, and mark increasing aridity in conjunction with cooling, culminating in widespread formation of aeolian deposits and calcrete in the Quaternary.

4. Differential vertical movements

The general orientation and parallelism of the Eucla Basin palaeoshorelines suggests that the primary control on shoreline position was the gentle topographic slope established along the southern Australian margin as a consequence of earlier Mesozoic rifting (Fig. 1a, b) associated with the separation of Antarctica and Australia (Benbow, 1990, Alley et al., 1999). However, significant disparities in elevations of correlative near-shore sequences across the Eucla have long been evident (Jones 1990; Benbow et al., 1995b; Hou et al., 2001a, 2003a; de Broekert and Sandiford, 2005), to the extent that the relative position of shorelines formed during successive transgressions shows systematic variations across the basin. For example, the palaeoshoreline associated with the distinctive sponge spicular facies of the Princess Royal Spongolite (in the west) and Khasta Formation (in the east; Zone P16/17, Fig. 3) deposited in shallow (<40 m) water at the highstand of the Tuketja Transgression of Late Eocene age (Clarke 1994a; Gammon et al., 2000; Hou et al., 2001a, 2003a, b, c, 2006), can be used to compare elevations of the western and eastern Eucla margins (Fig. 4). In the eastern Eucla Basin the Khasta Formation reaches no higher than 170 m above present sea level (Hou et al., 2001a), whereas in the western part of the basin the Princess Royal Spongolite occurs at 300 m near Lake Lefroy (Fig. 4; de Broekert and Sandiford, 2005), and at 325 m at Cundeelee and Mulga Rock (Jones, 1990), requiring ~150 m of relative post-Eocene vertical motion across the basin. Similarly marginal marine (carbonaceous) carbonate facies deposited during the Tortachilla Transgression of the latest Middle Eocene (Zone P14, Fig. 3) further confirm such relative vertical motion (Fig. 4), with a ~130 m difference in elevation between the tops of the Norseman Limestone in the western Eucla margin (264 m asl at Lake Cowan, Clarke, 1993; 1994a) and the Paling Formation in the eastern Eucla margin (136 m asl in CRAE-RCH2, Hou et al., 2001a). Significant differentials in heights of near-shore Nullarbor Limestone and associated palaeoshore-lines along the northern boundary of the Nullarbor Plain imply that at least some of this relative vertical motion occurred after the Middle Miocene (de Broekert and Sandiford, 2005; Sandiford 2007). However, ongoing relative vertical motion since the Late Eocene is evident from the fact that Miocene palaeoshorelines in the eastern Eucla are typically as high as, if not higher than, older Eocene shorelines, with marginal marine facies extending further up the Kingoonya Palaeochannel on the Gawler Craton than older Eocene marine sequences (Fig. 1). In contrast, Miocene palaeoshorelines in the western Eucla are significantly lower than Eocene shorelines, by up to 80 m along the north-western margin of the basin (Sandiford, 2007). Similarly ongoing differential vertical motion is evident in the case for "reverse flow" in the Garford and Kingoonya palaeovalleys on the Gawler craton, implying a north-east down, south-west up relative landscape tilting.


A
Late Palaeocene
Middle Eocene
Early Miocene
Middle Miocene
DRY
WARM
COOL
West wind
Drift
Eucla Basin
Estimated palaeotemperature
Present MAT
Ocean current
Warmer and wetter than present (Palaeocene and Eocene)
Note: entire continent warmer and wetter than now in the Early and Middle Miocene
B
Eustatic curve & supercycle sets
Tejas A
Tejas B
Sea level falling
Oceanic isotopes
δ 18O‰
Cycle Ni
Cycle Pi
Water temp falling
Endorheic drainage central-southern Australia
Accelerated seafloor spreading onset
Basin formation & rejuvenation
Southern Australian magin
Tilt/uplift
Basin inversion
Plioc
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
Ma

Perhaps the most profound and obvious impact of this interpreted long-wavelength "tilting" across the Eucla Basin is evident in the contrasting palaeo-coastal morphologies of the western and eastern margins. Along the western margin, progressive offlap has resulted in a relatively simple trend of younger shorelines to lower elevations. In contrast, in the eastern Eucla, the repeated inundation of earlier formed shorelines systems and their associated barriers, lagoons and palaeovalley systems is evident, and the stratigraphic record is far more complex than simple progressive offlap. The arrangement of these coastal features has been also greatly influenced by other factors, including both eustatic and climate regimes.

It is now well understood that the type of epeirogenic, differential vertical motion on horizontal scales of ~1000 km, as evident across the Eucla Basin, must reflect processes deep within the Earth related to interactions between the lithosphere and deeper convective mantle, contributing to what is known as 'dynamic topography' (e.g., Gurnis, 2001; Sandiford, 2007). As such, the differential motion across the Eucla Basin can be related to a continental wide N-side down tilting proposed by Sandiford (2007) resulting from dynamic effects between the relatively fast moving Indo-Australian plate and its underlying mantle. Sandiford (2007) suggested that at the scale of the continent this tilting has produced about 300 m of differential vertical motion between the southwestern and the northern Australian margins in the Neogene, and reflects at least in part the movement of Australia towards the dynamic topographic low, geoid high associated with the southeast Asian subduction realm. The approximate tilt axis derived from Sandiford's (2007) analysis of the distribution of exposed Miocene shorelines around the Australian continent is shown in Fig. 6 along with the modelled in situ stress field (e.g., Coblentz et al., 1995; 1988), and reflects a profound asymmetry in the distribution and elevation of Cenozoic marine sediments around the continent. In detail, the dynamic tilting at the scale of the continent is almost certainly more complex than a rigid plate tilt about a constant axis (Sandiford, 2007), and the full details of the Cenozoic tilting record remain to be elaborated.

In addition to the evidence for long-wavelength, dynamic tilting, the Eucla Basin shows mild tectonic deformation particularly in the Late Miocene–Early Pliocene in the form of numerous minor faults which displace the Nullarbor surface by up to about 10 m, and which are clearly evident in the Shuttle radar topographic data (Fig. 2). In the Eucla Basin most of these structures trend between NNW and NNE, more-or-less orthogonal to the prevailing in situ stress field, and displace the Nullarbor Limestone, but not the Pliocene sequences of the Roe Plain, and thus testify to activity between 15 and 4 Ma. As such this deformation can be related to prevailing in situ stress field (Fig. 6), as has been demonstrated by Sandiford (2003) and Sandiford et al. (2004) for neotectonic deformation across southern Australia. Sandiford et al. (2004) concluded that the terminal Miocene tectonic activity was characterized by regional-scale tilting, and local uplift and erosion in south-eastern Australia (e.g., Dickinson et al., 2002). This reflects increased coupling of the Australian-Pacific plate boundary in the late Miocene (Fig. 6). Such a contention is supported by plate scale stress modelling (Coblentz et al., 1995, 1988).

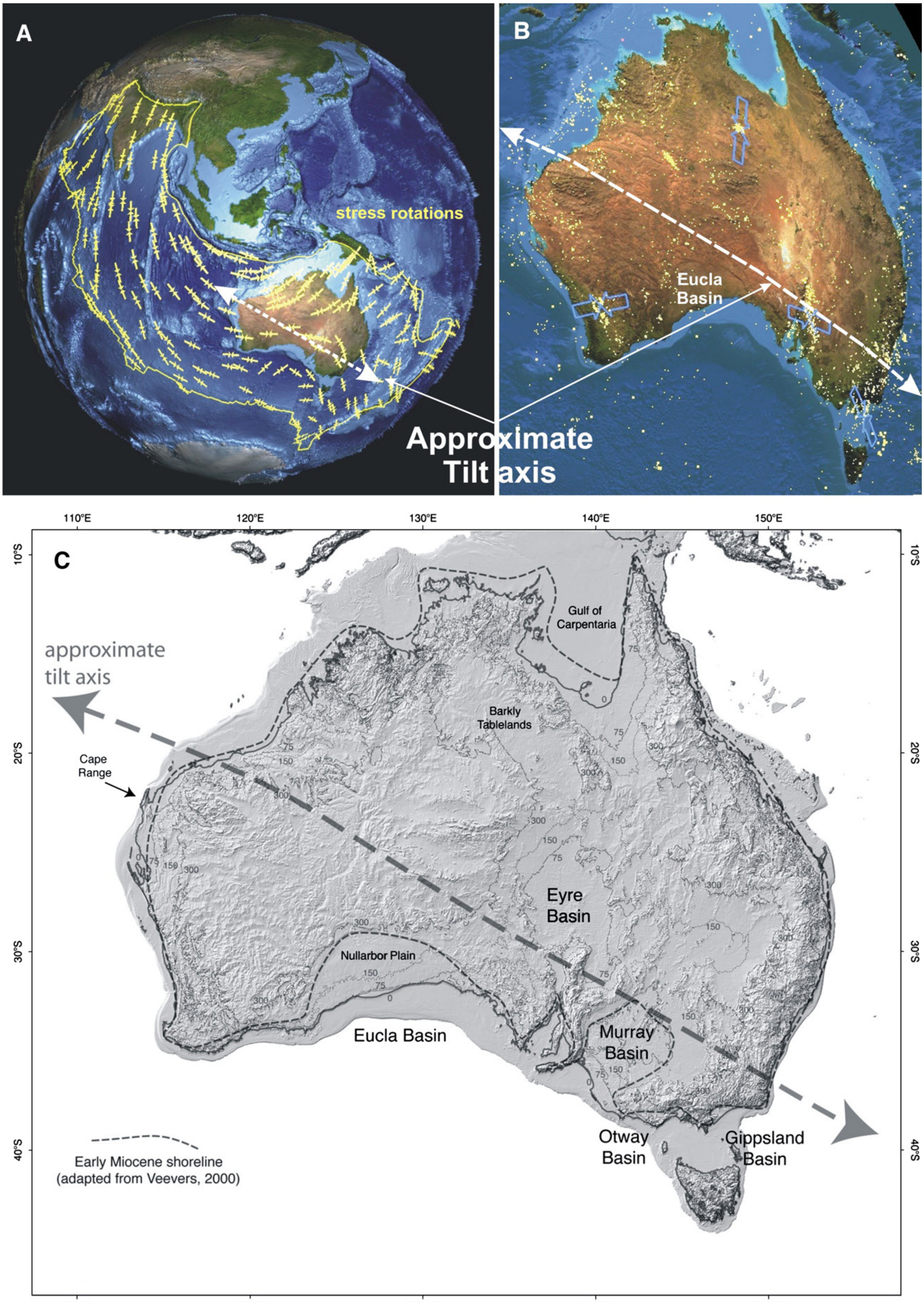
5. New tectono-eustatic landscape evolution model for the Eucla Basin

The unique combination of eustatic, dynamic topographic and climatic factors evident in the stratigraphic record of the Eucla Basin and associated palaeovalley sediments provide the basis for a new integrated model for the evolution of the basin and its hinterland. Here we outline the pertinent aspects of this model, before considering its implications, particularly for placer mineral prospectivity.

5.1. Mesozoic

Intense erosion of the weathered crystalline basement rocks and inferred Permian sedimentary cover (Clarke and Alley, 1993) in the palaeovalley areas occurred during the Jurassic (Alley et al., 1999), probably promoted by the development of the rift basins along the present southern continental margin (Krieg, 1995). Less reliably dated is the initiation of palaeovalley incision. Clarke (1994a) suggested that most of the palaeovalleys probably began to drain the Yilgarn Craton during the Jurassic when rifting commenced in the south-western margin of the basin. It is evident that the palaeovalley incision commenced in the eastern Eucla margin during the Early Cretaceous (Aptian to Albian) (Barnes and Pitt, 1976; Fulwood and Barwick, 1990) as the lower reaches of the palaeovalleys contain the Madura Formation of Hauterivian–Barremian age (Jones, 1990). However, we consider these palaeovalleys as Mesozoic valleys rather than the Eucla (Tertiary) palaeovalleys. The latter more likely reoccupied the former, as the topographic lows developed on the Early Tertiary land surface were easily eroded. The close spatial and genetic association of the palaeovalleys with the Eucla-Bight basins (Fig. 1) suggest that the form of their bedrock surface was largely established by fluvial erosion during the late Mesozoic (e.g., Beard, 1973, 1998, 1999; Johnstone et al., 1973; van de Graaff et al., 1977; Clarke, 1994b;Alley and Lindsay, 1995; Alley et al., 1999). However, the scarcity of known Mesozoic sediment within these palaeovalleys indicates that subsequent incision of the palaeovalleys was accompanied by the generation of a regional unconformity involving widespread stripping of sediment and perhaps also bedrock

Fig. 5. A) Australia's migration on a time-latitude grid, with the continent shown in its Late Palaeogene, Middle Eocene, Early Miocene and Middle Miocene latitudes (modified from Frakes, 1999). The West Wind Drift is from Kemp (1978). B) Cenozoic eustatic supercycle sets Tejas A and Tejas B (Haq et al., 1987, 1988) and water temperature curves approximating the Palaeogene (Pi) and Neogene (Ni) oceanic oxygen-isotopic cycles (Abreu et al., 1998). Summary of tectonic events in southern Australia modified from Li et al. (2004).


A
stress rotations
B
Eucla
Basin
Approximate
Tilt axis
C
110°E
120°E
130°E
140°E
150°E
10°S
20°S
30°S
40°S
Gulf of
Carpentaria
approximate
tilt axis
Barkly
Tablelands
Cape
Range
Eyre
Basin
Nullarbor Plain
Eucla Basin
Murray
Basin
Otway
Basin
Gippsland
Basin
Early Miocene shoreline
(adapted from Veevers, 2000)

well beyond the palaeovalley flanks (Alley et al., 1999; de Broekert, 2002).

5.2. Paleocene–Early Eocene

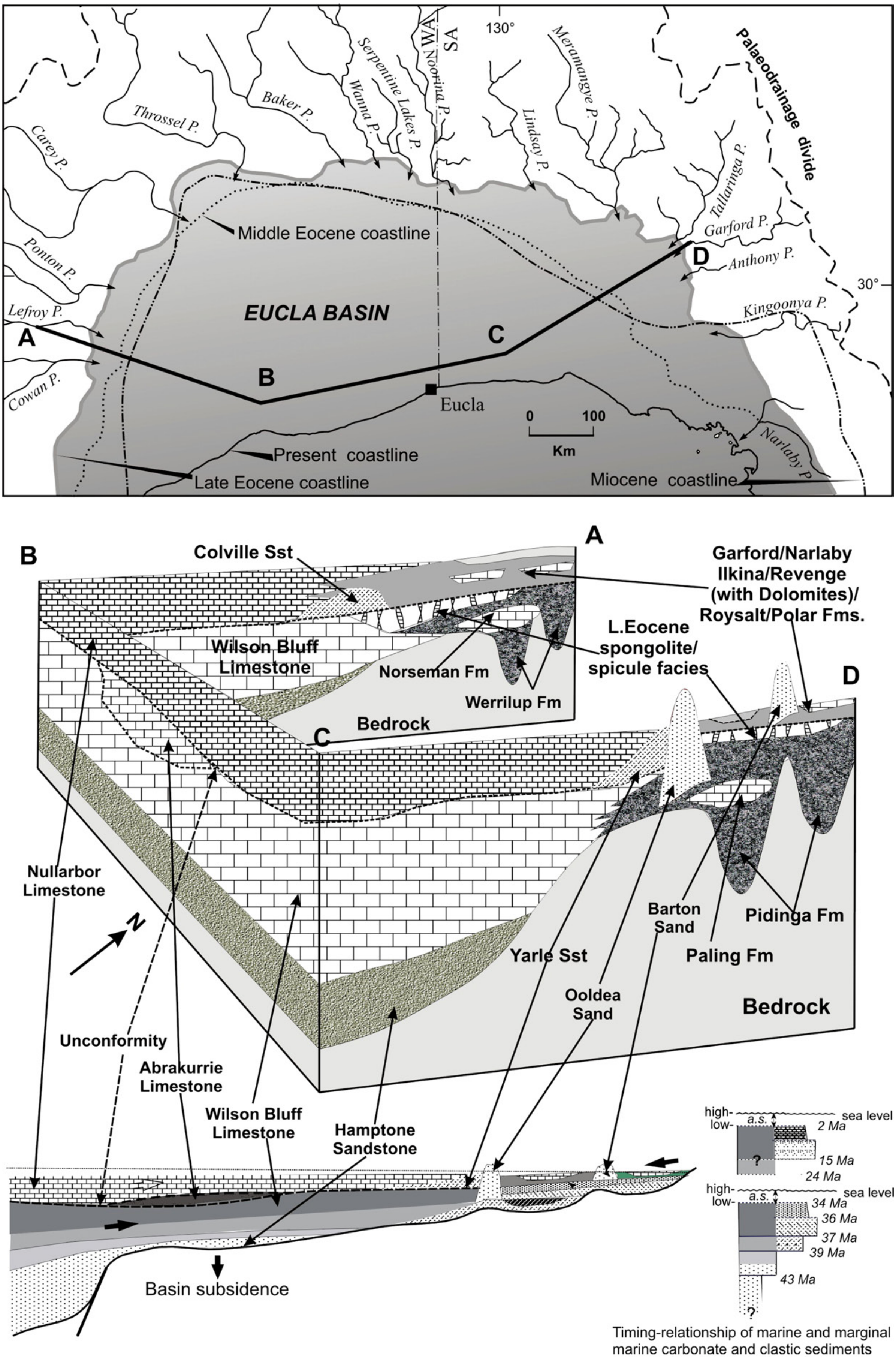
The Australian continent lay at higher latitudes (~60–70°S) in the Palaeocene but global temperatures were higher than in later times (McGowran, 1979; Frakes et al., 1987), and a zone of westerly winds prevailed at 60–80°S (Kemp, 1978) (Fig. 5). Before palaeovalley incision, the surface was mantled by a deep weathering profile reflecting a warm, humid climate (Fig. 3; Alley et al., 1999; de Broekert and Sandiford, 2005). The general absence of Palaeocene sediments along the margins suggests a regime of erosion and palaeovalley incision (Alley et al., 1999), or relative landscape stability. Uplift along the Stuart Range-Billa Kalina Basin axis (Benbow et al., 1995b) at this time provided a regional palaeodrainage divide for the eastern Eucla palaeovalleys (Figs. 1 and 2), and contributed recycled palynomorphs from Lower Cretaceous Eromanga Basin sediments found in the Maralinga Member of the Pidinga Formation of (Alley and Beecroft, 1993).

Although the age of palaeovalley incision can not be directly dated in the cratonic regions they drained, it is clear that they began to fill by the late Middle–Late Eocene (Middle *N. asperus* Zone) in the Yilgarn Craton region (Kern and Commander, 1993; de Broekert 2002), and by the Early–Middle Middle Eocene (Lower *N. asperus* Zone; Alley and Beecroft, 1993; Benbow et al., 1995a), or Early Eocene (*Proteacidites asperopolus* Zone; Hou et al., 2006) in the eastern Eucla. Initial filling of the palaeovalleys along the inner margin of the Eucla Basin during the Wilson Bluff Transgression by the Hampton Sandstone and lowermost Pidinga Formation (Jones, 1990; Hou et al., 2003a, 2006) indicates a pre-middle Middle Eocene age (>43 Ma) for the palaeovalleys in that area. Therefore, palaeovalley incision must have been completed by the late Lutetian (~43 Ma) before the onset of the Wilson Bluff Transgression in the latest Lutetian at ~42.5 Ma (Fig. 3), with the transition from incision to filling of the inset valleys probably reflecting the impact of a rapid eustatic sea-level rise (Li et al., 2003). It is likely that prior to the Middle Eocene the Eucla palaeovalleys delivered a substantial volume of siliciclastic sediment to the shoreline which remained at or seaward of its present position (Quilty, 1994) until the Wilson Bluff transgression. A prograding wedge of marginal to shallow marine siliciclastic sand recognised in seismic data (Feary and James, 1998), and Ocean Drilling Program boreholes (Leg 182, Li et al., 2003) beneath the continental shelf and slope in the Bight Basin (Fig. 1) suggest that the sand wedge unconformably underlies the Hampton Sandstone (Bein and Taylor, 1981) and is probably of early Middle Eocene age (Li et al., 2003). Incision propagated inland and may have been promoted by a deterioration of climate at the Early/Middle Eocene boundary (Frakes, 1997; Alley et al., 1999).

5.3. Middle–Late Eocene

Middle–Late Eocene relative sea-level rises facilitated sediment accumulation in the Eucla Basin and incised valleys (Fig. 7). Macrofloral and palynofloral evidence indicates that rainforest of meso- to megathermal aspect prevailed in the Eucla Basin and palaeovalley areas (Macphail et al., 1994; Benbow et al., 1995b). That mesothermal rainforest was predominant in the eastern Eucla Basin is also indicated by palynological and cuticle studies (Milne, 1988; Clarke, 1994a). Minor tectonic subsidence of the central southern parts of Eucla Basin (present central basin, Fig. 1), and formation of the modern continental slope probably began in the middle Lutetian (Lu 3, ~44 Ma; Li et al., 2003; McGowran et al., 2004). The Middle Eocene Wilson Bluff Transgression shoreline has been placed at the most landward position of the Hampton Sandstone in the central Eucla Basin (Fig. 7), with its current position overlain by lower Wilson Bluff Limestone (Hou et al., 2003b, 2006). Increased sediment supply resulting from palaeovalley incision coeval with marine transgression contributed to construction of ebb deltas and localised progradation of the Wilson Bluff shoreline. The influence of late Middle Eocene Tortachilla and Late Eocene Tuketja–Tuit Transgressions extended some several hundred km up the palaeovalleys in the Eucla Basin (Figs. 3 and 7; e.g., Alley et al., 1999). During these stages, with the terrigenous flux, extensive aggradation occurred, first as non-marine to marginal marine sediments and then, as highstand deposition of biogenic sediments (Alley et al., 1999). The Tortachilla Transgression shoreline is marked as drowning of a large part of the palaeovalley area occurred, promoting deposition of marine carbonate facies (Wilson Bluff Limestone) well inland to the landward limit of the Bunda Plateau in the northwest and Ooldea barrier in the northeast (Fig. 7; Alley et al., 1999). There followed a higher marine transgression during the Tuketja–Tuit Transgressions. The shoreline migrated farther inland (Fig. 7) and its position extended to the inland margin of the Neales Plateau in the northwest (Clarke and Hou, 2000) and Barton barrier–Wilkinson estuary in the northeast (Hou et al., 2003b, 2006; Fig. 1). The absence of Tortachilla and Tuketja–Tuit coastal barriers in the western Eucla margin (Fig. 2b) reflects the onset of dynamic tilting of the Eucla Basin. Together with a longshore drift towards the east under the influence of prevailing westerlies (Figs. 1 and 5; Kemp, 1978), tilting contributed to a general eastward sediment transport. Provenance studies of the Ooldea Barrier system (Reid and Hou, 2006) indicate that at least a minor component of sediment was supplied from the Albany-Fraser Orogen to the west and south-west of the Eucla Basin.

Fig. 6. Stress orientation trajectories showing the stress rotations and tilt axis across the Australian continent due to plate boundary forces. (A) Intraplate stress orientation trajectories. (B) Interpreted tilt axis across the continent and relationship to Australian earthquake epicenters (yellow) and stress orientations (blue arrows). (C) Shaded relief image of the Australian continent and its continental shelf (elevations shown for +75,+150 and+300 m). The inferred position of mid Miocene (~15 Ma) shoreline is shown by the thin dashed line. The approximate tilt axis (thick dashed line with arrows) demarcates the region of the continent, to the south and west, where marine Miocene sediments can be traced onshore from that region with no record of onshore marine Miocene sediments (adapted from Sandiford, 2007).



130°
WA
SA
Palaeodrainage divide
Throssel P.
Baker P.
Serpentine Lakes P.
Wanna P.
Noorina P.
Meramangye P.
Lindsay P.
Carey P.
Tallaringa P.
Garford P.
Anthony P.
Middle Eocene coastline
Ponton P.
Lefroy P.
EUCLA BASIN
Kingoonya P.
30°
A
B
C
D
Cowan P.
Eucla
0 100
Km
Present coastline
Late Eocene coastline
Miocene coastline
Narlaby P.
Colville Sst
Garford/Narlaby
Ilkina/Revenge
(with Dolomites)/
Roysalt/Polar Fms.
Wilson Bluff Limestone
L.Eocene spongolite/ spicule facies
Norseman Fm
Werrilup Fm
Bedrock
Nullarbor Limestone
N
Barton Sand
Pidinga Fm
Yarle Sst
Paling Fm
Ooldea Sand
Unconformity
Abrakurrie Limestone
Wilson Bluff Limestone
Hamptone Sandstone
Basin subsidence
high-
low-
a.s.
sea level
2 Ma
15 Ma
24 Ma
34 Ma
36 Ma
37 Ma
39 Ma
43 Ma
?
Timing-relationship of marine and marginal marine carbonate and clastic sediments

5.4. Oligocene–Early Miocene

The change from a humid (Eocene) to a dominantly dry climate during the Oligocene–Early Miocene protected the Eocene valleys and their fills from significant fluvial erosion during the early Neogene (Frakes, 1997; Alley et al., 1999). Oligocene and Early Miocene conditions in the onshore Eucla Basin and palaeovalleys are represented largely by a phase of non-deposition, erosion and weathering, during which the extensive silcrete probably formed (Alley et al., 1999). In the central Eucla Basin, following a phase of minor subsidence associated with deposition of the Abrakurrie Limestone during the Late Oligocene–Middle Miocene (Fig. 3), continued dynamic tilting exposed the western Eucla margin, draining the associated palaeovalleys (Fig. 7). Benbow et al. (1995a) also noted that such tilting occurred but did not quantify the amount of uplift.

5.5. Middle Miocene–Pliocene

The prolonged nature of the dynamic tilting is indicated by the north-eastward decline in elevation of the Eocene key-surfaces and 'reverse flow' features of the Neogene valleys in the western Gawler Craton (Fig. 4; Hou, 2004; Hou et al., 2001a). Consequently, marine carbonates of the Nullarbor Limestone were deposited in a new depocentre located in the Nullarbor Plain during the Middle Miocene–Early Pliocene transgressions (Figs. 3 and 7). Extensive chains of shallow, alkaline lakes developed along the Eucla palaeovalleys were probably promoted by interruption of the drainage by the large Ooldea and Barton barrier/dune systems, and decreases in channel flow in the north-eastern onshore basin. The small volumes of sandy sediments in the Gamma Island and Garford Formations and Cowan Dolomite suggest that the relief around the Eucla margins was relatively gentle. Similarly, the presence of lacustrine facies throughout most Eucla palaeovalleys, implies relatively low stream gradients and interrupted flow (Alley et al., 1999).

Although later Tertiary events are poorly dated (Alley et al., 1999), a series of marine transgressions occurred in the Eucla Basin from Oligocene times (Benbow et al., 1995a, b) through to the Pliocene. These extended across the shelf to the inland margin of the Bunda Plateau (Fig. 3), but do not appear to have breached the Ooldea Range and thus had almost no influence on sedimentation in the palaeovalleys north and northeast of the Ooldea Range (Alley et al., 1999). Therefore, the Middle Miocene–Early Pliocene shorelines largely followed the Ooldea barrier/dune system (Fig. 7). There is some evidence to suggest that there may have been Neogene contributions to the Eocene barriers/dunes along the Ooldea Range (Benbow et al., 1995a). Several phases of rejuvenation of the Ooldea barrier/dune are indicated by younger phases of Ooldea Sand during highstands in the Early Miocene Upper Mannum Longford (Alley et al., 1999) and Middle Miocene Cadell/ Balcombe Transgressions (Benbow et al., 1995a) (Fig. 3).

The Eocene barriers/dunes may have been partly reworked and redeposited as Neogene coastal sands (Yarle Sandstone and Ilkina Formation; Benbow et al., 1995a) along the Ooldea Range, particularly at the southeastern ends of the Ooldea and Barton Ranges (i.e., western Eyre Peninsula) where a series of Neogene strandlines have been recognised (Figs. 1 and 2) (Benbow, 1990; Hou et al., 2003b, Hou and Warland, 2005). This is supported by the presence of marine dinoflagellates south of the Ooldea Range, indicating marine influence in the palaeovalleys extending at least into the central Eyre Peninsula (Alley et al., 1999). Significantly, the Neogene shorelines developed in the southwestern Gawler Craton during Middle Miocene–Early Pliocene transgressions extended farther inland than those of the Eocene (Fig. 7; Hou, 2004). In the upper and middle reaches of the Kingoonya and Narlaby Palaeovalleys, for instance, the Kingoonya Member of the Garford Formation (Fig. 3) contains minor marine micro-plankton and pollen, and their frequency increases significantly farther west into the lower reaches of the palaeovalleys, indicating estuarine and marginal marine conditions that were open to the ocean (Hou, 2004). Uplift and tilting of the Eucla Basin and palaeovalleys followed in Middle–Late Miocene times (Benbow et al., 1995b) (Fig. 6). In the onshore basin, mainly fluvio-lacustrine evaporites were deposited in the Eucla palaeovalleys during early Pliocene times, and palynological information shows that dry open woodland and chenopod shrubland containing isolated pockets of forest in edaphically suitable sites prevailed from the southeast Yilgarn to the north east Gawler Cratons (e.g., Bint, 1981; Truswell and Harris, 1982; Clarke, 1994a; Benbow et al., 1995b). This, together with the absence of clastic materials, indicates very reduced, intermittent flow along palaeovalleys and a marked drying and/or warming. Increasing aridity during the Pliocene was punctuated by warm, wet intervals (Benbow et al., 1995b), which may have facilitated the widespread weathering, silicification and ferruginisation that characterises the Pliocene sediments in the Eucla Basin and palaeovalleys (Fig. 3). This fits with a model of increased aridity and desertification for Australia as a whole from 2–5 Ma as reported by Fujioka et al. (2005).

6. Implications for mineral exploration

The Eucla Basin and palaeovalley sediments are potential hosts to significant mineral resources including beach and valley placer deposits, sedimentary uranium and coal deposits, groundwater resources, and palygorskite (e.g., Benbow et al., 1995a; Hou et al., 2001a, 2007a,b; de Broekert, 2002; Hou, 2004). Knowledge of their stratigraphic context, including the impacts of climate and neotectonics on landscape evolution are important factors that can aid exploration success.

6.1. Beach placers/heavy mineral sands

Our models of landscape evolution of the Eucla Basin margin and associated shorelines can be utilised extensively to develop

Fig. 7. Schematic fence diagram showing stratigraphical relationships across the Tertiary Eucla Basin and adjacent onshore sediments in marginal marine and palaeovalley settings. A schematic interpreted relationship between marine carbonate deposition and the extent of marginal marine carbonate and clastic equivalents over time is summarized in the inset diagram.

improved understanding of how to search for beach placers in the region. Information provided on Heavy Mineral (HM) source and tilting of the Eucla Basin gives encouragement that HM accumulations may well be found further to the west than the current batch of discoveries, since a major source of the zircons is not in the immediate vicinity, but probably lies far to the west. A detailed understanding of the sedimentary architecture and transport systems of the Eocene Eucla Basin are important for assisting discovery of new HM accumulations within this emerging mineral sands province. While the Eocene shorelines along the inland margin of the Eucla Basin extend over the entire ~2000 km from east to west, HM concentration is not known to have occurred continuously along this shoreline. The role of local control on sediment dynamics leading to localised HM concentrations in specific regions is essentially unknown. Given the predominant eastward longshore drift in the Eocene beach system (Fig. 1), knowledge of the cratonic source region for the HM is an important predictive exploration tool. For example, if a solely Gawler Craton origin could be shown, then mineralisation would not be expected to extend for any significant distance westward, as this is not supported by the present models derived from the landscape evolution, including source of supply, Eocene longshore drift, and epeirogenic tilting of the basin. In contrast, a source solely from the Yilgarn/Albany-Fraser region would significantly extend the prospective area of the Eucla Basin palaeobeach placer province. Therefore, although our studies indicate a predominantly Musgrave Province source for the zircon fraction, multiple source regions for other heavy minerals remain a possibility. Future work must consider dating of other mineral fractions such as titanite, rutile and monazite to provide a clearer picture of the source region.

This study provides a framework of climatic and tectonic controls on sedimentation along the Eucla Basin margins against which recent HM discoveries can be interpreted. The location and stratigraphic context of individual deposits provides the basis for assessing the potential for reworking, dispersion and reconcentration. This will be a factor in developing strategies to explore for additional deposits. Such strategies need to consider the impacts of later sea-level change, predominant wind and longshore drift directions and the effect of dynamic tilting on reworking and realigning beach and barrier deposits, during marine transgressions, particularly during Neogene times.

7. Conclusions

The Eucla Basin near-shore coastal barrier systems, coastal lagoons and palaeovalleys contain remarkably well-preserved and varied sedimentary facies of mainly Cenozoic age. The Eucla Basin and palaeovalleys had their origins prior to the Eocene and palaeovalleys were probably incised in older valleys initiated in the Cretaceous. Stratigraphic correlation of the sediments across the Eucla Basin and palaeovalleys shows that the marginal basin and adjacent palaeovalleys include at least three main phases of sedimentation: Middle to Late Eocene, Middle Miocene–Early Pliocene, and Quaternary. Prominent weathering and erosion facies are of Cretaceous–Early Eocene, Oligocene–Early Miocene, and Late Pliocene age. Differences in elevations of marginal marine or lagoonal carbonaceous carbonate sediments of late Middle Eocene and sponge spicule-bearing sandstones of Late Eocene age across the Eucla margins imply ~130 m relative vertical motion. Progressive (relative) east-down tilting in combination with persistent westerly weather systems explains the absence of large coastal barriers in the western margin of the basin; the smoothly curved Ooldea Barrier; a western and northern source of sediment supplies indicated by sediment provenance studies; the series of parallel 'J-Shape' (Barton) barriers of Late Eocene age; 'reverse flow' features of Neogene channels draining the Gawler Craton; and progressive reworking of older Eocene barriers during the Neogene along the western Eyre Peninsula. Our analysis provides new insights into the geological history of the entire Eucla Basin and associated palaeovalleys that establishes a basis for future investigations of the landscape and tectonic history of the southern part of the Australian continent. This has particular relevance to exploration for heavy mineral placer deposits along the northern and eastern margins of the basin, where our interpretation should assist in the definition of new exploration targets in this, extraordinary, vast and still largely unexplored palaeocoastline.

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