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Can deepwater bottom currents generate clinothems? An example of a large, asymmetric mounded drift in Upper Jurassic to Lower Cretaceous sediments from northwestern Australia

O. Mantilla[1,2], F.J. Hernández-Molina[1]* and N. Scarselli[1]
[1]Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK
[2]Ecopetrol S.A, Colombian Petroleum Company, 110311 Bogotá, Colombia

ABSTRACT

Clinoforms and clinothems are ubiquitous in shallow marine and shelf margin environments, where they show remarkable seaward progradation trends. Consensus holds that these features do not form in deepwater settings. This study describes an example of a large, asymmetric mounded deposit formed in Upper Jurassic to Lower Cretaceous sediments along the Exmouth Plateau (offshore northwestern Australia). Although it formed in deepwater environments, the deposit has previously been interpreted to reflect either a deltaic or shelf margin system based on clinoform and clinothem geometries. We support that this deposit shares similarities with a delta drift that evolved into a large, mounded drift (~180 km in length, ~120 km in width, and up to ~1.7 km in sedimentary thickness) that exhibits two migration trends: one westward and the other northeastward. Three evolutionary phases are proposed: (1) an onset drift stage (ca. 146.5–143.5 Ma); (2) a growth drift stage (ca. 143.5–138.2 Ma); and (3) a burial stage (ca. 138.2 Ma), which marks the completion of the drift and a shift in depositional style. The drift asymmetry and clinoform orientations indicate the influence of a northward-flowing water mass with two main cores. Our analysis thus suggests that bottom currents can create complex deposits with geometries that resemble clinothems in deepwater environments.

INTRODUCTION

Clinothems are sedimentary bodies that prograde in a seaward direction with geometrically defined topset, foreset, and bottomset deposits bound by surfaces with a distinctively curved (clinoform) geometry (Rich, 1951; Miller et al., 2013), which are interpreted as palaeo-bathymetric profiles (Rich, 1951; Patruno et al., 2015; Pellegrini et al., 2020). These appear at scales and in locations that clearly associate them with shallow marine environments such as deltas and shelf edge areas (Patruno and Helland-Hansen, 2018).

Over the past decade, studies have documented prominent examples of deepwater bottom-current depositional features that show extensive lateral migration of their associated sediments (e.g., McCave and Tucholke, 1986; Hernández-Molina et al., 2010; Mosher et al., 2017; Thiéblemont et al., 2020). Such deposits may form over millions of years with lateral migrations that span tens of kilometers in width, hundreds of kilometers in length, and reach sedimentary thicknesses exceeding 1 km (Rebesco et al., 2014). These deposits are defined as asymmetric mounded drifts and consist of opposing flanks dominated by depositional and erosional features. Occasionally, their internal stacking pattern is so similar to progradational detail bodies that the term "delta drifts" was defined for these drifts (Eberli and Betzler, 2019). The Exmouth Plateau, offshore northwestern Australia, hosts an example of the aforementioned deposit in Upper Jurassic to Lower Cretaceous units (Fig. 1A). Our study sought to (1) demonstrate that bottom currents can form prograding clinoforms in deep-marine environments, (2) present an evolutionary model for the drift, and (3) evaluate its conceptual implications.

We analyzed two-dimensional (2-D) and 3-D multichannel seismic reflection data covering a 26,000 km² area (Fig. 1A). Provided by Geoscience Australia (Canberra, Australia), the 2-D seismic data set consisted of 47 seismic profiles with an average line spacing of ~8 km at average frequencies of 20–30 Hz (30–40 m vertical resolution). The Mary Rose 3-D seismic cube (from the TGS seismic survey in 2012) spanned 9900 km² with a dominant frequency of 30 Hz and an average vertical resolution of ~30 m. The seismic interpretation followed the standard seismic stratigraphic analysis of Mitchum et al. (1977). Exploration wells (Geoscience Australia) and Ocean Drilling Program (ODP) Leg 122 data (Fig. 1A) provided chronostratigraphic calibration, and age horizon assignments followed the palynological scheme of Kelman et al. (2013).

GEOLOGICAL SETTING

The Exmouth Plateau (ExP) is located between 800 m and 2000 m water depth in the Northern Carnarvon Basin, offshore of NW Australia (Fig. 1A), and is affected by the influence of intermediate water masses (Fig. 1A; Woo and Pattiaratchi, 2008). The formation of the margin and its sedimentary architecture date back to the breakup of Gondwana (Longley et al., 2002), which occurred as a result of intermittent phases of rifting between West Australia and India from Triassic to Early Cretaceous time (Gibbons et al., 2013). During the Jurassic–Cretaceous transition, uplift linked to tectonic pulses increased sediment supply toward the ExP (Reeve et al., 2016). This led to the development of an extensive sedimentary succession referred to as the Barrow Group (Tait, 1985), which corresponds to the K10 sedimentary interval of Longley et al. (2002) and is the focus of our study. The top of this deposit is marked by a regional discontinuity that is coeval to the final separation of India and Australia. This event led to seafloor spreading and the development of a passive margin (Longley et al., 2002).

SEISMIC ANALYSIS

The sedimentary succession described and interpreted herein is referred to as SU1. It is bounded by two major regional discontinuities,

*E-mail: javier.hernandez-molina@rhul.ac.uk

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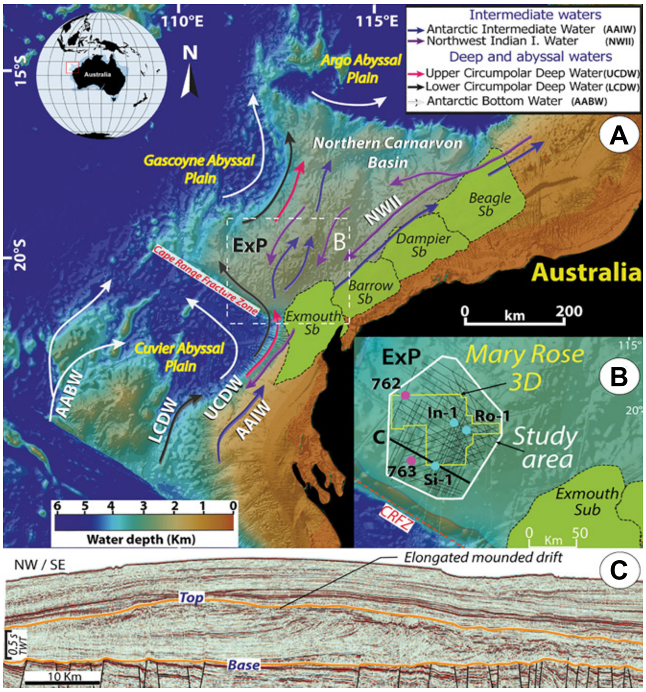

Figure 1. (A) Map showing the location of the Exmouth Plateau (ExP) and the modern ocean circulation pattern and sub-basins (Sub, Sb). (B) Study area (white polygon), 2-D seismic survey (black lines) and 3-D survey (yellow polygon). Ocean Drilling Program wells (purple dots) and exploration wells (blue dots) are labeled as follows: Si-1—Sirius-1, Ro-1—Royal Oak-1, and In-1—Investigator-1. (C) Two-dimensional seismic profile shows the mounded deposits studied.

D0 and D4, at its base and top, respectively (Fig. 1B). Both discontinuities appear as high-amplitude reflections and are interpreted as erosional surfaces. Downlap reflection terminations appear above D0 (Fig. 2). Seismic data show a large, northeast-trending, asymmetric mounded deposit within SU1 (Fig. 2). This feature extends ~180 km in length, spans a width of ~120 km, and reaches an average thickness of ~1.5 s (~1.7 km). The deposit exhibits an external convex shape with a northeast-trending crest that resembles that observed among clinoforms (Figs. 1B and 2A).

SU1 includes four subunits (a–d) divided by three discontinuities (D1, D2, and D3). These correspond to high-amplitude reflections that outline erosional truncation, toplap, or downlap terminations (Fig. 2). SU1a, SU1b, and SU1c formed from Tithonian to late Berriasian time (ca. 146.5–139.4 Ma). SU1d developed during the Valanginian (ca. 139.4–138.2 Ma; Fig. 2). The subunits vary in thickness from 30 m to 700 m and form elongate, northeast-southwest–trending depocenters along the ExP (Fig. 3A). All subunits include complex internal reflections that display a prominent lateral sedimentary migration to the northeast and northwest (Fig. 2).

SU1a exhibits sigmoidal clinoforms with bidirectional downlap, a primarily aggradational stacking pattern, and a low to moderate foreset angle ranging from 0.8° to 2°. This unit trends northeastward along the ExP and spans an average thickness of 0.5 s TWT (~600 m) (Fig. 2; Fig. S1 in the Supplemental Material[1]). Internally, SU1a seismic facies consist of wavy to discontinuous, variable-amplitude reflections

[1]Supplemental Material. 3-D seismic profiles, horizon slices (RMS attribute) and palaeoceanographic model of the India-Australia gateway. Please visit https://doi.org/10.1130/GEOL.S.19309343 to access the supplemental material, and contact editing@geosociety.org with any questions.

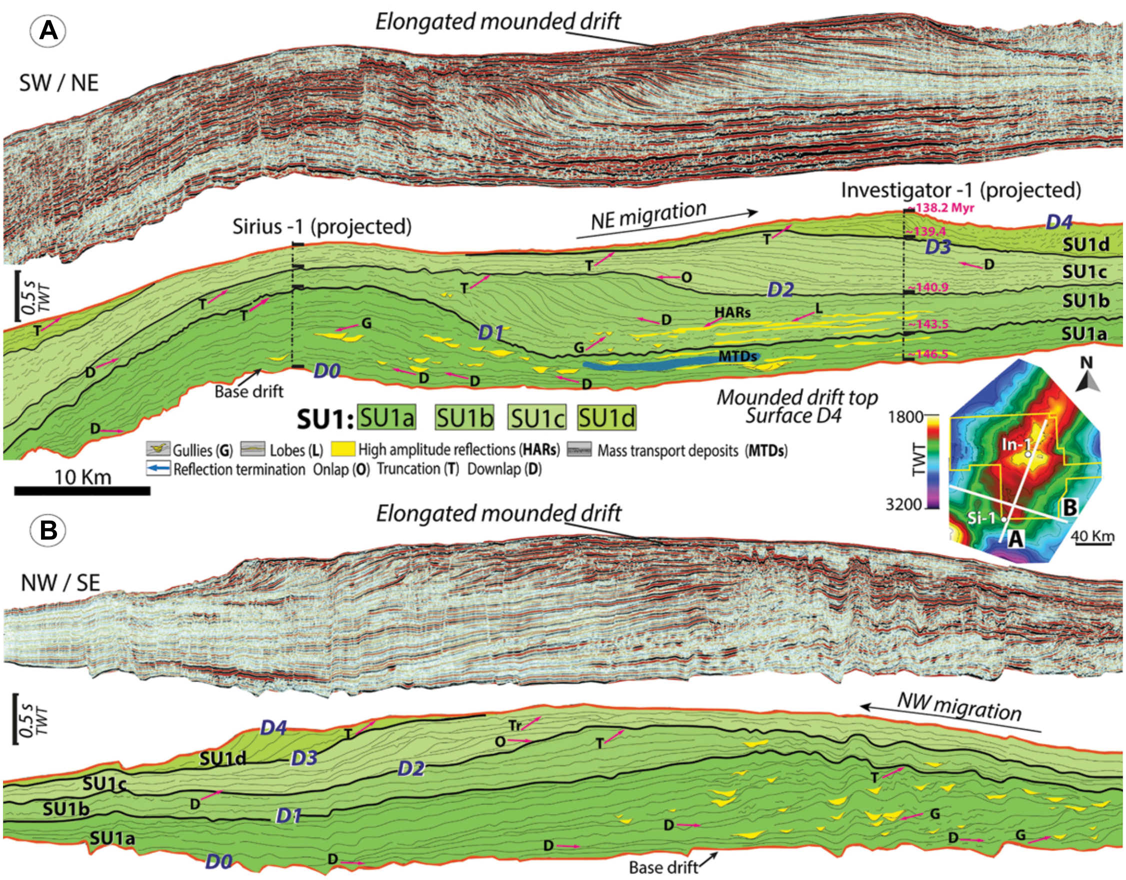

Figure 2. Two-dimensional seismic profiles indicate the migration of the mounded drift toward (A) the northeast and (B) the northwest.

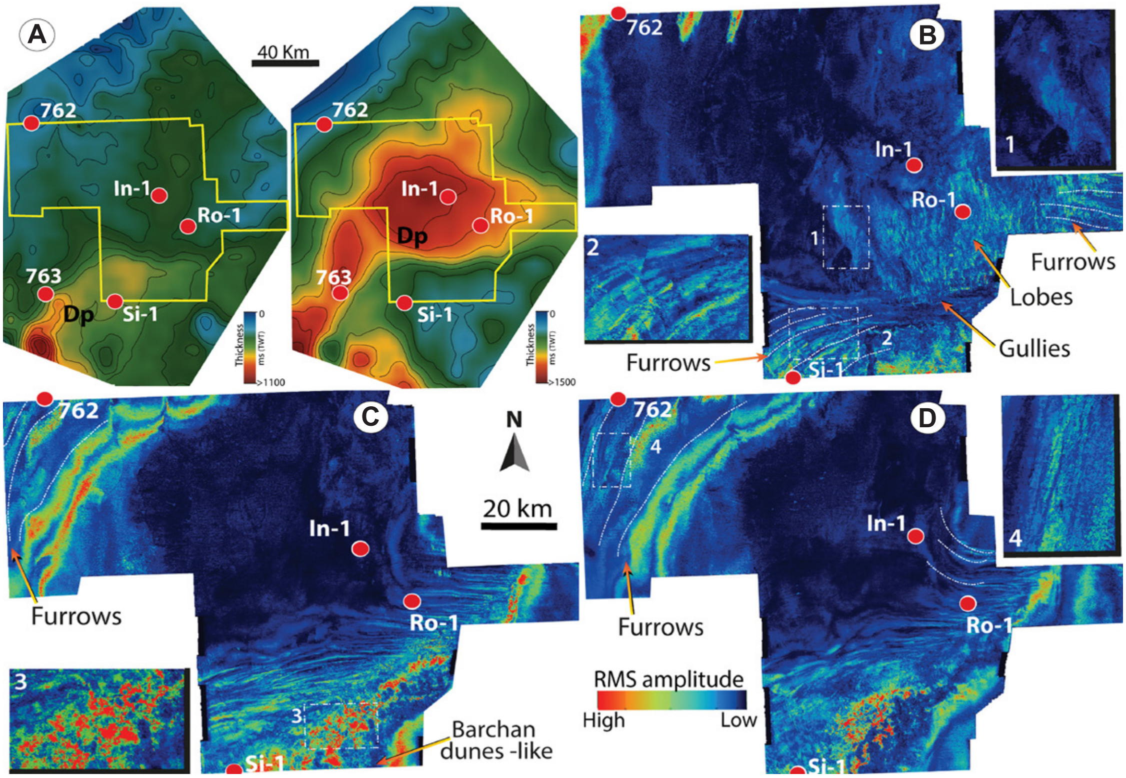

Figure 3. (A) Thickness map of SU1a and a combined map of SU1b, SU1c, and SU1d showing a depocenter (Dp) orientation parallel to the Exmouth Plateau. Root mean square (RMS) time slices for (B) 2700 ms, (C) 2400 ms, and (D) 2300 ms show furrows, channels, gullies, sedimentary lobes, and dune-like features (insets 1–4).

in southwesterly areas of the deposit (Fig. 2A), which are truncated along the upper surfaces by D1. In the bottomset, SU1a appears as high-amplitude, sub-parallel reflections. Root mean square (RMS) amplitude attribute extraction across SU1a reveals sizeable linear furrows trending southwest to northeast and reaching up to 25 km in length and 500–1000 m in width (Fig. 3B; Fig. S2A). SU1a also exhibits erosive U- and V-shaped features (50–500 ms deep and widths of up to 3 km) with linear to sinuous northeast orientations. These were interpreted as small channels or gullies (Figs. 2 and 3B). Continuous, high-amplitude reflections (HARs) outlining sheeted to lensoidal shapes form the distal terminations of these small channels. Spanning widths of 2–7 km and lengths of 4–12 km, these correlate with lobate forms that appear in the RMS attribute and are interpreted as sedimentary lobes (or small fans). The bottomset exhibits chaotic to semi-transparent reflections of variable amplitude that are interpreted as mass transport deposits (MTDs; Fig. 2A).

Relative to SU1a (< 7 km), subunits SU1b, SU1c, and SU1d tended to show a prograding (10 km and 20 km) stacking pattern with clinoforms outlined by remarkable sigmoidal to oblique reflection configurations (Fig. 2; Fig. S1). This indicates prominent lateral accretion of the deposit similar to that observed among progradational systems. Within these subunits, the topsets, seismic facies appear as wavy to discontinuous reflections (Fig. 2), which are truncated by their erosional top boundaries (D2, D3, and D4). Sand ribbons and barchan dune-like bedforms appear in the RMS extractions for SU1c. These span 500 m in width and up to 1 km in length (Fig. 3C; Fig. S2B). Foreset angles ranged from 4° to 8° in SU1b, from 2° to 4° in SU1c, and from 5° to 8° in SU1d (Fig. 2). Bottomset reflections become more continuous but are interrupted by gullies and sedimentary lobes common in SU1b but scarce in SU1c and rare in SU1d (Figs. 3C and 3D). Sedimentary lobe sizes and distribution resemble those observed in SU1a. The RMS extraction shows abundant furrows of similar scale to those observed in SU1a (Figs. 3C and 3D).

SHALLOW OR DEEP-MARINE SYSTEMS?

The mounded deposit described here has been interpreted as reflecting progradation of either a deltaic system (Tait, 1985; Ross and Vail., 1994; Reeve et al., 2016) or shelf margin system (Carvajal et al., 2009; Paumard et al., 2018, 2019, 2020). Our analysis indicates an alternative depositional environment.

(1) Shelf break*:* During deposition of SU1, the position of the shelf break and delta front along the margin occurred ~150–200 km southeast of the ExP (e.g., Longley et al., 2002; Fig. 4; Fig. S3). Thus, the deposit studied formed along the upper/middle slope at water depths of up to 600 m (Paumard et al., 2018). The occurrence of submarine channels and sedimentary lobes in distal environments across the upper slope beyond the shelf break but before the ExP (Kirk, 1985) and coeval with the mounded body deposition further suggest a deep-marine setting.

(2) Clinoforms: Deltaic and shallow-marine clinoforms are smaller than those identified in the ExP. They reach tens of meters in height and exhibit low foreset gradients (<4°) and rapid progradation rates of 10^{-1}–10^{-2} km/k.y. (Carvajal et al., 2009; Patruno and Helland-Hansen, 2018). Shelf-edge clinoforms exhibit foreset heights of 100–300 m and average foreset gradients of 0.6–4.8° (Patruno and Helland-Hansen, 2018). However, the clinoforms recognized in this study reach hundreds of meters in height (up to 200 m in SU1a, 400 m in SU1b, 250 m in SU1c, and 160 m in SU1d) and exhibit higher foreset gradients (up to 8°) that extend up to 20 km in length (Fig. 2). Studies by Exon et al. (1992) suggest sedimentation rates of at least 30 cm/k.y. at Site 763 and 7 cm/k.y. at Site 762. These could vary due to erosion or depositional hiatuses during its ~8 m.y. depositional history (Haq et al., 1990).

(3) Depocenters: The southwest-northeast elongation of depocenters and northeast migration of the drift both trend parallel (rather than perpendicular) to the paleomargin and the ExP (Fig. 3A).

(4) Topset features: Reflections in the topset dip southwest (opposite the direction of deposit migration) and do not appear horizontal as do typical clinoforms. Previous studies suggest uplifting of the southern part and tilting toward the north of the ExP after the mounded deposit formation (Boyd et al., 1993; Longley et al., 2002; Reeve et al., 2016); therefore, post-depositional tilting or subsidence would not explain the topsets dipping southwest. The RMS extractions

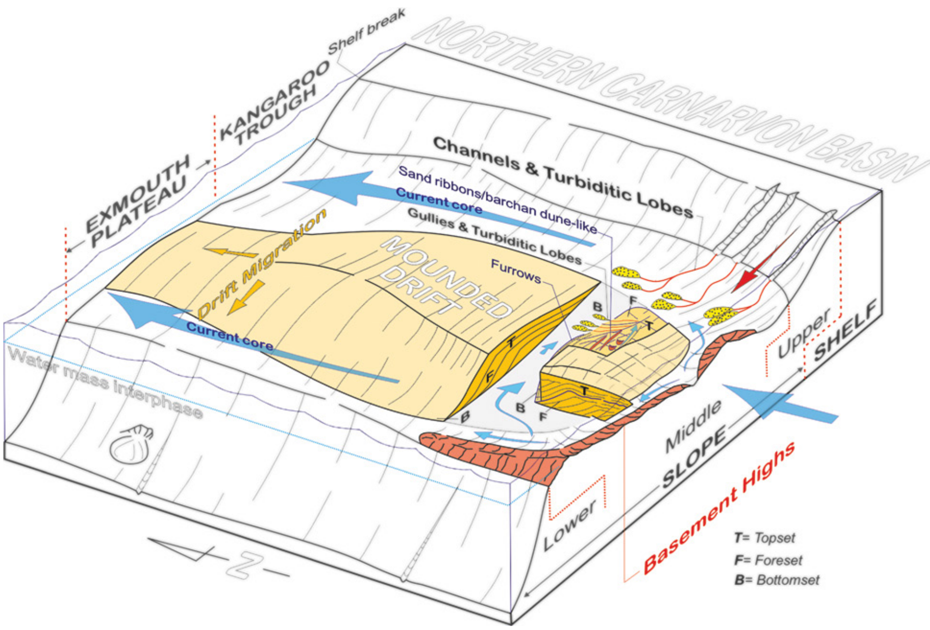

Figure 4. Conceptual sketch depicts the formation of the Exmouth drift. Distribution of coeval gravity features along the upper slope was adapted from Kirk (1985).

(Fig. 3; Fig. S2) do not show networks of distributary channels in proximal deposits (topset) typically observed in delta plain environments (Carvajal et al., 2009). Interestingly, no previous studies in the literature describe any evidence of rivers or fluvial systems related to the proximal domain of these progradational bodies. Additionally, wells that sample topsets (e.g., ODP Site 763 and Sirius-1 (drilled by Esso Australia Ltd in 1980; Si-1 in Figs. 1–3) do not show facies that become progressively more proximal, nor do they reveal evidence of coastal/alluvial or fluvial facies that characterize delta plain environments (Rich, 1951).

The above evidence supports the interpretation of a deep-marine environment for the mounded feature described here. Our interpretation incorporates studies of Integrated Ocean Drilling Program Sites 762 and 763 (Haq et al., 1990) and those of Haq et al. (1992) and Paumard et al. (2018), which ascribe open-marine conditions with water depths ranging from 200 m to 600 m or deeper basin environments (Longley et al., 2002) for the ExP sediments analyzed.

PALEOCURRENT AND EVOLUTIONARY MODEL

The deposit described here is interpreted as an elongated mounded drift (Rebesco, 2005) and is herein referred to as the "Exmouth Drift." Within the SU1a and SU1c subunits, it shares some similarities with a delta drift (Eberli and Betzler, 2019) but instead evolved into a large, asymmetric mounded drift. Erosional features and clinoform directions suggest that the drift formed under the influence of two cores belonging to a single water mass. One core flowed northeastward, causing erosion along the western edge of the Kangaroo Trough and lateral deposition over the ExP (Fig. 4). The second core flowed in a northeast direction along the ExP. These cores formed due to the interaction of an intermediate water mass from an Antarctic source with the pronounced relief of the plateau and local basement highs (Fig. 4). Critically, the changing thickness of the water masses and their interfaces may control accommodation space for lateral sedimentary accretion of these contouritic drifts (Kirby et al., 2021). The plateau's morphology affected current dynamics by intensifying and accelerating ocean flows, which formed the asymmetric mounded drift. Similar buried and active drifts have been identified offshore of Argentina (Hernández-Molina et al., 2010), Mozambique (Thiéblemont et al., 2020), South Africa (Niemi et al., 2000), and in the western Atlantic (Tucholke, 2002; Mosher et al., 2017).

The paleogeographic setting offered two routes for water mass arrival (Fig. S3). One route would be through the African–Southern Ocean gateway, which formed at ca. 159 Ma (Castelino et al., 2016) but did not become a major ocean circulation pathway until the Albian (Thiéblemont et al., 2020). The second route would be a path between India and Australia. Seafloor spreading of the Cuvier Abyssal plain began around ca. 135 Ma (Gibbons et al., 2013). A narrow gateway formed during early separation may have permitted surface and intermediate ocean circulation. This latter pathway comports with interpretations of southerly water masses previously proposed by Baumgartner et al. (1992) and Baumgartner (1993).

Morphological analysis and changes in drift architecture suggest three evolutionary stages for the drift:

(1) The onset stage (SU1a) consists of aggradational growth that archives the arrival of bottom currents and coeval, active turbiditic currents (Figs. 2 and 4). At this time, channels from the upper slope were active (Kirk, 1985; Reeve et al., 2016) coevally with the gullies along the ExP. Such features formed concurrently with tectonic pulses and uplift during the India–Australia breakup (Reeve et al., 2016). Meanwhile, northeast-flowing currents redistributed sediment transported by gravitational processes to shape the drift (Fig. 4).

(2) A growth stage (SU1b to SU1d) consisted of pronounced lateral accretion of the drift. The considerable thickness of the drift along the ExP suggests deepening of the margin due to thermal subsidence and high rates of sedimentation (Reeve et al., 2016) contemporaneous with sea-level changes (Ross and Vail, 1994). This stage recorded repeated cycles of erosion along southerly areas and drape deposition to the north. During this time, gravitational processes triggered by tectonic events continued throughout SU1b (Reeve et al., 2016). The gravity flows declined significantly during SU1c and did not influence SU1d deposition (Figs. 3B–3D). Currents became more dominant.

(3) A burial stage (ca. 138.2 Ma) marks the burial of the Exmouth drift.

CONCLUSIONS

Having vigorous bottom currents, deepwater environments can hold sedimentary features with stratigraphic patterns and geometries that resemble clinothems, such as delta drifts and asymmetric mounded drifts. Evaluating such deposits in terms of their deepwater environments can expand our understanding of ocean currents and their impact on controlling the sedimentary stacking pattern and shaping of continental margins. The analysis and interpretation given here also show that the plate tectonic motions, gateways, and the onset of ocean circulation are clearly articulated in the growth of extensive contourite depositional systems.

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