Title: The Stratigraphic Record of Pre-breakup Geodynamics: Evidence from the Barrow Delta, offshore Northwest Australia

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Key points:

- Delta systems represent an important sedimentary archive of geodynamic processes
- Anomalously rapid uplift and subsidence shown to have taken place in the last stages of breakup
- A phase of depth-dependent extension or dynamic topography is suggested to precede breakup

Abstract

The structural and stratigraphic evolution of rift basins and passive margins has been widely studied, with many analyses demonstrating that delta systems can provide important records of post-rift geodynamic processes. However, the apparent lack of ancient syn-breakup delta systems and the paucity of seismic imaging across continent-ocean boundaries means the transition from continental rifting to oceanic spreading remains poorly understood. The Early Cretaceous Barrow Group of the North Carnarvon Basin, offshore NW Australia was a major deltaic system that formed during the latter stages of continental rifting, and represents a rich sedimentary archive, documenting uplift, subsidence and erosion of the margin. We use a regional database of 2D and 3D seismic and well data to constrain the internal architecture of the Barrow Group. Our results highlight three major depocenters: the Exmouth and Barrow sub-basins, and southern Exmouth Plateau. Over-compaction of pre-Cretaceous sedimentary rocks in the South Carnarvon Basin, and pervasive reworking of Permian and Triassic palynomorphs in the offshore Barrow Group, suggests that the onshore South Carnarvon Basin originally contained a thicker sedimentary succession, which was uplifted and eroded prior to breakup. Backstripping of sedimentary successions encountered in wells in the Exmouth Plateau depocenter indicate anomalously rapid tectonic subsidence ($\leq$0.24 mm yr^{-1}) accommodated Barrow Group deposition, despite evidence for minimal, contemporaneous upper crustal extension. Our results suggest that classic models of uniform extension cannot account for the observations of uplift and subsidence in the North Carnarvon Basin, and may indicate a period of depth-dependent extension or dynamic topography preceding breakup.

1. Introduction

Although the structural and stratigraphic evolution of rift basins and passive margins has been widely studied, the transition from continental rifting to oceanic spreading, which is highly variable in terms of the timing and distribution of extension, uplift, subsidence and magmatism, remains a relatively poorly understood process [Dunbar & Sawyer, 1989; Taylor et al., 1999; Rosenbaum et al., 2008]. The sedimentary and stratigraphic record of continental breakup is influenced by uplift, subsidence and erosion and may therefore provide important insights into how continents break up. However, isolating the tectonic signal in the stratigraphic record from climatic and eustatic signals is challenging [Schumm et al., 2000; Catuneanu, 2006; Espurt et al., 2009]. Understanding the tectonic processes prior to break up and how they are expressed in the sedimentary record is key to constraining the final stages of continental rifting, and ultimately in understanding how continents break up.

Along continental margins, large deltaic systems perhaps represent the best available records of sedimentary basin evolution, because they are highly sensitive to changes in allogenic controls (e.g. climate, tectonics, sediment supply) over comparatively short timescales [Catuneanu, 2006; Plint & Wadsworth, 2006]. As a result, deltas deposited in the last stages of continental rifting can potentially record the sedimentary expression of geodynamic processes taking place prior to breakup. However, many large-scale deltas on passive continental margins have evolved post-breakup, such as the Niger Delta [Cohen & McClay, 1996], the Cenozoic deltas of the Gulf of Mexico [Galloway 1989; Sydow & Roberts 1994] and the Orinoco Delta [Van Andel, 1967; Aslan et al., 2003]. The Ceduna Delta system of the southern Australian Bight Basin formed during breakup but our understanding of its sedimentological and stratigraphic evolution is limited due to a lack of high-quality seismic reflection and well data, compromising attempts to constrain the geodynamic processes operating during its deposition on a regional scale [e.g. Espurt et al., 2009; King & Backé, 2010; MacDonald et al., 2010]. The North Carnarvon Basin, offshore NW Australia (Figure

1), however, is an ideal study area in which to investigate how the stratigraphic architecture of a large-scale delta system (i.e. the Early Cretaceous Barrow Delta) evolved during the final stages of continental rifting.

Fundamental questions remain unanswered concerning the processes and mechanisms that operated during the deposition of the Barrow Delta and contemporaneous break up [AGSO North West Shelf Study Group, 1994; Stagg & Colwell, 1994] and how these processes are expressed in terms of uplift [e.g. Rohrman, 2015], subsidence, magmatism and distribution of extension [e.g. Driscoll & Karner, 1998; Huismans & Beaumont, 2011]. In particular, despite considerable academic and exploration interest, the source area of the Barrow Group remains controversial [e.g. Veevers & Powell, 1979; Exon & Buffler, 1992; Ross & Vail, 1994]. Discriminating between the proposed source area models is therefore important in order to constrain the distribution and timing of pre-breakup uplift, which in turn provides crucial information for elucidating mechanisms of rifting and breakup. This study aims to constrain the structural and stratigraphic evolution of the Barrow Delta, to gain insights into the geodynamic processes operating in the final stages of continental rifting in the North Carnarvon Basin. We investigate the structural architecture and distribution of the Barrow Group using an extensive dataset of high-resolution, 2D and 3D seismic reflection surveys and borehole data (Figure 2). Onshore borehole data constrains the uplift history of the South Carnarvon Basin, and we use data from offshore boreholes on the Exmouth Plateau to perform 1D isostatic backstripping to understand the subsidence history of this area (Figure 2).

2. **Geological Setting**

2.1. Regional geology

The Palaeozoic-to-Recent North Carnarvon Basin forms the southwestern part of Australia's Northwest Shelf (Figure 1), covering ~535,000 km^2, and is sub-divided into a number of smaller tectonic elements: the thick Mesozoic depocenters of the Exmouth, Barrow, Dampier, Dixon and Beagle sub-basins, and the Exmouth Plateau to the northwest, which lacks a thick Mesozoic section (Figures 3 & 4) [Stagg & Colwell, 1994; Longley et al., 2002]. We here focus on the Exmouth and Barrow sub-basins, and the southern Exmouth Plateau. The Exmouth and Barrow sub-basins are NE-trending, en-échelon, principally Jurassic depocenters, separated by the N-trending Alpha Arch, which comprises horst blocks of Triassic age (Figure 3) [Stagg & Colwell, 1994; Tindale et al. 1998]. In contrast, the Exmouth Plateau is a block of thin crystalline crust (*c.* 10km thickness), overlain by a thick sedimentary sequence [Stagg et al., 2004]. Previous authors have suggested the crystalline basement of the Exmouth Plateau comprises continental crust on the basis of geophysical evidence, such as gravity, magnetic and velocity data, although the composition of basement in this area has not been directly confirmed by sampling by drilling or dredging [Stagg et al. 2004]. The Exmouth Plateau is bound on its northern and northwestern margins by oceanic crust of the Argo and Gascoyne Abyssal Plains respectively, and to the south by the Cuvier Abyssal Plain, from which it is separated by the Cape Range Fracture Zone (CRFZ) (Figure 1) [Purcell & Purcell 1988; Hopper et al. 1992; Longley et al. 2002]. The CRFZ has been interpreted as a sheared rifted margin that accommodated continent-continent transform motion during breakup along the Cuvier segment of the margin [Lorenzo & Vera 1992; Lorenzo 1997].

The structural and stratigraphic architecture of the North Carnarvon Basin developed during multiple phases of rifting between Australia and Greater India that intermittently occurred from the Late Carboniferous until the Early Cretaceous [Stagg & Colwell, 1994; Longley et al., 2002; Gibbons et al., 2012]. Significant discrepancies exist in the literature concerning the timing of these rifting events, although most authors suggest that Mesozoic rifting in the Exmouth and Barrow sub-basins commenced in the Rhaetian [e.g. Hocking, 1992; Longley et al., 2002; Jitmahantakul & McClay, 2013]. Rifting continued throughout the Early and Middle Jurassic, until the onset of seafloor spreading in the Argo abyssal plain to the north of the Exmouth Plateau during the Callovian [Hocking, 1992; Tindale et al., 1998]. A period of tectonic quiescence occurred during the Oxfordian to Kimmeridgian, prior to the onset of the final rifting phase in the Tithonian, which culminated in the onset of seafloor spreading in the Gascoyne and Cuvier abyssal plains during the Valanginian [Driscoll & Karner ,1998; Gibbons et al., 2012; Magee et al., 2015].

The crystalline basement of the Exmouth Plateau is overlain by a 10–15 km thick sedimentary succession [Stagg et al. 2004] dominated by the Triassic Locker Shale and Mungaroo formations, which are cross-cut by Jurassic rift-related normal faults (Figs 4 and 5) [Lorenzo & Vera, 1992; AGSO North West Shelf Study Group, 1994; Stagg & Colwell, 1994; Tindale et al., 1998]. For much of the Jurassic, however, the Exmouth Plateau was sediment starved, with preservation of only a thin veneer of Jurassic claystones and marls (Figure 4) [Barber, 1988; Exon et al., 1992; Driscoll & Karner, 1998]. Jurassic deposition was focused instead in the Exmouth, Barrow and Dampier sub-basins to the southeast. In the Exmouth and Barrow sub-basins, up to 3.5 km of sedimentary rocks were deposited during the Jurassic in a predominantly low-energy marine environment [Tindale et al. 1998]. The Jurassic succession of the Exmouth and Barrow sub-basins comprises the Athol (Pliensbachian-Callovian) and Calypso (Callovian to early Oxfordian) formations, and the Dingo Claystone (Oxfordian to Kimmeridgian) (Figure 5) [Hocking et al., 1987; Hocking, 1992; Labutis, 1994]. These shale- and siltstone-dominated units are overlain by submarine fan deposits of the sandstone-rich Dupuy Formation (Kimmeridgian to Tithonian) [Tait, 1985; Hocking et al., 1987].

2.2. Barrow Group Stratigraphy

In the latest Jurassic, a major change in deposition occurred in the North Carnarvon Basin. During the Tithonian, a large delta prograded northwards across the Exmouth and Barrow sub-basins and southern Exmouth Plateau, depositing the Barrow Group (Figures 6 & 7) [Tindale et al., 1998]. Deposition of the Barrow Group spans latest Tithonian to early Valanginian times (*c.* 146.7 – 138.2 Ma) (*P. iehiense* – *E. torynum* dinoflagellate zones) and corresponds to the final phase of rifting in the North Carnarvon Basin (Figure 6) [Ross & Vail, 1994; Driscoll & Karner, 1998; Smith et al., 2002]. The basal Barrow Group in the Exmouth sub-basin includes sandstone-rich, sediment gravity-flow deposits of the Eskdale and Macedon members, siltstones and mudstones of the Muiron Member, and the upward-coarsening Pyrenees Member (Figure 6) [Scibiorksi et al., 2005; Hurren et al., 2013; O'Halloran et al., 2013]. The main phase of Barrow Group deposition is sub-divided into the Malouet (delta bottomsets) and Flacourt (delta foresets and topsets) formations (Figure 6) [Hocking et al., 1987; Ross & Vail, 1994].

The top of the Barrow Group is marked by the intra-Valanginian unconformity (Figure 6), which is observed across much of the North Carnarvon Basin and is generally considered to coincide with the onset of seafloor spreading in the Gascoyne and Cuvier Abyssal Plains [Arditto, 1993; Labutis, 1994 Romine & Durrant, 1996]. The intra-Valanginian unconformity is locally overlain by Valanginian deltaic rocks of the Zeepaard Formation (138.2 – 134.9 Ma) (*S. areolata* dinoflagellate zone), which were deposited during a regional marine transgression, and the Birdrong Sandstone Formation, deposited in shoreface environments [Hocking et al., 1987; Arditto, 1993]. The regional intra-Hauterivian unconformity marks the top of the Birdrong Sandstone (Figure 6). Continued marine transgression during the

Hauterivian resulted in deposition of the Mardie Greensand, which grades conformably into the Muderong Shale (Hauterivian to Aptian) (Figure 6) [Hocking et al., 1987; Driscoll & Karner, 1998; Tindale et al., 1998].

2.3. Onshore areas

The general northward progradation of the Barrow Delta suggests that its sediment source area lies to the south. It is therefore important to understand the geology of adjacent onshore areas south of the area of Barrow Group deposition, in order to constrain which of these potential areas were sediment sources during the Early Cretaceous.

2.3.1. Onshore tectonic elements

The onshore areas adjacent to the North Carnarvon Basin comprise two major groups of tectonic elements. A complex assemblage of Archean to Mesoproterozoic igneous and metamorphic rocks, comprising the Pilbara Craton, Gascoyne Complex, and Hamersley, Edmund and Collier basins is adjoined by the South Carnarvon Basin to the west (Figure 3) [Martin et al., 2007]. The South Carnarvon Basin (or Onshore Carnarvon Basin) covers ~115,000 km^2, comprising dominantly Paleozoic-age sedimentary rocks of the Gascoyne Platform, Bernier Ridge and Merlinleigh and Byro sub-basins (Figure 3 & 5). The Gascoyne Platform is underlain by a 4–5 km thick sedimentary succession [Iasky et al., 2003], and is bound to the northwest by the Bernier Ridge, a NE-SW trending basement high [Lockwood & D'Ercole, 2003]. The oldest unit encountered on the Gascoyne Platform is the Ordovician Tumblagooda Sandstone, which is overlain by dominantly shallow marine or terrestrial rocks of Palaeozoic age (Figure 5) [Iasky & Mory, 1999; Iasky et al., 2003]. Across much of the Gascoyne Platform, rocks of Permian to Jurassic age are scarce, and the Palaeozoic sequence is unconformably overlain by up to 300 m of Cretaceous sediments, deposited during a post-breakup sea-level highstand (Figure 5) [Iasky et al., 2003]. The Mesozoic history of the Gascoyne Platform is poorly constrained, and the origin of the "base Cretaceous unconformity" or "main unconformity" is unknown [Iasky et al., 2003]. Some authors suggest Jurassic sediments were deposited on the Gascoyne Platform, and were later uplifted and eroded [Mihut & Müller, 1998]; others suggest the Gascoyne Platform was a structurally high area of non-deposition for much of the Mesozoic [Iasky et al., 2003; Mory et al., 2003].

The ~32 000 km^2 Merlinleigh Sub-basin is an elongate NNE-trending depocenter of dominantly Palaeozoic age (Figure 3). It contains a similar, albeit thicker (6-7 km), stratigraphic succession to that encountered on the Gascoyne Platform [Iasky et al., 1998]. The oldest unit penetrated by wells is the Ordovician Tumblagooda Sandstone, which is overlain by a Silurian to Early Carboniferous pre-rift sequence, and a mixed clastic and carbonate sequence associated with Late Carboniferous to Late Permian rifting (Figure 5) [Iasky et al., 1998; Mory et al., 2003]. In the western part of the Merlinleigh sub-basin a major unconformity separates Palaeozoic and Cretaceous-to-Cenozoic sequences (Figure 5), with Palaeozoic rocks outcropping in the east [Hocking, 2000; Mory et al., 2003]. Like the adjoining Gascoyne Platform, the Mesozoic history of the Merlinleigh Sub-basin is rather poorly constrained, and the origin of the Triassic to Early Cretaceous unconformity is unknown.

2.3.2. Onshore equivalents to the Barrow Group

Across much of the South Carnarvon Basin, a major unconformity spans much of the Permian to Lower Cretaceous interval, and thus stratigraphy time-equivalent to the Early Cretaceous Barrow Group is generally not preserved. However, close to the rift margins, Berriasian-Valanginian correlatives to the Barrow Group are preserved locally. Around the Cape Range Peninsula and Gulf of Exmouth area (Figure 2), the fluvial Wogatti Sandstone

Formation is preserved (Figure 8); Hocking et al. [1987; 1988] suggest the unit is approximately time-equivalent to the offshore Barrow Group, although precise age determination is not possible due to a lack of preserved organic matter with which to date the unit. The Yarraloola Conglomerate Formation is a fluvial-alluvial fan deposit encountered both at outcrop and in the subsurface on the Peedamullah Shelf, inboard of the Barrow Sub-basin (Figures 3 & 8) [Hocking, 1988]. This unit comprises a pebble- to cobble-grade polymict conglomerate, containing clasts of banded iron formation, quartzite and nearby Precambrian rocks [Hocking et al., 1987; 1988]. Although accurate age determination of this formation is lacking, dating of organic material suggest an Early Cretaceous age [Hocking et al., 1987] and the unit's stratigraphic relationships indicate it is partially time-equivalent to the Barrow Group [Hocking et al., 1988]. The Yarraloola Conglomerate shows substantial lateral variations in thickness, interpreted to relate to pre-existing topography, with the present distribution of the unit appearing to be confined to and thus define the ancient courses of the Robe, Ashburton, Fortescue and Cane rivers (Figure 8) [Thomas 1978; Hocking et al. 1987; Hocking et al. 1988].

2.4. Source area of the Barrow Group

Although the Barrow Delta has been the subject of considerable academic and exploration interest, the source area for the sediments of the Barrow Group remains debated. Discriminating between source area models is crucial for constraining the distribution of pre-breakup uplift in the North Carnarvon Basin, and we thus outline previous Barrow Group source models here.

2.4.1. The Cape Range Fracture Zone

The most widely discussed group of models for the origin of the Barrow Group involve uplift of the Cape Range Fracture Zone (CRFZ), which forms the southwestern margin of the Exmouth Plateau [e.g. Veevers & Powell 1979; Eriyagama et al. 1988; Tindale et al. 1998]. These models suggest that thermally driven uplift and resultant erosion along the CRFZ led to progradation and deposition of Barrow Group sediments to the north (Figure 9a). Veevers & Powell [1979] observed erosional truncation of sediments adjacent to the CRFZ and suggested that this was a result of transient thermal uplift, caused by conduction of heat as the incipient spreading ridge in the Cuvier Abyssal Plain migrated along the transform margin after Valanginian breakup (Model a, Table 1; Figure 9b). On the basis of seismic profiles from the Exmouth Plateau, Exon & Buffler [1992] suggest that the Barrow Group prograded northward adjacent to the CRFZ, suggesting the associated delta was partially sourced from a ridge located at the present site of the CRFZ (Model b, Table 1; Figure 9a). They also propose the CRFZ experienced Berriasian to Valanginian uplift during due to asthenospheric upwelling associated with incipient breakup.

2.4.2. Sources south of the Cape Range Fracture Zone

The second group of hypotheses for the Barrow Group source area suggest a sediment source directly southwest of the Cape Range Fracture Zone. This area, such as the Gascoyne Terrane of Bradshaw et al. [2012], would have formed the pre-breakup conjugate margin to the Cuvier rift (Figure 9c). Ross & Vail [1994] suggest that a large area of the Indian craton, which lay to the south of the CRFZ, was uplifted and eroded in the Berrisian and deposited north of the CRFZ to form the 'lower' Barrow Delta in a depocenter within the Exmouth Plateau (Model c, Table 1; Figure 9c); this model infers a subsequent switch in the latest Berriasian to deposition of an 'upper' delta sequence in a depocenter within the Exmouth Sub-basin (Figure 9d). This upper delta sequence was suggested to be sourced from the uplifted flanks of the incipient Cuvier rift valley [Ross & Vail, 1994].

Based on the presence of Archean-age detrital zircon grains in Barrow Group deposits on the southern Exmouth Plateau, Lewis & Sircombe [2013] suggested that a component of Barrow Group sediment may have been derived from Greater India by a north-flowing river system. (Model d, Table 1). Rohrman [2015] suggests that Barrow Group sediments were sourced from an uplifted area to the southwest of the CRFZ, based on delta progradation directions and the presence of conglomerates in the Exmouth Sub-basin (Model e, Table 1). This model invokes a mantle plume centered on the CRFZ to account for Late Jurassic and Early Cretaceous uplift of this area (Figure 9c). Tait [1985], Scibiorski et al. [2005] and Bradshaw et al. [2012] use observations of delta progradation directions to propose models involving erosion of a continental block to the southwest of the CRFZ (Figure 9c); however, they do not propose a specific mechanism driving Early Cretaceous regional uplift.

2.4.3. Sources on the Australian plate

Hocking [1988] suggests that the Barrow Delta was sourced from onshore areas adjacent to the North Carnarvon Basin, namely the northern Gascoyne Platform and, to some extent, the neighbouring Pilbara Craton and Hamersley Basin (Model g, Table 1; Figure 9e). Boote & Kirk [1989] also suggest that the Gascoyne Platform provided a major source of sediment for the Barrow Delta, as a result of pre-breakup uplift of the eastern flank of the Cuvier rift (Model h, Table 1). Longley et al. [2002] propose that a large volume of Barrow Group sediment was derived from the Perth Basin area to the south, in association with the onset of Berriasian rifting of Greater India (Model f, Table 1; Figure 9f). A number of authors [e.g. Veevers & Powell, 1979; Exon & Buffler 1992a; Ross & Vail, 1994; Lewis & Sircombe, 2013; Rohrman, 2015] also suggest the Barrow Delta was at least partially derived from sources on the Australian plate, in combination with contribution from sediments from other source areas.

3. Dataset and Methodology

3.1. Dataset

The structure of the study area was constrained by mapping key horizons in a ~165,000 km^2 grid of 2D seismic reflection lines and ten 3D seismic reflection volumes (Figure 3). 2D line spacing varies from 0.5–10 km, but is typically <5 km. Vertical record length varies between 3.5–16 s two-way time (TWT). We also use wireline logs, checkshot data, sidewall and conventional core data, formation tops, petrological data and commercial palynology reports from 11 onshore and 46 offshore wells. To assign ages to each horizon (Figure 6), we use the palynological zonation scheme and absolute ages of Kelman et al. [2013]. Depth conversion of surfaces derived from seismic data was performed in Petrel seismic interpretation software, using velocity information from 29 offshore wells (Figure 2).

3.2. Methodology

3.2.1. Seismic interpretation

Seismic reflections corresponding to the top and base of the Barrow Group were mapped within the 2D and 3D seismic datasets and depth converted in order to construct an isopach map. In addition, ten reflections corresponding to seismically imaged clinoforms were mapped locally in the Exmouth Plateau area and depth converted in order to constrain clinoform height, which is used as a proxy for water depth through time [Immenhauser, 2009]. Ages were assigned to these seismic horizons based on correlation with biostratigraphic zones in the Sirius-1 and Investigator-1 wells. Clinoform progradation directions were also measured, which can potentially be used to discriminate between different sediment source areas. These progradation directions were estimated from the maximum dip direction of clinoform fronts as interpreted on intersecting 2D seismic lines.

3.2.2. Stratigraphic correlation

To constrain variations in Barrow Group depositional environment both temporally and spatially, stratigraphic correlations were produced between 11 offshore wells (shown on Figure 10). At these well locations, the Barrow Group was sub-divided into three main depositional environments; prodelta, delta front and delta plain. This sub-division is based on seismically resolved clinoforms, and data provided by wireline logs and descriptions of cuttings and cores from well completion reports. Correlation between wells was performed on the basis of this sub-division and dinoflagellate zone depths as described in well completion reports.

3.2.2. Uplift estimation from compaction

In order to investigate the uplift and exhumation history of potential source areas of the Barrow Group, we employ a compaction-based approach. Lithologies such as sandstone and shale are assumed to exhibit a predictable behaviour in terms of their porosity loss with increasing burial depth (Figure 11a). This assumption gives rise to the notion of a ‘compaction curve’ that describes the normal trend of porosity loss with depth for a given lithology [Giles, 1997; Corcoran & Doré, 2005]. Deviation from a ‘normal’ compaction trend may thus be indicative of anomalous compaction, resulting from, for example, overpressure development (i.e. under-compaction) or exhumation (i.e. over-compaction) (Figure 11b) [e.g. Corcoran & Doré, 2005; Tassone et al., 2014]. If sedimentary rocks in a potential Barrow

Group source area (e.g. the South Carnarvon Basin) consistently show lower porosity values than would be predicted from normal compaction curves, this may indicate that these rocks have been uplifted and their overburden eroded.

To estimate exhumation from compaction, a reliable reference compaction curve for a normally compacted succession is required [Corcoran & Doré, 2005]. Because no such compaction curve exists for the South Carnarvon Basin, we plot porosity versus depth from our study area against the typical porosity-depth trends established by Giles [1997] for comparable lithologies. We consider only sandstone and shale-dominated units, excluding carbonate-dominated rocks due to the limited reference compaction curves available and strong variability seen in normal compaction trends for such rocks [Giles, 1997].

Porosity at depth can be estimated from well data by either: (1) direct measurement from sidewall or conventional cores; or (2) indirect calculation from wireline logs [Bassiouni, 1994]. Where conventional or sidewall core porosities are available in well completion reports, these have been used; for formations where no sidewall core data are available, estimated porosities have been calculated from wireline logs (see supporting information section for details). Sandstone or shale-dominated intervals were selected, based on core and cutting descriptions from well completion reports and wireline log indicators such as gamma ray. For each interval, the unit's average porosity was plotted against midpoint depth.

We assume that all units above the Early Cretaceous 'main unconformity' of the South Carnarvon Basin underwent normal compaction and therefore their current burial depth is close to their maximum burial depth. To account for the effects of post-exhumation re-burial of units below the 'main unconformity' (Figure 11c) [Corcoran & Doré, 2005], the depth to the unconformity in each well is subtracted from the depth of each porosity measurement. This calculation effectively restores the units to their depths prior to re-burial by Cretaceous and younger sediments, which allows assessment of whether rocks in the South Carnarvon Basin correspond to a normal compaction trend and, therefore, whether this area is a possible candidate source area for the Barrow Group.

3.2.3. Reworking of palynomorphs

In addition to compaction-based methods, we also utilize a methodology based on reworking of palynomorphs to understand Barrow Group sediment provenance. The presence of pre-Cretaceous palynomorphs within Barrow Group strata may correspond to sedimentary rocks present in the delta source area [e.g. Muller, 1959]. This may, in turn, allow us to constrain which areas adjacent to the North Carnarvon Basin were most likely to have been uplifted and eroded during the Early Cretaceous [Dickinson, 1988]. The interpretation of palynomorph reworking was based on commercial palynology reports provided from offshore wells. When presented in reports, the relative proportion of reworking at different depths was also noted in order to gain insights into variation in reworking signatures through time.

3.2.4. Decompaction and backstripping

Decompaction and backstripping was performed to constrain the subsidence history of the offshore Barrow Group. This removes the effects of progressive compaction of the sedimentary succession and changes in eustatic sea level to estimate total tectonic subsidence. 1D Airy isostatic backstripping was used to investigate the tectonic subsidence history of sedimentary successions encountered by wells on the Exmouth Plateau (see supplementary information for details of parameter values used and Allen & Allen [2013] for full details of the backstripping procedure), and the resulting values of water-loaded tectonic subsidence were plotted against time for each well. Decompacted sediment thicknesses were also used to investigate average sediment accumulation rates through time.

4. Results

To constrain the Early Cretaceous evolution of the Barrow Delta and neighboring onshore areas, this section details observations from both the offshore Barrow Group and the onshore South Carnarvon Basin.

4.1. Distribution, thickness and stratigraphic architecture of the Barrow Group

4.1.1. Distribution, thickness and volume

Three major NE-trending Barrow Group depocenters are identified: (i) in the central Exmouth Sub-basin (maximum thickness ~3 km, location A in Figure 10); (ii) on the Exmouth Plateau (maximum vertical thickness ~1.9 km, location B in Figure 10); and (iii) in the Barrow Sub-basin (maximum thickness ~2.6 km, location C in Figure 10). The Barrow Group terminates to the W and N along a gently arcuate, broadly E-trending front, which corresponds to the location of the last clinoform of the delta (see below; see also Figure 10). In the main Exmouth Plateau depocenter (the 'Investigator Sub-basin' of Tindale et al., 1998) the clinoform front trend approximately north-east not east. The thickness of the Barrow Group decreases southwards, and the unit is absent near the Macedon High and Ningaloo Arch (location Figure 3); it also decreases in thickness onto the southern flank of the Exmouth Plateau and is absent over some areas of the Alpha Arch (Location D in Figure 10). Calculation of Barrow Group volume (Figure 10) gives a total sediment volume of *c.* 48,000 km^3, although this is likely a minimum because seismic coverage of the Exmouth Plateau depocenter is incomplete adjacent to the Cape Range Fracture Zone. This estimate also excludes any Barrow Group sediments originally deposited southwest of the Cape Range Fracture Zone.

The height and orientation of clinoforms within the Barrow Group can be used to constrain water depth and the progradation direction of the delta throughout its evolution. Clinoform heights can be used as a proxy for water depth, on the assumption that the clinoform topsets were deposited at or close to sea level [Patruno et al. 2015]. Palynological studies suggest that Barrow Delta topsets in the Exmouth Plateau depocenter were deposited in very shallow marine or subaerial conditions, based on low dinoflagellate cyst abundance and the large proportion of spore pollen reported [e.g. Twartz, 1981b; Hooker, 2003]. These are important parameters to determine because water depths through time provide constraints for backstripping models. Furthermore, progradation directions provide insights into possible source areas for each Barrow Group depocenter [e.g. Exon & Buffler, 1992; Ross & Vail, 1994].

Clinoform progradation directions are broadly towards the north although some variability is observed (Figure 10). In the Exmouth Sub-basin depocenter (Location A in Figure 10) the Barrow delta prograded towards the NE-to-N, whereas in the Barrow Sub-basin depocenter (Location C in Figure 10) the delta prograded towards the NW. In the southern Exmouth Plateau depocenter, progradation directions are largely northward, but become NW-to-W in the western part of the depocenter. Very few normal faults are observed to cross-cut the Barrow Group on the Exmouth Plateau, and there is no evidence of significant thickening of the Barrow Group in the hangingwalls of these faults (Figures 4 & 7).

Temporal variability in clinoform heights are also measured within the Exmouth Plateau depocenter. The oldest clinoforms, which lie in proximity to the CRFZ, have been affected by post-depositional strike-slip deformation [Exon et al., 1992] and clinoform geometries and scale cannot easily be recognized. The oldest recognizable clinoforms in the depocenter are of earliest Berriasian age (144.5 – 143.2 Ma) (*K. wisemaniae* dinoflagellate zone), prograde northwards and have heights of ~260 m (Figure 7). In the middle Berriasian (143.2 – 142.2 Ma) (*C. delicata* dinoflagellate zone), clinoform heights up to 380 m are recorded, with a decrease to 260 – 300 m in the late Berriasian (142.2 – 140.9 Ma) (*D. lobispinosum* dinoflagellate zone). Clinoforms in the latest Berriasian to early Valanginian (140.9 – 139.6 Ma) (*B. reticulatum* dinoflagellate zone) increase in height to 390 – 440 m, and prograde generally to the north or northeast.

4.1.2. Sub-seismic stratigraphic architecture

In order to constrain the sub-seismic stratigraphic architecture of and facies distribution within the Barrow Group, we used well data to construct a stratigraphic correlation between several wells in the Exmouth Sub-basin and on the Exmouth Plateau (Fig. 12). The line of section is illustrated in Figure 11, and broadly represents the most proximal areas of the delta at Eskdale-1 in the southeast, and the most distal areas beyond the last clinoform front at Eendracht-1. The largest Barrow Group thickness in this correlation occurs at Investigator-1, where *c.* 1750 m of Barrow Group deposits are encountered. In proximal areas (Eskdale-1), the entire preserved Barrow Group succession is late Tithonian to early Berriasian (146.7 – 144.5 Ma) (upper *P. iehiense* dinoflagellate zone), and comprises a complete, upward-coarsening, prodelta to delta plain sequence. Any younger Barrow Group deposits are truncated by the intra-Valanginian unconformity (Figure 12). Beyond the last clinoform front, at Eendracht-1, a highly condensed (150 m thickness) Barrow Group equivalent is encountered, comprising prodelta shales and siltstones. Some variability is observed in the timing of deposition between the Exmouth Plateau and Exmouth Sub-basin depocenters. For example, the oldest delta plain deposits in the Exmouth Plateau depocenter are early Berriasian (late *C. delicata* dinoflagellate zone; i.e. Sirius-1), whereas in the Exmouth Sub-basin depocenter delta plain deposits are not encountered until the late Berrisian – Valanginian (*c.* 140.9 – 139.6 Ma) (*B. reticulatum* dinoflagellate zone; i.e. Resolution-1). This observation is consistent with northward delta progradation and supports observations made from seismically imaged clinoforms.

An along-strike, E-W oriented correlation panel is also shown in Figure 13, illustrating Barrow Group thickness in wells in the Exmouth and Barrow Sub-basin depocenters, and on the Alpha Arch (i.e. Ramillies-1). In the Exmouth Sub-basin depocenter, the base of the Barrow Group is not penetrated by Altair-1. The estimated total thickness (~2250 m) is based on depth conversion of the interpreted base Barrow Group seismic horizon at the well location (Figure 13). Although no palynology data are available, it is considered likely that older dinoflagellate zones (e.g., those observed at Bay-1, Figure 13) are present below the base of Altair-1. In both the Barrow and Exmouth Sub-basin depocenters, a thick sequence of Late Berriasian age (142.2 – 140.9 Ma) (*D. lobispinosum* dinoflagellate zone) is encountered, with no deposits of this age or younger encountered on the Alpha Arch at Ramillies-1. Latest Berriasian Barrow Group deposits (140.9 – 139.6 Ma) (*B. reticulatum* dinoflagellate zone) are present in both depocenters and over the Alpha Arch, with a thicker *B. reticulatum* sequence observed in the Barrow Sub-basin than in the Exmouth Sub-basin (Figure 13). The relatively thick latest Berriasian Barrow Group deposits in the Barrow Sub-basin may be a primary depositional feature [e.g., Ross & Vail, 1994], or the result of erosion of the uppermost Barrow Group west of the Alpha Arch by the Valanginian Zeepaard Delta (Figure 13) [Arditto, 1993]. Differences in the timing of deposition are also observed between the Exmouth Sub-basin and Barrow Sub-basin depocenters. In the Exmouth Sub-basin depocenter, the oldest recorded delta front deposits are late Berriasian (*c.* 142.2 – 140.9 Ma) (*D. lobispinosum* dinoflagellate zone; i.e. Altair-1, i), whereas on the Alpha Arch and in the Barrow Sub-basin depocenter the oldest delta front deposits are latest Berriasian to early Valangian (*c.* 140.9 – 139.6 Ma) (*B. reticulatum* dinoflagellate zone) (Figure 13).

4.2. Reworking of palynomorphs

Figure 14 shows well locations where reworking of various ages has been recorded within the Early Cretaceous Barrow Group. Reworking of Jurassic palynomorphs is predominantly observed within the Exmouth Sub-basin and in marginal areas of the Exmouth Plateau, with intermittent Jurassic reworking locally observed further north on the Exmouth Plateau (i.e. Investigator-1; Figure 14a). In the Barrow Sub-basin, Jurassic reworking is significantly less pervasive, being only observed at Robot-1A, Bay-1 and Errol-1.

Triassic palynomorphs are observed in most wells in the Exmouth Sub-basin, and a significant distance north onto the Exmouth Plateau (Figure 14b). For example, at Eendracht-1, Triassic reworking is recorded intermittently within distal prodelta siltstones and claystones of the Barrow Group [Twartz, 1981a]. Triassic reworking is not recorded in wells on the Alpha Arch or Gorgon Platform, and is only recorded at two locations within the Barrow Sub-basin, where Triassic reworking is minimal. For example, at Bay-1, Triassic reworking is only observed in one sidewall core from the Barrow Group [Rapaic & Christiansen, 1996].

The distribution of reworking of Permian age palynomorphs is similar to that of Triassic age palynomorphs (Figure 14c), where reworking is observed pervasively in wells in the Exmouth Sub-basin and on the Exmouth Plateau. Permian reworking is particularly common around the Macedon High and southern Exmouth sub-basin, where many wells record the presence of a ‘Permian reworking unit’ [e.g. Backhouse, 2001; James, 2004; Locke, 2004] that lies within the upper *P. iehiense* dinoflagellate zone of the basal Barrow Group. Within the Permian reworking unit, the abundance of reworked Permian taxa reaches 69% of the total palynomorph count in some samples [Locke, 2004]. Figure 15 shows a typical section from a well in the southern Exmouth Sub-basin, which encounters the Permian reworking unit. In Eskdale-1, a component of Jurassic and Triassic reworking is observed in samples throughout much of the Barrow Group, but a sharp increase in the abundance of Permian reworking is observed at the base of the Lower Pyrenees Member (2743 m; Figure. 15), where 39% of the total palynomorph count is represented by reworked Permian forms. Significant Permian reworking is present in all samples throughout the rest of the Barrow Group, and abruptly ceases at the top of the Barrow Group. Analogously to the results for Permian and Triassic reworking, the majority of wells in the Exmouth Sub-basin, in addition to wells on the southern Exmouth Plateau, show reworking of palynomorphs of Carboniferous and older (Figure 14d). On the Alpha Arch and in the Barrow Sub-basin, no reworking of Carboniferous age or older palynomorphs is recorded.

4.3. Constraining uplift history

To constrain the uplift history of the potential onshore Barrow Group source area of the South Carnarvon Basin, this section presents porosity-depth results from wells in the Merlinleigh Sub-basin and the Gascoyne Platform. Some stratigraphic successions in the South Carnarvon Basin have been affected by the precipitation of cements during burial [Baker & Martin, 1996], which will have led to a reduction in porosity and, therefore, an erroneous interpretation that these units had been more deeply buried and thus exhumed. Accordingly, results from heavily cemented intervals have been excluded from our analysis (Figure 16).

For sandstone-dominated units, almost all porosity values lie significantly outside the global 'normal' porosity-depth envelope (Figure 16a). The only exception is two core-derived porosity values from Yaringa East-1, which lie close to the envelope of typical minimum porosity as defined by Giles [1997]. These anomalous values may relate to the presence of unusually coarse clastic material at some intervals within the Kopke Formation, where some samples are noted as containing pebble grade sediment [Yasin & Mory, 1999]. In short, all other samples show significantly lower porosity values than would be anticipated from any of the 'normal' porosity-depth trends from the global compilations.

A similar trend is exhibited in shale-dominated units (Figure 16b), although there are fewer data points due to the sandstone- and carbonate-dominated nature of the Paleozoic sequence of the South Carnarvon Basin (Figure 5). Although the trend is challenging to assess due to the rapid initial porosity loss of shale during burial shown by the compaction trends (Figure 16b), all data show similar trends to those obtained for sandstone units (i.e. porosity values lower than predicted by any global porosity-depth trends).

Although a well-constrained baseline compaction-depth trend is required to reliably estimate the magnitude of exhumation from porosity-depth plots, an approximation can be gained by comparison of these results with the minimum global baseline of Giles [1997] (dashed line in Figure 16 a,b). This comparison consistently suggests 500-1500 m of exhumation, with isolated samples suggesting values up to 2500 m exhumation. This is consistent with results of previous thermal maturity modeling studies from the Gascoyne Platform, which indicate that 500-1800m of uplift took place in the Early Cretaceous [Ghori 1999].

4.4. Decompaction and backstripping

To constrain the magnitude of Early Cretaceous tectonic subsidence in the North Carnarvon Basin, 1D backstripping was performed on the Barrow Group successions penetrated at Sirius-1 and Investigator-1 in the Exmouth Plateau depocenter (Figure 17). Some uncertainty is associated with estimating subsidence during the Jurassic on the Exmouth Plateau due to the thin Jurassic successions present (e.g. Figure 7) and poorly constrained dinoflagellate zones. However, Sirius-1 and Investigator-1 show similar results, with <200 m subsidence estimated during the Jurassic, consistent with previously published studies [e.g. Exon & Buffler, 1992]. During Barrow Group deposition (146.7 – 138.2 Ma), increased tectonic subsidence took place: ~1.2 km at Sirius-1 and 1.3 km at Investigator-1 (Figure 17). A significant decrease in subsidence rates subsequently occurs at both well locations, with ~1.35 km of subsidence occurring at Sirius-1 and 1 km at Investigator-1 between *c.* 138 Ma and the present day (Figure 17). It should be noted that some uncertainty is associated with backstripping of stratigraphic horizons of 100 Ma or younger age in these wells, due to a lack of age and lithology constraints for the Upper Cretaceous and Cenozoic section at Sirius-1 and Investigator-1.

1D decompaction of the stratigraphic succession of Eskdale-1, further southeast on the edge of the Exmouth Sub-basin, was also performed to better understand sediment accumulation rates during Barrow Group deposition. Immediately prior to Barrow Group deposition, the average decompacted sediment accumulation rate for the middle to late Tithonian (149.3 – 146.7 Ma) (*D. jurassicum* dinoflagellate zone) was ~0.12 m kyr^{-1}. During Barrow Group deposition in the late Tithonian to early Berriasian (146.7 – 144.5 Ma) (*P. iehiense* dinoflagellate zone), average sediment accumulation rate increases to 0.87 m kyr^{-1}. This is likely a minimum value, since the Barrow Group at Eskdale-1 may have been eroded at its top along the Intra-Valanginian unconformity (Figure 15); thus the true average sediment accumulation rate for this interval is likely to be greater.

5. Discussion

There is considerable uncertainty regarding the source location for Barrow Group sediments. This reflects, in part, a failure to integrate geophysical (e.g. seismic reflection) and geological (e.g. well) data, and the likely erroneous approach of using local observations to build a regional model for Barrow Group deposition. In this section, we improve our knowledge of the tectono-stratigraphic development of the Barrow Group by integrating observations from offshore and onshore areas to constrain possible Early Cretaceous sediment source areas. In addition, we consider the implications our revised model has for understanding the regional distribution of pre-breakup uplift and subsidence, and the implications this has for processes operating during continental breakup.

5.1. Evidence for source area of the Barrow Group

5.1.1. Evidence from Barrow Group architecture

The thickness, distribution and stratigraphic architecture of the Barrow Delta together provide an important first-order framework within which inferences can be made regarding its likely source area(s). Regional stratigraphic correlation (Figure 12) indicates that the onset of Barrow Group deposition was likely coeval in the Exmouth Plateau and Exmouth Sub-basin depocenters (Late Tithonian – Early Berriasian, 146.7 – 144.5 Ma) (*P. iehiense* dinoflagellate zone), and that regional factors, such as tectonic uplift, triggered sediment input. However, significant variability in the timing and distribution of facies between different depocenters is observed (e.g. Figure 12). This suggests that the Barrow Group does not represent the evolution of a simple point-sourced delta system, but rather a number of time-equivalent systems, which were likely deposited as a result of the same regional forcing mechanism.

The general clinoform progradation directions suggest that the source area of the Barrow Group lay to the south, an observation consistent with previous studies (Figure 10) [e.g. Exon & Buffler, 1992; Ross & Vail, 1994; Longley et al., 2002]. However, in the Exmouth Plateau depocentre, clinoforms locally prograde to the northwest and west, indicating that the sediment source area for these deposits likely lay to the southeast. This may be inconsistent with models suggesting that these sediments were sourced from the uplifted CRFZ (Figure 8a,b) [Eriyagama et al., 1988; Exon & Buffler, 1992; Tindale et al., 1998], which imply sediment transport was to the northeast, away from the area of uplift. As the observed progradation directions are sub-parallel to the CRFZ, it is considered unlikely that the CRFZ was the only source of Barrow Group sediment in the Exmouth Plateau depocentre [cf. Veevers & Powell, 1979; Exon & Buffler, 1992]. Thickening of the Barrow Group towards the southwestern margin of Exmouth Plateau is also inconsistent with the notion that the CRFZ was uplifted during the Early Cretaceous, which would predict thinning of the Barrow Group towards this structurally high area (Figure 10).

The estimated total volume of the Barrow Group can also be used to potentially discriminate between different source areas. Lorenzo & Vera [1992] present a coupled thermal uplift and erosion model for the CRFZ, which allows us to estimate the total eroded sediment volume. Assuming that the ~350 km length of the CRFZ was uplifted simultaneously and subject to uniform erosion, a total sediment volume of ~36,000 km^3 would have been eroded over 130 Ma following the onset of thermal uplift. The Barrow Delta was deposited in <9 Ma, during which time the Lorenzo & Vera [1992] model would predict ~5,500 km^3 of sediment erosion. This is incompatible with our estimates of the total volume of sediment in the Barrow Group, which suggest ≥45,000 km^3 was deposited during the Tithonian-Valanginian.

5.1.2. Evidence from the South Carnarvon Basin

One of the previously proposed source areas of the Barrow Delta is the South Carnarvon Basin [e.g. Hocking 1988; Boote & Kirk 1989]. Understanding the timing and distribution of uplift in this area, therefore, is crucial to assessing whether it was a source area for Barrow Delta sediments. However, the area's uplift history is poorly constrained and the origin of the regionally identified 'main unconformity' [Iasky et al., 2003] is not clear. This unconformity may be the product of a prolonged period of non-deposition [Iasky et al. 2003; Mory et al. 2003] or it may signify a regional uplift event [Mihut & Müller, 1998]. As noted in the results section, both sandstone and shale beneath the main unconformity on the Gascoyne Platform and Merlinleigh Sub-basin exhibit porosity values consistent with overcompaction and exhumation. If the main unconformity was generated by a protracted period of non-deposition, it is likely that no significant overcompaction would occur and porosity-depth values would plot much closer to the typical trends of Giles [1997]. The presence of diagenetic cements in some South Carnarvon Basin successions may also give important insights into the burial history of the area. At Burna-1, conventional cores indicate the Moogooloo Sandstone Formation of the Wooramel Group (Figure 5) is heavily affected by quartz overgrowth cementation, which has led to significant porosity loss [Percival, 1985; Baker & Martin 1996]. Quartz cementation typically begins at 70 – 80°C [Harwood et al. 2013], suggesting that, given a reasonable continental geothermal gradient for the upper crust (30°C km^{-1}) [Allen & Allen, 2013], these rocks have been buried to >2 km. The Moogooloo Formation at Burna-1 occurs between 400 – 480 m, suggesting that these rocks have been uplifted by >1.5 km. Based on observations of overcompaction and the presence of anomalous quartz cementation, we therefore suggest that the Gascoyne Platform and

Merlinleigh Sub-basin originally contained a significantly thicker Permian-Jurassic sequence than presently observed; this sequence was subject to Early Cretaceous uplift and erosion.

5.1.3. Evidence from reworking of palynomorphs

Reworking of Triassic, Permian and older palynomorphs is widely observed offshore in wells in the Exmouth Sub-basin and Exmouth Plateau depocenters, west of the Alpha Arch (Figure 14). This finding is consistent with observations from previous studies [e.g. Exon & Buffler, 1992; Exon et al., 1992], which report similar patterns of reworking in the Barrow Group at Ocean Drilling Program (ODP) well locations on the southern Exmouth Plateau. In contrast, in the Barrow Sub-basin depocenter, which is located east of the Alpha Arch, reworking of Triassic and older palynomorphs is only observed in low abundance and in only isolated locations. The apparent discrepancy between the patterns of reworking of palynomorphs to the east and west of the Alpha Arch therefore suggests that this structural high controlled sediment dispersal by the fluvial systems that fed the Barrow Group delta. The river system to the west of the Alpha Arch, which fed the Barrow Delta in the Exmouth Sub-basin depocenter, is interpreted to have eroded a source area rich in Permian and Triassic sedimentary rocks, from which abundant palynomorphs would have been reworked. Wells within the Exmouth Plateau depocenter show the same signature of pervasive reworking of Jurassic and older palynomorphs, suggesting that the source area for this depocenter was compositionally similar to that of the Exmouth Sub-basin depocenter.

In contrast, the minimal reworking of palynomorphs in Barrow Group deposits in the Barrow Sub-basin depocenter suggests that river systems east of the Alpha Arch were eroding a compositionally different source area, where palynomorph-bearing, Permo-Triassic sedimentary rocks were absent. This is consistent with petrological evidence from Barrow

Group sandstones in the Barrow Sub-basin, which suggests their source area was dominated by igneous and metamorphic rocks [De Boer & Collins, 1988; Martin, 2002]. We therefore suggest that sediments of the Barrow Group were eroded from different sources and that pre-existing structural highs controlled sediment dispersal.

5.1.4 Evidence from onshore structure and stratigraphy

Having established that the likely source area for the Barrow Group in the Exmouth and Barrow Sub-basins lay to the south or southeast, we can now refine this model by considering the distribution and composition of onshore strata broadly age-equivalent to the Barrow Group. The distribution of the Wogatti Sandstone and the Yarraloola Conglomerate broadly correlate to the inferred location of the western and eastern Barrow Delta fluvial systems respectively (Figure 8). We suggest that these units may, therefore, at least partially represent the stratigraphic record of the original onshore drainage network supplying sediment to the offshore delta complex. Although the provenance of the Wogatti Sandstone is uncertain, its proximity to the Gascoyne Platform and Merlinleigh Sub-basin suggests that the western river system may have been eroding these areas, which we interpret to have uplifted in the Early Cretaceous. The provenance of the Yarraloola Conglomerate is less ambiguous, due to the presence of abundant clasts of Precambrian rock types, including banded iron formations, which suggest that the eastern river system was likely eroding the neighboring Pilbara Craton, Gascoyne Complex and Hamersley, Edmund and Collier basins [Myers, 1990; Thorne & Seymour, 1991]. Comparison of the distribution of the Yarraloola Conglomerate with modern rivers around the Peedamullah Shelf indicates the thickest isopach trends occur sub-parallel to the modern courses of the Ashburton, Robe and Cane rivers (Figure 8). This suggests that the eastern river system feeding the Barrow Sub-basin depocenter may have comprised the ancestral courses of these three rivers (Figure 18) [Thomas 1978; Romine & Durrant 1996].

The evidence presented for two time-equivalent drainage networks eroding compositionally different source areas in the Early Cretaceous suggests a drainage divide separated these eastern and western river systems (Figure 8). Offshore, the delta systems appear to have been separated by the Alpha Arch (Figure 3), and onshore, the division between eastern and western rivers may correspond to the Yanrey Ridge, which represents a structurally high area between the Peedamullah Shelf and Merlinleigh Sub-basin (Figure 8) [Crostella & Iasky, 1997; Crostella et al., 2000]. Due to the absence of pre-Cretaceous strata on the Yanrey Ridge, it is unclear whether this area was elevated during Barrow Group deposition. However, comparison of the palynological ages of post-Barrow Group stratigraphy deposited during a subsequent regional transgression can be used to constrain the evolution of this area. At locations west and east of the Yanrey Ridge (North Giralia-1, Cunaloo-1), the oldest Birdrong Formation preserved lies within the lower *M. australis* dinoflagellate zone [Golden West Hydrocarbons Pty, 1985; Helby et al., 1987; McLoughlin et al. 1995; Ingram, 1996], whereas at Tent Hill-1, located on the Yanrey Ridge, deposition of the Birdrong Formation did not begin until the upper *M. australis* zone (Supplementary Figure 1) [Ingram, 1990]. This indicates progressive younging of Birdrong Sandstone onto the Yanrey Ridge, implying that this structure was elevated during and was not flooded until the late. We thus consider it likely that the Yanrey Ridge formed positive relief during Barrow Group deposition.

5.2. Implications for margin evolution

Having established the likely sediment source areas for the Barrow Delta (Figure 18), we now consider the tectonic significance of the inferred distribution of uplift and subsidence generated during and recorded by, Barrow Group deposition, and their broader implications for the evolution of the Carnarvon Basin in the Early Cretaceous.

5.2.1. Uplift

The onset of Barrow Group deposition in the Tithonian marked a regionally significant change in deposition style, with dominantly low-energy marine claystone and siltstone deposition in the Exmouth and Barrow Sub-basins, and condensed shallow marine deposits on the Exmouth Plateau (Figure 19a), passing into to a major clastic delta complex [Hocking et al., 1987; Hocking, 1992]. The onset of Barrow Group deposition in the Exmouth and Barrow Sub-basins and on the Exmouth Plateau was broadly coeval, suggesting that the observed change in depositional style may reflect a regional tectonic, climatic or eustatic driver. Insights into the timing of this event may be gained by considering evidence from the Exmouth Sub-basin depocenter.

One of the most likely source areas of Barrow Group sediment deposited in the Exmouth Sub-basin was the South Carnarvon Basin, which underwent uplift and erosion in the Early Cretaceous. Using palynological and sedimentological data, we are able to date the onset of uplift (Late Tithonian – Early Berriasian, 146.7 – 144.5 Ma) at a higher resolution than that afforded by previous basin modeling studies, which suggested uplift occurred during a *c.* 30 Ma time window between the Late Jurassic and Early Cretaceous [e.g. Ghori, 1999]. Decompaction of the sedimentary succession at Eskdale-1 yields average sediment accumulation rates of 0.12 and 0.87 m kyr^{-1} for the Eskdale Member and Barrow Group intervals, respectively (Figure 15). Comparison of the average Barrow Group sediment accumulation rate with the compiled values of Sadler [1999] (*c.* 0.5 m kyr^{-1} over timescales of 2 Ma) for typical sediment accumulation rates in deltaic environments suggests very rapid sediment accumulation rates during the late Tithonian and early Berriasian. This increase in sedimentation rate is also coincident with an abrupt increase in the abundance of reworked palynomorphs, particularly of Permian age (Figure 15). This pattern is consistently observed in Barrow Group deposits in the southern Exmouth Sub-basin, where numerous wells describe the presence of a 'Permian reworking unit' (Figure 14). High sedimentation accumulation rates and the onset of abundant palynomorph reworking in the Tithonian may reflect an abrupt increase in sediment supply and erosion rate, which may in turn be the record sea level change (in particular a sea-level fall, which may have driven onshore incision), or a major climate ('wetting' of the climate, which may have led to increased erosion and sediment supply) or tectonic event [Catuneanu, 2006]. Considering these potential controls, we note that global eustatic sea level curves for the Mesozoic [e.g. Haq et al., 1988; Sahagian et al., 1996] do not indicate a significant sea level fall during the late Tithonian or early Berriasian, thus we reject eustacy as the major driver for the inferred increase in erosion and sediment supply. Macphail [2007] suggests that near the Jurassic-Cretaceous transition the palaeoclimate of northwest Australia was warm, humid and stable; this suggests no major changes in climate took place at the onset of Barrow Group deposition, and that climate change does not account for the Early Cretaceous increase in sediment supply. Since eustacy and climate do not appear to be the likely drivers for the Early Cretaceous change in sedimentation pattern, we interpret that high sedimentation accumulation rates and the abrupt increase in reworking of palynomorphs during early Barrow Group deposition instead record hinterland uplift. Late Tithonian and early Berriasian erosion of Permian and Triassic sedimentary rocks from the actively uplifting South Carnarvon Basin may have generated large volumes of palynomorph-bearing sediment that was deposited in the offshore Exmouth Sub-basin to form the Permian reworking unit (Figure 13c).

5.2.2. Subsidence

We now consider the implications of our results for the timing and distribution of subsidence generation during the final stages of continental breakup in the North Carnarvon Basin. As discussed, the isochore map of the Barrow Delta (Figure 11) indicates three major depocenters: the Exmouth and Barrow Sub-basins and on the southwestern Exmouth Plateau. During Jurassic rifting, extension and subsidence was strongly localised in the Exmouth and Barrow Sub-basins, resulting in the accumulation of a thick syn-rift sedimentary succession [Driscoll & Karner, 1998; Tindale et al., 1998]. Across much of the Exmouth Plateau, the time-equivalent Jurassic sedimentary section is extremely thin compared to the Exmouth and Barrow Sub-basins (Figures 4,7, 19a), suggesting this area was relatively tectonically stable and underwent limited subsidence during Jurassic rifting in the North Carnarvon Basin. This interpretation is consistent with backstripping results from Investigator-1 and Sirius-1 (Figure 17), which suggest <200 m of tectonic subsidence during the Jurassic.

At the onset of Barrow Group deposition, a significant increase in the rate of subsidence generation is observed on the Exmouth Plateau. Backstripping results suggest that ~1.2 km subsidence took place over 4.9 Ma at Sirius-1 and 1.3 km over 7.1 Ma at Investigator-1, yielding average subsidence rates of *c.* 0.24 and 0.18 mm yr^{-1}, respectively. Comparison of these subsidence rates with typical values for rifted margins (<0.2 mm yr^{-1} over 10 - 100 Ma; Allen & Allen [2013]) suggests that the southern Exmouth Plateau underwent a period of anomalously rapid tectonic subsidence over a short time period prior to continental breakup.

Accounting for anomalously rapid tectonic subsidence on the Exmouth Plateau is challenging, as there appears to be only low amounts of concurrent upper crustal extension during the Tithonian to Valanginian rift event. For example, seismic data from the Exmouth Plateau show that the Barrow Group is largely unaffected by syn-rift faulting (Figure 7); this observation is consistent with the those of Driscoll & Karner [1998], who state that the final phase of rifting in the North Carnarvon Basin is associated with overall low magnitudes of upper crustal stretching (β<1.18). Due to the lack of concurrent faulting during Barrow Group deposition in the Exmouth Plateau, it is hard to appeal to this as a driving mechanism for the rapid subsidence in this area, and an alternative mechanism to the classic model of depth-independent extension is therefore required.

5.2.3. Tectonic mechanisms

For a tectonic driving mechanism to be a valid explanation for observations from the Barrow Group, it must be able to account for the inferred distribution of both uplift and subsidence in the Early Cretaceous. Firstly, we discuss possible causative mechanisms by which the Gascoyne Platform and Merlinleigh Sub-basin were uplifted in the Early Cretaceous. For each mechanism that can potentially explain our observations, we then consider whether it could explain the generation of subsidence during Barrow Group deposition.

Müller et al. [2002] discuss the driving mechanism for the inferred pre-breakup uplift of the Bernier Ridge, an area immediately adjacent to the Gascoyne Platform (Figure 3). They suggest that uplift of the Bernier Ridge was likely a result of rift flank uplift adjacent to the Cuvier segment of the NW Australian margin. Previous studies suggest that rift flank uplift can result from: (i) depth-dependent extension; (ii) heating of rift flanks by small-scale convection; (iii) flexure resulting from lithospheric strength during rifting; (iv) low-angle lithosphere-scale detachments; (v) asthenospheric partial melting; (vi) long-wavelength dynamic topography; and (vii) lower crustal flow due to sediment loading [Daradich et al. 2003; Morley & Westaway, 2006]. Each of these models can be assessed in terms of its likelihood of explaining the magnitude, pattern and timing of Early Cretaceous uplift observed in the South Carnarvon Basin.

5.2.3.1. Depth-dependent extension

Several authors suggest that depth-dependent extension occurred on the Exmouth Plateau during continental break-up [Stagg & Colwell, 1994; Driscoll & Karner, 1998; Huismans & Beaumont, 2011]. Models based on depth-dependent extension allow for non-uniform generation of regional subsidence, by allowing for variable magnitudes and distributions of extension in the upper and lower crust, or in the crust and underlying mantle lithosphere (Figure 19c) [Allen & Allen, 2013]. In addition, a common feature of models of depth-dependent extension is uplift of rift flanks at the onset of stretching (Figure 19b) [e.g. Royden & Keen, 1980; Rowley & Sahagian, 1986; Allen & Allen, 2013]. Because uplift of the South Carnarvon Basin is inferred to have begun soon after the onset of rifting in the Tithonian, this mechanism may be able to account for the observed pattern of pre-breakup uplift in the North Carnarvon Basin. This model is also consistent with observations from previous studies that have suggested significant bulk crustal thinning across the Exmouth Plateau but with minimal evidence for upper crustal extension, which thus defines the discrepancy between the magnitude of upper and lower crustal extension [e.g. Driscoll & Karner, 1998; Gartrell, 2000]. Based on these observations we suggest that depth-dependent extension, which can explain the overall crustal architecture of the Exmouth Plateau, in addition to the distribution of Early Cretaceous uplift and subsidence, potentially played a key role in the breakup of this part of the Northwest Shelf.

5.2.3.2. Convection and flexure

As noted by Müller et al. [2002], small-scale convection and flexural uplift of the flanks of the Cuvier rift are both considered as viable mechanisms to account for observations of uplift from the Bernier Platform and Carnarvon Terrace areas (Fig. 2). Constraining the relative importance of these two mechanisms is difficult, as it requires an understanding of the thermal structure or rheological profile of the lithosphere during rifting. Braun & Beaumont [1989] discuss the relationship between uplifted rift flanks and the breakup unconformity in the context of lithospheric strength. These factors may provide constraints on the viability of this mechanism in explaining observations from the North Carnarvon Basin, however, detailed discussion of the breakup unconformity is beyond the scope of this study.

5.2.3.3. Large-scale detachments

Large-scale detachment mechanisms have frequently been invoked to explain the structural evolution of the North Carnarvon Basin [e.g. AGSO North West Shelf Study Group, 1994; Etheridge & O'Brien, 1994; Driscoll & Karner, 1998]. Models of this type explain discrepancies between upper and lower crustal extension by means of simple shear deformation along low-angle lithosphere-scale detachments, which relay extension between the crust and the mantle [Wernicke, 1985; Allen & Allen, 2013]. The model of Wernicke [1985] predicts uplift in the region of lower crust and mantle thinning, and concurrent subsidence in the area of upper crustal extension. This is inconsistent with our observations from the southern Exmouth Plateau, which suggest subsidence took place during the Tithonian to Valanginian without significant upper crustal extension [Driscoll & Karner, 1998]. Additionally, as noted by Gartrell [2000], low-angle detachment faults in the North Carnarvon Basin tend to have limited regional extent, and are therefore unlikely to account for the basin-scale distribution of uplift and subsidence in the Early Cretaceous.

5.2.3.4. Asthenospheric partial melting

Rohrman [2015] discusses the potential role of asthenospheric partial melting in generating uplift in the North Carnarvon Basin, and proposes that uplift may have resulted from the effects of a mantle plume centered on the CRFZ in the Late Jurassic and Early Cretaceous. However, Müller et al. [2002] suggest that mantle plume-driven uplift is implausible, based on the lack of evidence for voluminous magmatism observed onshore during the Early Cretaceous, and the absence of a present-day plume whose reconstructed path would track back to this area of the Northwest Shelf. Similarly, the model of Rohrman [2015] does not suggest that the inferred mantle plume extended under the South Carnarvon Basin in the Early Cretaceous, and that the plume location remained largely static between 165 – 136 Ma.

Furthermore, the proposed onset of plume activity in this model is *c.*165 Ma, which precedes the timing of uplift suggested in this study by around 20 Ma, and thus is not a likely causative mechanism for the substantial Early Cretaceous uplift we observe.

5.2.3.5. Dynamic topography

Another possible mechanism for generation of uplift in the Early Cretaceous is dynamic topography (Figure 19c). Dynamic topography represents vertical displacement of the Earth's surface as a result of mantle convection [Braun, 2010]. Typically, Earth motions due to dynamic topography have a maximum amplitude of around a kilometer, over wavelengths of a few hundred to thousands of kilometers, and can change at rates of a few tens of meters per million years [Braun, 2010; Allen & Allen, 2013]. The extent of the uplifted area (*c.* 400 km) observed here is therefore consistent with the shortest wavelengths typical of dynamic topography. However, the uplift of the South Carnarvon Basin during the Tithonian to Valanginian may be inconsistent with uplift rates associated with dynamic topography. For example, a minimum estimate of 1.5 km of uplift during Barrow Group deposition (146.7 – 138.2 Ma) would correspond to uplift rates of *c.* 180 m Ma^{-1}, which may be too rapid to explain by the effects of positive dynamic topography. The subsidence generated during Barrow Group deposition is also potentially of a wavelength consistent with the shortest wavelengths typically associated with dynamic topography (*c.* 300 km) [Braun, 2010]. The rates of tectonic subsidence at Investigator-1 and Sirius-1 during Barrow Group deposition (*c.* 180 and 240 m Myr^{-1} respectively), however, are anomalously fast for negative dynamic topography, which predict a few tens of meters of subsidence per million years.

Although dynamic topography could potentially account for both uplift and subsidence, the estimated rates of both processes may be too great to explain our observations from the Barrow Group. In addition, concurrent uplift of the flanks of the Cuvier rift would require an area of positive dynamic topography immediately adjacent to an area of negative dynamic topography under the southern Exmouth Plateau (Figure 19b). We therefore consider it unlikely that this mechanism can fully account for the Early Cretaceous uplift and subsidence of the North Carnarvon Basin, but this process may have nonetheless played a role.

5.2.3.6. Lower crustal flow

The final possible mechanism for rift flank uplift is lower crustal flow in response to sediment loading. This process is induced by a rapid increase in sediment flux and deposition of a large sediment volume in a basin (Figure 19d) [Morley & Westaway, 2006; Clift et al. 2015]. This model invokes that an increase in sedimentary load, caused by rapid sediment deposition, produces increased pressure at the base of the brittle layer relative to the rift flanks, resulting in the generation of a lateral pressure gradient that drives thinning of the lower crust below the sedimentary basin to maintain isostatic equilibrium. Thinning is achieved by a net flow of lower crust away from the basin, causing an increase in uplift and erosion at the rift flanks. This model is potentially attractive because it requires only low magnitudes of upper crustal extension, and because it generates coupled rift flank uplift and basin subsidence (Figure 19d).

However, our results demonstrate that the inferred uplift of the South Carnarvon Basin began during earliest Barrow Group deposition in the Tithonian, prior to accumulation of substantial thicknesses of Barrow Group deposits. We therefore consider it unlikely that initial rift flank uplift was driven solely by lower crustal flow. Lateral lower crustal pressure gradients generated after a sufficient thickness of Barrow Group sediment was deposited may, however, have played a role in continued rift flank uplift during the Berriasian-Valanginian. However, in the examples of Morley & Westaway [2006] and Clift et al. [2015], extreme sediment thicknesses (>6 km) are required to generate lateral pressure gradients in the lower crust. The observed maximum thickness of Barrow Group deposits in the Exmouth Plateau depocenter (*c.* 1.75 km) may be insufficient to produce a sufficiently large tectonic load to drive lower crustal flow.

The model of Morley & Westaway [2006] also assumes that crustal thicknesses are roughly similar below the depocenter and the adjacent sediment source area. However, previous studies indicate that the total crustal thickness of the Exmouth Plateau is between 15 – 20 km [e.g. Symonds et al. 1998; Stagg et al. 2004], whereas recent seismic and potential field studies indicate the crustal thickness of the South Carnarvon Basin is on the order of 30 – 32 km [Gessner et al. 2013]. This may be incompatible with generating the required lower crustal pressures beneath the Exmouth Plateau relative to the South Carnarvon Basin. We therefore suggest it is unlikely that the observed distribution and timing of Early Cretaceous uplift and subsidence in the North Carnarvon Basin is purely the result of lower crustal flow. However, it is possible that this process may have played a role in addition to the effects of another, more dominant driving mechanism.

6. Conclusions

Using an extensive database of geological and geophysical data, we present a regional-scale study of the Early Cretaceous Barrow Group. Three major depocenters are identified, corresponding to the Exmouth and Barrow Sub-basins and the southern Exmouth Plateau. Our results suggest that the fill of these depocenters records deposition by a number of time-equivalent delta systems with different sediment source areas, driven by a regional scale tectonic forcing prior to continental breakup in the North Carnarvon Basin (Figure 18). We suggest that the onshore South Carnarvon Basin originally contained a significantly thicker Permian – Jurassic sedimentary succession, which underwent substantial uplift and erosion in the Early Cretaceous, and was a major source area for sediments of the offshore Barrow Group. Pre-breakup erosion of the South Carnarvon Basin is attributed to rift flank uplift of the Cuvier segment of the margin during the final stages of continental rifting. The Exmouth Plateau depocenter is interpreted to record a period of anomalously rapid tectonic subsidence prior to breakup. We suggest that classic models of uniform extension cannot account for the interpreted distribution and timing of subsidence and uplift in the North Carnarvon Basin, and this may instead indicate a period of depth-dependent extension or dynamic topography preceding continental breakup. Lower crustal flow in response to sediment loading may also have played a role in generating the interpreted subsidence and uplift, in conjunction with one or more other mechanisms. For models of continental rifting and breakup to be valid in the North Carnarvon Basin, they must account for these observations of pre-breakup uplift and subsidence in the context of the area's overall tectonic history.

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Figure 1 Simplified map of the southern Northwest Shelf, showing topography, bathymetry, major bathymetric elements and main basin sub-divisions (after Longley et al. [2002]). Elevation data is based on the 2009 Australian Bathymetry and Topography grid (Geoscience Australia).

Figure 2 – Map showing coverage of 2D and 3D seismic reflection data used in this study, and locations of wells used to constrain the velocity structure of the Barrow Group for depth

conversion. Locations of seismic lines shown in Figures 4 and 7 are shown by black lines, and the location of Figure 11 is shown by the inset black box.

Figure 3 – Map of the main structural elements of the North and South Carnarvon Basins, and adjacent Precambrian tectonic elements. After Crostella et al. [2000], Longley et al. [2002], Iasky et al. [2003] and Martin et al. [2006]

Figure 4 – (a) Uninterpreted and (b) interpreted WNW-SSE oriented composite seismic section showing main structural elements of the Exmouth Sub-basin and Exmouth Plateau. Black vertical lines indicate locations of wells shown in Figure 11. Seismic data are displayed with reverse polarity, where a downward increase in acoustic impedance is represented by a negative (red) reflection event, and a downward decrease in acoustic impedance is represented by a positive (black) reflection event.

Figure 5 – Generalized stratigraphic column for the Exmouth Plateau, Exmouth Sub-basin, Gascoyne Platform and Merlinleigh Sub-basin, showing dominant lithology and general depositional environment for each unit. Numerical ages in the left-hand column are quoted in Ma. After Hocking et al. [1987], Hocking [1992], Iasky et al. [1998], Tindale et al. [1998], Longley et al. [2002], Iasky et al. [2003] & Mory et al. [2003].

Figure 6 – Detailed stratigraphic column for the Exmouth and Barrow Sub-basins and Exmouth Plateau, showing generalized stratigraphic relationships between Late Jurassic and Early Cretaceous units, in addition to generalized lithology and dinoflagellate zones corresponding to each unit. Generalized facies variation is indicated from proximal (right hand side) to distal environments (left hand side). After Arditto [1993], Ross & Vail [1994], Smith et al. [2002] Scibiorski et al. [2005] and Kelman et al. [2013].

Figure 7 – (a) Uninterpreted and (b) interpreted seismic section, showing the internal architecture of the Barrow Group depocenter on the Exmouth Plateau. Numbered bold

horizon interpretations in (b) correspond to major dinoflagellate zone boundaries, which are interpreted based on ties to dinoflagellate zones reported in the Investigator-1 and Sirius-1 wells. Dashed lines in (b) indicate clinoform interpretations within the Barrow Group

Figure 8 – Map showing the distribution of the very thin onshore correlatives to the Barrow Group, in addition to the location of modern rivers and water bodies. After Thomas [1978], Hocking et al. [1988], Boote & Kirk [1989], Iasky et al. [1998] and Crostella et al. [2000].

Figure 9 – Schematic illustrations of proposed source area models for the Barrow Group. (a) Uplift of the Cape Range Fracture Zone [Exon & Buffler, 1992]. (b) Uplift adjacent to Cuvier Abyssal Plain spreading center [Veevers & Powell, 1979]. (c) Uplift of the Gascoyne Terrane [Exon & Buffler, 1992; Ross & Vail, 1994; Rohrman, 2015]. (d) Uplift of flanks of the Cuvier rift [Ross & Vail, 1994]. (e) Uplift of the South Carnarvon Basin (A) and Pilbara Craton (B) [Hocking, 1988; Boote & Kirke, 1989; Exon & Buffler, 1992]. (f) Uplift of the Perth Basin [Longley et al. 2002]. Black arrows indicate schematic sediment transport directions for each model. The tectonic configuration in (a) indicates the inferred location of the Gascoyne Terrane and Wallaby and Zenith Plateaus prior to continental breakup (after Gibbons et al. [2012]). The grey dashed line in (c) indicates the inferred limit of the mantle plume head model proposed by Rorhman [2015]. Note that all schematic models show the Berriasian – Valanginian configuration of the North Carnarvon Basin, with exception of (b), which shows the basin configuration after the onset of seafloor spreading in the Cuvier Abyssal Plain in the Valanginian.

Figure 10 – Vertical thickness map of the Barrow Group, based on seismic interpretation. White arrows indicate estimated clinoform progradation directions. Locations A, B & C relate to Barrow Group depocenters on the Exmouth Plateau and in the Exmouth and Barrow Sub-basins respectively. Location D relates to the Alpha Arch structural high. The dashed

black line indicates the approximate location of the break point of the last clinoform of the Barrow Group at maximum regression. Solid black lines indicate the location of Figures 12 and 13. White circles indicate well locations.

Figure 11 – (a) Porosity depth relationship for a normally compacted sandstone unit with top depth z1 and base depth z2, and corresponding normal compaction trend (compaction curve 1). (b) Porosity-depth relationship for the sandstone unit following exhumation to a top depth z1' and base depth z2' . (c) Porosity-depth relationship for the sandstone unit following post-exhumation reburial to a top depth z1'' and base depth z2''. Squares represent porosity-depth values for normally compacted upper sandstone unit in (c).

Figure 12 – Well correlation panel showing gamma ray logs and generalized lithology from key wells in the Exmouth Sub-basin and Exmouth Plateau depocenters. Age correlation (black lines) is based on dinoflagellate zones, and inferred facies divisions within the Barrow Group are based on well completion reports and gamma ray logs. Wells are displayed using the Base Barrow Group unconformity as a datum. Well locations are shown in Figure 11.

Figure 13 – Along-strike E-W oriented well correlation panel showing variations in Barrow Group thickness in the Exmouth and Barrow Sub-basins, and on the Alpha Arch. Internal facies correlation is based on well completion reports and gamma ray logs. Age correlation (black lines) is based on dinoflagellate zones. Wells are displayed using base Muderong Shale as a datum. Note at Altair-1, the base of the Barrow Group is not intersected, and the estimated total thickness of this unit is based on the Barrow Group thickness map shown in Figure 10.

Figure 14 – Map showing locations of wells where reworking of palynomorphs of (a) Jurassic, (b) Triassic, (c) Permian and (d) Carboniferous or older age is recorded. Hollow symbols show well locations where no reworking of the given age is recorded

Figure 15 - Type section of the Barrow Group 'Permian Reworking Unit' encountered at Eskdale-1 in the Exmouth Sub-basin (location in Figure 14). Blue and purple crosses indicate sample depths where the presence of Jurassic and Triassic age palynomorphs respectively was recorded. Orange bars indicate the percentage of the total palynomorph count represented at each sample depth by reworked Permian age palynomorphs. The greater abundance of reworking towards the base of the Barrow Group at Eskdale-1 may occur due to fluvial erosion of sediments in delta top environments, resulting in basinward reworking of previously deposited palynomorphs into the delta front and prodelta.

Figure 16 – Porosity-depth measurements for (a) sandstones and (b) shales from the Merlinleigh Sub-Basin and Gascoyne Platform. Filled symbols indicate sidewall core porosity measurements and hollow symbols indicate wireline-derived porosity values. Grey envelope and black lines indicate compiled porosity-depth trends from Giles [1997]. (c) Map showing location of wells shown in (a) and (b).

Figure 17 – (a) Graph illustrating calculated water-loaded tectonic subsidence at the Exmouth Plateau wells Sirius-1 and Investigator-1, based on results of 1D isostatic backstripping. Black bars indicate estimated absolute water depth through time for the Investigator-1 well. The abrupt decrease in water depth at *c.* 140 Ma is a result of progradation of the clinoform front, and transition from prodelta to delta top environments at this time. (b) Graph illustrating calculated decompacted sediment accumulation rates for the Investigator-1 well for each of the backstripped time intervals shown in (a). Note that the horizontal axis is shared in graphs (a) and (b).

Figure 18 – Summary model of Barrow Group deposition, showing Barrow Group distribution, uplifted source areas and inferred Early Cretaceous river systems. (1) North-flowing river system eroding the South Carnarvon Basin and feeding the Exmouth Sub-basin

depocenter. (2) Northwest-flowing river system eroding the South Carnarvon Basin and feeding the Exmouth Plateau depocenter. (3) Northeast-flowing river system eroding the Gascoyne Terrane and feeding the Exmouth Plateau depocenter. (4) Northwest-flowing river system eroding the Pilbara Craton and Hamersley, Edmund and Collier Basins feeding the Barrow Sub-basin depocenter.

Figure 19 – Schematic cross-sections illustrating possible mechanisms for generation of uplift and subsidence during Barrow Group deposition. Line of section is approximately NW-SE. (a) Late Jurassic configuration prior to Barrow Group deposition. A thin, shallow marine Jurassic sequence (1) overlies horst and graben type geometries of the Exmouth Plateau (2). (b) Model illustrating the effect of depth-dependent extension during Barrow Group deposition. Depth-dependent extension during the Early Cretaceous causes lower crustal thinning below the Exmouth Plateau ((3) and (4)), generating subsidence of the depocenter (5) and uplift of the adjacent rift flanks (6). (c) Model illustrating the effect of dynamic topography during Barrow Group deposition. Dynamic downwelling below the Exmouth Plateau generates subsidence (7) and dynamic upwelling below the South Carnarvon Basin produces uplift and erosion (8). (d) Model illustrating the effect of lower crustal flow during Barrow Group deposition. Loading by Barrow Group sediments (9) increases lower crustal pressures and deflects the Moho downwards (10). Lower crustal thinning (11) is accomplished by outward flow (12), generating uplift and erosion of the rift flanks and subsidence in the basin center.

Table 1 – Table showing a summary of main previously published models for the source area of the Barrow Group. A key reference for each model is included, in addition to the main evidence previously published by these authors to support the proposed source area model.

Figure 1. Figure

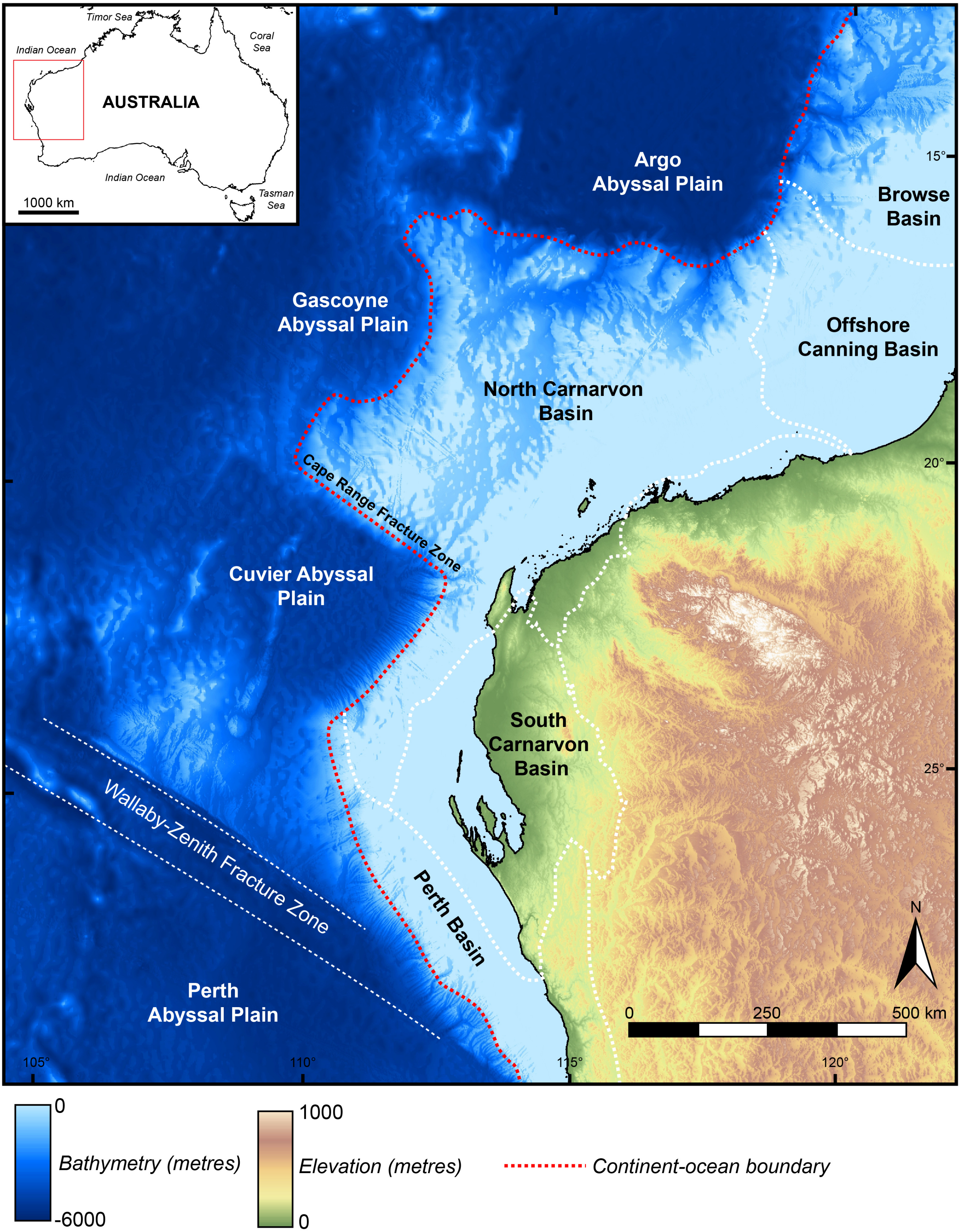
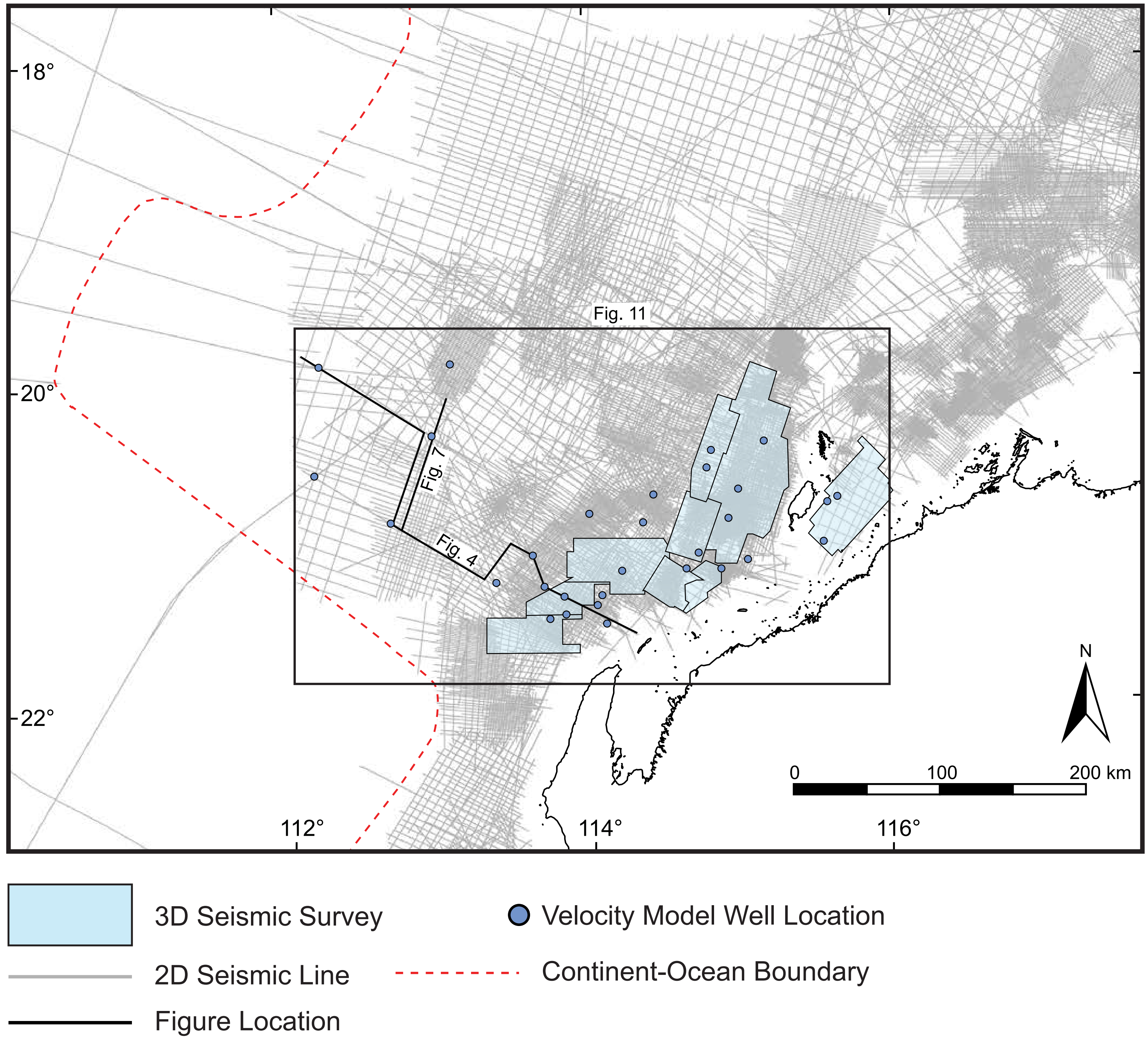

Timor Sea
Coral Sea
Indian Ocean
AUSTRALIA
Indian Ocean
Tasman Sea
1000 km
Argo Abyssal Plain
Browse Basin
Gascoyne Abyssal Plain
Offshore Canning Basin
North Carnarvon Basin
Cape Range Fracture Zone
Cuvier Abyssal Plain
South Carnarvon Basin
Wallaby-Zenith Fracture Zone
Perth Basin
Perth Abyssal Plain
15°
20°
25°
105°
110°
115°
120°
N
0
250
500 km
0
Bathymetry (metres)
-6000
1000
Elevation (metres)
0
Continent-ocean boundary

Figure 2. Figure



18°
20°
22°
112°
114°
116°
Fig. 11
Fig. 7
Fig. 4
N
0
100
200 km
3D Seismic Survey
2D Seismic Line
Figure Location
Velocity Model Well Location
Continent-Ocean Boundary

Figure 3. Figure

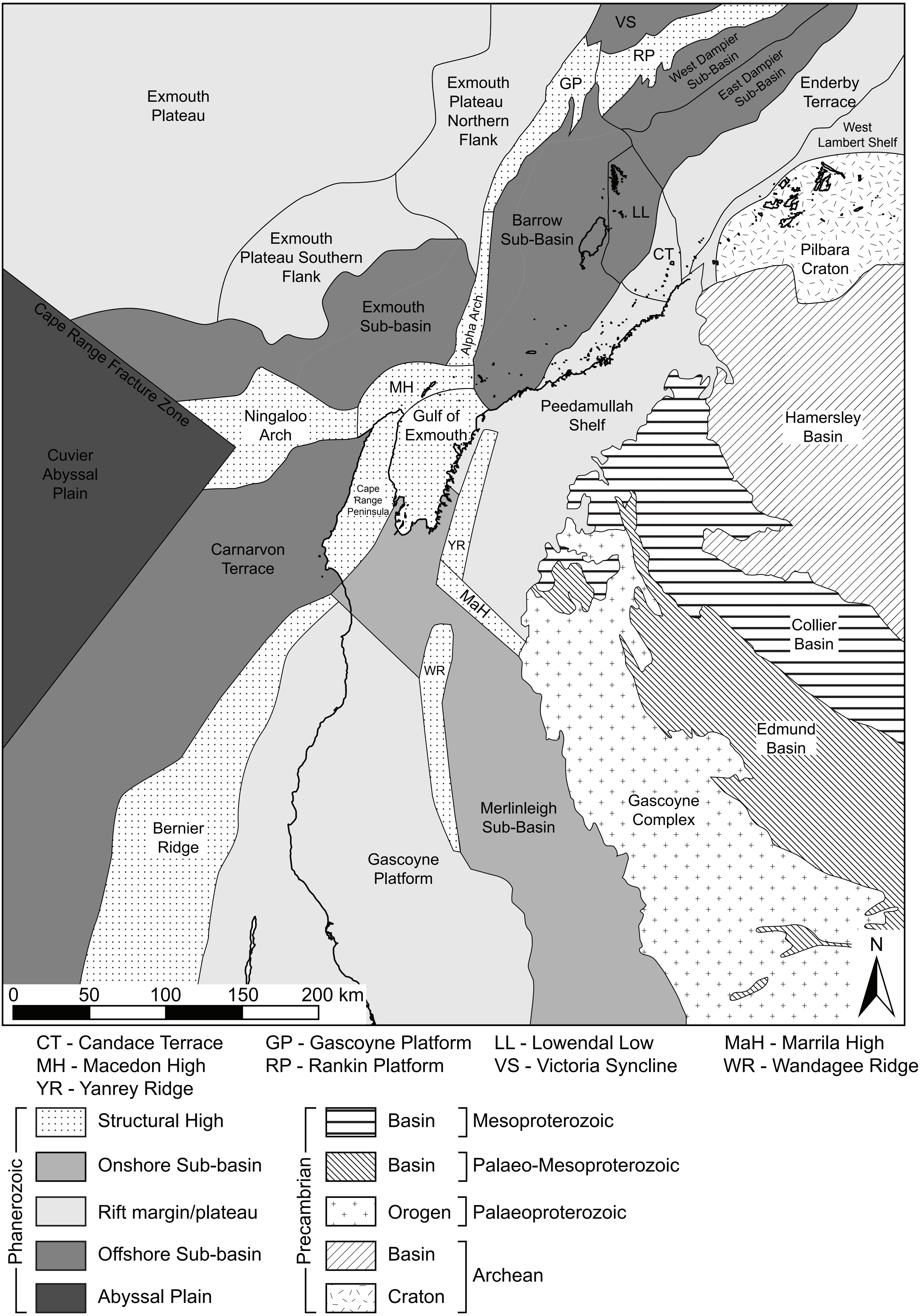

VS
RP
GP
West Dampier Sub-Basin
East Dampier Sub-Basin
Enderby Terrace
West Lambert Shelf
Exmouth Plateau
Exmouth Plateau Northern Flank
Exmouth Plateau Southern Flank
Barrow Sub-Basin
LL
CT
Pilbara Craton
Exmouth Sub-basin
Alpha Arch
Cape Range Fracture Zone
MH
Ningaloo Arch
Gulf of Exmouth
Peedamullah Shelf
Hamersley Basin
Cuvier Abyssal Plain
Cape Range Peninsula
Carnarvon Terrace
YR
MaH
Collier Basin
WR
Edmund Basin
Gascoyne Complex
Merlinleigh Sub-Basin
Bernier Ridge
Gascoyne Platform
N
0
50
100
150
200 km
CT - Candace Terrace
MH - Macedon High
YR - Yanrey Ridge
GP - Gascoyne Platform
RP - Rankin Platform
LL - Lowendal Low
VS - Victoria Syncline
MaH - Marrila High
WR - Wandagee Ridge
Phanerozoic
Structural High
Onshore Sub-basin
Rift margin/plateau
Offshore Sub-basin
Abyssal Plain
Precambrian
Basin
Mesoproterozoic
Basin
Palaeo-Mesoproterozoic
Orogen
Palaeoproterozoic
Basin
Craton
Archean

Figure 4. Figure

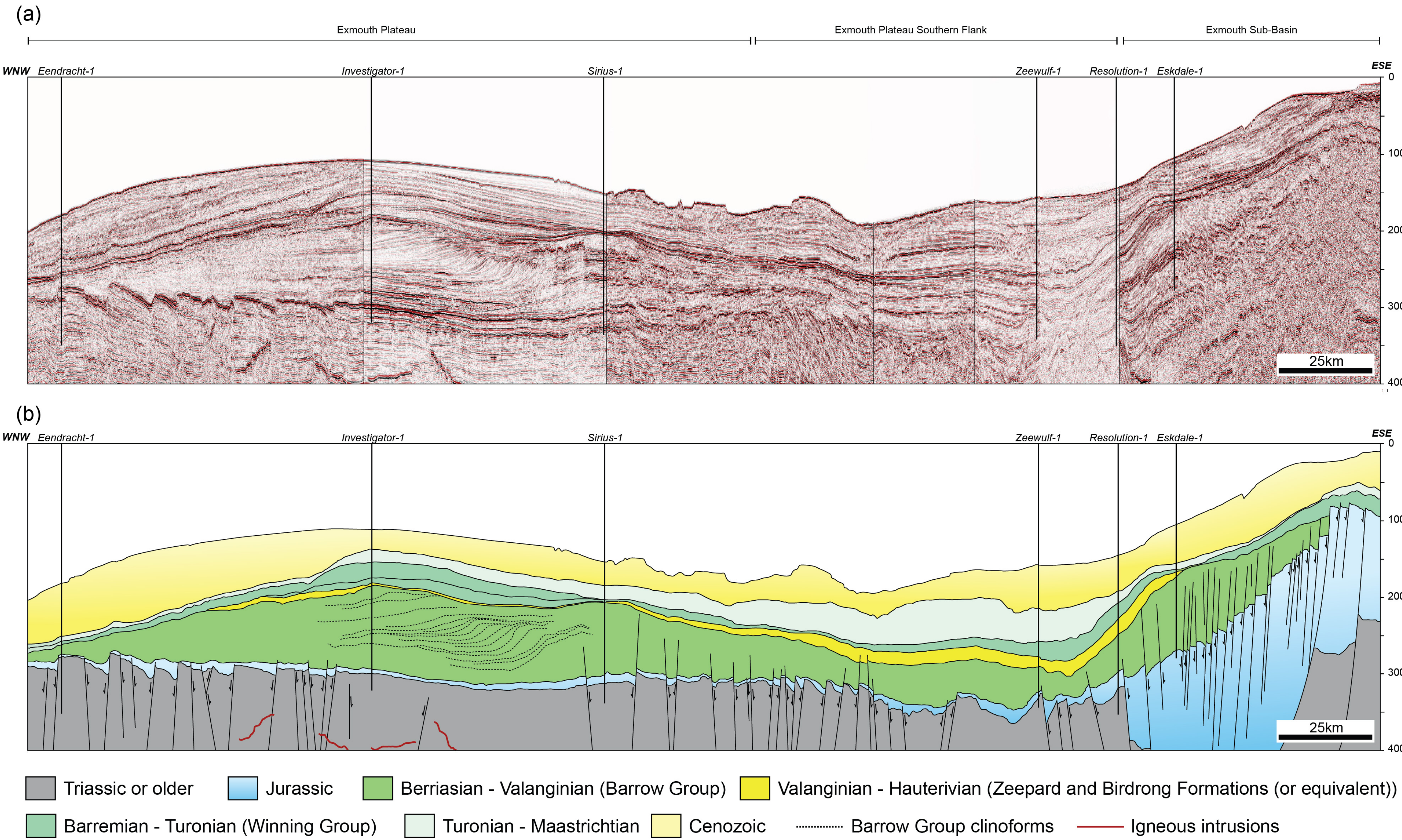
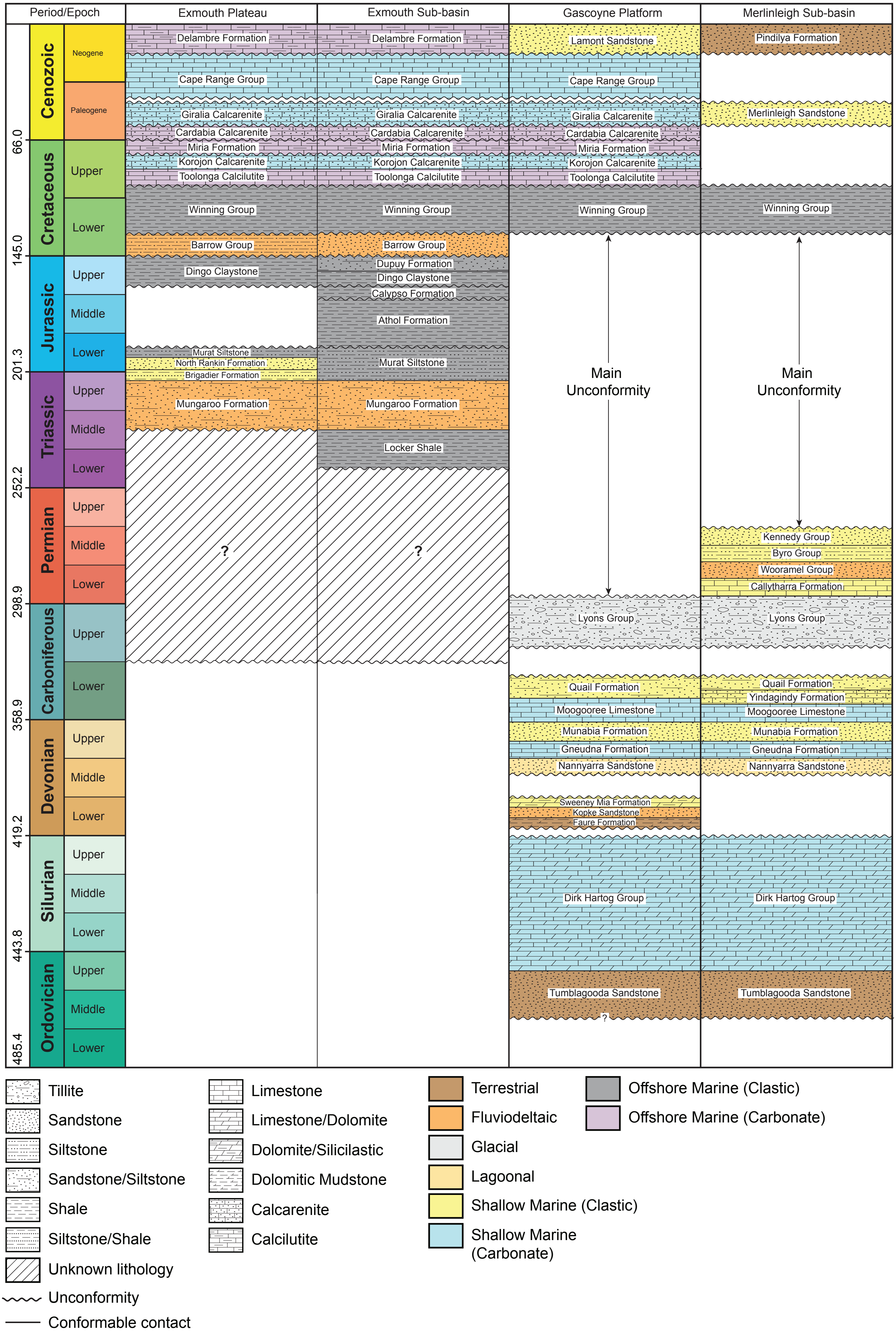
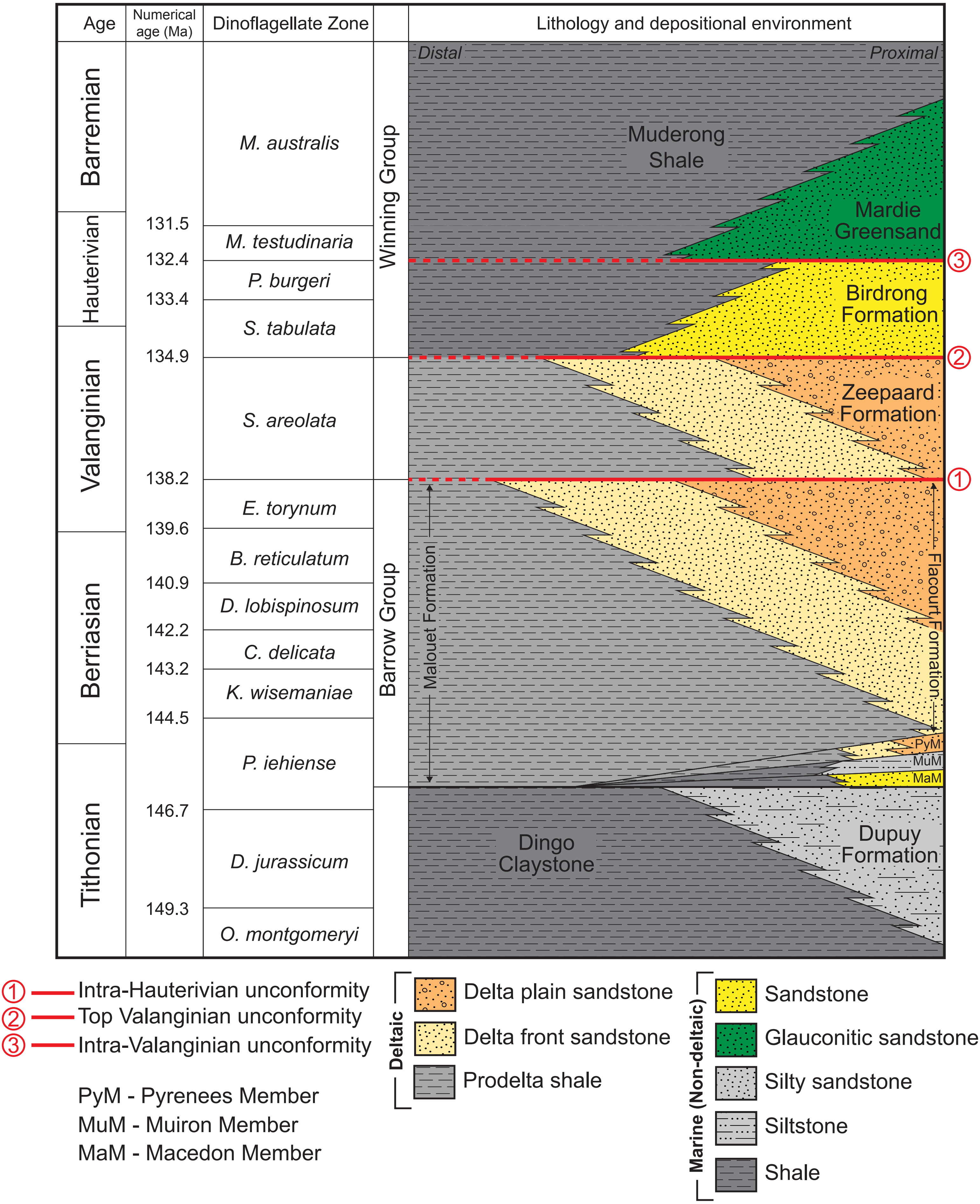

(a)
Exmouth Plateau
Exmouth Plateau Southern Flank
Exmouth Sub-Basin
WNW
Eendracht-1
Investigator-1
Sirius-1
Zeewulf-1
Resolution-1
Eskdale-1
ESE
25km
0
1000
2000
3000
4000
Two-way time (ms)
(b)
WNW
Eendracht-1
Investigator-1
Sirius-1
Zeewulf-1
Resolution-1
Eskdale-1
ESE
25km
0
1000
2000
3000
4000
Two-way time (ms)
Triassic or older
Jurassic
Berriasian - Valanginian (Barrow Group)
Valanginian - Hauterivian (Zeepard and Birdrong Formations (or equivalent))
Barremian - Turonian (Winning Group)
Turonian - Maastrichtian
Cenozoic
Barrow Group clinoforms
Igneous intrusions

Figure 5. Figure



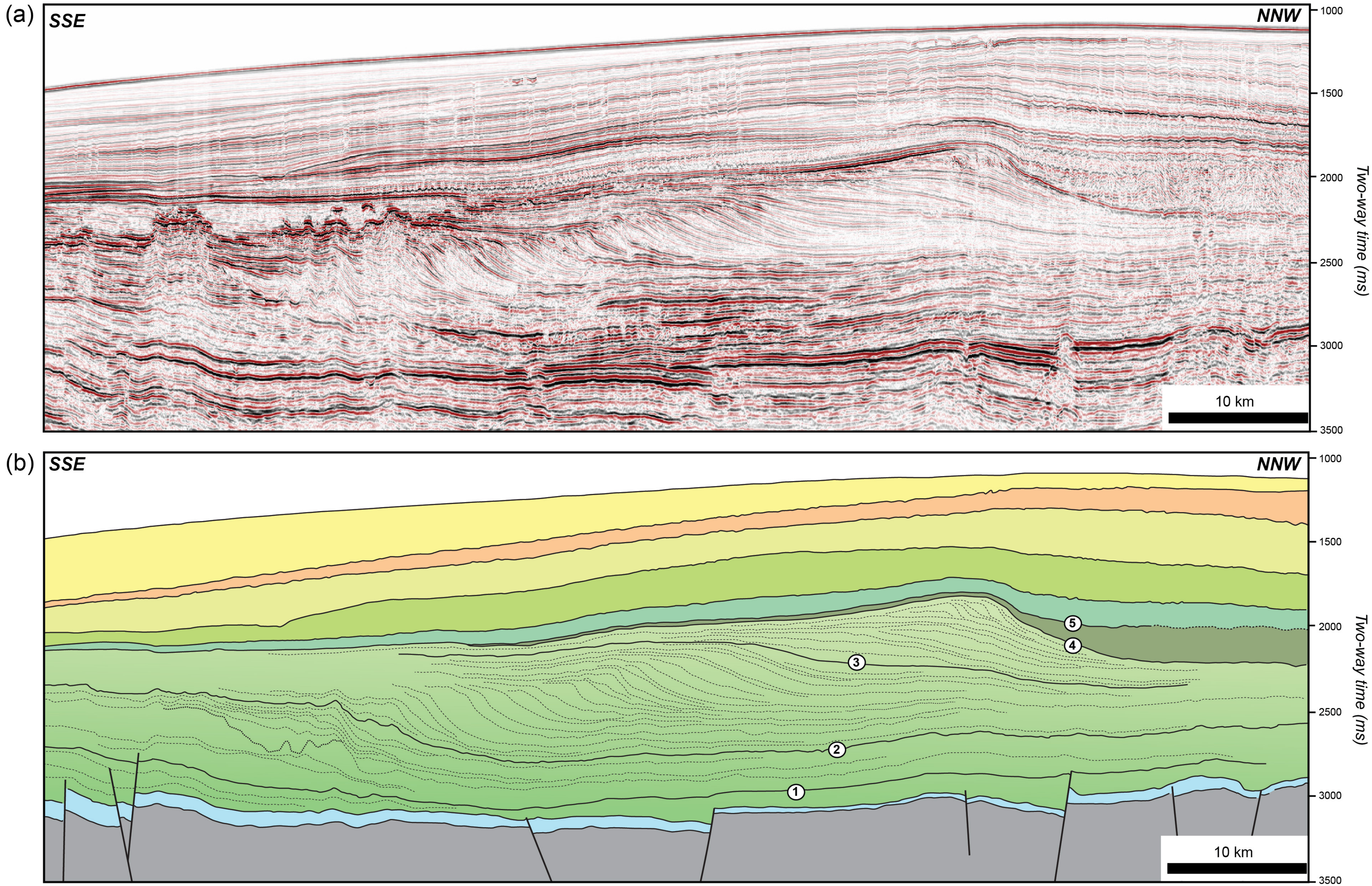
Period/Epoch
Exmouth Plateau
Exmouth Sub-basin
Gascoyne Platform
Merlinleigh Sub-basin
Cenozoic
Neogene
Paleogene
Cretaceous
Upper
Lower
Jurassic
Upper
Middle
Lower
Triassic
Upper
Middle
Lower
Permian
Upper
Middle
Lower
Carboniferous
Upper
Lower
Devonian
Upper
Middle
Lower
Silurian
Upper
Middle
Lower
Ordovician
Upper
Middle
Lower
66.0
145.0
201.3
252.2
298.9
358.9
419.2
443.8
485.4
Delambre Formation
Cape Range Group
Giralia Calcarenite
Cardabia Calcarenite
Miria Formation
Korojon Calcarenite
Toolonga Calcilutite
Winning Group
Barrow Group
Dingo Claystone
Murat Siltstone
North Rankin Formation
Brigadier Formation
Mungaroo Formation
?
Delambre Formation
Cape Range Group
Giralia Calcarenite
Cardabia Calcarenite
Miria Formation
Korojon Calcarenite
Toolonga Calcilutite
Winning Group
Barrow Group
Dupuy Formation
Dingo Claystone
Calypso Formation
Athol Formation
Murat Siltstone
Mungaroo Formation
Locker Shale
?
Lamont Sandstone
Cape Range Group
Giralia Calcarenite
Cardabia Calcarenite
Miria Formation
Korojon Calcarenite
Toolonga Calcilutite
Winning Group
Main Unconformity
Lyons Group
Quail Formation
Moogooree Limestone
Munabia Formation
Gneudna Formation
Nannyarra Sandstone
Sweeney Mia Formation
Kopke Sandstone
Faure Formation
Dirk Hartog Group
Tumblagooda Sandstone
?
Pindilya Formation
Merlinleigh Sandstone
Winning Group
Main Unconformity
Kennedy Group
Byro Group
Wooramel Group
Callytharra Formation
Lyons Group
Quail Formation
Yindagindy Formation
Moogooree Limestone
Munabia Formation
Gneudna Formation
Nannyarra Sandstone
Dirk Hartog Group
Tumblagooda Sandstone
Tillite
Sandstone
Siltstone
Sandstone/Siltstone
Shale
Siltstone/Shale
Unknown lithology
Unconformity
Conformable contact
Limestone
Limestone/Dolomite
Dolomite/Silicilastic
Dolomitic Mudstone
Calcarenite
Calcilutite
Terrestrial
Fluviodeltaic
Glacial
Lagoonal
Shallow Marine (Clastic)
Shallow Marine (Carbonate)
Offshore Marine (Clastic)
Offshore Marine (Carbonate)

Figure 6. Figure



Age
Numerical age (Ma)
Dinoflagellate Zone
Lithology and depositional environment
Distal
Proximal
Barremian
Hauterivian
Valanginian
Berriasian
Tithonian
131.5
132.4
133.4
134.9
138.2
139.6
140.9
142.2
143.2
144.5
146.7
149.3
M. australis
M. testudinaria
P. burgeri
S. tabulata
S. areolata
E. torynum
B. reticulatum
D. lobispinosum
C. delicata
K. wisemaniae
P. iehiense
D. jurassicum
O. montgomeryi
Winning Group
Barrow Group
Malouet Formation
Flacourt Formation
Muderong Shale
Mardie Greensand
Birdrong Formation
Zeepaard Formation
PyM
MuM
MaM
Dingo Claystone
Dupuy Formation
1 Intra-Hauterivian unconformity
2 Top Valanginian unconformity
3 Intra-Valanginian unconformity
PyM - Pyrenees Member
MuM - Muiron Member
MaM - Macedon Member
Deltaic
Delta plain sandstone
Delta front sandstone
Prodelta shale
Marine (Non-deltaic)
Sandstone
Glauconitic sandstone
Silty sandstone
Siltstone
Shale

Figure 7. Figure



Triassic | Jurassic | Berriasian - Valanginian (Barrow Group) | Valanginian - Hauterivian (Zeepard/Birdrong Formation Equivalent)

Barremian - Aptian (Muderong Shale) | Albian - Cenomanian | Turonian - Maastrichtian | Palaeocene - Oligocene | Miocene - Recent

1 Early Berrisian (c. 143.2 Ma) (top *K. wisemaniae*) 2 Middle Berriasian (c. 142.2 Ma) (top *C. delicata*) 3 Late Berriasian (c. 140.9 Ma) (top *D. lobispinosum*)

4 Intra-Valanginian unconformity (c. 138.2 Ma) (top *E. torynuym*) 5 Intra-Hauterivian unconformity (c. 132.4 Ma) (top *P. burgeri*)

Figure 8. Figure

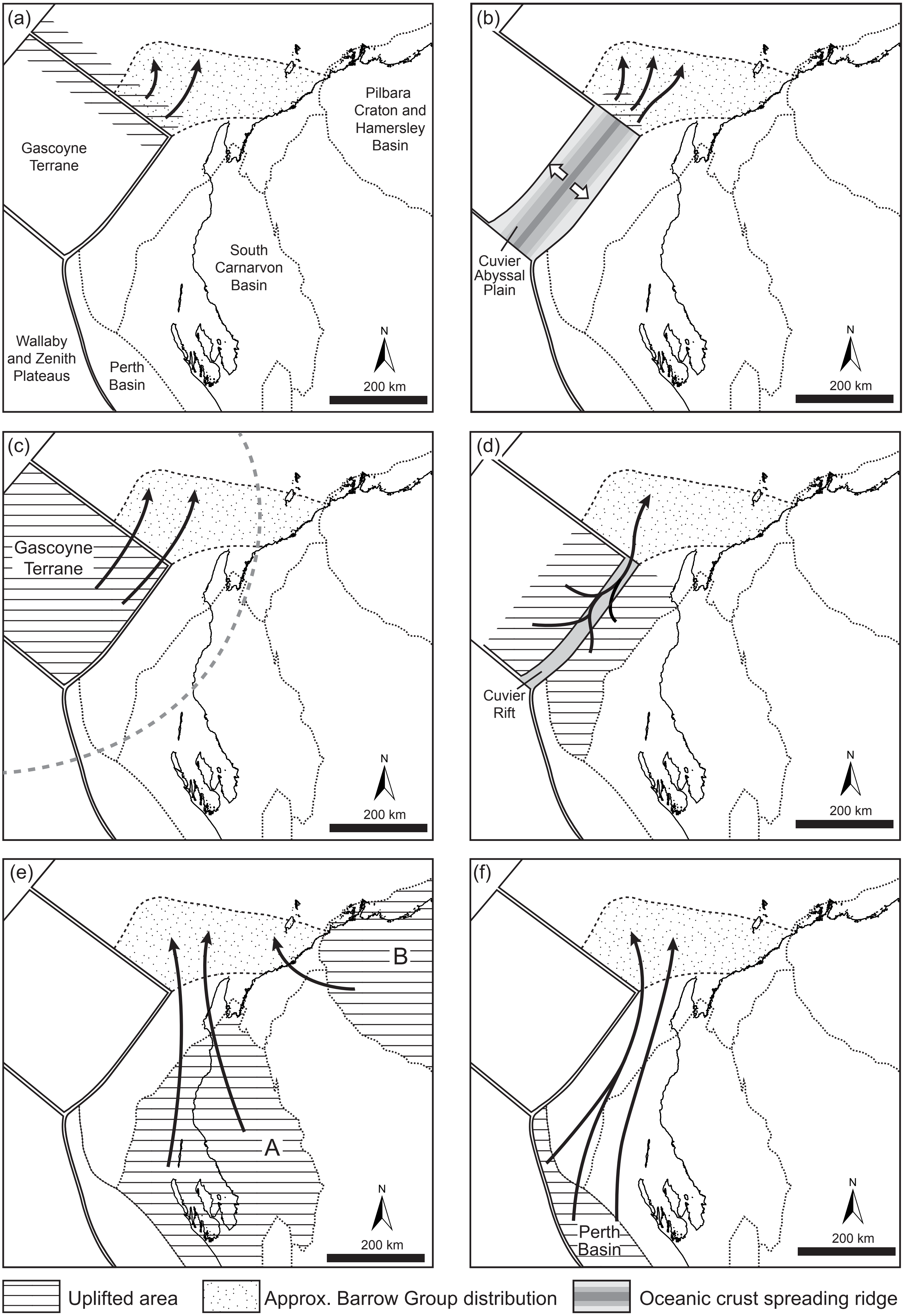
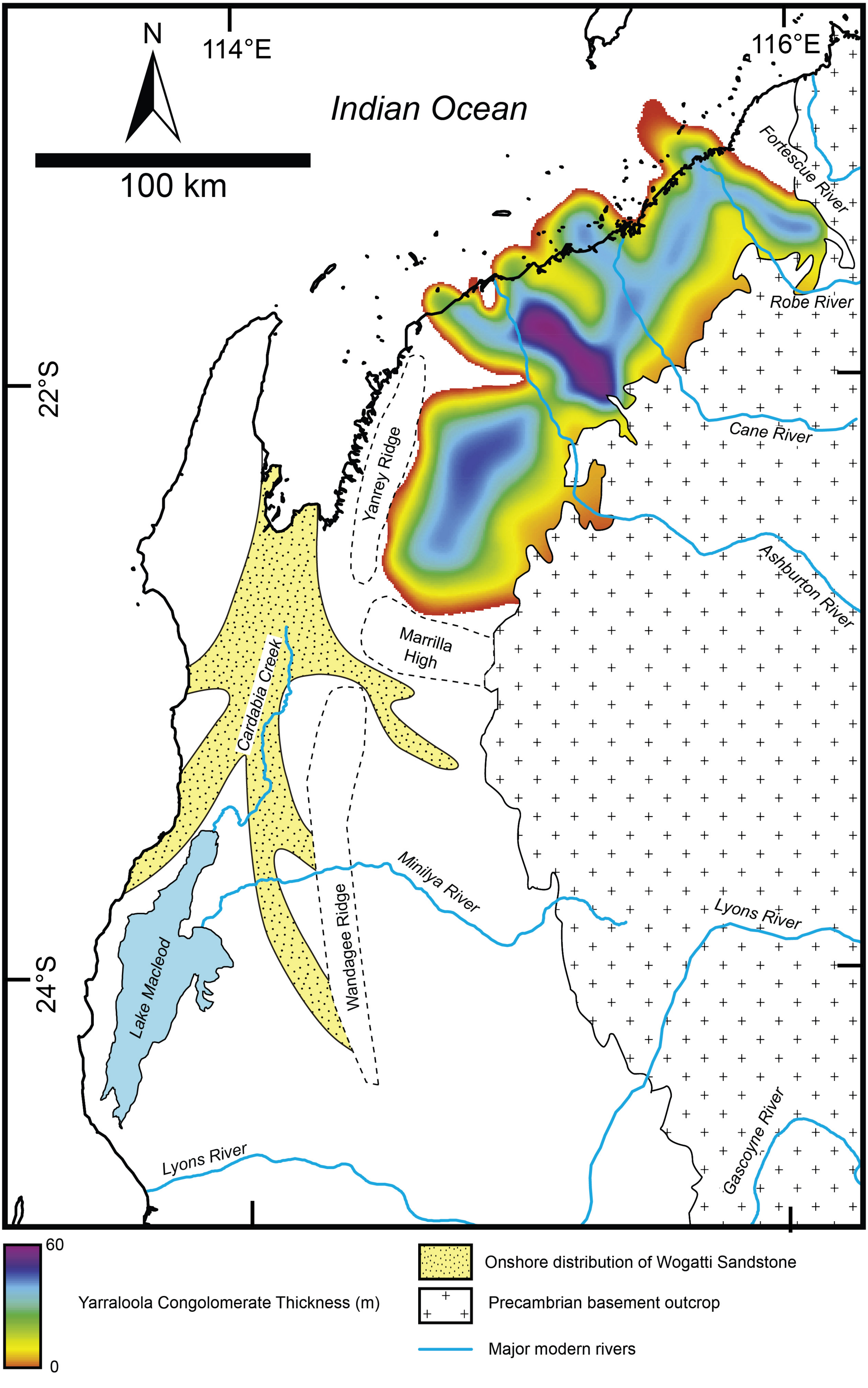
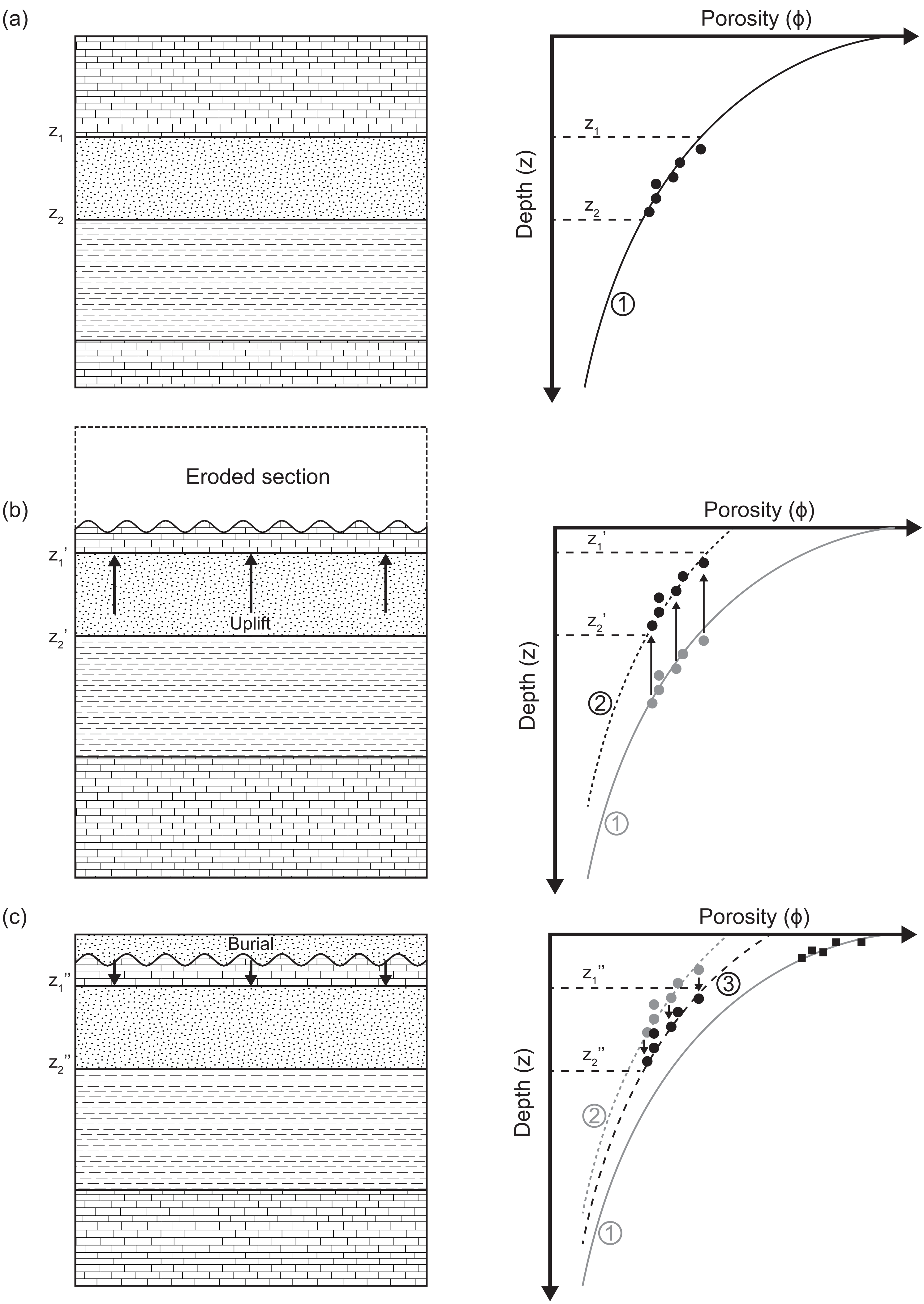

(a)
Pilbara Craton and Hamersley Basin
Gascoyne Terrane
South Carnarvon Basin
Wallaby and Zenith Plateaus
Perth Basin
N
200 km
(b)
Cuvier Abyssal Plain
N
200 km
(c)
Gascoyne Terrane
N
200 km
(d)
Cuvier Rift
N
200 km
(e)
B
A
N
200 km
(f)
Perth Basin
N
200 km
Uplifted area
Approx. Barrow Group distribution
Oceanic crust spreading ridge

Figure 9. Figure



N
114°E
116°E
100 km
Indian Ocean
22°S
24°S
Fortescue River
Robe River
Cane River
Ashburton River
Yanrey Ridge
Marrilla High
Cardabia Creek
Wandagee Ridge
Minilya River
Lyons River
Lake Macleod
Lyons River
Gascoyne River
60
0
Yarraloola Congolomerate Thickness (m)
Onshore distribution of Wogatti Sandstone
Precambrian basement outcrop
Major modern rivers

Figure 10. Figure



(a)
z_1
z_2
Porosity (ϕ)
Depth (z)
z_1
z_2
1
(b)
Eroded section
z_1'
z_2'
Uplift
Porosity (ϕ)
Depth (z)
z_1'
z_2'
2
1
(c)
Burial
z_1''
z_2''
Porosity (ϕ)
Depth (z)
z_1''
z_2''
3
2
1

Figure 11. Figure

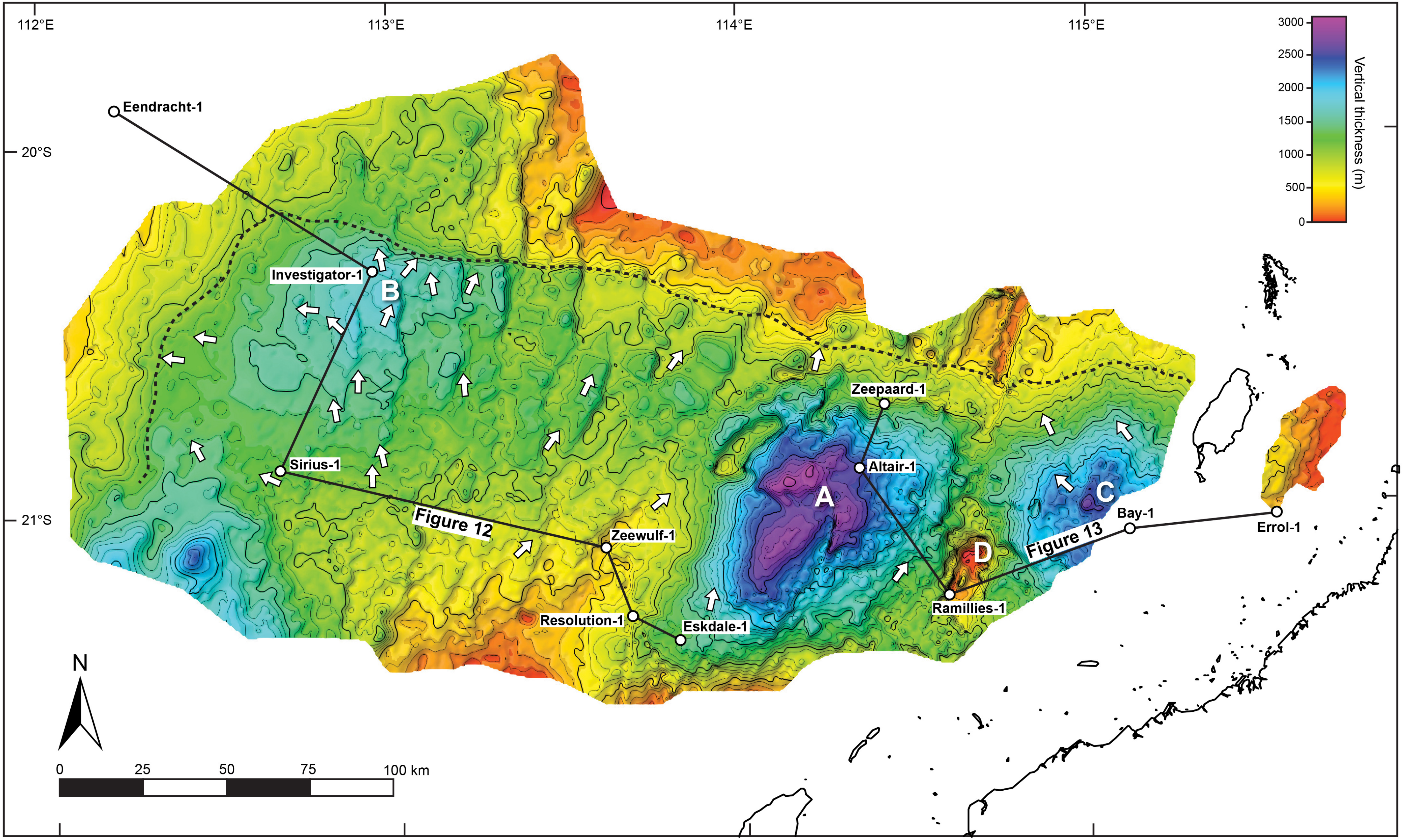
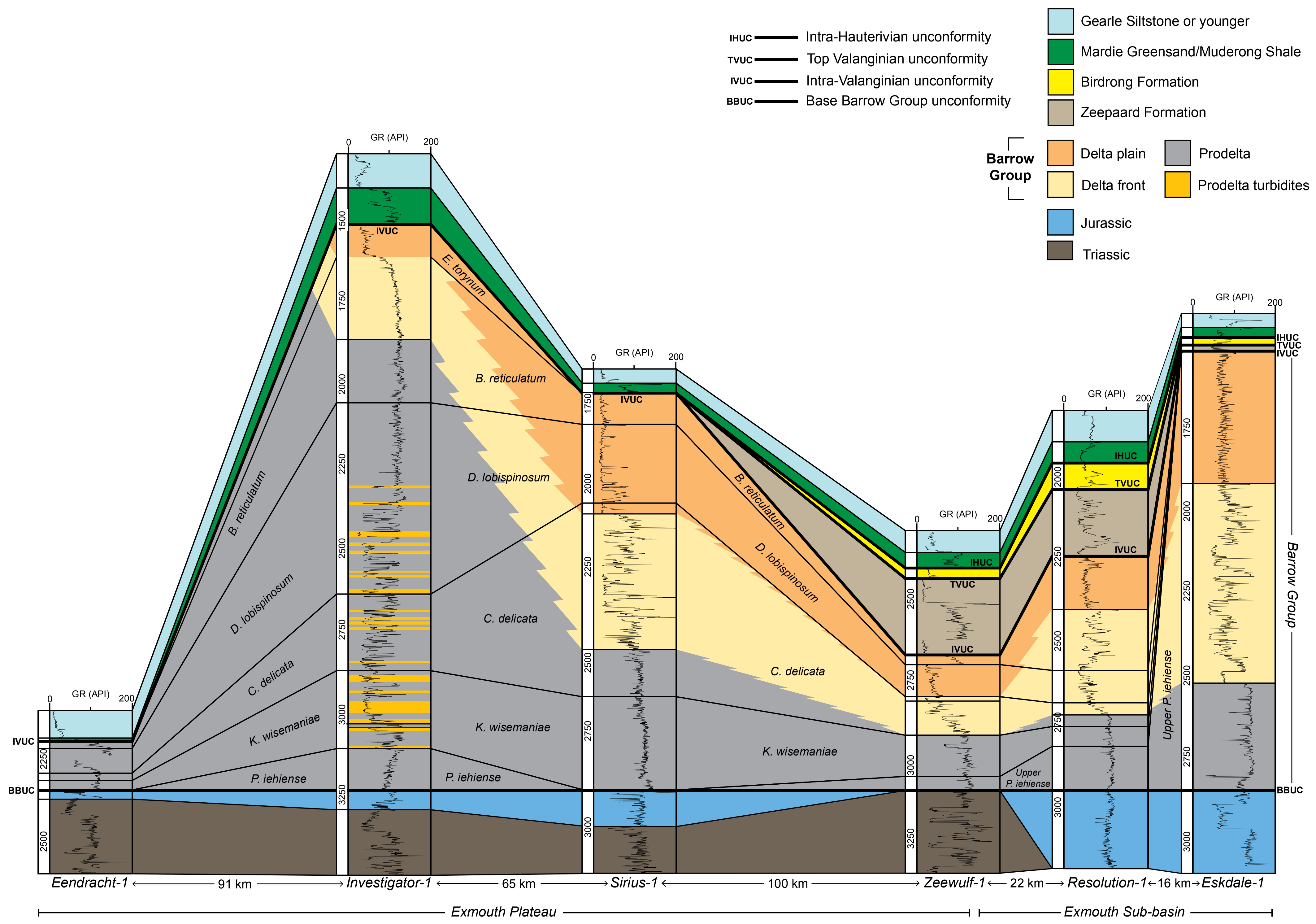

112°E
113°E
114°E
115°E
20°S
21°S
Vertical thickness (m)
0
500
1000
1500
2000
2500
3000
Eendracht-1
Investigator-1
Sirius-1
Zeewulf-1
Resolution-1
Eskdale-1
Zeepaard-1
Altair-1
Ramillies-1
Bay-1
Errol-1
Figure 12
Figure 13
A
B
C
D
N
0
25
50
75
100 km

Figure 12. Figure



IHUC Intra-Hauterivian unconformity
TVUC Top Valanginian unconformity
IVUC Intra-Valanginian unconformity
BBUC Base Barrow Group unconformity
Gearle Siltstone or younger
Mardie Greensand/Muderong Shale
Birdrong Formation
Zeepaard Formation
Barrow Group
Delta plain
Prodelta
Delta front
Prodelta turbidites
Jurassic
Triassic
GR (API)
B. reticulatum
D. lobispinosum
C. delicata
K. wisemaniae
P. iehiense
E. torynum
Upper P. iehiense
Eendracht-1 ← 91 km → Investigator-1 ← 65 km → Sirius-1 ← 100 km → Zeewulf-1 ← 22 km → Resolution-1 ← 16 km → Eskdale-1
Exmouth Plateau
Exmouth Sub-basin
Barrow Group

Figure 13. Figure

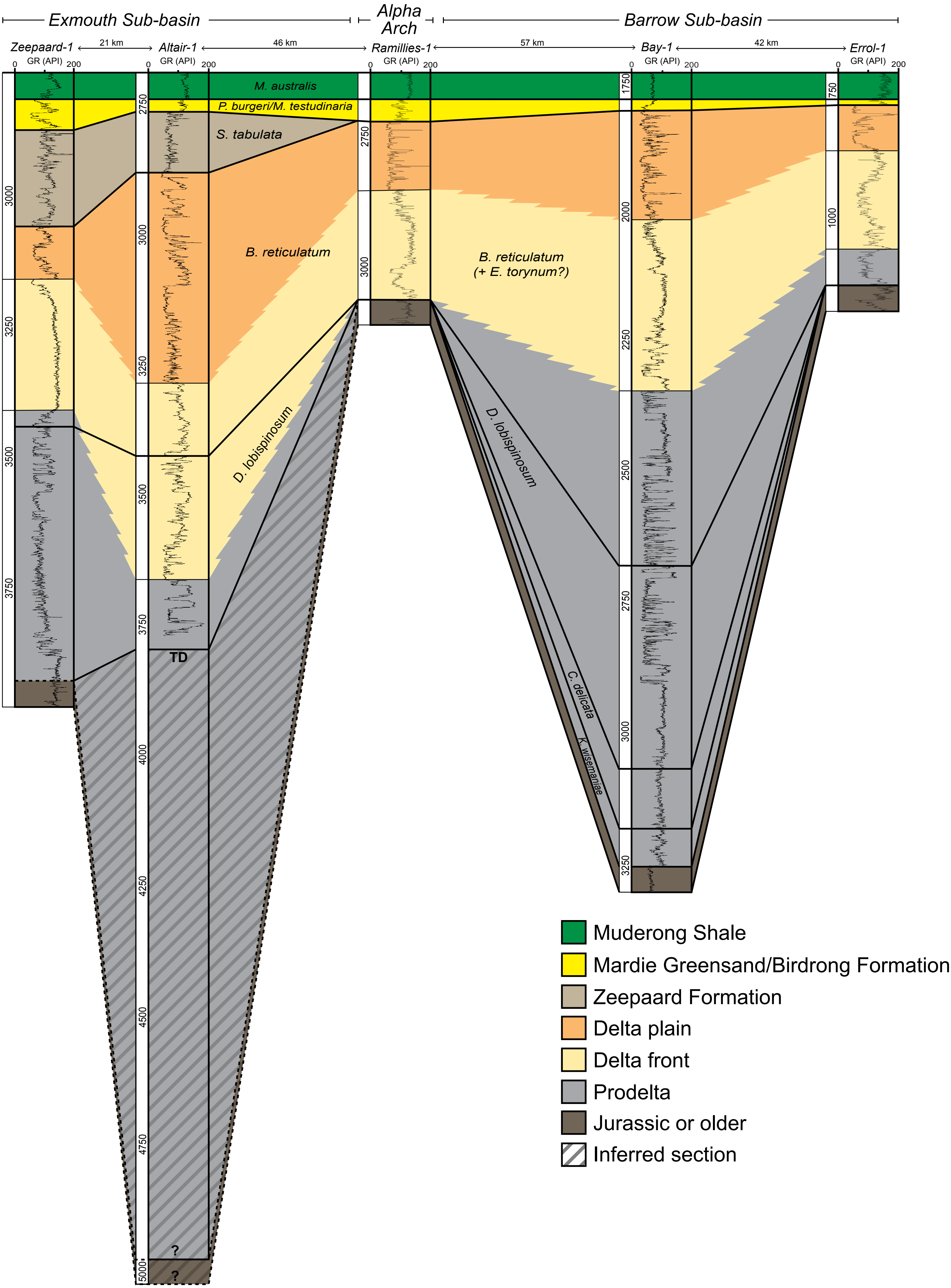

Exmouth Sub-basin
Alpha Arch
Barrow Sub-basin
Zeepaard-1
21 km
Altair-1
46 km
Ramillies-1
57 km
Bay-1
42 km
Errol-1
GR (API)
0
200
M. australis
P. burgeri/M. testudinaria
S. tabulata
B. reticulatum
B. reticulatum
(+ E. torynum?)
D. lobispinosum
D. lobispinosum
C. delicata
K. wisemaniae
TD
?
?
3000
3250
3500
3750
2750
4000
4250
4500
4750
5000
1750
2000
2250
2500
750
1000
Muderong Shale
Mardie Greensand/Birdrong Formation
Zeepaard Formation
Delta plain
Delta front
Prodelta
Jurassic or older
Inferred section

Figure 14. Figure

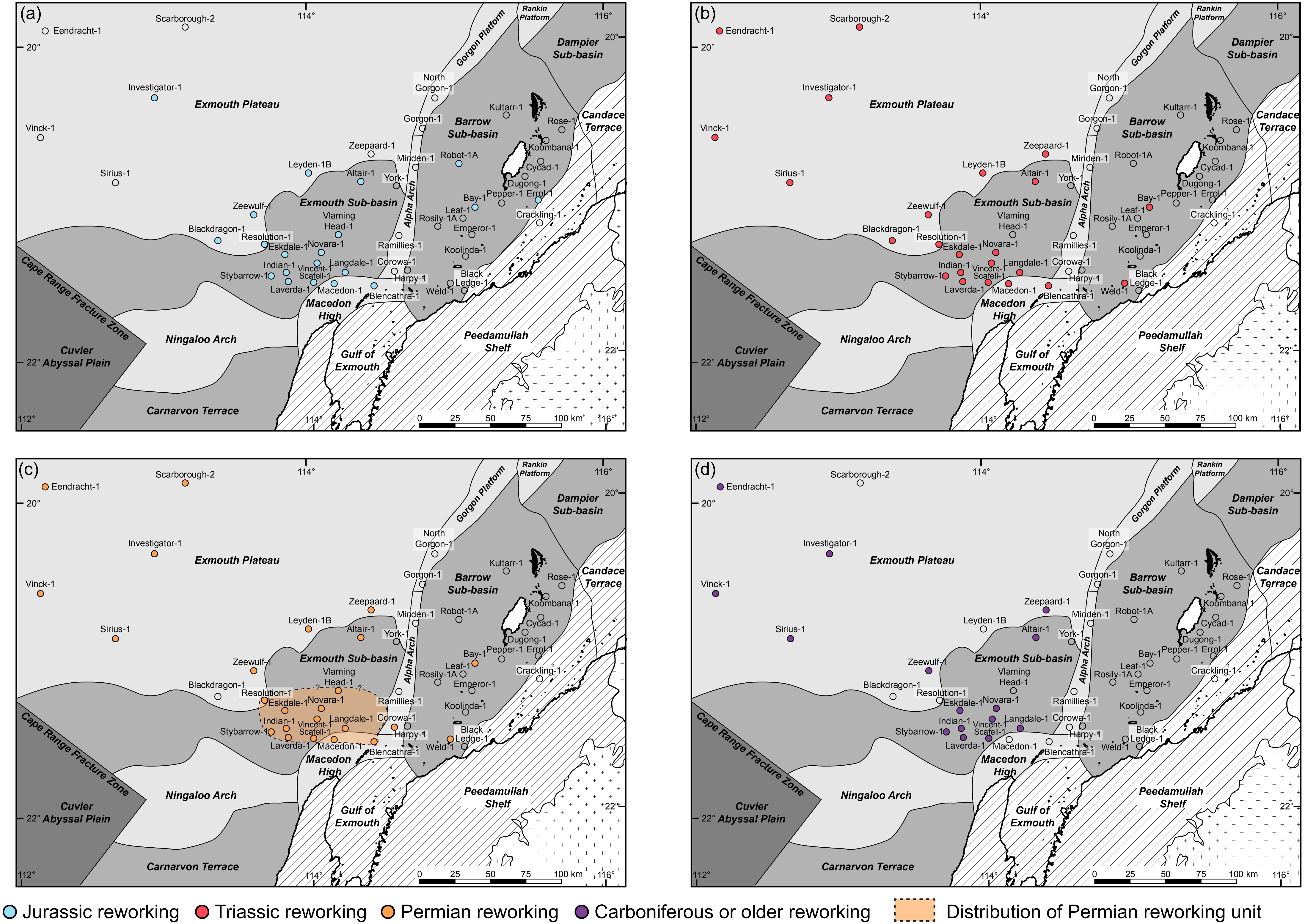

(a)
(b)
(c)
(d)
Exmouth Plateau
Exmouth Sub-basin
Barrow Sub-basin
Dampier Sub-basin
Rankin Platform
Gorgon Platform
Candace Terrace
Alpha Arch
Macedon High
Gulf of Exmouth
Peedamullah Shelf
Ningaloo Arch
Cuvier Abyssal Plain
Carnarvon Terrace
Cape Range Fracture Zone
Eendracht-1
Scarborough-2
Investigator-1
Vinck-1
Sirius-1
Leyden-1B
Zeepaard-1
Altair-1
York-1
Minden-1
Robot-1A
North Gorgon-1
Gorgon-1
Kultarr-1
Rose-1
Koombana-1
Cycad-1
Dugong-1
Pepper-1
Errol-1
Bay-1
Leaf-1
Rosily-1A
Emperor-1
Crackling-1
Koolinda-1
Ramillies-1
Corowa-1
Harpy-1
Black Ledge-1
Weld-1
Blencathra-1
Macedon-1
Laverda-1
Scafell-1
Vincent-1
Langdale-1
Indian-1
Stybarrow-1
Eskdale-1
Novara-1
Vlaming Head-1
Resolution-1
Blackdragon-1
Zeewulf-1
0 25 50 75 100 km
112°
114°
116°
20°
22°
Jurassic reworking
Triassic reworking
Permian reworking
Carboniferous or older reworking
Distribution of Permian reworking unit

Figure 15. Figure

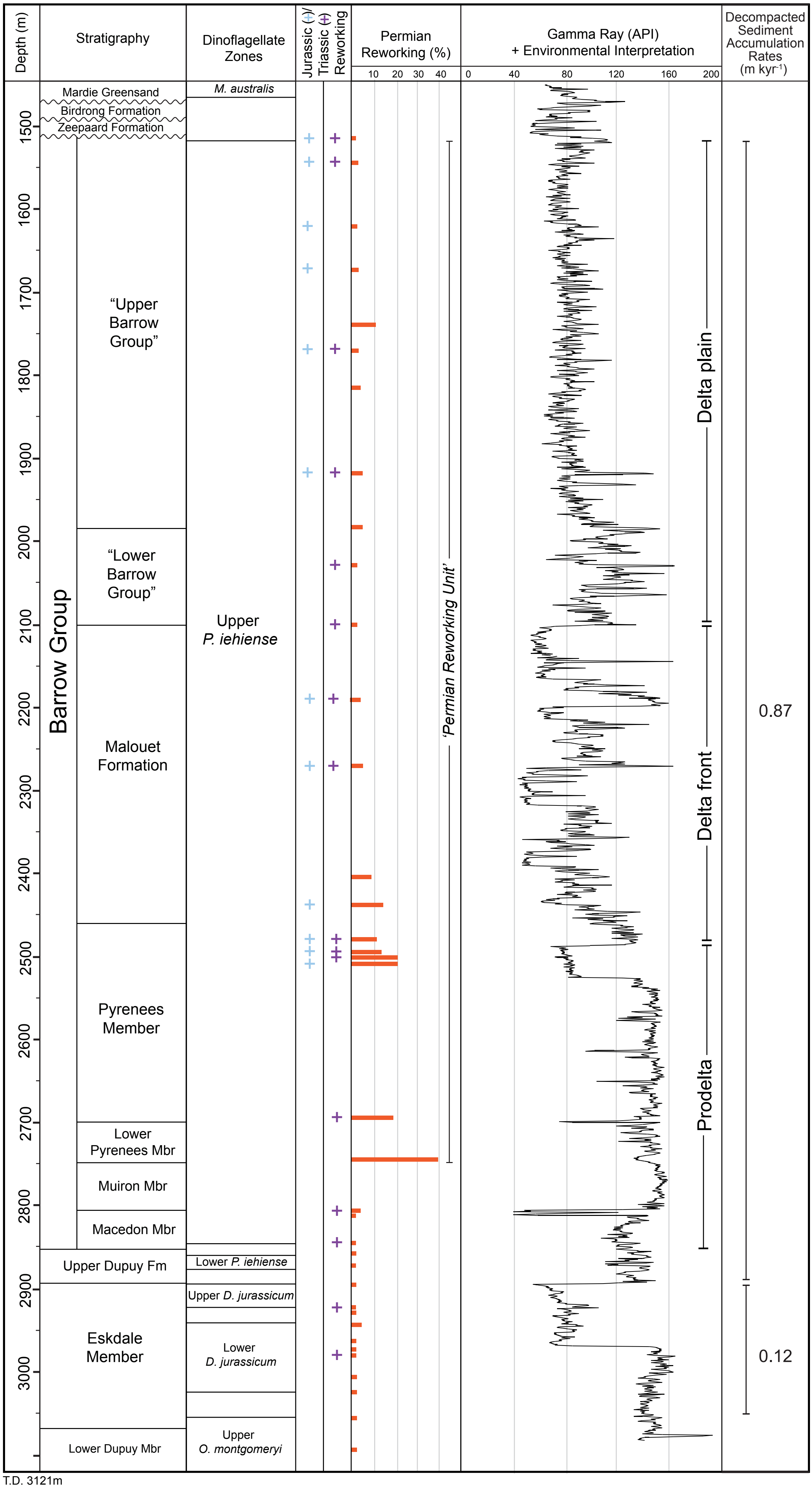
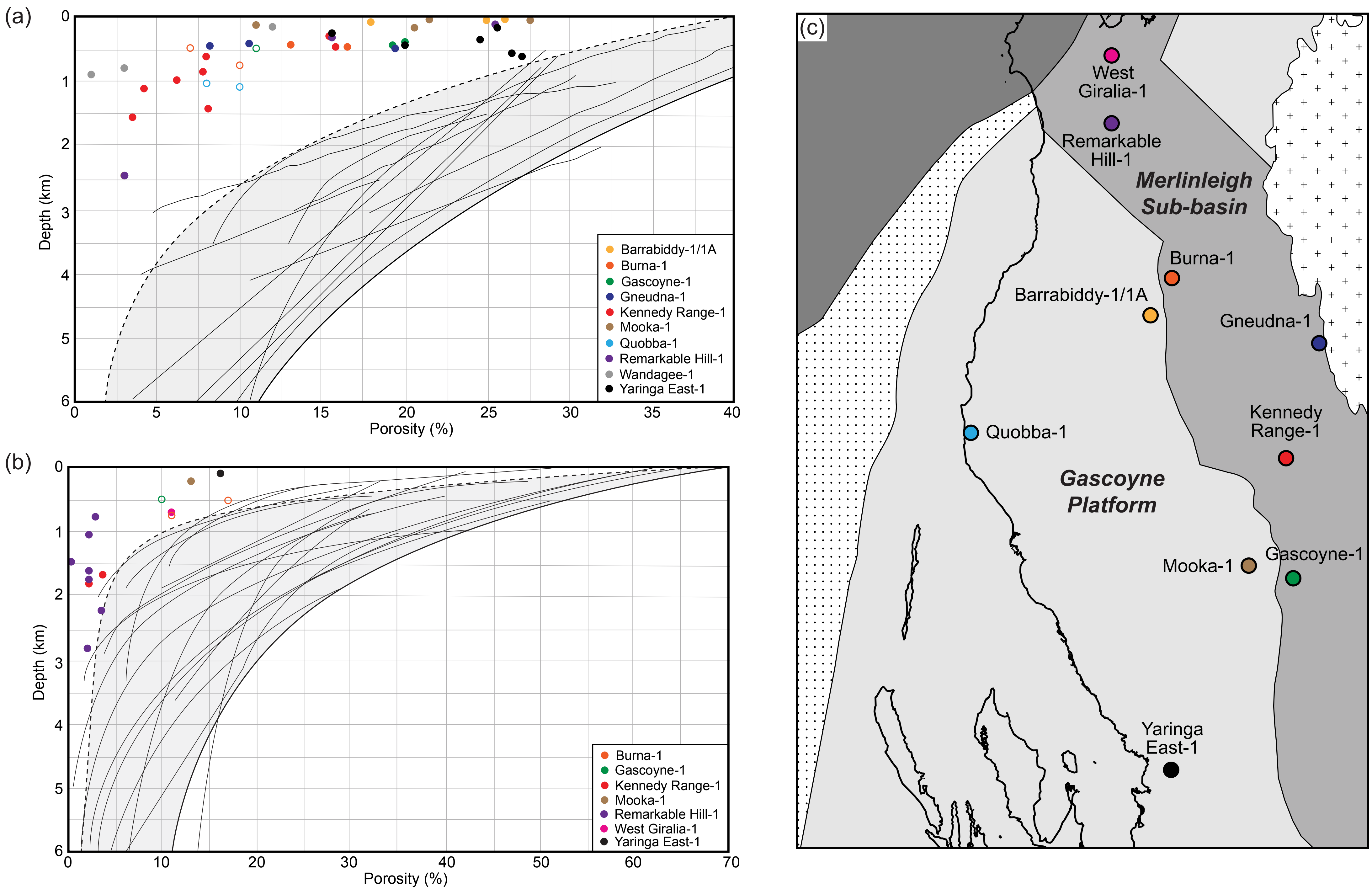

Depth (m)
Stratigraphy
Dinoflagellate Zones
Jurassic (+)/ Triassic (+) Reworking
Permian Reworking (%)
Gamma Ray (API) + Environmental Interpretation
Decompacted Sediment Accumulation Rates (m kyr-1)
10 20 30 40
0 40 80 120 160 200
1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000
Mardie Greensand
Birdrong Formation
Zeepaard Formation
"Upper Barrow Group"
"Lower Barrow Group"
Malouet Formation
Pyrenees Member
Lower Pyrenees Mbr
Muiron Mbr
Macedon Mbr
Barrow Group
Upper Dupuy Fm
Eskdale Member
Lower Dupuy Mbr
M. australis
Upper P. iehiense
Lower P. iehiense
Upper D. jurassicum
Lower D. jurassicum
Upper O. montgomeryi
'Permian Reworking Unit'
Delta plain
Delta front
Prodelta
0.87
0.12
T.D. 3121m

Figure 16. Figure



(a)
Depth (km)
Porosity (%)
Barrabiddy-1/1A
Burna-1
Gascoyne-1
Gneudna-1
Kennedy Range-1
Mooka-1
Quobba-1
Remarkable Hill-1
Wandagee-1
Yaringa East-1
(b)
Depth (km)
Porosity (%)
Burna-1
Gascoyne-1
Kennedy Range-1
Mooka-1
Remarkable Hill-1
West Giralia-1
Yaringa East-1
(c)
West Giralia-1
Remarkable Hill-1
Merlinleigh Sub-basin
Burna-1
Barrabiddy-1/1A
Gneudna-1
Kennedy Range-1
Quobba-1
Gascoyne Platform
Mooka-1
Gascoyne-1
Yaringa East-1

Figure 17. Figure

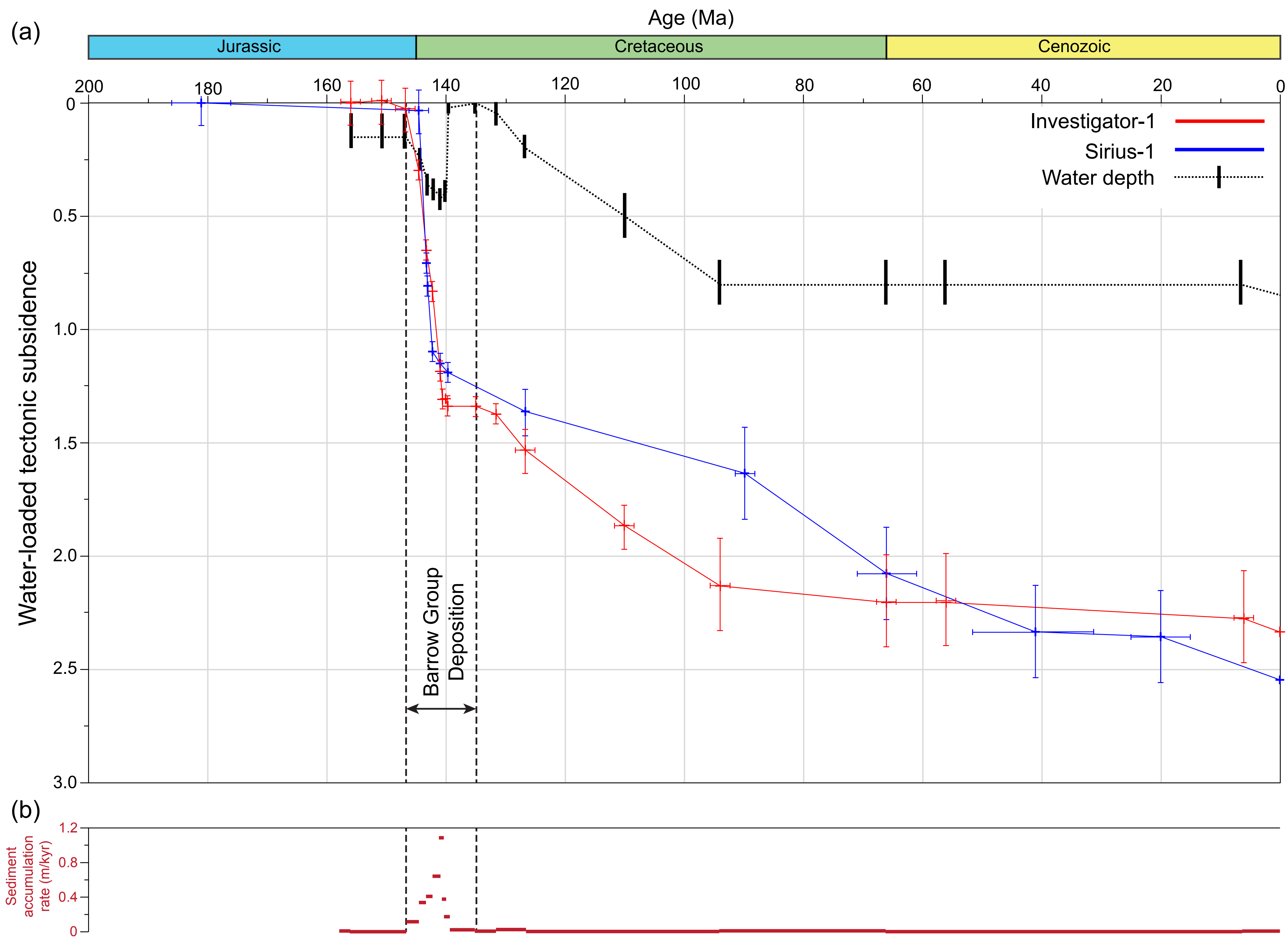
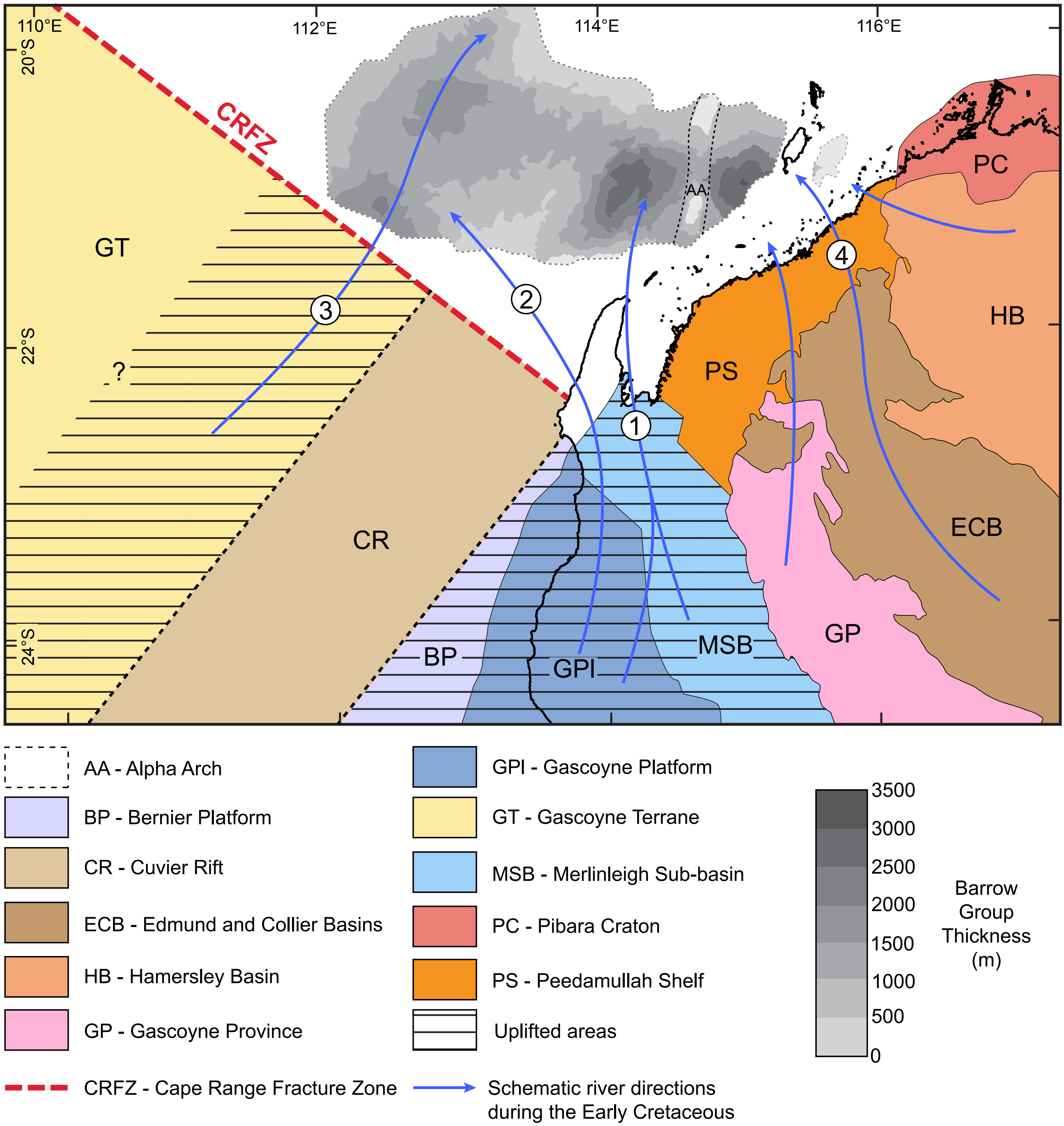
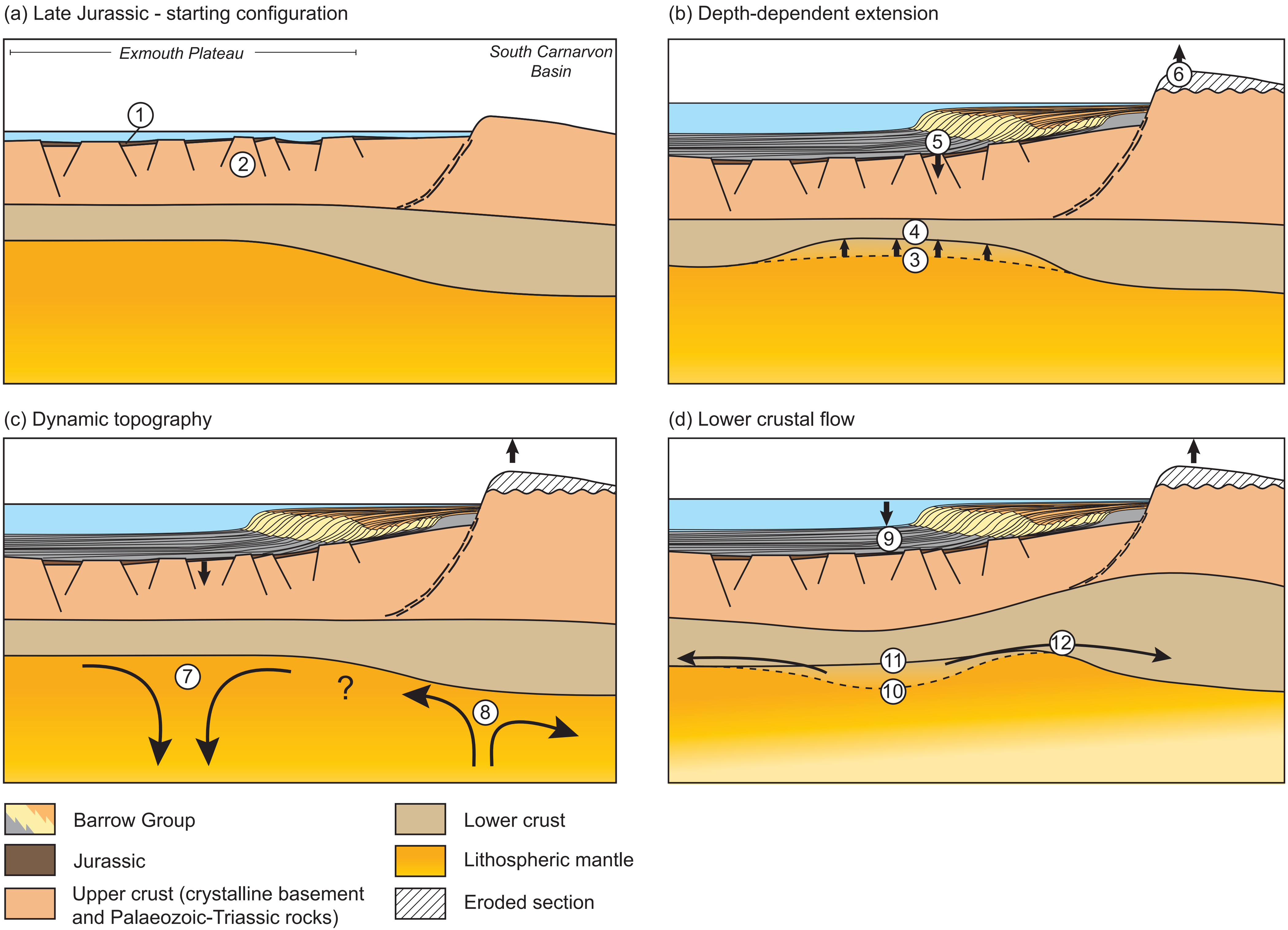

(a)
Age (Ma)
Jurassic
Cretaceous
Cenozoic
200
180
160
140
120
100
80
60
40
20
0
Water-loaded tectonic subsidence
0
0.5
1.0
1.5
2.0
2.5
3.0
Investigator-1
Sirius-1
Water depth
Barrow Group
Deposition
(b)
Sediment accumulation rate (m/kyr)
1.2
0.8
0.4
0

Figure 18. Figure



110°E
112°E
114°E
116°E
20°S
22°S
24°S
CRFZ
GT
?
CR
BP
GPI
MSB
GP
PS
ECB
HB
PC
AA
1
2
3
4
AA - Alpha Arch
BP - Bernier Platform
CR - Cuvier Rift
ECB - Edmund and Collier Basins
HB - Hamersley Basin
GP - Gascoyne Province
CRFZ - Cape Range Fracture Zone
GPI - Gascoyne Platform
GT - Gascoyne Terrane
MSB - Merlinleigh Sub-basin
PC - Pibara Craton
PS - Peedamullah Shelf
Uplifted areas
Schematic river directions during the Early Cretaceous
3500
3000
2500
2000
1500
1000
500
0
Barrow Group Thickness (m)

Figure 19. Figure


(a) Late Jurassic - starting configuration
Exmouth Plateau
South Carnarvon Basin
1
2
(b) Depth-dependent extension
3
4
5
6
(c) Dynamic topography
7
8
?
(d) Lower crustal flow
9
10
11
12
Barrow Group
Jurassic
Upper crust (crystalline basement and Palaeozoic-Triassic rocks)
Lower crust
Lithospheric mantle
Eroded section

	Source Area	Model	Evidence
(a)	*CRFZ*	Transient thermal uplift along CRFZ due to conduction from adjacent oceanic spreading ridge in the Cuvier Abyssal Plain in the Valanginian	Erosional truncation of strata adjacent to CRFZ and clinoforms prograding away from CRFZ identified in seismic profiles.
(b)	*CRFZ*	Pre-breakup thermal doming of the CRFZ in the Berriasian due to asthenospheric upwelling	Structurally high areas identified in seismic data adjacent to the CRFZ, northward progradation of Barrow Group clinoforms in seismic profiles from the southern Exmouth Plateau
(c)	*Greater India/Gascoyne Terrane*	Erosion of a large domal uplift on the Indian Craton prior to breakup feeding the 'lower' Barrow Delta. Collapse of the dome in the late Berriasian led to a change in drainage pattern and deposition of an 'upper' Barrow Delta sourced from the uplifted flanks of the Cuvier rift	Thicker 'lower delta' sequence present in wells on the southern Exmouth Plateau. Thicker 'upper delta' sequence in wells in the Exmouth and Barrow Sub-basins.
(d)	*Greater India/Gascoyne Terrane*	Erosion and northward transport of sedimentary rocks of Greater India prior to breakup.	Presence of Archean-age detrital zircon grains in Lower Barrow Group deposits encountered in wells on the southern Exmouth Plateau
(e)	*Greater India/Gascoyne Terrane*	Late Jurassic and Early Cretaceous uplift of the southern Exmouth Plateau and Greater India by a mantle plume centred on the CRFZ	Progradation directions of Barrow Group clinoforms away from the CRFZ. Presence of Lower Barrow Group conglomerates in the northern Exmouth Sub-basin, indicating a proximal source to the south.
(f)	*Perth Basin*	Rifting in the Perth Basin in the Berriasian, resulting in erosion of a large volume of sediment. This sediment was then transported northwards and deposited in the North Carnarvon Basin	General northward progradation direction of Barrow Group deposits
(g)	*Northern Gascoyne Platform, Pilbara Craton & Hamersley Basin*	Erosion of onshore areas around Cape Range in the Early Cretaceous feeding a northward-prograding delta complex offshore	None
(h)	*Gascoyne Platform*	Uplift of the eastern flank of the Cuvier rift segment in the Early Cretaceous during the final phase of rifting prior to breakup	Northward progradation of Barrow Group deposits in the Exmouth and Barrow Sub-basins, adjacent to the Gascoyne Platform

Citation
Veevers & Powell 1979
Exon & Buffler 1992
Ross & Vail 1994
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Rohrman 2015
Longley et al. 2002
Hocking 1988
Boote & Kirke 1989