RESEARCH ARTICLE

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

Correspondence to:
M. T. Reeve,
matthew.reeve09@imperial.ac.uk

The stratigraphic record of prebreakup geodynamics: Evidence from the Barrow Delta, offshore Northwest Australia

Matthew T. Reeve[1], Christopher A.-L. Jackson[1], Rebecca E. Bell[1], Craig Magee[1], and Ian D. Bastow[1]

[1]Basins Research Group, Department of Earth Science and Engineering, Royal School of Mines, Imperial College London, London, UK

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 postrift geodynamic processes. However, the apparent lack of ancient synbreakup delta systems and the paucity of seismic imaging across continent-ocean boundaries mean that 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 2-D and 3-D seismic and well data to constrain the internal architecture of the Barrow Group. Our results highlight three major depocenters: the Exmouth and Barrow subbasins and southern Exmouth Plateau. Overcompaction 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 indicates that anomalously rapid tectonic subsidence ($\leq 0.24\,\mathrm{mm\,yr^{-1}}$) 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 and Sawyer*, 1989; *Taylor et al.*, 1999; *Rosenbaum et al.*, 2008]. The sedimentary and stratigraphic records of continental breakup are 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 breakup 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, and sediment supply) over comparatively short time scales [*Catuneanu*, 2006; *Plint and 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 postbreakup, such as the Niger Delta [*Cohen and McClay*, 1996], the Cenozoic deltas of the Gulf of Mexico [*Galloway*, 1989; *Sydow and 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 and Backé*, 2010;
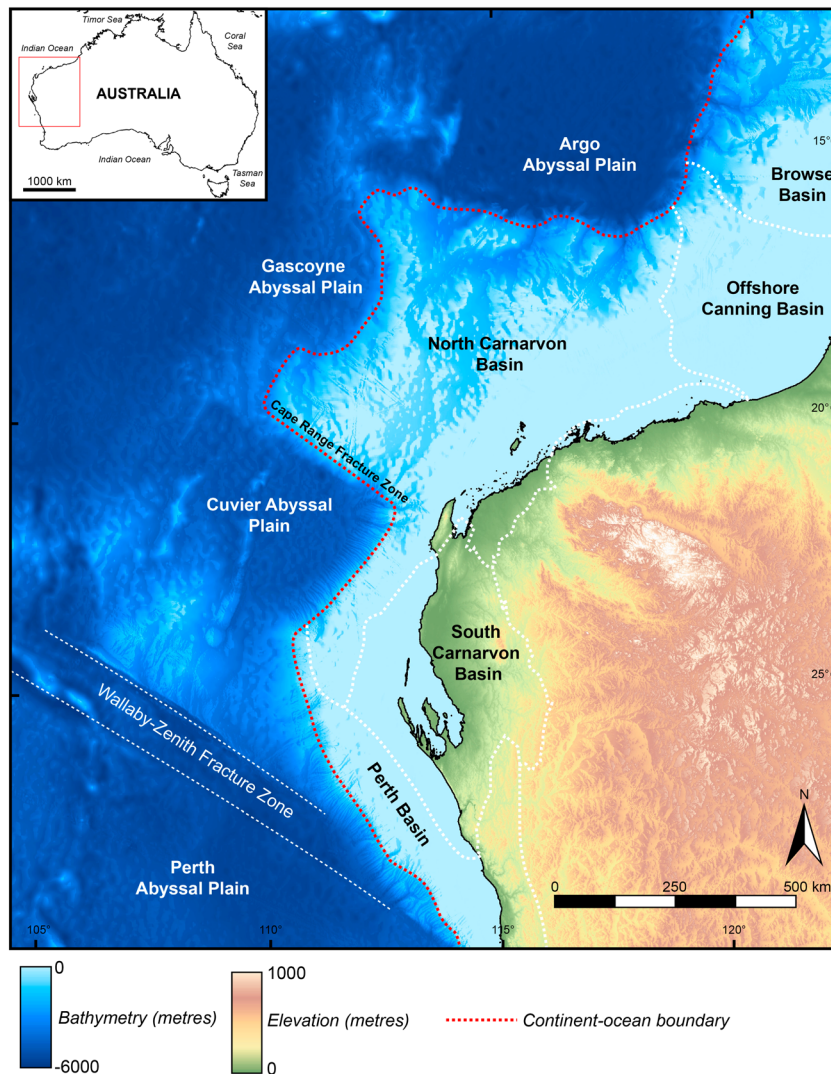
Figure 1. Simplified map of the southern Northwest Shelf showing topography, bathymetry, major bathymetric elements, and main basin subdivisions [after *Longley et al.*, 2002]. Elevation data are based on the 2009 Australian Bathymetry and Topography grid (Geoscience Australia).

MacDonald et al., 2012]. 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 breakup [*Australian Geological Survey Organisation* (*AGSO*) *North West Shelf Study Group*, 1994; *Stagg and 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 and Karner*, 1998; *Huismans and Beaumont*, 2011]. In particular, despite considerable academic and exploration interests, the source area of the Barrow Group remains controversial [e.g., *Veevers and Powell*, 1979; *Exon and Buffler*, 1992; *Ross and Vail*, 1994]. Discriminating between the proposed source area models is therefore important in order to constrain the distribution and timing of prebreakup 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 by using an extensive data set of high-resolution, 2-D and 3-D seismic reflection surveys and borehole data (Figure 2). Onshore borehole data constrain the
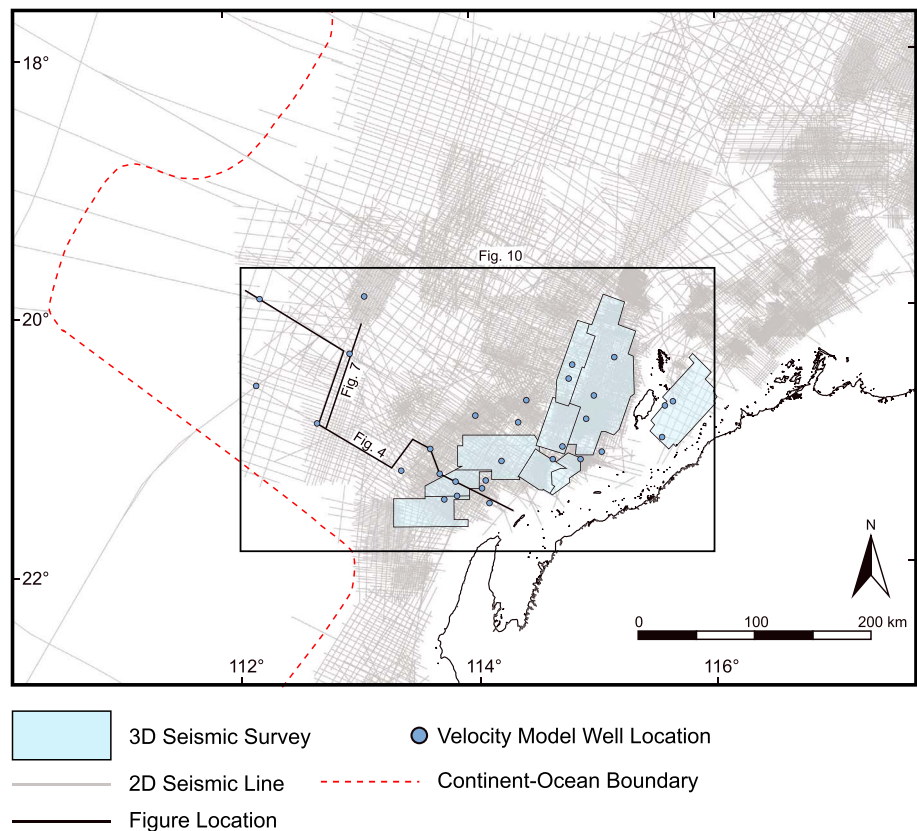
Figure 2. Map showing the coverage of 2-D and 3-D seismic reflection data used in this study and locations of wells used to constrain the velocity structure of the Barrow Group for depth conversion. Locations of seismic lines shown in Figures 4 and 7 are shown by black lines, and the location of Figure 11 is shown by the inset black box.

uplift history of the South Carnarvon Basin, and we use data from offshore boreholes on the Exmouth Plateau to perform 1-D 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 subdivided into a number of smaller tectonic elements: the thick Mesozoic depocenters of the Exmouth, Barrow, Dampier, Dixon, and Beagle subbasins and the Exmouth Plateau to the northwest, which lacks a thick Mesozoic section (Figures 3 and 4) [*Stagg and Colwell*, 1994; *Longley et al.*, 2002]. We here focus on the Exmouth and Barrow subbasins and the southern Exmouth Plateau. The Exmouth and Barrow subbasins 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 and Colwell*, 1994; *Tindale et al.*, 1998]. In contrast, the Exmouth Plateau is a block of thin crystalline crust (~10 km thickness), overlain by a thick sedimentary sequence [*Stagg et al.*, 2004]. Previous authors have suggested that 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 by 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 and 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 and Vera*, 1992; *Lorenzo*, 1997].
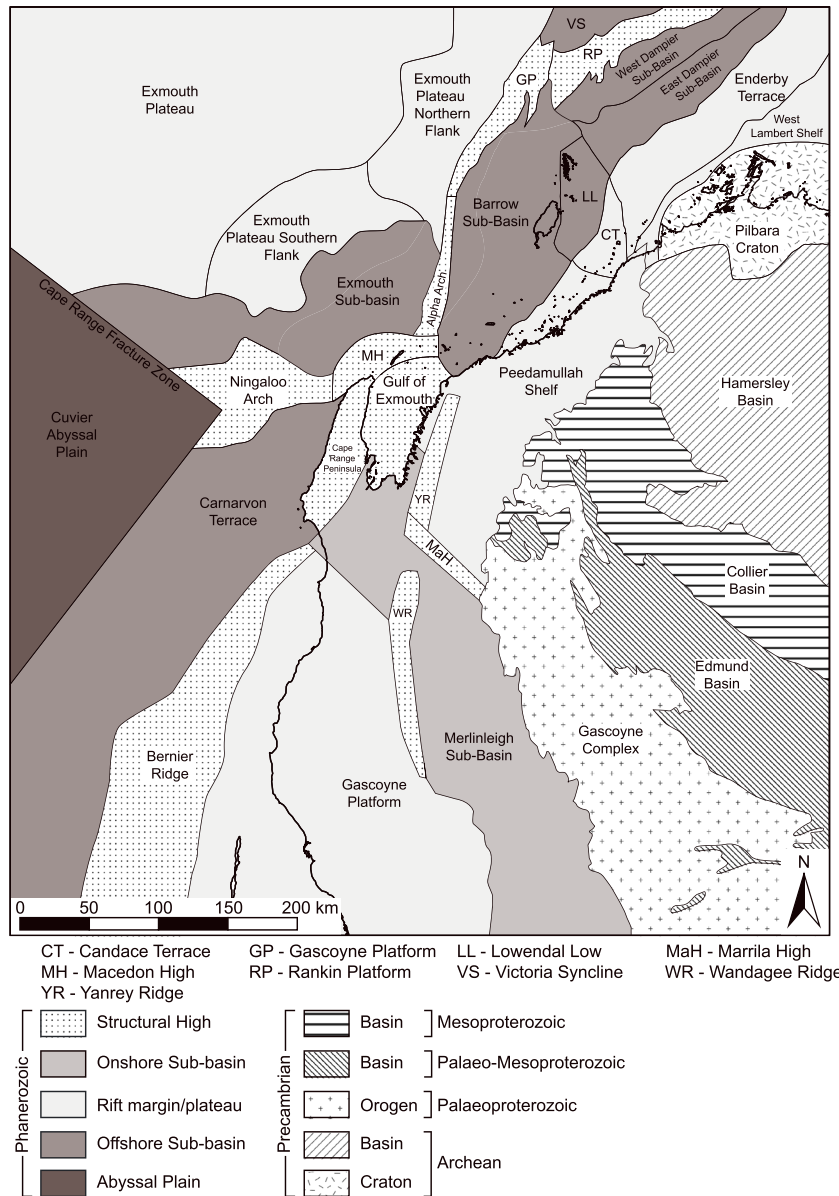
Figure 3. Map of the main structural elements of the North and South Carnarvon Basins, and adjacent Precambrian tectonic elements [after *Crostella et al.*, 2000; *Longley et al.*, 2002; *Iasky et al.*, 2003; *Martin et al.*, 2007].

The structural and stratigraphic architecture of the North Carnarvon Basin was developed during multiple phases of rifting between Australia and Greater India that intermittently occurred from the Late Carboniferous until the Early Cretaceous [*Stagg and 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 subbasins commenced in the Rhaetian [e.g., *Hocking*, 1992; *Longley et al.*, 2002; *Jitmahantakul and 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 and 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 crosscut
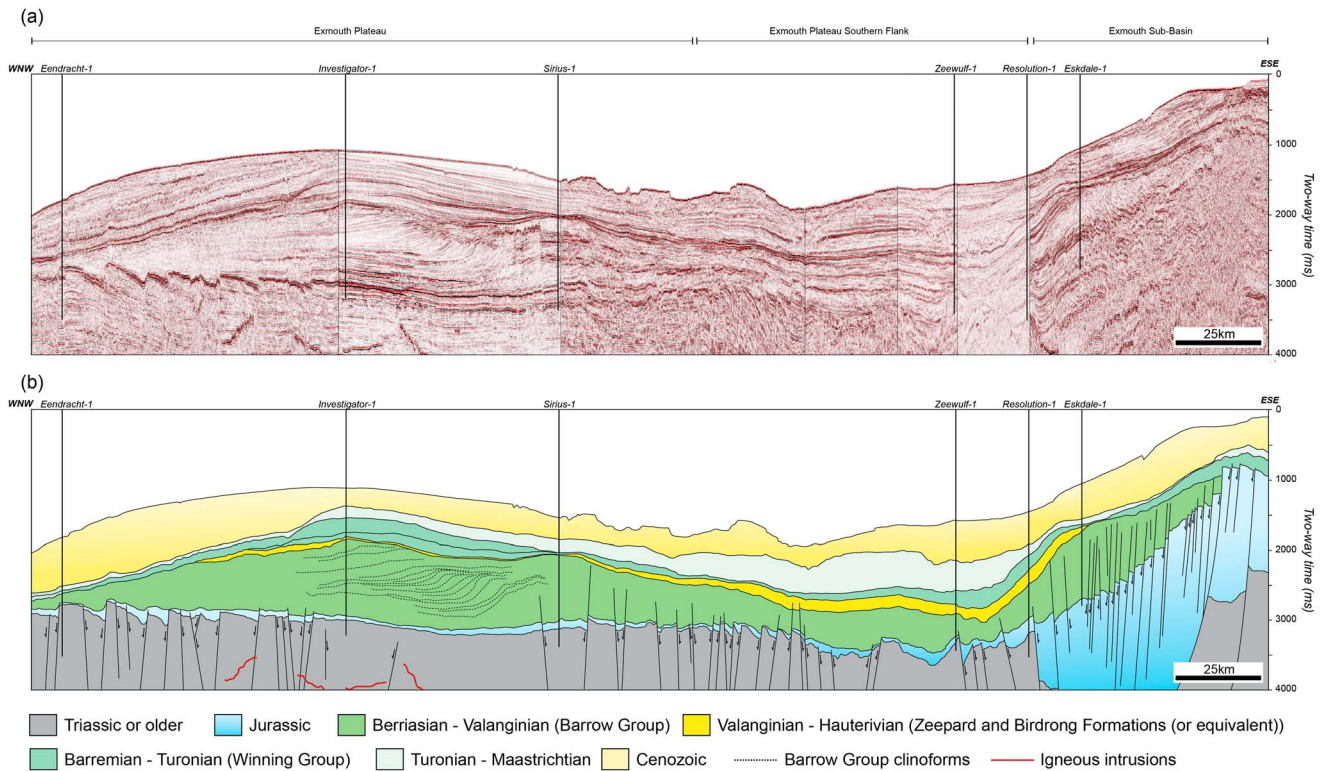
Figure 4. (a) Uninterpreted and (b) interpreted WNW-SSE oriented composite seismic section showing main structural elements of the Exmouth subbasin and Exmouth Plateau. The black vertical lines indicate locations of wells shown in Figure 11. Seismic data are displayed with reverse polarity, where a downward 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.

by Jurassic rift-related normal faults (Figures 4 and 5) [*Lorenzo and Vera*, 1992; *AGSO North West Shelf Study Group*, 1994; *Stagg and 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 and Karner*, 1998]. Jurassic deposition was focused instead in the Exmouth, Barrow, and Dampier subbasins to the southeast. In the Exmouth and Barrow subbasins, 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 subbasins 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 northward across the Exmouth and Barrow subbasins and southern Exmouth Plateau, depositing the Barrow Group (Figures 6 and 7) [*Tindale et al.*, 1998]. Deposition of the Barrow Group spans latest Tithonian to early Valanginian times (~146.7–138.2 Ma) (*Pseudoceratium iehiense-Egmontodinium torynum* dinoflagellate zones) and corresponds to the final phase of rifting in the North Carnarvon Basin (Figure 6) [*Ross and Vail*, 1994; *Driscoll and Karner*, 1998; *Smith et al.*, 2002]. The basal Barrow Group in the Exmouth subbasin 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) [*Scibiorski et al.*, 2005; *Hurren et al.*, 2013; *O'Halloran et al.*, 2013]. The main phase of Barrow Group deposition is subdivided into the Malouet (delta bottomsets) and Flacourt (delta foresets and topsets) formations (Figure 6) [*Hocking et al.*, 1987; *Ross and Vail*, 1994].

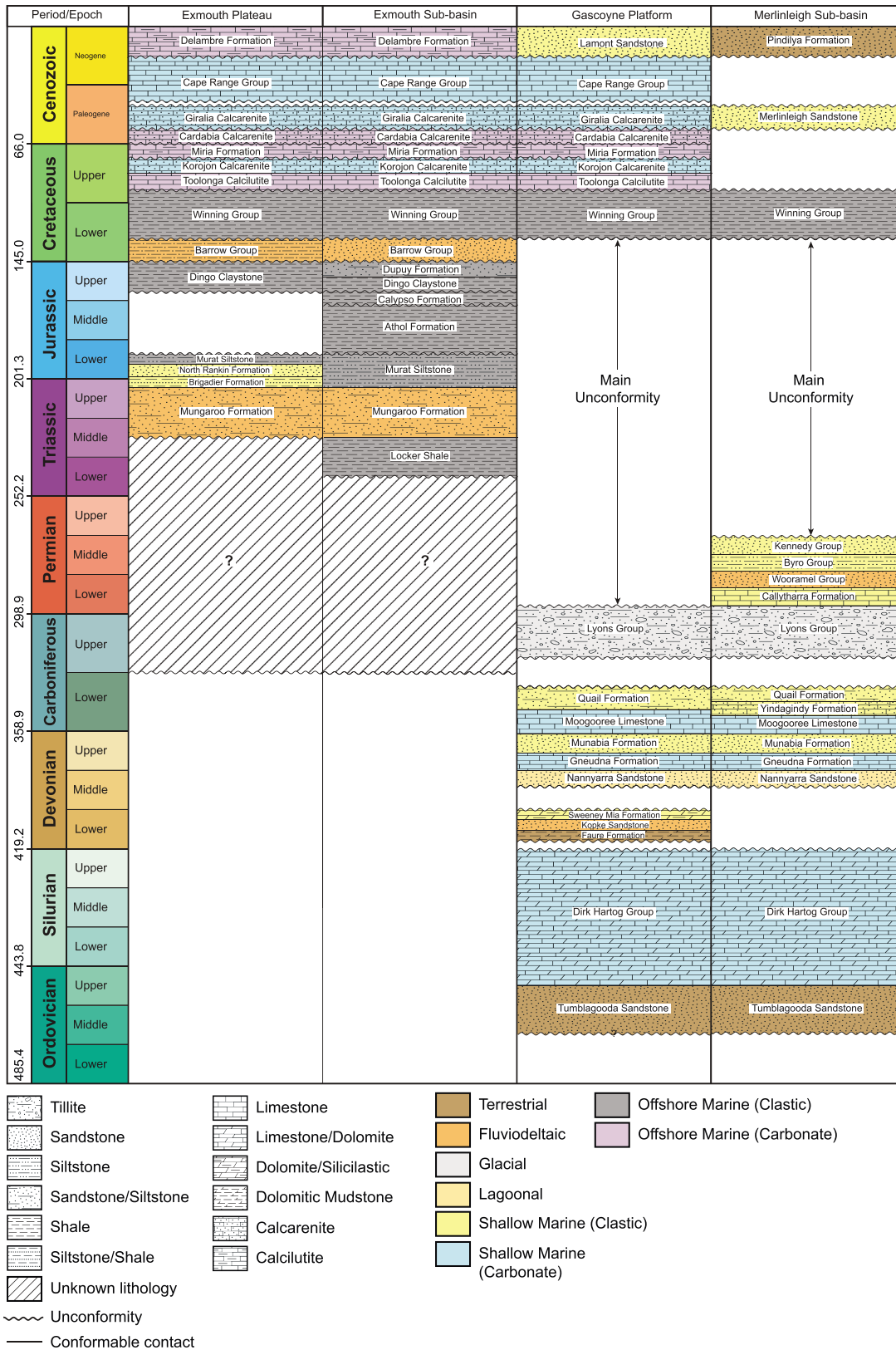**Figure 5.** Generalized stratigraphic column for the Exmouth Plateau, Exmouth subbasin, Gascoyne Platform, and Merlinleigh subbasin, showing dominant lithology and general depositional environment for each unit. Numerical ages in the left-hand column are quoted in Ma [after *Hocking et al.*, 1987; *Hocking*, 1992; *Iasky et al.*, 1998; *Tindale et al.*, 1998; *Longley et al.*, 2002; *Iasky et al.*, 2003; *Mory et al.*, 2003].
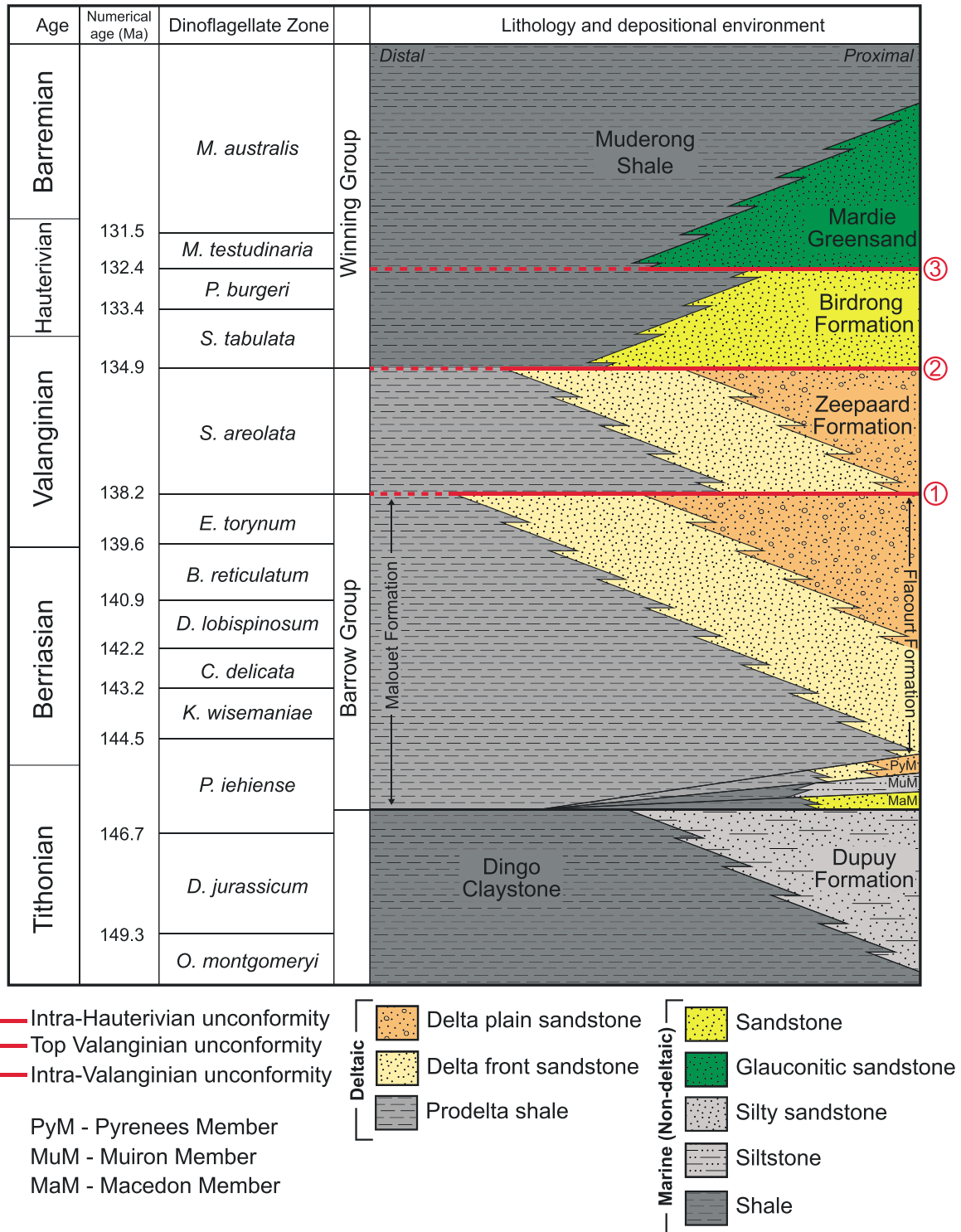
Figure 6. Detailed stratigraphic column for the Exmouth and Barrow subbasins and Exmouth Plateau showing generalized stratigraphic relationships between Late Jurassic and Early Cretaceous units in addition to generalized lithology and dinoflagellate zones corresponding to each unit. Generalized facies variation is indicated from proximal (right-hand side) to distal environments (left-hand side) [after *Arditto*, 1993; *Ross and Vail*, 1994; *Smith et al.*, 2002; *Scibiorski et al.*, 2005; *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. The numbered bold horizon interpretations in Figure 7b correspond to major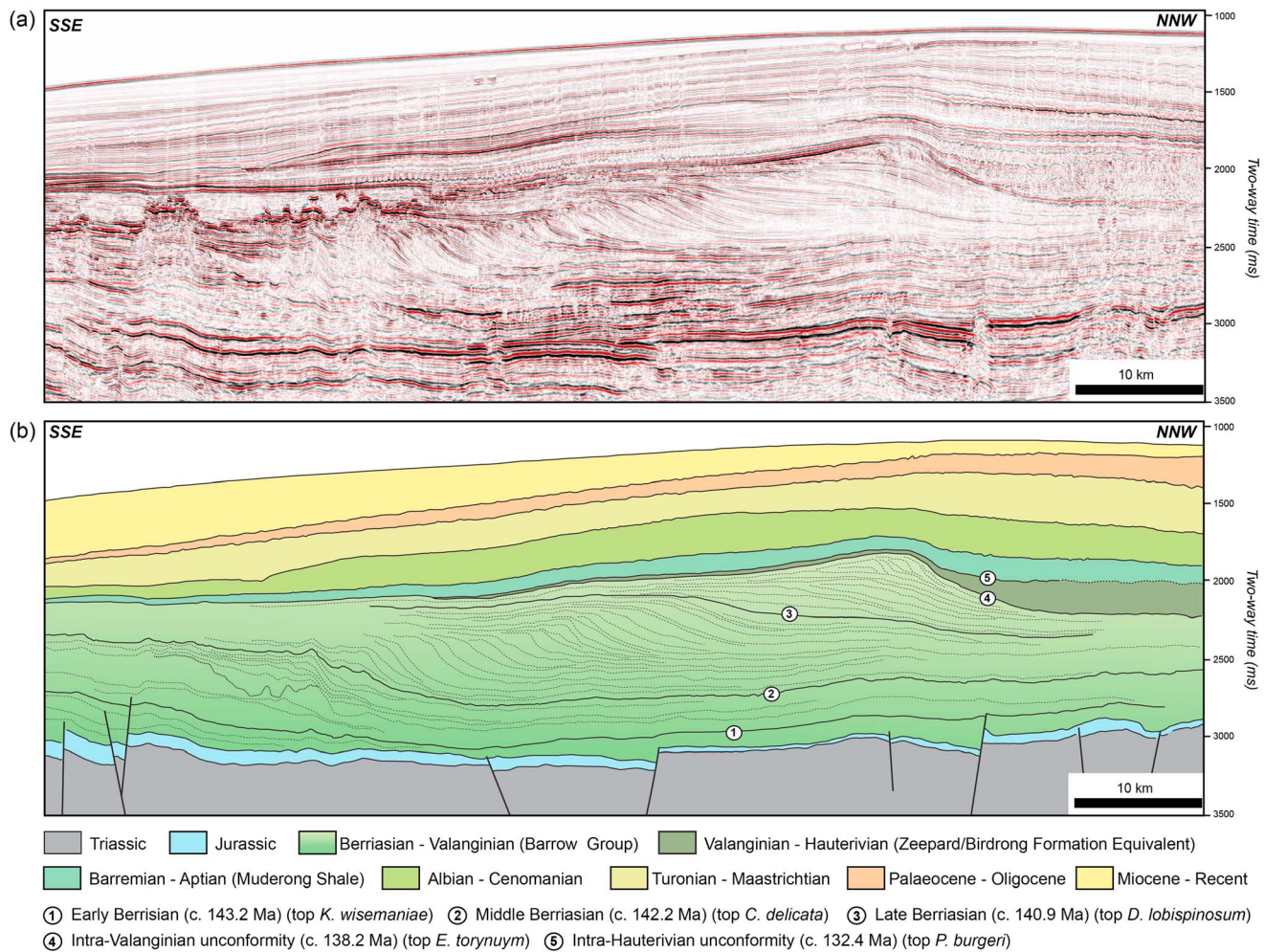 dinoflagellate zone boundaries, which are interpreted based on ties to dinoflagellate zones reported in the Investigator-1 and Sirius-1 wells. The dashed lines in Figure 7b indicate the clinoform interpretations within the Barrow Group.

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 and Durrant*, 1996]. The intra-Valanginian unconformity is locally overlain by Valanginian deltaic rocks of the Zeepaard Formation (138.2–134.9 Ma) (*Systematophora 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 conformally into the Muderong Shale (Hauterivian to Aptian) (Figure 6) [*Hocking et al.*, 1987; *Driscoll and 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 subbasins (Figures 3 and 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 and 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 and 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 postbreakup 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 that Jurassic sediments were deposited on the Gascoyne Platform and were later uplifted and eroded [*Mihut and Müller*, 1998]; others suggest that the Gascoyne Platform was a structurally high area of nondeposition for much of the Mesozoic [*Iasky et al.*, 2003; *Mory et al.*, 2003].

The ~32 000 km^2 Merlinleigh subbasin is an elongated 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 prerift 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 subbasin 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 subbasin 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 that 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 subbasin (Figures 3 and 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 suggests an Early Cretaceous age [*Hocking et al.*, 1987], and the unit's stratigraphic relationships indicate that 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 preexisting 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 prebreakup 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 involves uplift of the Cape Range Fracture Zone (CRFZ), which forms the southwestern margin of the Exmouth Plateau [e.g., *Veevers and 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
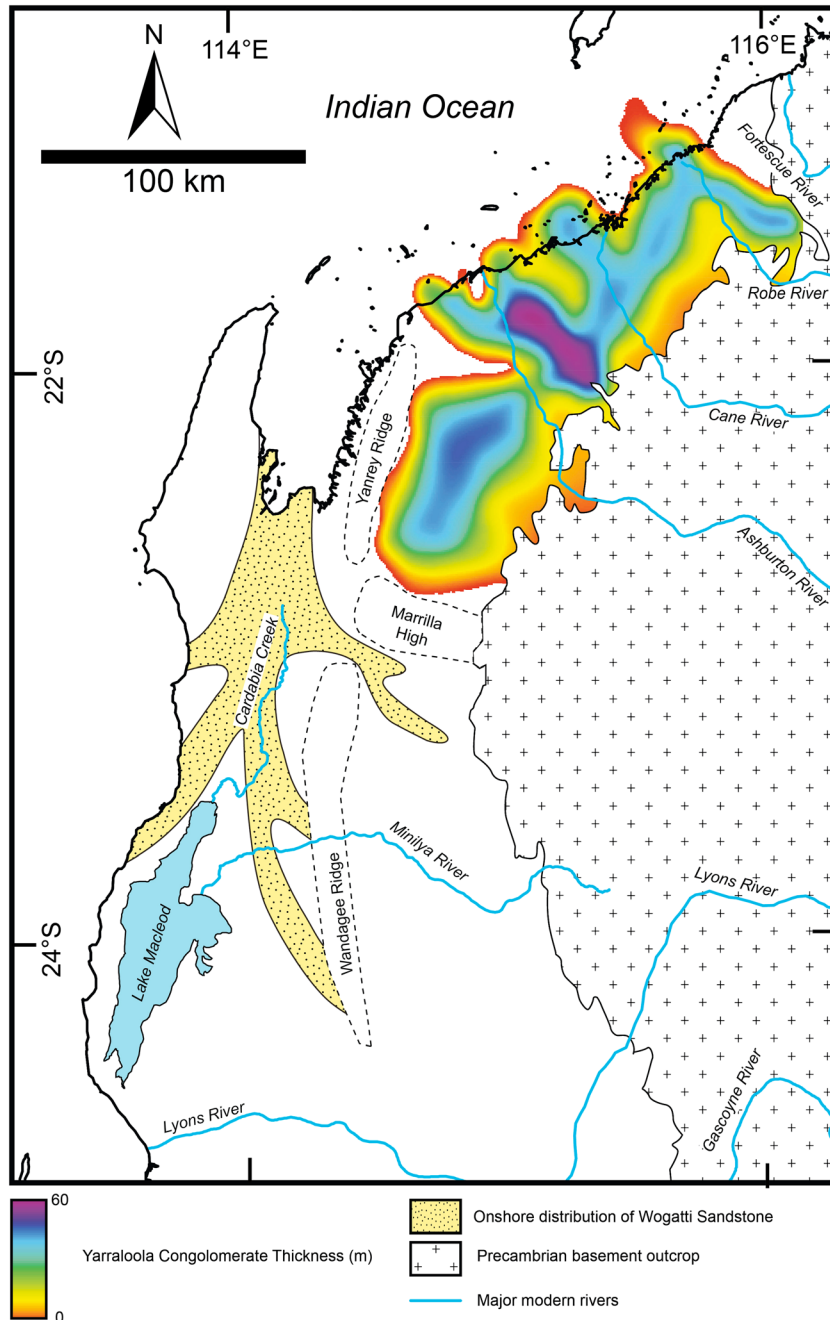
Figure 8. Map showing the distribution of the very thin onshore correlatives to the Barrow Group in addition to the location of modern rivers and water bodies [after *Thomas*, 1978; *Hocking et al.*, 1988; *Boote and Kirk*, 1989; *Iasky et al.*, 1998; *Crostella et al.*, 2000].

to the north (Figure 9a). *Veevers and 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 and Figure 9b). On the basis of seismic profiles from the Exmouth Plateau, *Exon and Buffler* [1992] suggest that the Barrow Group prograded northward adjacent to the CRFZ, suggesting that the associated delta was partially sourced from a ridge located at the present site of the CRFZ (Model b, Table 1 and Figure 9a). They also propose that the CRFZ experienced Berriasian to Valanginian uplift due to asthenospheric upwelling associated with incipient breakup.
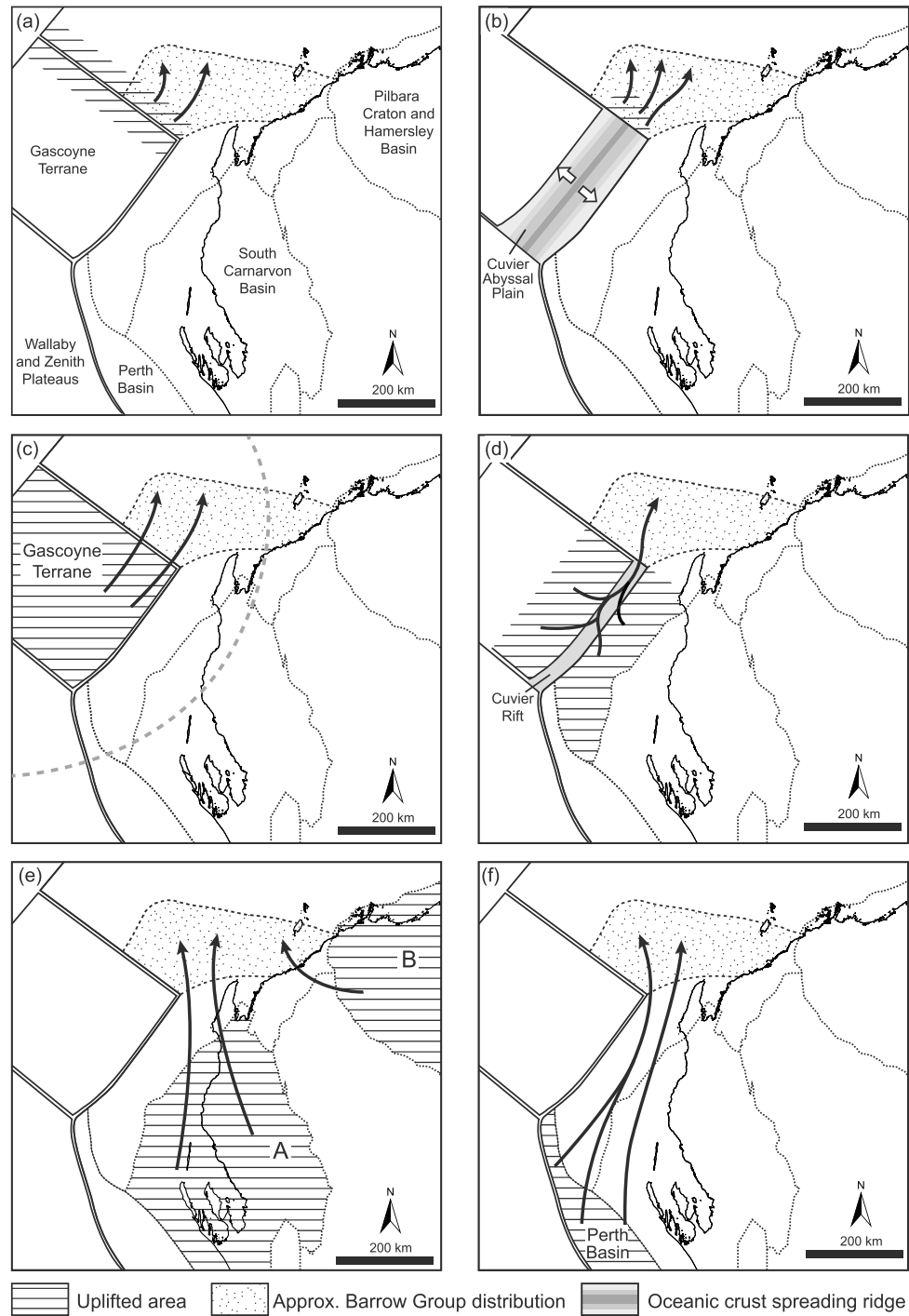
Figure 9. Schematic illustrations of proposed source area models for the Barrow Group. (a) Uplift of the Cape Range Fracture Zone [*Exon and Buffler*, 1992]. (b) Uplift adjacent to Cuvier Abyssal Plain spreading center [*Veevers and Powell*, 1979]. (c) Uplift of the Gascoyne Terrane [*Exon and Buffler*, 1992; *Ross and Vail*, 1994; *Rohrman*, 2015]. (d) Uplift of flanks of the Cuvier rift [*Ross and Vail*, 1994]. (e) Uplift of the South Carnarvon Basin (A) and Pilbara Craton (B) [*Hocking*, 1988; *Boote and Kirk*, 1989; *Exon and Buffler*, 1992]. (f) Uplift of the Perth Basin [*Longley et al.*, 2002]. The black arrows indicate the schematic sediment transport directions for each model. The tectonic configuration in Figure 9a 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 Figure 9c indicates the inferred limit of the mantle plume head model proposed by *Rohrman* [2015]. Note that all schematic models show the Berriasian-Valanginian configuration of the North Carnarvon Basin, with exception of Figure 9b, which shows the basin configuration after the onset of seafloor spreading in the Cuvier Abyssal Plain in the Valanginian.

Table 1. Table Showing a Summary of Main Previously Published Models for the Source Area of the Barrow Group[a]

Source Area	Model	Evidence	Citation
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	Veevers and Powell [1979]
CRFZ	Prebreakup 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	Exon and Buffler [1992]
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 subbasins	Ross and Vail [1994]
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	Lewis and Sircombe [2013]
Greater India/ Gascoyne Terrane	Late Jurassic and Early Cretaceous uplift of the southern Exmouth Plateau and Greater India by a mantle plume centered on the CRFZ	Progradation directions of Barrow Group clinoforms away from the CRFZ. Presence of Lower Barrow Group conglomerates in the northern Exmouth subbasin, indicating a proximal source to the south	Rohrman [2015]
Perth Basin	Rifting in the Perth Basin in the Berriasian, resulting in erosion of a large volume of sediment. This sediment was then transported northward and deposited in the North Carnarvon Basin	General northward progradation direction of Barrow Group deposits	Longley et al. [2002]
Northern Gascoyne Platform, Pilbara Craton, and Hamersley Basin	Erosion of onshore areas around Cape Range in the Early Cretaceous feeding a northward prograding delta complex offshore	None	Hocking [1988]
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 subbasins, adjacent to the Gascoyne Platform	Boote and Kirk [1989]

[a]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.

2.4.2. Sources South of the Cape Range Fracture Zone

The second group of hypotheses for the Barrow Group source area suggests 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 prebreakup conjugate margin to the Cuvier rift (Figure 9c). *Ross and 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 and 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 subbasin (Figure 9d). This upper delta sequence was suggested to be sourced from the uplifted flanks of the incipient Cuvier rift valley [*Ross and Vail*, 1994].

Based on the presence of Archean-age detrital zircon grains in Barrow Group deposits on the southern Exmouth Plateau, *Lewis and 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 subbasin (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 neighboring Pilbara Craton and Hamersley Basin (Model g, Table 1 and Figure 9e). *Boote and Kirk* [1989] also suggest that the Gascoyne Platform provided a major source of sediment for the Barrow Delta, as a result of prebreakup 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 and Figure 9f). A number of authors [e.g., *Veevers and Powell*, 1979; *Exon and Buffler*, 1992; *Ross and Vail*, 1994; *Lewis and Sircombe*, 2013; *Rohrman*, 2015] also suggest that 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. Data Set and Methodology

3.1. Data Set

The structure of the study area was constrained by mapping key horizons in an ~165,000 km^2 grid of 2-D seismic reflection lines and 10 3-D seismic reflection volumes (Figure 3). Two-dimensional line spacing varies from 0.5 to 10 km but is typically <5 km. Vertical record length varies between 3.5 and 16 s two-way time. 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 2-D and 3-D seismic data sets and depth converted in order to construct an isopach map. In addition, 10 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 2-D 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 subdivided into three main depositional environments; prodelta, delta front, and delta plain. This subdivision 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 subdivision and dinoflagellate zone depths as described in well completion reports.

3.2.3. 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 behavior 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
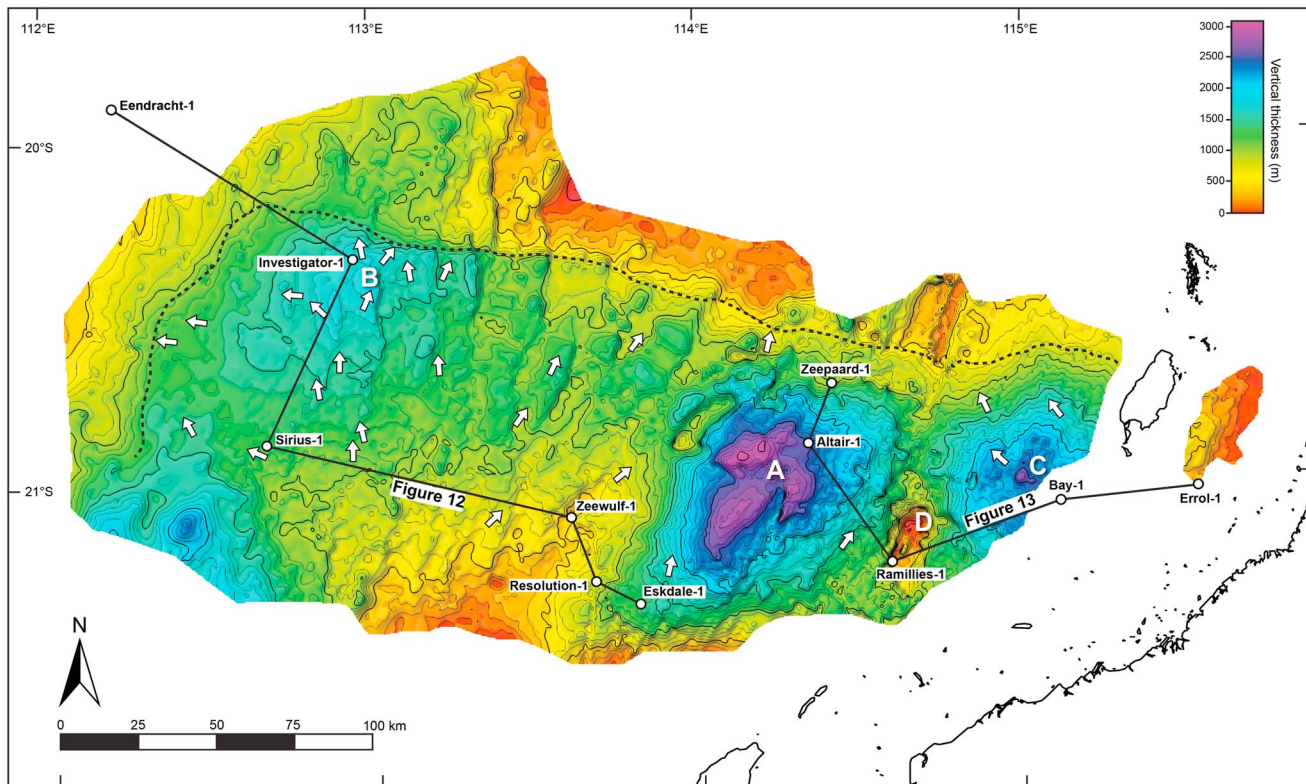
Figure 10. Vertical thickness map of the Barrow Group based on seismic interpretation. The white arrows indicate the estimated clinoform progradation directions. Locations A–C relate to Barrow Group depocenters on the Exmouth Plateau and in the Exmouth and Barrow subbasins, respectively. Location D relates to the Alpha Arch structural high. The dashed black line indicates the approximate location of the breakpoint of the last clinoform of the Barrow Group at maximum regression. The solid black lines indicate the location of Figures 12 and 13. The white circles indicate the well locations.

porosity loss with depth for a given lithology [*Giles*, 1997; *Corcoran and Doré*, 2005]. Deviation from a "normal" compaction trend may thus be indicative of anomalous compaction, resulting from, for example, overpressure development (i.e., undercompaction) or exhumation (i.e., overcompaction) (Figure 11b) [e.g., *Corcoran and 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 and 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 the 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 postexhumation re-burial of units below the main unconformity
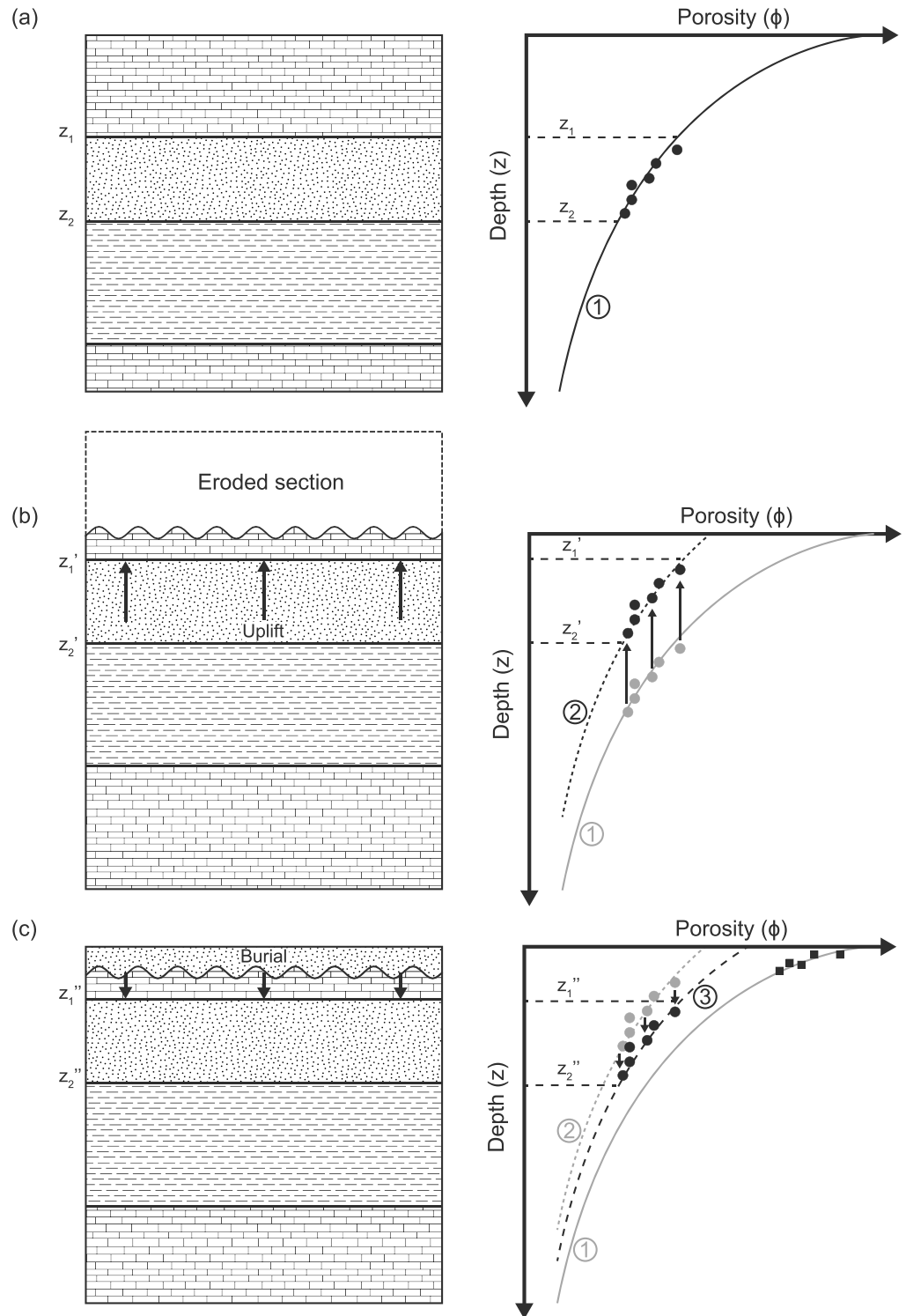
Figure 11. (a) Porosity depth relationship for a normally compacted sandstone unit with top depth z1 and base depth z2, and corresponding normal compaction trend (compaction curve 1). (b) Porosity-depth relationship for the sandstone unit following exhumation to a top depth z1′ and base depth z2′. (c) Porosity-depth relationship for the sandstone unit following postexhumation reburial to a top depth z1″ and base depth z2″. The squares represent porosity-depth values for normally compacted upper sandstone unit in Figure 11c.

(Figure 11c) [*Corcoran and 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.

3.2.4. Reworking of Palynomorphs

In addition to compaction-based methods, we also utilize a methodology based on reworking of palyno-morphs 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 interpreta-tion 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.

3.2.5. Decompaction and Backstripping

Decompaction and backstripping were 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. One-dimensional Airy isostatic backstripping was used to investigate the tectonic subsidence history of sedimentary successions encountered by wells on the Exmouth Plateau (see the supplementary information for details of parameter values used and *Allen and 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 subbasin (max-imum 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 subbasin (maximum thickness ~2.6 km; location C in Figure 10). The Barrow Group terminates to the west and north along a gently arcuate, broadly east 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 subbasin" of *Tindale et al.* [1998]) the clinoform front trends approximately north-east not east. The thickness of the Barrow Group decreases southward, 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 ~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 sedi-ments 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 para-meters 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 and Buffler*, 1992; *Ross and Vail*, 1994].

Clinoform progradation directions are broadly toward the north, although some variability is observed (Figure 10). In the Exmouth subbasin depocenter (location A in Figure 10) the Barrow delta prograded toward the NE to N, whereas in the Barrow subbasin depocenter (location C in Figure 10) the delta prograded toward 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 crosscut 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 and 7).

Temporal variability in clinoform heights is also measured within the Exmouth Plateau depocenter. The oldest clinoforms, which lie in proximity to the CRFZ, have been affected by postdepositional 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) (*Kalyptea wisemaniae* dinoflagellate zone), prograde northward, and have heights of ~260 m (Figure 7). In the middle Berriasian (143.2–142.2 Ma) (*Cassiculosphaeridia 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) (*Dissimulidinium lobispinosum* dinoflagellate zone). Clinoforms in the latest Berriasian to early Valanginian (140.9–139.6 Ma) (*Batioladinium reticulatum* dinoflagellate zone) increase in height to 390–440 m and prograde generally to the north or northeast.

4.1.2. Subseismic Stratigraphic Architecture

In order to constrain the subseismic 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 subbasin and on the Exmouth Plateau (Figure 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 ~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 subbasin 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 subbasin depocenter delta plain deposits are not encountered until the late Berriasian-Valanginian (~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 subbasin depocenters and on the Alpha Arch (i.e., Ramillies-1). In the Exmouth subbasin 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 subbasin 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 subbasin than in the Exmouth subbasin (Figure 13). The relatively thick latest Berriasian Barrow Group deposits in the Barrow subbasin may be a primary depositional feature [e.g., *Ross and 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 subbasin and Barrow subbasin depocenters. In the Exmouth subbasin depocenter, the oldest recorded delta front deposits are late Berriasian (~142.2–140.9 Ma) (*D. lobispinosum* dinoflagellate zone; i.e., Altair-1, i), whereas on the Alpha Arch and in the Barrow subbasin depocenter the oldest delta front deposits are latest Berriasian to early Valangian (~140.9–139.6 Ma) (*B. reticulatum* dinoflagellate zone) (Figure 13).
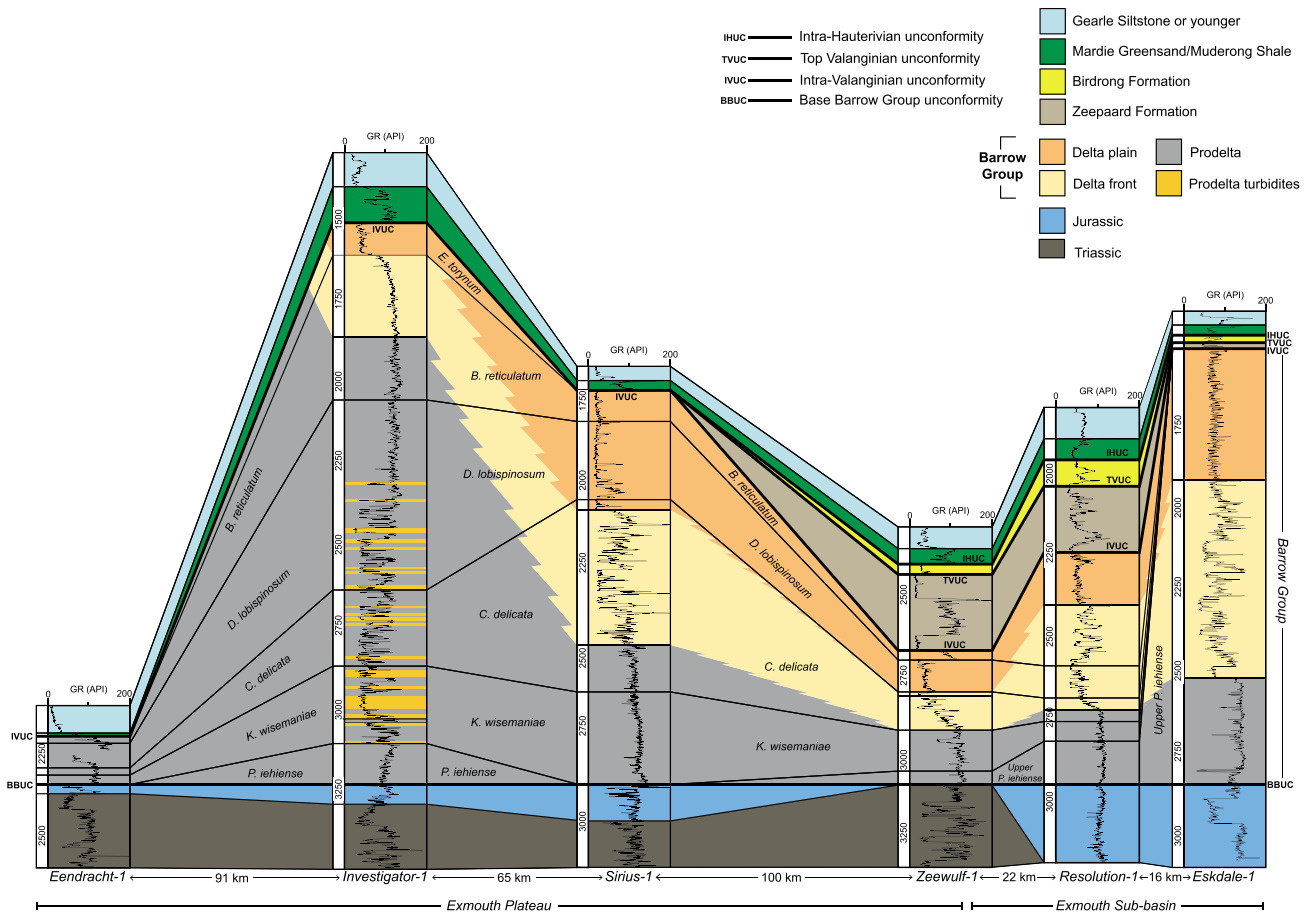
Figure 12. Well correlation panel showing gamma ray logs and generalized lithology from key wells in the Exmouth subbasin and Exmouth Plateau depocenters. Age correlation (black lines) is based on dinoflagellate zones, and inferred facies divisions within the Barrow Group are based on well completion reports and gamma ray logs. Wells are displayed using the Base Barrow Group unconformity as a datum. Well locations are shown in Figure 11.

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 subbasin 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 subbasin, 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 subbasin 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 subbasin, where Triassic reworking is minimal. For example, at Bay-1, Triassic reworking is only observed in one sidewall core from the Barrow Group [*Rapaic and 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 subbasin and on the Exmouth Plateau. Permian reworking is particularly common around the Macedon High and southern Exmouth subbasin, 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 subbasin, which encounters the Permian reworking unit. In Eskdale-1, a component
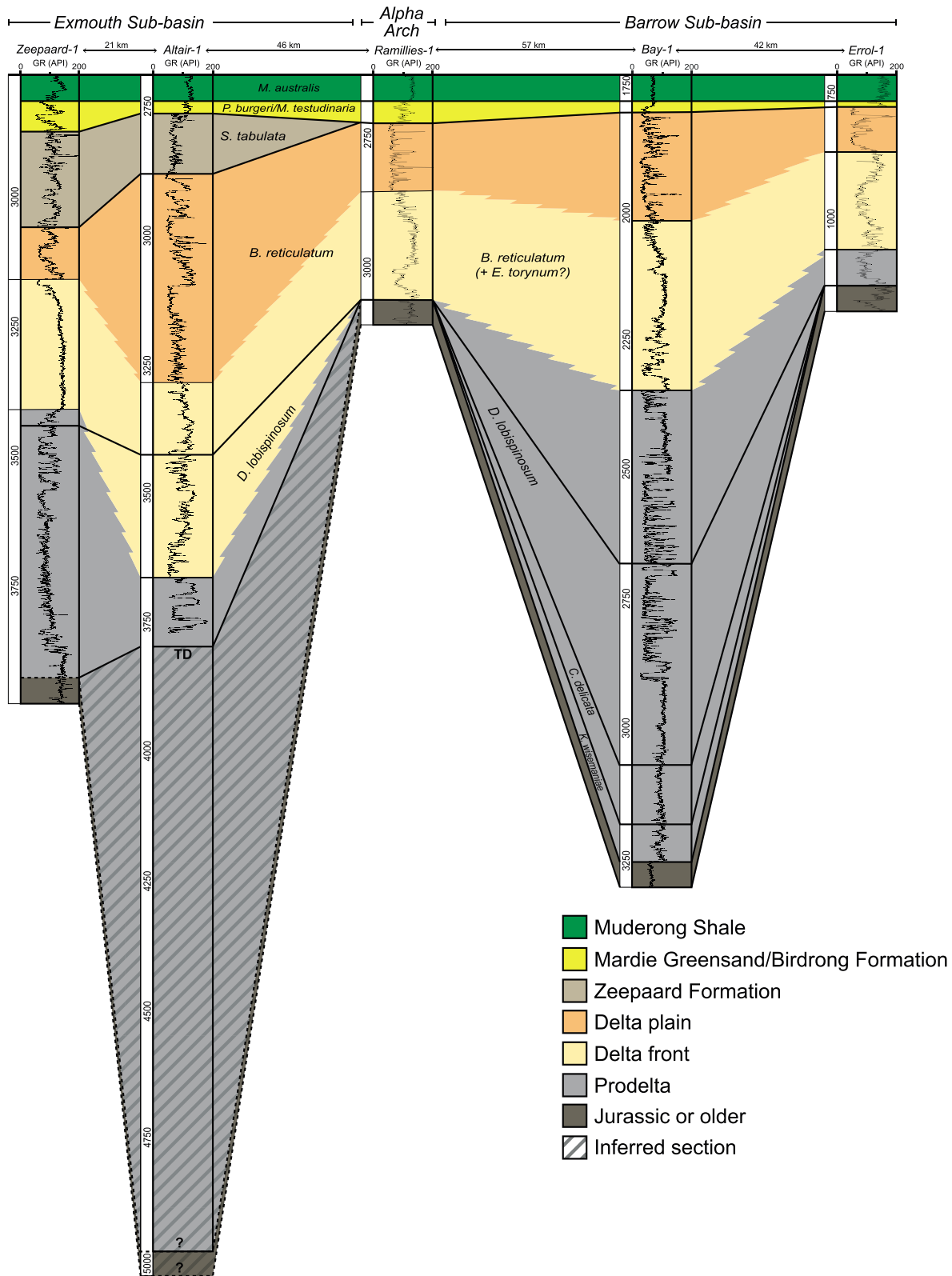
Figure 13. Along-strike E-W oriented well correlation panel showing variations in Barrow Group thickness in the Exmouth and Barrow subbasins and on the Alpha Arch. Internal facies correlation is based on well completion reports and gamma ray logs. Age correlation (black lines) is based on dinoflagellate 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.
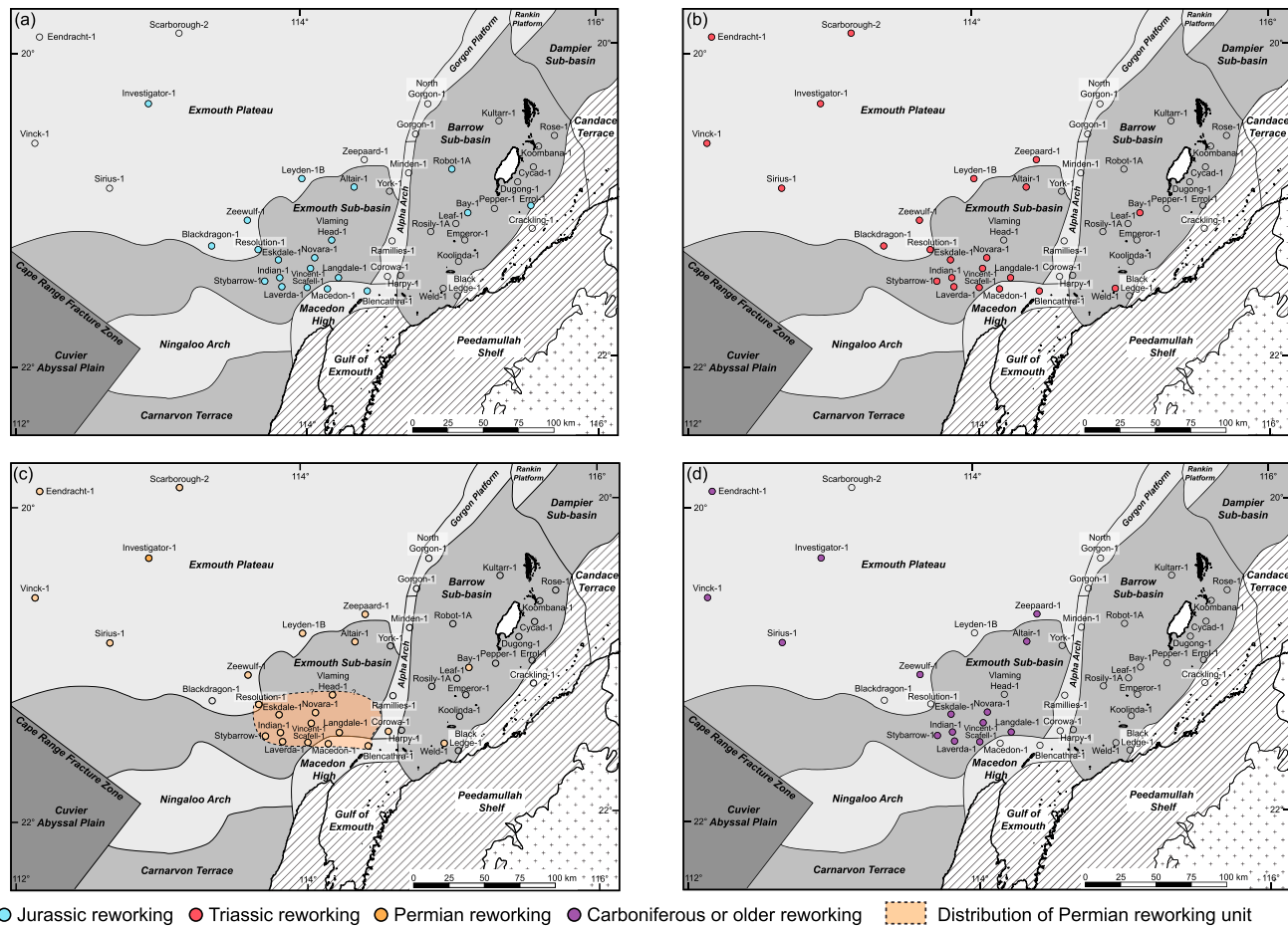
Figure 14. Map showing locations of wells where reworking of palynomorphs of (a) Jurassic, (b) Triassic, (c) Permian, and (d) Carboniferous or older age is recorded. The hollow symbols show well locations where no reworking of the given age is recorded.

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 subbasin, 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 subbasin, 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 subbasin and the Gascoyne Platform. Some stratigraphic successions in the South Carnarvon Basin have been affected by the precipitation of cements during burial [*Baker and 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 and Mory*, 1999]. In
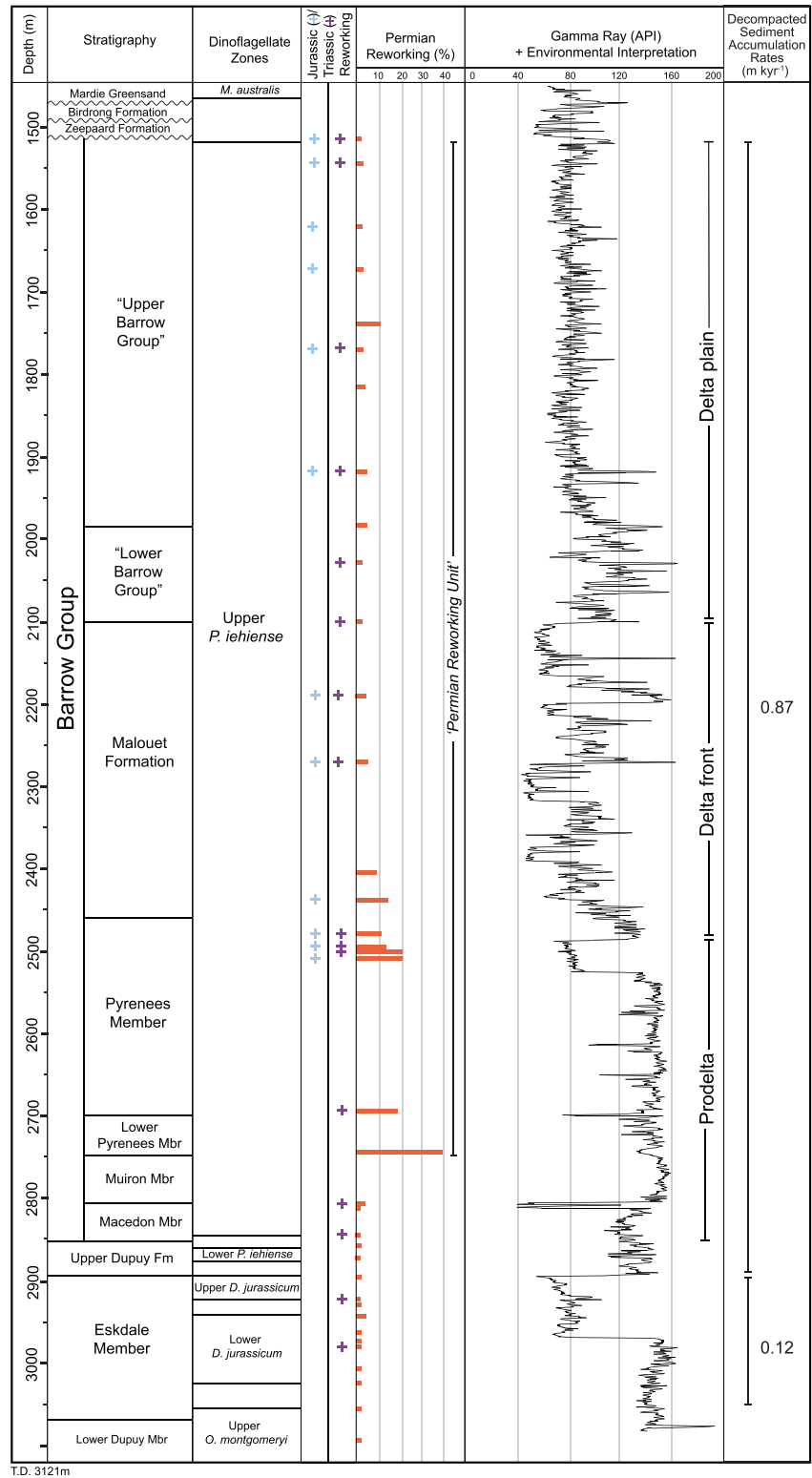
Figure 15. Type section of the Barrow Group Permian Reworking Unit encountered at Eskdale-1 in the Exmouth subbasin (location in Figure 14). The blue and purple crosses indicate the sample depths where the presence of Jurassic and Triassic age palynomorphs, respectively, was recorded. The orange bars indicate the percentage of the total palynomorph count represented at each sample depth by reworked Permian age palynomorphs. The greater abundance of reworking toward 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.
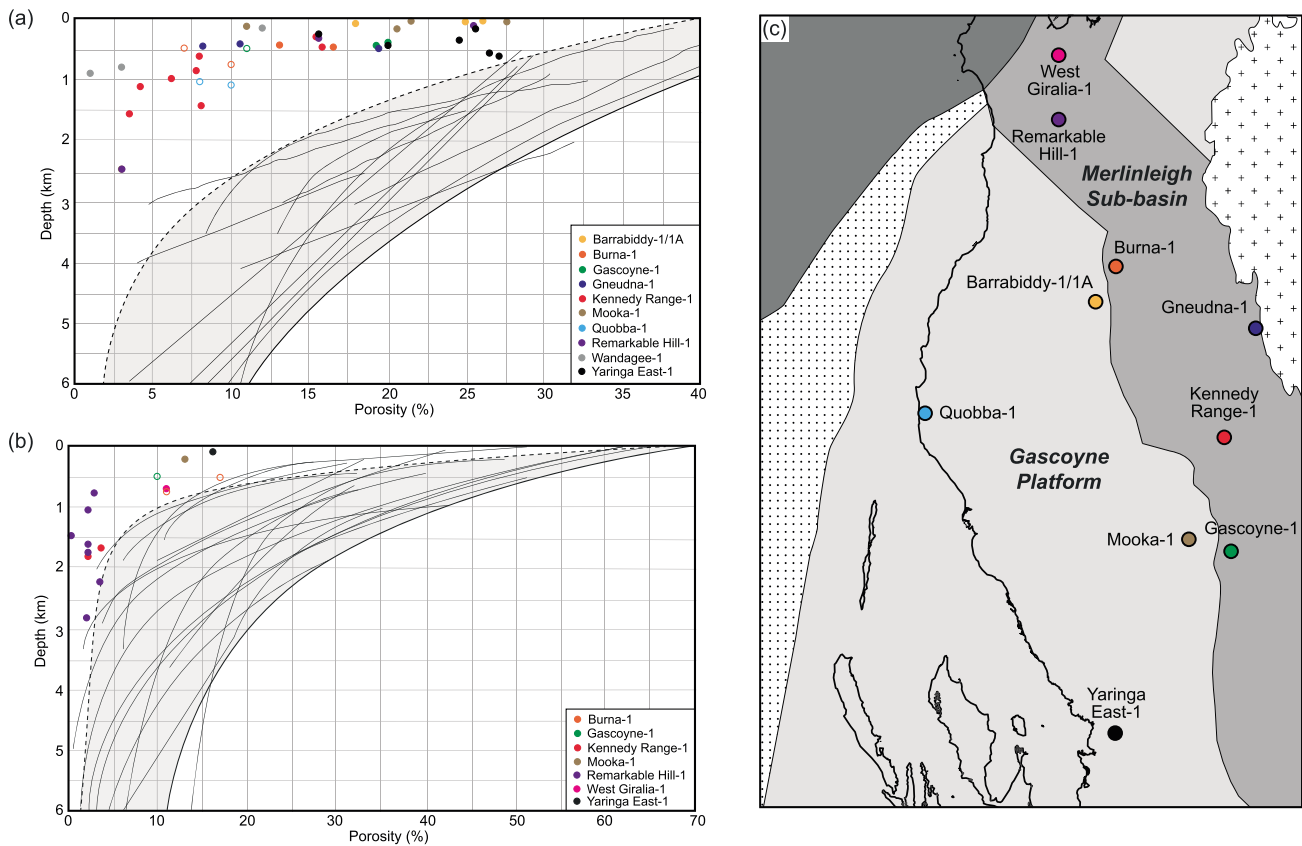
Figure 16. Porosity-depth measurements for (a) sandstones and (b) shales from the Merlinleigh subbasin and Gascoyne Platform. The filled symbols indicate the sidewall core porosity measurements, and the hollow symbols indicate the wireline-derived porosity values. The grey envelope and black lines indicate the compiled porosity-depth trends from *Giles* [1997]. (c) Map showing location of wells shown in Figures 16a and 16b.

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 Figures 16a and 16b). This comparison consistently suggests 500–1500 m of exhumation, with isolated samples suggesting values up to 2500 m exhumation. This is consistent with the results of previous thermal maturity modeling studies from the Gascoyne Platform, which indicate that 500–1800 m 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, 1-D 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 and 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
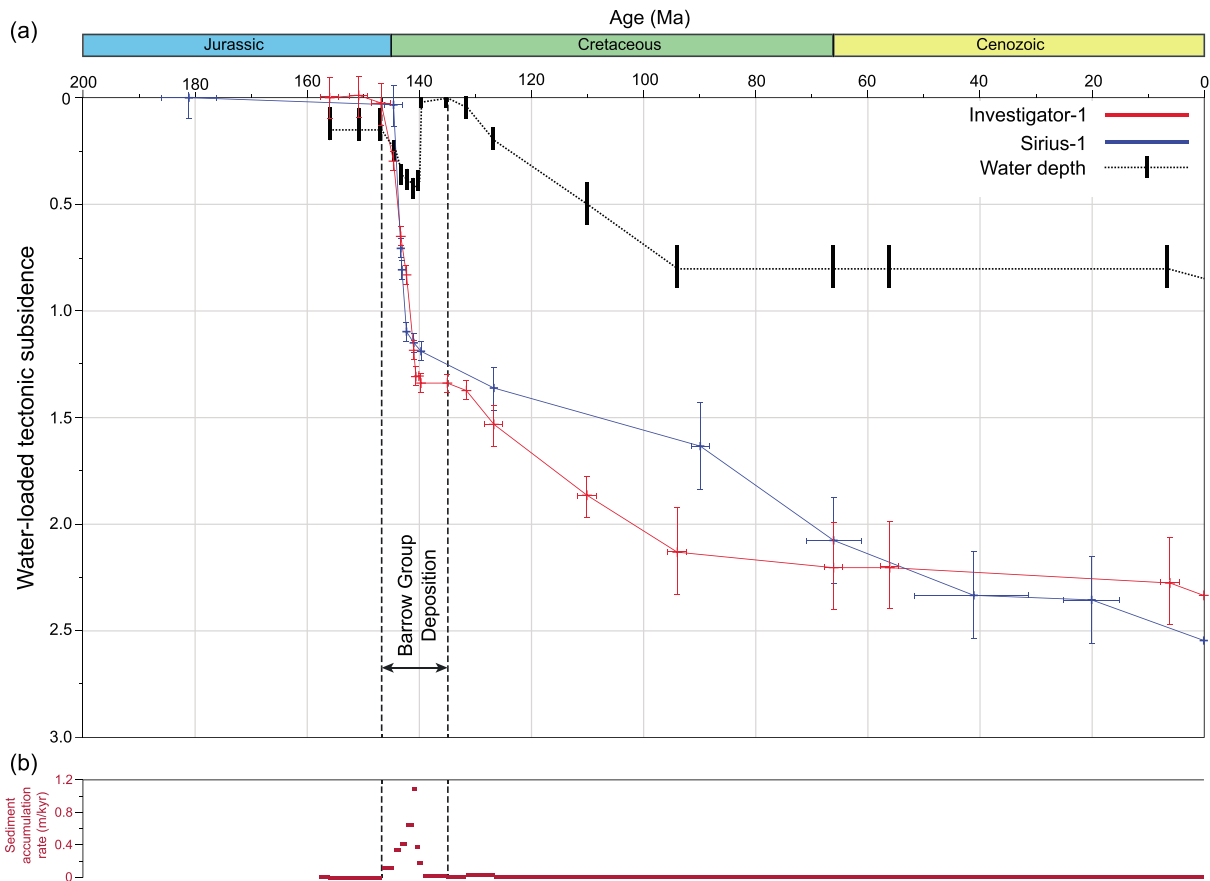
Figure 17. (a) Graph illustrating calculated water-loaded tectonic subsidence at the Exmouth Plateau wells Sirius-1 and Investigator-1 based on results of 1-D isostatic backstripping. The black bars indicate the estimated absolute water depth through time for the Investigator-1 well. The abrupt decrease in water depth at ~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 Figure 17a. Note that the horizontal axis is shared in graphs in Figures 17a and 17b.

subsequently occurs at both well locations, with ~1.35 km of subsidence occurring at Sirius-1 and 1 km at Investigator-1 between ~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.

One-dimensional decompaction of the stratigraphic succession of Eskdale-1, further southeast on the edge of the Exmouth subbasin, 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) (*Dingodinium 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 prebreakup 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 subbasin 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 and Buffler*, 1992; *Ross and Vail*, 1994; *Longley et al.*, 2002]. However, in the Exmouth Plateau depocenter, 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 (Figures 8a and 8b) [*Eriyagama et al.*, 1988; *Exon and Buffler*, 1992; *Tindale et al.*, 1998], which imply that sediment transport was to the northeast, away from the area of uplift. As the observed progradation directions are subparallel to the CRFZ, it is considered unlikely that the CRFZ was the only source of Barrow Group sediment in the Exmouth Plateau depocenter [cf. *Veevers and Powell*, 1979; *Exon and Buffler*, 1992]. Thickening of the Barrow Group toward 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 toward 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 and 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 and 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 that ≥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 and 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 nondeposition [*Iasky et al.*, 2003; *Mory et al.*, 2003] or it may signify a regional uplift event [*Mihut and Müller*, 1998]. As noted in section 4, both sandstone and shale beneath the main unconformity on the Gascoyne Platform and Merlinleigh subbasin exhibit porosity values consistent with overcompaction and exhumation. If the main unconformity was generated by a protracted period of nondeposition, 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 that 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 and 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 and Allen*, 2013], these rocks have been buried to >2 km. The Moogooloo Formation at Burna-1 occurs between 400 and 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 subbasin 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 subbasin and Exmouth Plateau depocenters, west of the Alpha Arch (Figure 14). This finding is consistent with observations from previous studies [e.g., *Exon and Buffler*, 1992; *Exon et al.*, 1992], which report similar patterns of reworking in the Barrow Group at Ocean Drilling Program well locations on the southern Exmouth Plateau. In contrast, in the Barrow subbasin 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 subbasin 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 subbasin depocenter.

In contrast, the minimal reworking of palynomorphs in Barrow Group deposits in the Barrow subbasin depocenter suggests that the 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 subbasin, which suggests that their source area was dominated by igneous and metamorphic rocks [*De Boer and Collins*, 1988; *Martin*, 2002]. We therefore suggest that sediments of the Barrow Group were eroded from different sources and that preexisting 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 subbasins 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 correlates 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 subbasin 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 and Seymour*, 1991]. Comparison of the distribution of the Yarraloola Conglomerate with modern rivers around the Peedamullah Shelf indicates that the thickest isopach trends occur subparallel to the modern courses of the Ashburton, Robe, and Cane rivers (Figure 8). This suggests that the eastern river system feeding the Barrow subbasin depocenter may have comprised the ancestral courses of these three rivers (Figure 18) [*Thomas*, 1978; *Romine and 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 subbasin (Figure 8) [*Crostella and 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
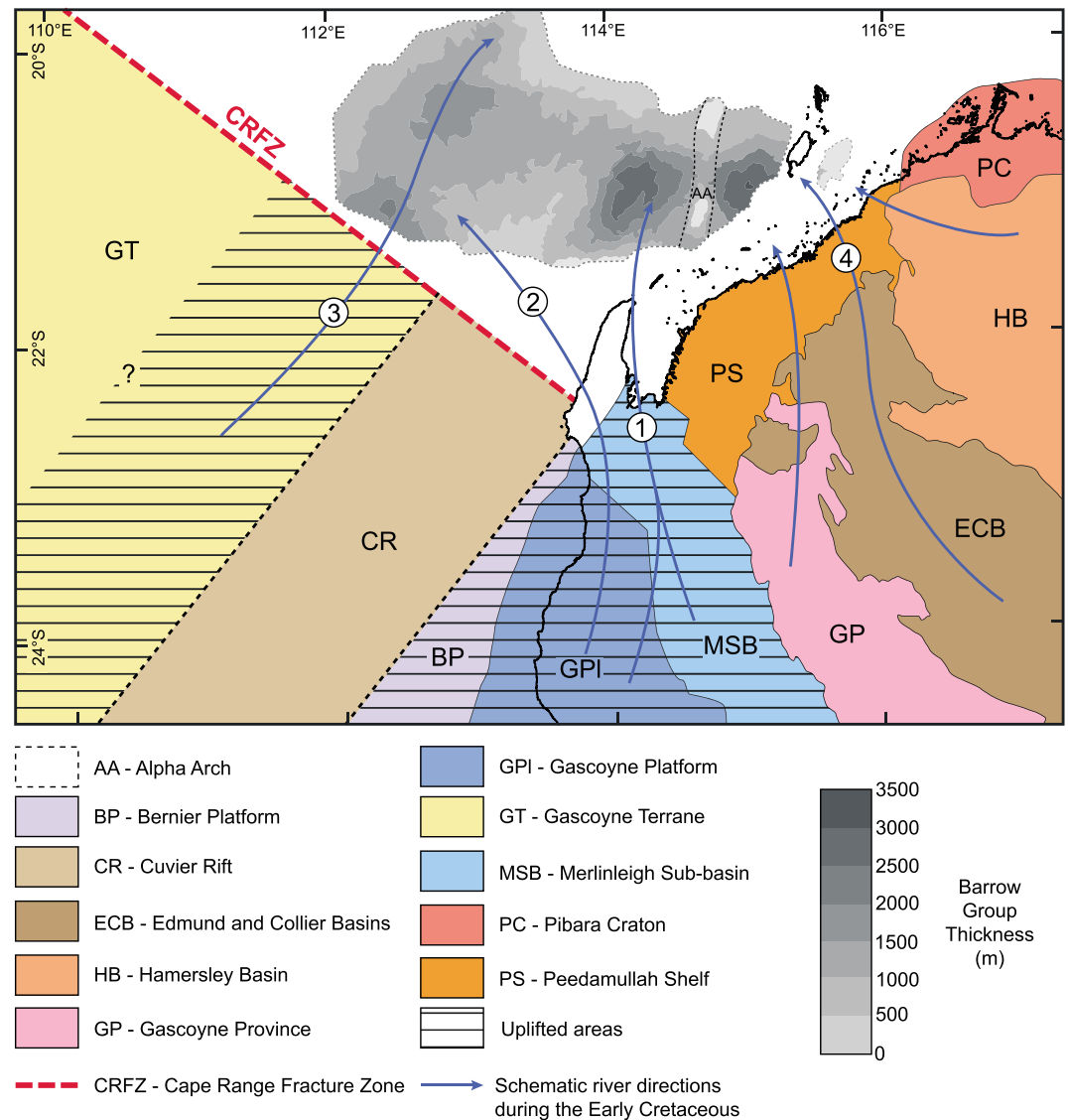
Figure 18. Summary model of Barrow Group deposition showing Barrow Group distribution, uplifted source areas, and inferred Early Cretaceous river systems. (1) North flowing river system eroding the South Carnarvon Basin and feeding the Exmouth subbasin depocenter. (2) Northwest flowing river system eroding 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 subbasin depocenter.

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 *Muderongia australis* dinoflagellate zone [*Golden West Hydrocarbons Pty Ltd*, 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
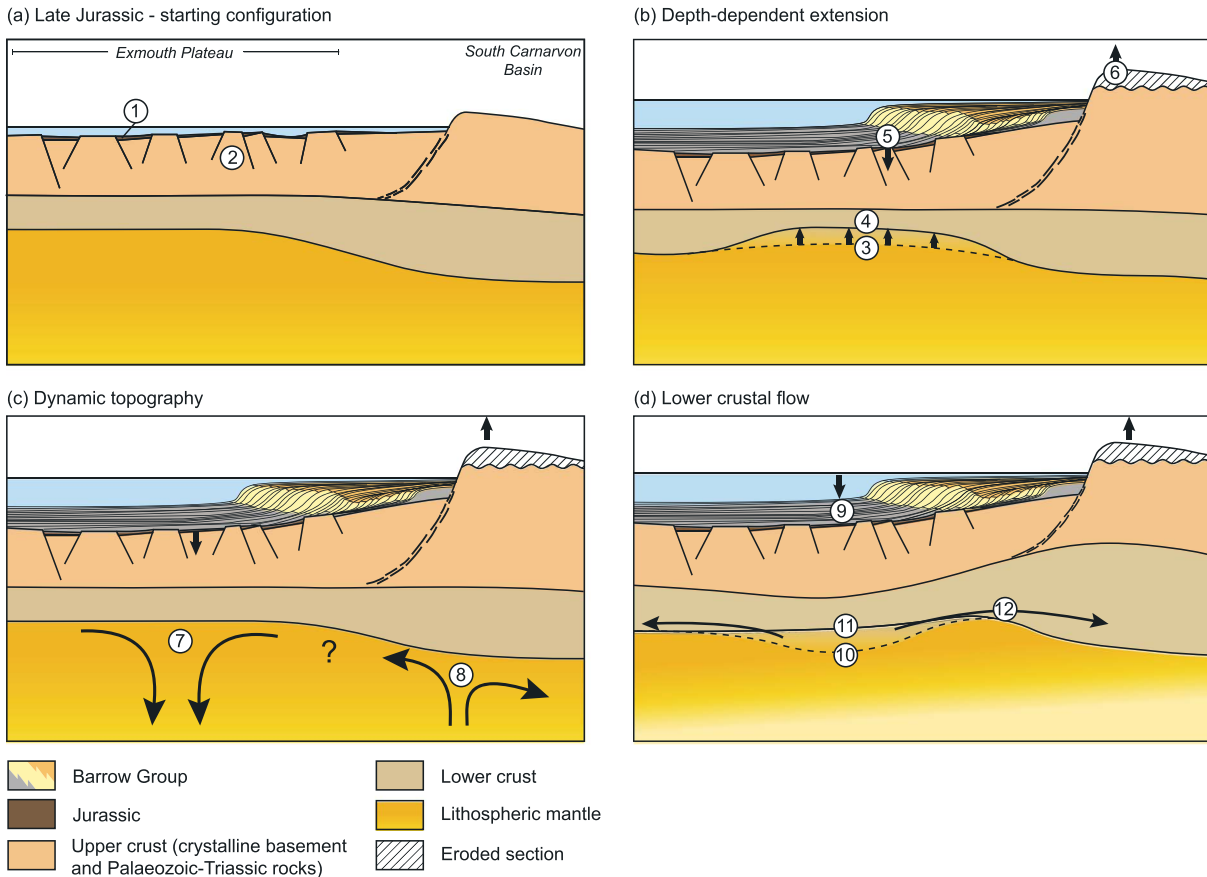
Figure 19. Schematic cross sections illustrating possible mechanisms for generation of uplift and subsidence during Barrow Group deposition. The line of section is approximately NW-SE. (a) Late Jurassic configuration prior to Barrow Group deposition. A thin, shallow marine Jurassic sequence (1) overlies 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.

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 subbasins, 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 subbasins 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 subbasin depocenter.

One of the most likely source areas of Barrow Group sediment deposited in the Exmouth subbasin 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 ~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] (~0.5 m kyr^{-1} over time scales 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 subbasin, 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 that 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 subbasin 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: in the Exmouth and Barrow subbasins and on the southwestern Exmouth Plateau. During Jurassic rifting, extension and subsidence were strongly localized in the Exmouth and Barrow subbasins, resulting in the accumulation of a thick synrift sedimentary succession [*Driscoll and 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 subbasins (Figures 4, 7, and 19a), suggesting that 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 ~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 and 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 synrift faulting (Figure 7); this observation is consistent with the those of *Driscoll and 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 ($\beta < 1.18$). 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. First, we

discuss possible causative mechanisms by which the Gascoyne Platform and Merlinleigh subbasin 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 prebreakup 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 and 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 breakup [*Stagg and Colwell*, 1994; *Driscoll and Karner*, 1998; *Huismans and Beaumont*, 2011]. Models based on depth-dependent extension allow for nonuniform 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 and 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 and Keen*, 1980; *Rowley and Sahagian*, 1986; *Allen and 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 prebreakup 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 and 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 (Figure 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 and 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 and O'Brien*, 1994; *Driscoll and 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 and 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 that subsidence took place during the Tithonian to Valanginian without significant upper crustal extension [*Driscoll and 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 and 136 Ma. Furthermore, the proposed onset of plume activity in this model is ~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 and Allen*, 2013]. The extent of the uplifted area (~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 ~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 (~300 km) [*Braun*, 2010]. The rates of tectonic subsidence at Investigator-1 and Sirius-1 during Barrow Group deposition (~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 and 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 and 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 (~1.75 km) may be insufficient to produce a sufficiently large tectonic load to drive lower crustal flow.

The model of *Morley and 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 that 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 that it is unlikely that the observed distribution and timing of Early Cretaceous uplift and the 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 subbasins 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. Prebreakup 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 prebreakup uplift and subsidence in the context of the area's overall tectonic history.

References

AGSO North West Shelf Study Group (1994), Deep reflections on the North West Shelf: changing perceptions of basin formation, in *The Sedimentary Basins of Western Australia: Proceedings of the Western Australian Basins Symposium*, edited by P. G. Purcell and R. R. Purcell, pp. 63–76, Perth.

Allen, P. A., and J. R. Allen (2013), *Basin Analysis: Principles and Application to Petroleum Play Assessment*, John Wiley & Sons, Chichester.

Arditto, P. A. (1993), Depositional sequence model for the post-Barrow Group Neocomian succession, Barrow and Exmouth sub-basins, Western Australia, *APEA J.*, *33*, 151–160.

Aslan, A., W. A. White, A. G. Warne, and E. H. Guevara (2003), Holocene evolution of the western Orinoco Delta, Venezuela, Geol. *Soc. Am. Bull.*, *115*(4), 479–498.

Backhouse, J. (2001), *Review of Selected Intervals in Macedon 1 to 5, Pyrenees 1 & 2, and Resolution 1A, Carnarvon Basin*, Woodside Energy Ltd, Perth, W. A.

Baker, J. C., and K. R. Martin (1996), Petrology, diagenesis and reservoir quality of the Moogooloo Sandstone, Southern Carnarvon basin, Western Australia, *Report S31179A1*, Geological Survey of Western Australia, Perth.

Barber, P. M. (1988), The Exmouth Plateau deep water frontier: A case history, in *The North West Shelf, Australia: Proceedings of the Petroleum Exploration Society of Australia*, edited by P. G. Purcell and R. R. Purcell, pp. 173–186, Perth.

Bassiouni, Z. (1994), *Theory, Measurement, and Interpretation of Well Logs*, Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers, Richardson, TX.

Boote, D. R., and R. B. Kirk (1989), Depositional wedge cycles on evolving plate margin, western and northwestern Australia, *AAPG Bull.*, *73*(2), 216–243.

Bradshaw, M., I. Borrisova, D. S. Edwards, G. M. Gibson, T. Hashimoto, G. J. Nelson, N. Rollet, and J. Totterdell (2012), Out of Gondwana, in *Shaping a Nation: A Geology of Australia*, edited by R. S. Blewett, pp. 173–226, ANU Press, Canberra.

Braun, J. (2010), The many surface expressions of mantle dynamics, *Nat. Geosci.*, *3*(12), 825–833.

Braun, J., and C. Beaumont (1989), A physical explanation of the relation between flank uplifts and the breakup unconformity at rifted continental margins, *Geology*, *17*(8), 760–764.

Catuneanu, O. (2006), *Principles of Sequence Stratigraphy*, Elsevier, Amsterdam.

Clift, P. D., S. Brune, and J. Quinteros (2015), Climate changes control offshore crustal structure at South China Sea continental margin, *Earth Planet. Sci. Lett.*, *420*, 66–72.

Cohen, H. A., and K. McClay (1996), Sedimentation and shale tectonics of the northwestern Niger Delta front, *Mar. Pet. Geol.*, *13*(3), 313–328.

Corcoran, D. V., and A. G. Doré (2005), A review of techniques for the estimation of magnitude and timing of exhumation in offshore basins, *Earth Sci. Rev.*, *72*(3–4), 129–168.

Crostella, A., and R. P. Iasky (1997), *Structural Interpretation and Hydrocarbon Potential of the Giralia Area, Carnarvon Basin*, 38 pp., Geological Survey of Western Australia, Perth.

Crostella, A., R. P. Iasky, K. A. Blundell, A. R. Yasin, and K. A. R. Ghori (2000), *Petroleum Geology of the Peedamullah Shelf and Onslow Terrace, Northern Carnarvon Basin, Western Australia*, 119 pp., Geological Survey of Western Australia, Perth.

Daradich, A., J. X. Mitrovica, R. N. Pysklywec, S. D. Willett, and A. M. Forte (2003), Mantle flow, dynamic topography, and rift-flank uplift of Arabia, *Geology*, *31*(10), 901–904.

De Boer, R., and L. B. Collins (1988), Petrology and diagenesis of the Flag Sandstone, Harriet Field, Barrow Sub-Basin, in *The North West Shelf, Australia: Proceedings of the Petroleum Exploration Society of Australia*, edited by P. G. Purcell and R. R. Purcell, pp. 225–235, Perth.

Dickinson, W. R. (1988), Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins, in *New Perspectives in Basin Analysis*, edited by K. L. Kleinspehn and C. Paola, pp. 3–25, Springer, New York.

Driscoll, N. W., and G. D. Karner (1998), Lower crustal extension across the Northern Carnarvon basin, Australia: Evidence for an eastward dipping detachment, *J. Geophys. Res.*, *103*(B3), 4975–4991, doi:10.1029/97JB03295.

Dunbar, J. A., and D. S. Sawyer (1989), How preexisting weaknesses control the style of continental breakup, *J. Geophys. Res.*, *94*(B6), 7278–7292, doi:10.1029/JB094iB06p07278.

Eriyagama, S., L. Collins, and R. Hocking (1988), Depositional framework and major lithostratigraphic variations of the Barrow Group, paper presented at The North West Shelf, Australia. Proc. Pet. Explor. Soc. Aust. Symp.

Espurt, N., J.-P. Callot, J. Totterdell, H. Struckmeyer, and R. Vially (2009), Interactions between continental breakup dynamics and large-scale delta system evolution: Insights from the Cretaceous Ceduna delta system, Bight Basin, Southern Australian margin, *Tectonics*, *28*, TC6002, doi:10.1029/2009TC002447.

Etheridge, M. A., and G. W. O'Brien (1994), Structural and tectonic evolution of the Western Australian margin basin system, *Petrol. Explor. Soc. Aust. J.*, *22*, 45–63.

Exon, N., and R. T. Buffler (1992), Mesozoic seismic stratigraphy and tectonic evolution of the western Exmouth Plateau, in *Proceedings of the Ocean Drilling Program, Scientific Results*, edited by U. Von Rad et al., pp. 61–81, Ocean Drilling Program, College Station, Tex.

Exon, N., B. Haq, and U. Von Rad (1992), Exmouth Plateau revisited: Scientific drilling and geological framework, in *Proceedings of the Ocean Drilling Program, Scientific Results*, edited by U. Von Rad et al., pp. 3–20, Ocean Drilling Program, College Station, Tex.

Galloway, W. E. (1989), Genetic stratigraphic sequences in basin analysis II: Application to northwest Gulf of Mexico Cenozoic basin, *AAPG Bull.*, *73*(2), 143–154.

Gartrell, A. P. (2000), Rheological controls on extensional styles and the structural evolution of the Northern Carnarvon Basin, North West Shelf, Australia, *Aust. J. Earth Sci.*, *47*(2), 231–244.

Gessner, K., T. Jones, J. A. Goodwin, L. A. Gallardo, P. R. Milligan, J. Brett, and R. Murdie (2013), Interpretation of magnetic and gravity data across the Southern Carnarvon Basin, and the Narryer and Youanmi Terranes, in *Youanmi and Southern Carnarvon Seismic and Magnetotelluric (MT) Workshop 2013*, edited by S. Wyche, T. J. Ivanic, and I. Zibra, pp. 65–77, Geological Survey of Western Australia.

Ghori, K. A. R. (1999), Silurian–Devonian petroleum source-rock potential and thermal history, Carnarvon Basin, Western Australia, *Rep. 72*, Geological Survey of Western Australia, Perth.

Gibbons, A. D., U. Barckhausen, P. van den Bogaard, K. Hoernle, R. Werner, J. M. Whittaker, and R. D. Müller (2012), Constraining the Jurassic extent of Greater India: Tectonic evolution of the West Australian margin, *Geochem. Geophys. Geosyst.*, *13*, Q05W13, doi:10.1029/2011GC003919.

Giles, M. R. (1997), *Diagenesis: A Quantitative Perspective. Implications for Basin Modelling and Rock Property Prediction*, pp. 526, Kluwer Acad., Dordrecht, Netherlands.

Golden West Hydrocarbons Pty Ltd (1985), North Giralia No. 1 Well Completion Report, Carnarvon Basin, Western Australia, Perth, W. A.

Haq, B. U., J. Hardenbol, and P. R. Vail (1988), Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change, in *Sea-level Changes: An integrated approach*, edited by C. K. Wilgus et al., pp. 40–45.

Harwood, J., A. C. Aplin, C. I. Fialips, J. E. Iliffe, R. Kozdon, T. Ushikubo, and J. W. Valley (2013), Quartz cementation history of sandstones revealed by high-resolution SIMS Oxygen Isotope Analysis, *J. Sediment. Res.*, *83*(7), 522–530.

Helby, R., R. Morgan, and A. Partridge (1987), A palynological zonation of the Australian Mesozoic, *Mem. Assoc. Australas. Paleontol.*, *4*, 1–94.

Hocking, R. M. (1988), Regional geology of the northern Carnarvon basin, in *The North West Shelf, Australia: Proceedings of the Petroleum Exploration Society of Australia*, edited by P. G. Purcell and R. R. Purcell, pp. 21–43, Perth.

Hocking, R. M. (1992), *Jurassic Deposition in the Southern and Central North West Shelf, Western Australia*, pp. 101, Geological Survey of Western Australia, Perth.

Hocking, R. M. (2000), *Geology of the Southern Carnarvon Basin, Western Australia - A Field Guide*, pp. 102, Geological Survey of Western Australia, Perth.

Hocking, R. M., H. T. Moors, and W. J. E. Van de Graff (1987), *Geology of the Carnarvon Basin Western Australia*, pp. 289, Geological Survey of Western Australia, Perth.

Hocking, R. M., J. W. K. Voon, and L. B. Collins (1988), Stratigraphy and sedimentology of the Basal Winning Group, in *The North West Shelf, Australia: Proceedings of the Petroleum Exploration Society of Australia*, edited by P. G. Purcell and R. R. Purcell, pp. 203–224, Perth.

Hooker, N. P. (2003), *Palynological Review of Selected Wells, Exmouth Sub-Basin, Carnarvon Basin, Western Australia (Phase 2, New Analyses)*, Morgan Palaeo Associates, Maitland, SA.

Hopper, J. R., J. C. Mutter, R. L. Larson, and C. Z. Mutter (1992), Magmatism and rift margin evolution: Evidence from northwest Australia, *Geology*, *20*(9), 853–857.

Huismans, R., and C. Beaumont (2011), Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins, *Nature*, *473*(7345), 74–78.

Hurren, C., G. O'Halloran, G. Duncan, and R. Hill (2013), Detailed dtratigraphic architecture of the Macedon Member turbidite reservoirs of the Stybarrow Field, NW Australia: An integration of well, production and 3D/4D seismic data, in *The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by M. Keep and S. J. Moss, Perth.

Iasky, R. P., and A. J. Mory (1999), *Geology and Petroleum Potential of the Gascoyne Platform, Southern Carnarvon Basin, Western Australia*, Geological Survey of Western Australia, Perth.

Iasky, R. P., A. J. Mory, K. A. R. Ghori, and S. I. Shevchenko (1998), *Structure and Petroleum Potential of the Southern Merlinleigh Sub-Basin, Carnarvon Basin, Western Australia*, Geological Survey of Western Australia, Perth.

Iasky, R. P., C. D'Ercole, K. A. R. Ghori, A. J. Mory, and A. M. Lockwood (2003), *Structure and Petroleum Prospectivity of the Gascoyne Platform, Western Australia*, pp. 56, Geological Survey of Western Australia, Perth.

Immenhauser, A. (2009), Estimating palaeo-water depth from the physical rock record, *Earth Sci. Rev.*, *96*(1–2), 107–139.

Ingram, B. S. (1990), Tent Hill No. 1 Palynology Report, in *Tent Hill-1 Well Completion Report*, Minora Resources NL, Perth, W. A.

Ingram, B. S. (1996), *Palynology Report WP 17/96 Study of a Limited Interval From Cunaloo No. 1*, Western Palynoservices, Dianella W. A.

James, A. (2004), *Eskdale-1 Well Completion Report Interpretive Volume*, BHP Petroleum Pty Ltd, Perth, W. A.

Jitmahantakul, S., and K. R. McClay (2013), Late Triassic–Mid-Jurassic to Neogene extensional fault systems in the Exmouth Sub-Basin, Northern Carnarvon Basin, North West Shelf, Western Australia, in *The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by M. Keep and S. J. Moss, Perth.

Kelman, A. P., R. S. Nicoll, J. M. Kennard, A. J. Mory, D. J. Mantle, S. le Poidevin, G. Bernardel, N. Rollet, and D. Edwards (2013), *Northern Carnarvon Basin Biozonation and Stratigraphy*, Geoscience Australia.

King, R. C., and G. Backé (2010), A balanced 2D structural model of the Hammerhead Delta–Deepwater Fold-Thrust Belt, Bight Basin, Australia, *Aust. J. Earth Sci.*, *57*(7), 1005–1012.

Labutis, V. R. (1994), Sequence stratigraphy and the North West Shelf of Australia, in *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by P. G. Purcell and R. R. Purcell, pp. 159–180, Perth.

Lewis, C. J., and K. N. Sircombe (2013), Use of U-Pb geochronology to delineate provenance of North West Shelf sediments, Australia, in *The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by M. Keep and S. J. Moss, Perth.

Locke, A. (2004), *Stybarrow-1/1CH Well Completion Report Interpretive Volume*, BHP Billiton Petroleum Pty Ltd, Perth, W. A.

Lockwood, A. M., and C. D'Ercole (2003), *Geophysical Investigation of the Bernier Ridge and Surrounding Area, Southern Carnarvon Basin, Western Australia*, pp. 53, Geological Survey of Western Australia, Perth.

Longley, I. M., C. Buessenschuett, L. Clydsdale, C. Cubitt, R. Davis, M. K. Johnson, N. M. Marshall, A. P. Murray, R. Somerville, and T. B. Spry (2002), The North West Shelf of Australia—A Woodside perspective, in *The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by M. Keep and S. J. Moss, pp. 27–88, Perth.

Lorenzo, J. M. (1997), Sheared continent-ocean margins: An overview, *Geo Mar. Lett.*, *17*(1), 1–3.

Lorenzo, J. M., and E. E. Vera (1992), Thermal uplift and erosion across the continent-ocean transform boundary of the southern Exmouth Plateau, *Earth Planet. Sci. Lett.*, *108*(1–3), 79–92.

Macphail, M. (2007), Australian palaeoclimates: Cretaceous to Tertiary - A review of palaeobotanical and related evidence to the year 2000, 266 pp., CRC LEME Special Volume Open File Report 151.

Magee, C., O. B. Duffy, K. Purnell, R. E. Bell, C. A. L. Jackson, and M. T. Reeve (2015), Fault-controlled fluid flow inferred from hydrothermal vents imaged in 3D seismic reflection data, offshore NW Australia, *Basin Res.*, 1–20.

Martin, K. R. (2002), Petrography of rotary sidewall core samples from the Mardie Greensand and Top Barrow Group in Errol-1, TR-1, Barrow Sub-Basin, in *Errol-1 Well Completion Report Interpretive Data*, Apache Energy Limited, Perth, W. A.

Martin, D. M., S. Sheppard, A. M. Thorne, T. R. Farrell, and P. B. Groenewald (2007), *Proterozoic Geology of the Western Capricorn Orogen — A Field Guide*, Geological Survey of Western Australia, Perth.

MacDonald, J., G. Backé, R. King, S. Holford, and R. Hillis (2012), Geomechanical modelling of fault reactivation in the Ceduna Sub-basin Bight Basin, Australia, *Geol. Soc. London, Spec. Publ.*, *367*(1), 71–89.

McLoughlin, S., D. W. Haig, J. Backhouse, M. A. Holmes, G. Ellis, J. A. Long, and K. J. McNamara (1995), Oldest Cretaceous sequence, Giralia Anticline, Carnarvon Basin, Western Australia: Late Hauterivian-Barremian, *AGSO J. Aust. Geol. Geophys.*, *15*(4), 445–468.

Mihut, D., and R. D. Müller (1998), Volcanic margin formation and Mesozoic rift propagators in the Cuvier Abyssal Plain off Western Australia, *J. Geophys. Res.*, *103*(B11), 27,135–27,149, doi:10.1029/97JB02672.

Morley, C. K., and R. Westaway (2006), Subsidence in the super-deep Pattani and Malay basins of Southeast Asia: A coupled model incorporating lower-crustal flow in response to post-rift sediment loading, *Basin Res.*, *18*(1), 51–84.

Mory, A. J., R. P. Iasky, and K. A. R. Ghori (2003), *A Summary of the Geological Evolution and Petroleum Potential of the Southern Carnarvon Basin, Western Australia*, pp. 26, Geological Survey of Western Australia, Perth.

Muller, J. (1959), Palynology of recent Orinoco delta and shelf sediments: Reports of the Orinoco Shelf Expedition; Volume 5, *Micropaleontology*, *5*(1), 1–32.

Müller, R., D. Mihut, C. Heine, C. O'Neill, and I. Russell (2002), Tectonic and volcanic history of the Carnarvon Terrace: Constraints from seismic interpretation and geodynamic modelling, in *The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by M. Keep and S. J. Moss, pp. 719–740, Perth.

Myers, J. S. (1990), Precambrian tectonic evolution of part of Gondwana, southwestern Australia, *Geology*, *18*(6), 537–540.

O'Halloran, G., C. Hurren, and T. O'Hara (2013), Seismic stratigraphic relationships within a lowstand reservoir system: Examples from the Barrow Group, Southern Exmouth Sub-Basin, NW Australia, in *The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by M. Keep and S. J. Moss, Perth.

Patruno, S., G. J. Hampson, and C. A. L. Jackson (2015), Quantitative characterisation of deltaic and subaqueous clinoforms, *Earth Sci. Rev.*, *142*, 79–119.

Percival, I. G. (1985), *Burna-1 Well Completion Report, Merlinleigh Sub-basin, Western Australia*, Esso Australia Limited, Sydney, NSW.

Plint, A. G., and J. A. Wadsworth (2006), Delta-plain paleodrainage patterns reflect small-scale fault movement and subtle forebulge uplift: Upper Cretaceous Dunvegan Formation, Western Canada Foreland Basin, in *Incised-Valley Systems in Time and Space*, edited by R. W. Dalrymple, D. A. Leckie and R. W. Tillman, pp. 219–237.

Purcell, P. G., and R. R. Purcell (1988), The North West Shelf, Australia—An introduction, in *The North West Shelf, Australia: Proceedings of the Petroleum Exploration Society of Australia*, edited by P. G. Purcell and R. R. Purcell, pp. 3–15, Perth.

Rapaic, M., and D. Christiansen (1996), *Bay 1 Well Completion Report Volume 1*, Western Mining Petroleum, Perth, W. A.

Rohrman, M. (2015), Delineating the Exmouth mantle plume (NW Australia) from denudation and magmatic addition estimates, *Lithosphere*, *7*(5), 589–600.

Romine, K., and J. Durrant (1996), *Carnarvon Cretaceous-Tertiary Tie Report*, Australian Geological Survey Organisation, Canberra.

Rosenbaum, G., R. F. Weinberg, and K. Regenauer-Lieb (2008), The geodynamics of lithospheric extension, *Tectonophysics*, *458*(1–4), 1–8.

Ross, M. I., and P. R. Vail (1994), Sequence stratigraphy of the lower Neocomian Barrow Delta, Exmouth Plateau, northwestern Australia, in *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by P. G. Purcell and R. R. Purcell, pp. 435–447, Perth.

Rowley, D. B., and D. Sahagian (1986), Depth-dependent stretching: A different approach, *Geology*, *14*(1), 32–35.

Royden, L., and C. E. Keen (1980), Rifting process and thermal evolution of the continental margin of Eastern Canada determined from subsidence curves, *Earth Planet. Sci. Lett.*, *51*(2), 343–361.

Sadler, P. M. (1999), The influence of hiatuses on sediment accumulation rates, *GeoRes. Forum*, *5*(1), 15–40.

Sahagian, D., O. Pinous, A. Olferiev, and V. Zakharov (1996), Eustatic curve for the Middle Jurassic--Cretaceous based on Russian platform and Siberian stratigraphy: Zonal resolution, *AAPG Bull.*, *80*(9), 1433–1458.

Schumm, S. A., J. F. Dumont, and J. M. Holbrook (2000), *Active Tectonics and Alluvial Rivers, Cambridge Univ*. Press, Cambridge.

Scibiorski, J., M. Micenko, and D. Lockhart (2005), Recent discoveries in the Pyrenees Member, Exmouth Sub-basin: A new oil play fairway, *APPEA J.*, *45*(1), 233–251.

Smith, N., C. Dempsey, M. Jackson, and J. Preston (2002), Overcoming historical biases: An integrated geological and engineering assessment of the Coniston prospect, Exmouth Sub-basin, in *The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by M. Keep and S. J. Moss, pp. 363–383, Perth.

Stagg, H., and J. Colwell (1994), The structural foundations of the Northern Carnarvon Basin, in *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, edited by P. G. Purcell and R. R. Purcell, pp. 349–364, Perth.

Stagg, H. M. J., M. B. Alcock, G. Bernardel, A. M. G. Moore, P. A. Symonds, and N. F. Exon (2004), *Geological Framework of the Outer Exmouth Plateau and Adjacent Ocean Basins*, Geoscience Australia.

Sydow, J., and H. H. Roberts (1994), Stratigraphic framework of a late Pleistocene shelf-edge delta, northeast Gulf of Mexico, *AAPG Bull.*, *78*(8), 1276–1312.

Symonds, P., S. Planke, O. Frey, and J. Skogseid (1998), Volcanic evolution of the Western Australian continental margin and its implications for basin development, in *The Sedimentary Basins of Western Australia 2: Proceedings of the Petroleum Exploration Society of Australia*, edited by P. G. Purcell and R. R. Purcell, pp. 33–54, Perth.

Tait, A. (1985), A depositional model for the Dupuy Member and the Barrow Group in the Barrow Sub-basin, northwestern Australia, *APEA J.*, *25*, 282–290.

Tassone, D. R., S. P. Holford, M. S. Stoker, P. Green, H. Johnson, J. R. Underhill, and R. R. Hillis (2014), Constraining Cenozoic exhumation in the Faroe-Shetland region using sonic transit time data, *Basin Res.*, *26*(1), 38–72.

Taylor, B., A. M. Goodliffe, and F. Martinez (1999), How continents break up: Insights from Papua New Guinea, *J. Geophys. Res.*, *104*(B4), 7497–7512, doi:10.1029/1998JB900115.

Thomas, B. M. (1978), Robe River—An onshore shallow oil accumulation, *APEA J.*, *18*, 3–12.

Thorne, A. M., and D. B. Seymour (1991), *Geology of the Ashburton Basin*, pp. 141, Geological Survey of Western Australia, Perth.

Tindale, K., N. Newell, J. Keall, and N. Smith (1998), Structural evolution and charge history of the Exmouth Sub-basin, northern Carnarvon Basin, Western Australia, in *The Sedimentary Basins of Western Australia 2: Proceedings of the Petroleum Exploration Society of Australia*, edited by P. G. Purcell and R. R. Purcell, pp. 473–490, Perth.

Twartz, S. K. (1981a), *Eendracht-1 Well Completion Report, Exmouth Plateau, Western Australia*, Esso Australia Limited, Sydney, NSW.

Twartz, S. K. (1981b), *Sirius-1 Well Completion Report, Exmouth Plateau, Western Australia*, Esso Australia Limited, Sydney, NSW.

Van Andel, T. H. (1967), The Orinoco Delta, *J. Sediment. Petrol.*, *37*(2), 297–310.

Veevers, J. J., and C. M. A. Powell (1979), Sedimentary-wedge progradation from transform-faulted continental rim: Southern Exmouth Plateau, Western Australia: Geologic notes, *AAPG Bull.*, *63*(11), 2088–2096.

Wernicke, B. (1985), Uniform-sense normal simple shear of the continental lithosphere, *Can. J. Earth Sci.*, *22*(1), 108–125.

Yasin, A. R., and A. J. Mory (1999), *Yaringa East 1 Well Completion Report, Gascoyne Platform, Southern Carnarvon Basin, Western Australia*, 53 pp., Geological Survey of Western Australia.