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Middle Miocene tropical oligotrophic lagoon deposit sheds light on the origin of the Western Australian coral reef province

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A R T I C L E I N F O

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A B S T R A C T

The Western Australian margin is a unique coral reef province, with modern coral reef development occurring at latitudes as far south as 29°S. The genesis of this coral reef province may go back to the Oligo-Miocene, since geological features ~30 million-year-old and younger interpreted as coral reefs are known from offshore seismic surveys. The nature of these seismic reefs is, however, uncertain, as they are only sparsely sampled, and as time-equivalent outcrops are only present in a few remote and understudied locations. This study investigates middle Miocene shallow-water limestones with tropical fauna formed along the North West Shelf (NWS) between ~13 Ma and ~15 Ma, when the southward extension of the seismic reefs was at its maximum. The outcrops and cores investigated are dominantly composed of peloidal packstones and micritic floatstones containing larger benthic foraminifera, *Halimeda* sp. and scleractinian corals, including reef-building genera, that accumulated in a protected and oligotrophic, warm-water lagoonal environment. Climate was therefore warm during the middle Miocene acme of seismic reefs development, despite the NWS being located ~7° further south than its present position at that time. Results of this investigation also support the existence of a strong southward flowing Leeuwin-current-style oceanic circulation during the middle Miocene, which could have transported fauna from south-east Asia along the Western Australian margin. Development of the lagoon and seismic reefs may have also been promoted by middle Miocene aridification of the coast bordering the NWS, and by repeated eustatic-driven exposures of the NWS.

1. Introduction

Western Australia is a modern coral reef province located along the western margin of a continent with coral reefs and coral colonies developing respectively at latitudes as far south as 29°S and 32°S (Collins, 2002; Fairbridge, 1950; Gallagher et al., 2017a; Hatcher, 1991). This latitudinal extent is unusual, as elsewhere coral reefs do not develop at latitudes higher than 2°S along western margins of continents (Kiessling, 2001), and as, for comparison, the Pacific atolls are restricted to the tropics (Darwin, 1842; Hatcher, 1991). This coral reef latitudinal extent is due to the impact of the south-flowing Leeuwin Current (Collins, 2002; Gallagher et al., 2014; Hatcher, 1991), which warms the margin of the western Australian coast and suppresses coastal upwelling (James et al., 2004; Karas et al., 2011; Smith, 1992).

Types of coral reefs are diverse along the western margin of Australia, and include fringing reefs (i.e., Ningaloo Reef), isolated oceanic reefs rising from water depths of up to 700 m (e.g., Rowley Shoals, Scott Reef, Seringapatam Reef, Houtman Abrolhos reefs, Ashmore Reef), island-associated shelf reefs in both turbid tropical waters (e.g., reefs of the Kimberley coast) and clear tropical waters (e.g., Dampier Archipelago), and island-associated offshore reefs (e.g., Pilbara reefs, including those around Barrow Island and the Montebello Islands, *Pocillopora* reefs at Rottnest Island; Fairbridge, 1950; Hatcher, 1991; Collins et al., 2000, 2015; Collins, 2002; Collins and Testa, 2011; Kordi and O'Leary, 2016).

Coral reefs may have started to develop ~30 million years ago, as interpretation of 2D and 3D reflection seismic datasets showed the presence of Oligo-Miocene seismic reefs (sensu Schlager, 2005) along the Australian North West Shelf (NWS; Jones, 1973; Bradshaw et al., 1988; Romine et al., 1997; Young, 2001; Collins, 2002; Gorter et al., 2002; Cathro et al., 2003; Power, 2008; Ryan et al., 2009; Liu et al., 2011; Rosleff-Soerensen et al., 2012, 2016; Saqab and Bourget, 2016;

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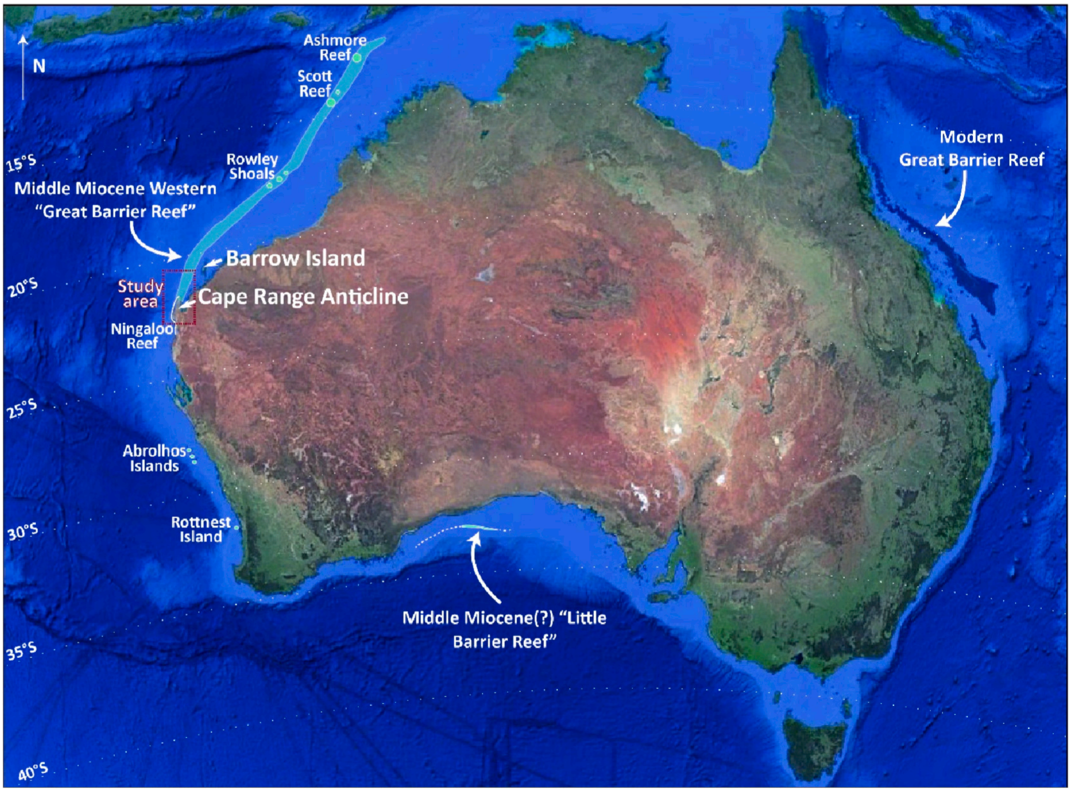

Fig. 1. Possible extent of the middle Miocene seismic reef tract (NWS extent after McCaffrey et al., 2020; "Little Barrier Reef" extent after Feary and James, 1995 and O'Connell et al., 2012) compared with the location of the modern coral reefs along the coast of Western Australia, and the modern Great Barrier Reef. Base map from Google Earth.

Belde et al., 2017; Van Tuyl et al., 2018a, 2018b, 2019; Anell and Wallace, 2020; McCaffrey et al., 2020). During the middle Miocene (i.e., 16–15 Ma; McCaffrey et al., 2020), the seismic reefs were forming a ~2000 km long reef tract, possibly concomitant with the development of the 'Little Barrier Reef' – another seismic reef - in the Bight Basin (Feary and James, 1995; O'Connell et al., 2012; Fig. 1).

This seismic reef tract is one of the largest fossil reef tracts discovered yet (Kiessling, 2001; Fig. 1). To date, however, none of these seismic reefs have been cored, descriptions of time equivalent outcrops and cores are few (Condon et al., 1955; Apthorpe, 1965; Chaproniere, 1975, 1977; McNamara and Kendrick, 1994; Collins et al., 2006; Riera et al., 2019) and Oligo-Miocene coral framestones are undescribed in Australia. Additionally, if the geological maps of the Cape Range Anticline indicate the presence of Miocene coralgal limestones and possibly reefal facies (van de Graaff et al., 1982; Van de Graaff et al., 1980), a more recent field investigation points toward an absence of Miocene reefal facies in the Cape Range area, with possibly a climate "too cold for prolific coral reef production" (Collins et al., 2006, p. 13).

The presence of Miocene fossil coral-reefs along the Western Australian margin is, however, to be expected, as field investigations of the Miocene Nullarbor Limestone – cropping out more than 1000 km southeast of the NWS - revealed the presence of zooxanthellate corals at a palaeo-latitude of ~40°S (O'Connell et al., 2012). Additionally, late Oligocene to Miocene debris of corals were observed in the northern, offshore part of the NWS (i.e., Timor Sea, Browse Basin area and Roebuck Basin area) from well cuttings (Apthorpe, 1988; Gallagher et al., 2017b; Gorter et al., 2002; McCaffrey et al., 2020). Finally, there is global development of reefs during the Oligo-Miocene, and Oligo-Miocene tropical platforms with reefs are described from the Indian Ocean, Pacific Ocean and Atlantic Ocean (see reviews from Kiessling, 2001; Perrin, 2002; Michel et al., 2020). Oligo-Miocene reefal environments are particularly abundant in the Mediterranean area (e.g., Kenter et al., 1990; Franseen and Mankiewicz, 1991; Braga and Martín, 1996; Franseen et al., 1998; Geel, 2000; Bosellini and Perrin, 2010; Janson et al., 2010), but Oligo-Miocene reefal environments are also described from South-East Asia (e.g., Wilson and Rosen, 1998; Wilson et al., 2012; Santodomingo et al., 2016; Novak and Renema, 2018), adjacent to Australia.

This study presents the first detailed description of middle Miocene (i.e., foraminiferal zones N9 to N11; Langhian-Serravallian; Figs. 2, 3) outcrops and cores from the Cape Range Anticline (i.e., North West Cape peninsula, NWS, Western Australia) that contain scleractinian corals. Facies described here are time-equivalent to the offshore seismic reefs (McCaffrey et al., 2020; Young, 2001). This investigation also allowed a reconstruction of the middle Miocene palaeo-environment of the NWS, and discussion of palaeo-environmental implications – such as the possible Miocene or older origin of a 'Leeuwin-current style' oceanic circulation along the Western Australian margin, and the inferred middle Miocene continental aridification of the coast bordering the NWS.

2. Geological setting

The NWS of Australia is a ~ 2400 km long rifted continental margin formed through the Paleozoic to Mesozoic break-up of Pangaea (Yeates et al., 1987, Keep et al., 2007). The NWS has been a subsiding margin since ~135 Ma (Gibbons et al., 2012; Müller et al., 1998; Paumard et al., 2018), but has nevertheless been affected by localised fault inversion events during the Cenozoic (Driscoll and Karner, 1998; Romine et al., 1997; Tindale et al., 1998). There is a notable climax in fault inversion during the middle to late Miocene (Tindale et al., 1998), coincident with the onset of collision between the Australian Plate and the Pacific Plate (Malcolm et al., 1991; Cathro et al., 2003; Keep et al., 2007). Associated folding of the Cape Range Anticline, along with other ranges in the region, may have started during the Miocene, and could still be forming

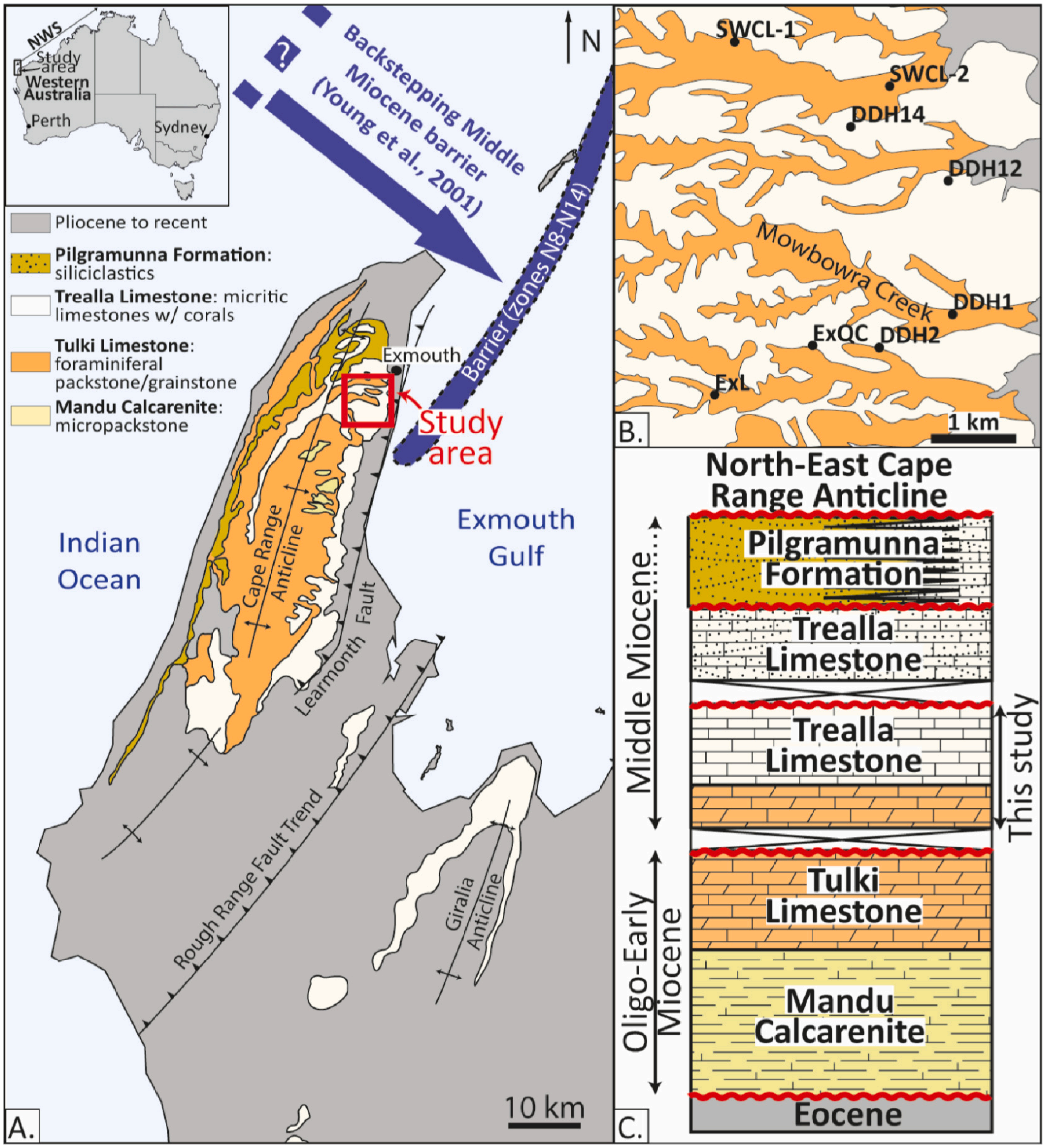

Fig. 2. A. Geological map showing the location of the Oligo-Miocene outcrops in the Cape Range Anticline (modified after Condon et al., 1955; Allen, 1993; Riera et al., 2019) with simplified modern structures after Malcolm et al. (1991) together with the approximate location of the middle Miocene barrier reef based on 2D seismic interpretation (Young et al., 2001). B. Close-up map of the study area with location of sections analysed indicated on the geological map (modified from Condon et al., 1955). C. Stratigraphic columns from the study area in the north-eastern part of the Cape Range Anticline (modified after Condon et al., 1955; Chaproniere, 1975; Riera et al., 2019).

today (Hillis et al., 2008; van de Graaff et al., 1976).

The NWS migrated from sub-polar to tropical latitudes during the Cenozoic (Veevers and Cotterill, 1978; Young et al., 2001), and evolved from a siliciclastic shelf to a carbonate margin affected by episodic continental siliciclastic influx (Apthorpe, 1988). During the late Oligocene and early Miocene, the NWS was covered by an extensive carbonate ramp (Anell and Wallace, 2020; Apthorpe, 1988; Belde et al., 2017; Cathro et al., 2003; McCaffrey et al., 2020; Moss et al., 2004; Rankey, 2017; Riera et al., 2021; Romine et al., 1997; Saqab and Bourget, 2016; Young et al., 2001). This ramp evolved into a rimmed platform (sensu Bosence, 2005) at the beginning of the middle Miocene, when a ~2000 km long seismic reef tract formed along the NWS (Anell and Wallace, 2020; McCaffrey et al., 2020; Romine et al., 1997; Ryan et al., 2009). During the middle Miocene, this tract extended up to the Cape Range Anticline (then not formed) southward (Young, 2001, Fig. 2).

At present, the Oligo-Miocene marine strata are predominantly located offshore, only cropping out along the localised uplifted portions of the NWS, in the Cape Range Anticline, on Barrow Island and in the Giralia Range Anticline (Condon et al., 1955; Crespin, 1955; Chaproniere, 1977; Van de Graaff et al., 1980; van de Graaff et al., 1982; Mcnamara and Kendrick, 1994; Hickman and Strong, 2003; Collins et al., 2006; Martin et al., 2015, Fig. 2A). The outcropping Oligo-Miocene strata are divided into four lithostratigraphic units: (1) deep-water mudstones to marls of the Mandu Calcarenite; (2) larger benthic foraminiferal packstones of the Tulki Limestone; (3) micritic limestones of the Trealla Limestone,; and (4) siliciclastic sandstones of the Pilgramunna Formation (Condon et al., 1955; Chaproniere, 1975; Collins et al., 2006, Fig. 2C). In addition, middle Miocene fossil sand shoals from the Poivre Formation crop out on Barrow Island (McNamara and Kendrick, 1994). In the eastern part of the Cape Range Anticline, accumulation of Tulki Limestone and Trealla Limestone continued into the Langhian and Serravallian respectively, while accumulation of the Pilgramunna Formation began during the Serravallian (i.e., after ~13.34 Ma; Riera et al., 2019).

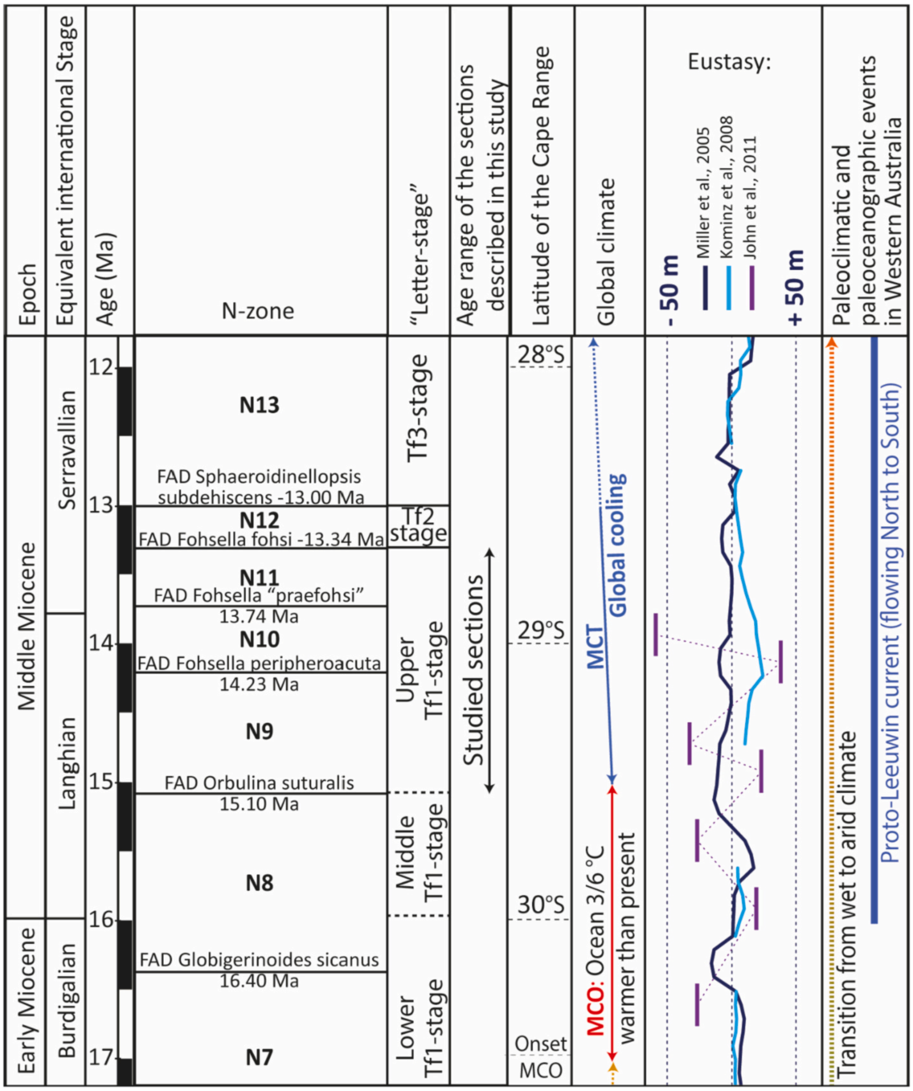

Fig. 3. Chronostratigraphic framework of the sections investigated shown together with planktic foraminiferal N-zones (Blow, 1969), first and last appearance of key planktic foraminifera (Wade et al., 2011), Australasian larger benthic foraminiferal "Letter-stages" (following BouDagher-Fadel, 2018) and numerical ages of Epochs and Stages (after Cohen et al., 2018). FAD: first appearance datum, LAD: last appearance datum, Ma: millions of years. Latitude of the study area after Seton et al. (2012) in the application GPlate (Müller et al., 2018). Miocene evolution of global climate summarised after Flower and Kennett (1993), Zachos et al. (2001), Shevenell (2004), Mudelsee et al. (2014) and Sangiorgi et al. (2018). Eustasy after Miller et al. (2005), Kominz et al. (2008) and John et al. (2011). Continental climate of Western Australia summarised from Martin (2006). Palaeo-activity of the proto-Leeuwin current after McGowran et al. (1997), O'Connell et al. (2012) and Wyrwoll et al. (2009).

Fig. 4. Outcrop photograph of a palaeo-karst (Ka) in Exmouth Limestone Quarry.

Table 1
Summary of the sedimentary facies defined in the middle Miocene outcrops and cores. v.r.: very rare, r.: rare, c.: common, a.: abundant.

Facies name	Facies number	Grains
Mudstone with *Flosculinella* and bivalves	F1	v.r. broken branching corals, r. to a. bivalves, r. to a. gastropods, r. *Flosculinella* sp., v.r. *Sorites* sp., a. micrite
Branching coral float-pillarstone	F2	a. branching corals, r. bivalves, r. gastropods, r. *Flosculinella* sp., a. micrite
Pack-floatstone with *Flosculinella* and diverse corals	F3	c. to a. branching corals, c. green algae, including *Halimeda* sp., r. gastropods, c. *Sorites* sp., r. *Austrotrillina* sp., c. *Flosculinella* sp., v. r. acervulinids, c. to a. small miliolids, v.r. planktic foraminifera, a. micrite
Halimeda floatstone with diverse corals	F4	c. corals (diverse morphologies), c. to a. *Halimeda* sp., r. *Flosculinella* sp., r. coralline algae, a. micrite
Miliolid pack-grainstone with branching corals	F5	r. to c. broken branching corals, c. to a. green algae, including *Halimeda* sp., r. encrusting coralline algae, r. articulated coralline algae, r. bivalves, r. gastropds, r. echinoderm debris, c. *Sorites* sp., c. *Austrotrillina* sp., c. to a. *Flosculinella* sp., r. acervulinids, a. small porcelaneous foraminifera, including a. *Peneroplis* sp., r.small hyaline foraminifera, v.r. to a. micrite
Wacke-packstone with miliolids, *Lepidocyclina* and rare solitary corals	F6	r. corals, c. to a. green algae, including *Halimeda* sp., r. to c. encruting coralline algae, v.r. bivalves, v.r. gastropods, r. echinoderm debris, r. bryozoans, r. to c. *Sorites* sp., r. to c. *Austrotrillina* sp., r. to c. *Flosculinella* sp., c. *Lepidocyclina* sp., r. acervulinids, r. small porcelaneous foraminifera, r. small hyaline foraminifera, a. micrite
Peloidal wacke-grainstone	F7	r. solitary corals, r. green algae, r to c. branching coralline algae, r. to a. bivalves, r. to a. gastropods, c. echinoderm debris and v.r. fragmented tests of irregular echinoderms, r. bryozoan, v.r. *Austrotrillina* sp., v.r. *Flosculinella* sp., c. acervulinids, v.r. *Lepidocyclina* sp., r. to c. *Operculina* sp., r. to a. *Amphistegina* sp., r. small porcelaneous foraminifera, r. to a. small hyaline foraminifera, r. planktic foraminifera, r. to a. peloids, v.r. to a. micrite

3. Methods

Field campaigns were undertaken in the Cape Range Anticline from 2015 to 2017 to re-investigate published sections, and collect detailed sedimentary data from previously undescribed areas. This study focuses specifically on four outcrops designated SWCL-1 (21°57′30.11"S, 114° 5'20.59"E), SWCL-2 (21°58′0.20"S, 114° 6'24.98"E), Exmouth Limestone Quarry (21°59′49.64"S, 114° 4'53.10"E) and Exmouth Concrete Quarry (21°59′36.11"S, 114° 5'36.48"E). To complement the field data, samples from the onshore cores DDH1 (21°59′32.69"S, 114° 6'38.19"E), DDH2 (21°59′41.50"S, 114° 6'5.40"E), DDH12 (21°58′39.77"S, 114° 6'44.66"E) and DDH14 (21°58′12.44"S, 114° 6'6.13"E) drilled by BHP in the Cape Range Anticline (McEwen, 1964; Apthorpe, 1965) were integrated in the study and analysed through thin sections and acetate peels.

Lithological terminology follows the textural classification schemes of Insalaco (1998) modified from Dunham (1962) and Embry and Klovan (1971). Grains present are characterised semi-quantitatively. Here, "rare", "common" and "abundant" indicate components forming around <2%, 2% to 10%, and >10% of the rock volume, respectively. Interpretations of depositional conditions are based on lithological textures, and biogenic content, including identification of larger benthic foraminifera inferred to be relatively precise palaeoenvironmental indicators (Hallock and Glenn, 1986; Hottinger, 1997).

4. Stratigraphic framework

The sections investigated are exclusively of middle Miocene age (i.e., Langhian to early Serravallian, planktic foraminiferal zones N9-N11, ~15.10–13.34 Ma, Figs. 2, 3). They are either mapped as Tulki Limestone or Trealla Limestone (Condon et al., 1955). Dating of the different sections is based on either: (1) identification of key planktic foraminifera and larger benthic foraminifera during previous investigations (Exmouth Limestone Quarry, DDH1, DDH2, Riera et al., 2019); or (2) identification of *Flosculinella* sp. and/or *Austrotrillina* sp. (SWCL-1, SWCL-2, DDH14, DDH12, upper part ExCQ). Pseudo-breccia filled with *terra rosa* interpreted as palaeo-karst (Fig. 4) were noted along several outcrops, but it was neither possible to date them, nor to correlate them.

5. Facies

5.1. Mudstone with Flosculinella and bivalves (F1)

The mudstone with *Flosculinella* sp. and bivalves (F1, Table 1, Fig. 5) is a white limestone with rare *Flosculinella* sp. and rare dislocated moulds of bivalve shells. Locally, it contains abundant complete bivalve moulds and gastropod moulds. This facies also contains scarce debris of branching corals and *Sorites* sp.. Aragonitic skeletons, from bivalves, gastropods, and corals, are always dissolved, and therefore only preserved as moulds (Fig. 5B–C). Locally developed crinkly laminated mudstones, possibly being fossil microbial mats, were also noted (Fig. 5D).

5.2. Branching coral float-pillarstone (F2)

The branching coral float-pillarstone facies (F2, Table 1, Fig. 6) is a white limestone with a micrite matrix, characterised by the abundance of moulds of branching corals. Rare thin-shelled bivalves and gastropods, with wall thickness commonly <1–2 mm, and rare *Flosculinella* sp. were also observed. The coral moulds, which form up to ~20% of the rock volume, are typically 1–2 cm in diameter. Corals are tentatively interpreted as *Acropora* sp., although the widespread leaching makes identification uncertain. Encrusting coralline algae were not encountered.

5.3. Pack-floatstone with Flosculinella and diverse corals (F3)

The pack-floatstone with *Flosculinella* sp. and diverse corals (F3, Table 1, Fig. 7) is a white to cream, micritic packstone with locally thick branching corals forming floatstones. The presence of rare mud-wackestone intervals was also noted. This facies contains a diverse bioclast assemblage including gastropods, *Halimeda* sp., common *Sorites* sp., rare *Austrotrillina* sp., common *Flosculinella* sp., very rare acervulinids, common to abundant small miliolids and very rare planktic foraminifera. As in facies F1 and F2, aragonite tests and shells are dissolved, and are now moulds.

5.4. Halimeda floatstone with diverse corals (F4)

The *Halimeda* floatstone with diverse corals (F4, Table 1, Figs. 8, 9) is a white to yellow floatstone with abundant disarticulated *Halimeda* sp., common scleractinian corals, rare encrusting coralline algae and rare *Flosculinella* sp. The scleractinian coral fauna – exclusively preserved as

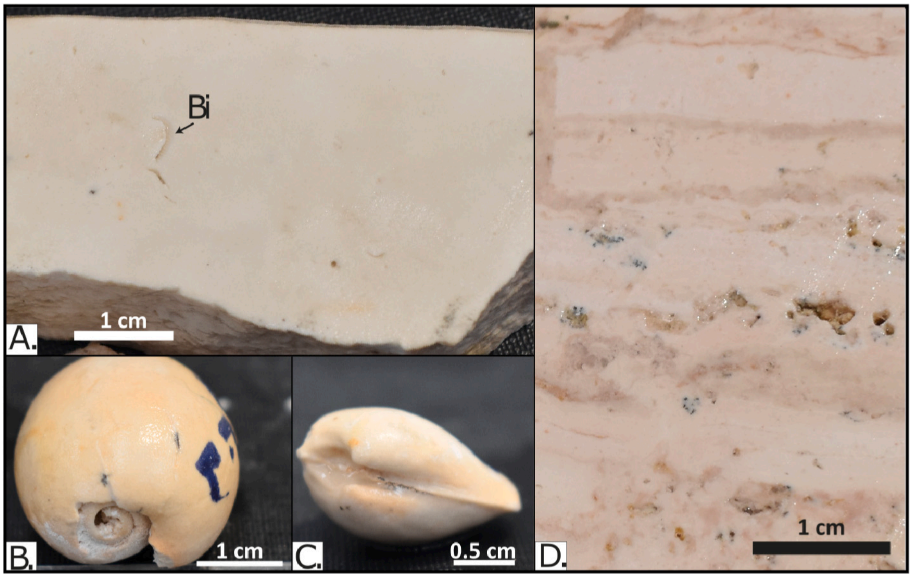

Fig. 5. Core sample photographs and photomicrographs of the mudstone with *Flosculinella* sp. and bivalves (facies F1). A. Sample from the upper part of DDH2 rich in micrite with bivalve mould (Bi). B. Gastropod interior mould in F1. C. Interior mould of a complete, articulated bivalve. D. The thin interval of crinkly laminated micritic mudstones with vugs.

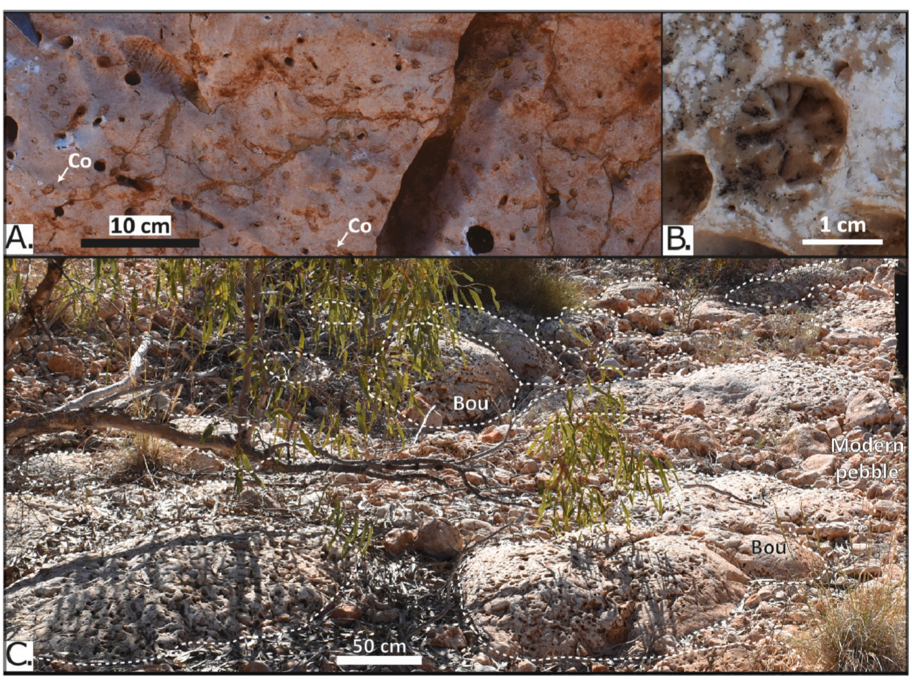

Fig. 6. Outcrop photographs and photomicrographs of branching coral float-pillarstone (facies F2). A. Outcrop of F2 in Exmouth Concrete Quarry. B. Close-up view of a branching coral in Mowbowra Creek. C. Extensive branching coral boundstone in Mowbowra Creek. Co: coral, Bou: boundstone.

moulds - is fairly diverse, including branching *Acropora* sp. (Figs. 8B, 9C), small colonies with plocoid morphologies (Fig. 9D–E), colonial corals possibly of the family Agariciidae (Fig. 8C) as well as solitary species (Fig. 9A). Corals are generally dispersed and represent around 5% of the facies by volume.

5.5. *Miliolid pack-grainstone with branching corals (F5)*

The miliolid pack-grainstone with branching corals (F5, Table 1, Fig. 10) is a white limestone characterised by the abundance of Miliolida – including abundant *Peneroplis* sp., and the presence of broken branching corals interpreted as *Acropora* sp. This facies also contains rare articulated bivalves, gastropods, *Halimeda* sp., rare encrusting coralline algae, rare articulated coralline algae, rare echinoderm debris, common *Sorites* sp., common *Austrotrillina* sp., common to abundant *Flosculinella* sp., rare acervulinids and rare small hyaline foraminifera. Matrix is rare to abundant, and is always micritic.

5.6. *Wacke-packstone with miliolids, Lepidocyclina and rare solitary corals (F6)*

The wacke-packstone with miliolids, *Lepidocyclina* sp. and rare solitary corals (F6, Table 1, Fig. 11) is a beige limestone characterised by the presence of rare to common *Sorites* sp., *Austrotrillina* sp., *Flosculinella* sp.

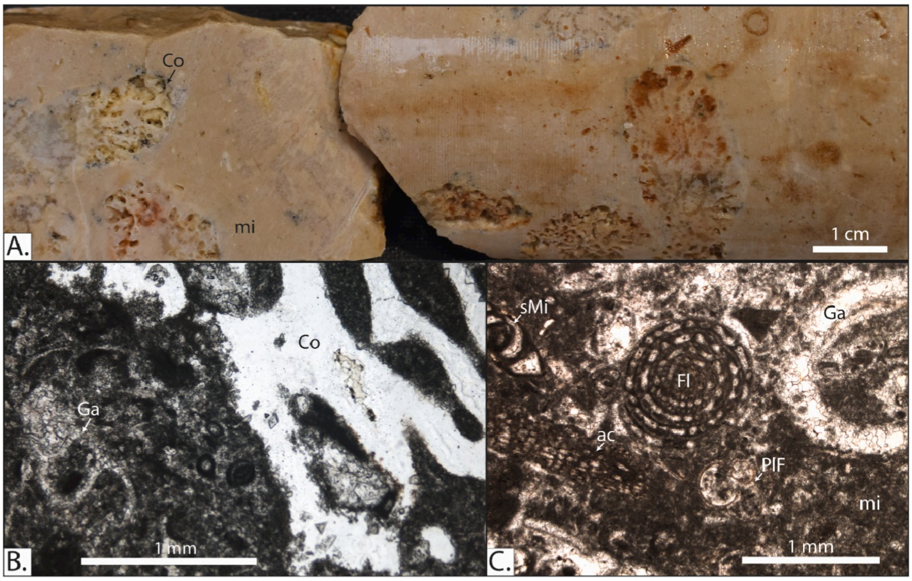

Fig. 7. Photographs and photomicrographs of pack-floatstone with *Flosculinella* sp. and diverse corals (facies F3). A. Sample from the upper part of core DDH14 showing corals (Co) in a micrite (mi) matrix. B. Photomicrograph of a coral mould (Co) and gastropod mould (Ga) in a micritic matrix. C. Photomicrograph of a *Flosculinella* sp. (Fl), an acerculinid (ac), a planktic foraminifera (PlF), small miliolid foraminifera (sMi) and a gastropod mould in a micritic matrix (mi).

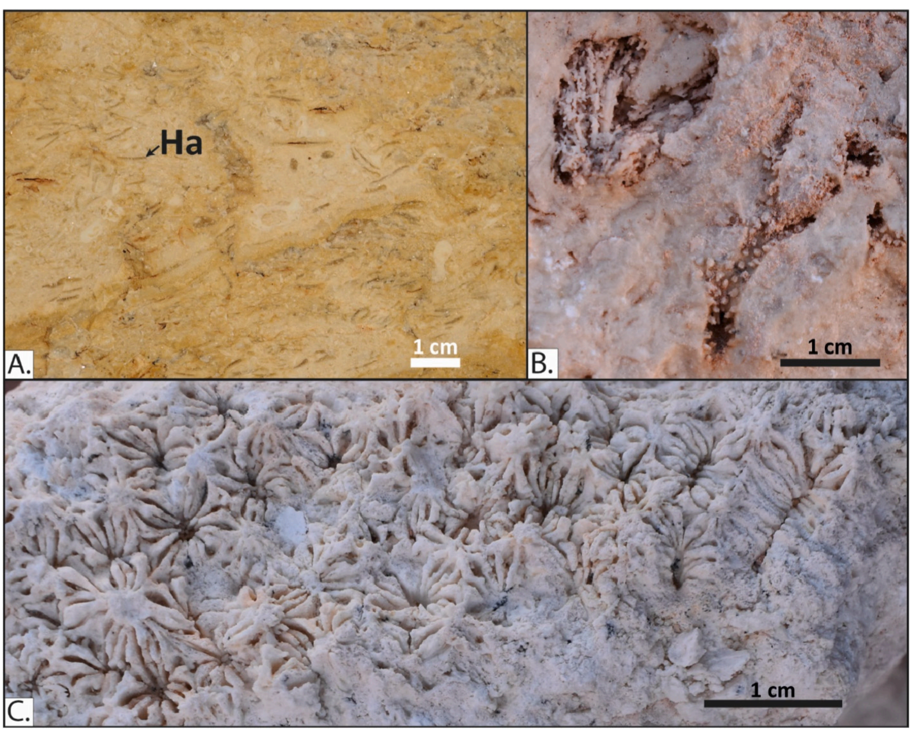

Fig. 8. Outcrop photographs of the *Halimeda* sp. floatstone with diverse corals (facies F4). A. Close-outcrop view showing the abundance of *Halimeda* plates (Ha) in the facies. B. Close view on a branching *Acropora* mould recognizable through its well-defined corallite mould infills. C. Mould of a massive colonial coral colony, possibly of the family *Agariciidae*.

and *Lepidocyclina* sp. in a micritic matrix (Fig. 11 A–C). The facies also contains rare solitary corals, very rare broken branching corals as well as very rare bivalves, very rare gastropods, common to abundant green algae, including *Halimeda* sp., rare to common encrusting coralline algae, rare echinoderm debris, rare bryozoans, rare acervulinids, rare small porcelaneous foraminifera and rare small hyaline foraminifera (Fig. 11). Corals are locally encrusted by coralline algae (Fig. 11D).

5.7. Peloidal wacke-grainstone (F7)

The peloidal wacke-grainstone (F7, Table 1, Fig. 12) is a white to orange limestone that differs from the other facies because it contains minimal micrite. It contains rare to abundant bivalves and gastropods, very rare tests of irregular echinoderms and rare solitary corals (Fig. 12C). Although this facies has a homogeneous macroscopic appearance, in thin section it shows strong textural variability (Fig. 12D–E). Diverse bioclasts were observed, including rare green

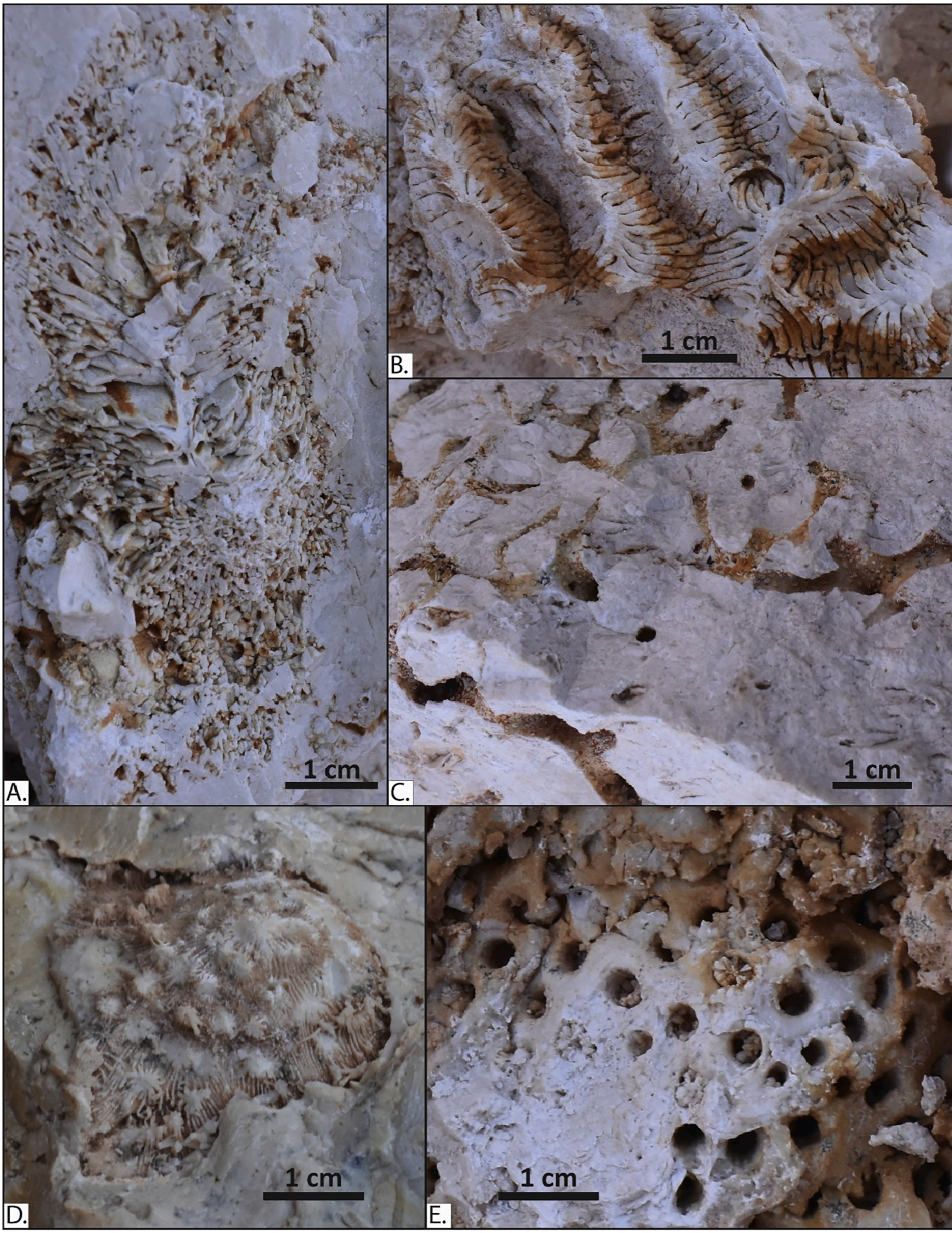

Fig. 9. Outcrop photographs of the *Halimeda* sp. floatstone with diverse corals (facies F4) illustrating the diversity of coral morphologies in this facies. A. Mould of solitary coral, possibly from the family *Fungiidae*, the elongated growth forms could indicate a relation the genus *Ctenactis*. B. Mould of a coral tentatively interpreted as *Oulophyllia* sp.. C. Mould interpreted as a branching *Acropora* sp., based on well defined corallites. D. Mould of a coral colony with plocoid morphology, possibly from the family *Faviidae*, E. Mould of a coral colony with a plocoid growth structures.

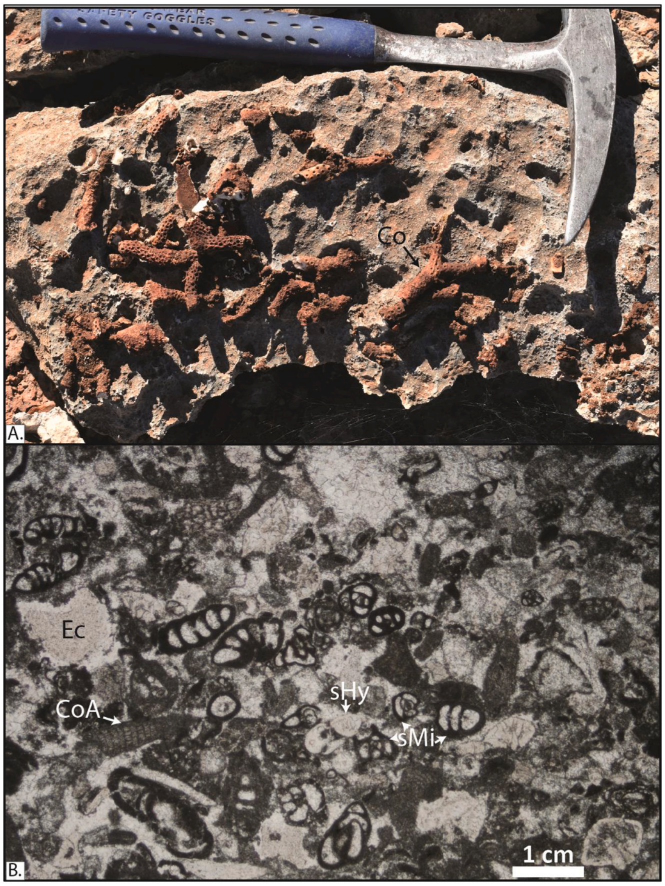

Fig. 10. Outcrop photograph and photomicrograph of the miliolid grainstone with branching corals (facies F5). A. Outcrop photograph along the SWCL-1 section, showing horizontal concentration of branching corals (Co) fragments. B. Photomicrograph illustrating the abundance of small miliolids (sMi), and the presence of echinoderm debris (Ec), coralline algae (CoA) and small hyaline foraminifera (sHy).

algae, rare to common branching coralline algae, common echinoderm debris, rare bryozoan, very rare *Austrotrillina* sp., very rare *Flosculinella* sp., common acervulinids, very rare *Lepidocyclina* sp., rare to common *Operculina* sp., rare to abundant *Amphistegina* sp., rare small porcelaneous foraminifera, rare to abundant small hyaline benthic foraminifera and rare planktic foraminifera, as well as rare to abundant peloids (Fig. 12 D–E). The facies locally forms beds up to 5 m thick (SWCL-1, Fig. 12A).

5.8. Spatial organisation of facies

Among the eight sections described (Figs. 2B, 13), the most widespread facies is the peloidal wacke-packstone (facies F7). This facies is present at the base of all sections, with the exception of Exmouth Quarry (ExCQ, Fig. 13). The total thickness of facies F7 is unknown, as its base was not observed. Sub-horizontal bedding of facies F7 is better developed in the western part of Mowbowra Creek, as displayed along section SWCL-1. The branching coral float-pillarstone (F2) is also common, while only in the upper part of outcrops and cores, and it was observed in core DDH1, in Mowbowrra Creek (i.e., SWCL-1 and SWCL-2), as well as in Exmouth Concrete Quarry (i.e., ExCQ, Fig. 13). In ExCQ, facies F2 is present between the *Halimeda* floatstone with diverse corals (Facies F4) and the mudstone with *Flosculinella* and bivalves (Facies F1). Facies F1 is also present in the upper part of core DDH2. The wacke-packstone with miliolids, *Lepidocyclina* and solitary corals (F6) is also quite common, as it was observed overlying facies F7 in the Exmouth Limestone Quarry and in cores DDH12 and DDH14. The pack-floatstone with *Flosculinella* and diverse corals (facies F3) is only noted in the uppermost part of the core DDH14, whereas the miliolid grainstone with branching corals (facies F5) is only observed between facies F2 and F7 in the westernmost outcrops from North Mowbowra Creek (i.e., SWCL-1 section, Fig. 13). Palaeo-karst levels, characterised by the presence of a pseudo-breccia embedded in a red *terra rosa* matrix, are present in the western part of Mowbowra Creek. The presence of these karstic horizons was noted at four locations of the Exmouth Limestone Quarry, where they are exclusively formed in facies F7, but also at the contact between facies F7 and F2 in section SWCL-2, and at the top of facies F4 and F1 in the Exmouth Concrete Quarry (i.e., SWCL-2, ExL and ExCQ, Fig. 13).

6. Discussion

6.1. Depositional model and palaeo-environment

The presence of *Flosculinella* sp. in all facies described herein indicates accumulation in the photic zone of a warm, tropical marine environment, possibly at water depth shallower than 40 m (Hottinger, 1997). The occurrence of *Operculina* sp. and *Halimeda* sp. may indicate surface water temperature in excess of ~25 °C (Hillis-Colinvaux, 1980; Langer and Hottinger, 2000), then further supporting accumulation in a warm environment. The diversity of hermatypic corals – including reef building genera - further supports an accumulation in a tropical carbonate platform, possibly reef rimmed. Overall, the abundance of micrite in all facies, with the exception of the peloidal wacke-grainstone (F7), points toward deposition in low energy, protected environments (e.g., facies map of the Great Bahama Bank for comparison, Reijmer et al., 2009). Facies F1, F2, F3, F4 and F5 – that all contain hermatypic corals - may have formed in a shallow and protected lagoon, a notion supported by the fact that they all contain miliolid foraminifera whereas larger rotaliid foraminifera are absent (Hallock and Glenn, 1986; Beavington-Penney and Racey, 2004, Fig. 14). In the pack-floatstone with *Flosculinella* sp. and diverse corals (F3) and in the miliolid grainstone with branching corals (F5), local abundance of epiphytic organisms such as *Sorites* sp. and acervulinids, together with *Halimeda* sp., may indicate the presence of tropical seagrass meadows and thus, accumulation at shallow water depth (Brandano et al., 2019; Perry and Beavington-Penney, 2005). In addition, facies F5 contains *Peneroplis* sp., a foraminifera whose modern representatives dominantly live in waters shallower than 20 m (Beavington-Penney and Racey, 2004). In the pack-floatstone with *Flosculinella* sp. and diverse corals (F3) and the *Halimeda* floatstone with diverse corals (F4), the presence of *Halimeda* sp., together with the abundance of micrite and the diversity of corals, may indicate that the facies formed on a shallow-subtidal reef flat, although deposition at a lagoonal margin to platform interior inter-reef area is not excluded (Marshall and Davies, 1978; Jell and Webb, 2012). The abundant fragmented *Acropora* branches in the coral float-pillarstone (F2) seem reworked, but their dominant presence is plausibly an indication of accumulation in a calm area in close proximity to a coral colony. The mudstone with *Flosculinella* and bivalves (F1) could have accumulated in an even more restricted environment compared to other facies, as biogenic grains are generally scarce. The possible presence of microbial mat intervals may indicate accumulation under harsh conditions, such as a hypersaline setting or a marginal-marine zone with changing ecological conditions (Gerdes, 2010). Although the wacke-packstone with miliolids, *Lepidocyclina* sp. and rare solitary corals (F6) does not contain colonial corals, it may also have formed in a reef-rimmed lagoon, as it contains *Halimeda* sp., molluscs and foraminifera (Chevillon, 1996). In this facies, the absence of colonial corals and the presence of *Lepidocyclina* sp. may reflect an accumulation in a deeper, more open part or the lagoon (Hallock and Glenn, 1986; Hottinger, 1997; Fig. 14). Only the peloidal wacke-grainstone (F7) stands out, as it likely accumulated in a deeper and more open marine environment (i.e., either inside or outside the lagoon), as indicated by the presence of

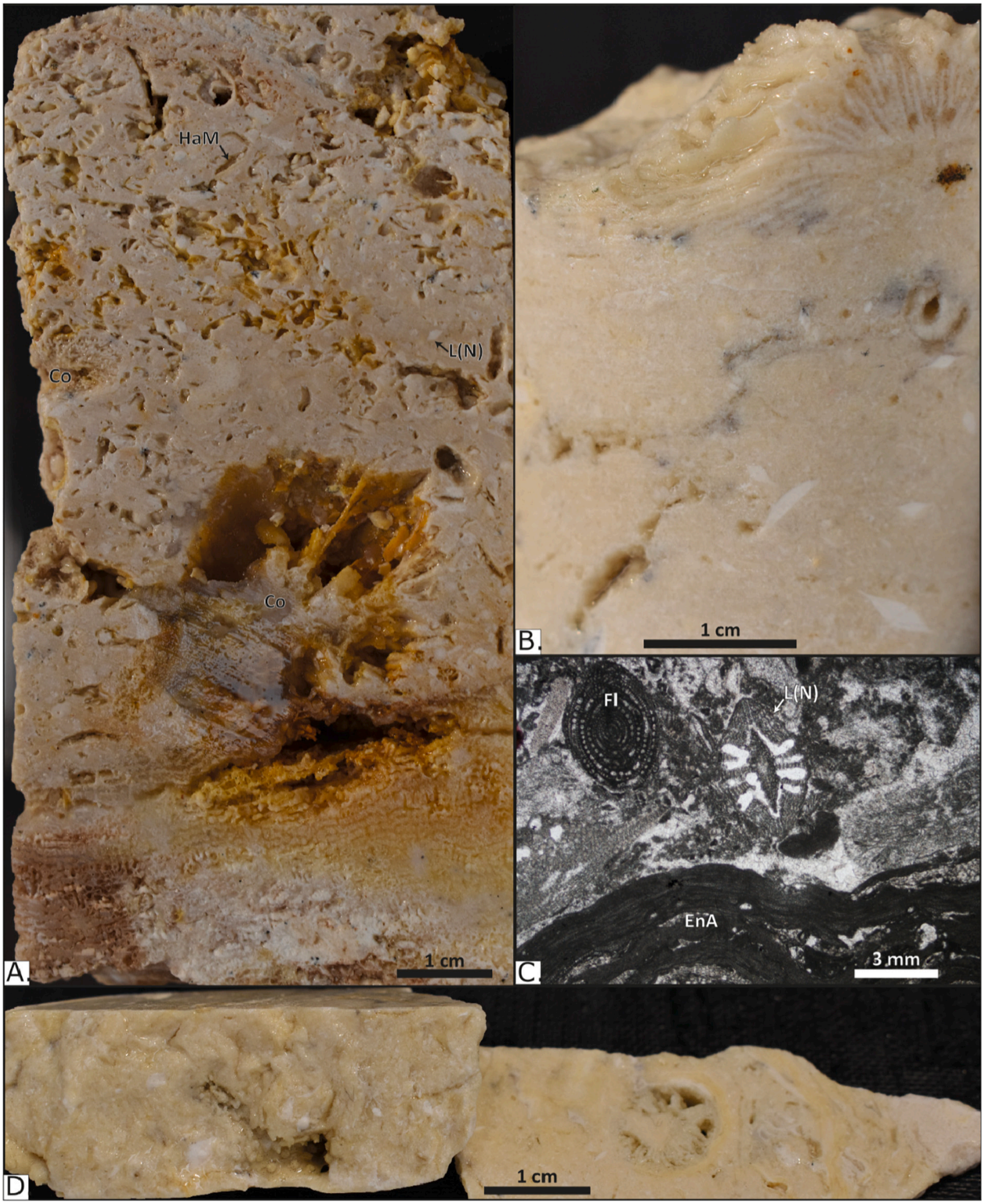

Fig. 11. Core sample photographs and photomicrograph of the wacke-packstone with miliolids, *Lepidocyclina* sp. and diverse corals (facies F6). A. Sample from DDH14; note the abundance of *Lepidocylina* sp. (L(N)) and the presence of a coral mould (Co). B. Sample from DDH12, in a mudstone interval, note the presence of a solitary coral in the uppermost part of the sample. C. Photomicrograph of *Flosculinella* sp. (Fl), *Lepidocyclina* sp. (L(N)) and encrusting algae (EnA), Exmouth Quarry. D. Sample from DDH12 with coral moulds locally encrusted by coralline algae.

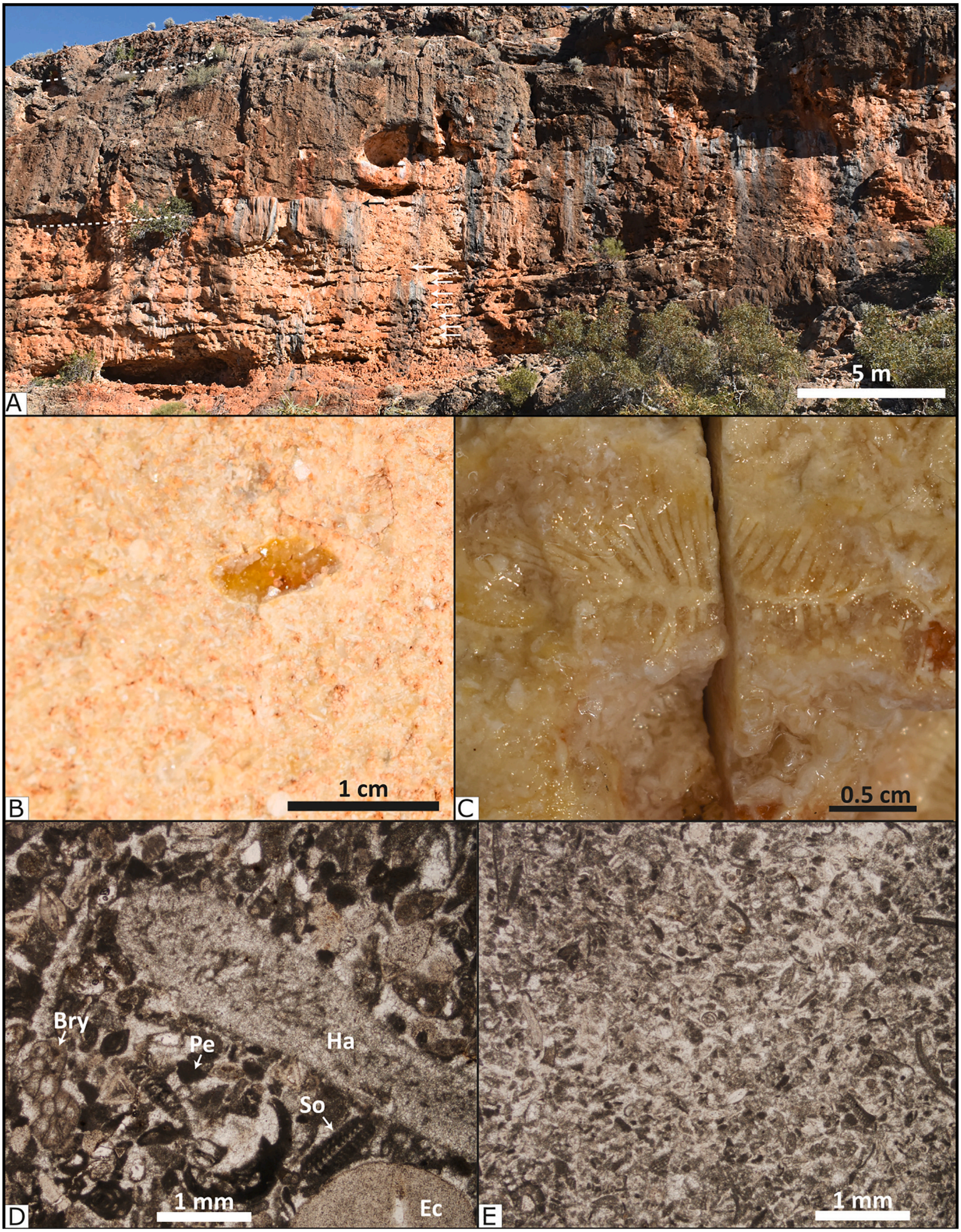

Fig. 12. Outcrop, core sample photographs and photomicrographs of the peloidal pack-grainstone with miliolids, *Lepidocyclina* sp. and solitary corals (facies F7). A. Cliff face adjacent to section SWCL-1; note presence of bedding, with comparatively thin beds at the base of the cliff and thicker beds in the upper part; B. Close view of the peloidal pack-grainstone in the Exmouth Limestone Quarry. C. Close view of a solitary coral in a sample from DDH12. D. and E. Thin section photographs illustrating the microfacies variability, with peloids (Pe) and diverse bioclasts such as bryozoans (Bry), *Halimeda* sp. (Ha), *Sorites* sp. (So) and echinoid debris (Ec); note the scarcity of micrite.

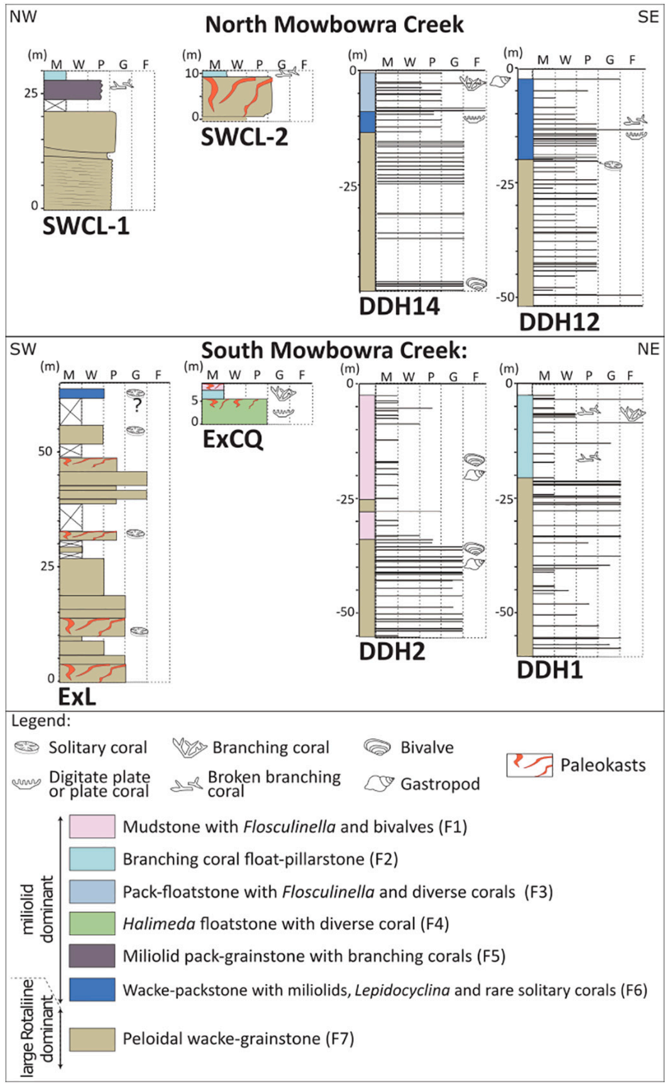

Fig. 13. Vertical distribution of facies along the middle Miocene sections investigated here.

planktic foraminifera (BouDagher-Fadel, 2018) and by the reduced amount of micrite compared to the other facies. The presence of thick bedding, together with the local abundance in *Amphistegina* sp., may point toward local facies accumulation as sand shoals (e.g., Parker and Gischler, 2015), in keeping with accumulation taking place in a more energetic environment than the other facies. Overall, facies analysis reveals that the waters from the NWS were warm during the middle Miocene, with environmental conditions that appears favourable to the development of a reef-rimmed warm-water carbonate platform.

6.2. Biogeography and proto-Leeuwin current

Nowadays, the extent of the western Australian coral reef province seems controlled by the intensity of the southward flowing Leeuwin current, with coral reefs developed at most southerly latitudes when this current is strongest (Wyrwoll et al., 2009). A Leeuwin-current style oceanic circulation may have existed along the western Australian margin since the Eocene, with a particularly strong flow during the early middle Miocene (McGowran et al., 1997). A strong middle Miocene southward current is further supported by the presence of middle Miocene hermatypic corals in the Nullarbor Plain and of the seismic “Little Barrier Reef” at a palaeo-latitude of ~40°S (Feary and James, 1995; O'Connell et al., 2012). The middle Miocene tropical facies presented here – that contain hermatypic corals and other taxa with tropical water affinities - also reinforce the view that a strong southward current was warming the western Australian margin during the middle Miocene, as the Cape Range area was then at palaeo-latitude of ~29°S (Fig. 3). Interestingly, this palaeo-latitude corresponds to the southernmost latitude of true coral reef development along the modern western Australian margin (Collins, 2002; Hatcher, 1991). A strong southward flow is also supported by the close relations between early middle Miocene larger benthic foraminifera encountered in the Cape Range Anticline – such as *Flosculinella* sp. and *Lepidocyclina sp.* - and Asian taxa (Chaproniere, 1980; Crespin, 1955; McGowran et al., 1997; Riera et al., 2019). This is in line with previous investigation of the area which demonstrates a taxonomic connection between middle Miocene mollusc and echinoid taxa from Barrow Island (180 km northeast of the Cape Range Anticline) and Miocene taxa from Indonesia and other Indo-West Pacific localities (McNamara and Kendrick, 1994). Then, a biogeographic connection possibly existed between south-east Asia and the western Australian margin during the middle Miocene, hence further supporting the view of a strong southward current. With the proximity of the NWS to the ‘Coral triangle’ centre of diversity of corals, which has been a global diversity hot-spot since at least the Miocene (Renema et al., 2008; Wilson, 2015; Wilson and Rosen, 1998) it is tempting to relate the Cape Range corals to this hotspot, even if mediocre coral

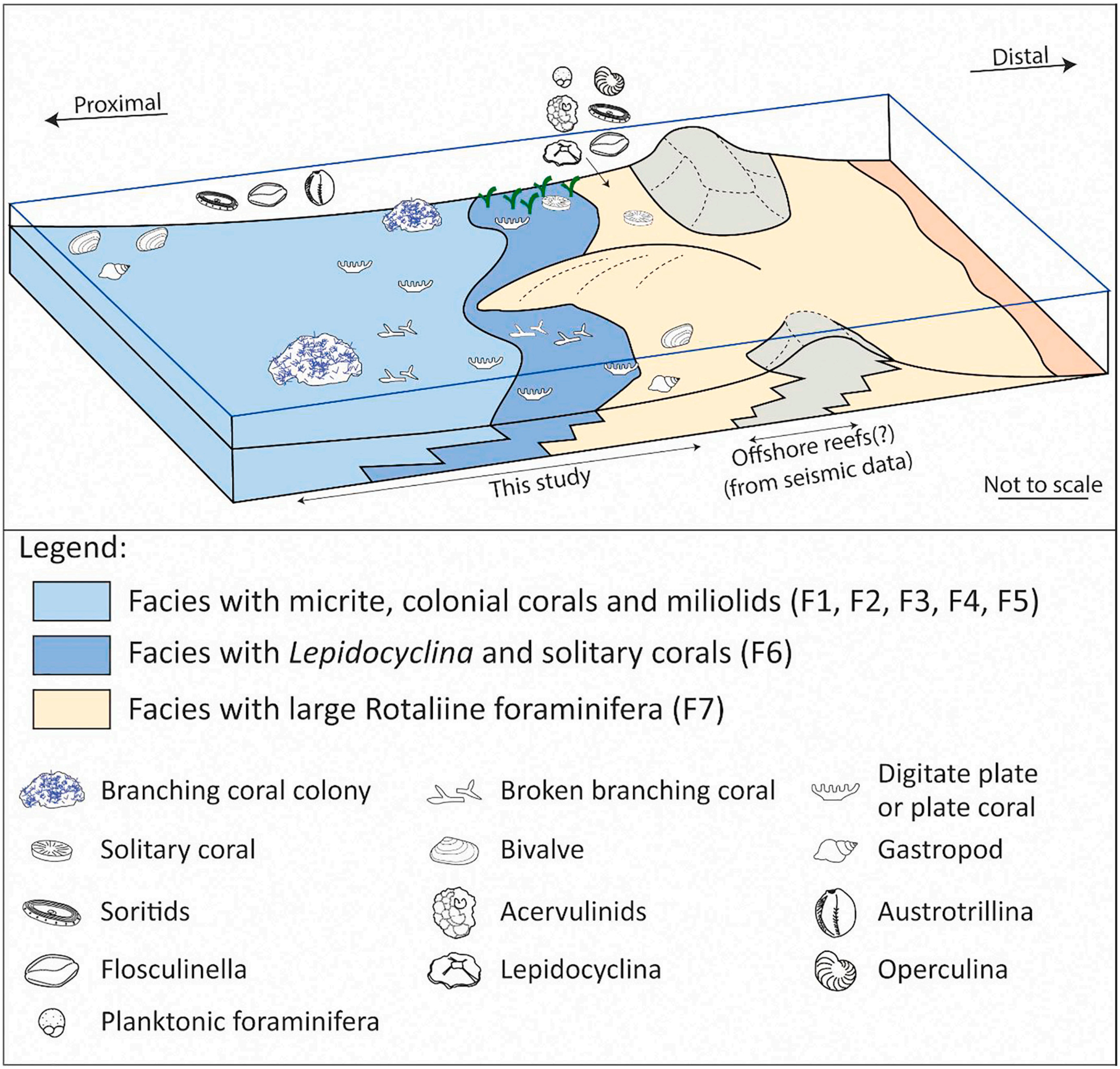

Fig. 14. Depositional model of the middle Miocene facies observed in the Cape Range Anticline. Note that the geometry of deposition is speculative, and that the model is not to scale.

preservation and the consequent limitations to detailed taxonomic work prevent any firm conclusion.

6.3. Eustatic and climatic controls on seismic reef development

As previously noted by Schlager (2005), seismic reefs are large geological objects, that can be formed by a mixture of reef and non-reefal deposits, such as sand shoals. In the absence of core of the Western Australian Oligo-Miocene seismic reefs, it is not possible to know what exactly is forming these structures. However, the results presented here show that maximum reef development occurred at a time when no macroscopic nor microscopic quartz grains were transported to the Cape Range area. This absence of quartz grains supports an arid middle Miocene climate (cf. Martin, 2006; Groeneveld et al., 2017), with no significant river runoff, hence allowing high aragonite saturation in the marine waters (cf. Hallenberger et al., 2019). Rosleff-Soerensen et al. (2012) noted that, in the Browse Basin (i.e., 1200 km northeast of the study area), the first reefs developed after a drop in sediment clay content, possibly indicating a decrease in nutrient influx from rivers during the middle Miocene when compared to the early Miocene. This provides further evidences for a middle Miocene aridification of the coast bordering the NWS (Martin, 2006), with repercussions on carbonate sedimentation all along the NWS. Additionally, middle Miocene outcrops from the Cape Range Anticline contain more aragonitic bioclasts (i.e., corals, bivalves, gastropods) than the early Miocene ones (cf. Riera et al., 2021). This further supports an increased aragonite saturation in marine waters along the NWS during the middle Miocene, compared with the early Miocene, hence possibly promoting early lithification of the seismic reefs.

The observation of multiple palaeokastic features in the middle Miocene strata (Figs. 4, 13), and the possible presence of middle Miocene outliers colonised by corals (SWCL-2, Fig. 13), may further indicate that middle Miocene sediments and rocks were repeatedly emerged and lithified, hence promoting the cementation and preservation of the seismic reefs. The existence of repeated middle Miocene subaerial exposures is supported by the observation of karst reported from both seismic and outcrop data (Cathro et al., 2003; Cathro and Austin, 2001; Matonti et al., 2021). Such emergences could also have impacted the continental climate, as the continental climate along the modern NWS tends to be drier during lowstands, when most of the shelf is emerged (Hesse et al., 2004). A dynamic Miocene Antactic Ice Sheet (cf. Gasson et al., 2016) and an increase in polar ice sheet volume during the Miocene Climatic Transition (Flower and Kennett, 1994; Zachos et al., 2001) are a likely cause of these repeated lowstands.

7. Conclusions

Tropical taxa such as hermatypic corals, *Halimeda* sp. and larger benthic foraminifera was present on the North West Shelf during the middle Miocene (i.e., planktic foraminiferal zones N9-N11, ~15.10–13.34 Ma). A total of seven middle Miocene facies has been identified in the Cape Range Anticline: (F1) Mudstone with *Flosculinella* and bivalves; (F2) Branching coral float-pillarstone; (F3) Pack-floatstone with *Flosculinella* and diverse corals; (F4) *Halimeda* floatstone with diverse corals; (F5) Miliolid pack-grainstone with branching corals; (F6) Wacke-packstone with miliolids, *Lepidocyclina* and rare solitary corals; and (F7) Peloidal wacke-grainstone. Facies analysis confirms that oceanic waters of the NWS were warm and oligotrophic during the middle Miocene, and that hermatypic corals were present during the development of the 2000 km long seismic reef tract. The middle Miocene development of a seismic reefs tract along the western margin of Australia was possibly promoted by a strong 'Leeuwin current style' oceanic circulation, that warmed the shelf water and most likely provided a route for colonization of the western shelf of Australia. Additionally, formation and preservation of the seismic reefs may have been enabled by aridification of the coast bordering the NWS, and by repeated shelf emersions driven by a dynamic Antarctic ice-sheet.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Core samples, thin sections and acetate peels from the onshore cores DDH1, DDH2, DDH12 and DDH14 are archived at the Department of Mines, Industry Regulation and Safety, Western Australia (sampling approval numbers P929). Field samples and thin sections from field samples are archived at the Edward de Courcy Clarke Earth Science Museum, University of Western Australia (UWA180000- UWA180418).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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