[PS]Seismic Geomorphology and Evolution of the Early-Mid Miocene Isolated Carbonate Build-Ups, North West Shelf of Australia*

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Abstract

Almost half of the world's petroleum production is from carbonate reservoirs, with many discoveries in isolated platforms. Although major discoveries continue to be made in these play types, many areas remain understudied. Analysis of extensive 2D and 3D seismic data reveals the presence of about sixty isolated carbonate build-ups (ICBs) of early-mid Miocene age spreading over a wide area of the north-western Bonaparte Basin. Individual build-ups are ~ 100 m thick, with an average diameter of 3 km. Integration of full-volume 3D seismic attribute analysis with extensive biostratigraphic and lithological data from exploration wells allow examining the evolution of ICBs and their associated morphologies at high-resolution. The development of ICBs took place above a seismically flat surface. The stratigraphic architecture of the build-ups typically consists of: (1) mid Burdigalian initiation (Tf1/CN2), (2) lateral expansion during late Burdigalian (CN3), and (3) backstepping and drowning during Langhian (Tf2/CN4). This is followed by a sub-aerial exposure probably corresponding to the major eustatic fall during Serravalian. Only small patch reefs (pinnacles) developed afterwards during the late Miocene. The various growth phases of ICBs correspond to sea level fluctuations, and major changes in global climate and oceanography. The role of local tectonics in the initiation and demise of these carbonate platforms is minimal. Growth of the ICBs is synchronous with establishment of tropical carbonate factories elsewhere along the Australia's North West Shelf that suggest an acme of reef development during the early to middle Miocene.

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Seismic geomorphology and evolution of early-mid Miocene isolated carbonate build-ups, North West Shelf of Australia

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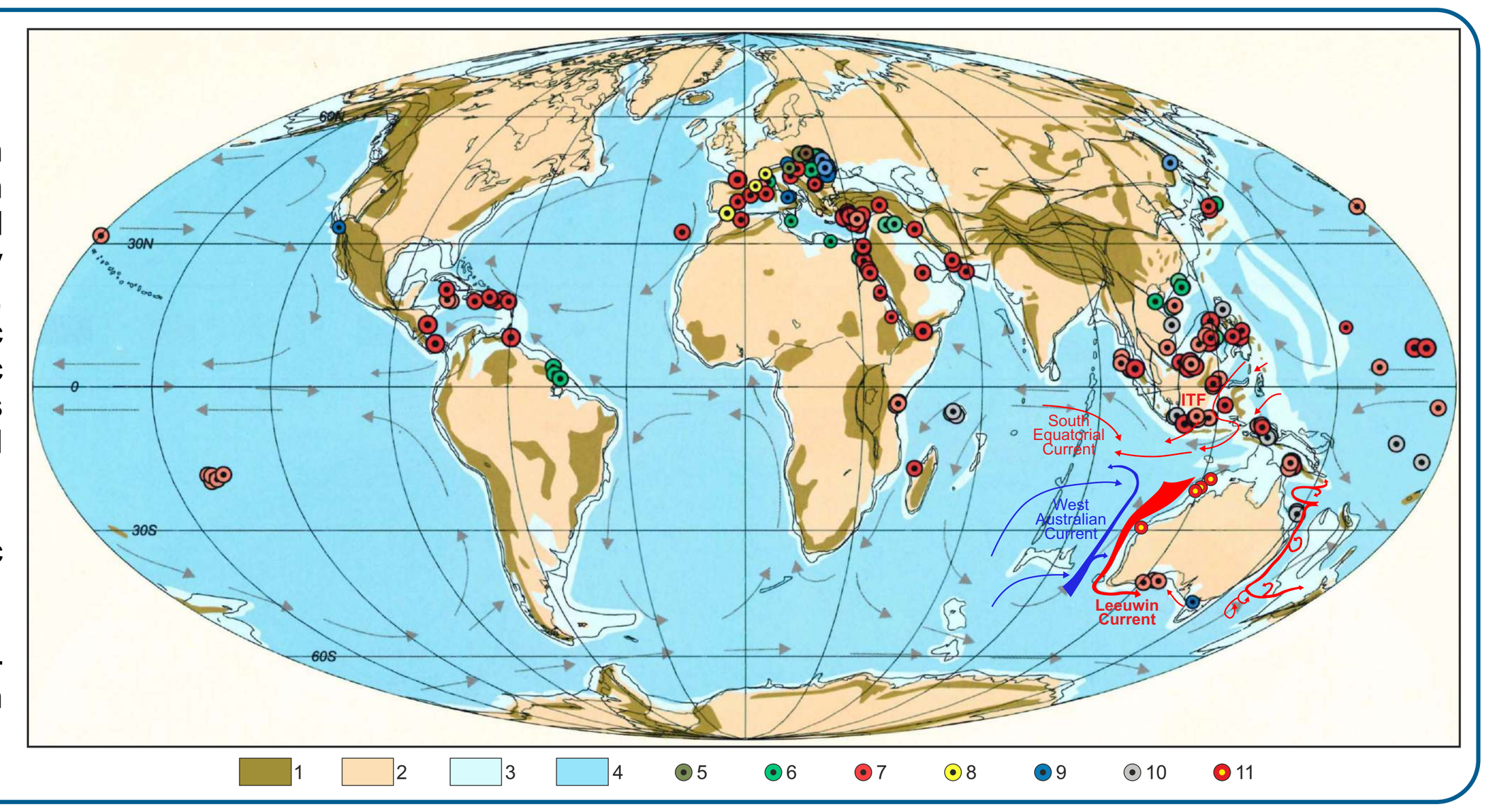
Introduction

The early–mid Miocene was the only time during the Cenozoic when the global cooling trend was reversed. Carbonate factories are highly responsive to these changes and as a result extensive carbonate deposition took place around the world during this time, particularly in SE Asia and Australia (Perrin, 2002). On the North West Shelf of Australia, the Cenozoic era was associated with a growth of extensive temperate to tropical carbonate platforms. In the Bonaparte Basin, early to middle Miocene carbonate build-ups were recognized by Gorter et al. (2002) through examination of well cuttings and seismic data. This work focuses on the nature, distribution and seismic characteristics of the Miocene ICBs in the northwestern Bonaparte Basin. 3D seismic geomorphology provides excellent morphological details of the ICBs and new insights into their stratigraphic architecture. The growth of these ICBs (and the coeval shelf-margin reefs present in the Bonaparte Basin) is compared with the record of accommodation (subsidence and eustasy), paleogeography, climate and oceanography.

The term **isolated carbonate build-up (ICB)** is implied here for carbonate strata deposited with a topographic relief above the adjacent strata, without specification about scale and origin of the carbonate material.

Key to symbols: 1-mountains; 2-land; 3-shelf; 4-ocean. Dominant reef biota: 5-microbes; 6-algae; 7-corals; 8-bivalves; 9-bryozoans; 10-unknown; 11-reefs along the Australian North West Shelf. Major oceanic currents in the Australasia are indicated (warm=red; cold=blue; ITF=Indonesian Throughflow).



Abstract

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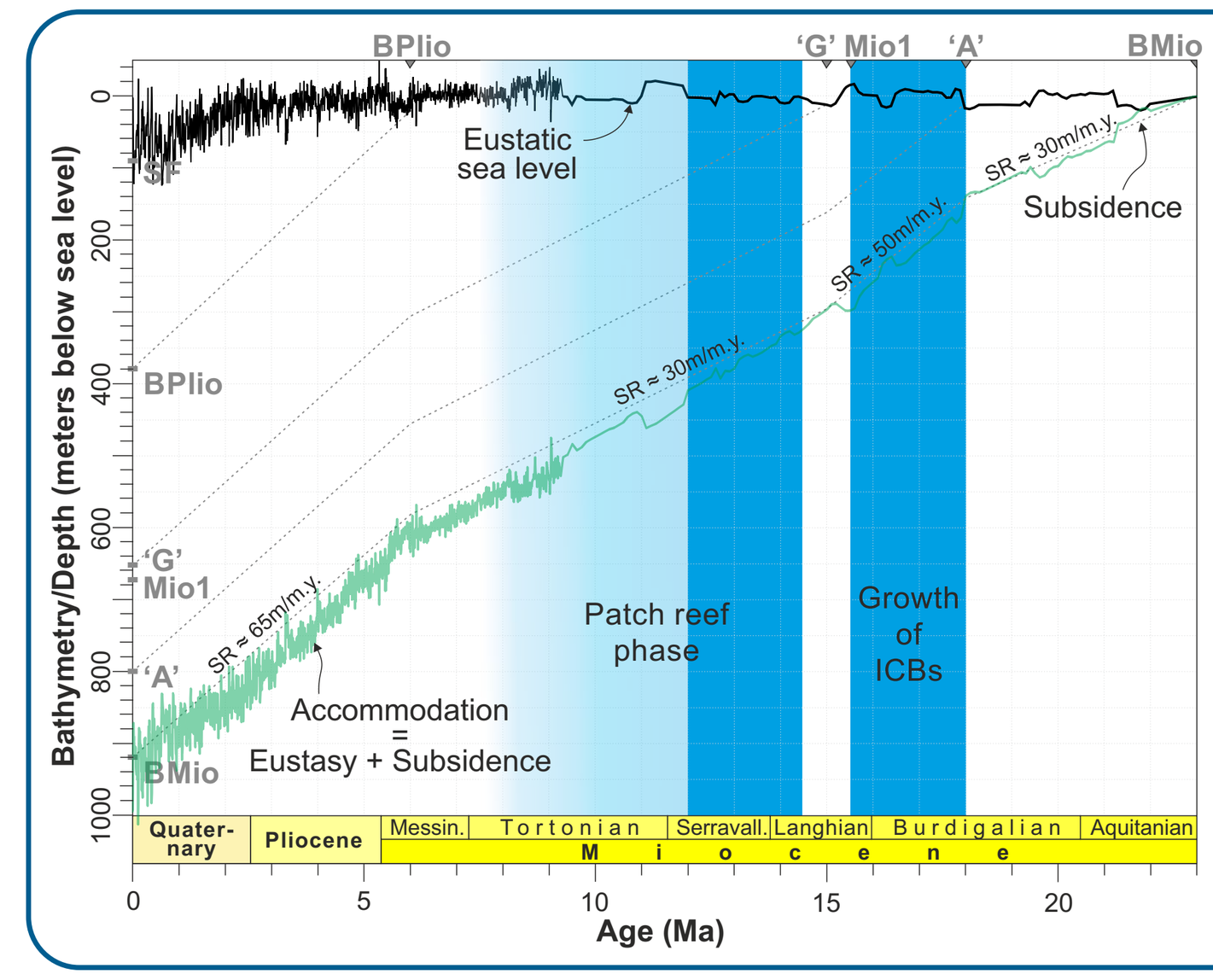
Subsidence curve

Sea-level records were combined with paleobathymetry, sedimentary thickness and facies data from the well Lucas-1 to provide an estimation of subsidence history.

The plot suggests low subsidence rates (~30 m/m.y.) during the Miocene except a period of relatively increased subsidence (~50 m/m.y.) during mid Burdigalian–mid Langhian (18–15 Ma). The subsidence rates increase to ~65 m/m.y. during Pliocene–Quaternary (after ca. 6 Ma). Accommodation curve (combination of calculated subsidence with the over-printing eustasy) is characterized by amplified sea-level rises and attenuated falls.



Geological settings

The North West Shelf is an extensive area flanking the northwestern coast of Australia that comprises four large discrete basins, namely the Northern Carnarvon, Roebuck, Browse and Bonaparte basins.

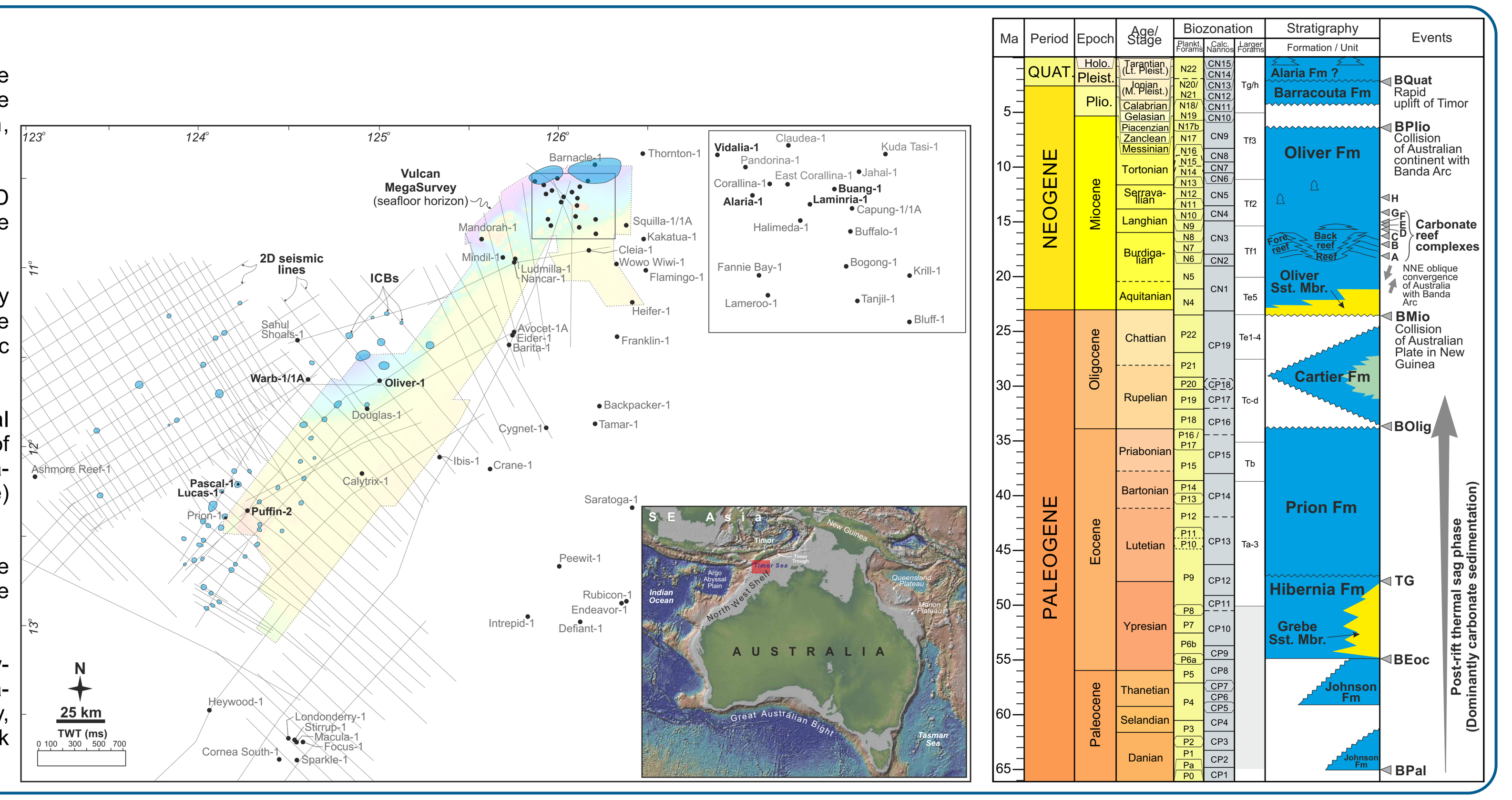
This study is mainly based on the analysis of 2D and 3D seismic data along the present-day shelf margin in the northwestern Bonaparte Basin.

The Bonaparte Basin contains >15 km of sedimentary rocks underlain by ~30 km thick continental crust. The tectonic history of the basin is dominated by Mesozoic rifting and arc-continent collision during the Neogene.

During the Paleogene, a temperate to subtropical carbonate ramp system developed. Discrete episodes of terrigenous input occurred during shortlived relative sea-level lowstands in the early Eocene (Grebe Sandstone) and late Oligocene–early Miocene (Oliver Sandstone).

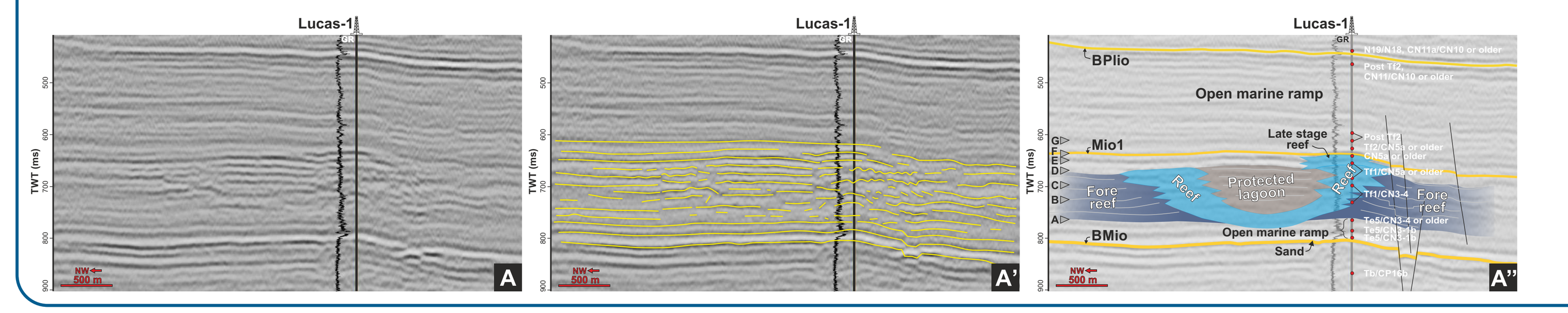
A transgression during early Miocene flooded the entire shelf and was accompanied by the onset of carbonate growth along a low gradient, wide continental shelf.

Plio-Quaternary sequences are dominated by shallow-water, tropical carbonates aggrading along the shelf, intra-shelf basin and shelf edge areas. During late Quaternary, onset of a mixed carbonate-siliciclastic sedimentation took place along the northern Bonaparte Basin.



Seismic facies

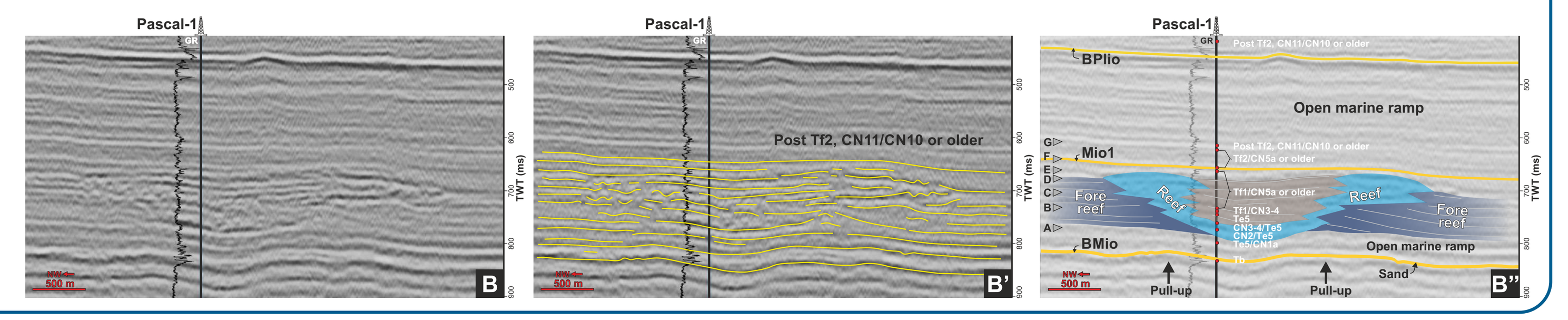
The ICBs occur as laterally restricted patches of distinct seismic character associated with symmetrical, bowl-shape geometries on seismic cross-sections. Overall, the seismic amplitudes of these features are brighter than the surrounding continuous and parallel reflections. Their internal seismic reflectors change from a chaotic character at the bases and margins, to higher-amplitude, well-bedded and sub-parallel reflectors within their centre. These seismic facies are respectively interpreted as high-velocity carbonate reef deposits surrounding flat lying 'lagoon' deposits. The changes in seismic facies at the margins of the ICBs suggest that the reef deposits wedge out both in the fore-reef and the back-reef directions.



Biostratigraphy & sedimentology

The ICBs developed between ca. 18 Ma (CN2–CN3; mid Burdigalian; horizon 'A') and ca. 15.5 Ma (Tf1/Tf2; mid Langhian; horizon 'F'/Mio1).

Samples within the fore-reef and reef seismic geomorphologies of the ICBs consist of recrystallized (dolomitic) wacketsones–packstones grading upward to moldic packstones, containing abundant massive and branching coral debris along with algal remnants and benthic foraminifera (Rotaliida, Cellanthus and Flosculinella; Gorter et al., 2002).



Evolution model & controlling factors

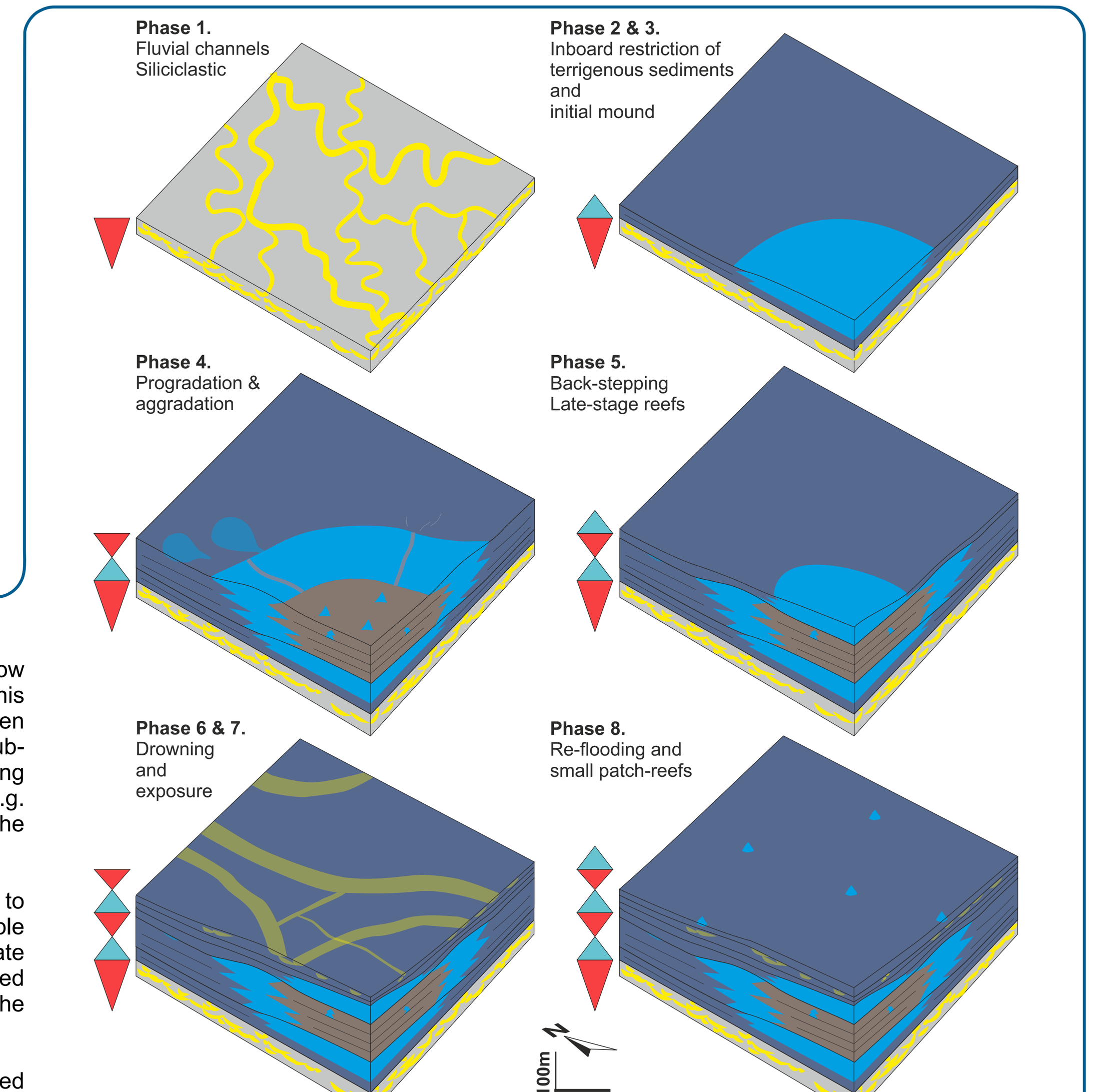
Results show that the transition from an open marine ramp (dominated by benthic foraminifera) to a shallow shelf associated with the growth of the coralgal ICBs did not initiate until the mid Burdigalian, ca. 18 Ma. This timing coincides with the first onset of coralgal reef growth in the adjacent Browse Basin (Rosleff-Soerensen et al., 2015). Isolated carbonate build-ups also started to develop in the middle Miocene in the Rowley Sub-basin, located south of the study area (Ryan et al., 2009). This age consistency across a >1000 km long margin suggests a regional change in the parameters controlling carbonate production at that time (e.g. oceanography, tectonics, climate and eustasy). The lack of observed coral reefs during the Paleogene in the Australian North West Shelf may be due to its sub-tropical position during that time.

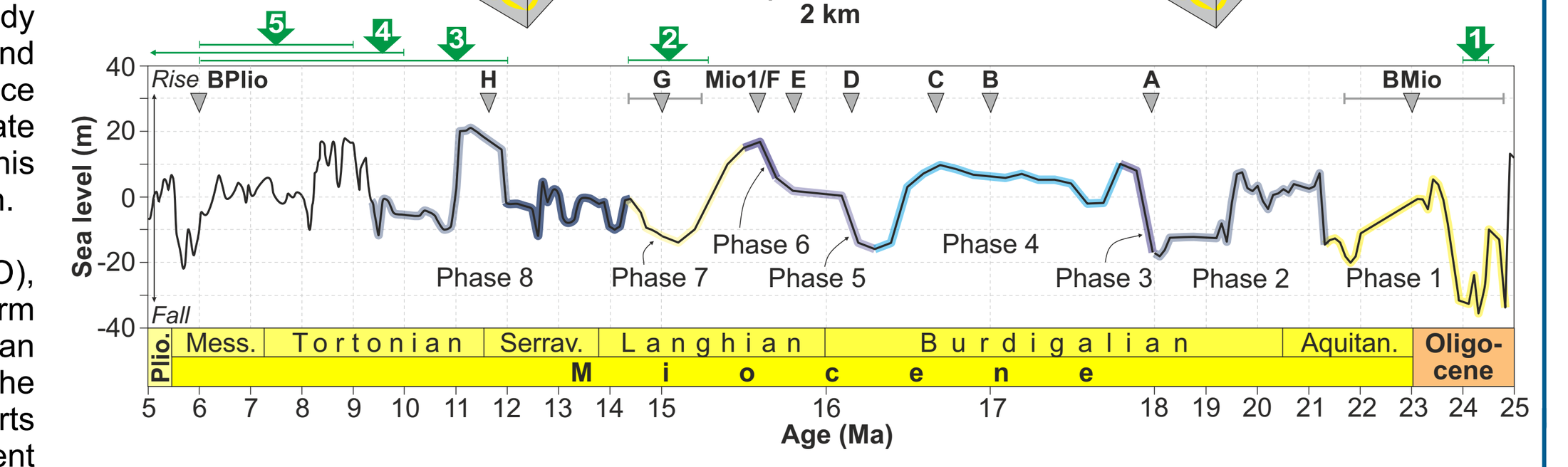
Tectonics and subsidence: Role of local tectonics on the stratigraphic architecture of the mid-Burdigalian to Langhian ICBs seems minimal. The ICBs initiated on a low-angle antecedent topography with no visible structural control. Subsidence calculations from Lucas-1 show that the growth of ICBs took place in moderate subsidence rates (~50 m/m.y.). While these moderate rates of accommodation creation would have provided good conditions for the growth of ICBs during the mid-Burdigalian, subsidence cannot be the cause for the initiation of coralgal build-ups at that time.

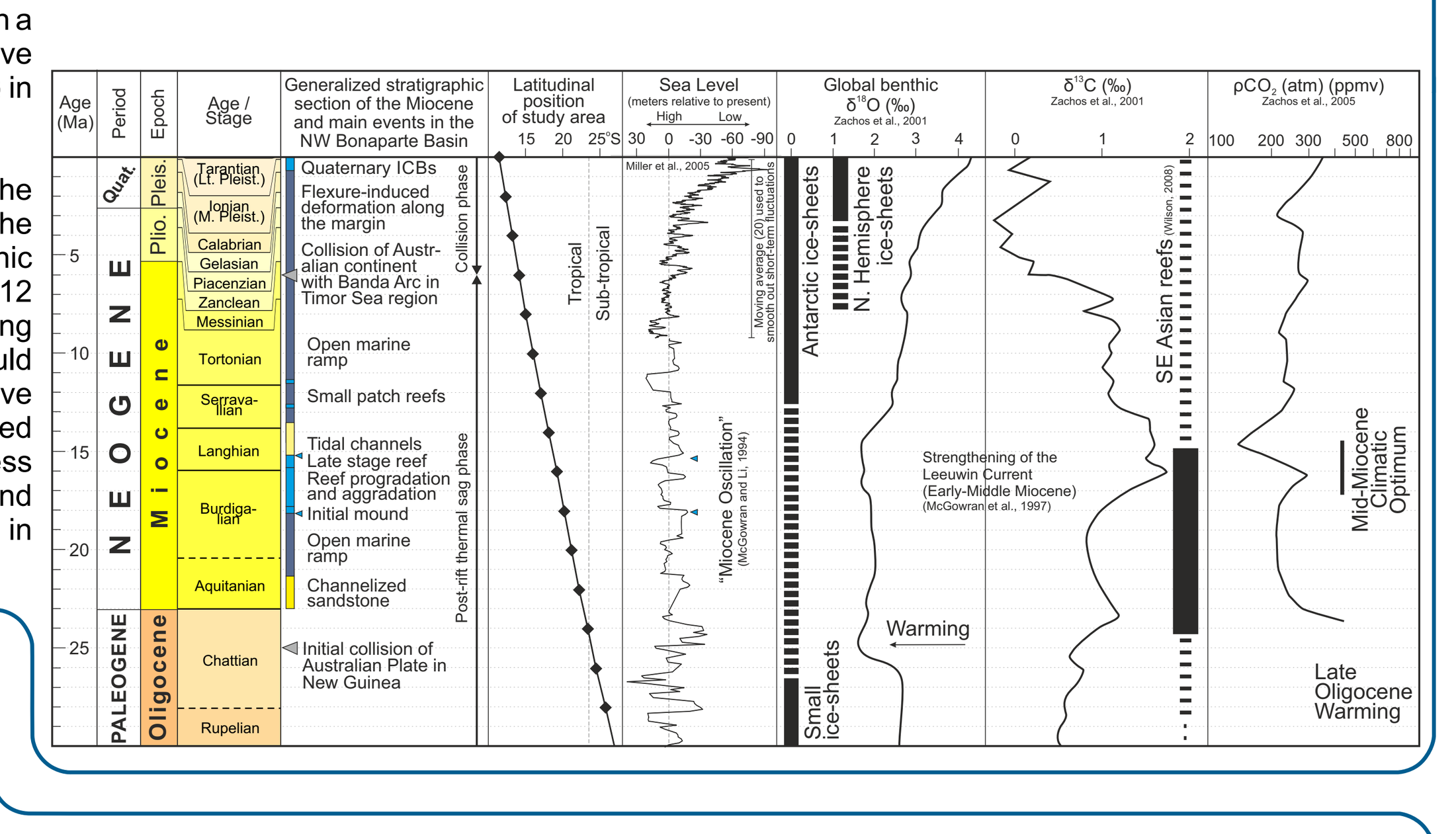
Eustasy: During early–mid Miocene, sea-level changes were in the order of 30 to 60 m and mostly governed by the growth and decay of the Antarctic ice sheet. Initiation and growth of the coralgal build-ups in the study area seems to coincide with a rapid sea-level rise event at ca. 18 Ma followed by a global sea-level highstand between 18 and 16.5 Ma. Coral growth may have been promoted at this time due to their ability to keep pace with rapid sea-level rises. However, several sea-level rise events of similar amplitude are recorded in the late Oligocene and early Miocene and these were not accompanied with coralgal growth in the study area. This suggests that eustasy was not the main trigger for the initiation of ICBs in the northwestern Bonaparte Basin.

Climate and oceanography: The transition in global climate to the Mid Miocene Climatic Optimum (MMCO), marked by globally high-temperatures and CO_2, correlates with the initiation of ICBs. During this warm period, the zone of tropical reef growth extended far to the south in the Great Australian Bight. In addition, an exceptionally strong Leeuwin Current during the early– mid Miocene (ca. 18–16 Ma) also accounts for the presence of tropical reefs in southern Australia (Feary and James, 1995). The Leeuwin Current transports low-salinity warm-water and low-latitude (tropical) biota along the western margin of Australian continent towards the southern margin (Pearce, 1997). Thus, an increase in the oceanic current intensity coupled with a MMCO warm climate and higher tropical sea-surface temperatures (SSTs) than present could have enhanced coralgal development in the northwestern Bonaparte Basin and (through the Leeuwin Current) in the southern basins of the North West Shelf of Australia.

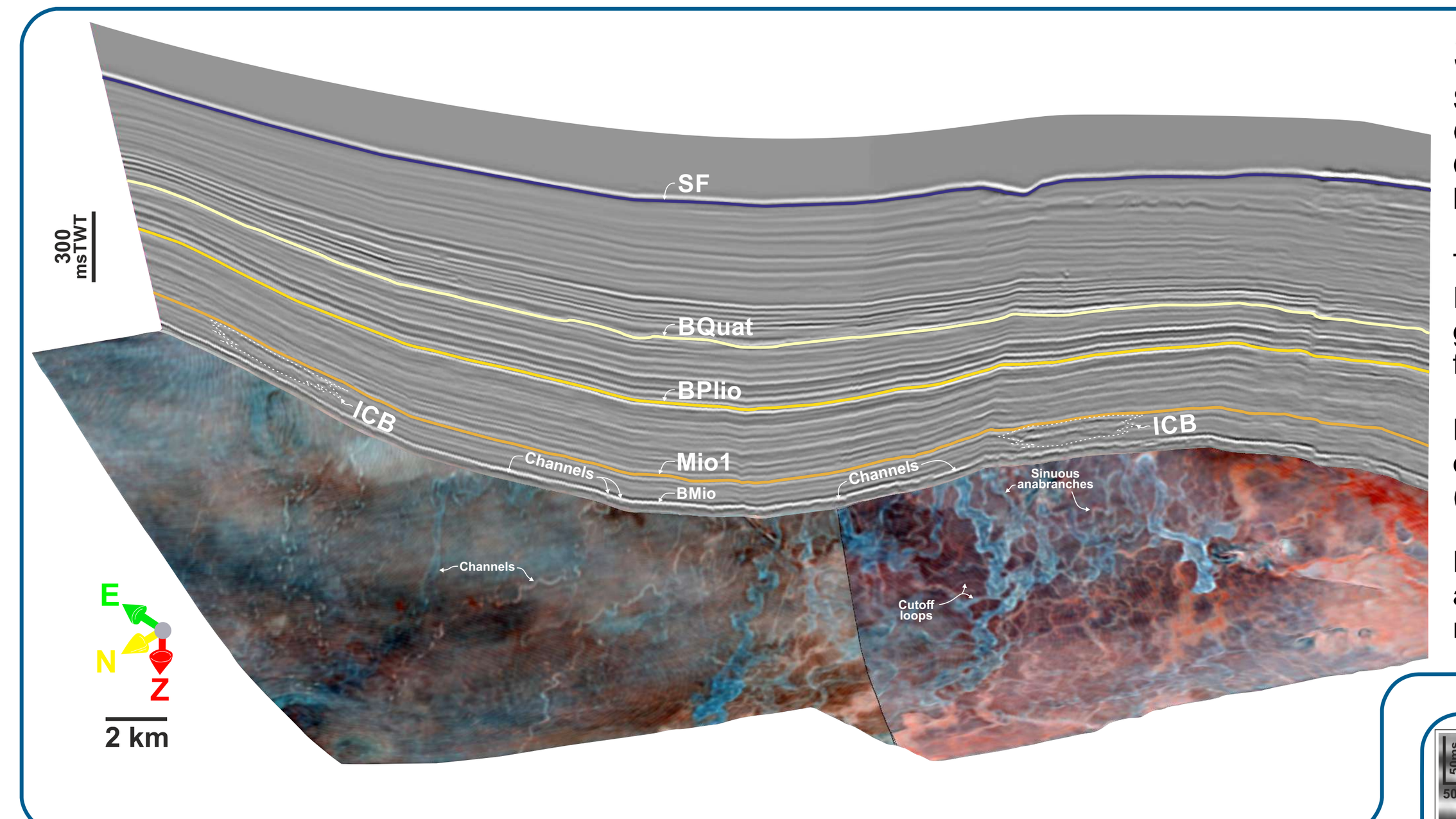
Backstepping and demise of the mid Burdigalian–Langhian ICBs: The ICBs stepped back during the early Langhian, to form small knolls without inner lagoons above the earlier accumulations. Drowning of the carbonate build-ups took place at 15.5 Ma (horizon 'F'/Mio1). There is no evidence for a major plate tectonic reorganization or local tectonics activity in the region until volcanic activity started in the Banda Arc at ca. 12 Ma. Therefore, it is here postulated that eustasy and oceanography were the primary cause of backstepping and drowning of the ICBs. The 16.5 Ma sea-level rise, in combination with background subsidence, could have caused a rapid increase in accommodation space across the middle Miocene platform, and progressive backstepping of the ICBs. In addition, cooling of the global climate at the end of the MMCO and reduced oceanic circulation could have promoted oceanographic conditions (temperatures and nutrients) less favourable to coralgal development. Therefore, we hypothesize that the combination of sea-level rise and climate and oceanographic change led to the drowning of the mid-Burdigalian to Langhian ICBs in northwestern Bonaparte Basin.







Seismic stratigraphy



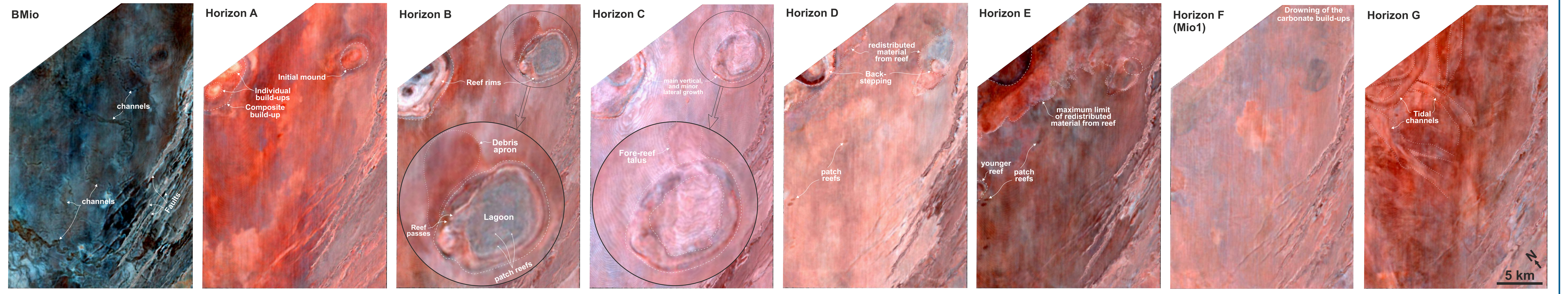
Seven major Cenozoic stratigraphic surfaces, i.e. Base Paleocene (BPal), Base Eocene (BEoc), Top Grebe (TG), Base Oligocene (Bolig), Base Miocene (BMio), Base Pliocene (BPlio) and Base Quaternary (BQuat) were mapped in the seismic dataset. These correspond to regional sequence boundaries that can be identified throughout the Bonaparte Basin.

The BMio unconformity is associated with truncation of the underlying strata. Seismic attributes along BMio reveal the presence of a dense network of channelized geomorphologies. The planform geometries of individual channels (sinuous anabranches and cut-off loops) suggest a flow direction from south to north.

Miocene sequence is generally characterized by parallel and semi-continuous to continuous reflectors of low- to medium-amplitudes. Overall thickness of the Miocene sequence is relatively uniform (350–550 ms TWT [~385–605 m]) suggesting a wide and low-gradient platform.

Mio1 horizon subdivides the Miocene sequence in two seismic units. The basal unit (underlying Mio1) is associated with parallel and continuous reflections. Locally, the continuous reflector passes into relatively higher amplitude, chaotic facies that have been interpreted as ICBs.

Seismic geomorphology and growth of Miocene ICBs



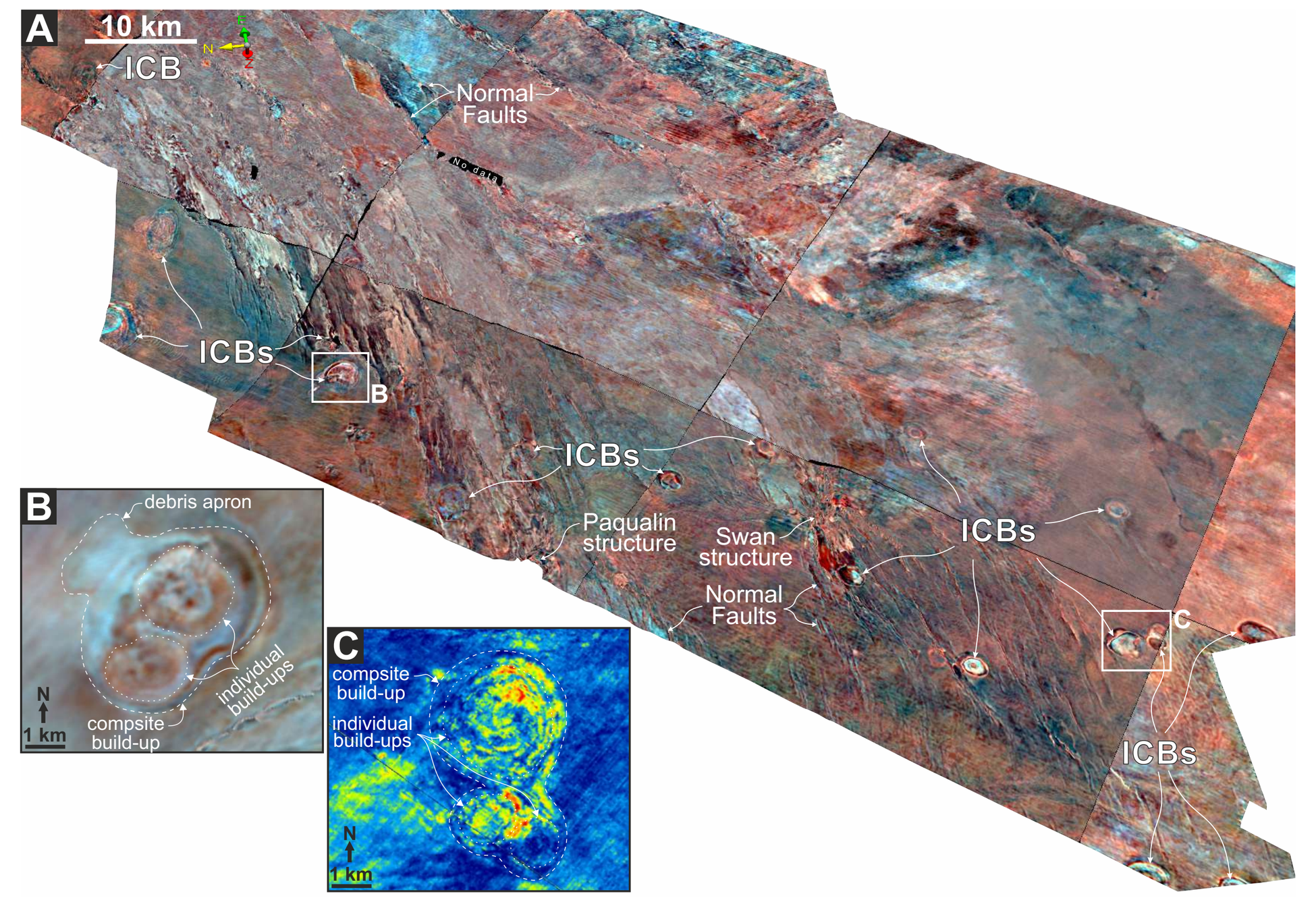
3D seismic coverage over the carbonate build-ups provides the opportunity to study their seismic morphologies in detail.

Start-up and catch-up: ICBs initiated at horizon 'A' (~25–30 ms TWT above the Bmio unconformity). Spectral decomposition data shows that the ICBs initiated as small individual build-ups (1.5–2 km^2) which rapidly coalesced during the early stages, in some cases, into larger (>5 km^2) composite build-ups. Internally, the ICBs form concentric rings.

Keep-up: Above horizon 'A' the geometry of the build-ups expands both laterally and vertically which is interpreted as a product of carbonate progradation and aggradation. The rims of the ICBs prograde over 1–1.5 km between horizons 'A' and 'B'. Reef rims and internal lagoon geometries can be clearly identified on seismic attribute maps. Above horizon 'B', only minor lateral growth occurred in most ICBs.

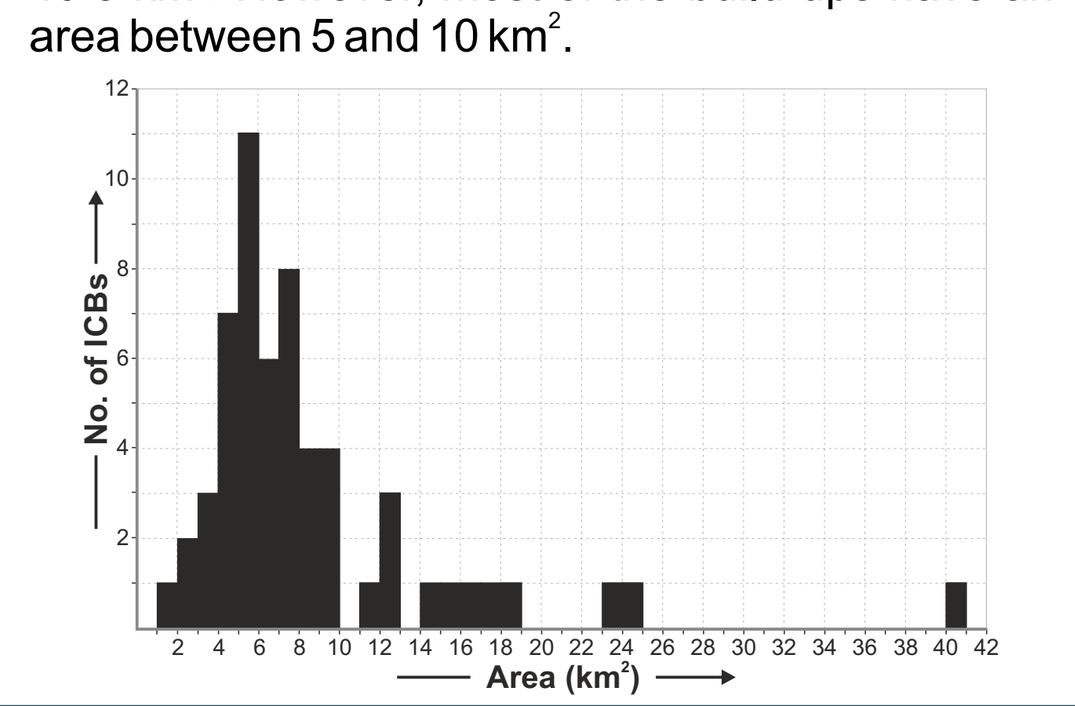
Backstepping and demise: Size of the build-ups is reduced considerably above horizon 'C'. Along horizon 'D', seismic attributes also show the redistributed material from the build-ups, spreading over the surrounding area. Subsequently, the build-up sediments were further scattered and horizon 'E' marks the maximum limit of their dispersion. The ICBs disappear at horizon 'F' (Mio1) which is interpreted as a drowning surface. Large rectilinear channels of low sinuosity are present along horizon 'G'. Northwest trending straight and narrow equiwidth (~200 m wide) channels are also present along the horizon 'G' in the Laminaria High area.

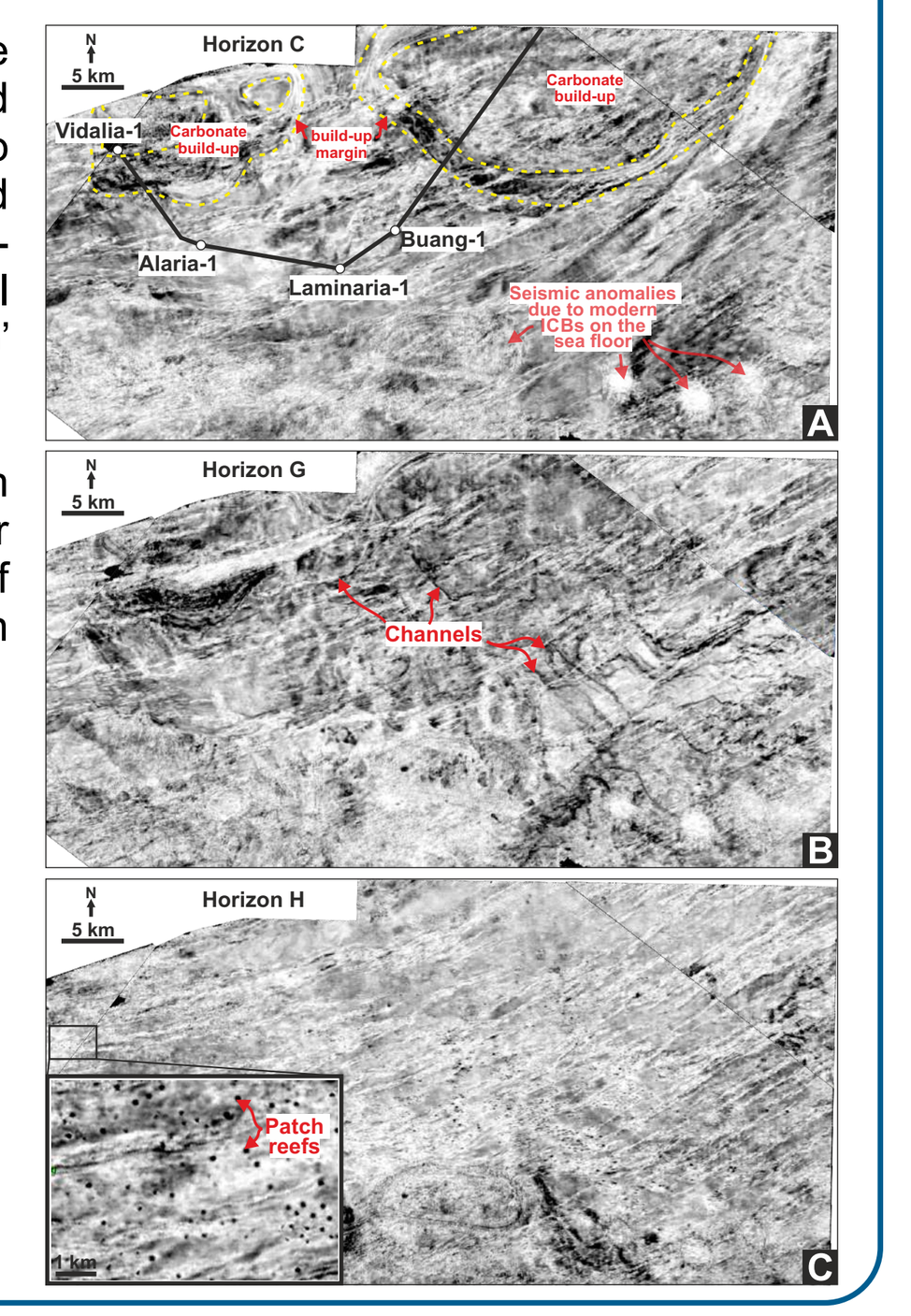
Patch reef phase: Carbonate reef growth resumed above the horizon 'G'. A number of small, often isolated patch reefs (pinnacles) associated with high-amplitude anomalies are observed. In map-view, these features appear as sub-circular spots distributed over a wide area.



In the Laminaria High area, large build-ups are observed at horizon 'C'. Coalescing bodies and lateral accretion of the build-margin are also evident. These build-ups are asymmetrical and elongated in plan-view, in contrast with the sub-circular ICBs in the southwest. Channels and small patch reefs are also observable along horizons 'G' and 'H', respectively.

The diameter of individual build-ups ranges from 0.5 to 12 km, with an average value of 3 km. Their surface area varies from 1.61 km^2 to a maximum of 40.5 km^2. However, most of the build-ups have an area between 5 and 10 km^2.

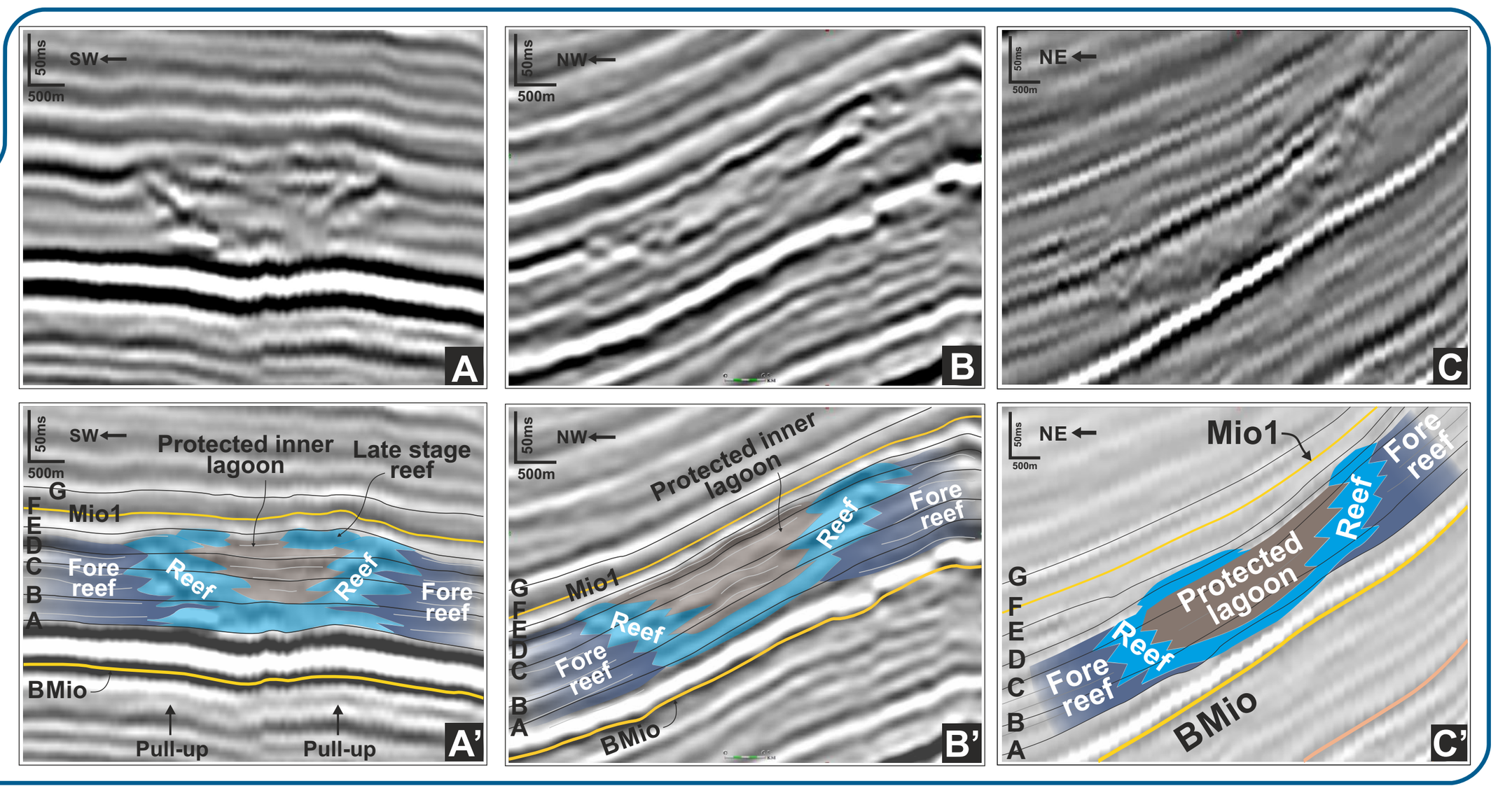




Miocene ICBs

The Miocene ICBs of the study area are well-imaged on seismic data, mainly because they are buried below only ~700 m of fine-grained overburden. Sixty ICBs have been identified based on their similar cross-sectional and map-view geometries on 2D and 3D seismic data in the northwestern Bonaparte Basin. The ICBs occur within the same stratigraphic interval, and are spread over a wide area (>25,000 km^2). The location of the ICBs does not seem to be related to antecedent topography, at least at the resolution of seismic data. The build-ups developed on a flat surface, approximately 30 ms TWT above the BMio unconformity. Pull-ups below the ICBs are also observed, indicating high-velocity reef intervals. This effect fades away with depth as the ICB interval is not very thick, and because velocity contrast is not very high as the build-ups are contained within a carbonate succession.

Seismic amplitude and spectral decomposition attributes were mapped across each reflection surface within the Miocene sequence. However, eight seismic horizons ('A' to 'G') within the early Miocene interval were selected to illustrate the geomorphological evolution of the ICBs from their initiation to their demise.



Miocene paleogeography

The distribution of the Miocene ICBs over a wide area suggests that they developed over a broad shallow carbonate platform. These results in combination with observations of Rosleff-Soerensen et al. (2015) in the Browse Basin suggests that a barrier reef system extending for >1200 km developed along the North West Shelf at that time. A similar geography can be seen in the modern Great Barrier Reef (GBR) in northeast Australia, which forms a very extensive rimmed margin comprising numerous coral reef build-ups inboard of the barrier complex.

Conclusions

- The ICBs developed during early–mid Miocene period (ca. 18–15.5 Ma) in the NW Bonaparte Basin.
- Their growth coincides with the Mid Miocene Climatic Optimum, a phase of global climate warming corresponding to an acme for carbonate reef development in northwestern Australia.
- The regional paleogeographic reconstruction, through integration of these new results with data from the Browse Basin, suggests that a Miocene barrier reef extended for >1200 km along the North West Shelf.

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