Successive Rifting Events in Marginal Basins: The Example of the Coral Sea Region (Papua New Guinea)

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AGU PUBLICATIONS

Tectonics

RESEARCH ARTICLE
10.1002/2017TC004783

Key Points:
- Extensive data coverage allows us to link onshore and offshore geological structures of the Coral Sea region, Papua New Guinea
- Sedimentary basins formed during successive rifting events implying fault reactivation
- Mechanisms controlling the development of polyphased oceanic basins are highlighted

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5

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Citation:
Bulois, C., Pubellier, M., Chamot-Rooke, N., & Delescluse, M. (2017). Successive rifting events in marginal basins: The example of the Coral Sea region (Papua New Guinea). *Tectonics*, *36*. https://doi.org/10.1002/2017TC004783

Received 26 AUG 2017
Accepted 9 NOV 2017
Accepted article online 13 NOV 2017

Successive Rifting Events in Marginal Basins: The Example of the Coral Sea Region (Papua New Guinea)

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Abstract Reactivation of extensional structures is commonly inferred during rift evolution. In that context, we present original seismic interpretation to explore the geometry and interactions of three successive rifting events in the Coral Sea region, Papua New Guinea. The first event (R_1), poorly documented, occurred during the Triassic along an older N-S Permian structural fabric. During the Jurassic, extensional faults were reactivated through a second extensional episode (R_2), which formed small (~10/20 km) basins bounded by N-S, NE-SW, and E-W listric faults. Extension prolonged during the Lower Cretaceous with seafloor spreading in the Owen Stanley Oceanic Basin, now incorporated in the Papuan fold and thrust belts. A third Late Cretaceous extensional phase (R_3) gently reactivated some of the faults with very limited landward tilt in most basins and deformation located along the present continent-ocean transition. Seafloor spreading in the Coral Sea followed from Danian to Ypresian. This extensional system is sealed by unequally preserved Eocene strata that mark the onset of postrift thermal subsidence prior to the margin inversion from Oligocene onward. This overall evolution suggests various extensional systems that are geographically and temporarily defined the one another. The early rifting of the crust is controlled by preexisting continental features resulting in the local Pangaea breakup. In contrast, the Coral Sea propagator cuts through the rifted margin and is controlled by a subduction complex in accordance with the Tasman Sea opening. This evolution underlines the interactions existing between two extension modes in agreement with variations of the regional geodynamical setting around Australia.

1. Introduction

Rifting can either occur in the midst of continental plates depending of the mantle behavior (i.e., passive and active hypothesis due to far-field boundary forces or mantle plume) (Sengör & Burke, 1978) or as a result of trench pull caused by neighboring subduction zone (i.e., backarc extension due to the rollback of the slab) (Honza, 1995; Tamaki & Honza, 1991; Uyeda & McCabe, 1983). The latter case produces rifted slivers separated by marginal basins such as in Southeast Asia (Pubellier & Meresse, 2012) or in the West Pacific (Cluzel et al., 2012). In these two extreme models of rifting, polyphased direction of extension may change over time, resulting in variations of the basin geometries and an organization of trapped sediments within specific megasequences that undersign the polyphased evolution of rifted basins. Polyphased rifting is a common phenomenon in many extensional settings of longstanding history, such as the North Atlantic Rift system (e.g., Doré et al., 1999; Roberts et al., 1999; Tankard & Balkwill, 1989; Ziegler, 1989), the Red Sea/East African Rift system (e.g., Huchon & Khanbari, 2003; Montenat et al., 1988; Versfelt & Rosendahl, 1989) or the South China Sea (e.g., Franke et al., 2014; Fyhn, Boldreel, et al., 2009; Fyhn, Nielsen, et al., 2009; Savva et al., 2014). It implies fault reactivation and deposition of specific sequences, among which the dynamics understanding requires much geological and geophysical information. In that context, the frontier region of the Coral Sea, located in between Papua New Guinea and Australia (Figure 1), constitutes a typical example of such a complexity as intimately linked juxtapositions of rifting, seafloor spreading, and marginal accretion episodes are found adjacently (e.g., Baldwin et al., 2012; Corbet, 2005; De Smet et al., 1998; Doust & Noble, 2008; Hill & Hall, 2002; Sheppard & Cranfield, 2012). Most detailed publications consist of studies that deal with specific aspects of the Cenozoic compression evolution in the Papuan mainland and its associated natural resources. Offshore studies mostly focused on the eastern Cenozoic tectonostratigraphy of the Coral Sea (e.g., Botsford et al., 2012; Home et al., 1990; Jablonski et al., 2006; Mutter, 1975) or on the evolution of the Recent silicastic-carbonate systems (e.g., Francis et al., 2008; Carson et al., 2008; Jorry et al., 2008). Comparatively, preceding rifting architecture is poorly documented due to the paucity of regional subsurface datasets resulting from the thick Cenozoic sedimentary cover.

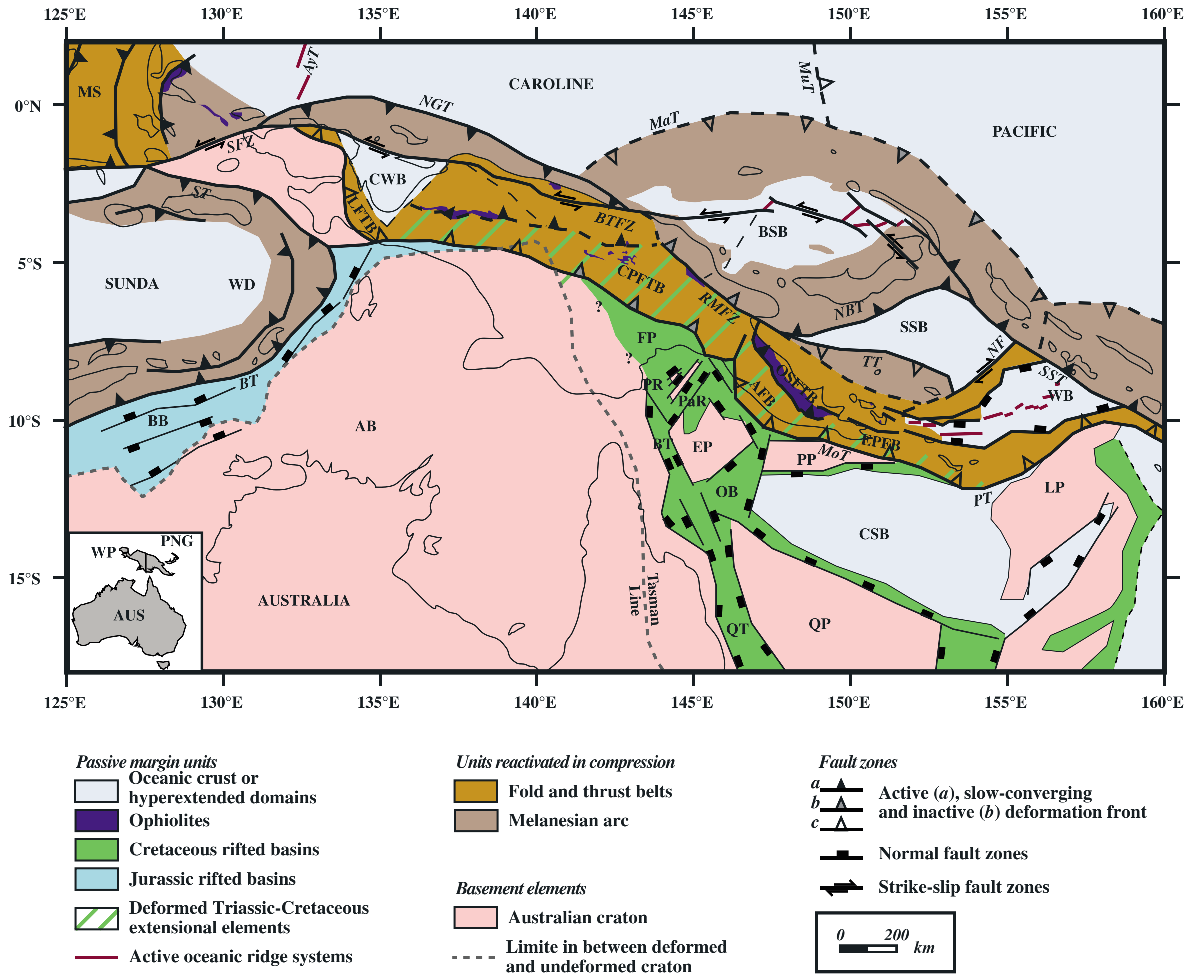

Figure 1. Simplified structural map of New Guinea and surrounding areas. Map is adapted from Bulois (2016). Words in capital letters are for lithospheric plates, abbreviations in capital letters are for structural elements, and abbreviations in italics are for mountain ranges and fault zones. Abbreviations: AB: Arafura Basin, AFB: Aure fold belt, AUS: Australia, AyT: Ayu Trough, BB: Bonaparte Basin, BSB: Bismarck Sea Basin, BT: Bligh Trough, BTFZ: Bewani-Torricelli fault zone, CSB: Coral Sea Basin, CPFTB: Central Papuan fold and thrust belt, CWB: Cenderawasih Basin, EP: Eastern Plateau, EPFB: Eastern Papuan fold belt, FP: fly platform, LFTB: Lengguru fold and thrust belt, LP: Louisiade Plateau, MaT: Manus thrust, MoT: Moresby thrust, MS: Molucca Sea, MuT: Musseau Trough, NBT: New Britain Trench, NGT: New Guinea Trench, NF: Nubura fault, OB: Osprey Basin, OSFTB: Owen Stanley fold and thrust belt, PaR: Pandora Ridge, PP: Papuan Plateau, PR: Pasca Ridge, PT: Pocklington Trough, PNG: Papua New Guinea, QT: Queensland Trough, QP: Queensland Plateau, RMFZ: Ramu-Markham fault zone, SSB: Solomon Sea Basin, SST: South Solomon Trench, SFZ: Sorong fault zone, ST: Seram Trench, TT: Trobriand Trough, WB: Woodlark Basin, and WP: West Papua.

The overall region is generally described as two following rift systems extending either along the NW Shelf of Australia or in the Coral Sea region (Figure 1) (Struckmeyer et al., 1993; Symonds et al., 1984). Jurassic rifting along the NW Shelf is well-understood regarding structural directions and associated infillings (e.g., Chen et al., 2002; Elliott et al., 1996; Heine & Müller, 2005; Stagg et al., 1999). In comparison, the Coral Sea extension is mostly evidenced from early Cenozoic oceanic crust bounded by large rifted continental plateaus detached from the Australian craton (e.g., Drummond et al., 1979; Ewing, Hawkins, et al., 1970; Ewing, Houtz, et al., 1970; Gaina et al., 1999; Gardner, 1970; Symonds et al., 1984; Taylor & Falvey, 1977; Weissel & Watts, 1979). The best explored features lie in shallow waters (e.g., Papuan Basin and Eastern and Papuan plateaus) (e.g., Home et al., 1990; Jablonski et al., 2006; Botsford et al., 2012; Ott & Mann, 2015) and are often interpreted as a result of the Cretaceous rifting preceding seafloor spreading. Yet older rifted sequences are also suggested onshore and offshore but their dynamic setting is still under debate. In particular, it remains uncertain if the NW Shelf and Coral Sea rift systems actually connected in the past along a large rifted margin now partially shortened and imbricated in the Papuan fold and thrust belts (e.g., Hill, 1991; Hirst & Price, 1996).

Hereafter, we specifically focus on detailed mapping of extensional features along the northern margin of the Coral Sea Basin to better understand the initiation and propagation of the extension through the Australian craton and how rift systems may interact over time. We present a comprehensive analysis of geological and geophysical datasets, comprising original industrial 2D seismic data correlated to local wells together with magnetic and gravimetric observations. We argue that the Coral Sea region underwent at least three overprinted extensional episodes prior to Mid-Cenozoic basement-involved shortening, controlling the formation and reactivation of fault systems over time.

2. Geological Setting

Papuan present-day deformation is generally viewed as a result of the 70-Myr-long, oblique and rapid convergence between the Australian and Pacific plates (Gaina & Müller, 2007; Tregoning et al., 1998; Wallace et al., 2014). This resulted in the accretion of lithospheric terranes (Audley-Charles, 1991; Cloos et al., 2005; Crowhurst et al., 1996; Dewey & Bird, 1970; Hamilton, 1979; Hill & Hall, 2002; Pigram & Davies, 1987; Quarles van Ufford & Cloos, 2005) interspaced by the formation of oceanic basins (e.g., Coral and Tasman seas) and sometimes backarc or propagator basins (e.g., Solomon and Bismarck seas or Woodlark Basin) (Figure 2) (e.g., Gaina & Müller, 2007; Gaina et al., 1998, 1999; Hayes & Ringis, 1973; Joshima et al., 1987; Martinez et al., 1999; Taylor, 1979; Taylor et al., 1999). These involve Proterozoic to Cenozoic crustal provinces separated by major fault zones reactivated over time.

In the Coral Sea region, in particular, crustal elements and faults have been involved in a number of rift events that are mostly recognized in the Papuan Basin (Hill & Hall, 2002; Home et al., 1990; Jablonski et al., 2006) but remain uncertain farther east due to compression and thick sediments. It implies discrepancies regarding the regional significance of these events.

2.1. Prerift Basement Geology

The Coral Sea region has recorded a long-lasting evolution from the Precambrian and involved crystalline basement structures susceptible of locating subsequent extensional deformation (Figure 2). Basement rocks appear as large plateaus rifted from the Australian craton (Drummond et al., 1979; Mutter, 1977; Symonds et al., 1984; Taylor & Falvey, 1977). Drillings and seismic reflection surveys showed that the Queensland and Eastern plateaus are largely composed of Palaeozoic or older crystalline basement overlain by thick Cenozoic sediments. Similar crystalline rocks are indirectly evidenced in the adjacent ridges (e.g., Pandora Ridge) as well as underneath the Papuan and Louisiade plateaus (Jablonski et al., 2006; Rogerson, Hilyard, Francis, et al., 1987).

Onshore, Mid-Proterozoic cratonic basement along the Arafura Platform and the Lengguru Fold and Thrust Belt underlie Silurian-Devonian metasediments (Pieters et al., 1983). Eastward (Papuan fold and thrust belts), various undeformed sediments deposited on top of Precambrian plutons and Palaeozoic (Permian or older) metasediments intruded by Early to Middle Triassic granites (Figure 3) (e.g., Crowhurst et al., 1996, 2004; Davies, 2012; Page, 1976; Parris, 1994; Rogerson, Hilyard, Francis, et al., 1987; Rogerson, Hilyard, Finlayson, et al., 1987; Struckmeyer et al., 1993; van Wyck & Williams, 2002). This implies two basement types from east to west, which the boundary may correspond to the northward prolongation of the Tasman Line, a major lithospheric-scale discontinuity underlying the New England Orogen in Australia (Figure 1) (Direen & Crawford, 2003; Schreibner, 1974). Nonetheless, its geographic extent in Papua New Guinea remains discussed (e.g., Hill & Hall, 2002).

2.2. The Australian Continental Breakup

Following Palaeozoic times, the region encompassed a period of long-lasting extension affecting Pangaea supercontinent (Figure 3). Early synrift sediments (?Permian) are seismically interpreted west of the Pandora Ridge (Jablonski et al., 2006). Wells drilled on the Fly Platform (*Well Kanau-1*) and in the Australian part of the Papuan Basin (*Well Anchor Cay-1*) penetrated younger (Triassic) synrift sediments (e.g., Home et al., 1990). Further Mid-Late Triassic formations (e.g., *Kana Volcanics* and the *Jimi Greywacke*) are interpreted as part of this synrift setting (Home et al., 1990) or as a result from the Bowen-Fitzroy Orogeny in northeastern Australia (e.g., Jablonski & Saitta, 2004). As a result, this early synrift episode remains poorly constrained spatially.

During the Early to Middle Jurassic, northern Australia experienced a more widespread rifting event, resulting in a transgressive megasequence defined in onshore Papua as the *Bol Arkose Formation* (Lower Jurassic

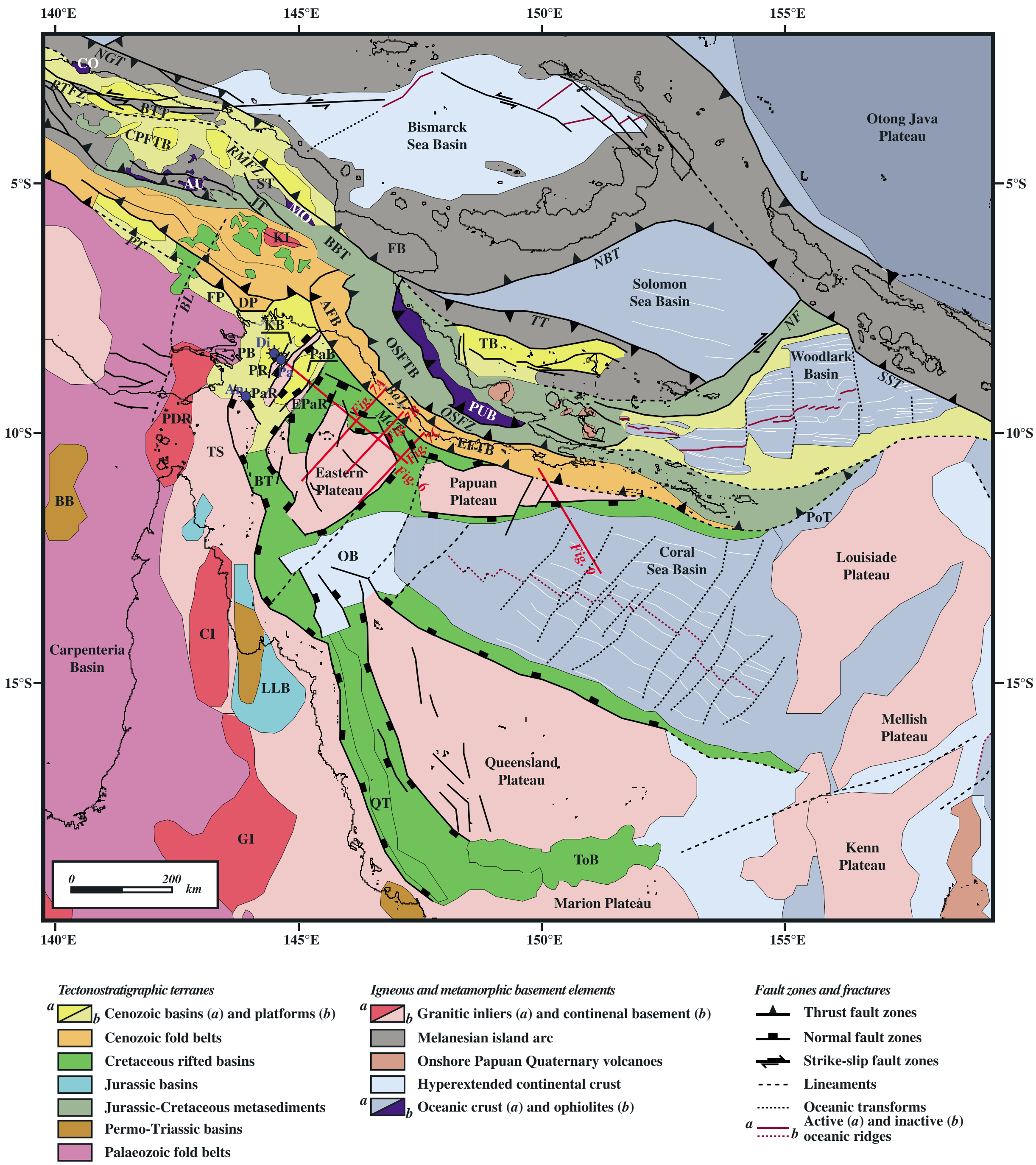

Figure 2. Tectonostratigraphic elements in the eastern Papuan Basin. Structural elements are principally adapted from Pigram and Davies (1987), Norwick (2003), Collot et al. (2009), and Bouysse et al. (2014). Abbreviations in capital letters are for structural elements; abbreviations in italics are for mountain ranges and fault zones. Wells cited in the text are also plotted on the map in blue (An for Anchor Cay; Di for Dibiri-1A; and Pa for Pasca). Abbreviations: AFB: Aure fold belt, AU: April Ophiolite, BB: Bamaga Basin, BBT: Bena Bena Terranes, BL: Bosavi Lineament, BT: Bligh Trough, BTFZ: Bewani-Torricelli fault zone, BoT: Bogora thrust, BTT: Bewani-Torricelli Terranes, CI: Coen Inlier, CO: Cyclops Ophiolite, CPFTB: Central Papuan fold and thrust belt, DP: Darai Plateau, EP: Eastern Plateau, EPaR: East Pandora Ridge, EPFB: Eastern Papuan fold belt, FB: Finisterre block, FP: Fly platform, GI: Georgetown Inlier, JT: Jimi Terranes, KB: Kutubu Basin, KI: Kubor Inlier, LLB: Laura-Lakefield Basins, LP: Louisiade Plateau, MO: Marum Ophiolite, MoT: Moresby thrust, NBT: New Britain Trench, NGT: New Guinea Trench, NF: Nubura fault, OB: Osprey Basin, OSFTB: Owen Stanley fold and thrust belt, OSFZ: Owen Stanley fault zone, PaB: Pandora Basin, PaR: Pandora Ridge, PB: Papuan Basin, PDR: Penisula-Daru Ridge, PR: Pasca Ridge, PoT: Pocklington Trough, PT: Papuan thrust, PUB: Papuan ultramafic belt, QT: Queensland Trough, QP: Queensland Plateau, RMFZ: Ramu-Markham fault zone, SST: South Solomon Trench, ST: Schrader Terranes, TB: Trobriand Basin, TS: Torres Strait, ToB: Townsville Basin, and TT: Trobriand Trough.

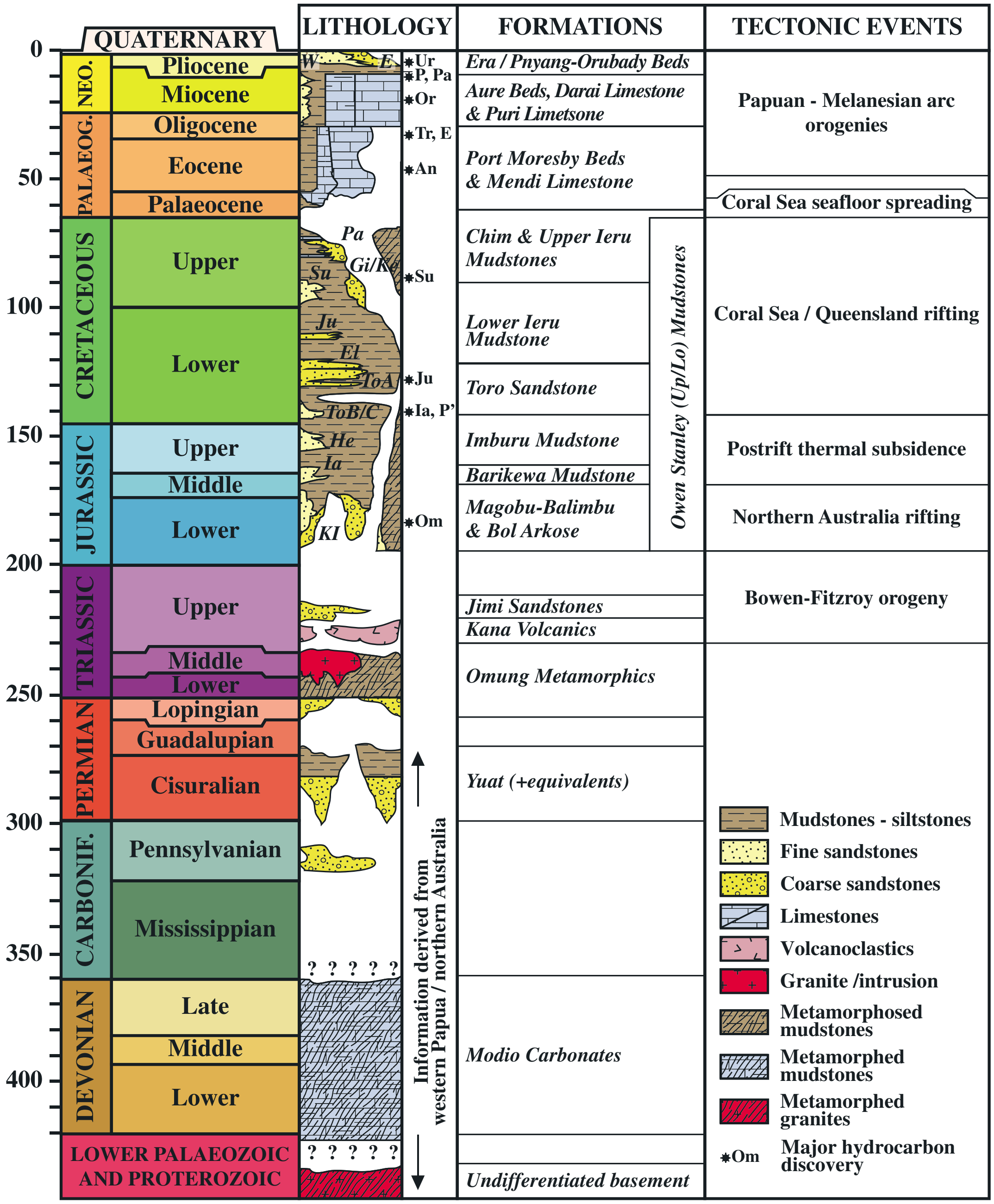

Figure 3. Simplified stratigraphic column in the study area, including the Coral Sea Basin, the Aure fold belt, and Papuan fold belt. Stratigraphy and tectonic events are principally adapted from Home et al. (1990), Jablonski et al. (2006), and Craig and Warvakai (2009). Interpretation in the current study differs from these publications, namely, regarding the significance of tectonic events.

to Bajocian) and the *Mogabu Coal* and *Balimbu Greywacke* formations (Bathonian to Early-to-Middle Jurassic) (Figure 3) (Hill & Hall, 2002; Home et al., 1990; Pigram & Panggabean, 1984). The synrift area is usually described as being limited by a series of anticlines (e.g., Kubor and Muller) to the north and by the Pasca Ridge to the east, although synrift sediments remains accurately untested offshore. There are also issues regarding the opening mechanism (e.g., backarc basin versus aborted continental rift) depending on the continuity of synrift elements (e.g., Hamilton, 1979; Monnier et al., 2000; Pigram & Panggabean, 1981, 1984; Pigram & Symonds, 1991).

Both rift events were followed by a passive margin setting (Figure 3). Postrift strata are alternatively picked from the top of the *Koi-Iange Member* (Middle Jurassic) or from the *Barikewa Mudstone Formation* and its lateral *Iagifu* or *Hedinia* sandy equivalents (Middle to Upper Jurassic) (Figure 3) (e.g., Hill & Hall, 2002; Home et al., 1990; Norwick, 2003). Full thermal subsidence is marked by the development of the *Imburu Mudstone Formation* (Late Callovian to Oxfordian) that seals most of Jurassic extensional features and onlap onto northern structural highs until the earliest Cretaceous (Dow, 1977; Home et al., 1990). Postrift strata are likely to have been affected by following Cretaceous extensional and Cenozoic compression events in many places.

2.3. The Cretaceous Extension and the Opening of the Coral Sea Basin

Many authors argued that the Late Jurassic passive margin setting continued during much of the Neocomian (e.g., Home et al., 1990; Pigram et al., 1989; Struckmeyer et al., 1993) or that this period actually corresponds to a new phase of rifting controlling the deposition of transgressive *Toro Sandstone* and *Lower Ieru Mudstone* formations (respectively Neocomian and Upper Cretaceous, Figure 3) (Hill & Hall, 2002; Norwick, 2003). Variations are due to the duration definition and geometric relation between contemporaneous rifted basins. Also, it is possible that an oceanic basin, now overthrusted in the Owen Stanley Fold and Thrust Belt (i.e., *Papuan Ultramafics Belt*) was separated from a second continental rift setting along an axis linking the Kubor Anticline to the Pasca Ridge (Hill & Hall, 2002; Home et al., 1990).

Rifting continued during the Upper Cretaceous along the northeastern margin of Australia (Blight, Queensland, and Townville basins) and in the Coral Sea Basin (Home et al., 1990; Struckmeyer & Symonds, 1997; Norwick, 2003), while most of the southern margin along the Papuan Basin and eastern Australia was uplifting at the time (e.g., Francis, 1990; Gurnis et al., 2000; Pigram & Symonds, 1993) This resulted in the deposition of marine mudstones (e.g., *Chim* and *Upper Ieru* mudstone formations) and localized sandstones (Figure 3) prior Palaeocene-Eocene seafloor spreading in the deep Coral Sea Basin (Gaina et al., 1999; Weissel & Watts, 1979). Here again, the duration and extensional mechanisms have been debated as their definition depends on the interconnexion of rift episodes (e.g., Home et al., 1990; Norwick, 2003). In addition, large parts of these rifted basins are assumed to have been shortened or completely subducted during the Cenozoic compression (e.g., Hill & Hall, 2002; Matthews et al., 2015; Schellart & Spakman, 2015), implying drastic variation regarding the extent of the Coral Sea extension.

3. Data Analysis and Rifting Architecture of the Coral Sea

As described in the above, the Coral Sea region experienced a long-lasting and polyphased extensional evolution. To date, only first-scale rift-related morphostructures, (e.g., plateaus and large basins) are geographically defined (Figure 2). In addition, the lack of regional seismic and well datasets implies a strong dating bias of stratigraphic sequences. In this paper, about 20,000 km of 2D seismic lines, supported by occasional wells and filtered regional Bouguer gravity anomalies, were correlated along the northern Coral Sea margin to link the well-documented Papuan Basin to eastern, poorly-explored features. Herein, wells *Dibiri-1A* and *Pasca C1* (Phillips Australian Oil Company, 1968, 1969, 1975a, 1975b) are selected from classical reference wells and are compared to adjacent boreholes *Kanau 1* and *Anchor Cay 1* (PNG Petroleum, 1975; Tenneco, 1969), to better constrain regional sequences and surfaces (Figures 4 and 5). In the area, only *Well Dibiri-1A* tested pre-Cenozoic strata so that the synrift succession dating mostly relies on stratigraphic relationships with onshore geology or on classic seismic stratigraphic methods (*sensu* Mitchum et al., 1977).

3.1. Well and Seismic Correlations of the Synrift Section in the Kutubu Basin

The best preserved synrift succession is observed into the onshore part of the Papuan Basin where an almost continuous Triassic to Lower Cretaceous section is unconformably overlain by Late Cretaceous sediments (*Well Kanau-1*; Figure 4). Offshore wells recovered unequal Triassic and Jurassic sediments, and Cretaceous sediments remain absent. In the study area, *Well Pasca-C1* bottomed an approximately 50m-thick, poorly metamorphosed quartzite dated in well reports as Upper Palaeozoic age. It is topped by an erosional unconformity, undersigned by the absence of Triassic and Lower Jurassic sediments in wells *Dibiri-1A* and *Pasca-C1* or by very coarse sandstones and conglomerates and local pyroclastics of Triassic age in adjacent wells *Kanau-1* and *Anchor Cay-1*. Overlying sequences show transgressive Lower Jurassic sandstones, followed by more widespread Middle Jurassic sandstones, siltstones, and mudstones. Although the age cannot be

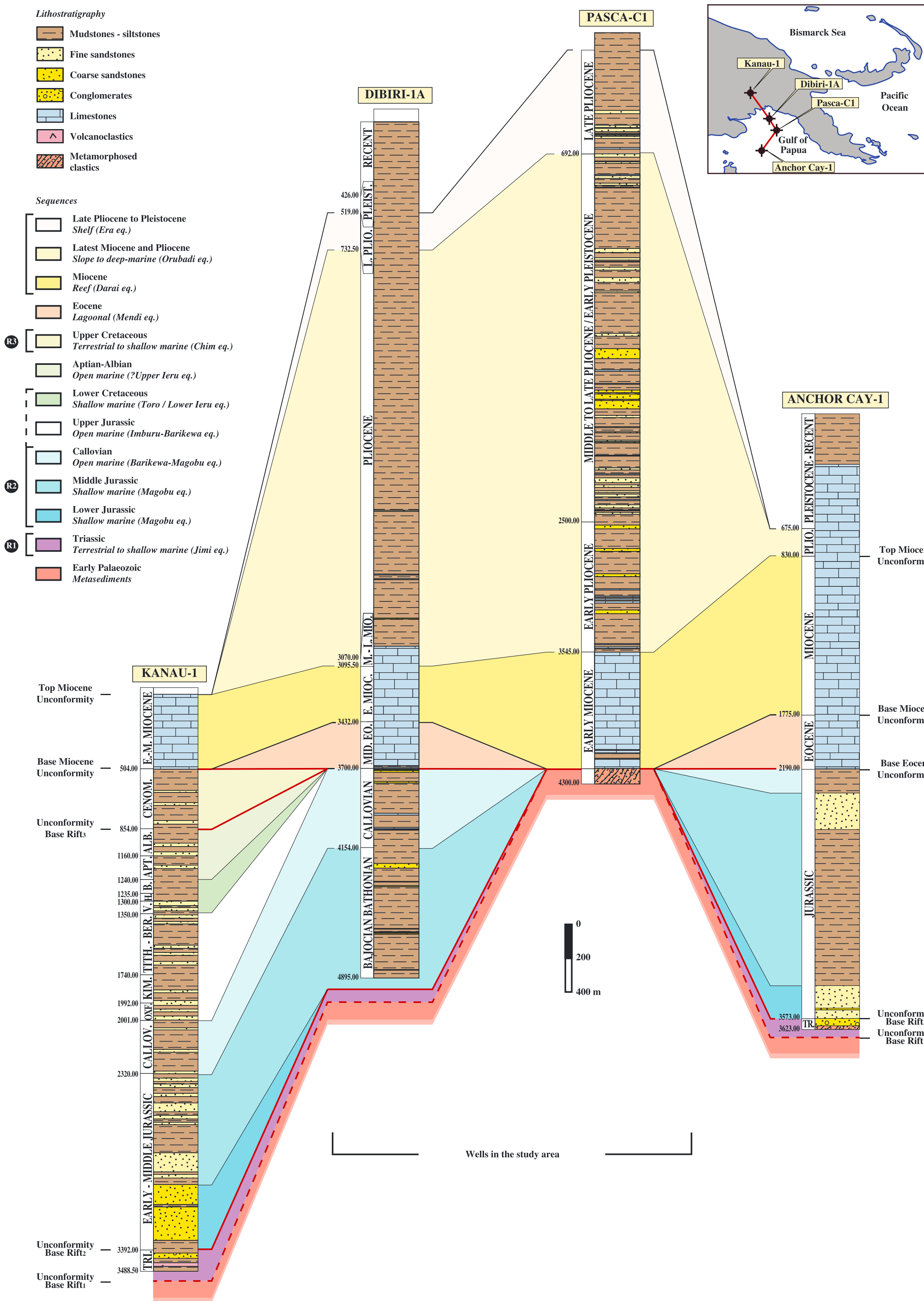

Figure 4. Simplified logs of selected wells in the Coral Sea Basin. R_1, R_2, and R_3 refer to rift settings recognized onshore and offshore. Rift-related unconformities are highlighted in red. These may either be within depocenters (e.g., wells *Kanau-1*, *Dibiri-1A* or *Anchor Cay-1*) or on top of horst (e.g., *Pasca-C1*). Ages are directly taken from well reports (Phillips Australian Oil Company, 1968, 1975b; PNG Petroleum, 1975; Tenneco, 1969). The names of equivalent formations are only here for information.

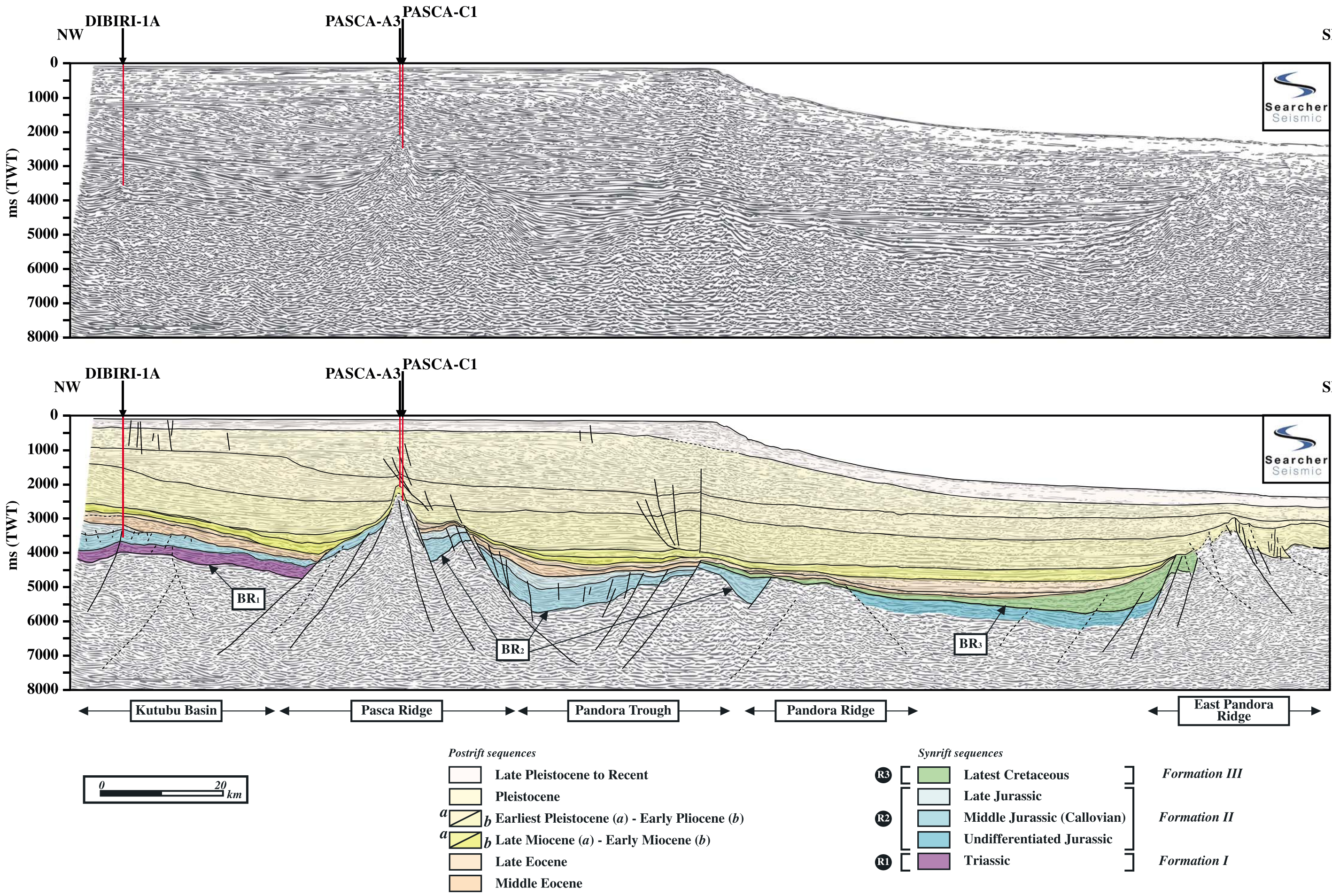

Figure 5. Details of seismic line in the Papuan Basin (west of the study area) calibrated to wells. BR_1, BR_2, and BR_3 refer to basal rift unconformities (see text for further explication). Basin names are adapted from existing nomenclature (e.g., Kutubu, Pasca, or Pandora features) as well as from the name of local languages in Papua New Guinea. Note that seismic interpretation enabled to further subdivide the sequences identified in the wells. Seismic line location is displayed in Figure 6.

determined accurately due to poor biostratigraphic information, we follow various unpublished studies from oil companies that correlate the top marine sequence with Callovian sediments recovered in adjacent *wells Kanau-1* and *Anchor-Cay-1*. Subsequent sequence (Upper Jurassic) contains fine clastics and rare carbonates witnessing of progressive terrestrial to open marine conditions, which is likely to have prolonged during the Lower Cretaceous in the west. Subsequent sediments deposited in a terrestrial to shallow marine setting during the Cenomanian, whose section remains on the offshore (*Well Kanau-1*). This supposes a regional unconformity, which capped the Mesozoic section in all offshore wells (e.g., Brown et al., 1980; Home et al., 1990). The surface is overlain by Eocene-Miocene carbonate correlative reefs that preceded the deposition of thick silicastic carbonates related to the construction of the Pliocene to Recent shelf (e.g., Francis et al., 2008; Tcherepanov et al., 2008).

Therefore, there is a specific stratigraphic distribution that is likely to reveal the complex, extensional and compressional evolution on the region. This polyphased development is mainly characterized by specific first-order unconformities or disconformities, which are used together with internal seismic characteristics to map the various sequences through the seismic volume. Due to data density, the Kutubu Trough region is specifically chosen hereafter to illustrate the regional rifting architecture (Figure 5).

Basal strata form a chaotic seismic package interspaced with local, discontinuous beddings that continue eastward with truncated metasediments on top of the Pasca Ridge (*Well Pasca-C1*, Figure 4). They are interpreted as a part of the Palaeozoic basement that has been rifted afterward (e.g., Bain et al., 1975; Jablonski et al., 2006).

Prerift metasediments are bounded by a strong-amplitude reflector covered by a series of continuous, lower amplitude beds that delineate a megasequence (referred as *Formation I*, purple in Figure 5). It slightly thickens westward (i.e., poor tilt) and is limited by the Pasca Ridge eastward. Internally, it is affected by normal faults that did not propagate in overlying sediments. Therefore, *Formation I* is interpreted as resulting from an early synrift setting (called hereafter R_1). This implies that the base of the sequence corresponds to an unconformity referred as Base $Rift_1$ Unconformity (later shorten as BR_1, Figures 4 and 5). Home et al. (1990) described a similar pattern within Triassic sediments in the vicinity of *Well Anchor Cay-1*, and Hill and Hall (2002) suggested a Triassic synrift event from onshore observations. We therefore propose to remain herein with an undifferentiated Triassic age for *Formation I*.

It is overlain by two main sequences that form a regional megasequence called herein *Formation II* (blue in Figures 4 and 5). They thin progressively toward the Pasca Ridge and are better observed in adjacent Pandora Trough. Both sequences are affected by a number of normal faults that express either internally or progressed through overlying strata. Therefore, *Formation II* suggests a second synrift setting (called hereafter as R_2) dated of Middle to Upper Jurassic age. It is limited by two truncational unconformities of different meanings. For instance, the bottom one called Base $Rift_2$ Unconformity (later shorten as BR_2, Figures 4 and 5) marks the onset of the rifting R_1, while the top surface correlates to the Jurassic-Cenozoic transition in *Well Dibiri-1A* and therefore marks a Cenozoic event.

To the east, a package with clear growth faulting and different seismic facies is intercalated between Jurassic and Cenozoic strata (green in Figure 5). This rift style difference implies a third rifting phase, called R_3. The base of related *Formation III* is marked by a tenuous unconformity (Base $Rift_3$ Unconformity, later shorten as BR_3). Sediments are correlated with the Upper Cretaceous sediments identified in the onshore Papuan Basin (Figure 4).

There is therefore a specific stratigraphic distribution in the Kutubu Trough that reveals the polyphased extensional history (Triassic to Upper Cretaceous). It appears, in particular, that the rift megasequences are bounded by specific synrift unconformities (called BR_1 to BR_3) that all relate to the three subsequent rifting events (R_1 to R_3) (Figures 4 and 5). These synrift unconformities specifically show that the rifting evolution was discontinuous through time in the Kutubu Basin.

3.2. Structural Expression of the Rifting Along the Northern Margin of the Coral Sea

Table 1 displays the seismic characteristics of the three different rift formations *I* to *III* in the Kutubu and adjacent basins to constrain the strata distribution and the bounding unconformities along the northern Coral Sea margin (Figure 6). The first sediments are bounded by reactivated extensional faults in the Moresby Basin and unconformably overlie basement rocks along a regional unconformity (BR_1). Strata are usually poorly tilted and subtlety thicken toward the East Pandora Ridge or progressively thin eastward to finally disappear in the other basins. Internal seismic facies are similar to *Formation I* identified in the Kutubu Basin (Table 1), so that deposition was likely controlled by the R_1 event. Similar strata may exist in other places but are traced with less confidence, implying that the BR_1 Unconformity cannot be mapped accurately at a regional scale.

A much clearer rift setting, analyzed as the R_2 event, extends beyond the Triassic rifted basins with many normal faults that are typically separated by 2-to-5km and along which tilting is important (Figure 6 and Table 1). Internally, the rift-related *Formation II* is composed of several onlapping units, each bounded by the BR_2 Unconformity at the base and several other angular unconformities in the above. Although growth faulting clearly occurs, it does not necessarily represent a common characteristic to all internal sediments, implying differential thickening throughout. This likely implies timing variation between extension and sedimentation within a progressively deepening, continental to marine environment. Thus, the distribution of *Formation II* is unequal between the various basins, and herein, we assign a Lower to Upper Jurassic age for most depocenters. Yet some bounding faults may have been active until the lowermost Cretaceous, resulting in thin, localized deposits.

Other fault reactivation occurred along the most major Jurassic faults either without large rotation (e.g., Moresby Basin) or, most likely, along newly formed faults that clearly controlled the fault-blocks gradient (Figure 6). The tilt, generally high in basins in prolongation of the continent-ocean transition, is used to discriminate Early from Late Cretaceous rifted depocenters. Thus, *Formation III* is generally contained into small-rifted basins south of the study area. It corresponds to coarse to fine clastics that likely link to onshore Upper

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Table 1
Seismic Sequence Characteristics in Rifted Basins of the Northern Coral Sea Basin

Inferred maximum age range	Sequence boundary geometry	Internal facies properties			External form	Palaeoenvironment interpretation	Tectonic event
		Reflection	Continuity	Amplitude			
Palaeogene (mostly Palaeocene and Eocene, locally Oligocene)	Unconformity with erosional truncation landward, onlap and downlap at the base	Parallel or oblique prograding	Continuous	High	Thickening oceanward	Open marine, sometimes shallow marine (when thin sections visualized)	Thermal subsidence
Upper Cretaceous	Unconformity with very localized erosion at the top (neck of fault block only), onlap and downlap at the base	Parallel, locally oblique prograding	Continuous and/ or transparent	High, locally moderate	Important thickening toward bounding faults	Terrestrial to shallow marine	Rift (R_3)
Lower Cretaceous	Erosional truncation at the top (usually Palaeogene, sometimes Miocene), gentle onlap and downlap at the base	Parallel	Continuous	High to moderate	Gentle normal faulting	Open marine	Rift (R_2)
Upper Jurassic	Erosional truncation at the top (usually Palaeogene, sometimes Miocene), onlap and downlap at the base	Parallel to subparallel	Continuous	Medium	Normal faulting, localized thickening	Open marine	Rift (R_2)
Middle Jurassic (Callovian to the top of Well Dibiri-1A)	Concordant at the top, gentle onlap, and downlap at the base	Transparent, locally parallel	Continuous	-	Normal faulting, poor thickening	Shallow marine	Rift (R_2)
Lower Jurassic	Gentle erosional or concordant at the top, onlap and downlap at the base	Chaotic with parallel bedding toward the top	Variable but often moderate	Low to medium	Slight thickening toward bounding faults	Rapid facies changes, most likely terrestrial to shallow marine	Rift (R_2)
Triassic	Erosional truncation at the top, onlap and downlap at the base	Subparallel to chaotic, truncated at the top	Continuous	Medium	Slight thickening toward bounding faults, depression at the bottom	Terrestrial to shallow marine	Rift (R_1)
Palaeozoic (basement)	Erosional at the top	Chaotic	Discontinuous	Medium	Basement	Metasediments	-

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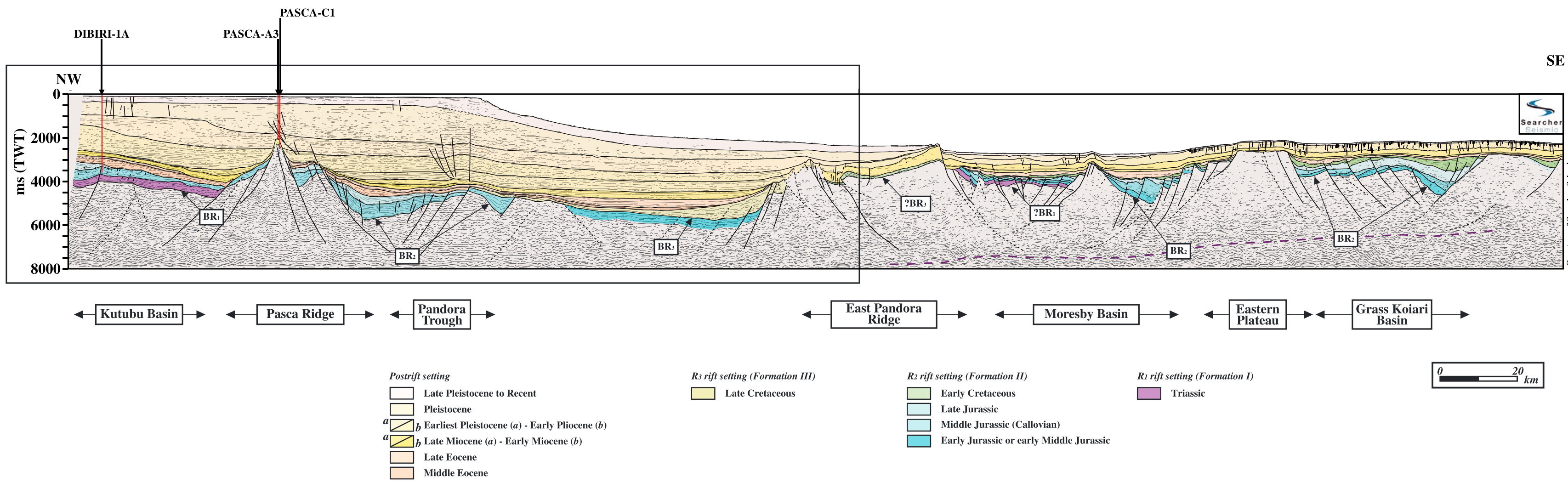

Figure 6. Seismic line across the western part of the study area. Note the differences from west to east regarding the preservation of depocenters. Black box indicates the location of Figure 5. Seismic line location is displayed in Figure 2, noninterpreted seismic lines may be found in Figure S1 in the supporting information.

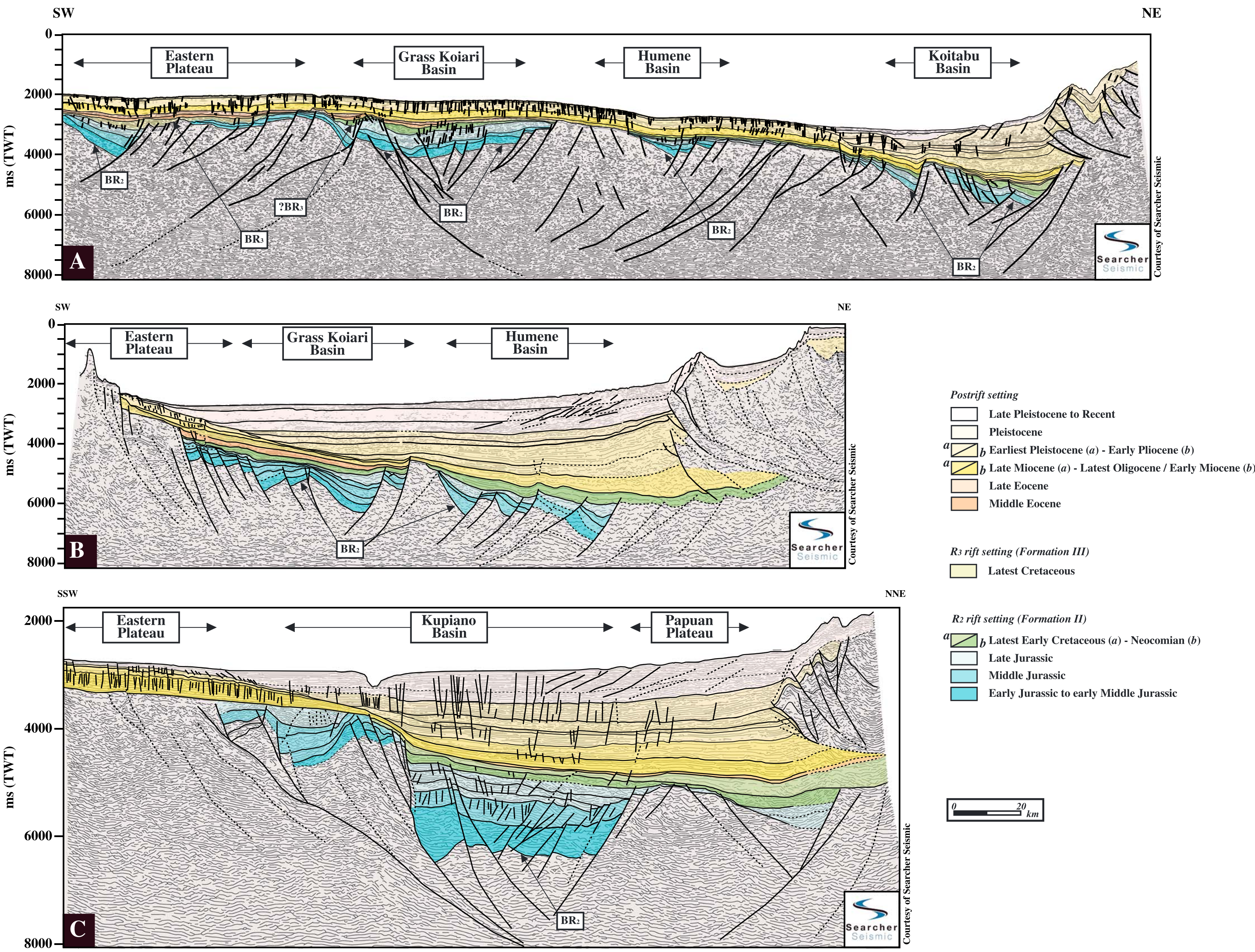

Figure 7. Examples of seismic lines across the northern margin of the Coral Sea Basin. (a and b) Seismic line showing the overall shape of rifted basins east of the East Pandora Ridge and the Eastern Plateau geometry. (c) Seismic line showing the overall shape of rifted basins in the vicinity of the Eastern and Papuan Plateaus. Seismic lines location is displayed in Figure 2; noninterpreted seismic lines may be found in Figures S2–S4.

Cretaceous rocks (Figure 4 and Table 1). All together, it implies a crosscutting rift setting, identified as R_3, marked by a lesser density of faults.

Similar polyphased extensional settings are observed on deep lines across the region (Figure 7). The R_1 event appears absent in most of the eastern basins. Comparatively, the extension maximum occurs during the second rifting phase (R_2) along major regional and counterregional, listric faults limiting crustal boudins. Extension likely propagated in basins north of the Eastern Plateau during the Lower Cretaceous without strong consequences on the tilting of sediments. Finally, subsequent Cretaceous faulting (R_3) rejuvenated locally some of the main bounding faults in the southwest of the Eastern Plateau, resulting in strong basin tilt. In this polyphased extension, continental plateaus and ridges show coeval uplift episodes.

3.3. Structural Orientations Versus Time

The seismic interpretation enabled the construction of a structural map of the rift setting at the level of the BR_2 unconformity (i.e., Lower to Middle Jurassic; Figure 8), to which the filtered Bouguer anomalies are superimposed in order to better constrain the general basin trends. Three main faults are distinguished according to their orientations and ages. The first direction occurs along a N-S to N10 trend and corresponds to the overall direction of the Pasca, Pandora and East Pandora ridges. It controls Triassic depocenters and is

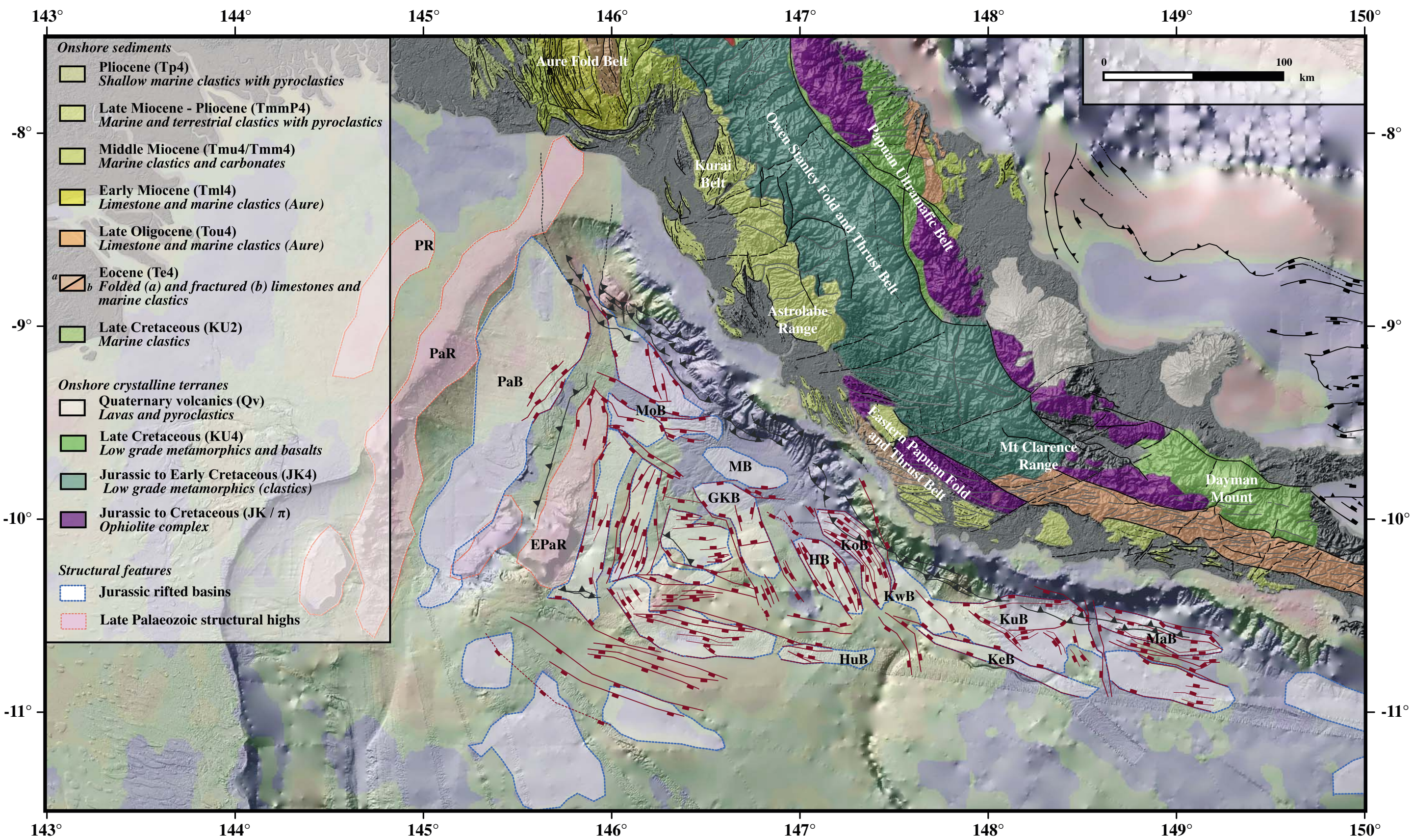

Figure 8. Structural map of the rifted domain in the study area. Underlying bathymetric data are from Daniell (2008) and Beaman (2010). Gravimetric data are derived from the used Bouguer anomaly database. Only main basins are named (names are derived from local ethnicities languages). Abbreviations: EPaR: East Pandora Ridge, GKB: Grass Koiari Basin, HB: Humene Basin, HuB: Hula Basin, KB: Kutubu Basin, KeB: Keapara Basin, KoB: Koitabu Basin, KwB: Kwikila Basin, MaB: Mailu Basin, MB: Motu Basin, MoB Moresby Basin, PaB: Pandora Basin, PaR: Pandora Ridge, PR: Pasca Ridge, and UB: Uare Basin.

therefore attributed to the R_1 rifting event. The second direction extends around N160 and corresponds to the general orientation of the western Eastern and Aure fold belts. It formed during the R_2 rifting event and was slightly reactivated during the Cretaceous. The third structural trend corresponds to a N100 to N110 direction, which is the general orientation of the continent-ocean transition the Coral Sea. This R_3 faulting is much more prominent in the distal part of the margin.

Therefore, the overall geometry of the northern Coral Sea margin results from three groups of faults. These express both the timing and the location of extension. In other words, three rifting episodes overlap in the region and they all seem to have a specific expression resulting from the fault timing and orientation.

4. Synrift to Postrift Transition and Oceanic Spreading of the Coral Sea

Seismic interpretation has shown that the geometry of the three rifting events R_1 to R_3 is different, namely in terms of basinal rotation. This is likely to reflect the position along a margin and, in particular, to the continent-ocean transition. The characterization of the synrift to postrift transition is never an easy matter in polyphased rift basins, namely because extension is not necessarily followed by a clear breakup unconformity but rather by a set of unconformities and sometimes extensional faulting (Bulois, 2016). Herein, we use detailed seismic lines to better identify the rifting event(s) responsible of the Coral Sea Basin *sensu stricto*, within this overlapping rifting framework.

To do so, we have investigated the deep oceanic domain using seismic, gravimetric and magnetic data. In particular, the easternmost seismic line of our database imaged the oceanic crust that is well dated from IODP drillings and magnetic anomalies (Figure 9) (e.g., Gaina et al., 1999; Weissel & Watts, 1979). These anomalies were used in turn to date sediments above and underneath the breakup unconformity. We also

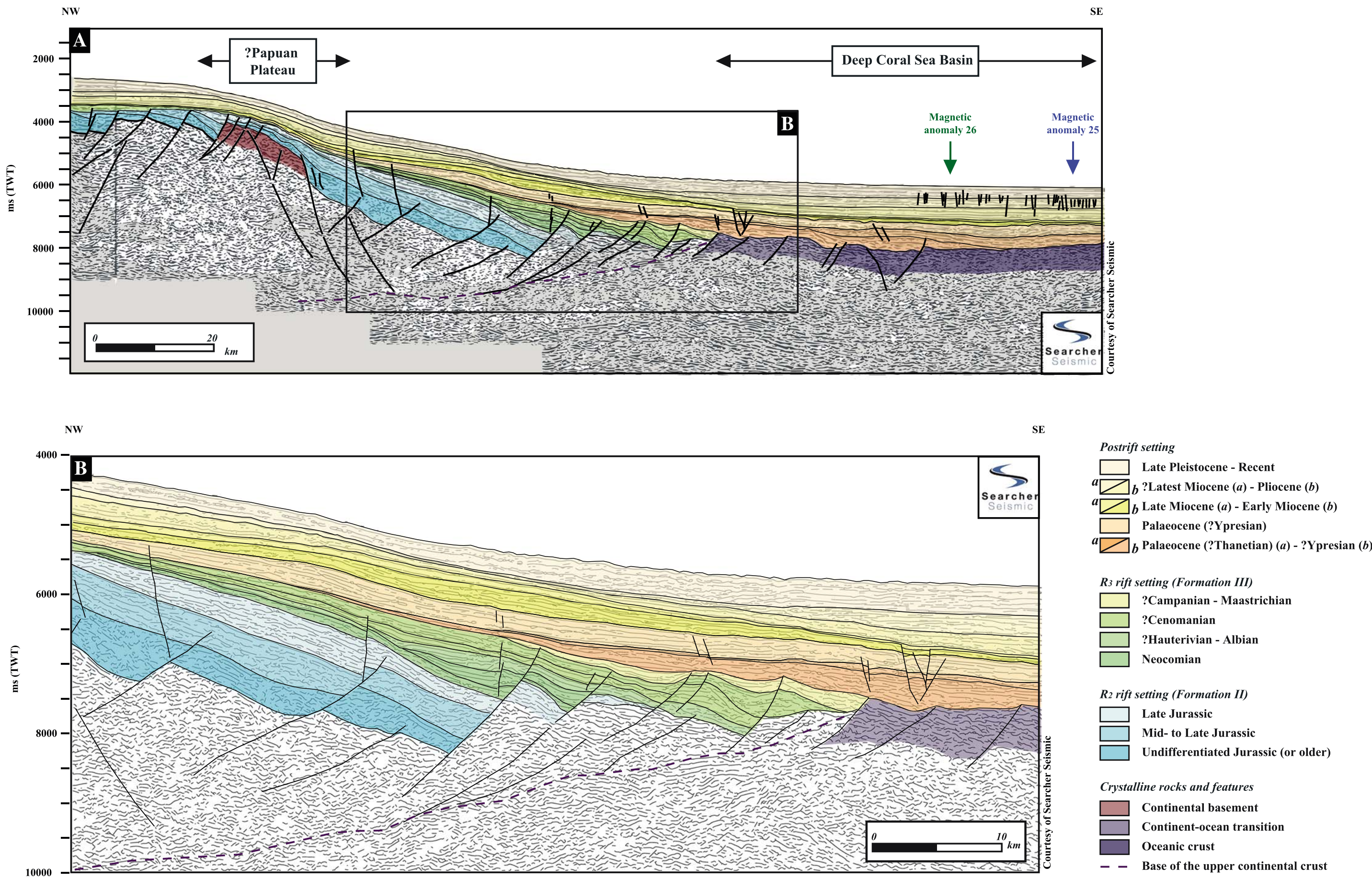

Figure 9. Seismic data showing the continent-ocean transition (COT) in the deep Coral Sea Basin. (a) General seismic line showing the two rift settings (Jurassic and Cretaceous) in the Coral Sea Basin and their relationships with the oceanic crust and overlying postrift deposits. Note the relatively narrow rifted margin of Late Cretaceous age that is believed to represent the hyperstreched domain prior the early Cenozoic seafloor spreading. Note also the presence of basement high that separates the Late Cretaceous rifted margin from the Jurassic rifted margin. (b) Zoom on the continent-ocean transition, showing the Cretaceous rotated fault-blocks and the Coral Sea oceanic crust characterized by a prominent reflector and downlaps of postrift sediments. Seismic line location is displayed in Figure 2. Noninterpreted seismic line may be found in Figure S5.

have used academic magnetic data from the EMAG2 dataset (Maus et al., 2009) and anomaly picks supplied by Gaina et al. (1999) to better detail the ocean-continent transition and the associated structural trends. Free-air gravimetric anomalies from the DTU10 ocean wide gravity field (Andersen, 2010; Andersen et al., 2009) have also been filtered to separate long and short waves and map more accurately the transform faults in the oceanic domain.

4.1. Seismic Definition of Synrift and Postrift Packages in the Deep Coral Sea Basin

Figure 9 displays the geometry of rifted basins across the southern Papuan Peninsula to the oceanic crust and enables to better define the breakup unconformity and, in turn, of synrift sediments. To do so, we have derived the age of postrift sediments from the location of magnetic anomalies Chron26 and Chron25, both of Thanetian age (~58.5 and 56.5 Myr, respectively) (Figure 9a), while anomaly Chron 24 (~53.4 Myr, Ypresian) occurs much farther south. Therefore, the age of the postrift sediments is in between Thanetian and Ypresian. This is in accordance with the first Cenozoic sediments (Eocene) recovered in *Well Dibiri-1A* (Figure 4). Onlapping, continuous, medium- to strong-amplitude reflectors characterize pinching-out, fine-bedded clastic sediment contained with strongly tilted fault-blocks (Figure 9a). Such a geometry implies that these rifted sediments are therefore of Late Cretaceous age and represent the synrift setting responsible of the Coral Sea opening. We therefore correlate them to *Formation III*. Internal seismic patterns (Table 1) imply a deepening marine synrift deposition with sourced sediments derived from the nearby Papuan Plateau.

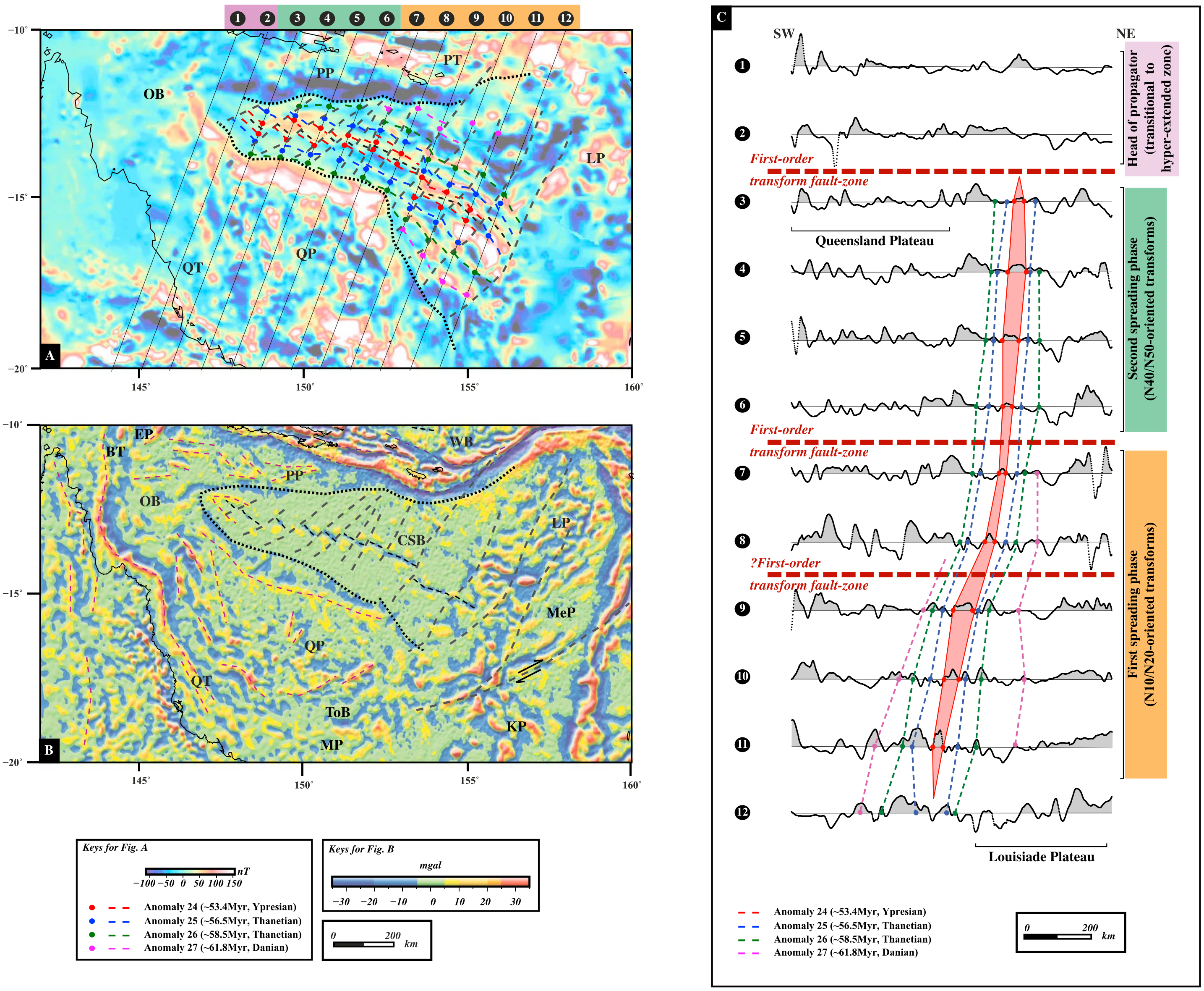

Figure 10. Magnetic and gravimetric data set in the deep Coral Sea Basin. (a) Magnetic data showing the differences in between the oceanic (smooth) and continental crusts in the deep Coral Sea Basin and the related position of the continent-ocean transition (COT, heavy dashed line). Magnetic anomalies are derived from Gaina et al. (1999); they are particularly useful for mapping transform zones and ridge segments. Note the presence of the strong anomaly at the COT, which correlates with the structural high displayed in Figure 9. (b) Filtered free air gravimetric data showing the signature of the continental and oceanic crusts in the study area. (c) Magnetic profiles showing the correlation of magnetic anomalies and the three main elements in the deep Coral Sea Basin. The position of magnetic profiles is displayed in Figure 10a. Abbreviations: LP: Louisiade Plateau, OB: Osprey Basin, PP: Papuan Plateau, QP for Queensland Plateau, QT for Queensland Trough, SSB for Solomon Sea Basin, and WB: Woodlark Basin.

In this region, fault-blocks show growth along reactivated Jurassic counterregional faults (Figure 9b), which are different (but not incompatible) with previously proposed basinward dipping faults in the region (Ott & Mann, 2015). This geometry differs from the other poorly-tilted Cretaceous fault-blocks observed westward (Figure 7). Therefore, we suspect two different rift systems that spatially overlap in this region.

4.2. Events Associated With the Synrift to Postrift Transition in the Deep Coral Sea Basin

The transition of synrift Late Cretaceous sediments with overlying Palaeocene to Oligocene sediments (breakup unconformity) is dated at 61.8 Myr from magnetic anomalies (Figure 10). Nonetheless, it is possible that the first postrift sequences deposited late after the first seafloor spreading event. Additional localized normal faults within these postbreakup packages seem also associated with unconformities or disconformities.

The top of the thickening sequences is characterized by a strong amplitude reflector that can be mapped landward from a series of more or less well-pronounced onlapping reflectors and is correlatable to the Eocene-Miocene unconformity observed in *Well Dibiri 1A* (Figure 4). It appears therefore likely that the first postrift sediments (i.e., post-Ypresian) corresponds to a transitional stage and that the "true" postrift succession actually occurred from the Miocene onward.

The age of this unconformity confirms the analysis of Ott and Mann (2015) who considered a first postrift subsidence setting during the Eocene, followed by a second deepening phase during the Oligocene to early Miocene. Burns et al. (1973) also proposed a clear postrift deepening of the Coral Sea during the early Middle Miocene, based on ODP 210 cores that tested deep-sea clays overlying unconformably fine-grained silicastics and shales. Their set of unconformities implies that postrift deepening was not continuous. This may be due to sea level fluctuations or fault reactivation during the transitional setting, possibly associated with plate reorganization.

4.3. Delimitation and Trends of the Oceanic Crust

Magnetic data from the EMAG2 mosaic show a strong character contrast between the oceanic crust (smooth and regular) and continental plateaus (rough) (Figure 10a). The boundary between both crustal domains is marked by two strong anomalies of more or less symmetrical but anticorrelative values. Correlation with seismic lines (Figure 9) shows that the northern anomaly corresponds to a structural high composed of basement rocks at the shoulder of the Upper Cretaceous rift system. Thus, both anomalies delineate the Papuan and Queensland plateaus of continental nature. The continent-ocean transition is also confirmed by gravity data from roughness variations (Figure 10b).

In the oceanic domain, magnetic data show a N110 fabric that runs parallel to the oceanic ridge system. It is offset by a series of structures which the direction markedly varies from N45 to the east (anomalies 27 to 25) to a N10 orientation to the west (absence of anomaly 27) (Figure 10a). Such a variation is more poorly constrained on gravity data (Figure 10b). This variation may correspond to a change in the spreading propagation around the Ypresian (anomaly 24) controlled by the onset of the regional compression (Bulois, 2016).

The accurate mapping of the continent-ocean transition enables to show that the strongest fault-block rotation is located along an area of about 100 km wide and 250 km long. This follows the strong anomaly marking the zone of hyperstretched continental crust that led to the Coral Sea Basin seafloor spreading (Figure 8). In that context, the Papuan Plateau somehow acts as a buttress for the propagation of the Coral Sea toward the north.

5. Discussion

5.1. Integration of the Coral Sea Rift Megasequences With Regional Geology

Our seismic analysis has shown three distinct extensional phases in the Coral Sea region. They are all responsible of specific regional rift-related megasequences deposition (referenced as *Formation I* to *Formation III*). However, their significance may differ from previous regional interpretations. For instance, Ott and Mann (2015) did not analyze Jurassic sediments in the study area and synrift sediments were only related to the Late Cretaceous-Palaeocene extensional event of the Coral Sea. In contrast, Swift (2012) underestimated postrift sedimentary thickness, resulting in thick synrift sequences deposited in overlapping poorly dated rift basins. These geometry and age differences most likely result from the data coverage and resolution; also, we correlate herein offshore and onshore stratigraphic information to better delimitate the spatial extent of these three identified extensional settings R_1, R_2, and R_3 at the scale of the northern Australian margin (Figure 11).

The Triassic rift setting R_1 is limited eastward to the Gulf of Papua in the Coral Sea (*Formation I*, Figure 11). Unconformities (BR_1 in the Kutubu Basin) and correlative disconformities in other places (Figure 5) bound various correlatable clastic sequences (e.g., *Jimi Formation* in the Aure Fold Belt, Bain et al., 1975; Home et al., 1990, *Tipuma Formation* in the Lengguru and Central Papuan fold and thrust belts, Fraser et al., 1993;

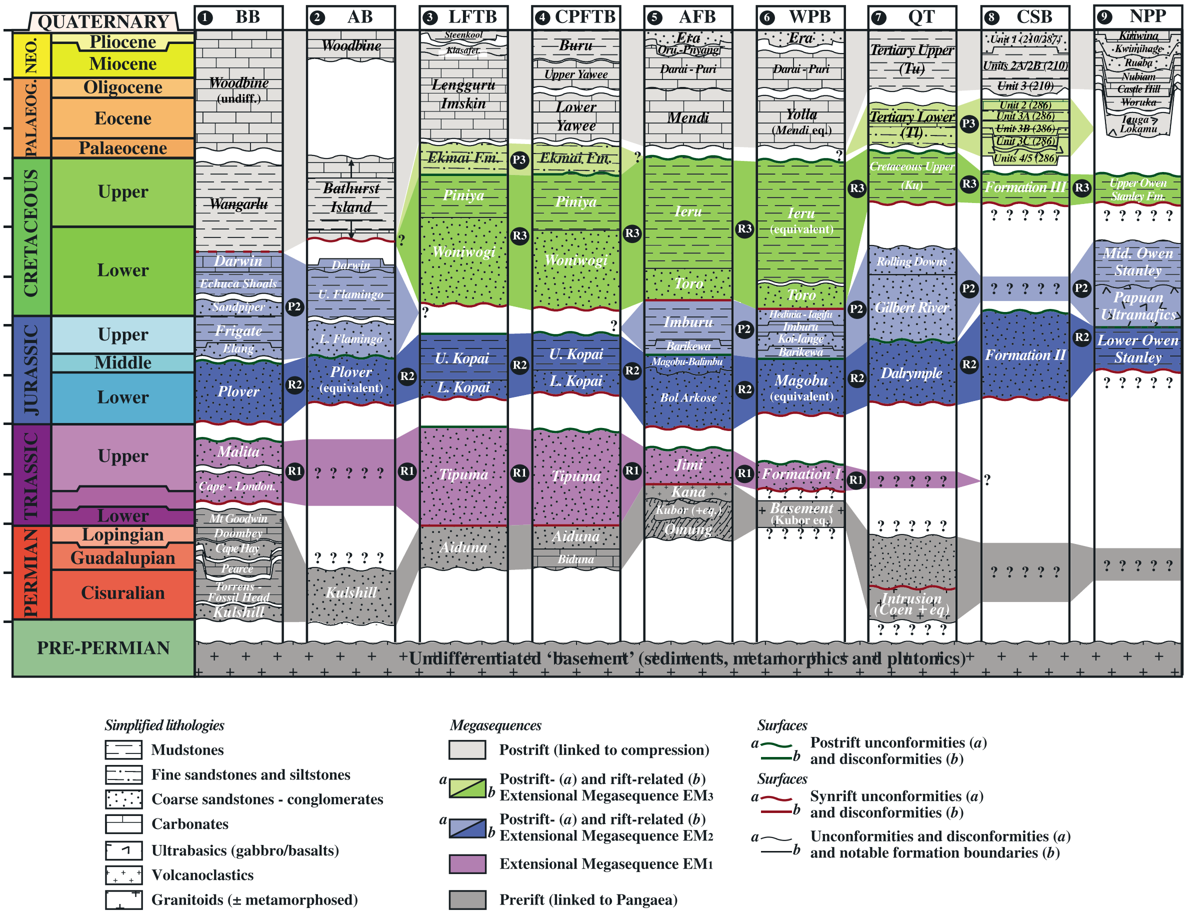

Figure 11. Permian-Actual synthetic stratigraphic column along strike the North Australian margin. Figure is adapted from Bulois (2016). Stratigraphic columns show the overall sedimentary intervals encountered in various key basins displayed in Figure 12. Note the presence of the three rift episodes R_1 to R_3 and their relative postrift settings (P) which together undersign extensional megacycles interspaced by periods of basin inversion or tectonic quiescence. The timing of the margin rifting is similar on the NW Shelf and Papuan New Guinea from the Late Permian to the Cretaceous and one can assume that there was a connexion between the basins nowadays jammed in the Papuan fold and thrust belts. Stratigraphic information are summarized from many sources among which (1) Geoscience Australia (2011) and Ahmad and Munson (2013a, 2013b) for the Bonaparte and Arafura regions; (2) Bailly (2009), Bailly et al. (2009), and Cloos et al. (2005) for the Lengurru and central Papuan region; (3) Home et al. (1990), Hill and Hall (2002), Jablonski et al. (2006), and Craig and Warvakai (2009) for the Aure Fold Belt and the Papuan Basin; (4) Dow et al. (1986), Struckmeyer (1990), Jablonski et al. (2006), Hill and Hall (2002), Corbet (2005), De Smet et al. (1998), and Sheppard and Cranfield (2012) for the Northern Papuan Peninsula and Coral Sea Basin; and (5) Symonds et al. (1984, 1996) and Struckmeyer et al. (1994) for the Queensland Trough. Abbreviations: AB: Arafura Basin, BB: Bonaparte Basin, CPFTB: Central Papuan fold and thrust belt, CSB: Coral Sea Basin, LFTB: Lengurru fold and thrust belt, NPP: Northern Papuan Peninsula, QT: Queensland Trough, and WPB: Western Papuan Basin.

Gunawan et al., 2012, *Cape Londondery Formation* and *Malita Formation* along the NW Shelf, Ahmad & Munson, 2013a, 2013b). These are grouped into a regional synrift megasequence, called *Megasequence* EM_1, which the definition is broadly equivalent to the *Gondwana Synrift Megasequence A* of Home et al. (1990) or the *Tipuma Formation* of *Visser and Hermes* (1962) and Pieters et al. (1983). *Megasequence* EM_1 witnesses of an early stage of graben formation throughout the region.

Subsequent rifting episode R_2 affected the entire northern Australian margin during the Jurassic and controlled the deposition of *Megasequence* EM_2 (Figure 11). The rifting onset is characterized by a regional basal unconformity (BR_2). It is situated at similar stratigraphic level of surfaces in Australia that were previously interpreted as the result of the Bowen-Fitzroy Orogeny in Australia (Jablonski & Saitta, 2004; Norwick, 2003) or of significant coeval volcanism (Pieters et al., 1983; Pigram & Panggabean, 1984). However, evidence of Triassic compression and volcanics are unclear in the Papuan region and extension may actually correspond to a backarc system. Subsequent sediments deposited in rifted basins observed all over the margin despite Cenozoic compression. For instance, the *Plover Formation* deposited from the earliest Lower Jurassic along the North West Shelf (Gunn, 1988; Pattillo & Nicholls, 1990; O'Brien et al., 1993; Baillie et al., 1994; Struckmeyer et al., 1998; Tovaglieri & George, 2014) and extends in West Papua into the squeezed Lower to Middle Jurassic basins containing the *Lower Kopai, Bol Arkose* and *Magobu* coarse clastic formations (Bailly et al., 2009; Bain et al., 1975; Pigram et al., 1982). These are correlatable to *Formation II* in the Coral Sea Basin, and we interpret them farther east with the lowermost part of the marine protolith of the *Owen Stanley Metamorphics* (individualized herein as the *Lower Owen Stanley Formation* and now thrusted under the Jurassic *Papuan Ultramafics*, Glaessner, 1949; Pieters, 1978; Davies, 1980; Davies & Jaques, 1984). Consequently, the *Papuan Ultramafics* and the subsequent *Middle Owen Stanley Metamorphics* mark the onset of regional postrift conditions in the study area. These are characterized anywhere else by thick mudstone deposits (e.g., *Imburu*, *Barikewa*, *Flamingo*, *Frigate*) and localized sandstone intervals (e.g., *Koi-Iange*, *Hedinia-Iagifu*, *Elang*) (Figure 11). Corresponding *Megasequence* EM_3 is therefore broadly equivalent to the *Gondwana Synrift Megasequence B* of Home et al. (1990).

The final rifting event R_3, restricted to the eastern part of the study area, controlled the deposition of a third megasequence (*Megasequence* EM_3) on top of an erosional surface (BR_3) (Figure 11). It is marked at the base by typical lowermost Cretaceous sandstones and mudstones, known onshore as the *Woniwogi-Piniya* and the *Toro-Ieru* intervals (Granath & Hermeston, 1993; Hirst & Price, 1996; Pieters et al., 1983; Pigram et al., 1982). These are stratigraphically correlative to *Formation III* in the Coral Sea Basin (indirectly dated from magnetic picks, Figure 8) and to the *Upper Owen Stanley Formation* (dated as Middle to Upper Cretaceousby Glaessner, 1949). Coeval rifted sediments are also reported in the Queensland and Townville basins (e.g., Struckmeyer et al., 1994; Symonds & Davies, 1988; Symonds et al., 1984). *Megasequence* EM_3 is broadly similar to the *Coral Sea Syn-Rift Megasequence* of Home et al. (1990), although lateral extent and dating differ in between the two interpretations.

It therefore appears that there is a vertical stack of extensional megacycles marked by characteristic extensional megasequences (EM_1 to EM_3) of specific temporal and geographical definitions (Figure 11). Each extensional megasequence is typically composed of synrift fining-upward rifted clastics bounded by unconformities ("R" nomenclature) and terminate by deep marine, postrift facies that are sometimes associated with seafloor spreading ("P" nomenclature). Unconformities may switch from postrift to synrift natures in such a context of overlapping extension, implying a strong control on strata preservation throughout.

5.2. Extension and Fault Reactivation in the Coral Sea Region

The overtime repetition of the three extensional megacycles, R_1, R_2 and R_3, implies fault reactivation within the basement or from previously formed rift systems. Herein, we propose a simple stretching model of the northern Australian margin in which preexisting continental structures have a decreasing influence through time.

5.2.1. Old Structural Trends and Early Development of Rift Basins (Triassic)

According to our seismic interpretation, Triassic sediments are most likely confined to poorly tilted graben systems containing coarse clastics. These basins mark the eastern boundary of an early rift system that propagated through the NW Shelf and West Papua and stopped in eastern Papua New Guinea along the alignment composed of the Kubor Anticline to the north and the Pasca-Pandora-East Pandora to the south (Figure 12). In the study area, the rifted system formed alongside NS trending Permian granites (e.g., Coen and Georgetown inliers, Peninsula-Daru Ridge) and older terranes belonging to the New England Belt (e.g., Glen, 2005; Norwick, 2003).

This easternmost border roughly aligns along the NS trending Tasman Line that controlled the polyphased tectonics of the Tasmanides Orogen across Australia since the Neoproterozoic (Direen & Crawford, 2003; Powell, 1996; Schreibner, 1974). The prolongation of the New England Orogen from the Queensland Peninsula to Papua is enigmatic as much of deep geophysical data do not enable to trustfully image related structure underneath the overprinted Papuan fold and thrust belts (Hill & Hall, 2002). Herein, we propose that the structure may extend in the Gulf of Papua through the Palaeozoic ridges (i.e., Pasca, Pandora and East Pandora). Another alternative is a series of NNE-SSW transform faults that controlled the rift axis and among which the Bosavi Lineament is probably the most characteristic feature (Figure 12) (e.g., Davies, 1990, 1991; Smith, 1990; Hill et al., 2004, 2010; White et al., 2014). These are associated with characteristic Neogene, adakitic volcanoes and older mantle-derived intrusives. Therefore, these crustal structures are likely to mark a change in the strength of the lithosphere behavior, inferring a strong basement influence to the west (i.e.,

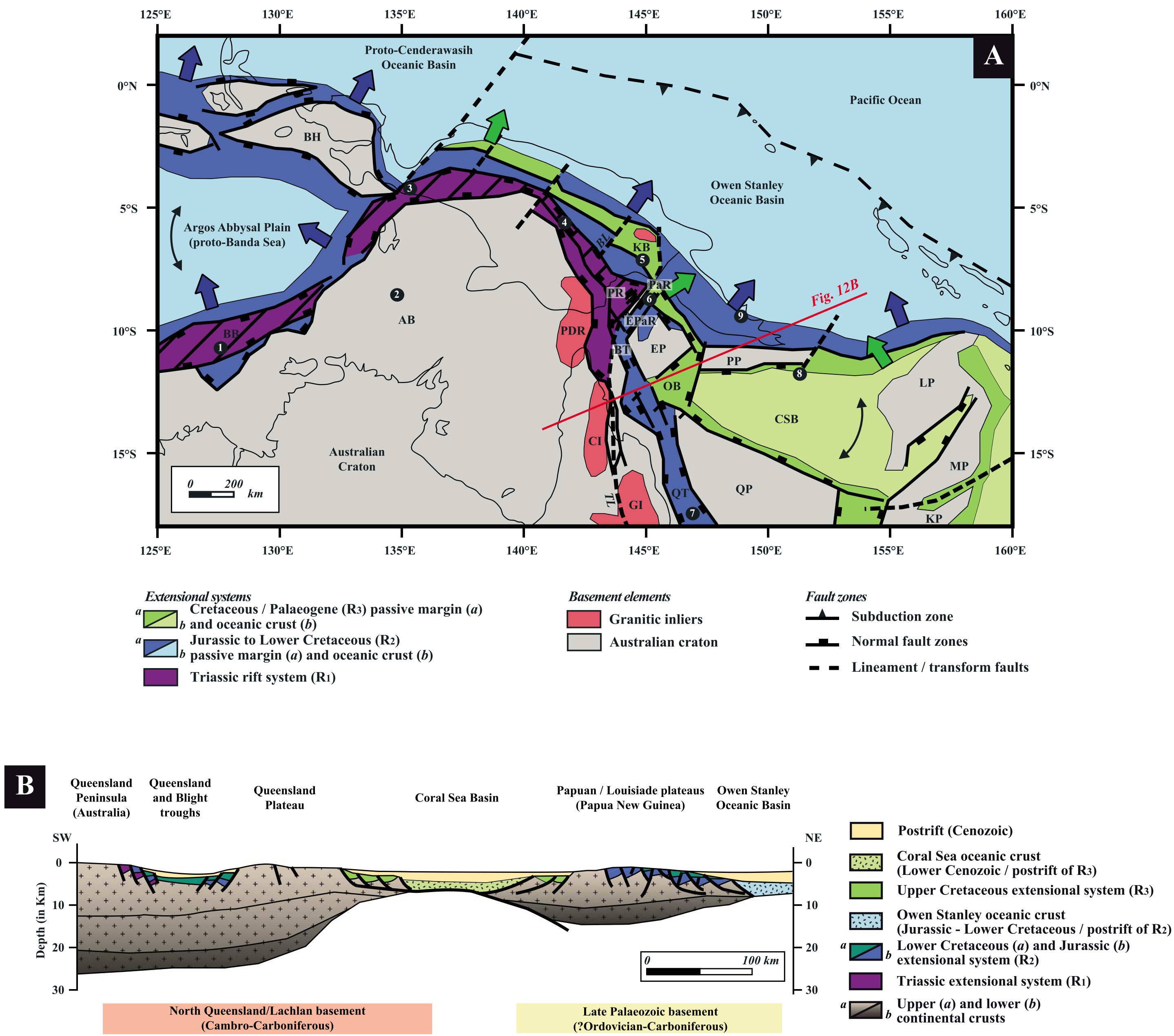

Figure 12. Rifting evolution of the Coral Sea region since the Permian to the early Tertiary. (a) Nonpalinspastic tectonic evolution showing the overprint of the three extensional megacycles along the northern margin of Australia. Numbers refer to stratigraphic columns displayed in Figure 11. (b) Reconstruction of the Coral Sea region prior Cenozoic compression, based on deep geophysical data of Ewing et al. (1970). The line shows the relationships between the various rifted domains. Section location is indicated in Figure 12a. Abbreviations: AB: Arafura Basin, BB: Bonaparte Basin, BH: Bird's head, BL: Bosavi Lineament, BT: Bligh Trough, CI: Coen Inlier, CSB: Coral Sea Basin, EP: Eastern Plateau, EPaR: East Pandora Ridge, GI: Georgetown Inlier, KI: Kubor Inlier, LP: Louisiade Plateau, NF: Nubura fault, OB: Osprey Basin, PaR: Pandora Ridge, PDR: Peninsula-Daru Ridge, PR: Pasca Ridge, QT: Queensland Trough, QP: Queensland Plateau, and ToB: Townsville Basin.

stable Precambrian craton of Australia) which tends to decrease eastward with the presence of Palaeozoic metasediments intruded by Early to Middle Triassic granites (e.g., Crowhurst et al., 1996; Page, 1976; Rogerson, Hilyard, Francis, et al., 1987; van Wyck & Williams, 2002).

In our model, the small lineaments (e.g., Bosavi) characterizes transfer zones ahead of the Australian craton, while the ridges system represents a limit of unrifted terranes in prolongation of the Tasman Line. The Triassic extensional megacycle R_1 was therefore controlled by basement structures (Figure 13a). However, it is still remains unclear whether extension initiated from an orogenic collapse or from global tectonic forces

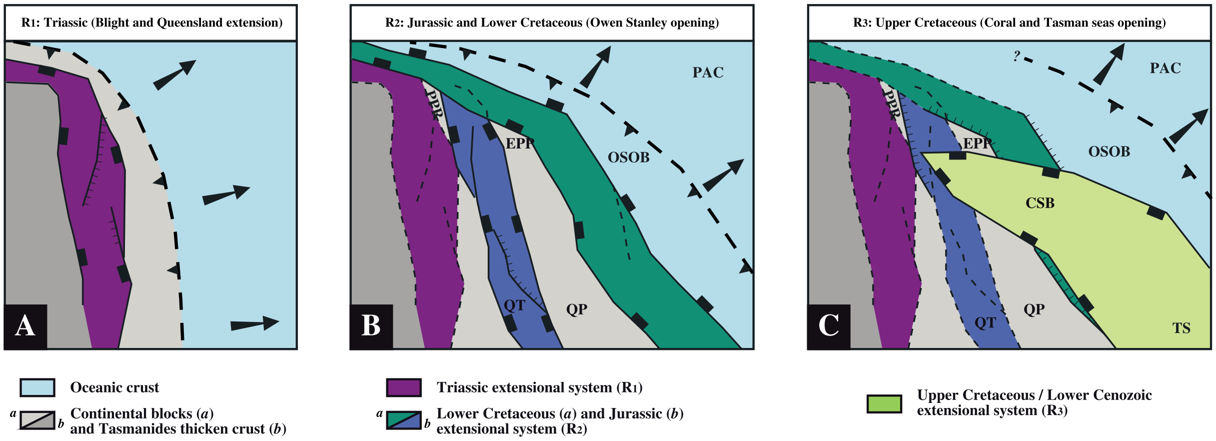

Figure 13. Evolutionary sketch of the overprint of extensional megacycles. (a) Rifting evolution along the Tasmanides, implying reactivation along north trending structures such as the Pasca/Pandora Ridges system and the Tasmanides faults. (b) Opening of the Owen Stanley Oceanic Basin as a backarc setting, reactivating Triassic structures and expending further as a pulling of a northern subduction zone. (c) Opening of the Coral Sea as a northward propagation of the Tasman Sea, reactivating the southern margin of Owen Stanley Oceanic Basin. Overall, the opening of the Owen Stanley Oceanic Basin is thought to take place along the northern Australian continent as a response of Pangaea breakup. This was first driven by the Late Palaeozoic geology of the New England Orogen (i.e., Tasmanides thicken crust) and then deformation progressively migrated oceanward. The Coral Sea Basin is seen as the continuation of the Tasman Sea. Note how it stopped when abutting the transversal Triassic rift system. Details of the basin shapes may be found in Norwick (2003). Abbreviations: CSB: Coral Sea Basin, EPP: Eastern/Papuan Plateaus, OSOB: Owen Stanley Oceanic Basin, PAC: Pacific Ocean, PP: Papuan Plateau, PPR, Pasca/Pandora Ridges, QP for Queensland Plateau, QT for Queensland Trough, and TS: Tasman Sea.

pulling the Australian and Gondwana continental masses apart. Yet the presence of conglomerates and very coarse clastics (Figure 4) suggests the development of molassic basins at the time.

5.2.2. Full Basin Development During Overprinted Extension (Jurassic-Lower Cretaceous)

The Lower to Middle Jurassic rift system R_2, recognized over much of the northern Australian margin (Figure 11), has controlled highly subsiding grabens by reactivating Triassic faults west of the Pasca-Pandora ridges and forming new basins in the Coral Sea (Figures 5 and 7). It resulted in crustal boudins along what we interpret as the southern margin of an oceanic basin now overthrusted in the Papuan fold and thrust belts (Figure 12). The so-called Owen Stanley Oceanic Basin contained distal marine sediments (*Lower and Middle Owen Stanley Metamorphics*) associated with the ophiolite of the *Papuan Ultramafic Formation* (Figure 11). This hypothesis is consistent with dating realized on the gabbroic zone and basalts of the ophiolite (respectively, 147–150 Ma and 116 Ma) (Lus et al., 2004). The age of sediments, although more debatable due to Cenozoic barrovian metamorphism (Dow et al., 1988; Pieters, 1978), is necessarily slightly older than the ophiolite emplacement dated at 66–56 Ma from granulites hornblendes at the sole (Lus et al., 2004). Various other authors proposed a Lower to Middle Cretaceous age for the Owen Stanley units protolith and for the *Papuan Ultramafics* before emplacement (Webb et al., 2014; Zirakparvar et al., 2012), which is consistent with our hypothesis. In our model, this implies that the Jurassic rifted strata and their overlying Cretaceous sediments deposited into the Owen Stanley Oceanic Basin rather than the Coral Sea, so that much of the Coral Sea actually remains intact from subsequent Cenozoic compression.

The presence of a large basin north of the Coral Sea has been earlier proposed by several authors but the geometries and extensional propagation are variable. Hamilton (1979) assumed a Middle Jurassic seafloor spreading along the entire margin, resulting in a large oceanic basin linking all Papuan ophiolites together. In contrast, Pigram and Panggabean (1981, 1984) and Pigram and Symonds (1991) suggested diachronous seafloor spreading with southwestward propagation from the Early Jurassic and a final breakup between Australia and Gondwana at Bajocian times. Other studies proposed the presence of a separated, aborted continental rift (e.g., Carman, 1990; Home et al., 1990; Boult, 1997; Swift, 2012). Our model considers that the Owen Stanley Oceanic Basin actually correlates with several other suprasubduction ophiolites and their related sedimentary covers (e.g., *Marum Ophiolite* and *April Ultramafics*) (Davies & Hutchison, 1982; Davies & Jaques, 1984; Jaques, 1981). This is confirmed by geochemical analysis showing a similar suprasubduction context for most Papuan ophiolites (e.g., Monnier et al., 2000; Pubellier et al., 2004; Worthing & Crawford, 1996). Although some ages may appear controversial due to Cenozoic tectonism (e.g., Hill & Raza, 1999; Jaques & Robinson, 1977; Jaques et al., 1978; Page, 1976), François et al. (2016) showed that the dating bias corresponds to the ophiolites emplacement rather than a particularly long-lasting spreading. Herein, we propose a southward dipping subduction zone north of Papua (Figure 12), which may connect southwestward to the New Caledonian ophiolites (e.g., Cluzel et al., 2001; Matthews et al., 2012; Whattam et al., 2008). To the west (i.e., from the Bird's Head to the NW Shelf), rifting also took place from the Late Permian to the Cretaceous but does not seem to be directly related to a backarc extension (Bradshaw et al., 1994; Norwick, 2003). Yet the extension could possibly be a response to a northwest subduction beneath the Sunda Plate (subduction of the Ceno-Tethys) (Metcalfe, 1998).

Thus, the extensional megacycle R_2 marks a further stage in the breakup of Pangaea intimately linked to a backarc setting along the northern Papua margin. The resulting opening of the Owen Stanley Oceanic Basin was facilitated by an already thinned Triassic margin, implying an "in-sequence" Jurassic extension (Figure 13b). Thus, the present-day northern margin of the Coral Sea Basin corresponds to the southern margin of the Owen Stanley Oceanic Basin, so that the various Papuan ophiolites formed ahead of the Coral Sea.

5.2.3. Crosscutting Opening of the Coral Sea Basin

The final rifting stage R_3 (Late Cretaceous) formed narrow (>100 km) fault-blocks containing *Extensional Megasequence EM_3* (Figures 11 and 12). These basins are part of a crosscutting extensional system, younger than the northern Owen Stanley Oceanic Basin, resulting in the Coral Sea seafloor spreading during the Danian-Ypressian period (Chron27 to Chron24) (Figure 10).

In our model, we relate the opening of the Coral Sea to the opening of the Tasman Sea between Chron33 and Chron24 (80 and 52 Myr, respectively) (Hayes & Ringis, 1973). The tectonic history of the Tasman Sea cannot be simply described as a rift propagator that cut through the Australian craton but rather as several blocks or microplates stretched apart (e.g., Weissel & Hayes, 1977; Stock & Molnar, 1982) accordingly to the southwest Pacific subduction history (e.g., Collot et al., 2009; Gaina et al., 1998; Seton, Flament et al., 2012; Seton, Müller, et al., 2012). We consider that the transition between both oceanic domains is controlled by a NE-SW transform system (Figure 12), visible on gravity data through the Marion and Kenn-Mellish plateaus and which rotated orthogonally the Tasman Sea hyperextension into the already-thinned Coral Sea region. Such assumption broadly confirms the description of a triple junction between the Queensland and Louisiade Plateaus and the Mellish Rise (Gaina et al., 1999) and also explains the apparent rejuvenation of the Eastern and Papuan Plateaus north of the Coral Sea (Figure 7).

This model also applies an important role to a series of transverse preexisting structures west of the Coral Sea Basin (e.g., Tasman Line and Pasca-Pandora-East Pandora ridges) that progressively attenuated the extension (Figure 12). This partially confirms Weissel & Watts, 1979 in which the Coral Sea spreading stopped along a sinistral strike-slip system from Chron 26 (58.5 Myr) and did not propagate westward along the Cretaceous rift system. This interruption may be due to a regional change of the plate tectonic setting.

Therefore, this late extensional megacycle cut through prior extensional settings (Figure 13b). This out-of-sequence scenario is consistent with the global transform faults orientation and the regional plate dynamics models which show a continuation of the Coral Sea with the Tasman Sea (e.g., Gaina et al., 1998, 2004; Matthews et al., 2012; Seton, Flament, et al., 2012; Weissel & Watts, 1979). Also, the orthogonal pattern between both oceanic domains may be due a dynamic change of the Pacific subduction eastward. At a regional scale, the Coral Sea should be therefore regarded as a propagator in prolongation of the Tasman Sea rather than an oceanic domain that has partially subducted.

6. Conclusion

The opening of the Coral Sea region shows three discontinuous extensional megacycles which controlled the deposition of specific megasequences separated by unconformities of local or regional extents. Each extensional megacycle is defined spatially and temporarily such as:

1. Extensional megacycle R_1 (Triassic), developed on the northern edge of the New England Orogen by reactivating old structural trends related to the Tasman Line (Figure 13a). Evidence of Triassic sediments is restricted to the west of the study area (ridges) and extends onshore in continuation of the synrift setting along the NW Shelf. Herein, we propose that old orogenic structures locate the propagation of the extension.
2. Extensional megacycle R_2 (Jurassic to Lower Cretaceous) marks the continuation of a wide rift setting along the northern Australian margin (Figure 13b). It first formed on top of the Triassic rifted basins and

then extended in a number of newly formed basins that are likely to connect to Jurassic-Lower Cretaceous; marine sediments and ophiolites now shorten in the Papuan fold and thrust belts system to form the so-called Owen Stanley Oceanic Basin. This oceanic domain is thought to connect with other Papuan ophiolites westward, which evolved in a suprasubduction domain.

3. Extensional megacycle R_3 (Upper Cretaceous to lowermost Eocene) is restricted to the northern margin of the deep Coral Sea and formed EW trending, 100 km narrow-rifted basins that bound the oceanic crust (Figure 13c). It had a minor impact on preexisting rifted basins (Triassic and Jurassic-Lower Cretaceous), suggesting a crosscutting extensional system with different boundary forces. Herein, we show that the Coral Sea Basin is the northward continuation of the Tasman Sea and that the oceanic spreading was controlled by the presence of major crustal discontinuities such as the Tasman Line to the west or transform fault systems along the southeastern margin of the Coral Sea Basin.

This spatial overlap implies to consider the reactivation of preexisting features that relate to the regional variations in the geodynamical settings and, as a result, to a succession of boundary forces that may evolve with time (Figure 13). The early extension phase R_1, guided by cratonic heterogeneities (basement highs), was, in turn, reactivated during the second rifting phase R_2 to control the crustal boudinage oceanward (i.e., in-sequence deformation). The late rift setting R_3 penetrated the previous rifted areas and stopped along transversal discontinuities (i.e., out-of-sequence deformation). Such an evolution suggests a progressive decrease of the continental crust influences that may illustrate the polyphased denudation processes of an old stable continental mass. These highlight the changing regional geodynamical framework through Geological Times with continental rifting *sensu stricto* (i.e., Gondwana breakup) and backarc extension (i.e., Pacific subduction). Because the extension of the margin is driven by the boundary forces imposed the Pacific subduction, one may consider that these specific extensional periods relate in turn directly to the variation of the dynamics of the subduction.

Acknowledgments
The study was funded by Ecole Normale Supérieure (Paris, France) through a research contract with Total S.A., La Défense (Paris). Permission to publish seismic lines has been kindly provided courtesy of Searcher Seismic. High-resolution bathymetric data displayed on Figure 8 have been accessed thanks to Robin J. Beaman from James Cook University and raw magnetic picks data in Figure 10 from Carmen Gaina from University of Oslo. We also would like to thank Professor Paul Mann and an anonymous reviewer for their constructive comments over the submission. Two authors, Manuel Pubellier and Nicolas Chamot-Rooke, belong to Centre National de la Recherche Scientifique, France.

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