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ScienceDirect
Earth-Science Reviews 83 (2007) 177–203
EARTH-SCIENCE REVIEWS
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Cenozoic tectonic and depth/age evolution of the Indonesian gateway and associated back-arc basins

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Received 16 May 2006; accepted 26 April 2007
Available online 25 May 2007

Abstract

We reconstruct the tectonic and paleo-age and -depth history of the Indonesian seaway and associated southeast Asian back-arc basins to create a comprehensive paleogeographic framework for the region during the Cenozoic. We combine published tectonic models with revised models of the evolution of back-arc basins based on available marine magnetic anomaly data and a recently published high-resolution (1 min) marine gravity anomaly grid which reveals many fine-scale tectonic features previously not resolved. Reconstructions of the now-subducted Ceno-Tethys ocean floor are integrated with a revised absolute plate motion reference frame for the Indian Ocean based on moving hotspots. All marginal seas north of Australia formed in a back-arc setting, with the Caroline and Celebes seas opening north of a northward dipping subduction zone, and the Solomon Sea south of a southward dipping subduction zone north of Australia. We suggest that the evolution of the two sub-basins of the Caroline Sea from 36 to 25 Ma followed different seafloor spreading patterns, with the western sub-basin being influenced by the Manus hotspot. Our model suggests that collision between the Melanesian and the Caroline arcs led to cessation of oceanic crustal production in the Caroline Basin shortly before 25 Ma. Combined geophysical and geological observations suggest that several major tectonic events occurred north of Australia at around 45 Ma, roughly at the time when Australia started moving northwards at fast rates similar to the present. We suggest that this event is related to a relocation of the subduction zone NW of Australia under the Philippine Sea plate due to a collision and subsequent accretion of old Pacific plate material to the northward subducting Australian plate. Our gridded oceanic paleo-depth maps capture the history of marginal seas north of Australia, and the stepwise destruction of the Ceno-Tethys ocean floor in the northern Wharton Basin and the west Pacific, providing boundary conditions for both paleoceanograpic and geodynamic models. A regional analysis of basement depth anomalies reveals that median negative anomalous depth of several back-arc basins is of the order of 650–800 m, with a range of 300–1100 m, accompanied by negative regional heatflow anomalies, suggesting that mantle-driven dynamic topography plays a larger role in modulating regional basement depth than previously suggested. Regional shear wave mantle tomography cross sections highlight that all marginal basins that exhibit large negative dynamic topography are underlain by massive buried slab material in the lower portion of the upper mantle and/or below the transition zone, supporting the notion that the observed paired negative dynamic topography and heatflow anomalies are due to basin formation above slab burial grounds.

Keywords: Southeast Asia; back-arc basin; tectonic reconstructions; paleo-depth; paleo-age; dynamic topography

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0012-8252/$ - see front matter
doi:10.1016/j.earscirev.2007.04.004

1. Introduction

The evolution of seaways and back-arc basins in Southeast Asia, at the boundary between the Indian (and its precursors) and Pacific ocean realms, has received widespread attention for a number of reasons. Cane and Molnar (2001) proposed that the northward displacement of New Guinea about 5 myr ago switched the source of flow through Indonesia from warm south Pacific to cold north Pacific waters, causing East African aridification about 3–4 million years ago. In terms of paleogeography, this hypothesis was largely based on inference, as the depth and width of the Indonesian seaway through the Late Tertiary has never been reconstructed. Hall (2001) used the distribution of land and sea between North Australia and Sundaland to trace the Wallace line (that divides Asian and Australian floras and faunas) from Early Oligocene (30 Ma) and concluded that an ancient deep water barrier hindered the migration of flora and fauna from one hemisphere to another. However, tectonic combined with regional oceanic paleo-depth reconstructions are not trivial as a large number of microplates and an entirely subducted ocean basin need to be restored through time. Due to complex interactions among major tectonic plates (Pacific, Australia, Philippine) in the Cenozoic, a complicated mosaic of small basins north of Australia has continuously altered its structure due to relocation of plate boundaries and redistribution of tectonic forces. Numerous pieces of this puzzle are scattered in the accreted crust north of the Australian craton, as isolated islands or archipelagos in southeast Asia and northeast of Australia or as oceanic basins squashed between newly formed subduction zones.

The southeast Asian marginal seas are also arguably the world's foremost "slab burial grounds" where a number of subduction zones have been active during the Cenozoic, inserting negatively buoyant, sinking slab material into the mantle. This sinking material is at least partly responsible for extensive seafloor depth anomalies in the region, even though the portion of these anomalies attributable to dynamic topography caused by subducted slabs is controversial (Lithgow-Bertelloni and Gurnis, 1997; Wheeler and White, 2000; Xie et al., 2006). Southeast Asia also remains one of the world's frontier petroleum exploration areas (Bruins et al., 2001) and whether or not dynamic topography, is a major contributing factor to accommodation space formation in southeast Asian sedimentary basins also has major implications for hydrocarbon maturation in these basins. In addition, it may be expected that heatflow anomalies associated with spatially varying mantle heatflow may also affect hydrocarbon maturation in regional basins.

2. Methodology

Most published works on the tectonic evolution of this area are based on geological or geophysical data from the exposed continental geology. Among the most comprehensive models are Rangin et al. (1990), Lee and Lawver (1995) and Hall (1996) which focused on southeast Asia, and more recently Hall (2002), Hall and Spakman (2002), Hill and Hall (2003) and Pubellier et al. (2003) who focus on the geology of Papua New Guinea or on recent advances in tomographic models to link the evolution of southeast Asia with the less well known oceanic history north of Australia.

The objective of this paper is to review the tectonic evolution of the region at the boundary between the southeast Asia and western Pacific and create a comprehensive regional tectonic model for the evolving Indonesian gateway and adjacent plates during the Cenozoic. We integrate published tectonic models with revised models of the evolution of back-arc basins in the area based on available marine magnetic anomaly data and a recently published high-resolution (1 min) marine gravity anomaly grid based on retracking altimeter waveforms (Sandwell and Smith, 2005). We integrate reconstructions of the now-subducted Ceno-Tethys ocean floor in the area into our model, following Heine et al. (2004) and compute present depth and heat flow anomalies in southeast Asian marginal basins as well as oceanic basement depth through time for all oceanic portions of the paleo-Indonesian seaway to generate boundary conditions for assessing the paleo-oceanic circulation and the biogeographical evolution of the area. Our aim is to quantify the amount of oceanic crust created and destroyed north of Australia by creating oceanic paleo-age reconstructions that take into account the available geological and geophysical information and to compute oceanic basement paleo-depth by converting oceanic age to depth according to a thermal boundary layer model.

3. Review of regional back-arc basin kinematics

3.1. Caroline Sea

The Caroline basin is a Tertiary feature that is located at the equator between the Pacific, Philippine and Indo-Australian plates (Fig. 1). Most authors (Weissel and Anderson, 1978; Bracey, 1983; Hill and Hegarty, 1988; Smith, 1990; Hill et al., 1993; Hall, 1996) agree that the Caroline basin formed in a back-arc environment due to the subduction of the plate to the south of it. Whether this plate was part of the Australian plate or an intermediate plate has been debated (Weissel and Anderson, 1978;

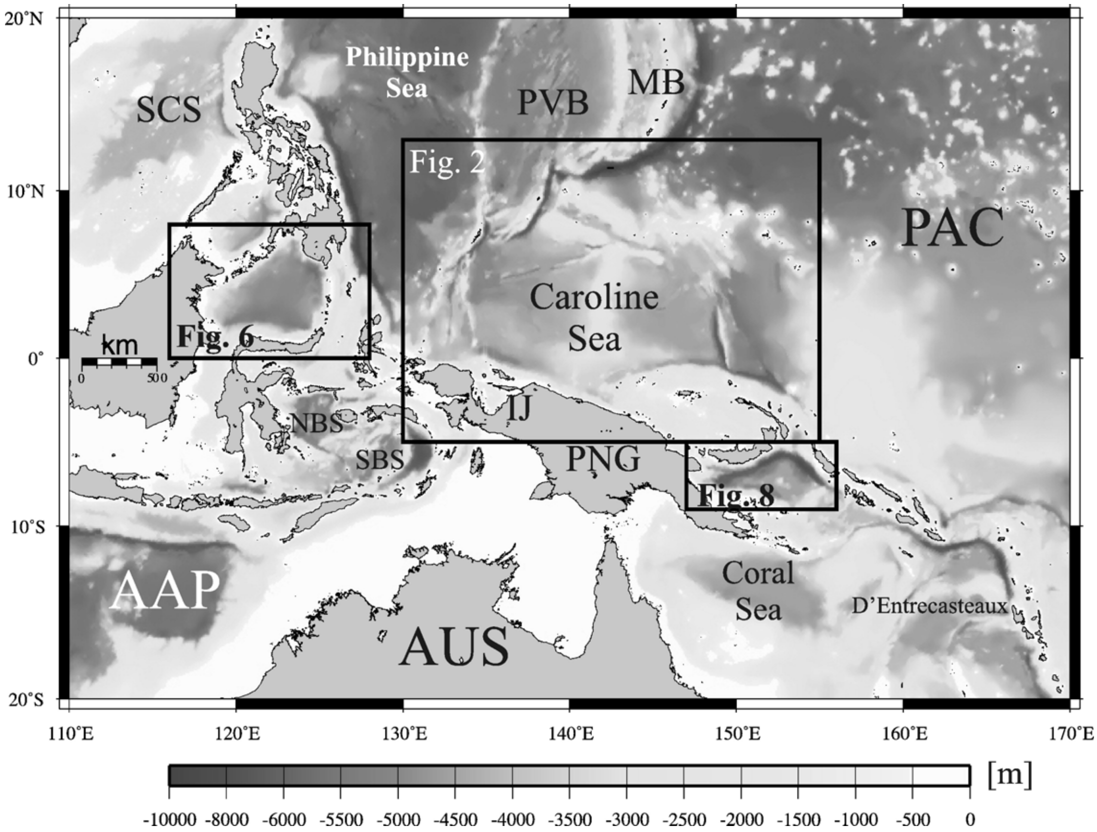


Fig. 1. Bathymetry (GEBCO 1 min) of the oceanic area NW, N and NE of Australia. Black polygons indicate from west to east the location of Celebes Sea (Fig. 6 polygon), Caroline Sea and Solomon Sea (Fig. 9 polygon). Abbreviations stand for AAP — Argo Abyssal plain, AUS — Australia, IJ — Irian Jaya, MB — Mariana Basin, NBS — North Banda Sea, PAC — Pacific, PNG — Papua New Guinea, PVB — Parece Vela Basin, SBS — South Banda Sea, and SCS — South China Sea.

Bracey, 1983; Hill and Hegarty, 1988). Hill et al. (1993) proposed that during Late Eocene to Late Oligocene, a slow, low angle subduction probably occurred along the Papua New Guinea (PNG) margin, at about 2000 km south of the northward subduction under the Caroline plate, but Hill and Hall (2003) suggested that the northward moving Australian plate was subducted under the westward moving Pacific plate creating the Caroline back-arc basin from Middle Eocene to Late Oligocene. Paleomagnetic results from PNG prompted Klootwijk et al. (2003) to suggest that two subduction zones were located about 5–8 degrees apart north of Australia from Middle to Late Eocene, therefore suggesting the existence of a buffer plate north of Australia. However, the exact structure of the oceanic area north of Australia is difficult to reconstruct and paleomagnetic data only are insufficient for this purpose. In a series of tectonic reconstructions Hall (2002) models the inception of the Caroline plate east of the Philippine plate as a result of a westward subduction of the Pacific plate. In his model, the Caroline plate is subjected to a clockwise rotation that relocated the trench from an NE–SW position to a more E–W location and subsequently the subduction of newly created crust north of Australia (in the so-called Solomon Sea).

The age of the Caroline Basin crust was determined by DSDP 62 and 63 cores (Fig. 2) to be Tertiary (Winterer et al., 1971). Although the first studies of this basin suggested east–west trending Tertiary seafloor spreading (Winterer et al., 1971) along the Eauripik Rise (Fig. 2), the acquisition of additional geophysical data showed that the spreading direction was north–south (Bracey and Andrews, 1974).

Hall et al. (1995) suggested that the collision between the Caroline arc and the Australian margin that took place in the Late Oligocene resulted in a new clockwise rotation of the Philippine Sea plate. A different idea was presented by Hill and Hegarty (1988) who consider the composite block of PNG as an extensional core complex developed during the Oligocene, therefore indicating that no collision took place in the Late Oligocene and that subduction south of the Caroline plate ceased

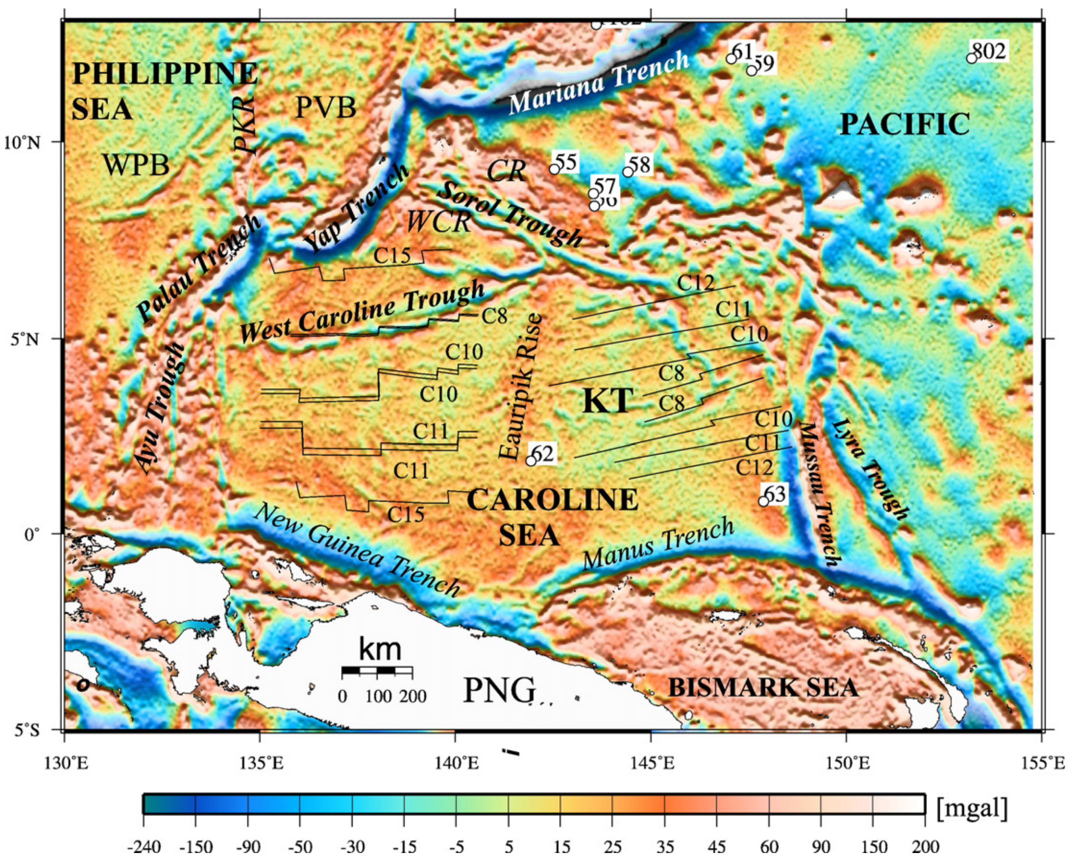


Fig. 2. Gravity anomaly derived from satellite altimetry (Sandwell and Smith, 2005) for the Caroline sea region. Superimposed are the interpreted magnetic lineations (C8–C16 stand for chron numbers, see detailed interpretation in Figs. 3 and 4). Locations of DSDP and ODP drilling are shown in white boxes. Abbreviations: CR — Caroline Ridge, PKR — Palau Kyushu Ridge, WCR — West Caroline Ridge, KT — Kiilsgaard Trough, PVB — Parece Vela Basin, WPB — West Philippine Basin.

because the back-arc basin reached a limiting ridge–trench distance of over 1000 km.

We interpreted a sequence of magnetic anomalies ranging from chron 8n to 15r (26–35 Ma) in the east and from chron 8r to 16n (26–36 Ma) in the west using the Cande and Kent (1995) magnetic reversal timescale (Figs. 3 and 4). Seafloor spreading in the East Caroline basin was fairly symmetric, but large seafloor spreading asymmetries occurred in the West Caroline basin. Based on our revised interpretation of combined magnetic and gravity data (Fig. 4b) it appears that the mid-ocean ridge propagated/jumped northward several times (at chron 12 (33.1 Ma), 10 (28.7 Ma) and 8 (26.6 Ma)). We model locations of the Manus hotspot relative to the Caroline Basin in a moving hotspot reference frame (O'Neil et al., 2005). According to this model, the Manus hotspot was located north of the West Caroline basin during the seafloor spreading process (Fig. 4b), leading to the suggestion that the numerous interpreted ridge jumps were caused by the proximity to a thermal mantle anomaly, the most common cause of major ridge jumps (Müller et al., 1998, 2001).

High-resolution gravity anomalies from satellite altimetry (Sandwell and Smith, 2005) were used to delineate basement ridges and troughs, including fracture zones, extinct spreading ridges, volcanic ridges, subduction zones and other active plate boundaries. The boundaries of the Caroline Plate are characterized by negative gravity anomalies (Fig. 2), delineating subduction zones. Southwest of the Western Caroline sub-basin a positive linear gravity anomaly shows the location of a younger spreading center (Ayu Trough). The Eauripik Rise, a volcanic rise, striking N–S and dividing the Caroline Plate into two parts, is expressed as a broad gravity high, and the Kiilsgaard Trough ridge from the eastern sub-basin is outlined by a negative gravity anomaly (Fig. 2). The boundary between the Sorol Trough and the Northern Mussau Trench is tectonically extremely complicated (Hegarty et al., 1983). The new 1-minute marine gravity anomaly map

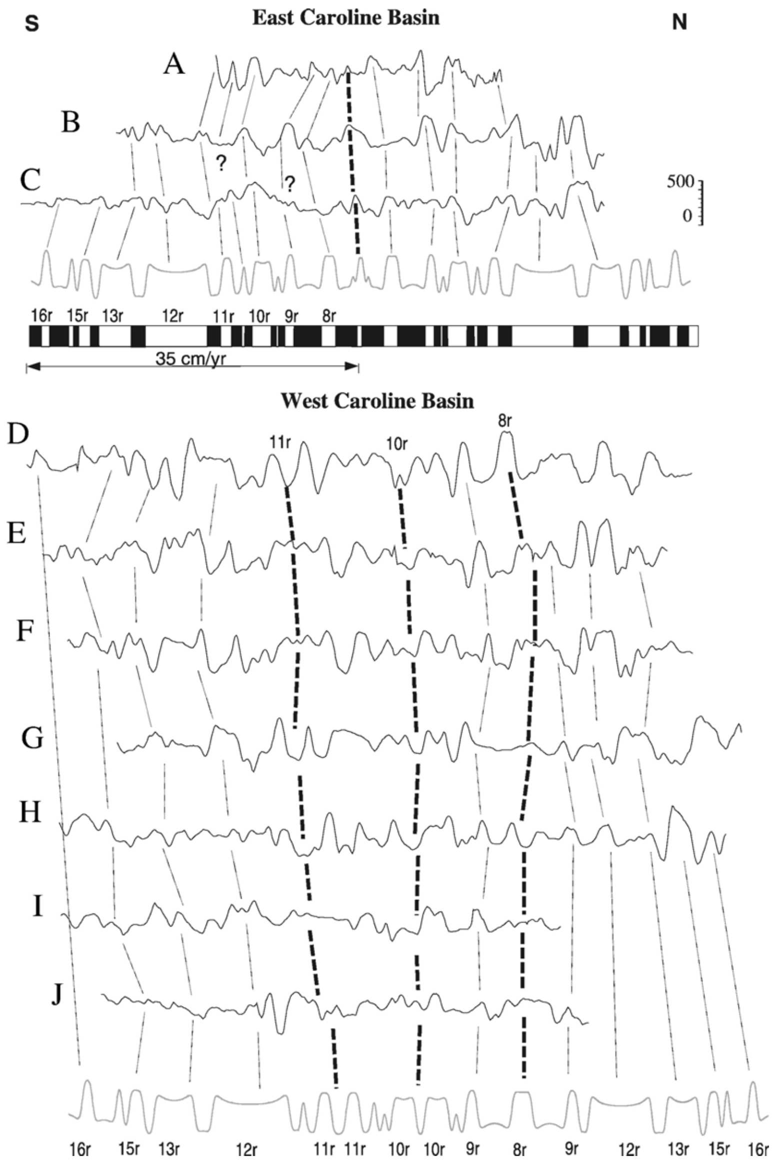


Fig. 3. Selected magnetic anomaly profiles of the Caroline Basin (see location in Fig. 4) compared with synthetic magnetic anomalies. The synthetic profiles are based on the Cande and Kent (1995) geomagnetic timescale.

shows a pattern of highly fragmented alternating positive and negative anomalies (Fig. 2) in considerably greater detail than on previous gravity anomaly maps.

The magnetic anomaly and new gravity data show that the opening of the two Caroline sub-basins occurred along two slightly different directions. In the western basin seafloor spreading took place along an east–west oriented ridge, whereas seafloor spreading in the eastern basin had a WSW to ENE orientation (Fig. 2). The finite rotations (Table 1) for the two microplates (East Caroline Plate and West Caroline Plate) were derived with interactive plate reconstruction software (PLATES4.1). Stage rotations are presented in Table 2. Our model quantifies the total maximum extension along the Eauripik Rise (Fig. 2) to approximately 28 km at its southern end, supporting the hypothesis that it formed by excess volcanism along a leaky transform fault (Weissel and Anderson, 1978). Relative positions of the Philippine and Caroline plates are described by finite rotations in Tables 3 and 4.

3.2. Celebes Sea

It has been proposed that the Celebes Sea, situated east of Borneo and bordered by the northern arm of Sulawesi in the south and Sulu Island Arc in the north

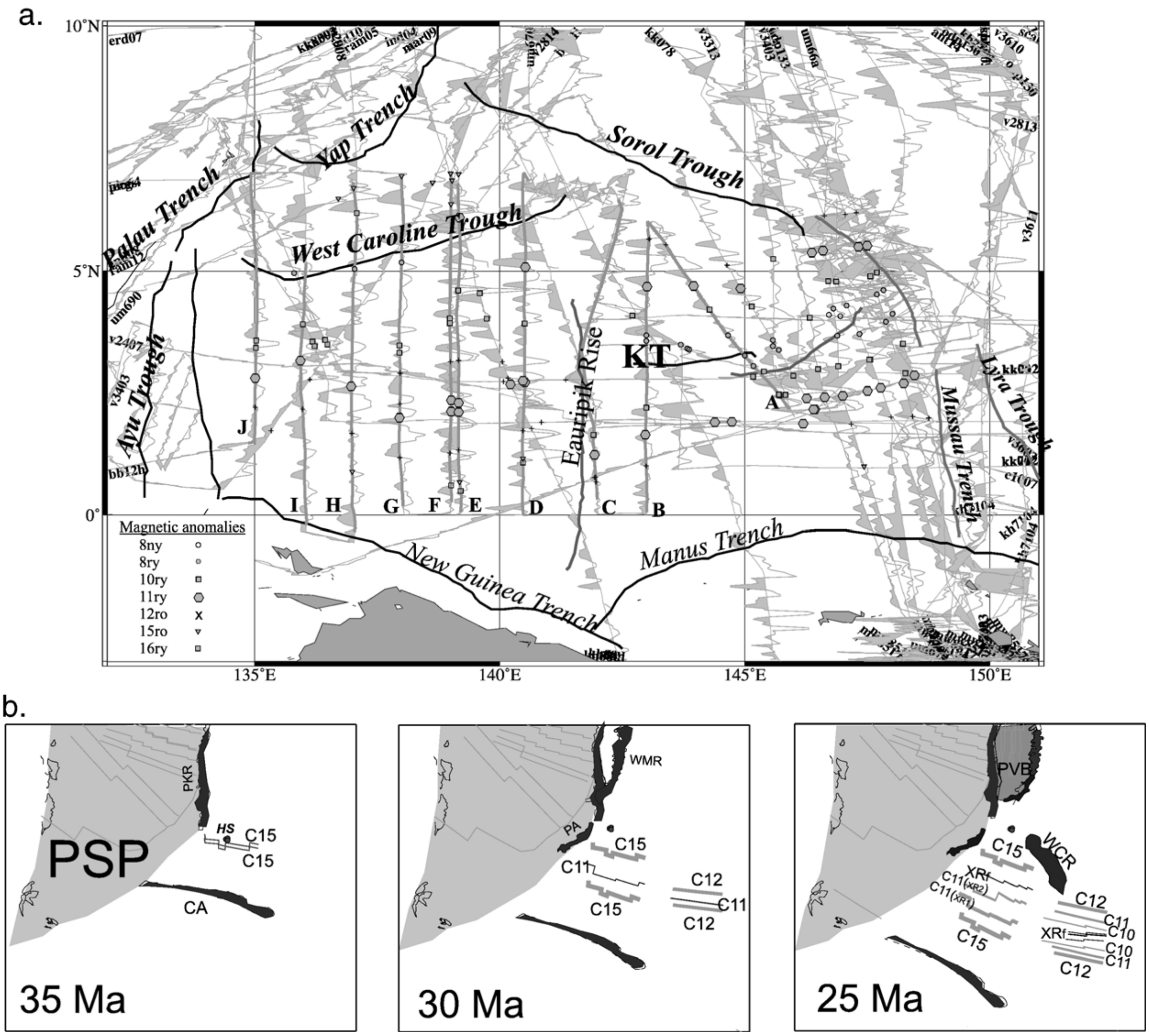


Fig. 4. a. Magnetic anomalies along track in the Caroline basin and identified magnetic anomaly picks. b. Set of reconstructions of Caroline Sea isochrons relative to a fixed Philippine Sea Basin (PSB). Note the northward ridge jump in the west Caroline basin, possibly due to the presence of a hotspot (HS). Abbreviations for island arcs are CA — Caroline Arc, PKR — Palau Kyushu Ridge, PA — Palau Arc, WMR — West Mariana Ridge.

(Fig. 5), formed either as an inter-arc subduction-related back-arc basin (Karig, 1971; Jolivet et al., 1989), a rifted part of the Eurasian plate (Rangin and Silver, 1990; Schluter et al., 1996) or part of the Philippine Sea basin (Nichols and Hall, 1999). Weissel (1980) identified magnetic anomalies 18 to 20 (42–47 Ma according to the LaBrecque and Cande (1977) timescale) trending ENE–WSW (65°) that formed at a mid-ocean ridge subsequently subducted under Northern Sulawesi at the North Sulawesi Trench. ODP Leg 124 results (Rangin and Silver, 1991) (sites 767 and 770, Fig. 5) confirmed that the Celebes Sea oceanic crust formed in the middle Eocene. Although the Celebes Sea is presently separated from the West Philippine Sea basin by the Philippine trenches and islands, the Sangihe Arc and Halmahera, Nichols and Hall (1999) suggested that the age and the sedimentary record of the Celebes basin indicate that it was connected to the West Philippine Sea basin whose mid-ocean ridge propagated westward as subduction was initiated south of the North Sulawesi arm. An alternative interpretation of the age of the Celebes Sea is suggested by Beiersdorf et al. (1997), who describe an E–W striking extinct ridge approximately 40 million years old, and symmetric isochrons ranging in age from 40 to 48 Ma. Beiersdorf et al.'s (1997) interpretation is based on a new set of magnetic data collected in the

Table 1
Finite rotations for microplates in the Caroline basins

East Caroline Basin				
Chron	Age (Ma)	Lat	Long	Angle
15r old	35.3	19.02	−118.23	4.35
12r old	33.1	19.02	−118.23	4.35
11r young	30.1	19.85	−129.30	3.04
10r young	28.7	15.43	−173.90	2.77
8r young	26.6	4.44	169.58	1.60
West Caroline Basin				
Chron	Age (Ma)	Lat	Long	Rot
15r old	35.3	1.45	−85.74	8.63
12r old	33.1	2.76	94.60	−3.40
11r young	30.1	0.00	0.00	−0.24
10r young	28.7	0.00	0.00	−0.15
8r young	26.6	0.00	0.00	−0.06

northeastern part of the basin that displays very low amplitude magnetic anomalies with a rather chaotic pattern.

Based on available geophysical data (magnetic anomalies and 1-minute gravity anomalies from satellite altimetry) we identified a magnetic anomaly series (chron 16 to 21 corresponding to 35 to 48 Ma on the Cande and Kent's (1995) timescale) (Figs. 6 and 7 and Table 5) similar to Weissel's (1980) NE–SW trend orientation. This trend is very clearly observed in the southwestern part of the basin, whereas the isochron geometry in the northern part of the basin is only weakly constrained by the sparse magnetic anomaly shiptracks. Since the only direct constraint of the age of Celebes Sea are the results provided by the ODP 124 Leg (Silver and Rangin, 1991), we have interpolated our interpretation of the southwestern part to the northeast area. The alternative interpretation proposed by Beiersdorf et al. (1997) of a symmetric magnetic anomaly pattern and an extinct ridge dated 35–40 Ma could have occurred as a result of a ridge jump due to the presence of the hotspot. In this case, the Celebes Basin seafloor could be divided similarly to the Caroline Sea into two sub-basins characterized by different asymmetry in the seafloor development due to a disturbing thermal anomaly.

In the gridded gravity anomaly data, weakly expressed NE–SW oriented lineations may reflect the abyssal fabric preserved between two subduction zones characterized by negative gravity anomalies: the Sulu Trench in the northwest and the North Sulawesi Trench in the south (Fig. 5). The new gravity data also reveal a pronounced NW–SE trending linear gravity anomaly high in the northern part of the basin, described by Beiersdorf et al. (1997) as a wrench fault that resulted from transpressive tectonic processes.

In our model, seafloor spreading in the Celebes Sea began shortly before chron 21 (49 Ma), due to northward subduction under the northern Sulawesi arm. A half spreading rate of 30–35 mm/yr is estimated for the seafloor spreading in this basin, and although it is slightly higher than in the West Philippine Sea basin (an average of 22 mm/yr for the same time span), the two spreading centers might have been continuous or linked by leaky transforms during the last 5 million years of their activity. Seafloor spreading ceased perhaps around 35 Ma (the youngest magnetic anomaly is C17y (36.6 Ma) — Fig. 6, tentatively we have interpreted also C16o (36.3) — Fig. 7).

Both northward and southward subduction consumed a considerable amount of Celebes Sea oceanic crust. Northward subduction beneath the Sulu Island Arc commenced in Late Miocene, and southward (or southwestward) subduction occurred due to clockwise rotation of the NW arm of Sulawesi. Shear wave mantle tomography cross sections (Ritsema, 2004) through the Celebes Sea (at 120° and 125° longitude) show 2 distinct subducting slabs (one deeper at the equator, the other one shallower, corresponding with the southern Celebes basin — Fig. 8). These slabs are probably the result from the northwestward subduction of the Molucca Sea and southward subduction of the Celebes Sea. Walpersdorf et al. (1998) show seismogenic traces of the Celebes Sea southward dipping slab that reaches depth of 200 to300 km suggesting that more than 250 km of oceanic crust has been subducted south of the Celebes Sea. A rough estimation of the amount of preserved oceanic crust in the Celebes Sea is about 350 km (along profile A, Fig. 7), and is interpreted to be 46 to 36 million years old. Until more data will be available from the Celebes basin to allow a more detailed interpretation of the age and seafloor spreading characteristics, we can

Table 2
Stage rotations for east and west Caroline basins

East Caroline Basin				
Stage	Age (Ma)	Lat	Long	Rotational angle
15r–12r	35.3–33.1	19.02	−118.23	0.95
12r–11r	33.1–30.1	14.42	−95.64	1.47
11r–10r	30.1–28.7	6.71	−66.80	2.13
10r–8r	28.7–26.6	26.04	−151.94	1.37
West Caroline Basin				
Stage	Age (Ma)	Lat	Long	Rotational angle
15r–12r	35.3–33.1	0.05	−68.24	9.27
12r–11r	33.1–30.1	0.00	0.00	−2.56
11r–10r	30.1–28.7	0.00	0.00	−0.01
10r–8r	28.7–26.6	0.00	0.00	−0.01

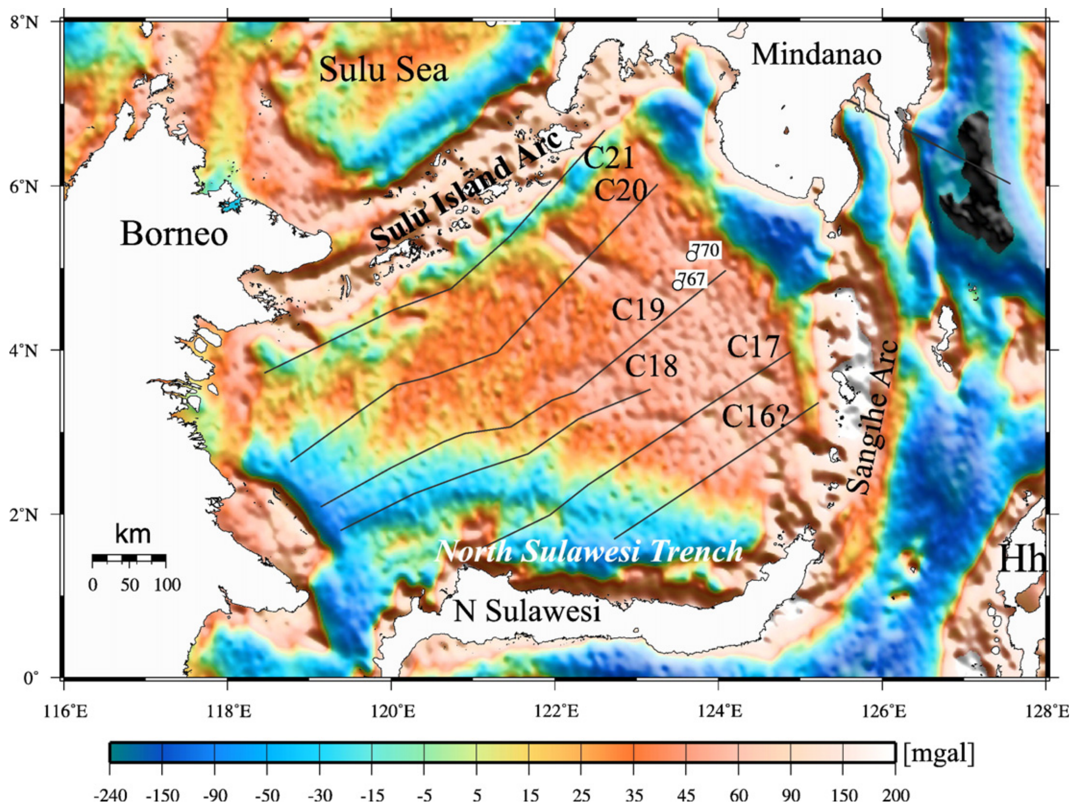


Fig. 5. Gravity anomalies derived from satellite altimetry (Sandwell and Smith, 2005) for the Celebes Sea region. Superimposed are interpreted seafloor isochrons. Hh is Halmahera.

conclude that asymmetric seafloor spreading may have characterized the Celebes basin formation.

3.3. Solomon Sea

The Solomon Sea is presently consumed by three subduction zones (Fig. 9), in the northwest by the New Britain trench, in the southwest by the Trobriand Trough, and in the northeast and east by the South Solomon trench (Bird, 2003). The age of this oceanic basin was tentatively established based mainly on geophysical data and the sedimentary thickness, as being either Late Paleocene to Mid Miocene (60 to 40 Ma) (Davies et al., 1984) or of Oligocene age (Joshima et al., 1987). Falvey and Pritchard (1982) inferred from paleomagnetic data that this basin opened as a result of rotational back-arc spreading related to volcanism between 45 and 30 Ma.

A review of the sparse magnetic data collected in the Solomon Sea (Figs. 10 and 11) indicates that the magnetic anomalies can be interpreted as chrons 19 to 15 (41.5–35 Ma, Table 5). Although the gridded gravity anomalies show few east–west trending features, none of them seem to represent an extinct ridge, correlatable with the asymmetric pattern of magnetic anomalies; therefore we assume that only a part of the southern flank has been preserved (Fig. 9). Considering a half spreading rate of approximately 35 mm/yr and supposing that the basin developed as a result of clockwise rotation of the Melanesian arc, the width of this basin before subduction started to consume it (around 25 Ma) could have been at least 1000 km, comparable with the present day Caroline basin.

Table 3
Finite rotations for Philippine plate

Age (Ma)	Lat	Long	Rotational angle	Fixed plate
50.0	−5.82	122.99	95.11	Pacific
50.0	9.14	141.86	83.54	Eurasia
40.0	19.22	158.31	38.67	Eurasia
25.0	19.22	158.31	38.67	Eurasia
5.0	48.2	157.0	5.45	Eurasia

4. Tectonic evolution of oceanic crust north of Australia

4.1. Overview

We have reviewed the tectonic evolution of the region at the boundary between the southeast Asia and western Pacific and have created a comprehensive regional tectonic

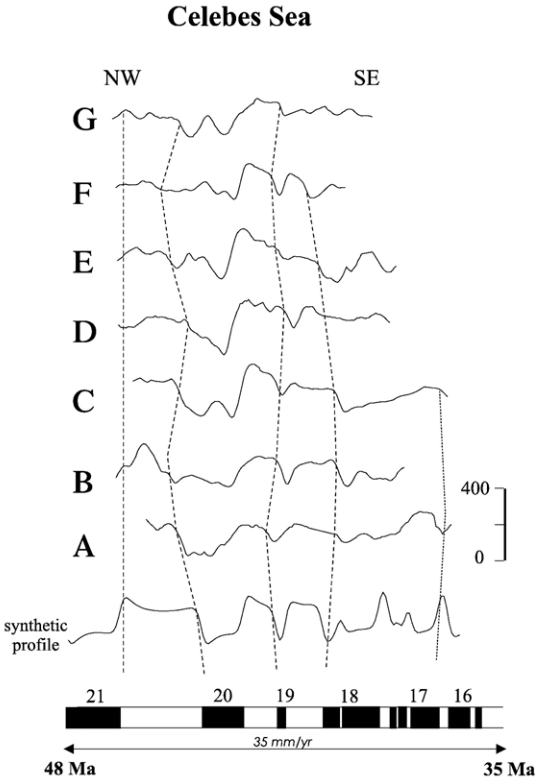


Fig. 6. Selected magnetic anomaly profiles from the Celebes Basin (see location in Fig. 7) compared with synthetic magnetic anomalies.

model for the evolving Indonesian gateway and adjacent plates during the Cenozoic, focusing on the evolution of marginal basins. This model combines published tectonic models based on geological or geophysical data from the exposed continental geology (Hall, 2002) with our revised models of the evolution of back-arc basins in the area based on available marine magnetic anomaly data and a high-resolution marine gravity anomaly grid (Sandwell and Smith, 2005). We present a series of reconstructions that show the evolution of oceanic crust north of Australia since mid-Eocene time. This model describes the subduction of Pacific Cretaceous crust north of Australia, the evolution of several back-arc basins that have been preserved until present day (the Philippine and Caroline Sea basins) or have been partially destroyed (Celebes Sea and Solomon Sea basins and the Molucca Sea) and the evolution of plate boundaries north of Australia. The reconstructions are presented in a moving hotspot reference frame from O'Neill et al. (2005).

4.2. Late Cretaceous–Early Eocene

At the beginning of the Late Cretaceous the northern and eastern margins of Australia switched from active to passive margins due to a change in the absolute motion of the Pacific plate. As a result, several continental blocks (among them the Lord Howe Rise) were rifted from eastern Australian margin and seafloor spreading formed the Tasman and Coral seas and a narrow corridor of oceanic crust that linked the two oceanic basins (Gaina et al., 1998, 1999). We suggest that a piece of Jurassic/Cretaceous crust from the Pacific plate has been trapped north of Australia due to the change in plate boundaries from strike–slip to subduction in the Early Cenozoic. Hill et al. (2002) showed that the ophiolite belt in New Guinea is offset by 125–250 km long compartments floored by Mesozoic oceanic crust and Jurassic to Late Cretaceous ophiolites have been described by Pigram and Symonds (1991) in Irian Jaya and PNG (Fig. 12a).

There is some disagreement over for how long subduction has operated along Sundaland and Indonesia. Hamilton (1988) claimed that subduction at the Java trench began in the Late Oligocene, whereas many other authors report evidence for earlier subduction. Here we briefly review evidence for pre-Oligocene subduction in this area. Letouzey et al. (1990) report that the pre-Tertiary basement complex outcrops in the Meratus Mountains of southeast Kalimantan and in southern Sulawesi are composed of melanges of blueschist and ophiolite fragments, reflecting material scraped off the subducting oceanic crust and intrusions. They interpret this material as rocks accreted along the "Sunda Land" craton in the Early Cretaceous (about 140–100 Ma). This subduction zone corresponds to the Cretaceous subduction zone along eastern Indonesia kinematically modelled by Whittaker et al. (2007). Lee and Lawver (1995) show subduction along the Sunda–Java Trench at 60 Ma, also in disagreement with Hamilton (1988) that subduction there was initiated in the Oligocene.

The scenario of continuous Cretaceous/Tertiary subduction along Indonesia is also supported by McCourt et al. (1996), who describe mineral ages from the Barisan Mountains of southern Sumatra encompassing four main periods of plutonic activity: Miocene-Pliocene (20–5 Ma), Early Eocene (60–50 Ma), Mid-Late Cretaceous (117–80 Ma) and Jurassic–Early Cretaceous (203–130 Ma). They correlate this period of plutonism with north-west subduction beneath the Sundaland continental margin, in line with north-westwards spreading between Greater India and Australia along the Wharton Basin spreading ridge, based on identified sea floor magnetic anomalies in the eastern Indian Ocean (Patriat and Achache, 1984; Royer and Sandwell, 1989). The existence of the Wharton Basin requires convergence of Greater India and Eurasia to the west of the Wharton Basin Ridge. Kinematic reconstructions result in an

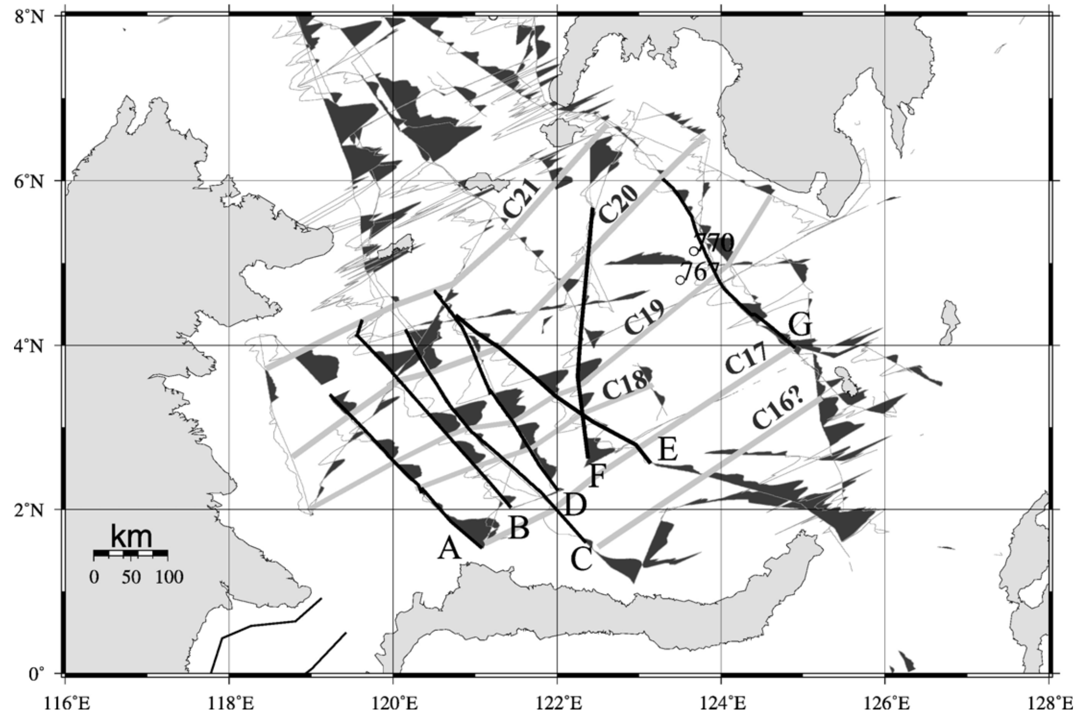


Fig. 7. Magnetic anomalies along track in the Celebes Sea.

intersection between the Wharton Basin spreading ridge with the Java Trench in eastern Indonesia (Whittaker et al., 2007), implying relatively fast subduction all along Indonesia in the Late Cretaceous. However, in addition, plate closure between Australia and Eurasia, east of the Wharton Basin Ridge, also requires convergence along Indonesia in the Late Cretaceous and Early Tertiary, after breakup between Australia and Antarctica around 95 Ma, resulting in northward motion of Australia (Tikku, 1999), paired with southward motion of Eurasia during the late Cretaceous in a moving hotspot absolute reference frame (O'Neill et al., 2005). Therefore, even if Whittaker et al. (2007) modelled intersection location of the Wharton Basin Ridge with Indonesia is not correct, a convergent tectonic regime still results both west and East of the Wharton Basin Ridge at nearly all times in the Late Cretaceous and Early Tertiary.

That subduction occurred along Indonesia before the Oligocene is also supported by the seismic tomographic images shown by Replumaz et al. (2004), which reveal seismically fast material beneath Indonesia/southeast Asia in the lower mantle to a depth of 1500 km. A comparison between the reconstructed position of the southern and western margin of southeast Asia at 50 Ma using a fixed Eurasian reference frame and this extensive lower mantle seismic anomaly provides evidence for long-term subduction along this margin that extended from Java–Sunda to the northern Tethys margin prior to and during Indian collision (Replumaz et al., 2004). Despite the suggestion in a recent study by Smyth et al. (2007) that subduction under East Java terminated in Early Cenozoic due to a collision with an Australian derived terrane, all other geological, plate kinematic and seismic tomography data support long-lived Sunda–Java subduction since the Late Cretaceous.

4.3. Middle Eocene 45–40 Ma (Fig. 12b,c)

Some time in the early Cenozoic (around 60 Ma) a series of trenches were initiated in the western Pacific and a new back-arc basin, the West Philippine Sea, was formed. The present model accounts for a trapped segment of Cretaceous crust (possible Pacific), currently located in the north (and possibly south) of the West

Table 4
Finite rotations for Caroline plate

Age (Ma)	Lat	Long	Rotational angle	Fixed plate
35.0	9.45	135.84	−13.98	Philippine
25.0	9.87	132.00	−25.00	Philippine
15.0	9.87	132.00	−25.00	Philippine

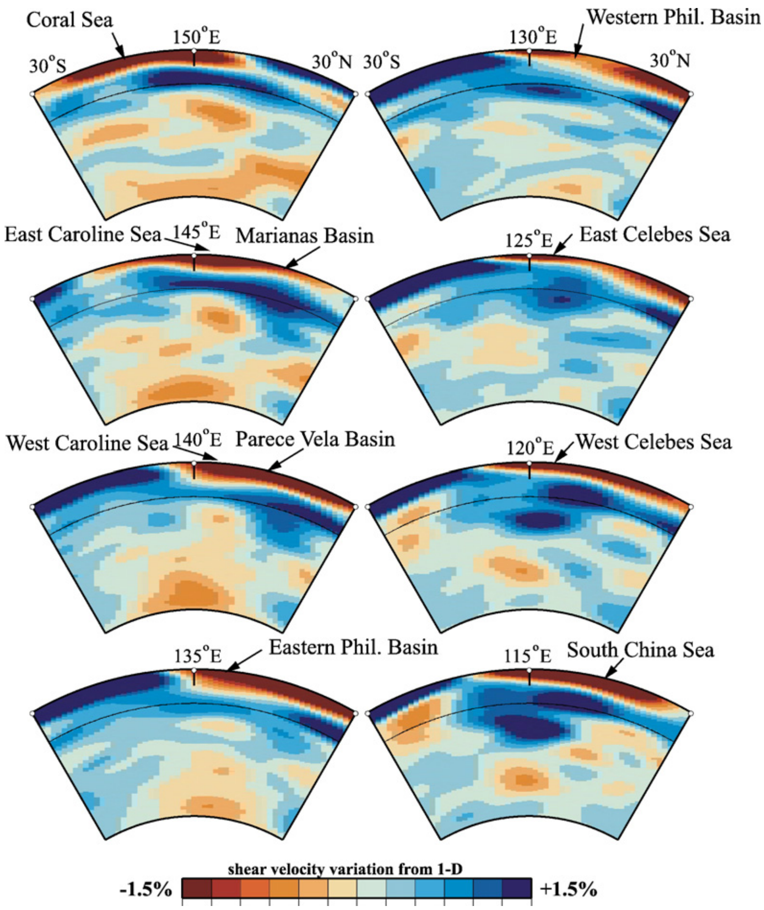


Fig. 8. Regional N–S shear wave mantle tomography cross sections from (Ritsema, 2004); 670 km boundary shown as thin, dotted line.

Philippine Basin (Deschamps and Lallemand, 2002). Continuous subduction of the oceanic Izanagi plate under the Eurasian plate led to diachronous subduction of the active ridge from Early Paleocene. We suggest that the West Philippine Sea Basin formed due to a southward jump of a segment of Izanagi–Pacific active

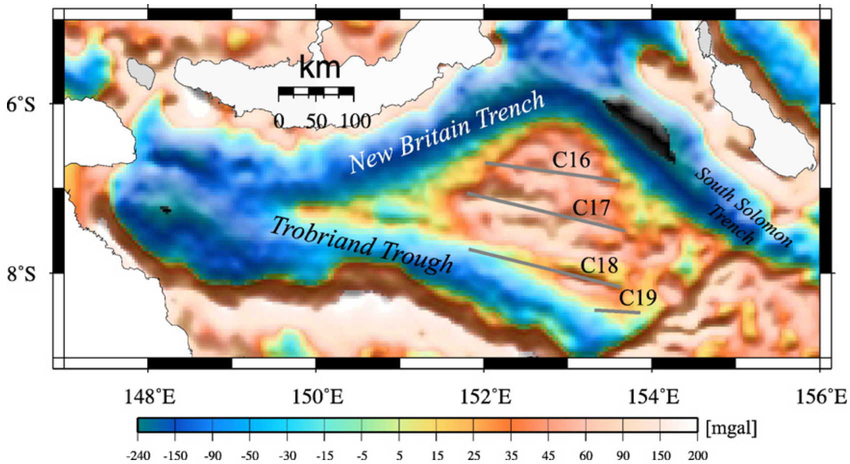


Fig. 9. Gravity anomalies derived from satellite altimetry (Sandwell and Smith, 2005) for the Solomon Sea region. Superimposed are interpreted seafloor isochrons.

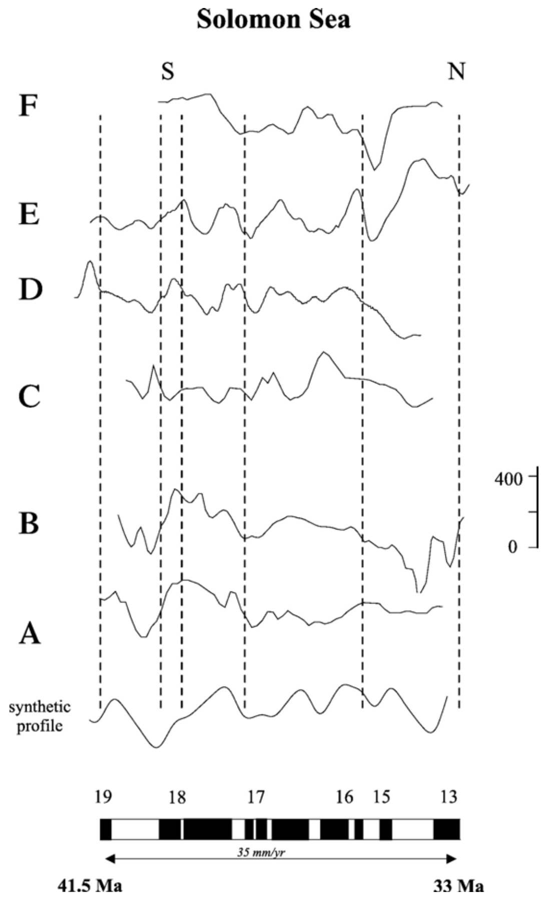


Fig. 10. Selected magnetic anomaly profiles from the Solomon Sea (see location in Fig. 11) compared with synthetic magnetic anomalies.

ridge, and the initiation of the Izu Bonin subduction zone occurred along a former Pacific–Izanagi fracture zone as modelled by Hall et al. (2003). Several tectonic events, both in the Indian and West Pacific realms appear to cluster around mid-Eocene time. The causal connection of these events remains unclear, but notable events such as the collision of the Indian plate with Eurasia and a change in the Pacific plate direction (observed in the bend of the Hawaiian-Emperor chain) might have triggered a series of regional changes in tectonic forces and plate boundaries. For example, as seafloor spreading ceased in the Wharton basin (NW of the Australian plate), and the oceanic crust north of Australia accreted on the northern and northeastern Australian craton (as a series of ophiolite (Hill and Hall, 2003)) the Australian plate northern plate boundary relocated to further north. The presence of a single northward subduction zone NW of Australia under the Philippine Sea plate, where old Pacific crust subducted rapidly, might have determined the change in the northward movement of the Australian plate at a higher speed at about 44 Ma. Shortly after 50 Ma, due to the re-arrangement of the location of the northward subduction under the Philippine plate and Sundaland, a new trench formed south of the northern arm of Sulawesi and a new back-arc–the Celebes Sea basin–started opening west of the West Philippine Sea. The boundaries between the West Philippine basin and the Celebes basin were mainly transform faults. Although it has been suggested that seafloor spreading occurred also in the Makassar Strait between Borneo and the Western Sulawesi arm (Cloke et al., 1999), new seismic data infirm this interpretation (Puspita et al., 2005).

The southward subduction of the Pacific plate under the NE Australian plate gradually created the Melanesian Arc by arc volcanism. Although there are controversial models for the origin of the Melanesian Arcs (arc system formed in the proximity of the Australian margin and subsequently rifted away (Crook and Belbin, 1978) versus an intra-oceanic formation followed by collision with the Ontong Java Plateau (Petterson et al., 1999) we prefer the model that places this arc close to the Australian margin; the arc's clockwise rotation then accounts for the formation of the Solomon Sea as in Hall's (2002) model. This approach doesn't contravene Petterson et al.'s (1999) model, who also suggests that part of this collage arc was formed on the Australian plate as a result of SW directed subduction. Our interpretation of magnetic data in the Solomon Sea suggests that this back-arc basin started to open sometime between 43 and 41 Ma (Table 6), with chron 19 (41.5 Ma) being identified very close to the southern compressional plate boundary (Fig. 9).

4.4. Middle Eocene–Early Oligocene 40–30 Ma (Fig. 12c–e)

At this time, two subduction zones were present north of Australia with opposed polarities. In the NE southward subduction led to the opening of the Solomon Sea, and in NW northward subduction under the Philippine Sea arc consumed old Pacific crust (whose scarce remains are found in the present day Molucca Sea). The two subduction zones were probably connected by a transform fault, a similar configuration as in the present day SW Pacific region.

The northward subduction under the Philippine arc created another volcanic chain, the Caroline arc, and around 36 Ma, seafloor spreading started in the west Caroline Basin and at 34 Ma in the east Caroline Basin. It is not straightforward to establish the type of plate boundaries shared by the Caroline and the Pacific plate. Unlike the Philippine Sea plate, that is surrounded by

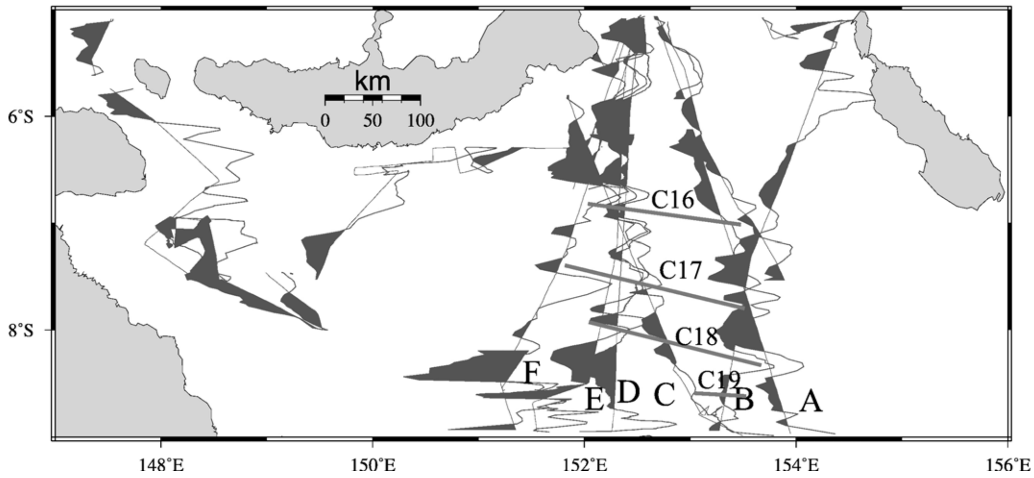


Fig. 11. Magnetic anomalies along track and interpreted seafloor isochrons in the Solomon Sea.

island arcs, the Caroline plate was presumably bounded southward by the so-called Caroline arc that later on collided with Papua New Guinea (probably the Torricelli, Adalbert and Finisterre terrane now part of the northern New Guinea (Hall, 1998)) and separated from the older Pacific crust only by transform faults (the oldest one — the Lyra Trough, is visible in the gravity anomaly grid as a linear negative anomaly) (Fig. 2), others were converted to trenches like the Mussau Trench where Caroline plate oceanic crust is being subducted only recently under the Pacific plate (Hegarty et al., 1983). The Palau and Yap Trenches situated NW of the Caroline plate (Fig. 2), at the boundary with the east Philippine and Parece Vela basins respectively, are thought to be the southern continuation of the Palau–Kyushu Ridge and Izu–Bonin–Mariana arc and trench. Today both these trenches seem to host reduced subduction activity, with low seismicity, no forearc and a small trench-arc distance. During the evolution of the Caroline Sea basin, the two trenches may have acted as convergent plate boundaries. The Palau Arc probably has the same origin as the Palau–Kyushu Ridge, which is situated east of the west Philippine Sea basin and has been formed around Eocene time by subduction related volcanism (Ozima et al., 1977). Mid to Late Eocene volcanic rocks recovered from the Palau Trench contain low K arc tholeiitic series and boninites that led Hawkins and Castillo (1998) to suggest that they were formed in an environment with steep thermal gradients in multiply depleted mantle. One of the mechanisms to generate boninites is to have hot, young lithosphere subducted under a young hot upper plate. If this was the case, then the Palau Trench might have started to be active as soon as the Caroline Sea started to form. The Yap Trench (and arc) seems to be a younger feature, with an age around 25 Ma (Ohara et al., 2002). Volcanism in the Yap Arc ceased sometime between 25 and 20 Ma, probably due to the collision with the Caroline Ridge (Fujiwara, 2000; Ohara et al., 2002). However, other regional tectonic events occurred around this time, so the exact succession of events is hard to be predicted. A renewed episode of volcanism started around 11–7 Ma (Ohara et al., 2002), but little subduction took place, mainly because the presence of the Caroline Ridge hindered subduction initiation (Lee, 2004).

Our reconstruction for 35 Ma shares many features with Hall's (2002) reconstruction, except that we have placed the Caroline Arc in an E–W position rather an NE–SW position (Table 4), as there is little evidence for a ~60° rotation in only 5 million years, as Hall's (2002)

Table 5
Finite rotations for North Sulawesi Arm (opening of Celebes Sea)

Chron	Age (Ma)	Lat	Long	Rotational angle	Fixed plate
	47.9	−9.0	100.0	18.3	N Celebes Sea
	43.8	−9.0	100.0	15.0	N Celebes Sea
	41.5	−9.0	100.0	11.0	N Celebes Sea
	40.1	−9.0	100.0	8.6	N Celebes Sea
	38.1	−9.0	100.0	4.5	N Celebes Sea
	35.6	−9.0	100.0	1.0	N Celebes Sea

Table 6
Finite rotations for Solomon Islands

Age (Ma)	Lat	Long	Rotational angle	Fixed plate
43.0	9.59	−22.13	−16.21	Australia
27.0	59.21	1.22	15.86	Australia
13.0	59.21	1.22	15.86	Australia

model implies. Seafloor spreading slowed down considerably in the West Philippine Basin after chron 16 (35.3 Ma) and finally ceased before 30 Ma (Deschamps et al., 2002). Although there is no direct evidence for the exact timing of cessation of seafloor spreading in the Celebes Sea (as at least half of the Celebes Sea has been subducted, including the extinct ridge), we propose that seafloor spreading ceased in this basin after the formation of magnetic anomaly 16 (35 Ma) in a similar fashion as in the West Philippine basin.

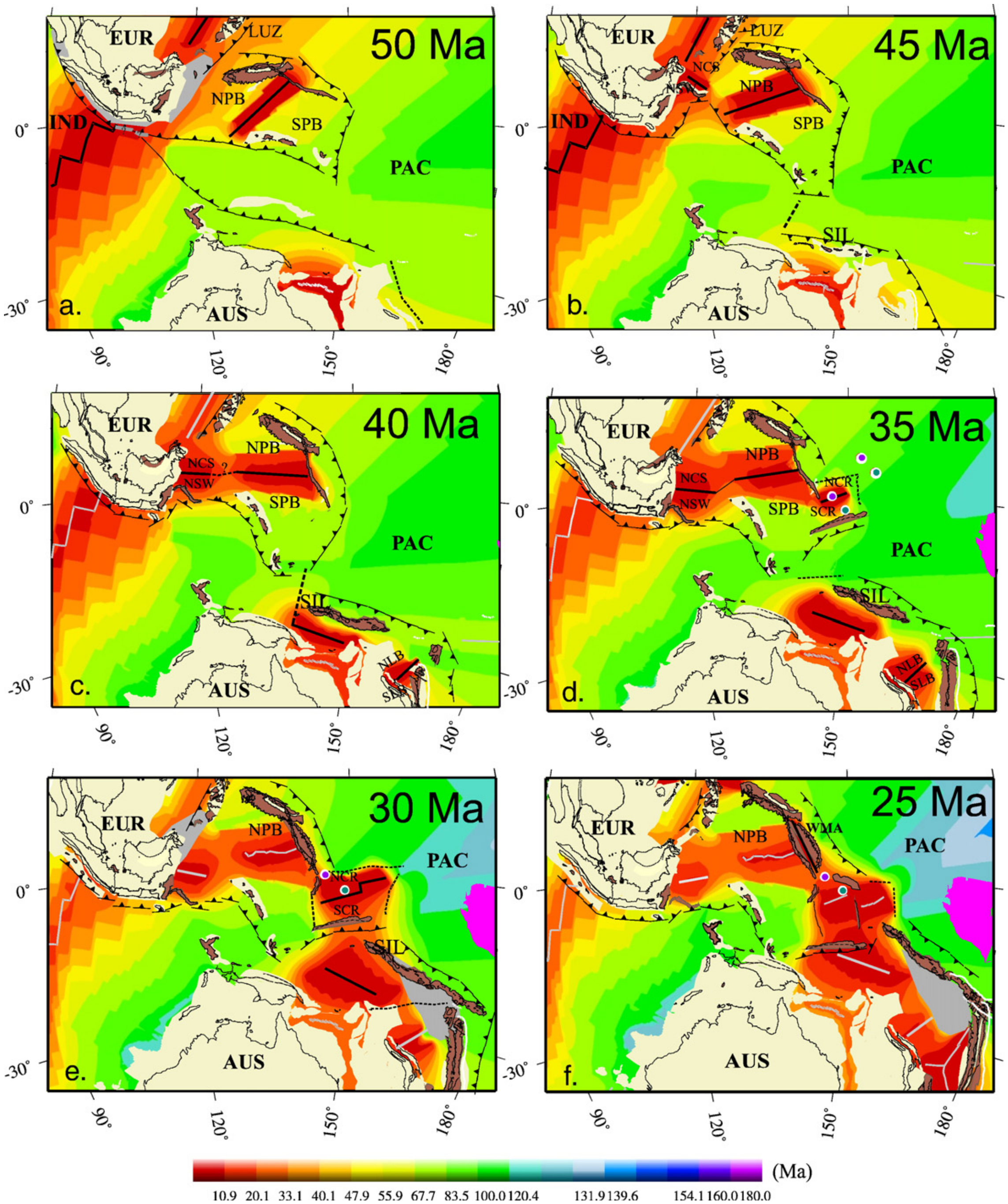
4.5. Early Oligocene–Early Miocene 30–20 Ma (Fig. 12e–g)

At around 30 Ma seafloor spreading in the Western Philippine Basin ceased and the Parece Vela Basin began forming to the east (around 30 Ma) (Okino et al., 1998) with a spreading direction perpendicular to the older magnetic lineations from the Western Philippine Sea. Seafloor spreading in the two sub-basins of the Caroline plate followed different patterns — in the eastern sub-basin symmetric seafloor spreading formed ENE–WSW oriented oceanic blocks, whereas in the western sub-basin, several northward directed ridge jumps created a highly asymmetric oceanic fabric. We suggest that the northward relocation of the active oceanic ridge was due to the proximity of a hotspot. It has been shown that the presence of a thermal anomaly in oceanic areas in proximity to mid-ocean ridges can trigger ridge propagation and therefore asymmetric seafloor spreading patterns (Müller et al., 1998). Two hotspots have been documented in this area: the Manus and the Caroline hotspots. The presence of a hotspot in the current Manus basin has been documented by a mantle tomography model (Spakman and Bijwaard, 2000) and its geochemical signature (Macpherson et al., 1998). Macpherson and Hall (2001) reconstructed the path of this hotspot and suggested that it was the thermal factor that influenced the production of boninites at the Izu–Bonin–Mariana arc in the Eocene. Because north of Australia a long-lived boundary between two large mantle domains migrated through time or allowed temporary mixing between the two types of magma (Hickey-Vargas et al., 1995), we have tested a Pacific or Indian mantle origin for the Manus hotspot using two newly published reference frames (O'Neil et al., 2005; Wessel et al., 2006). The locations of two alternative Manus hotspot locations are shown on the 35 to 15 Ma reconstructions (Fig. 12d–h). A Pacific mantle origin for the Manus hotspot could better explain the observed seafloor spreading asymmetry and the location and timing of the volcanic features that subsequently developed in the Caroline Sea. Fornari et al. (1979) found evidence in geochemical data from the Sorol Trough, proximal to DSDP Site 57, that basalts at this locality are similar to those found in rocks from seamounts in the eastern equatorial Pacific. This suggests that this area was underlain by Pacific mantle, and that the Manus hotspot was most likely fixed with respect to other Pacific hotspots, such as the Hawaiian and Louisville hotspots. However, the position of the Manus hotspot is slightly different from the one reconstructed by Macpherson et al. (1998) to account for the formation of the Eauripik Rise. Taking into account that several assumptions were made for both relative and absolute plate motions, there is no definitive explanation for the structure and composition of the crust that underlies the Caroline basin.

The rapid northward motion of the Australian plate due to seafloor spreading in the Southern Ocean and the northward pull of the subducted slab under the Philippine Sea plate, decreased the distance between the two tectonic plates considerably and eventually led to collision (at around 25 Ma). Our model suggests that shortly before the collision between the southern tip of the Philippine and the Caroline arcs and the northern

Fig. 12. Set of tectonic reconstructions that depict the evolution of oceanic crust north of Australia since Middle Eocene (50 Ma). Light yellow represent continental blocks, rotated present day coastline are in black, island arcs are colored in pale brown. Grey areas depict regions with insufficient data to constrain paleo-age grids. Black lines are active plate boundaries (if dashed — unconstrained plate boundary), light grey lines are extinct spreading ridges. The two blue circles show the location of the Manus (west) and Caroline (east) hotspots assuming an underlying Pacific mantle. An additional position for the Manus hotspot depicts its location if part of moving Indian Ocean hotspot (green circle). Large Igneous Provinces (in this case Ontong Java Plateau, NE of Australia and Kerguelen and Broken Ridge plateaus, SWof Australia) are colored in magenta. The active tectonic plates are mentioned as following: PAC — Pacific Ocean, AUS — Australia, IND — Indian plate, EUR — Eurasia, LUZ — Luzon, NPB and SPB — North and South Philippine Basin, NCS — North China Sea, NSW — North Sulawesi Arm, SIL — Solomon Islands, NLB and SLB — North and South Loyalty Basin, NCR and SCR — North and South Caroline Basin, P–M -, SI — Sulu Island Arc. Present day age grid abbreviations: Oceanic basins: AAP — Argo Abyssal Plain, SO — Southern Ocean, SCS — South China Sea, WPS — West Philippine Basin, PVB — Parece Vela basin, WMB — West Mariana basin, Su — Sulu Sea, CeS — Celebes Sea, MSt — Makassar Strait, MS — Molucca Sea, SBS — South Banda Sea, CaS — Caroline Sea, BS — Bismark Sea, SS — Solomon Sea, CoS — Coral Sea, LT — Louisiade Trough, CT — Cato Trough, TS — Tasman Sea, NFB — North Fiji Basin, SFB — South Fiji Basin, Dec — DEntrecasteaux, WB — Wharton Basin; Volcanic arcs (with possible continental remains): PA — Philippine Islands Archipelago, IB — Izu Bonin, Lz — Luzon, Hh — Halmahera, Nsw — North Sulawesi, SSw — South Sulawesi, SESw — SE Sulawesi, Jv — Java, Sum — Sumatra, MA — Melanesian Arc, SI — Solomon Islands, WMA — West Mariana Arc; Hotspots: CHS — Caroline hotspot, MHS — Manus hotspot.

Australian margin, collision between the Melanesian Arc and the Caroline Arc led to cessation of oceanic crustal production in the Caroline Basin (the youngest magnetic anomaly identified is 26 million years old) and presumably also in the Solomon Sea that will be partially consumed under the Caroline plate. The proximity of the Ontong Java Plateau (OJP) at around 25 Ma (and a possible early collision — note that the reconstructed OJP has its present day shape) will also preclude the subduction rollback that led to the clockwise rotation of the Melanesian arc and the formation of the Solomon Sea. This event might have also triggered a change in the absolute plate motion of the Australian plate from northeastward to northward. As a result the southern boundaries of the Philippine and Caroline plates changed from trenches to strike–slip faults.



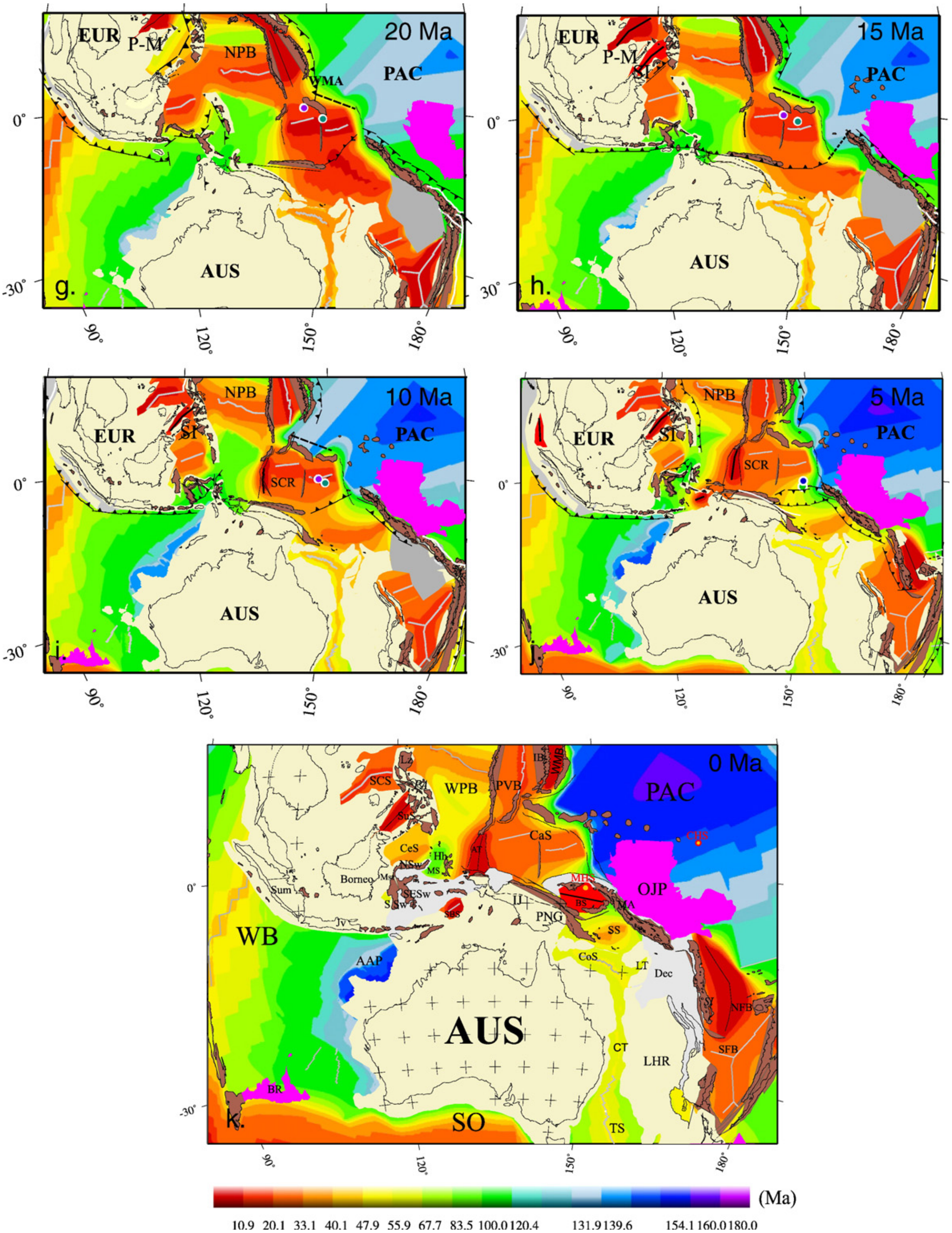


Fig. 12 (*continued*).

The timing of Ayu Trough (Fig. 2) formation is still debatable, for example Weissel and Anderson (1978) inferred from spreading rates a middle Miocene (15 Ma) age, whereas Fujiwara et al. (1995) suggested a Late Oligocene (25 Ma) age based on spreading rates, distribution of sediments thickness and basement subsidence. Fujiwara et al. (1995) describe NNE–SSW trending spreading directions in the north Ayu basin; this direction was also observed in the southern part of the basin (Lee, 2004). The new gravity anomaly data (Sandwell and Smith, 2005) show both NW–SE and NE–SW lineations that cross the Ayu Trough area. Several authors (Weissel and Anderson, 1978; Hegarty and Weissel, 1988) suggested that the Ayu Trough formed as a result of a counterclockwise motion of the Caroline plate. Further consequences of this event were compression/subduction along the Yap Trench (NW of the Caroline plate), New Guinea Trench (SW of the Caroline

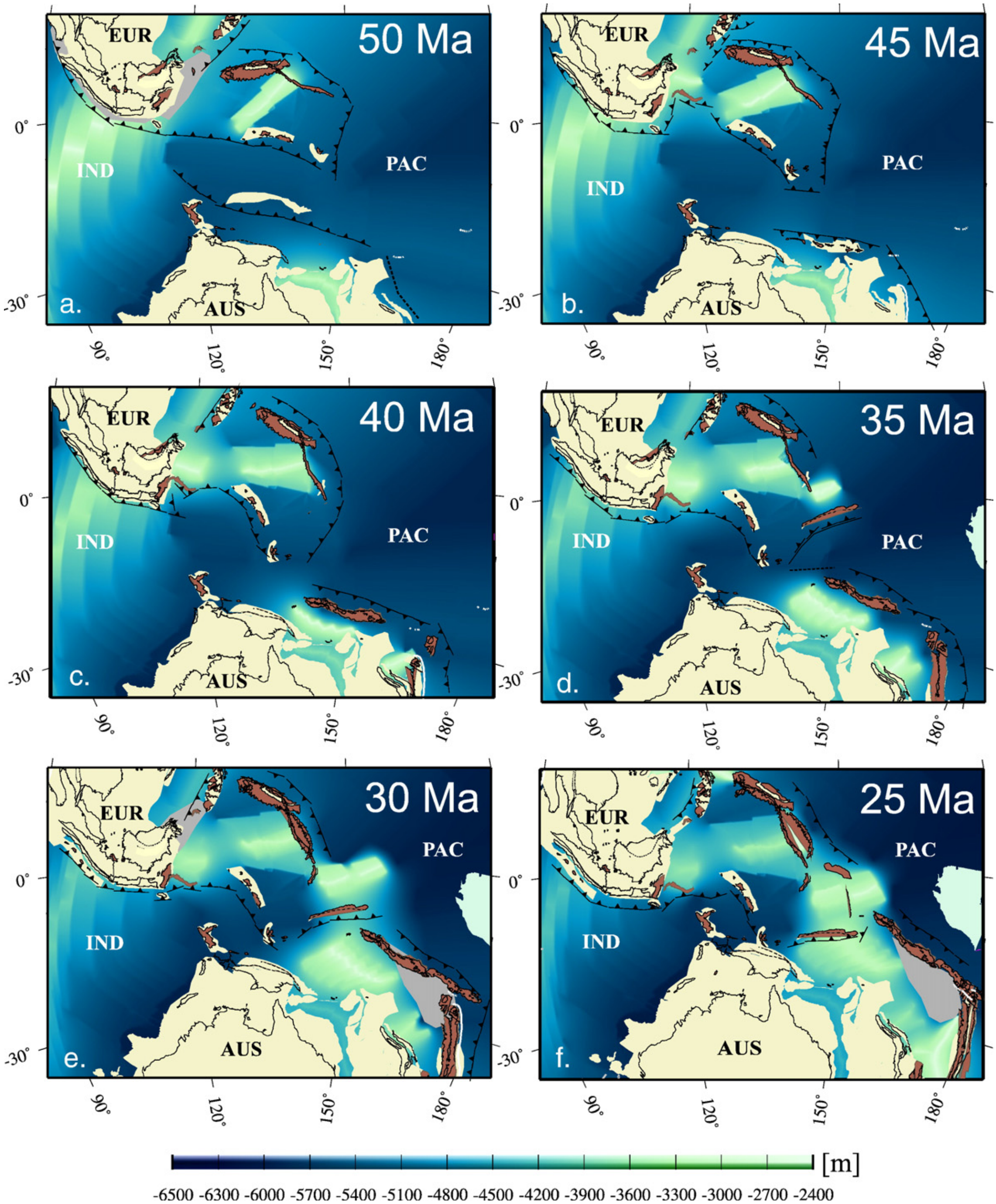


Fig. 13. Reconstructions of paleobathymetry north of Australia since Middle Eocene (50 Ma). See legend from the previous figure.

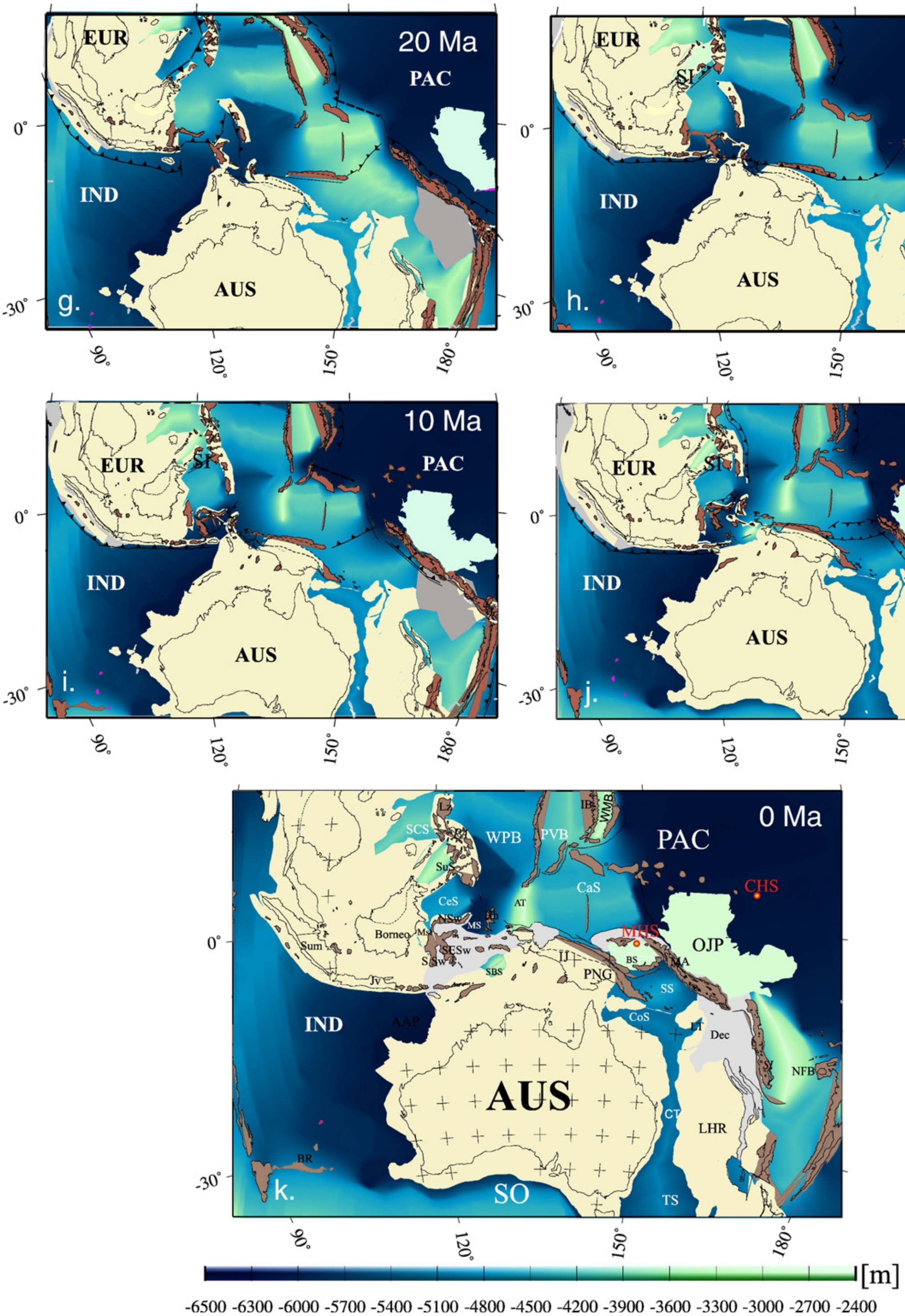


Fig. 13 (*continued*).

plate), and Mussau Trench (SE of the Caroline plate). Hall et al. (1995) proposed a renewal of the clockwise rotation of the Philippine Sea plate around 25 Ma, probably generated by the collision with the northern tip of the Australian continent. This collision might have forced the Caroline plate to become attached to the Philippine plate

Table 7
Summary of anomalous basin depth and heatflow

Basin	Age range	Depth anomaly (Median and MAD) (m)	Heat flow anomaly (Median and MAD) (mW/m^2)	Observations from seismic tomography and other data
Mariana Basin	0–5	−680±270	−207±120	Massive subducted slab volume below and above transition zone
Parece Vela/Shikoku basin	16–29	−810±140	−17±21	Massive subducted slab volume below and above transition zone
South China Sea	16–30	−645±255 Generally larger anomaly in south than north	−7±14	Subducted slab volume above transition zone, focussed on southern S China Sea
Caroline Sea	24–37	70±525 Positive anomalies associated with shallow volcanic rises, negative anomalies in Caroline abyssal plains	−10±18	Relatively thin layer of subducted slab material around transition zone
Celebes Sea	35–48	−725±290	23±22	Subducted slab volume below transition zone, but hot upper mantle lid
West Philippine Basin	32–60	−835±375	−14±11	Large slab volume below transition zone
Coral Sea	52–63	430±305	23±18 Highest in west	Positive upper mantle anomaly

for the next 10 million years, or to move very slowly relative to the Philippine plate. The oceanic crust in the Ayu Trough basin seems to have accreted only in the last 15 million years, as the configuration of tectonic plates north of Australia allow little extension between the Philippine and Caroline plates before 15 Ma. The docking of the Caroline arc north of Australia around 15 Ma could have generated a regional event that led to NNW–SSE seafloor spreading in the Ayu Trough basin and cessation of seafloor spreading in the Parece Vela basin, north of the Caroline plate.

Fuller et al. (1999) revised the paleomagnetic data of Borneo and concluded that it experienced an approximative 51° of counterclock (CCW) rotation in particular from Early to Middle Miocene. Hall (2002) proposed a 40° CCW rotation for Borneo starting at 25 Ma until 10 Ma. Although subduction north of Borneo and several collisional events between parts of Sundaland and the northern Australian margin require this rotation (as pointed out by Hall (2002)), available geophysical and geological data provide little evidence for severe deformation/strike–slip around Borneo during that time. We have adopted Morley's (2002) compromise solution suggesting that Borneo's CCW cannot be larger than 25° in order to account for a minimum displacement relative to Java and Sumatra.

4.6. Early Miocene–Late Miocene 20–10 Ma (Fig. 12g–i)

The Caroline Ridge (Fig. 2) is a shallow NW–SE striking complex of ridge and trough structure situated in the Northern Caroline Sea. It consists of two sub-parallel ridges: the Caroline Islands Ridge on the NE and the West Caroline Rise on the SW. The two halves of the Caroline ridge are separated by the Sorol Trough — a rift-like feature of an approximate depth of 4000 m. DSDP site 57 established an Oligocene age for the Caroline Ridge. Heezen et al. (1971), and Perfit and Fornari (1982) suggest that both MORB and hot-spot type sources have been involved in the generation of magmas in this region. Hegarty and Weissel (1988) proposed that the Caroline Ridge, the Caroline Seamounts (located east of 144°E) and the Euripik Rise have been formed by excessive volcanism on young and weak lithosphere of the Caroline Basin. Altis (1999) confirmed this scenario for the Caroline ridge and proposed an Oligocene age for the formation of the Caroline Ridge, and a Late Miocene age for the rifting that led to the opening of the Sorol Trough.

Our reconstruction suggests that the Manus hotspot was responsible for the excess volcanism that formed the Caroline Ridge as the Caroline plate started to head north after the 25 Ma collisional event that triggered the second clockwise rotation of the Philippine plate. The Eauripik Rise, which is a younger volcanic feature located on a former leaky transform fault, was likely built by hotspot volcanism due to the proximity of the Manus hotspot. Alternatively, rising magma originating from the subducting slab south of the Caroline Basin may have flown into the opening leaky transform fault, forming the Eauripik Rise. Following several million years of "soft" docking between the OJP and the

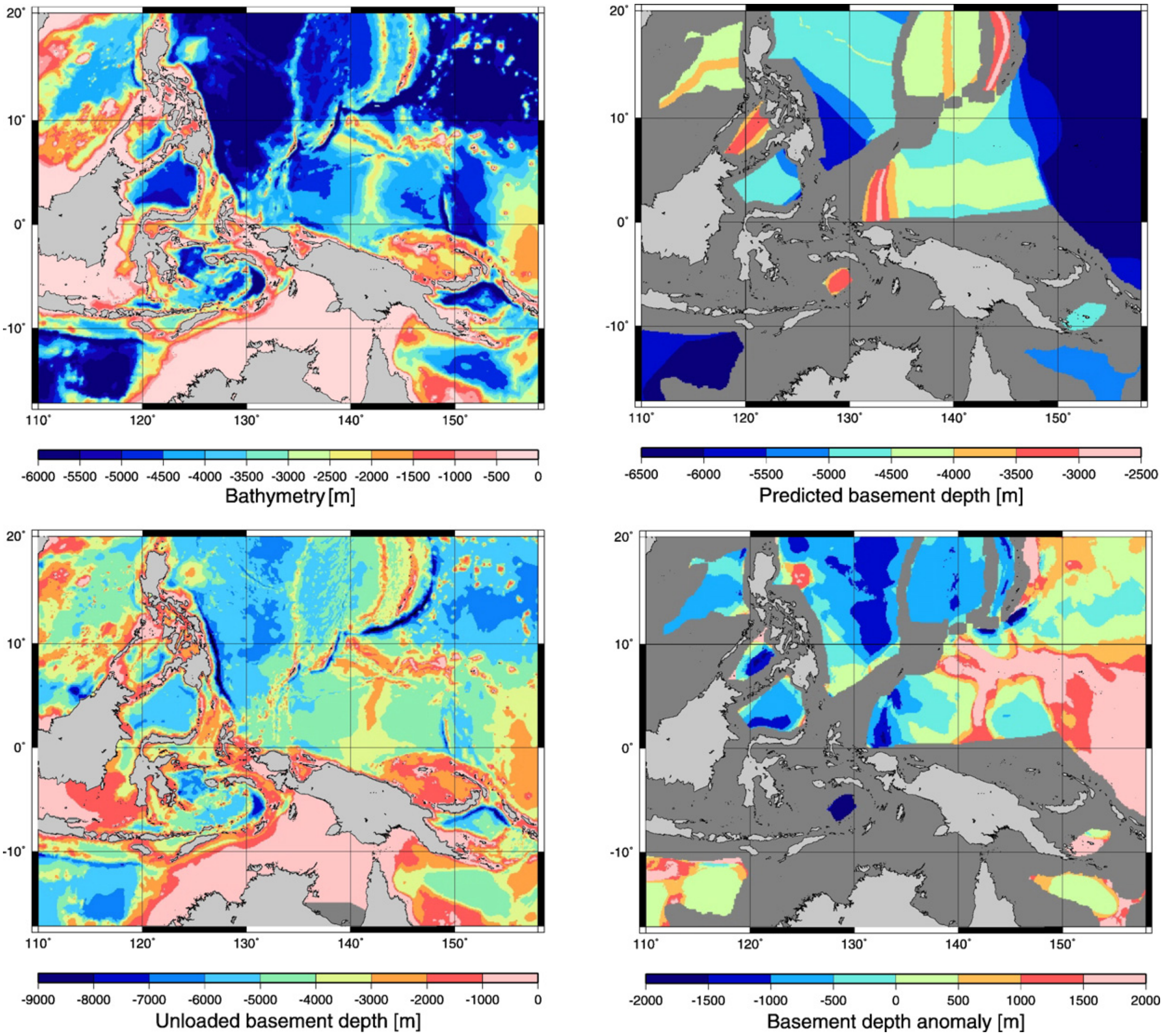


Fig. 14. Bathymetry, predicted basement depth (thermal boundary layer model age-depth conversion), corrected basement depth and residual bathymetry for the oceanic region north of Australia.

Melanesian Arc, the northwestward directed subduction gradually stopped and reversed its polarity, probably around 12 Ma (Petterson et al., 1999). The Melanesian Arc became part of the Pacific plate, and the Solomon Sea oceanic crust was subducted under the newly formed trench.

West of the Philippine Sea plate, the Celebes Sea also decreased in size, as a new subduction zone was created north of the North Sulawesi arm, probably after colliding with the northern margin of Australia (and the accretion to the southwest arm of Sulawesi). Part of the northern Celebes Sea might have also being subducted northward due to the opening of the Sulu Sea in the Middle Miocene (Shibuya et al., 1991).

4.7. Late Miocene–Present 10–0 Ma (Fig. 12i–k)

The northern margin of the northward moving Australian plate experienced extensive compressional and strike–slip regimes due to the continuing clockwise rotation of the Philippine and Caroline plate and the subduction under the westward moving Pacific plate. This resulted in the accretion of the Caroline Arc and ophiolite obduction to the northern PNG, thrust faulting in the PNG's Mobile Belt and the almost complete subduction of the Solomon Sea and Molucca Sea under the Pacific plate and the Philippine and Celebes seas respectively. Slab pull led to the opening of the Woodlark basin east of the New Guinea, which is now

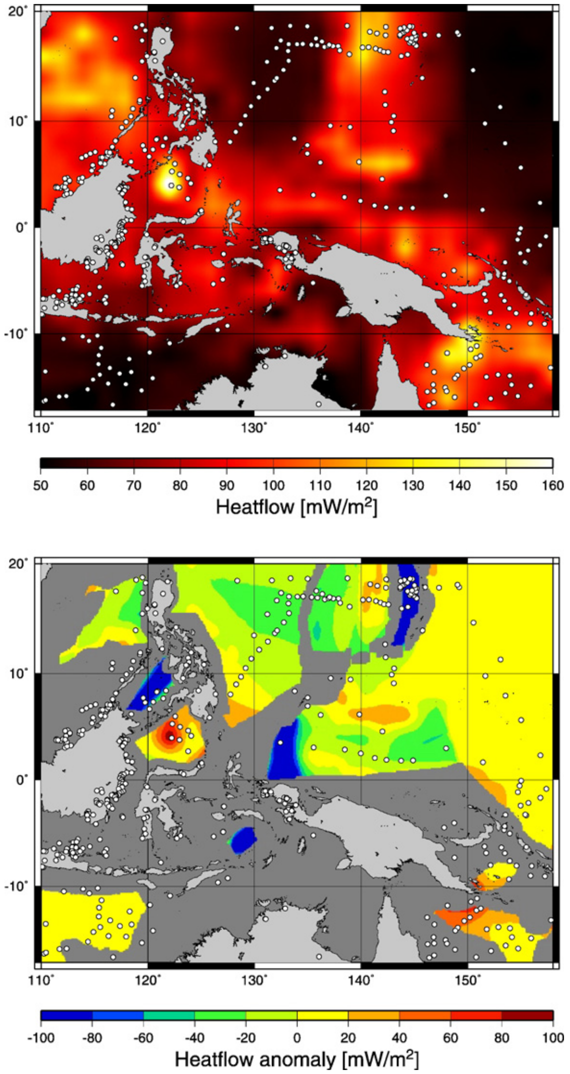


Fig. 15. Modelled (Shapiro and Ritzwoller, 2004) heatflow and predicted heatflow based on our oceanic agegrid north of Australia. White dots show the locations of heatflow data (Nyblade and Pollack, 1993).

subducting under the South Solomon Trench, and a new back-arc basin – the Bismark Sea – started to form north of the New Britain as a consequence of a newly formed trench (the Manus Trench) south of the Caroline plate (Taylor, 1979; Honza et al., 1987). Presently, only the eastern segment of the Manus Trench is active (Ryan, 1988). The westward continuation of this trench is the New Guinea Trench — that reflects a fairly recent convergence between the Caroline plate and the Australian plate, as a subducted slab has been detected via seismic tomography underneath that boundary (Tregoning and Gorbatov, 2004). A similar plate boundary formed east of the Caroline plate along the Mussau Trench — where the Caroline basin is being subducted under the Pacific plate (Hegarty and Weissel, 1988). Further north, a diffuse plate boundary (the "Disrupted Zone") probably reflects a much younger plate boundary, where the Caroline plate oceanic crust is overthrust onto the Pacific crust (Hegarty and Weissel, 1988), indicating an incipient subduction zone with reversed polarity compared to the Mussau Trench. The northwestard boundary of the Caroline plate with the Philippine and Parece Vela basins (the Palau and Yap trenches) and probably with the Mariana basin (at the Mariana Trench) display unusually deep bathymetry (7000–10,000 m) for plate boundaries with reduced subduction activity. The resistance of viscous asthenosphere against vertically subducting slabs (Kobayashi,

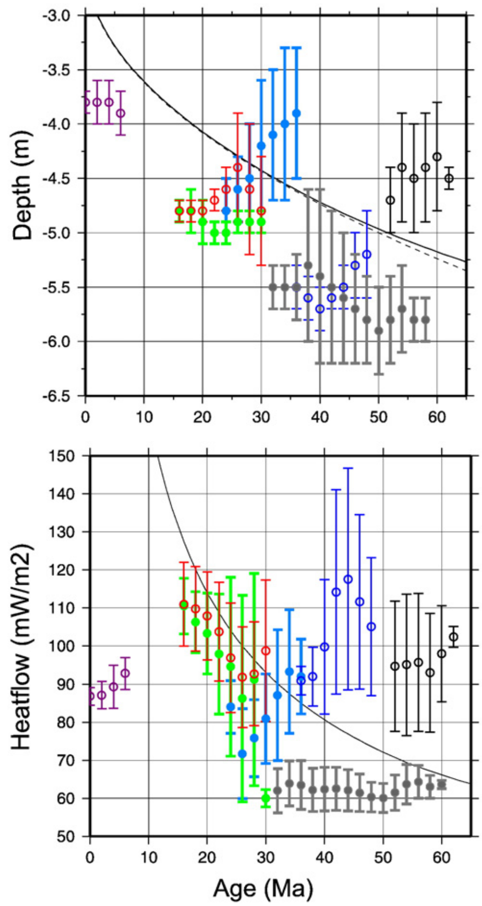


Fig. 16. Residual depth vs. age and anomalous heatflow vs. age with standard deviation error bars and a thermal boundary layer model (solid line) and plate model (dashed line) from Parsons and Sclater (1977) superimposed (colors are: Caroline — light blue (filled), Mariana — magenta, Shikoku — green (filled), Celebes — blue, Philippine — gray (filled), Coral — black, S China Sea — red).

2000) or a rapid rollback of the subducting Caroline plate (Fryer et al., 2003) has been invoked to account for these anomalous depths.

Northwestward subduction of the Australian plate along the Banda trench and southward subduction of Bird's head microplate along the Seram trench led to the opening of the North and South Banda basins between 12.5 and 3.5 Ma (Hinschberger et al., 2001). Subduction along the Timor trough decreased gradually and is considered to be almost inactive in the present day.

5. Paleobathymetry

The opening and closure of oceanic gateways, the distribution of land and sea and seafloor topography control the circulation of oceans that regulate the climatic system. The importance of "realistic" bathymetry (as opposed to a "bowl-shaped" bathymetry) as input for the global general circulation models (GCM) has been recognized by numerous authors who attempted to reconstruct paleobathymetry based on oceanic depth–age relationships. We reconstruct paleobathymetry using observed and synthetic reconstructed (now subducted) ocean floor isochrons to restore the age–area distribution of the seafloor as paleobathymetry grids. A similar approach has been used by Bice et al. (1998) who used a compilation of datasets to derive "realistic" Early Eocene paleobathymetry. Bice et al. (1998) utilized the Early Eocene paleobathymetry in ocean climate simulations and showed that the models are sensitive to bathymetry. Smoothed basin topography and changes in width and depth of ocean gateways cause a change in gyre transport, equatorial currents, and mid and low latitude meridional overturning (Bice et al., 1998). The study showed that "realistic" paleobathymetry is important in particular for local or regional ocean modelling.

Here we present a series of paleobathymetry reconstructions (Fig. 13) derived from the oceanic paleo-age grids by converting the age of the oceanic crust to depth by using a thermal boundary layer model for ocean crust younger than 20 Ma and a plate model for older ages, using depth–age relationships from Parsons and Sclater (1977). In addition, we analyse the present day residual depth and heatflow in order to assess the influence of dynamic topography on the present day bathymetry. Kuhnt et al. (2004) reviewed the tectonic–paleogeographic boundary conditions within the Indonesian gateway area since the Neogene and concluded that the deep-water exchange through the Indonesian passage was restricted since about 25 million years. They also pointed out that evidence for restricted surface water flow based on tectonic evidence only is more ambiguous and paleoceanographic proxies are needed to better assess the paleo throughflow.

Our reconstructions (Fig. 13) suggest that old deep basins situated north of Australia in the Eocene have been gradually subducted and shallower back-arc basins (Caroline and Solomon seas) floored the oceanic area since Late Eocene. A deep-water passage (around 4000 m), that connected the Indian and Pacific oceans might have existed northwest of the Caroline basin until about 25 Ma when volcanism created new waterflow obstacles like the West Caroline Ridge and the Palau Arc. The opening of the Ayu Trough, southwest of the Caroline Sea basin, placed a new a barrier (the mid-ocean ridge) between the Indian and Pacific basins. Northwest of Australia, the size of the oldest oceanic basin in the region, the Argo Abyssal Plain, is also decreasing with time, as Australia is approaching the Sundaland and finally collides around 5 Ma, closing the Indonesian gateway. Cane and Molnar (2001) proposed that the emergence of the Indonesian Archipelago, in particular the rapid uplift of Halmahera have dramatically reduced the Indonesian gateway. Past ocean circulation between the Pacific and Indian Ocean since the Miocene inferred from Nd isotopes (Gourlan et al., 2005) support the idea of rapid closure of the Indonesian seaway around 3–4 Ma.

6. Depth anomalies

The southeast Asian marginal seas are arguably the world's foremost "slab burial grounds" where a number of subduction zones have been active during the Cenozoic, inserting negatively buoyant, sinking slab material into the mantle. This material in turn exerts a time-dependent pulling force on the surface, resulting in what is termed dynamic topography. Mantle convection models predict large-amplitude dynamic topography in the southeast Asia (e.g. (Lithgow-Bertelloni and Gurnis, 1997)). However, the resolution of such models is poor both in terms of spatial resolution and their predicted amplitude. We utilize our gridded seafloor isochrons for southeast Asian marginal basins, together with an unloaded basement depth grid based on GEBCO bathymetry (IOC et al., 2003), NGDC's sediment thickness grid (http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html), and a published heatflow grid (Shapiro and Ritzwoller, 2004) to re-assess the present day depth–age and heatflow–age relationships observed in these basins, and investigate the magnitude and origin of depth and heatflow anomalies, which was last comprehensively assessed by Sclater (1972) and Sclater et al. (1976).

We compute unloaded basement depth using the relationship between sediment thickness and isostatic correction from Sykes (1996) (Fig. 14). Predicted basement depth is then computed from our oceanic age grid using a thermal boundary layer depth–age model (Parsons and Sclater, 1977). Although fairly different models have been proposed to model the thermal subsidence of oceanic lithosphere (e.g. (Stein and Stein, 1992) and more recently (Crosby et al., 2006)) we have used the Parsons and Sclater (1977) thermal boundary layer model for oceanic ages less than 20 million years and their plate model for older oceanic ages here as a reference model. The difference between predicted basement depth from the depth–age relationship and unloaded basement depth yields residual basement depth, which we mode-filter using a 200 km full filterwidth to remove small-scale residual topography such as seamounts and volcanic ridges not related to depth–age processes (Fig. 14). The mode-filtered residual basement depth anomaly grid reveals large negative depth anomalies in most basins analysed between about 650 and 800 km (see Table 7 for median depths and median absolute deviation (MAD)), with the exception of the Coral Sea which has a positive median depth anomaly of 430 m, and the Caroline Sea, which shows a large scatter of basement depth anomalies between about −500 and +500 m. Here the main conjugate abyssal plains show a negative basement depth anomaly, whereas the volcanic ridges show positive depth anomalies most likely reflecting crustal thickening.

Fig. 15 shows a heatflow anomaly grid based on the difference between heat flow predicted from a heat flow age relationship (Fowler, 2005) and modeled heat flow from Shapiro and Ritzwoller (2004), derived from a global seismic model of the crust and upper mantle that is used to guide the extrapolation of existing heat-flow measurements to regions of sparse or no heat flow data. Age-dependent depth and heat-flow anomalies in all basins analysed are highlighted in two summary plots showing mean depth and mean heatflow versus age (Fig. 16). Young ocean basins such as the Mariana Trough, the Sulu Sea and the Ayu Trough show a large negative heat flow anomaly, due to the loss of heat via hydrothermal convection in young seafloor (Phipps Morgan and Chen, 1993).

Both the Coral Sea and the Celebes Sea display a positive heat flow anomaly, whereas all other basins show a negative heatflow anomaly. The positive heatflow anomaly and positive depth anomaly in the Coral Sea is likely related to a mantle plume (based on a comparison with seismic tomography results by Montelli et al. (2004). The positive heatflow anomaly in the Celebes Sea is paired with a negative depth anomaly, likely reflecting negative dynamic topography caused by sinking slabs paired with a shallow thermal anomaly, whose origin is unclear but which could be mantle-wedge related. All other basins exhibit substantial negative dynamic topography paired with negative heatflow anomalies, reflecting the matching dynamic topography and reduced mantle heat flow effects of subducting slab material in the upper mantle. To further elucidate the origin of the observed anomalies we show a series of regional N–S shear wave mantle tomography cross sections from Ritsema (2004) (Fig. 8). The sections highlight the observation that all marginal basins that exhibit large negative dynamic topography are underlain by massive buried slab material in the lower portion of the upper mantle and/or below the transition zone, supporting the notion that the observed paired negative dynamic topography and heatflow anomalies are due to basin formation above slab burial grounds. Narrow zones of anomalous depth are associated with younger slabs, which create more localized dynamic topography effects. The coupling of the slab to the subducting plate (as opposed to detached slabs) could also play a role in the extent of dynamic topography affected area. Our results suggest the observed median negative anomalous depth of several basins is of the order of 650–800 m, with a range of 300–1100 m. These values are substantially larger than those suggested by Wheeler and White (2000) who concluded that the maximum amplitude of dynamic topography in the area is 300 m with a range of 0–500; however, their analysis was not based on regional grids of bathymetry and sediment thickness or on an up-to-date oceanic age grid of the region. The spatial resolution of published dynamic topography models is not sufficient to warrant a detailed comparison with our results, and we also have not quantified the potential effect of crustal thickness variations in the area — however this effect will largely attenuate negative dynamic topography due to excess volcanism such as in the Caroline Basin, rather than enhance it.

7. Conclusions

We present a series of reconstructions that depict the plate tectonic and age/depth evolution of the oceanic crust north of Australia since 50 Ma. This model combines revised interpretations of geophysical and geological data in the Caroline, Solomon and Celebes basins with recently developed regional plate tectonic reconstructions and a recently published moving Atlantic–Indian hotspot reference frame. Magnetic data prove the existence of two microplates in the Caroline region, separated by a leaky transform fault. A tectonic model for the complex West Caroline Basin, indicates three ridge jumps towards the north. Also, the West Caroline Ridge was confirmed to have ceased spreading before the Kilsgaard Trough in the east.

Magnetic anomalies observed in the preserved crust of the Solomon and Celebes basins suggest a Mid to Late Eocene seafloor spreading that ceased due to collisional events. More than half of these basin's oceanic floor have been subducted from Oligocene to present day. Pacific Mesozoic crust trapped north of Australia has been subducted under the Australian, Philippine and Caroline plate. Geophysical and geological observations suggest that several major tectonic events occurred north of Australia at around 45 Ma. A collision event forced the accretion of old Pacific crust to the northern Australian plate that started to subduct rapidly under Philippine Sea plate and Sundaland. Whether triggered by this collision (which is contemporaneous with the bend in the Hawaiian-Emperor chain), or by a Pacific-related event, around 45 Ma, subduction northeast and east of Australia also reversed its polarity and the Pacific plate started to be subducted under the Australian plate.

Our paleobathymetry reconstructions suggest that old deep basins situated north of Australia in the Eocene have been gradually replaced by shallower water that covered the newly formed back-arc basins (Caroline and Solomon seas) and that a deep water passage (around 4500 m), that connected the Indian and Pacific was closed in the last 20 million years due to the clockwise rotation of the Philippine and Caroline basins and the subsequent opening of new shallow basins. Our analysis of residual topography and heatflow in regional marginal basins shows that dynamic topography due to sinking slabs has likely contributed substantially to the subsidence of back-arc basins north of Australia to a larger degree than proposed by Wheeler and White (2000).

Acknowledgments

The authors wish to thank Robert Hall and the Editor for a thorough review and many constructive comments.

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