Jurassic-Paleogene spreading history of the northern Indian Ocean as a constraint on the evolution of the north Australian continental margin

Tim R. Charlton
Saint Omer Ridge, Guildford, Surrey GU1 2DD, U.K.
timrcharlton@gmail.com

ABSTRACT

The spreading history of the northern Indian Ocean is re-examined with the aim of interpreting the late Mesozoic-Paleogene evolution of the northern Australian continental margin in eastern Indonesia and Timor-Leste. The earliest seafloor spreading ('Argo phase') developed between approximately 155-131Ma (Kimmeridgian, Late Jurassic to Valanginian, Early Cretaceous). A clockwise pole of rotation relative to Australia ('Argo pole') is interpreted at 7°09'S, 133°07'E, a present-day location near the Tanimbar islands in eastern Indonesia. A second 'Gascoyne' phase of spreading, between 131-100Ma (late Early Cretaceous), had an interpreted clockwise rotation pole at 3°40'N, 125°00'E, a present-day location between the islands of Mindanao (southern Philippines) and Sulawesi (eastern Indonesia). A third 'Wharton' phase of spreading, commencing at the beginning of the Late Cretaceous (~100Ma) had a more distant pole (clockwise pole at 5°S, 171°E: Jacob et al., 2014), although more local rotations are interpreted for the Greater Sula Spur continental terrane, about a pole estimated at 9°24'S, 134°40'E, close to the earlier Argo pole.

The motions of two continental terranes are inferred from the spreading history. The Argoland Terrane, which is identified in this study as eastern Sundaland (Borneo and Java), would not have entirely detached from Australia before the mid Cretaceous due to the relatively proximal locations of the Argo and Gascoyne rotation poles. In this scenario Argoland could not have collided with Eurasia in the Cretaceous, as suggested by several previous studies. The Greater Sula Spur Terrane (several continental fragments in present-day eastern Indonesia) is repositioned in the initial reconstructions immediately north of Timor and did not move northward to its late Paleogene (pre-Neogene collision) location until the Wharton phase of rifting that commenced in the Late Cretaceous. This northward motion of the Greater Sula Spur was accommodated by the development of a narrow oceanic basin (the Banda Embayment).

The reconstructions suggest that the Argoland and Greater Sula Spur continental terranes formed a continuous crustal connection between SE Asia and northern Australia throughout the late Mesozoic and early Paleogene, and that the Indian Ocean

developed entirely within the body of the disrupting Gondwanaland supercontinent, rather than linking eastwards into the Pacific Ocean.

Keywords: *Northern Indian Ocean, Northern Australia, Jurassic, Paleogene*

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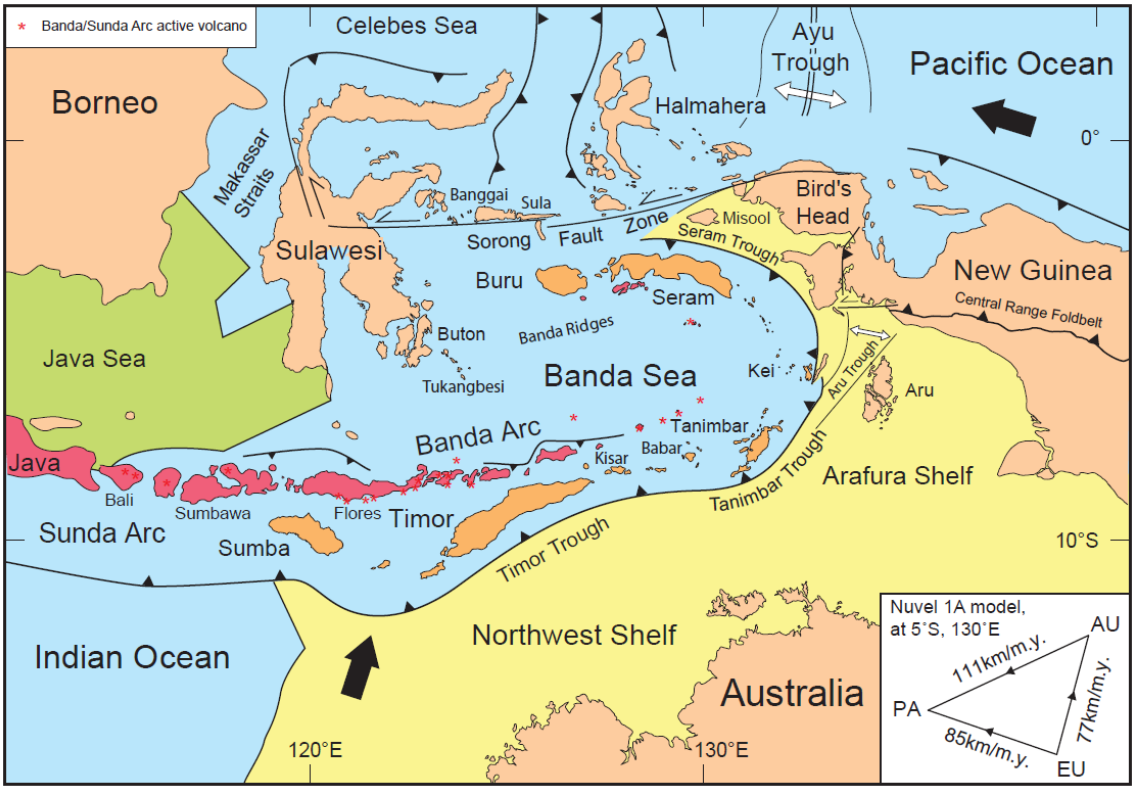


Figure 1: *Tectonic setting and island location map for present-day eastern Indonesia. The present Banda-Sunda volcanic arc is shown in red (with active volcanoes marked by red asterisks); the collisional forearc complex in orange brown. Offshore Australian shelf areas are shown in yellow, the offshore Sunda Shelf in green.*

INTRODUCTION

The Banda Arc in eastern Indonesia and Timor-Leste extends from Sumba Island in the west to the western margins of New Guinea in the east (Figure 1). This region is the Neogene zone of collision between the northwest continental margin of Australia and broadly 'Asian' structural elements to the north. The northwest Australian margin is widely interpreted as having an essentially passive continental margin structure prior to collision, while the Asian continental margin was bordered by subducting arcs including forerunners of the present-day Sunda Arc in western Indonesia. The pre-collisional Banda Arc is considered to be a direct eastward continuation of the older Sunda Arc subduction system. The present western continental margin of Australia was formed during phases of oceanic rifting in the developing Indian Ocean, which has a spreading history extending back to the Late Jurassic (Figure 2). Related phases of late Mesozoic and younger rifting have been speculatively invoked in previous publications for the

Banda sector of the Australian margin prior to collision, although interpretations differ considerably in the ages of rifting and the rifted margin geometry (e.g., Veevers & Heirtzler, 1974; Audley-Charles, 1988; Audley-Charles et al., 1988; Metcalfe, 1996; Charlton, 2001; 2012; Hall, 2012). The present study attempts a more systematic interpretation for the rift history of the north-western Australian margin by extrapolation from the known spreading history of the northern Indian Ocean (Figure 2) and taking into account the Late Jurassic to Paleogene geological record of eastern Indonesia.

In the present study a series of palaeo-plate reconstructions are presented (Figures 8-14) which suggest possible Late Jurassic to Paleogene oceanic spreading patterns in the region north and east of the present Indian Ocean (Figure 2). The reconstructions also suggest partial motion histories for two specific continental fragments: the Argoland Terrane and the Greater Sula Spur. The Argoland Terrane, which occupied the position of the present Argo oceanic embayment in the NE Indian Ocean prior to Late Jurassic rifting is a somewhat hypothetical body whose identity has been variously attributed to several present-day

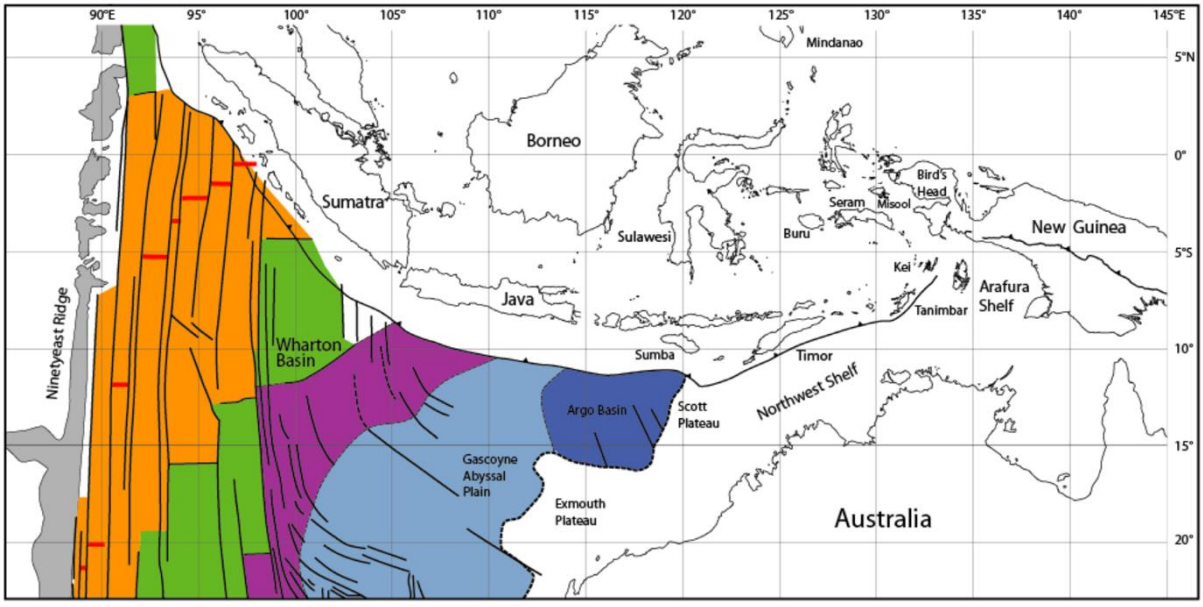


Figure 2: *Simplified spreading map of the northeast Indian Ocean. Oceanic spreading ages broadly decrease from southeast to northwest: dark blue = Argo spreading (of this study) ~155-131Ma (~Kimmeridgian-Valanginian); light blue = Gascoyne spreading 131-100Ma (~Hauterivian-Albian); purple, green and orange = Wharton spreading subdivided into age bands: purple = 100-83Ma (~Cenomanian-Santonian, Cretaceous magnetic quiet zone); green = 83-66Ma (~Campanian-Maastrichtian); orange = 66-43Ma (Paleocene-mid Eocene). Ages in the Wharton Basin follow Jacob et al. (2014, their figure 2).*

continental fragments (see later discussion), but in this study is equated with present-day eastern Sundaland (i.e. eastern Java and southern Borneo, together with intervening shelf seas; an interpretation in line with Metcalfe, 2011 and Hall, 2012). The Greater Sula Spur is an interpreted pre-collisional (pre-Neogene) amalgamation of various continental fragments now located in eastern Indonesia including the Bird's Head-Misool structural block, Banggai-Sula, eastern and south-eastern Sulawesi, Seram-Buru, and the Banda Ridges continental fragment (e.g., Charlton, 2016; see later discussion).

The spreading history of the Indian Ocean is now fairly well established (Fullerton et al., 1989; Royer & Sandwell, 1989; Heine & Muller, 2005; Gibbons et al., 2012; Krishna et al., 2012; Jacob et al., 2014; and many others), but most published studies have focused on the implications for the evolution of the western Indian Ocean, particularly the evolution of the Australia-India plate boundary. Relatively little detailed consideration has yet been given to the implications of the spreading history for the evolution of the north-western continental margin of Australia, and the present study aims to address this subject.

OCEANIC SPREADING IN THE NE INDIAN OCEAN (ARGO SPREADING PHASE)

The Argo Abyssal Plain is located in the NE Indian Ocean, in the angle between the western continental margin of Australia and the east-west trending Sunda-Banda subduction front (Figure 2). The Argo Basin is the location of the oldest known oceanic crust in the Indian Ocean. The physical morphology of this area is described as an almost featureless expanse of ocean floor under water depths of about 5700m (Gibbons et al., 2012). Seafloor spreading patterns are inferred primarily from correlation of magnetic profiles (additionally constrained by deep ocean drilling at sites DSDP261 and ODP765), with offsetting transform faults not having clear bathymetric or other geophysical expression.

In the Argo Basin, Fullerton et al. (1989) interpreted the oldest identified magnetic anomaly as M26 at the southern margin of the Argo Plain, with sequential younging to anomaly M16 immediately south of the Sunda subduction front (Figure 3a). Heine & Muller (2005) recognised essentially the same anomaly pattern for anomalies M26-M22A but interpreted the more northerly anomalies as M13-M10N, with anomalies M21-M14 absent as a result of an interpreted southward jump of the

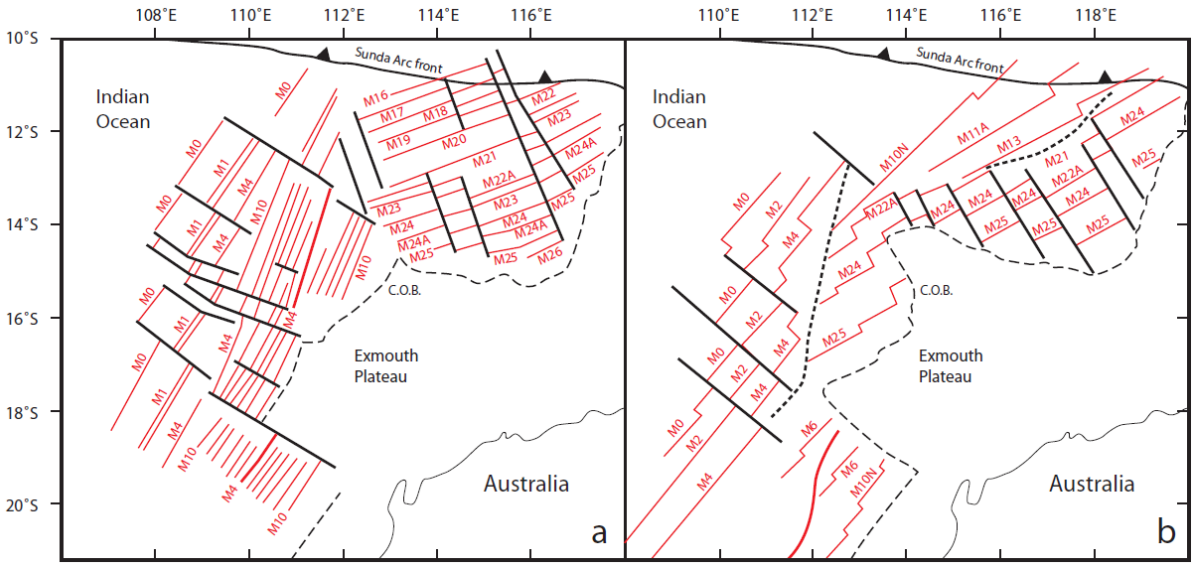


Figure 3: *Argo Basin spreading anomalies as interpreted by (a) Fullerton et al. (1989); and (b) Heine & Muller (2005). After Gibbons et al. (2012, their figure 2). Thin red lines: spreading anomalies. Thicker red lines fossil spreading ridges. Thick black lines: transform faults. C.O.B. (thin dashed lines): continent-ocean boundary. Thicker dashed lines: anomaly gaps resulting from ridge jumps.*

spreading centre at about M13 time (Figure 3b). While the anomaly identification is essentially the same in these two interpretations for the M26-M22 spreading phase, the orientation of the anomalies is slightly different. In the central Argo Basin Fullerton et al. (1989) indicated an anomaly trend of approximately 070°, while Heine & Muller, (2005) interpreted an orientation of 060° (Figure 3). A further significant difference between the two interpretations is that Heine & Muller (2005) extended the Jurassic spreading of the Argo Abyssal Plain to the west of the NW corner of the Exmouth continental plateau (Figure 3b), whereas Fullerton et al. (1989; Figure 3a) attributed anomalies in this western region to younger, Cretaceous spreading.

Gibbons et al. (2012) re-examined the Argo magnetic anomaly patterns. Although they did not provide a detailed mapping of anomalies and transforms as in Figure 3, their anomaly picks correlated between individual ship tracks appear to be closer in orientation to the mapping of Fullerton et al. (1989), although also recognising the gap in ages between anomalies M22A and M13 interpreted by Heine & Muller (2005). Furthermore, Gibbons et al. (2012) did not recognise the extension of Jurassic spreading west of the NW Exmouth Plateau as suggested by Heine & Muller (2005) but preferred an interpretation

similar to the Cretaceous (M10 and younger) spreading interpreted by Fullerton et al. (1989).

LATE JURASSIC-EARLIEST CRETACEOUS (KIMMERIDGIAN-MID VALANGINIAN) SPREADING.

The age of Jurassic-Cretaceous M-series magnetic anomalies (Figure 3) is imperfectly tied to geochronological time and to the chronostratigraphic scale due to both the difficulty in precisely dating the anomalies, and uncertainty in tying absolute ages to geological stages. The main studies of the Argo anomalies outlined above used different timescales current at the time of publication. Fullerton et al. (1989) employed the Harland et al. (1982) timescale; Heine & Muller (2005) the Gradstein et al. (1994) timescale; and Gibbons et al. (2012) a combined Gradstein et al. (1994) and Cande & Kent (1995) timescale. The present study uses the latest version of International Commission on Stratigraphy timescale (ISC 2022, version 10: Cohen et al., 2013 updated) and the geomagnetic polarity timescale of Ogg (2020).

Based on these timescales, oceanic spreading in the Argo Basin probably commenced close to the Oxfordian-Kimmeridgian boundary at about 155Ma (anomaly M26 ~154.2-154.8Ma: Ogg, 2020), with the first phase of spreading continuing until near the Kimmeridgian-Tithonian boundary at about 149Ma (anomaly M22A in the interpretation of Heine & Muller, 2005). In the central Argo Basin, the M26 and M22A anomalies are separated by 180km (profile a9314c: Gibbons et al., 2012), suggesting a half-spreading rate of 30km/m.y. if the time interval between the two anomalies is 6m.y.

In order to interpret the regional implications of this spreading, it is also necessary to estimate the location of the rotation pole to the spreading. Spreading ridges approximate to segments of great circles passing through the rotation pole, while transform faults approximate to segments of small circles around the pole. Unfortunately, in the case of the Argo Basin, transforms are not clearly expressed on the ocean floor (Gibbons et al., 2012), while ridge segments are typically close to parallel, so that intersections of projected great circles have relatively large uncertainties.

For the Heine & Muller (2005) Argo anomaly interpretation, Heine (2002) estimated a clockwise rotation pole located at 12°N, 155°E for the earliest spreading interval, a distant pole located in the west-

central Pacific. Fullerton et al. (1989) did not estimate a location for the pole associated with their Argo magnetic lineaments, but from the intersections of great circles through several ridge segments a pole is here estimated at 7°09'S, 133°07'E (Figure 4a), a present-day location between the Tanimbar and Aru Island groups in eastern Indonesia. This is in the same general area "just NE of Timor" as earlier estimated for the Argo pole by Falvey (1972), and as assumed by Veevers & Heirtzler (1974; also, Pigram & Panggabean, 1981, their figure 6). Although the Cretaceous age of anomalies interpreted by Falvey was subsequently established to be wrong, the geometry of the spreading should nevertheless accurately define the pole of rotation.

Figure 4b shows great circles through anomalies defined on the Argo ship track profiles of Gibbons et al. (2012). These great circle paths mostly intersect close to the pole estimated above for the Fullerton et al. (1989) anomaly mapping. The one anomalous great circle that does not intersect the others near to the Fullerton et al. pole is defined from only two ship tracks on the Gibbons et al. profiles; the other three great circles are best fits between anomalies defined on three or four ship tracks. Because of the good agreement between the rotation poles defined by the Fullerton et al. (1989) mapping and the ship track picks of Gibbons et al. (2012), the pole near the Tanimbar islands is preferred here over the more distant pole suggested by Heine (2002). The pole near Tanimbar is hereafter referred to as the Argo rotation pole.

The angle subtended between the intersections of anomalies M26 and M22A on profile a9314c (Gibbons et al., 2012) and the Argo rotation pole is 5.2°. If these anomalies are separated in time by 6m.y. (as discussed above), then the rate of rotation about the poles (full spreading) is approximately 1.7°/m.y. If this spreading continued between 155-136Ma (anomalies M26-M13 as discussed above; to the mid-Valanginian on the Ogg (2020) timescale), then the full spreading rate would open an oceanic rift 32° wide measured around the Argo pole.

NEOCOMIAN (MID VALANGINIAN-HAUTERIVIAN) SPREADING.

Heine & Muller (2005) mapped three Neocomian spreading anomalies in the Argo Basin (M13, M11A, M10N) for which Heine (2002) interpreted two distinct spreading events about clockwise rotation poles at 37.5°N, 168°E (M13-M11A) and 20°N, 148°E (M11A-M10). Gibbons et al.

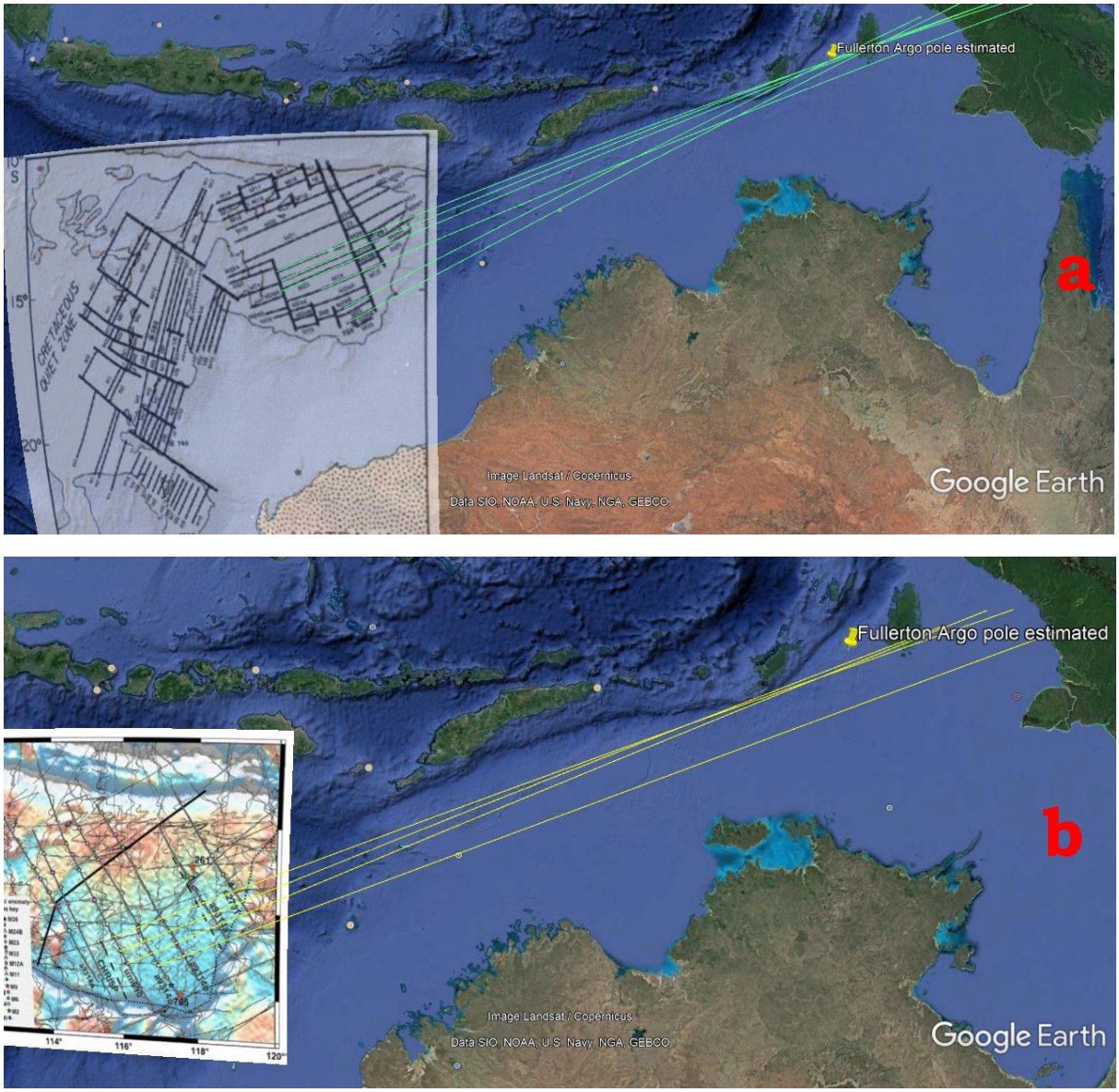


Figure 4: *(a) Argo Basin anomaly map of Fullerton et al. (1989) overlain on Google Earth, also showing selected ridge segments extrapolated as great circles (green lines), and the Argo spreading pole (7°09'S, 133°11'E) estimated here from the intersections of the great circles. (b) Selected best-fit great circles (yellow lines) through the Gibbons et al. (2012, their figure 3a) Argo anomaly picks along ship tracks. The great circles mostly intersect close to the Argo pole estimated from the Fullerton et al. (1989) anomaly mapping.*

(2012) identified three Neocomian anomalies (M12A, M11A, M11) on five ship profiles. There is, however, insufficient clear lateral continuity between ship track anomaly identifications to correlate anomalies between adjacent ship tracks without the possibility of intervening transform offsets. Distances between the younger two anomalies (M12A and M11) on the five profiles are (from west to east) 84km, 106km, 81km, 102km and 110km. There is no simple pattern of increasing

lateral separation, so it is not possible to define a rotation pole based on spreading rates. Nevertheless, a comparison of the anomaly identifications of Gibbons et al. (2012) with spreading about the Argo pole defined by the earlier spreading does show that several anomaly pairs line up fairly well along great circle paths through the Argo pole defined above, and on this basis the M13-M10N spreading interval is provisionally interpreted as a continuance of spreading around the Argo pole.

Heine & Muller (2005) interpreted the Neocomian spreading phase as ending between anomalies M10N and M10, dated

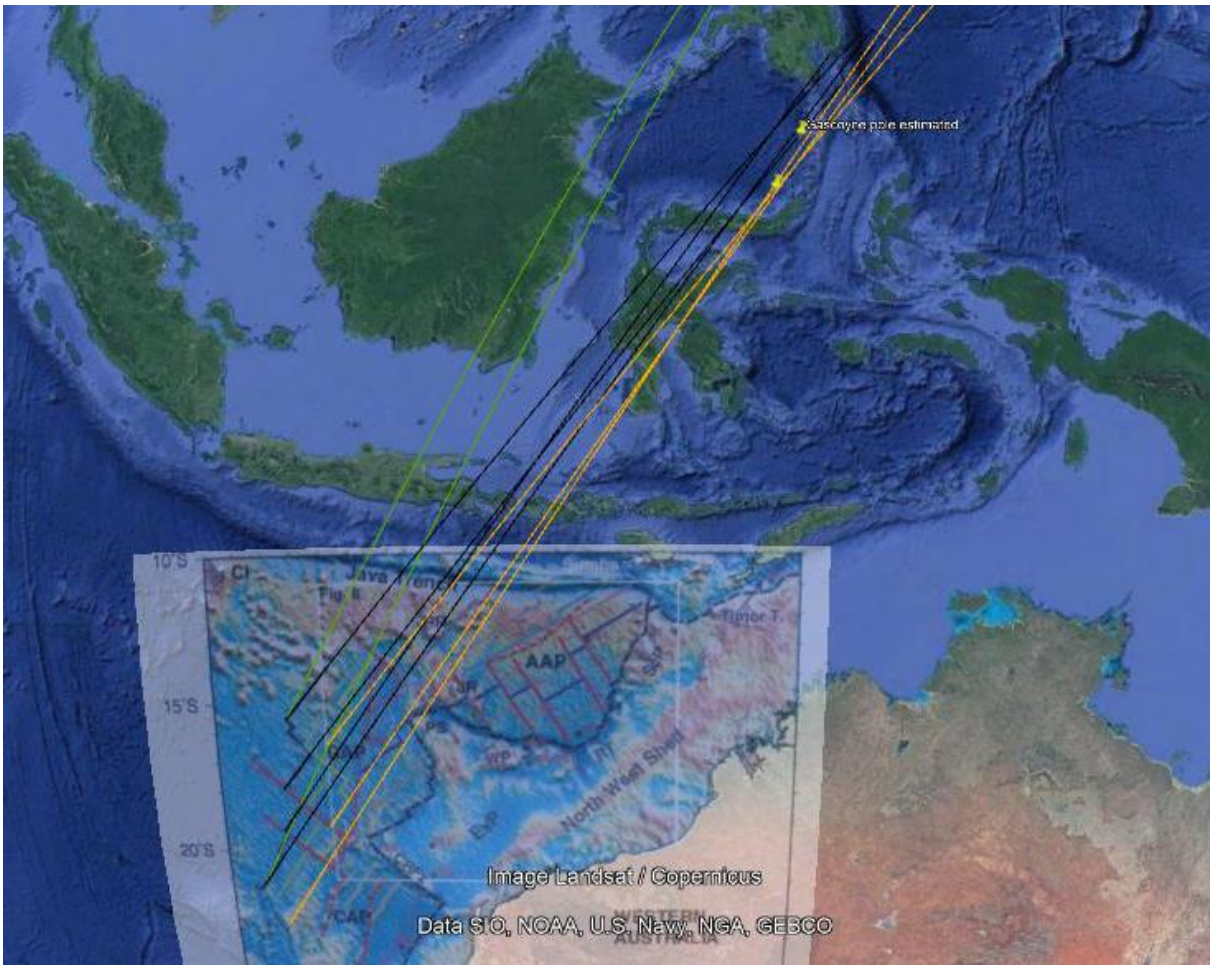


Figure 5: *Great circle extrapolation for ridge segments in the Gascoyne Abyssal Plain (Heine & Muller, 2005, figure 6). Black = anomaly M0; orange = anomaly M4. The three M4 anomaly great circles intersect fairly tightly near to the NE tip of Sulawesi Island, while the M0 anomalies primarily intersect slightly further to the north. An overall rotation pole for Gascoyne Basin spreading is generalised at a present-day location midway between NE Sulawesi and southern Mindanao islands (3°40'N, 125°00'E). Note that great circles through the spreading pole proposed by Heine (2002) (green lines though pole at 30°N, 135°E) do not match well with the M0 spreading segments.*

to about 131Ma on the Ogg (2020) magnetic polarity timescale, within the late Valanginian. Based on an assumption of continued opening of the oceanic basin by rotation about the Argo pole, this would result in an oceanic basin approximately 41° wide by the end of the Valanginian. This later phase of spreading is, however, less-well constrained than the Jurassic spreading.

LATE EARLY CRETACEOUS SPREADING (GASCOYNE SPREADING)

A major adjustment of spreading ridges in the Indian Ocean occurred between anomalies M10N and M10 (Heine & Muller, 2005; Gibbons et al., 2012), dated at approximately 131Ma (late Valanginian) on the Ogg (2020) magnetic polarity timescale. This new spreading phase was oriented WNW-ESE, with magnetic anomalies trending ENE-WSW. Spreading continued in an essentially similar orientation from anomaly M10 to anomaly M0, and then into the mid-Cretaceous Magnetic Quiet Zone. The next regional re-orientation of spreading directions may have occurred at about 100Ma, as part of a global re-ordering of plate boundaries (e.g., Matthews et al., 2012).

Figure 5 shows the anomaly mapping of Heine & Muller (2005) overlain on Google Earth, with great circle extrapolations of the M4 (orange) and M0 (black) magnetic anomalies in the Gascoyne Basin and the Perth Basin to the south. The three extrapolated M4 anomaly great circle segments intersect rather tightly near 1°46'N, 124°8'E – a present-day location near the NE tip of Sulawesi Island. The four extrapolated M0 anomaly sections pass close to, but slightly to the north and west of, this pole, with a less well-defined intersection nearer to present-day southern Mindanao Island. An intermediate location at 3°40'N, 125°00'E is taken here as an approximation for an overall late Early Cretaceous Gascoyne spreading pole. This Gascoyne pole, defined on the Heine & Muller (2005) anomaly mapping, also appears consistent with the anomaly mapping of Gibbons et al. (2012). Figure 6 shows very close agreement between great circle segments radiating from the proposed Gascoyne pole and a fossil spreading centre preserved in the Perth Abyssal Plain, dated by these authors as becoming extinct at 108Ma (mid-Albian), within the Magnetic Quiet Zone.

In the NE corner of the Perth Abyssal Plain, in the area of ship track inm06 (Gibbons et al., 2012, their figure 3c), the

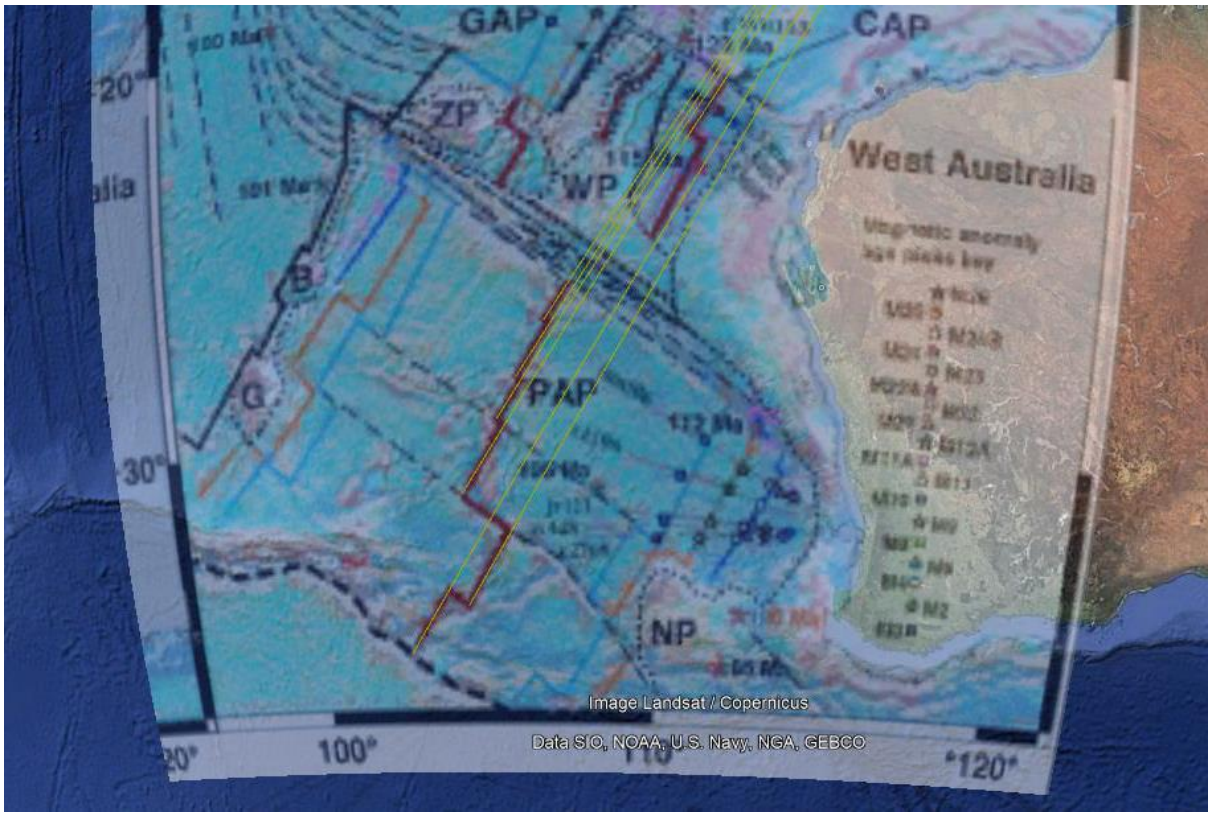


Figure 6: *Great circles (yellow) through the Gascoyne pole (3°40'N, 125°00'E; Figure 5) showing good agreement with fossil ridge segments in the Perth Abyssal Plain (PAP: Gibbons et al. (2012). These authors interpreted the spreading ridge as becoming extinct at 108Ma (mid Albian).*

M4 and M0 anomalies are separated by 215km, and by 3.3° around the Gascoyne pole. In the Ogg (2020) magnetic polarity timescale, anomaly M4 (=M5n) is dated at 127.5Ma and M0 at 121.4Ma, suggesting a full spreading rate of 70km/m.y. along that profile, corresponding to a rotation of 0.54°/m.y. around the Gascoyne pole. If this spreading phase continued between 131-100Ma, then approximately 17° of clockwise rotation would have occurred around the Gascoyne pole during this time.

LATE CRETACEOUS-PALEOGENE SPREADING (WHARTON SPREADING)

The mid-Cretaceous change in spreading directions in the Indian Ocean is not so clearly constrained by direct observation of magnetic anomalies because the change occurred during the Cretaceous Magnetic Quiet Zone. There was, however, a globally recognised re-organisation of plate boundaries at about 100Ma (Matthews et al., 2012), and this date is assumed for the boundary between the Gascoyne and Wharton spreading phases. Spreading in

the Wharton phase ceased at, or immediately after, anomaly C18 (~40Ma, Middle Eocene on the Ogg (2020) magnetic polarity timescale) or slightly later (as young as 35Ma, ~mid Late Eocene: Jacob et al., 2014). A Middle Eocene fossil spreading ridge is preserved in the NW Wharton Basin (Figure 2), extending from the Sunda Trench at the equator west of Sumatra to the Ninetyeast Ridge in a series of left-lateral offset ridge segments (Liu et al., 1983; Krishna et al., 2012; Jacob et al., 2014).

Jacob et al. (2014, their figure 4) determined a pole of rotation at approximately 5°N, 9°W, which was apparently stable through much of the Wharton spreading interval (anomalies C34-C18, ~Santonian-Middle Eocene). This pole, defining anticlockwise rotation of India relative to Australia, is equivalent to a clockwise rotation about a pole at 5°S, 171°E, located in the western Pacific to the east of Papua New Guinea. Krishna et al. (2012) estimated half-spreading rates of 48-58km/m.y. in the area immediately east of the Ninetyeast Ridge. A full spreading rate of ~100km/m.y. in the western Wharton Basin would equate to an angular spreading rate of ~0.65°/m.y. about the pole defined by Jacob et al. (2014).

The fossil spreading centre in the NW Wharton Basin is clearly tracking toward the eastern Indonesia/northern Australia region where it disappears under the Sunda Arc subduction front (Figure 2). Most paleo-reconstructions extending the Wharton spreading eastward take the spreading centre to the north of the Australian continent (e.g., Audley-Charles et al., 1988; Metcalfe, 1996). An alternative, as discussed further below, is that this spreading centre tracked directly towards its rotation pole east of New Guinea, entering the Banda region of eastern Indonesia (*cf.* earlier reconstructions by e.g., Veevers & Heirtzler, 1974; Pigram & Panggabean, 1981).

JURASSIC TO MIDDLE EOCENE EVOLUTION OF THE NORTHERN AUSTRALIAN RIFTED MARGIN

Figures 8-14 show schematic reconstructions of the northern Australian continental margin from the Middle/Late Jurassic through to the Middle Eocene. In addition to interpreted oceanic rifting in the northeast-ward extension of the Indian Ocean, the reconstructions also suggest movement histories for two continental fragments: the Greater Sula Spur and the Argoland Terrane. The



Figure 7: *(Left) Late Jurassic Kola Shale, Bula Besar River, NE Seram. (Right) Late Jurassic Tchinver Shale, Tchinver river, SE Timor-Leste. Seram photo courtesy of Dr. Sugeng Surjono (Universitas Gadjah Mada) and Kim Morrison (Lion Energy).*

following two sub-sections briefly outline these two continental fragments.

The Greater Sula Spur: restoration and positioning against the northern Australian margin

The Greater Sula Spur is an amalgamation of continental fragments now located in eastern Indonesia that is interpreted to have acted as a coherent continental fragment before disruption in the Neogene Asia-Australia collision. The reconstruction of the Greater Sula Spur in the present study was derived by re-aggregating the various continental fragments through an interpretation of the sequential disaggregation during development of the Neogene collision complex of eastern Indonesia (Charlton, 2016, figure 5). The core of this amalgamated terrane is the Bird's Head region of western New Guinea island, together with the offshore Berau Shelf that extends west to Misool Island, shown in light green on the reconstructions (see Figure 1 for island locations). To the southwest of the present-day Bird's Head are the islands of Seram and Buru, located in the present northern Banda Arc (light orange-brown in the reconstructions). These islands and the offshore region to the north have undergone a degree of fold and thrust belt structural shortening in the Neogene Banda Arc orogeny, but any shortening between Seram-Buru and Bird's Head-Misool is probably minor at the level of continental basement, and probably requires little or no compensatory shortening at the scale of the present reconstructions. To the north of the Bird's Head, left-lateral displacements on the Sorong Fault are

restored by placing the Neogene Tomori Basin in eastern Sulawesi immediately north of the Sorong Basin in the Bird's Head (Charlton, 1996), with the restored continental fragment (blue areas in the reconstructions) including the Sula and Banggai islands and the east arm of Sulawesi. The darker green body on the western margin of the reconstructed block consists of the southeastern arm of Sulawesi together with the offshore islands of Buton and the Tukangbesi group, while the area shown in yellow corresponds to the 'Banda Ridges' continental fragment of the present north-central Banda Sea (e.g., Villeneuve et al., 1994).

In the present-day Banda Arc region including Timor, the Tanimbar islands, Seram and Buru (Figure 1), two major phases of continental rifting have been recognised prior to the Late Jurassic Indian Ocean rifting (Charlton, 2001; 2012). The first rifting phase commenced during the latest Carboniferous/Early Permian, waning into the later Permian and Early/Middle Triassic, while the second commenced in the Carnian (early Late Triassic), and waned into the Early/Middle Jurassic. The present writer previously suggested that these rifting phases resulted in the development of a large continental basement terrane between the present northern and southern Banda Arcs, named as the Banda Embayment Terrane (Charlton, 2001, 2012; Charlton et al., 2002, 2009; see also Hall, 2012). The interpretation of a distinct Banda Embayment Terrane continental fragment is abandoned in the present reconstructions.

Instead, the northern Banda Arc islands of Seram and Buru are relocated immediately north of the southern Banda Arc in the present reconstructions, as shown in Figure 8. This placement of the southern margin of the Greater Sula Spur immediately north of Timor island is consistent with remarkably strong geological similarities between Timor, Seram and Buru (e.g. Audley-Charles et al., 1979), particularly during the Triassic-Jurassic and up until at least the Late Jurassic, with the Tchinver Formation in Timor-Leste (Charlton & Gandara, 2014) appearing remarkably similar to the Kola Shale of Seram in terms of both age (Kemp & Mogg, 1992) and lithology (Figure 7). Several studies of zircons from the Triassic clastic successions in Timor (Zobell, 2007; Ely, 2009; Sevastjanova et al., 2012; Zimmermann & Hall, 2014, 2016; Boger et al., 2017) suggest that sedimentary sourcing in the clastic Triassic successions of Timor was at least in part from the direction of the Bird's Head to the

(present day) northeast, rather than the more widely interpreted southern (Northwest Shelf) sedimentary provenance (*cf*. Charlton, 2002, figure 8). However, Triassic clastic successions in Timor (Babulu Formation/Group) are petrographically immature, and the long travel paths for sediments derived from the Bird's Head across the previously interpreted intervening Banda Embayment Terrane was problematic to the interpretation of a Bird's Head source for Timor Triassic sediments. Removing the necessity for a Banda Embayment Terrane through the reconstruction suggested in Figure 8 allows a northern (Bird's Head) source for part of the Babulu Triassic clastic successions in Timor, while at the same time allowing the sediments to be relatively proximal to source, accounting for their immature sedimentary petrography.

Identity of Argoland

The Argoland continental fragment (Veevers et al., 1991) is the name widely applied to the landmass that occupied the position of the Argo oceanic basin in the NE Indian Ocean prior to Late Jurassic oceanic rifting. The present-day identity of Argoland is uncertain, having been variously interpreted as South Tibet (Audley-Charles et al., 1988), West Burma (Metcalfe, 1990, 1996; Longley et al., 2002; Heine & Muller, 2005; Gibbons et al., 2011), the Kolonodale Block of SE Sulawesi (Villeneuve et al., 2010), East Java-West Sulawesi (Hall et al., 2009; Hall, 2012) and South West Borneo (Metcalfe, 2011). As indicated in Figure 8, the present study identifies the Argoland Terrane with eastern Sundaland (Borneo and Java islands, and the intervening shelf sea including the East Java Terrane of Granath et al., 2010, which is shown in light purple on the reconstructions). This interpretation is in broad agreement with Hall's identification of the Argoland Terrane as East Java-West Sulawesi, and Metcalfe's as Southwest Borneo.

JURASSIC-PALEOGENE EVOLUTION OF OCEANIC RIFT SYSTEMS NORTH OF AUSTRALIA

Figures 8-14 show a series of palaeotectonic reconstructions for the northern margin of the Australian continent based on an extrapolation of the various Jurassic-Paleogene rifting-spreading phases in the NE Indian Ocean summarised above. Immediately before the commencement of oceanic rifting in the Late Jurassic, the Argoland (present-day eastern Sundaland) and Greater Sula Spur continental fragments are restored

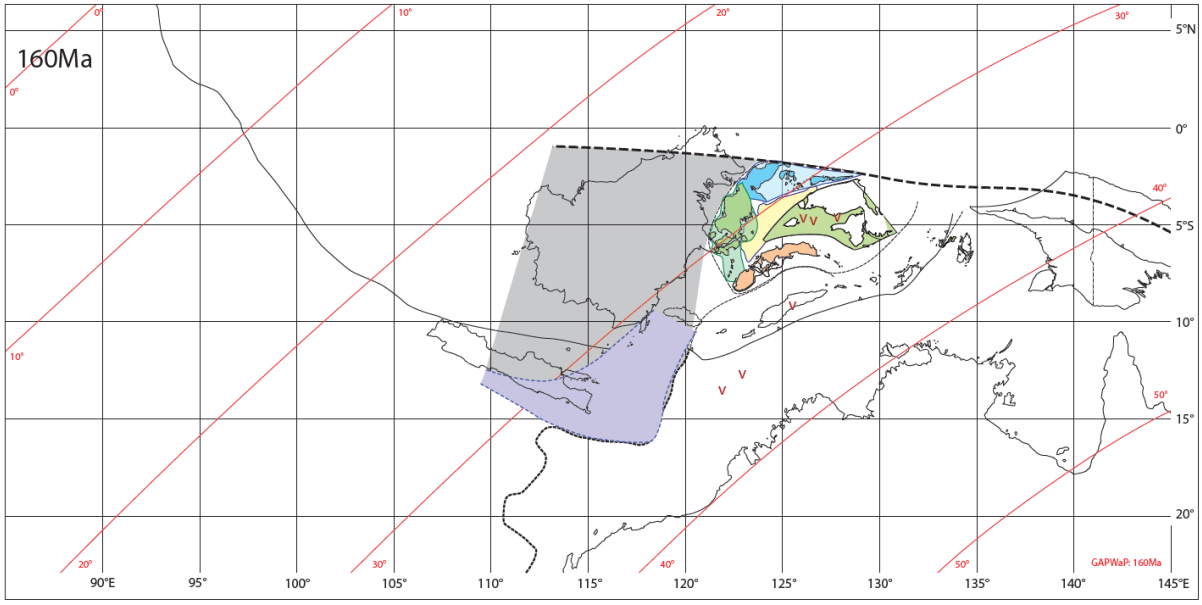


Figure 8: *Plate reconstruction of the northern Australian continental margin and associated continental terranes immediately before the commencement of Indian Ocean rifting in the Late Jurassic. The rectangular grid of latitudes and longitudes in black are for the present-day relative to the Australian continent. The small-circle lines in red are palaeolatitudes relative to the Australian continent based on the 160Ma (early Late Jurassic) palaeopole of Torsvik et al. (2012). The Greater Sula Spur block (continental fragments now located in eastern Indonesia) is reconstructed immediately north of the southern Banda forearc islands including Timor and Tanimbar. The Argoland continental terrane is shown in grey, identified as present-day eastern Sundaland (Borneo and Java) and including the East Java Terrane of Granath et al. (2010) shown in light purple. The speculative northern margin of the Australian continent prior to Indian Ocean rifting is indicated by the heavy dashed line. Early Middle Jurassic volcanism is marked by the red 'v' symbols.*

against the northern edge of the current Australian margin as shown in Figure 8. It is presumed that eastern Sundaland would have connected westward into western Sundaland (Sumatra and the Malay peninsula) as it does today, but these are not relocated in the reconstructions.

Oceanic spreading in the NE Indian Ocean commenced in the latest Oxfordian or earliest Kimmeridgian, at about 155Ma. As already discussed above, the geometry of the Late Jurassic spreading appears best satisfied by clockwise rotation about a pole located at 7°09'S, 133°11'E (present-day coordinates relative to Australia), at a present-day location between the Tanimbar and Aru islands in eastern Indonesia (the Argo pole in blue: Figure 9). Between the Oxfordian-Kimmeridgian commencement of spreading and a possible minor adjustment of spreading geometry in the mid-Valanginian, an oceanic basin estimated some 32° wide (measured

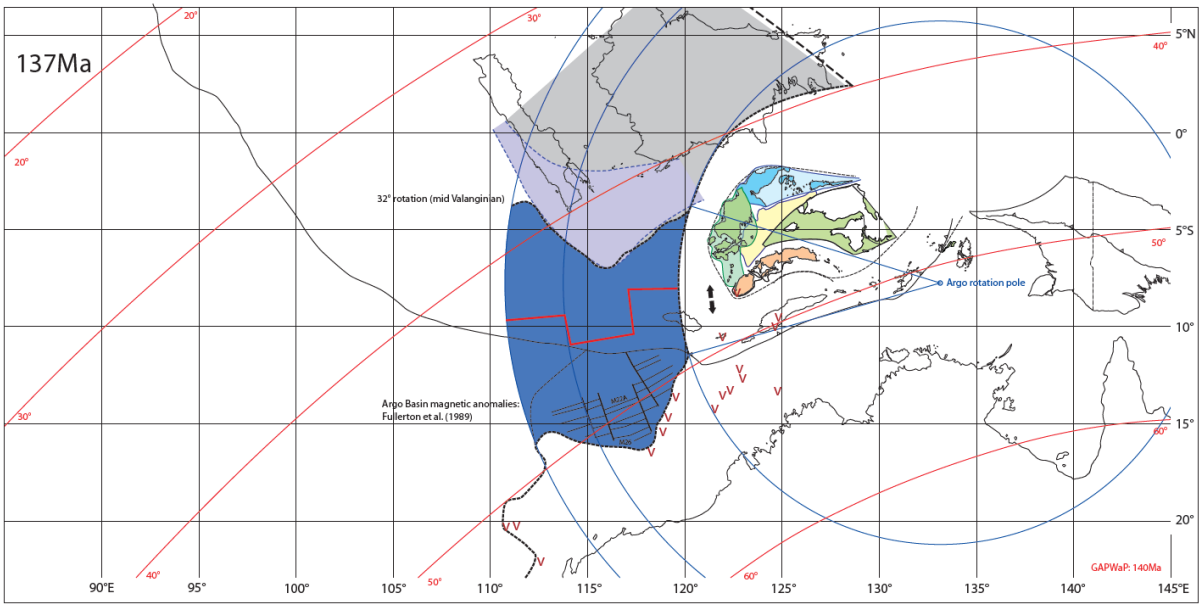


Figure 9: *Mid-Valanginian (Early Cretaceous) reconstruction extrapolating known spreading in the Argo Basin (Fullerton et al., 1989; Heine & Muller, 2005; Gibbons et al., 2012) by plate rotation about the Argo pole (in blue, see text). The Argoland continental terrane is rotated 32° clockwise relative to Australia about the Argo pole as a result of oceanic spreading. Note that small circles around the pole (blue lines) are drawn as simple circles about the pole in these 'flat earth' cartoon constructions, and this will introduce some error into the reconstructions. However, because the reconstructions are in equatorial latitudes (present-day reference frame) and because the small circles are relatively close to the pole, the difference between 2D circles drawn on the map and 3D circles drawn on a globe are relatively small (<10% at the limits of the map). Palaeolatitudes are based on the 140Ma (~Berriasian, earliest Cretaceous) pole of Torsvik et al. (2012). Volcanism (red 'v' symbol) is from the Late Jurassic-earliest Cretaceous interval.*

around the Argo pole) opened between Argoland and the northern margin of the Exmouth Plateau. Volcanism is recognised widely across the northwest margin of Australia during this interval (the Ashmore Volcanics: e.g., Mory, 1981), and also in the present Banda forearc islands of Timor (Sani et al., 1995), Savu (Harris et al., 2009) and Buru (Wanner, 1922; Tjokrosapoetro et al., 1993), and in the Bird's Head-Misool region (Fraser et al., 1993). It does not appear, however, that full oceanic spreading extended significantly into the eastern Indonesian region at this time because Late Jurassic-earliest Cretaceous sedimentary environments across the region appear to have been under uniformly shallow marine or non-marine conditions (no deeper than neritic water depths). However, some intracontinental rifting was probably active during this period, as indicated by the volcanism, and by a dramatic change in the sourcing of

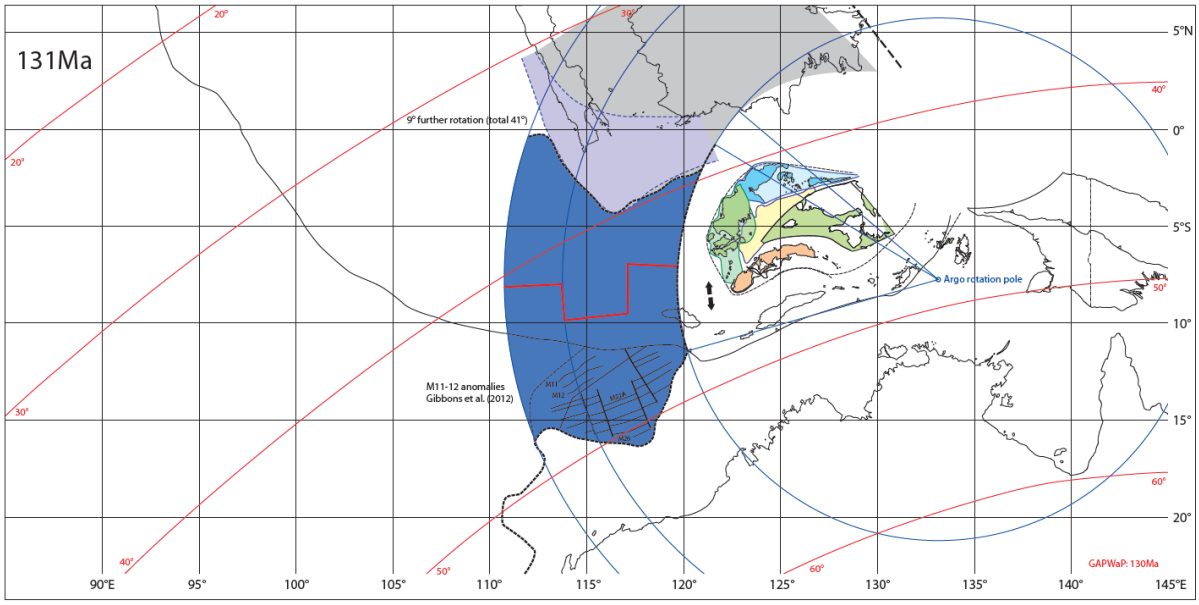


Figure 10: *Reconstruction at the end of the Argo spreading phase (~Valanginian-Hauterivian boundary, mid Early Cretaceous). Argoland is rotated a further 9° clockwise relative to Australia. Palaeolatitudes are based on the 130Ma pole of Torsvik et al. (2012).*

sediments as indicated by zircon studies. The Bird's Head sedimentary sourcing to Timor was cut off between the Early/Middle and Late Jurassic, to be replaced by more local sourcing of sediments containing an abundant supply of locally derived Jurassic igneous zircons (Zimmermann & Hall, 2016).

As discussed earlier, oceanic spreading about the Argo rotation pole may have continued beyond the mid-Valanginian (~136Ma) up to the end of the Valanginian (131Ma), although this spreading phase is less-well constrained. Figure 10 shows a reconstruction at 131Ma, at about the Valanginian-Hauterivian boundary, with a further 9° clockwise rotation of Argoland relative to the Exmouth Plateau about the Argo pole. During this time, it is likely that rifting began to extend into the Timor-Seram region to the east of the Argo oceanic basin, as indicated by deep bathyal to abyssal depositional environments developing in Timor (the Nakfunu Formation in West Timor, e.g. Clowes, 1997; the Wai Bua Formation in Timor-Leste), and comparable and contemporaneous deepwater facies in the Nief Group of Seram (Audley-Charles et al., 1979). This early rifting to the south of the Greater Sula Spur block would have followed the line of earlier Permo-Triassic rifting phases that tracked along the line of the present southern Banda Arc through Timor and the Tanimbar islands, and further east into the Goulburn

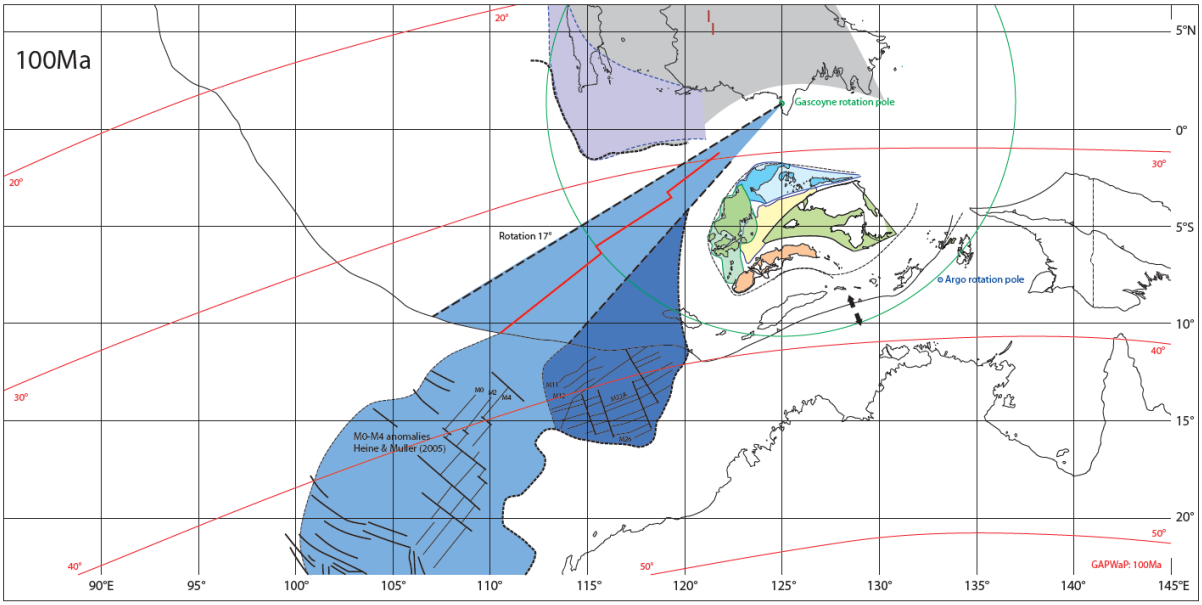


Figure 11: *Reconstruction at the end of the Gascoyne spreading phase (~100Ma, near the Early-Late Cretaceous boundary). The Gascoyne pole (in green) is located between the Argoland and Greater Sula Spur terranes, and consequently the Argoland terrane is rotated 17° clockwise, while the Greater Sula Spur undergoes no rotation relative to Australia. Palaeolatitudes are based on the 100Ma pole of Torsvik et al. (2012). Note the absence of volcanism in the Banda Arc and Bird's Head area at this time, but intrusive igneous activity of arc character developed between 120-80Ma in the Schwaner mountains of SW Borneo (Davies et al., 2014), indicated by the red 'I' symbols in the Argoland Terrane.*

Graben on the southern Arafura Shelf (Charlton, 2001; 2012).

It is particularly significant to note that the suggested Argo phase of oceanic spreading, if accurately modelled by rotation about the Argo pole as shown in Figures 9 & 10, does not significantly detach Argoland from the Australian continent. This is a consequence of the Argo pole being located relatively close to the spreading centres. A more distal pole, such as that suggested by Heine (2002) and implied in the constructions of Hall (2012), is required to fully detach Argoland from Australia during the Late Jurassic-Early Cretaceous rifting phase, and for this terrane to be available to accrete to Asia during the mid to late Cretaceous.

A new phase of spreading in the NE Indian Ocean was initiated in about Hauterivian times, with the spreading geometry defined by a new Euler pole located to the NW of the earlier pole (the Gascoyne pole, located at 3°40'N, 125°00'E relative to the Australian continent; a location near the NE tip of Sulawesi Island in present-day

coordinates: Figure 5). In the reconstruction (Figure 11) this pole was located between the Argoland and Greater Sula Spur continental fragments. In Figure 11 the Gascoyne oceanic spreading is interpreted as a triangular gore 17° wide which developed between the Hauterivian and the Albian (late Early Cretaceous). The positioning of the pole might have resulted in up to 17° of clockwise rotation of Argoland relative to the Greater Sula Spur, but there would have been no significant rotation of the Greater Sula Spur relative to Australia during this interval. Again, however, this spreading geometry would not significantly detach Argoland from the Australian continental margin.

It is also worth noting that the Red Sea-type oceanic rifting phase that appears to be indicated for the late Early Cretaceous Gascoyne spreading (Figure 11) developed contemporaneously with apparently similar rifting on the eastern margin of Australia, in the area immediately south and east of the map coverage in Figures 8-14. The Whitsunday Volcanic Province of Queensland in eastern Australia is a major igneous province typified by silicic (dacite, rhyolite) ignimbritic rocks with a calcalkaline geochemistry, but considered rift-related rather than island arc in origin (Ewart et al., 1992; Bryan et al., 1997, 2000). Magmatism in the Whitsunday Province is dated between about 130-95Ma (~Barremian-Albian), with a main phase of igneous activity in the range 120-105Ma (Aptian-Albian), and thus apparently close in age range to the Gascoyne phase of oceanic development in the Indian Ocean. The Gascoyne and Whitsunday Early Cretaceous rifting events would appear to be linked structural features that accommodated the relative movements of the Australian and Asian continents through the later Early Cretaceous.

The third (Wharton) phase of Indian Ocean spreading initiated at about the time of the Early-Late Cretaceous boundary (~100Ma). As already discussed above, present-day oceanic crust in the northern Indian Ocean defines a spreading pole at 5°S, 171°E (clockwise rotation relative to present-day Australia; Jacob et al., 2014), which is located in the western Pacific to the east of New Guinea island. The northern Indian Ocean spreading trace to the west of the Sunda subduction front is clearly tracking towards the pole east of New Guinea (Figure 2), and the spreading must either have tracked to the north of the Australian continent or died out against the northern continental margin. In Figures 12-14 it is suggested that the Indian Ocean spreading died out in an intracontinental rift between northern

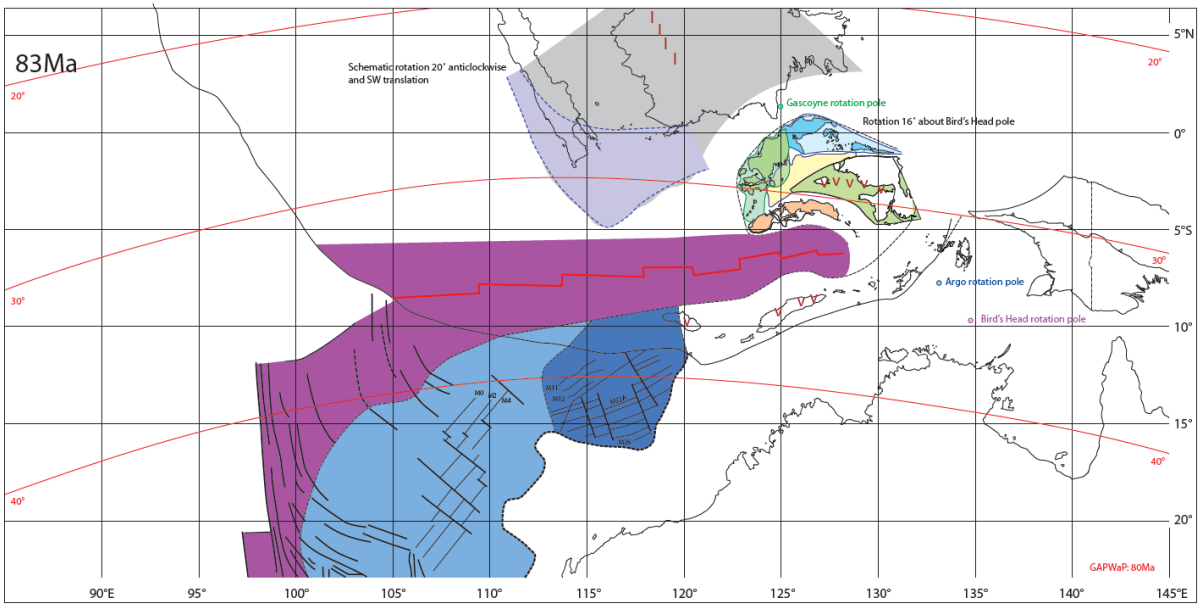


Figure 12: *Reconstruction at the end of the mid-Cretaceous Magnetic Quiet Zone (~83Ma, ~end-Santonian). As discussed in the text, the eastern segment of the Wharton spreading phase in the Banda embayment is interpreted in terms of plate rotation about a pole (Bird's Head pole in purple) located close to the earlier Argo pole. The Greater Sula Spur is interpreted to have rotated 16° clockwise about the Bird's Head pole relative to Australia since the 100Ma reconstruction. Palaeolatitudes are based on the 80Ma pole of Torsvik et al. (2012). Late Cretaceous volcanism in eastern Indonesia is indicated by the red 'v' symbols, and igneous intrusive in the Schwaner mountains of SW Borneo are indicated by the red 'I' symbols.*

Australia and the Greater Sula Spur continental terrane.

As outlined in more detail by Charlton (2023), there is good geological evidence from the Banda-Bird's Head-Misool region and the northwest Australian continental margin for a significant phase of rifting in this area during the Late Cretaceous and Paleogene. Evidence includes volcanism in Sumba, Timor and Bird's Head-Misool, contemporaneous with major passive margin subsidence recorded in petroleum exploration wells from the northern Australian margin to the south and southeast of Timor and in the Bird's Head-Misool region. Cretaceous zircon ages from volcaniclastic sediments in Sumba, Timor, Kisar, Babar and the Tanimbar islands (Figure 1) show a regionally consistent pattern of radiometric ($^{206}Pb/^{238}U$) dates from the Aptian through the Late Cretaceous, with so far, a complete absence of zircon radiometric ages between 136.7-124.0Ma (through the late Valanginian, Hauterivian and early Barremian). The Cretaceous volcanism in Timor and Sumba has been widely interpreted as allochthonous to the Australian margin successions, deriving

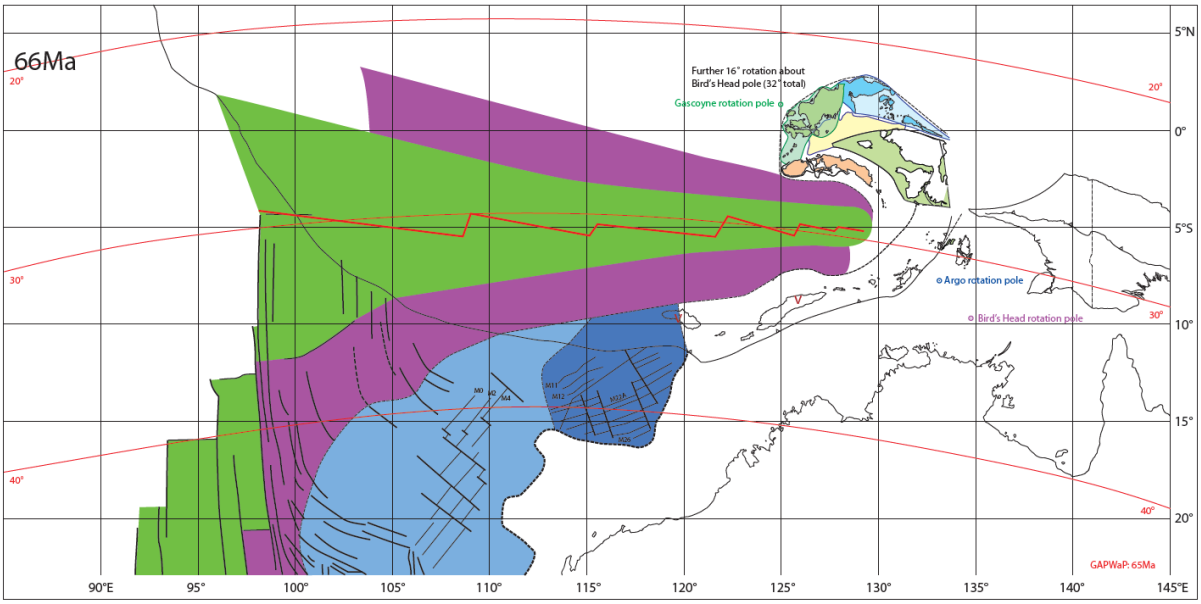


Figure 13: *Reconstruction at the end of the Cretaceous. The Greater Sula Spur block has rotated a further 16° clockwise relative to Australia. Palaeolatitudes are based on a palaeopole located midway between the 60Ma and 70Ma poles (i.e., ~65Ma palaeopole) of Torsvik et al. (2012).*

from an Asiatic subduction margin (e.g., Harris, 2006), but the geochemistry of the Timor Cretaceous-Paleogene igneous suites was interpreted by Standley (2007) as most likely formed in a marginal basin setting – i.e., in an oceanic rift developed behind a volcanic arc. Charlton (2023) suggested that an island arc may have rifted away from northern Australia during the Late Cretaceous. Part of this detaching arc might be SW Borneo (the Argoland Terrane: Figure 12), with arc magmatism in the Schwaner Mountains of Borneo dated between ~120-80Ma (~Aptian-Campanian: Davies et al., 2014). The possibly rift-related but calcalkaline geochemistry of the Timor volcanics might be comparable to the Whitsunday volcanism discussed above, while the Whitsunday volcanics are closely comparable in age to the Schwaner Mountains igneous activity.

In the reconstructions for the Late Cretaceous-Paleogene interval (Figures 12-14), the Greater Sula Spur is rotated clockwise around a pole at 9°24'S, 134°40'E (the Bird's Head pole on Figures 12-14, indicated in purple), located to the SE of the Tanimbar and Aru islands and close to the earlier Argo pole. This pole is defined solely by the interpreted necessity of moving the Greater Sula Spur continental block from its position immediately north of Timor in the late Early Cretaceous (Figure 11) to its inferred

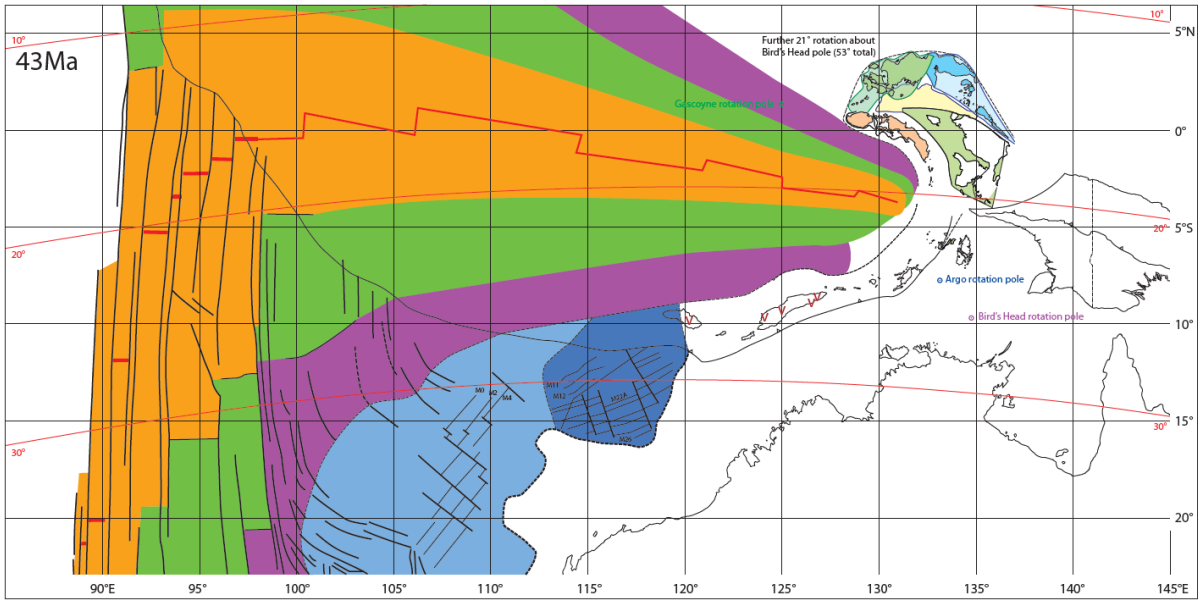


Figure 14: *Reconstruction at the end of the Wharton spreading phase at ~43Ma (mid-Eocene). The Greater Sula Spur is rotated a further 21° clockwise relative to Australia, coming to occupy the position suggested in the plate reconstructions at 30Ma in Charlton (2016). Palaeolatitudes are based on the 40Ma palaeopole of Torsvik et al. (2012).*

position in the late Paleogene (Figure 14) where it is interpreted to have remained relative to Australia up until the onset of regional collision at about 30Ma (Charlton, 2016). In the absence of any additional control, the total rotation of 53° clockwise about this pole is divided equally between the three-time intervals in the reconstructions, with 16° of rotation between 100Ma (Figure 11) and 83Ma (Figure 12); a further 16° of rotation between 83Ma and 66Ma (Figure 13); and a final 21° of rotation between 66Ma and 43Ma (Figure 14). It can be seen in Figures 12-14 that these rotations of the Greater Sula Spur block and the inferred oceanic spreading that separates the northward-moving terrane from Australia is consistent with the known spreading history of the northern Indian Ocean to the south and west of the Sunda subduction front.

The Argoland Terrane is only shown in the 83Ma, mid Late Cretaceous reconstruction (Figure 12), because this terrane was, by that time, probably moving independently of the Greater Sula Spur. In Figure 12 the Argoland Terrane is schematically rotated anticlockwise relative to the clockwise-rotating Greater Sula Spur Terrane and is shown displaced to the southwest. The Argoland Terrane (eastern Sundaland) was presumably attached westward to western Sundaland, and beyond that to mainland Asia, and it

seems likely that the two continental fragments (Argoland and the Greater Sula Spur) acted as counter-rotating rollers accommodating relative movements between Asia and Australia, which the reconstructions imply remained conjoined throughout the late Mesozoic and early Paleogene.

Figure 14 shows the interpreted location of the Greater Sula Spur in the mid-Eocene, at the end of the Wharton spreading phase and immediately before the commencement of the final and ongoing phase of oceanic spreading in the Indian Ocean to the south and west of Australia. The Greater Sula Spur would already have reached a palaeolatitude of about 15°S by this time based on the palaeopoles of Torsvik et al. (2012). Such a palaeolatitude is comparable, for instance, to measured palaeolatitudes of 15.8°S at 47.4Ma and 11.1°S at 56.3Ma determined from Java (Ngkoimani et al., 2006).

REGIONAL IMPLICATIONS

Although the primary aim of this study has been to reconstruct the evolution of the northwestern margin of the Australian continent through the Jurassic-Paleogene interval, these interpretations clearly have implications for the wider evolution of Southeast Asia, and these will now be considered briefly.

Perhaps the most significant conclusion of the present study is that the Argoland Terrane is unlikely to have entirely detached from the Australian continent in the Argo and Gascoyne phases of spreading during the Jurassic and Early Cretaceous. If Argoland is also correctly identified with present-day eastern Sundaland, this brings into question plate reconstructions for the late Mesozoic that interpret a separation of Argoland from Gondwana in the Late Jurassic, and its accretion to the southern margin of Asia in the Cretaceous (e.g., Audley-Charles et al., 1988; Metcalfe, 2011; Hall, 2012).

Secondly it is interpreted in this study that the Jurassic-Paleogene volcanic successions of eastern Indonesia are primarily related to phases of rifting on the Australian continental margin and are not part of a non-Australian 'allochthon' of island arc fragments. The (in part) calcalkaline geochemistry of these volcanic successions probably implies that this rifting was of marginal basin type (Standley, 2007), and hence that the crustal fragment which rifted away from northwestern Australia (including Argoland) was itself probably part of an island arc system. In some Late

Cretaceous palaeotectonic reconstructions of east Asia, Borneo is located at the southern end of a Pacific-facing island arc system (the 'Eastern Arc' of Morley, 2012, Figure 15 inset; location of the arc after Zahirovic et al., 2014). The southern termination of this Eastern Arc in Borneo, taken together with the interpretations in this study may suggest that Australia and Asia were in continuous connection via the Eastern Arc, Argoland and the Greater Sula Spur

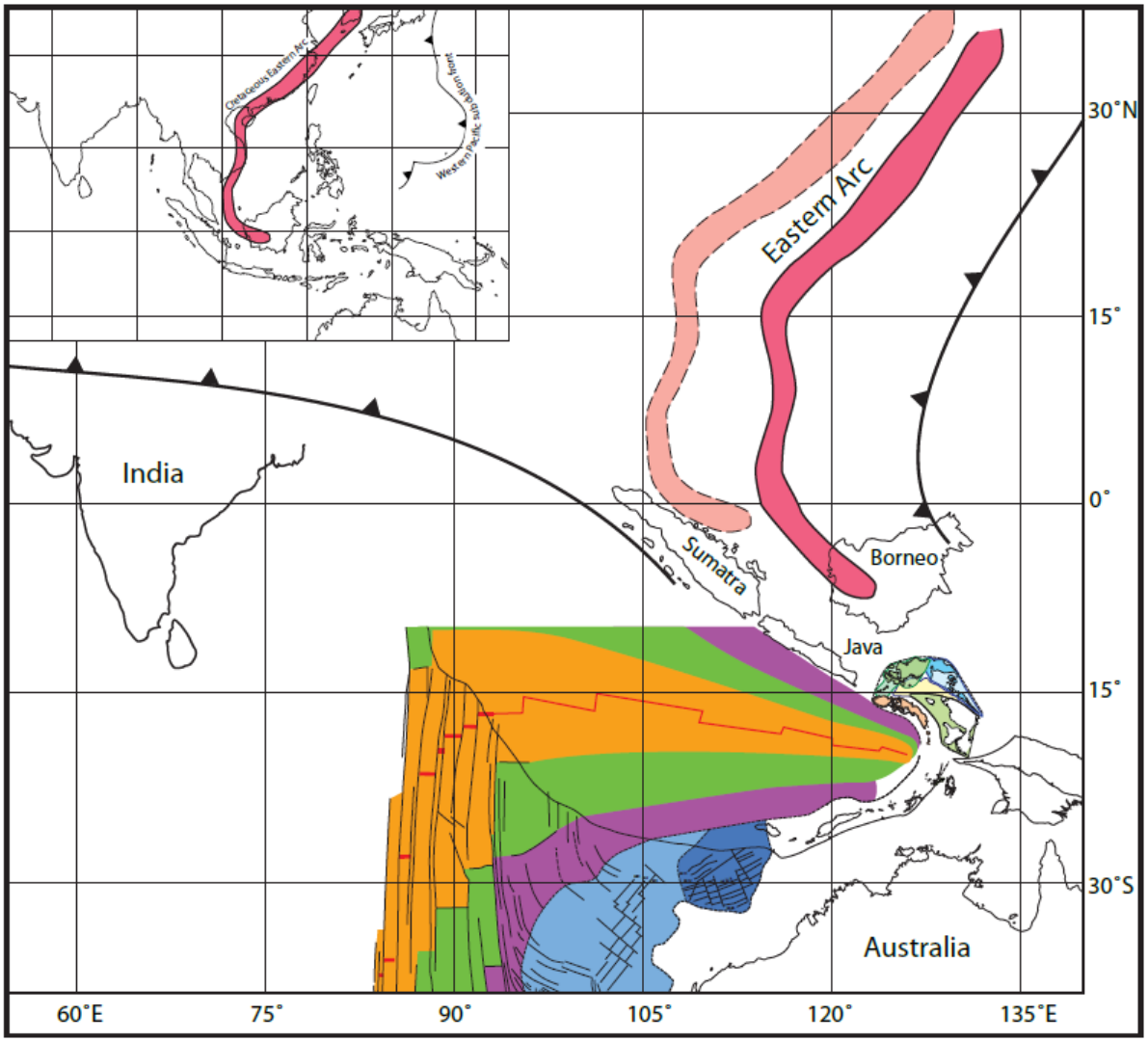


Figure 15: *(Inset) Present-day location of the Cretaceous 'Eastern Arc' (Morley, 2012; position from Zahirovic et al., 2014, their figure 4). (Main) Interpreted relative positions of Australia, India and SE Eurasia in the mid-Eocene, at the end of the Wharton spreading phase (cf. Figure 14). The Eastern Arc, which terminates southward in SW Borneo, may have been located further east at this time, and its subsequent northwestward displacement (to the present-day location indicated in pink) might be as a consequence of India's indentation into Eurasia from the Eocene.*

throughout the Cretaceous and early Paleogene. A further implication of this interpretation is that the Indian Ocean developed within the body of fragmenting Pangaea, with the ocean closing eastwards to a point in the Banda Embayment. Relative movements between Australia and Southeast Asia through the late Mesozoic would have been accommodated by block rotations of Argoland and the Greater Sula Spur as interpreted in this study, with part of the accommodation being in the form of marginal/backarc rifting during the development of the oceanic Banda Embayment in the Cretaceous, behind the southern end of the 'Eastern' island arc. It has been frequently argued that the 'Timor allochthon' originated on the Asian margin because of its close stratigraphic similarity to successions in Sulawesi and Borneo (e.g., Carter et al., 1976; Earle, 1979, 1983; Harris, 2006), but the present reconstructions suggest that this geological similarity arose because these various continental fragments including the future Timor remained largely connected until the later Paleogene.

A remaining important question is what caused the eventual separation of Argoland/Borneo from the Greater Sula Spur after the mid-Eocene? The commencement of oceanic spreading to the south of Australia at this time would have dramatically altered plate boundaries on the northern margin of the continent as spreading ceased to the north of Australia. At about the same time India began collision with Asia (Figure 15), and the beginning of Indian indentation may have dragged the southern continental margin of SE Asia westwards towards the Indian collision zone, pulling Argoland away from northern Australia. This westward drag of Southeast Asia might also account for the major phase of E-W extension in Sundaland during the Eocene (*cf.* Charlton, 2016).

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