Reconstructing the Lost Eastern Tethys Ocean Basin: Convergence History of the SE Asian Margin and Marine Gateways

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Plate tectonic reconstructions for the late Mesozoic–Cenozoic evolution of the eastern Tethyan Ocean Basin, separating eastern Gondwanaland from Proto- Southeast Asia, are usually based on geological data gathered from the different tectonic blocks accreted to Southeast Asia. However, this approach only provides few constraints on the reconstruction of the eastern Tethys Ocean and the drift path of various terranes. We have used marine magnetic anomalies in the Argo and Gascoyne Abyssal Plains off the Australian Northwest Shelf, jointly with published geological data, to reconstruct the seafloor spreading history and plate tectonic evolution of the eastern Tethys and Proto-Indian Ocean basins for the time between 160 Ma and the present. Based on the assumption of symmetrical seafloor spreading and a hotspot-track-based plate reference frame, we have created a relative and absolute plate motion model and a series of oceanic paleo-age grids that show the evolution of Tethyan mid-ocean ridges and the convergence history along the southeast Asian margin through time. A thermal boundary layer model for oceanic lithosphere is used to compute approximate paleo-depths to oceanic basement to predict the opening and closing of oceanic gateways. The proposed model not only provides improved boundary conditions for paleoclimate reconstructions and modelling of oceanic currents trough time, but also for understanding stress changes in the overriding plate and the formation of new accretionary crust along the Southeast Asian margin, driven by changing subduction parameters like hinge rollback and slab dip.

1. INTRODUCTION

The Indian Ocean margin of Southeast Asia is the product of long standing northward subduction of Tethyan and Indian Ocean lithosphere, and the amalgamation of continental blocks including the Cenozoic India-Eurasia collision [*Metcalfe,* 1999; *McCourt et al.,* 1996; *Ricou,* 1995; *Metcalfe,*1991]. Continental terranes were derived mainly from the northern Gondwanaland margin during three main rifting episodes in

Late Paleozoic-Early Cenozoic times and transferred to the north by seafloor spreading, opening and closing successive Paleo-, Meso,- and Neotethyan ocean basins

[*Stampfli and Borel,* 2002; *Metcalfe,* 1996; *Ricou,* 1995; *Görür and Sengör,* 1992]. Changing convergence direction and age of the subducted oceanic lithosphere, accompanied by changes in slab dip angle and associated accretion of terranes and pulses of magmatism on the overriding plate play a significant role in the tectonic evolution of an active continental margin (e.g. cordillera build-up or collapse due to changes in age of the subducting lithosphere). In Southeast Asia, the subduction history of its Tethyan/Proto- Indian Ocean margin has been poorly constrained, as nearly all oceanic lithosphere

documenting the last stages of the eastern Tethys and Proto-Indian Ocean have been subducted. *McCourt et al.* [1996] have shown that different stages of subduction related plutonism in Sumatra broadly correspond to changes in subduction direction and angle. They distinguished five main periods of plutonic activity between the Late Triassic and Pliocene.

Sutures, mobile belts and major fault zones in Southern Asia (Figure 1) are the remnants of different stages of the lost Tethys Ocean basins, represented by mélanges and ophiolites. They have been utilised to reconstruct the plate tectonic history of the eastern Tethys [*Ricou,* 1995; *Metcalfe,* 1994; *Görür and Sengör,* 1992]. However, traditional reconstructions based on terrane analysis and continental paleomagnetic data can only put weak constraints on the evolution and plate tectonic configuration of the Tethyan Ocean basins. With the advent of satellite derived marine gravity anomalies [*Sandwell and Smith,* 1997] and a growing amount of ship magnetic anom-
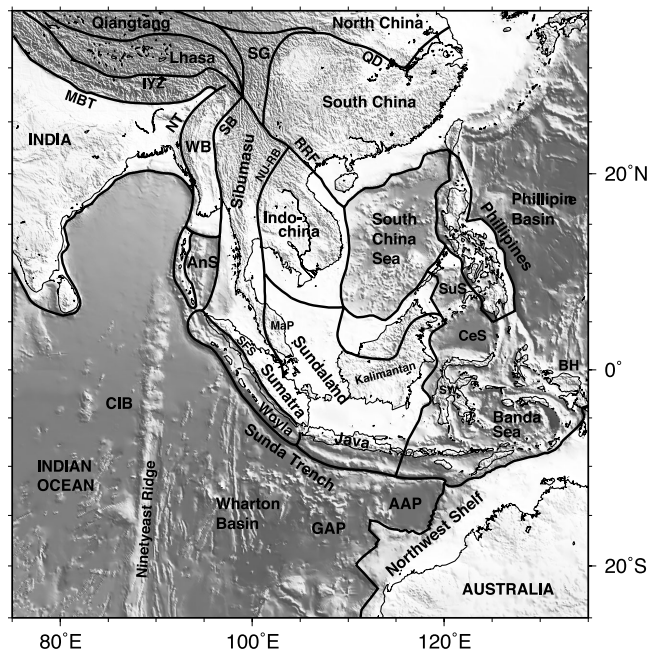

Figure 1. Morphological map of Southeast Asia and NW Australia showing tectonic elements and suture zones (based on various sources). Tectonic elements: AAP = Argo Abyssal Plain, AnS = Andaman Sea, BH = Bird's Head, CeS = Celebes Sea, CIB = Central Indian Basin, GAP = Gascoyne Abyssal Plain, MaP = Malay Peninsula, SG = Songpan Ganzi accretionary complex, SuS = Sulu Sea, WB = West Burma Block, Woyla = Woyla and Sikuleh-Natal terranes of western Sumatra — Suture zones: IYZ = Indus-Yarlung-Zangbo suture, MBT = Main Boundary Thrust, NT = Naga Thrust of west Burma, SB = Shan Boundary (or Sagaing Fault), NU-RB = Nan-Uttarradit Raub-Bentong Suture, RRF = Red River Fault, SFS = Sumatra Fault System, QD = Qinling Dabie Suture. Terrane boundaries according to those of *Metcalfe* [1996].

aly data, it has become easier to reconstruct drift paths of continents quantitatively and in much greater detail. For the Indian Ocean models based on the interpretation of magnetic anomaly, gravity and geological data provided essential, well-constrained input for the reconstruction of the post-chron C34 (83.5 Ma) convergence history along the Southeast Eurasian/Southeast Asian continental margin [*Hall,* 1996; *Royer et al.,* 1992; *Royer and Sandwell,* 1989; *Veevers et al.,* 1991; *Patriat and Segoufin,* 1988]. Before chron C34, the Cretaceous Quiet Period and only a very few documented Early Cretaceous/Late Jurassic magnetic anomalies result in a very poorly constrained, 80 My long gap in the tectonic history of the eastern Tethyan Ocean and the southern Eurasian margin [*Ricou,* 1995]. Recently, geodynamic models have provided additional constraints for the pre-chron C34 plate tectonic evolution of the central and eastern Tethyan Ocean and Southeast Asia by integrating plate boundary forces and dynamic plate boundaries [*Stampfli and Borel,* 2002] or using seismic tomography to estimate the amount of subducted slabs and discriminate between published tectonic models [*Hafkenscheid et al.,* 2001; *van der Voo et al.,* 1999] and mantle convection patterns [*Collins,* 2003]. In this paper we follow the convention that the Mesotethys was opened by the rifting of the Sibumasu sliver (including the Lhasa Block, according to *Stampfli and Borel* [2002]) and the Neotethys was opened by the rifting of the continental sliver rifting off the Australian Northwest Shelf in the Late Jurassic/Early Cretaceous.

The evolution of the Indian Ocean and its precursors, the Neotethys, is not only important in terms of the convergence and tectonic history of the Southeast Asian margin, but also in terms of climate and ocean circulation, as the final dispersal of Gondwanaland opened oceanic gateways from the southeastern Pacific through "inner" Gondwanaland—around Greater India—into the eastern and central Tethys. This might have played a significant role in climate and sedimentation patterns in Southeast Asia. In this paper we discuss the convergence history along the Indian/Tethys ocean margin of Southeast Asia in the light of a series of oceanic paleoage grids that were derived from a new plate tectonic model and will show the evolution of oceanic gateways in the eastern Tethys using computed paleo-bathymetry oceanic basement grids.

1.1. Mesozoic Ocean Crust in the Indian Ocean

Oceanic lithosphere of the Argo and Gascoyne Abyssal Plains (Figures 1 and 2) off Northwest Australia represents the only remaining "in situ" records of eastern Tethyan Ocean floor, hence they contain essential information about the timing and geometry of seafloor spreading and the plate tectonic configuration of the former eastern Tethys and Proto-Indian Ocean. Marine magnetic anomalies in the Argo and Gascoyne

Abyssal Plains document the breakup of a continental sliver in Late Jurassic time (155 Ma) and subsequent seafloor spreading that resulted in the gradual opening of the eastern Neotethys [*Müller et al.,* 1998; *Mihut and Müller,* 1998b; *Mihut,* 1997; *von Rad et al.,* 1992; *Veevers et al.,* 1991; *Fullerton et al.,* 1989; *Powell and Luyendyk,* 1982]. Subduction of the Neotethyan and Proto-Indian Ocean lithosphere beneath the southern Eurasian margin destroyed further details about the geometry and configuration of seafloor spreading north of Australia in the time between 130 Ma and present and thus the drift path of the continental block.

Two opening scenarios and models have been suggested by different authors, both with significant impact for the configuration and placement of continental blocks, position of seafloor spreading ridges and the age of oceanic lithosphere subducted beneath the southern Eurasian margin. The "traditional" model [*Metcalfe,* 1999, 1994; *Powell and Luyendyk,* 1982] assumes two different spreading directions revealed by magnetic lineations in the Argo Abyssal Plain and the India-Australia breakup extending all along the Western Australian margin as far as the Gascoyne Abyssal Plain. However, with respect to the evolution of the eastern Indian Ocean, this results in a triple junction off Northwestern Australia. It would firstly result in a much later spreading between Australia and the continental block that rifted off the Australian NW shelf (or earlier spreading between Australia and India) and secondly in a spreading ridge propagating west- or northwards around northern Greater India, which continues to be active after the India-Australia breakup. The second model proposed by *Mihut and Müller* [1998b], *Müller et al.* [1998] and *Mihut* [1997] assumes one single NW-SE direction of opening for all abyssal plains off the Australian western and northwestern margins. This would simplify the plate tectonic configuration but requires different spreading velocities in the different compartments.

Both published plate tectonic scenarios for the opening of the abyssal plain in the easternmost Indian Ocean are not supported by existing geological and geophysical data, e.g. see *Müller et al.* [1997], *Royer et al.* [1992] and *Royer and Sandwell* [1989]. Magnetic anomalies in the Southern (Enderby Basin) and Central Indian Ocean suggest, that India started to move rapidly northward from 99 Ma onwards, with Northwestern Greater India initially colliding with the southern Eurasian around 65–55 Ma [*Lee and Lawver,* 1995; *Klootwijk et al.,* 1992]. These high tectonic plate velocities can only be achieved by a large slab of oceanic crust pulling India to the north while a spreading ridge in the Proto-southern Indian Ocean pushes India from the south. This is not possible if the traditional "triple junction model" is utilised, as the northwestern ridge of a triple junction, invoked at around 140–130 Ma would prevent a fast northward motion of the Indian Plate.

It would have to travel all across the Neotethys within 30–40 my to be subducted beneath the Eurasian margin at around 100 Ma. Assuming that the width of the Neotethys was around 3000 km this would result in spreading velocities of around 50 cm/yr. The "one spreading direction model" by *Mihut and Müller* [1998b], *Müller et al.* [1998] and *Mihut* [1997] could not been confirmed by our revised interpretation of geological, magnetic and gravity data in the Argo and Gascoyne Abyssal Plains.

The plate tectonic configuration that can be derived using the preserved seafloor spreading record in the Argo and Gascoyne Abyssal Plains is essential, as it is the only possibility to reconstruct the convergence history of the Southeast Asian margin, the development and closure of oceanic gateways and the position of continental blocks that were rifted off the northeastern Gondwanaland margin. Plate tectonic reconstructions for this region have previously been based on the comparison of stratigraphic and structural data based on a global tectonic framework. Using a global isochron map it has become possible to quantitatively reconstruct relative plate motions constrained by global rotation trees and self consistent sets of plate rotations.

2. METHODOLOGY

The plate tectonic model we present is based on a revised interpretation of marine magnetic anomalies in the abyssal plains off the Australian northwest and western margins jointly with satellite-derived gravity anomalies [*Sandwell and Smith,* 1997]. According to this interpretation, the sea-floor spreading in the Argo Abyssal Plain and eastern part of the Gascoyne Abyssal Plain (Figure 2) started with M25A (154.5 Ma) in the Valanginian, separating the West Burma Block from the present day Australian Northwest Shelf creating the Argo and Gascoyne Abyssal Plain. The spreading center continued most likely around northern Greater India and joined up with the spreading ridge separating Madagascar/India from Africa. Following a southward ridge jump, a 15 degree counterclockwise change of the Argo spreading system occurred contemporaneously with the onset of seafloor spreading between India and Australia at around 132–130 Ma. From this time onwards the motions of the West Burma Block are fixed relative to Greater India. Figure 6 shows the rotation tree used for our model for certain times.

Based on the assumption of symmetrical seafloor spreading we have been able to reconstruct synthetic isochrons for the subducted oceanfloor in the eastern Meso- and Neotethys. Plate motions of Greater India are constrained by magnetic anomalies off Western Australia [*Mihut and Müller,* 1998a], in the Enderby Basin of the Southern Ocean [*Gaina et al.,* 2003] and fracture zones in the Indian Ocean. Cenozoic mag-
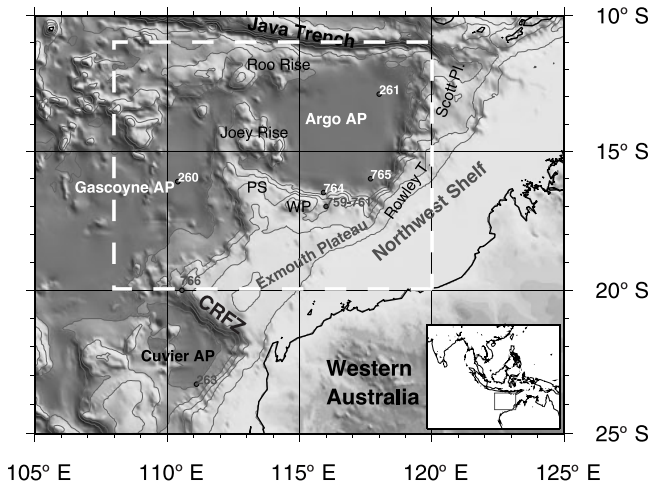
Figure 2. Morphological features of the Australian Northwest Shelf and adjacent abyssal plains. Abbreviations: AP = Abyssal Plain; Pl. = Plateau; T. = Terrace; PS = Platypus Spur; CRFZ = Cape Range Fracture Zone. Dashed white rectangle represents map boundaries of Figure 5.

netic anomalies in the eastern Indian Ocean constrain the post-anomaly C34 (83.5 Ma) continental positions [*Lee and Lawver,* 1995]. The derived isochrons were gridded for each timestep to create paleo-agegrids for certain times. Plate motions are in an absolute hotspot reference frame [*Müller et al.,* 1993].

Isochrons have been reconstructed using a global self- consistent set of rotations and have been gridded and colour coded to show the age-area distribution of the oceanic basement at a given time (see Section 2.1). However, it should be noted that this model assumes a simple seafloor spreading history for the reconstructed ocean-floor. We do not account for smaller plate tectonic reorganisations that are associated with trench pull or other forces acting on the active spreading ridge. Continental outlines used in our model are based on present-day continent-ocean boundaries (COB). The size of Greater India in our model is based on reconstructions of *Replumaz and Tapponier* [2003], and *Mihut,* [1997]. It is one of the main factors determining the time of collision of Greater India with the Eurasian margin.

Paleo-bathymetry reconstructions were derived by using paleo-age grids to restore the age-area distribution of the seafloor and converting the age of the oceanic crust to basement depth by using a combination of the thermal boundary layer model and the plate model. More than 35 years ago [*McKenzie,* 1967] suggested that there was a limit to the depth of cooling of the oceanic thermal boundary layer [*Turcotte and Oxburgh,* 1967] such that the lithosphere cools as a plate of finite thickness rather than as a semi-infinite half space. This model, entitled the "plate model", was based on the observa-

tion that oceanic basement does not deepen as the square root of lithospheric age for ages older than about 80 million years. However, even though the "plate model" provided a better fit to the observations, its suggested physics, namely small- scale convective "peel off" of the base of the lithosphere after exceeding a critical thickness has been both contested and supported. *Nagihara et al.* [1996] used high-quality heat flow data to argue that discrete reheating events are more likely than convective peel-off to cause the flattening of old ocean floor, but the data did not allow to clearly distinguish between the two mechanisms. More recently, *Doin and Fleitout* [2000] used depth-age and geoid-age data to argue that heat in the range between 35–50 mWm^{-2} is carried to the base of the lithosphere, either by small-scale convection or shear flow, but not by hotspots or dynamic topography. That mantle plumes are not responsible for the observed flattening is supported by the observation that old oceanic lithosphere away from any hotspot tracks still shows a distinct flattening at ages older than about 80 million years [*Parsons and Sclater,* 1977]. Here we choose to use *Parsons and Sclater's* [1977] plate model parameters to compute oceanic basement depth from age, even though the physics behind this model are still controversial, because a thermal boundary layer model would result in excessive depths of old ocean floor which are not supported by any observations from currently preserved ocean crust.

Sediment deposition and compaction effects and the subsidence of the oceanic crust through sediment loading were not taken into consideration. The basement depth provides important controls on sediment accumulation rates obtained by past and future ODP legs in the Indian Ocean.

2.1. Revised Magnetic Anomaly Interpretation in the Argo and Gascoyne Abyssal Plains

Magnetic anomalies in the Argo and eastern Gascoyne Abyssal Plain have been correlated by visual comparison using a computed synthetic magnetic sequence, which is shown as the topmost profile in Figures 3 and 4. It was assumed that the average seafloor spreading rate for the M25–M10 interval was constant around 80 mm/yr (full spreading rate). The magnetic data were interpreted jointly with the satellite derived gravity for the area of interest to help identifying major structural trends like fracture zones and extinct ridges. For the magnetic anomaly interpretation we followed the convention to pick the younger end of the normal (positive) polarised block.

Geological data from ODP/DSDP sites as well as published sequence stratigraphic and backstripping data from the Australian Northwest Shelf constrain the time of formation of the Argo Abyssal Plain to Oxfordian-Tithonian ages. Ambiguous K/Ar dating of basement drilled at ODP Site 765 [*Ludden,*

1992] (Figure 2) and discrepancies of oldest sedimentary rocks and basement age [*Kaminski et al.,* 1992; *Sager et al.,* 1992] left opportunities for speculating about the exact age of formation of the Argo Abyssal Plain. Previous works [*Mihut,* 1997; *Sager et al.,* 1992; *Fullerton et al.,* 1989; *Powell and Luyendyk,* 1982] have shown clearly that the general trend of younging is towards the northwest. Figure 2 gives an overview about the morphological features of the Australian Northwest Shelf and adjacent abyssal plains. We have correlated an M25A–M10N (154.5–130.9 Ma) sequence in the Argo and Gascoyne Abyssal Plains (Figures 3, 4 and 5). The best correlation of synthetic and observed anomalies in the Argo Abyssal Plain were found on the "a9314"(e) and "um63" (c) tracks (see Figure 3 and 5), extending from ODP Site 765 in the south across the central part of the basin to the northwest (Figure 5). Ages determined at ODP Site 765 acted as a tie-point for the interpretation. By following track "a9314" to the NW (Figure 5) the synthetic profile was matched, afterwards the interpretation was extended to the adjacent wiggles, covering the complete Argo Abyssal Plain and the
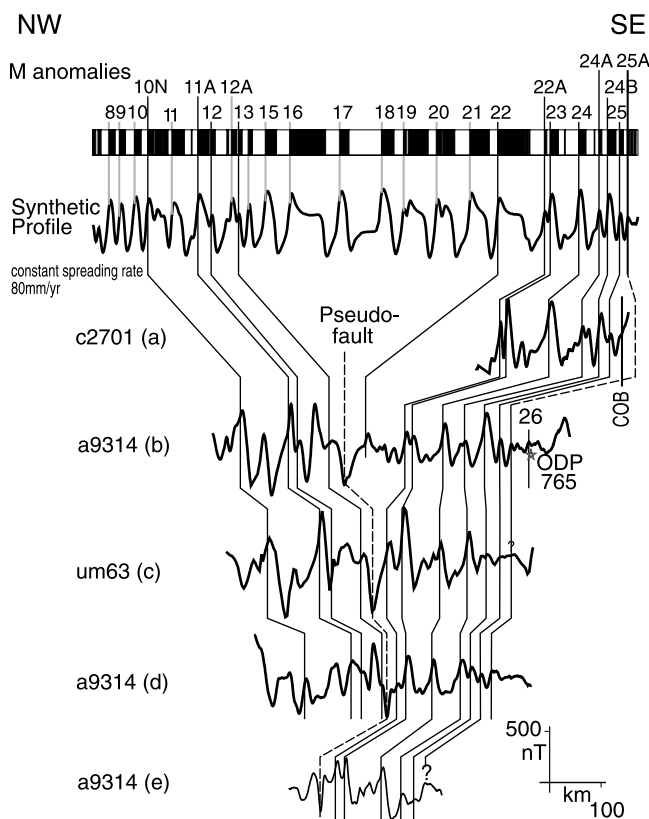

Figure 3. Magnetic correlation for the Argo Abyssal Plain. Shown as the topmost profile is the computed synthetic magnetic anomaly profile. Profiles below are shiptracks retrieved from the GEODAS archive. For location of tracks see Figure 5.

northwest of the Exmouth Plateau in the eastern Gascoyne Abyssal Plain (Figure 5). M26 (155.0 Ma) was the oldest anomaly that could be identified in the southern Argo Abyssal Plain next to ODP Site 765, limited to the "a9314" track. This confirms the dating by *Sager et al.* [1992]. The anomalies M26–M24A (155.0–153.1 Ma) are limited to the east and to the southwest by the COB of the Exmouth Plateau/Rowley Terrace-Scott Plateau margin. In the northeast the M24–M22A (152.1–150.4 Ma) anomalies are bounded by the Java trench. The magnetic lineations at DSDP Site 261 are M24–M23 (152.1–150.7 Ma) resulting in a basement age of Late Kimeridgian (according to the *Gradstein et al.* [1994] time scale), which matches well with the oldest dated sedimentary rocks (Kimmeridgian, according to the *Harland et al.* [1982] time scale). A continuous sequence is identified until M22A (150.4 Ma) where a major negative anomaly of about -500 nT is observed in all recorded profiles (Figure 3). This negative anomaly is presumably related to a southward ridge jump at M14 (135.8 Ma), as the correlation with the normal sequence (M22 and younger) north of the anomaly is lost. Instead, the M13– M10N (135.5–130.8 Ma) sequence shows a good fit to the recorded profiles (Figure 3) with a slight successive anti-clockwise rotation of the spreading direction from approximately N60ºE in the southern parts of the Argo Abyssal Plain to N45ºE in the northern part (Figure 5). This is well matched by an ENE–WSW trending, concave gravity signature representing the remnant signature of the ridge jump. Six northeast trending fracture zones segment the magnetic lineations into smaller compartments (Figure 5). North of the "ridge-jump"-pseudofault no unequivocal evidence for fracture zones was found either in the magnetic or in gravity data.

Higher amplitude magnetic anomalies in the northern part could be related to the decrease in water depth due to the regional southward tilt of the basin and the outer swell of the subduction zone in the Java Trench. The frequency of polarity reversals changes in the M26–M10 (155.0–130.8 Ma) sequence significantly from higher rates (M25–M22A, 154.1–150.4 Ma) to lower (M22–M16, 148.1–137.9 Ma) and back to higher rates for the M15–M10 (136.7–130.8 Ma) anomalies. The magnetic record of the Argo Abyssal Plain instead reflects a more or less constant rate of reversals with a slight decrease towards the center of the basin (Figure 3). If the spreading had continued normally from M22 onwards, one would expect the low-reversal frequency sequence M22–M15 in the central and northern part of the Abyssal Plain. Instead, the spacing between the anomalies is highest in the center of the basin with a sudden increase in the reversal frequency north of the interpreted pseudofault, supporting the interpretation of a southward ridge jump with the anomalies M22/M21 to M14 being transferred onto the conjugate plate rifting away from Australia.

Volcanic activity in the Joey and Roo Rise areas (Figure 2) biases the magnetic signal and in combination with sparse data (Figure 5) coverage no anomalies could be correlated here. In the north the identification of magnetic anomalies younger than M10N (130.8 Ma) is limited by the Java Trench. A second model has been tested for a younger M-sequence in order to decrease the discrepancy between oldest sedimentary rocks and basement ages in the Argo Abyssal Plain. In this case, however, lineated magnetic anomalies in the northern part of the Argo Abyssal Plain would be in the Cretaceous Normal Superchron (CNS).

In the eastern Gascoyne Abyssal Plain the magnetic anomaly interpretation was Argo Abyssal Plain more problematic because of the azimuth of the recorded profiles and the sparse data coverage (Figure 5). Magnetic lineations were previously interpreted to be related to the breakup along the western Australian margin in Valanginian–Hauterivian times and to have the same orientation as in the Cuvier and Perth Abyssal Plains [*Müller and Mihut,* 1998; *Mihut,* 1997; *Sager et al.,* 1992; *Fullerton et al.,* 1989; *Powell and Luyendyk,* 1982]. However, we have identified the anomalies M25A–M22A (153.5–150.4 Ma) parallel to the lineations in the Argo Abyssal Plain (Figures 3 and 5).

The identified lineations trend obliquely to all shiptracks in the area. A good correlation was found for the M24B – M22A magnetic anomalies over the "io050 – io055" (f, h, i, j) tracks (Figure 4 and 5). North of the northern tip of the Cape Range Fracture Zone (Figure 2) anomaly M25A was traced over four profiles, limited to the east by the "continental crust promontory" of the Wombat/Exmouth Plateau (Platypus Spur). A continuous sequence of magnetic anomalies is identified until M22A, with the same azimuth as anomalies in the Argo Abyssal Plain. The lineations are segmented by two fracture zones (Figure 5). North of the continental promontory anomaly M24 is the oldest identified, linking the two spreading compartments of the Gascoyne and Argo Abyssal Plains. A N–S striking pseudofault, caused by a northward propagating ridge event [*Müller and Mihut,* 1998; *Mihut and Müller,* 1998a], cuts off the anomalies to the west and is expressed by a combination of a smaller negative and major positive magnetic anomaly (Figures 4 and 5).

Volcanic activity between the Gascoyne and Argo Abyssal Plains formed the Joey Rise shortly after the formation of the seafloor [*Gopala Rao et al.,* 1994]. Identification of magnetic anomalies in this area has been problematic but some correlatable sequences (M24–M22A; Figure 5) have been found.

We have shown that the results from the magnetic interpretation require a new model for the opening and spreading history of the Argo and Gascoyne Abyssal Plains and provide vital information about the seafloor spreading geometry around northern Greater India in the Late Jurassic / Early Cretaceous.
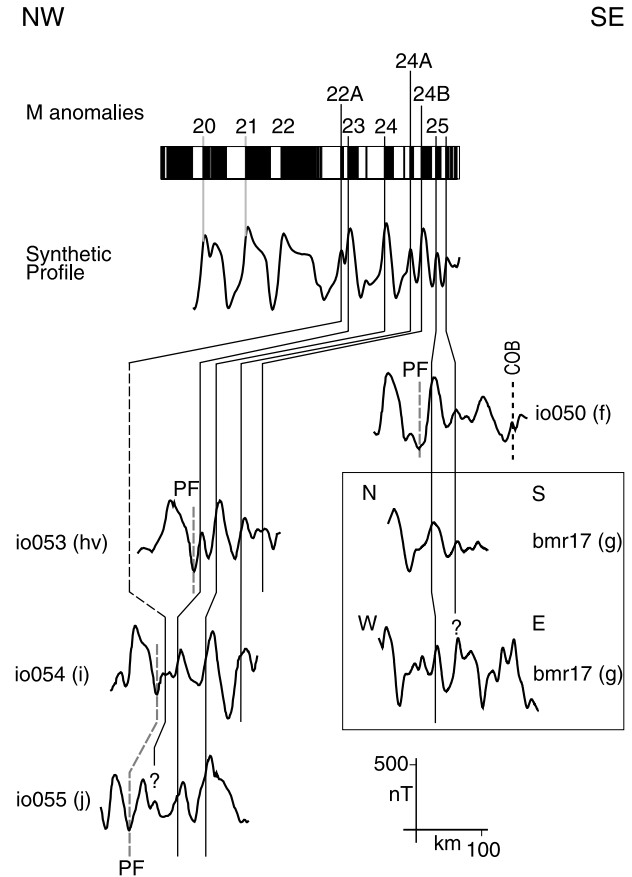

Figure 4. Magnetic correlation for the Gascoyne Abyssal Plain. Shown as the topmost profile is the computed synthetic magnetic anomaly profile. Profiles below are shiptracks retrieved from the GEODAS archive.

In the following section we will describe the new tectonic model for the opening of the abyssal plains NW of Australia and the implications of this model to the regional evolution.

3. CONVERGENCE HISTORY OF THE INDIAN OCEAN MARGIN OF SOUTHEAST ASIA SINCE 160 MA

We present a series of plate tectonic reconstructions in 20 my steps from 160 Ma, providing a regional quantified model to the evolution of the eastern Tethys Ocean Basin within a global tectonic framework and focusing on the convergence history along the Sunda Trench and its various precursors. The reconstructions are in an Atlantic–Indian fixed hotspot reference frame [*Müller et al.,* 1993]. For times between 160–130 Ma, for which no continuous hotspot tracks are available, the present model assumes that Africa was fixed relative to the mantle.
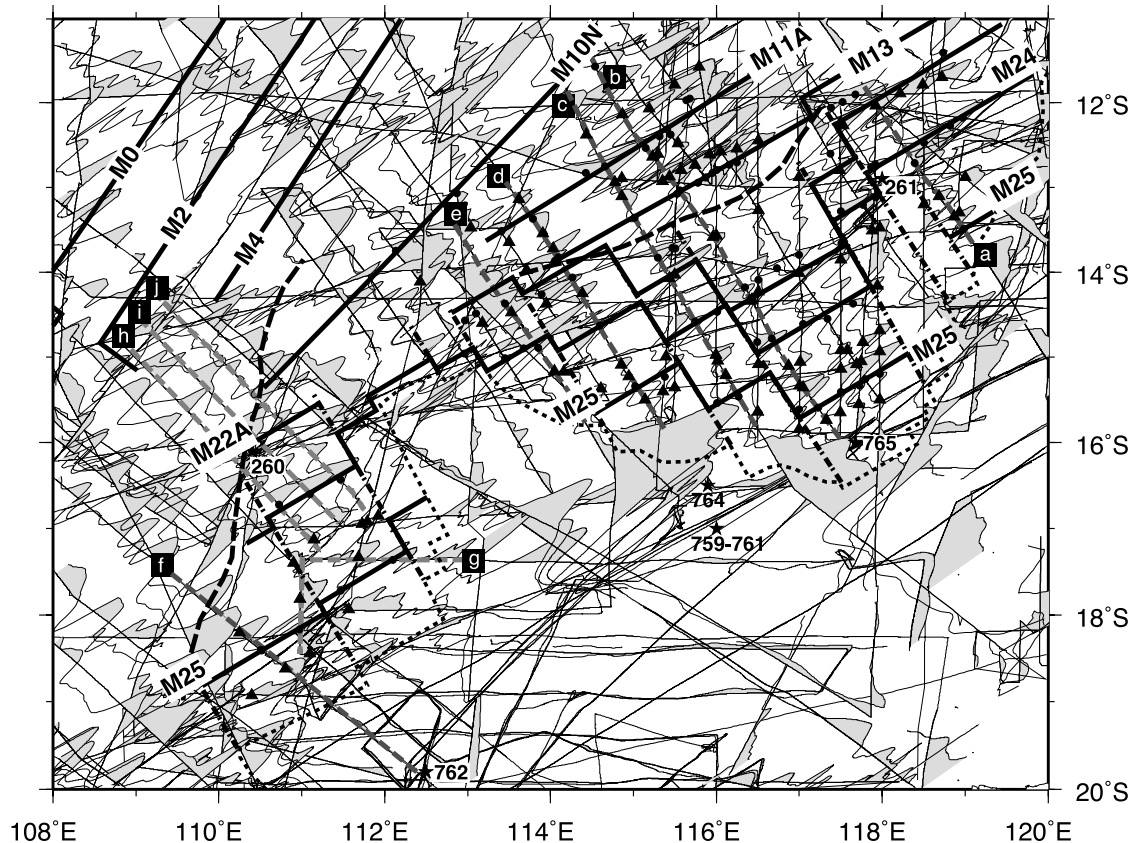
Figure 5. Magnetic anomaly correlation for the Argo and Gascoyne Abyssal Plains. Shown are isochrons (heavy lines, annotated), fracture zones (dashed lines), pseudofaults (large dashed lines) and the continent ocean boundary (stippled). Triangles indicate interpreted magnetic anomalies not included in the plate tectonic model. M4–M0 taken from *Mihut* [1997]. Stars indicated DSDP/ODP sites. Shiptracks used for the correlation of magnetic anomalies in Figures 3 and 4 are indicated by letters a-i and thick, dashed grey lines.

We have integrated as much published data as possible to constrain the timing and nature of tectonic and magmatic events along the Tethyan margins. However, it was not the scope to provide a local tectonic model of SE Asia for Cenozoic/Post-India collision times. Detailed work on the configuration and tectonic evolution of the Indonesian collisional complex and block motions in SE Asia is given by [*Gaina and Müller,* in press; *Replumaz and Tapponier,* 2003; *Hall,* 2002; *Hall,* 1996; *Lee and Lawver,* 1995; *Rangin et al.,* 1990].

Future collaborative work on the Pre-Cenozoic tectonic framework and timing of events along the SE Eurasian margin is needed to refine the model in terms of margin geometry (e. g. opening and closing of back arc basins) and margin-wide geological events to provide tighter geological constraints for regional tectonic events such as ridge subduction. Digital versions of the reconstructions shown in this paper can be obtained from the Australian Earth and Ocean Network (AEON) Online Resources at http://www.aeon.org.au/resources.html or in writing to the authors.

3.1. Plate Circuit Diagram

A hierarchical rotation file was used to organise the finite rotations, assigning Plate ID's to the relevant tectonic elements. Figure 6 shows the hierarchy of major plates and tectonics blocks used for the reconstructions. The motions of the West Burma Block have been linked to the continental Middle Greater India Block of *Mihut* [1997], that opened the Cuvier and southern Gascoyne Abyssal Plains when rifting between India and Australia started. The motions of this elongated slice of continental lithosphere relative to Greater India are irregular due to the closure of the plate circuit (relative motions between Antarctica-India and India-Madagascar are not well constrained).

The motions of Middle Greater India are constrained by M-anomalies in the Cuvier and southern Gascoyne Abyssal Plains and after 83.5 Ma it became attached to the Indian Plate [*Mihut,* 1997]. Linking the West Burma Block to this continental fragment provides the best possible reconstruction as the spreading between Australia–West Burma and Middle
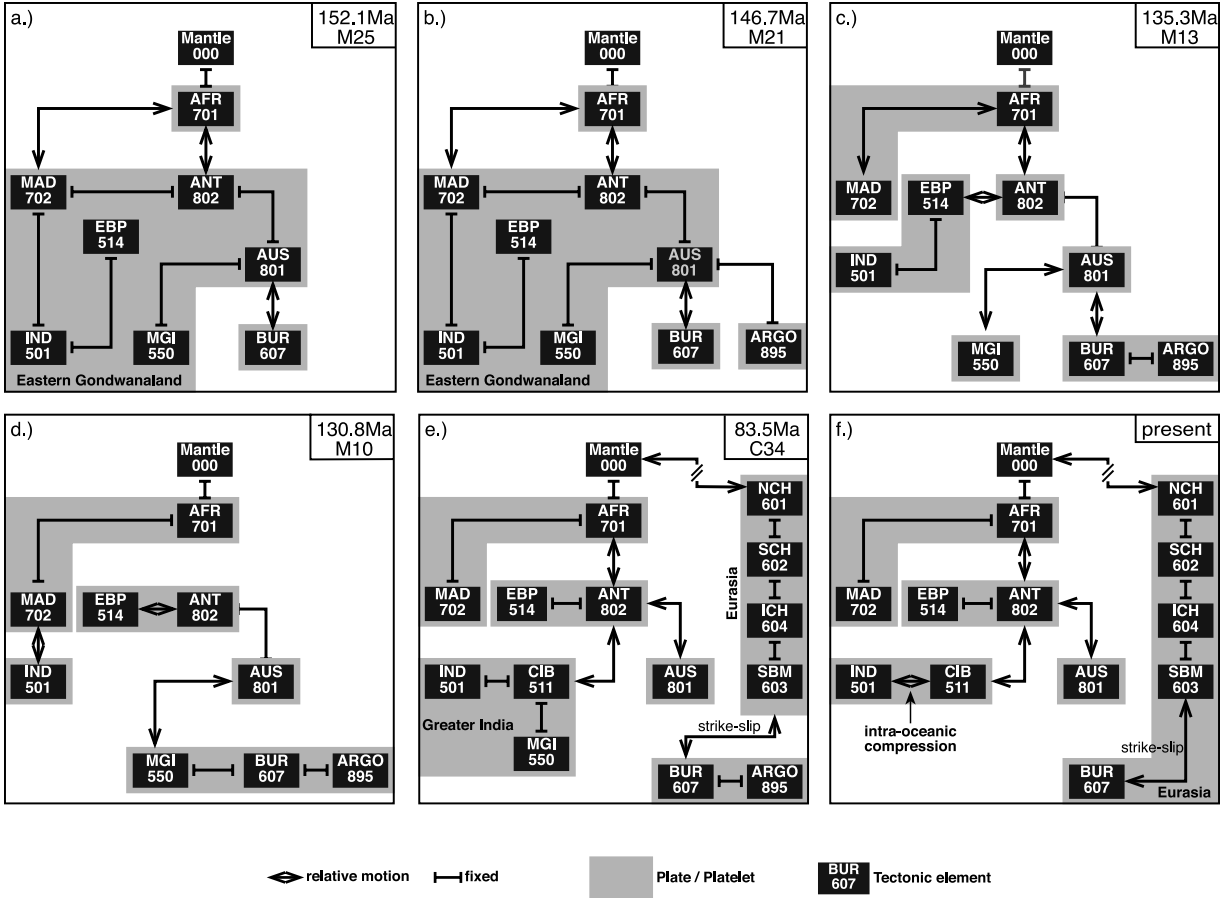
Figure 6. Rotation trees for the presented plate tectonic model at given times and respective magnetic chrons. Plate Circuit diagram. Shown are the motions of major tectonic blocks and platelets relative to the hotspot reference frame (fixed mantle) for certain time intervals. a.) Chron M25 (154.1 Ma), breakup of the West Burma Block from the northeastern margin of Gondwanaland; b.) Chron M20 (145.1 Ma), pre-ridge jump situation; c.) Chron M10 (130.2 Ma), post ridge-jump situation and eastern Gondwanaland breakup; d.) Chron M0 (121.0 Ma); e.) Chron C33 (74.5 Ma); f.) Present day situation. Abbreviations are: AFR–Africa, ANT–Antarctica, AUS–Australia, ARGO–Argo transitional plate, BUR–West Burma Block, CIB–Central Indian Basin, EBP–Elan Bank Plate (Enderby Basin), ICH–Indochina, MG–Middle Greater India, NCH–North China, SBM–Sibumasu Block, SCS–South China. Numbers represent Plate IDs used in our rotation file.

Greater India/India–Australia was joint by the time of chron M10 (130.8Ma).

3.2. Trench-parallel Age Profiles and Convergence Rate Histograms Through Time

A 4000-km long profile has been digitised parallel to the present day Sundaland Trench in the Indian Ocean from approximately Northwest Sumatra down to off southeast Java (compare Figure 1, 7j and 8). Along this profile we have computed the age of the subducting oceanic lithosphere and the convergence rate at the 2000-km point (Figure 8), which is located off central Sumatra in the Indian Ocean. For the reconstructions, the position of the profile has been fixed relative

to the Sibumasu Block (Figure 1) through time and the ages of the subducting Tethys and Indian Ocean lithosphere have been extracted and plotted accordingly. The program Seaflow was used to calculate the convergence rates in 5 My timesteps on the base of our finite rotations (Figure 8). Trench-parallel profiles of the age of the subducting oceanic plate and convergence rates through time at specific points along a subduction zone significantly improve the understanding of tectonic forces acting on the margin of the overriding plate.

3.3. Pre-160 Ma Setting

In Paleozoic and Early Mesozoic times continental terranes derived from northeastern Gondwanaland were accreted

to the southern Eurasian margin by opening and closing of the Paleo- and Mesotethys to form a "Sundaland core" [*Hall,* 2002; *Metcalfe,* 1996; *Audley-Charles,* 1988]. This collage of tectonic blocks was most likely a continental promontory that extended southeastward and was bounded by subduction zones to the east (Proto-Pacific), south and west (Tethys and Proto-Sunda Trench) [*Stampfli and Borel,* 2002; *Metcalfe,* 1996; *Ricou,* 1995] (Plate 1a). Subduction of Mesotethyan ocean floor had already begun after the Sibumasu (Sino-Burma-Malay-Sumatra) continental sliver (Figure 1) had been amalgamated to Sundaland in Permo-Triassic times [*Metcalfe,* 1999], coinciding with the oldest Sumatran magmatic arc described by *McCourt et al.* [1996] (Plate 1a).

3.4. Late Jurassic (160–140 Ma)

The Late Jurassic Mesotethys was a triangle-shaped ocean with a passive southern and active, northeastward subducting, northern margin. The active spreading ridge that opened the Mesotethys and separated the Sibumasu continental sliver from northeastern Gondwanaland had travelled up into the northern half of the Mesotethys. Subduction direction was northeastward, changing slightly to a more northerly direction with the rifting and active seafloor spreading around northern Gondwanaland that separated the West Burma Block (and probably associated smaller continental slivers like the Sikuleh-Natal terranes of present-day western Sumatra, Figure 1) from the present day Australian Northwest Shelf. The age of subducted ocean-floor along the Proto-Sunda Trench at 160 Ma ranged from 100–120 my in the northwest to approx. 20–30 my in the southeast. The age profile became younger in the Early Cretaceous (Figure 7b) as the active spreading ridge approached the trench (Plate 1b). Convergence rates in this time interval start with around 90 mm/yr and increase significantly with the opening of the Argo Abyssal Plain and spreading around the northern Gondwanaland margin to rates of up to 135 mm/yr (at 150 Ma; Figure 8). Slightly earlier than the seafloor spreading around the northern part of Australian Gondwanaland, the dispersal of Gondwanaland started with the separation of Madagascar/Greater India from Africa in the Mid Jurassic, around 165 Ma [*Coffin and Rabinowitz,* 1988; 1987]. Most likely, both spreading systems were linked around the northern margin of Greater India, suggested by the same azimuth of fracture zones in the Argo Abyssal Plain and Somali Basin at 160 Ma. To the east the Neotethys ridge presumably continued at least up to the present-day Bird's Head region of Irian Jaya. Uncertainties still exist in the geometry and plate tectonic setting of the Tethys-Pacific realm north of Irian Jaya/Papua New Guinea at this time.

3.5. Early Cretaceous (140–120 Ma)

By 140 Ma, the Mesotethys spreading ridge reached the Proto-Sunda Trench and was already subducted along the southeastern, but not in the northwestern part of the trench. The age of the subducted crust along trench was younger than 20 my (Figure 7 and Plate 1b). *McCourt et al.,* [1996] report extensive I-type, subduction related plutonism in Sumatra in Mid Jurassic to Early Cretaceous times. According to our model the Mesotethys spreading ridge was fully subducted by 130 Ma, and gradually older crust on the southern side of the Mesotethys ridge started being subducted. Oblique subduction of an active spreading ridge is normally associated with slab window formation and anomalously thermal (increased heat flow), physical and chemical effects in the surrounding mantle. Arc volcanism results mainly from hydration of the mantle wedge from the subducted slab [*Thorkelson,* 1996]. The formation of a slab window places hot and dry sub-slab mantle directly beneath the mantle wedge, causing a decrease in hydration and an increase in temperature. Therefore arc volcanism is likely to be diminished and replaced with volcanism of MOR or rift-type affinity [*Thorkelson,* 1996]. *McCourt et al.,* [1996] describe the obduction of ophiolites and the termination of one phase of subduction related plutonism at about 129 Ma, relating it to the accretion of the Woyla Terrane. According to some recent field investigations of *Barber* [2000] in western Sumatra, the Woyla terrane is regarded as accretionary complex underlain by continental basement, that was separated from the Sundaland margin in an extensional strike-slip regime during Late Jurassic-Early Cretaceous, opening the marginal Asai-Rawas-Peneta basin. According to our model this extension is likely to be related to the subduction of older Mesotethyan oceanfloor and associated hinge rollback prior to 140 Ma. Youngest fossils in the Sumatran Woyla Group indicate an Aptian–Albian age (approx. 120–100 Ma) for the closure of this basin [*Barber,* 2000]. Subduction rates drop suddenly in the time between 140–135 Ma to 30 mm/yr due to the subduction of the spreading ridge and a slightly changed spreading directions from a northward subduction towards a more NNW directed subduction due to the newly established spreading system separating India and Australia (Figure 8). After this plate tectonic reorganisation the rates increase again to values of around 80–90 mm/yr.

In our reconstruction, the synthetic isochrons shown for the Mesotethys are based on the assumption of symmetrical seafloor spreading and constant spreading velocities for the evolution of the Mesotethys. As no in situ record of this oceanic lithosphere exists, the error in the location of the spreading ridge and computed seafloor age might well be in excess of 10 Ma. Considering these error estimates, it could well be that the Mesotethys spreading ridge was subducted at some-
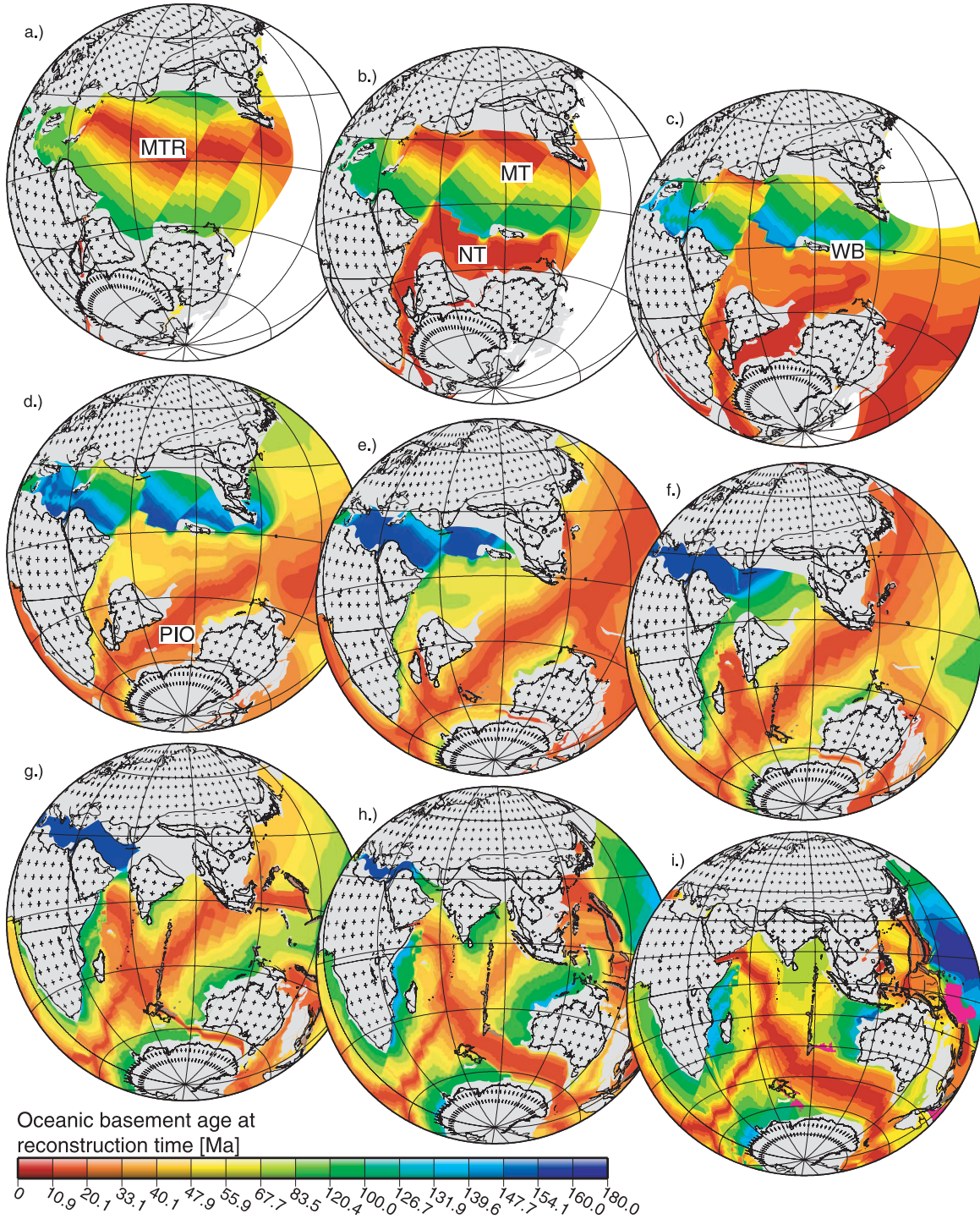
Plate 1. Paleo age grids for the time from 160 Ma to the present in 20 My steps. a - 160 Ma; b - 140 Ma; c -120 Ma; d - 100 Ma; e - 80 Ma; f - 60 Ma; g - 40 Ma; h - 20 Ma; i - present day. Colours show age of the oceanic basement in millions of years at a given reconstruction time. Tectonic blocks are outlined in black, continental and assumed shelfal areas in grey. Abbreviations are: MTR-Mesotethys spreading ridge; MT-Mesotethys; NT-Cenotethys; WB-West Burma Block; PIO-Proto-Indian Ocean.
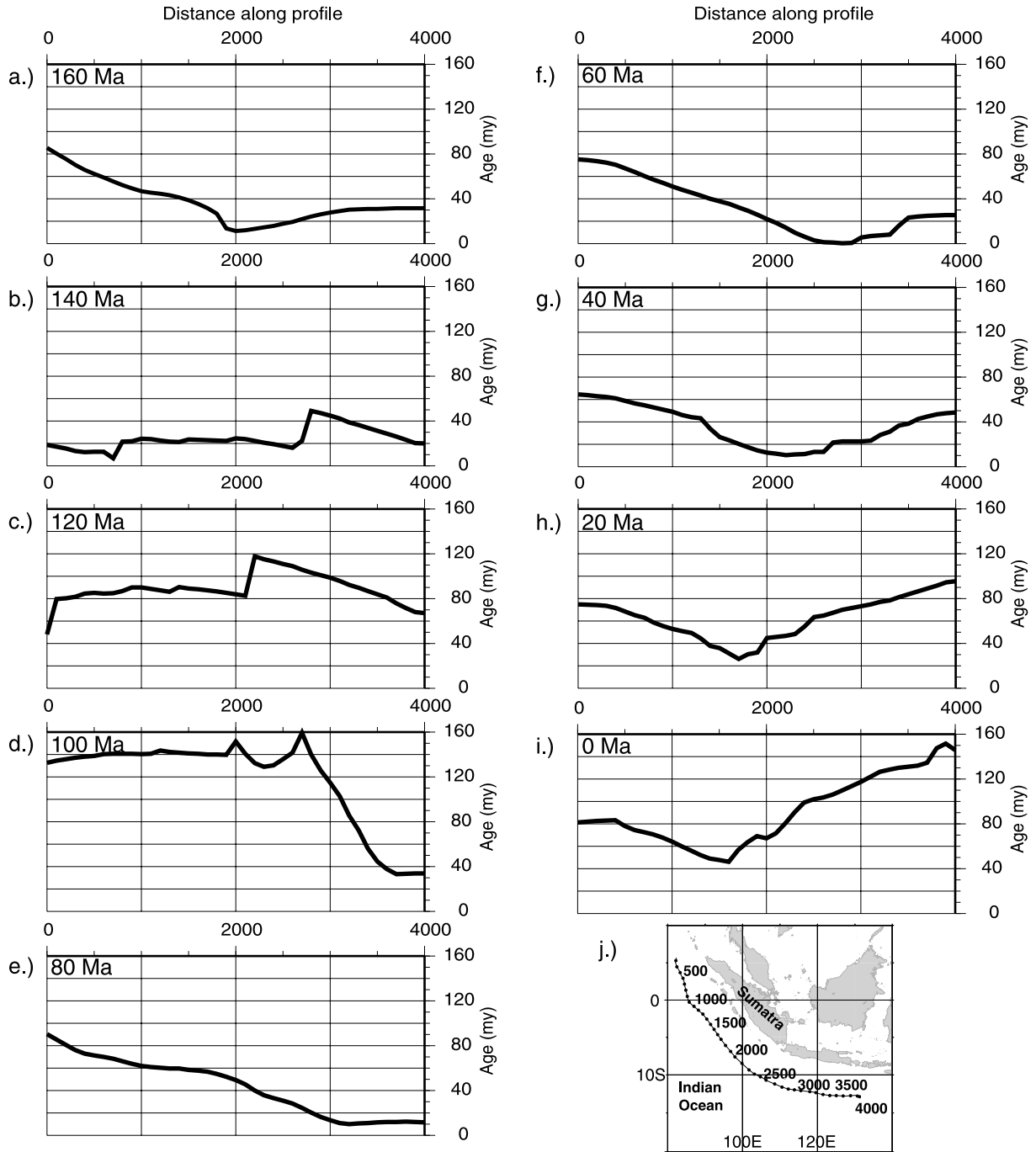
Figure 7. Age of the subducted oceanic lithosphere along a 4000 km-long, trench-parallel profile for the reconstruction times: a.) 160 Ma; b.) 140 Ma; c.) 120 Ma; d.) 100 Ma; e.) 80 Ma; f.) 60 Ma; g.) 40 Ma; h.) 20 Ma; i.) present-day; j.) location of the profile in present day coordinates.

what younger times compared with our model. In this case we would argue in favour of the observed geological record and link the period of diminishing arc volcanism [*McCourt et al.,* 1996], obduction of ophiolites and closure of the marginal basin at around 130–120 Ma to the subduction of the Mesotethys spreading ridge. Further support for this hypoth-
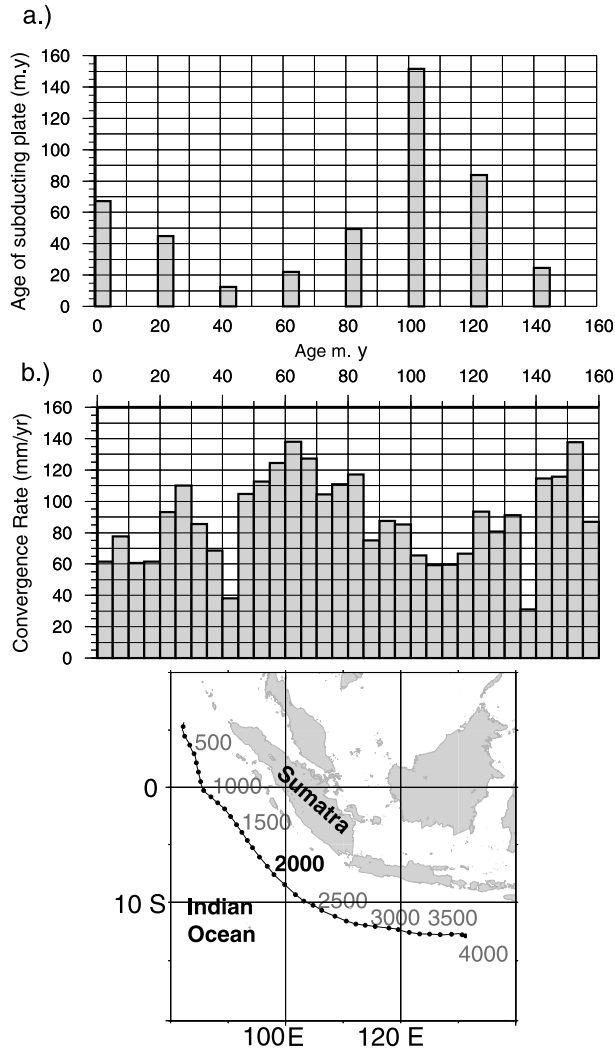
a.)

b.)

Figure 8. Age of the subducted oceanic lithosphere (a.) at the 2000 km point of the profile (lowest figure) through time and convergence rates (b.) in 5 My time steps from 0 to 160 Ma.

esis is given by *Barber* [2000] who reports oceanic crustal material and slices of mantle incorporated in the oceanic assemblage of the Woyla Group, recognised all along the west coast of Sumatra. Additionally *Barley et al.* [2003] relate composite tonalite-granodiorite batholiths in the Burmese Mogok Magmatic Belt to subduction of oceanic crust, indicating more likely the continued subduction of oceanic lithosphere beneath SE Asia rather than the accretion of a larger continental sliver.

At about 132 Ma rifting between India–Australia and India–Antarctica in the region of the subsequent Enderby Basin [*Gaina et al.,* 2003] begun, initiating the Proto-Indian Ocean. This event is associated with a further change in subduction direction of Tethyan ocean lithosphere in a northward

direction. Rifting and seafloor spreading between India and Australia started in the Valanginian (around 135 Ma) [*Mihut,* 1997], contemporaneous with the southward ridge jump in the Argo Abyssal Plain (Figure 3 and 5). According to *Mihut and Müller* [1998b] the oldest identified magnetic anomalies in the Cuvier and Perth Abyssal Plains are M10–M14 (130.8–135.8 Ma). This event was followed by a slight counterclockwise rotation of the spreading direction (10–15°) in the Argo Basin. At the same time the spreading center north of India became extinct. Together with the subduction of the Mesotethys spreading ridge and the closure of the marginal Asai-Rawa-Peneta Basin the change in spreading direction and thus in subduction direction along the southern Eurasian margin could have caused the termination of I-type subduction-related plutonism in Sumatra, as it was also suggested by *McCourt et al.* [1996].

3.6. Mid Cretaceous (120–100 Ma)

Around 120 Ma, the seafloor age being subducted along the Sundaland margin had further increased to 55–70 my in the northwest and to 80–100 my in the southeast (Plate 1c and Figure 7c). Spreading around Greater India/Madagascar divided Gondwanaland steadily without any major tectonic events. This might have been caused by a lack of detailed magnetic anomaly information due to the CNS Zone (83.5–118 Ma). Convergence rates for this time interval show "average" values, ranging between 60–70 mm/yr, related to continuous spreading in the Enderby Basin and in the abyssal plains of Western Australia.

McCourt et al. [1996] report an I-type, subduction related plutonic belt in Sumatra, that probably extended as far as present-day central Burma [*Mitchell,* 1993]. We relate this renewed subduction-related magmatism to the subduction of the southern flank of the Mesotethys spreading ridge with an increasing age of the subducted oceanic slab, that has likely triggered extension along the Sundaland margin in the time between 120–80 Ma (Plate 1c-d and Figure 7c-d).

3.7. Early Late Cretaceous (100–80 Ma)

The tectonic history for the eastern Tethys between 100–80 Ma is dominated by a major plate reorganisation at around 100–95 Ma. North-South oriented seafloor spreading along the Wharton Basin ridge and the Southern Ocean [*Gaina et al.,* 2003] most likely caused a change to northward- directed subduction along the Sundaland margin, resulting in oblique convergence. In Coniacian/Santonian times continental fragments drifting together with the West Burma Block (?Sikuleh-Natal Blocks?) have reached the southeastern part of the Proto-Sundaland Trench. Along the northwestern part of the

trench the last remnants of a narrowing Mesotethys were subducted, with slab ages greater than 150 Ma (Plate 1d and Figure 7d). The subduction of such old oceanic lithosphere might have caused slab roll back and associated extension along the western part of the Southeast Asian Tethys margin. *Mitchell* [1993] describes a phase of crustal extension of the Late Cretaceous magmatic arc (Mogok belt) in present-day central Burma, which he related to a probable retreat of the subducting plate. The rates of convergence off Sumatra show a major increase at around 85–90 Ma that is likely to be related a slight increase in spreading velocities at the Antarctic-Australia spreading ridge, pushing the Australian Plate and associated spreading systems in the north further towards the SE Asian margin.

3.8. Late Cretaceous-Paleocene (80–60Ma)

An initial contact of the West Burma Block with the Proto-Southeast Asia mainland occurred at the end of the CNS most likely in the vicinity of present day northern Sumatra/western Malay Peninsula (Plate 1e). The modelled time for this event depends on the shape and architecture of the Asian margin at that time, as smaller arc fragments and marginal basins might have been situated further south than the main continental margin. Possible changes of the spreading direction and velocities within the CNS might further complicate the exact dating of this event. The absence of plutonic rocks for the time between 75–60 Ma in Sumatra [*McCourt et al.,* 1996] is probably the strongest argument supporting a later collision of the West Burma Block along the central and northwestern part of the Proto-Sundaland Trench. The obliqueness of the collision of the West Burma Block with mainland Southeast Asia (Plate 1e–f) might have disintegrated the continental sliver into separate smaller blocks along the margin. After the amalgamation of this continental block (and associated smaller ones), the subduction zone jumped to the south, with the oldest Neotethyan ocean floor being subducted northward beneath the southeastern Eurasian margin. *Socquet et al.* [2002] report the obduction of ophiolites on metamorphic Mesozoic series of the Indo-Burman Ranges in Maastrichtian times (70–65 Ma) and related this to the subduction of a piece of thinned continental crust in the Campanian (83–72 Ma). The fairly old oceanic lithosphere (approx. 100–120 Ma) being subducted after the amalgamation on the western/southern side of the accreted blocks (Figure 7e–f) might have driven the northward acceleration of Greater India at that time due to increased slab pull forces, which is also supported by the convergence rates along the Sundaland Trench in this time interval (Figure 8). The rates reach a peak value of 140 mm/yr between 60–65 Ma that is related both to trench pull of the subducted old Neotethyan lithosphere and increased

spreading along the active Wharton Basin ridge and the Antarctic-Australia spreading system.

According to our model, the easternmost part of the active Wharton Basin ridge collided with the southernmost tip of the Proto-Sunda Trench around 75–70 Ma. Again, the exact timing of this event strongly depends on the position of the subduction zone at this time, as well as on the exact geometry of the now subducted portion of the Wharton Basin ridge.

3.9. Paleocene–Eocene (60–40 Ma)

With subduction of gradually younger Neotethyan ocean-floor as well as the active Wharton Basin spreading ridge (Plate 1f–g and Figure 7f–g), the slab dip might be expected to have decreased and caused further compression along the Tethyan Eurasian margin. A new subduction regime following the 75–60 Ma deformational event is expressed in a short-lived but extensive plutonic episode in Sumatra and probably further north [*McCourt et al.,* 1996]. The subduction direction along the Java Trench was fairly orthogonal, whereas convergence along the northwestern part (present-day Western Thailand, Burma) of the trench was oblique with an angle of about 30–40º (Plate 1g). Subduction of the Wharton Basin ridge has not been directly supported by geological observations in southern Southeast Asia [*Hall,* 2002], but the cessation of subduction-related I-type plutonic activity in Sumatra in the Middle Eocene (50–40 Ma) might be an indicator, that the active Wharton Basin ridge had been subducted beneath the Java/Sumatran Trench. Also, extension that started in Sundaland in the Paleogene, expressed by graben formation, could have been related to ridge subduction. Convergence rates dropped again from the 60 Ma peak continuously to 40 mm/yr in the 40–45 Ma time interval, related to the cessation of spreading along the Wharton Basin ridge and its following subduction (Figure 8).

3.10. Eocene–Early Miocene (40–20 Ma)

Our reconstructions suggest that a hard collision between the northeastern tip of India and the western part of the Burma Block started around 30–28 Ma in the Oligocene and caused strike slip motions along the Shan Boundary Fault. *Ni et al.* [1989] and *Mitchell* [1993] assume that at least 480 up to 1100 km of dextral strike slip motion occurred along this suture, with India mechanically dragging the West Burma Block northwards along the Sagaing Fault. Most likely the northern part of the Burma Block was sheared off by the leading edge of the Indian Plate and thrust beneath the forming eastern Himalayas. Subsequent NNE directed convergence between India and Eurasia gave rise to the Indo-Burman Ranges.

Spreading of the Wharton Basin ridge ceased around chron 18/19 (around 43 Ma) [*Lee and Lawver,* 1995; *Liu et al.,* 1983], with the northernmost extend of Greater India reaching the southern Eurasian margin at around 50 Ma according to *Replumaz and Tapponier* [2003]. The age of subducted oceanic lithosphere along the Sunda Trench varied roughly from 20–55 my in the southeastern part of the trench to 40–100 my in the northwestern part (Plate 1g–h and Figure 7g–h. In the central part below Sumatra and Java, young oceanic lithosphere of the Wharton Basin was subducted. In the southeast, gradually older Neotethys ocean floor (approx. 20–85 Ma at that time) is subducted orthogonally below Southeast Asia. *McCourt et al.* [1996] describe the subsequent onset of plutonic activity after NNE-directed subduction. Opening and closure of various back arc basins in the Western Pacific [*Gaina and Müller,* in press; *Hall,* 2002] complicated the tectonic history of the Southeast Asian Pacific margin.

After the cessation of spreading along the Wharton Basin ridge, the convergence rate along the SE Asian margin have been mostly controlled by the SE Indian Ridge system and trench pull related to the subduction of older Neotethyan lithosphere along the Indian Himalayan margin. Rates increase again after 40 Ma (Figure 8) likely related to the trench pull of the Neotethyan slab and increased spreading along the SE Indian ridge. This causes a segmentation of the Eurasian margin, as in the westernmost part (Himalaya) increasingly old Neotethys oceanfloor is subducted (resulting likely in extension due to hinge rollback) until Greater India collided with the margin. In the eastern part (Sundaland Trench) young oceanic lithosphere and the active Wharton Basin ridge was subducted (Plate 1g–h) which likely resulted in a more compressional regime along the southeastern Sundaland margin.

3.11. Early Miocene–present (20–0 Ma)

From 20 Ma onwards, the tectonic evolution of Southeast Asia has been dominated by the India–Eurasia collision, lateral extrusion and block rotations [*Replumaz and Tapponier,* 2003; *Hall,* 2002]. Plate 1i shows the present day configuration in which the Indian Plate is being subducted northward beneath the Himalayas and the West Burma Block. An intraoceanic compressional zone in the Central Indian Basin revealed a new plate boundary between the Australian and Indian Plates that might have started in the Early Miocene [*Royer and Chang,* 1991]. The strike slip motion between the West Burma Block and the Sibumasu continental sliver is accommodated by N–S directed spreading in the Andaman Sea. Extensional tectonics due to oblique convergence caused the subsidence of the Inner-Burman Tertiary Basin and continuing subduction of Indian Ocean lithosphere along the Indonesian part of the Sundaland trench. Along the northern

margin of the Australian plate the last remnants of the Neotethys Ocean (up to 160 Ma) are subducted beneath Southeast Asia. The age profile along the Sunda subduction zone is fairly homogeneous by now, with crustal ages in the north and southeast of 80–160 my and the central part of the Wharton Basin Ridge dated at 40–80 my (Figure 7h–i) is now being subducted beneath Sumatra (Plate 1i). Convergence rates are lower than in the 40–20 Ma interval due to the hard collision of India with the Eurasian margin and the related deceleration of India (Figure 8). Subduction of increasingly older lithosphere of the northern Australian abyssal plains might have triggered an increase in hinge rollback along the southeastern Sundaland trench, thus aiding the lateral extrusion of SE Asia caused by the India-Eurasia collision.

4. OCEANIC GATEWAY EVOLUTION

The evolution of oceanic gateways, seafloor topography and the distribution of land and sea surface are the most important factors controlling ocean currents and the world climate. Changes in ocean basin topography and the width of oceanic gateways cause changes in equatorial currents, mid and low latitudinal overturning and gyre transport [*Bice et al.,* 1998]. "Realistic" paleobathymetric maps showing the depth of ocean basement are not only useful to constrain ocean currents and paleoclimate, but can also be used as base-maps to constrain sediment accumulation through time and present-day sediment thickness.

The Tethys Ocean plays an important role for determining the Cretaceous climate and ecosystems. The separation of the West Burma Block (and probably associated smaller continental blocks) from the northern Gondwanaland margin and seafloor spreading in the southern Tethys changed the circulation patterns in the Tethyan Ocean towards a more restricted oceanic environment south of the active spreading ridge/continental sliver (Plate 2a–c).

Spreading and separation of Madagascar/India from Africa started around 165 Ma [*Coffin and Rabinowitz,* 1987; 1988]. Extension and the final separation of Africa/South America and Antarctica opened a "central Gondwana gateway" with marine connection from the Southeast Pacific to the Central Tethys [*Lawver et al.,* 1992]. About 20 my later, seafloor spreading in the Enderby Basin area caused the opening of a second "eastern Gondwanaland Gateway" between Antarctica, Greater India and Australia, with a marine connection to the eastern Tethys, isolating Madagascar and Greater India. Drifting of the West Burma Block across the Tethys influenced the circulation patterns of the Meso- and Neotethys (Plate 2c–g).

The separation of India from Australia and Africa, and later Africa and South America from Antarctica opened a first, gradually deepening marine gateway, connecting the Southwest
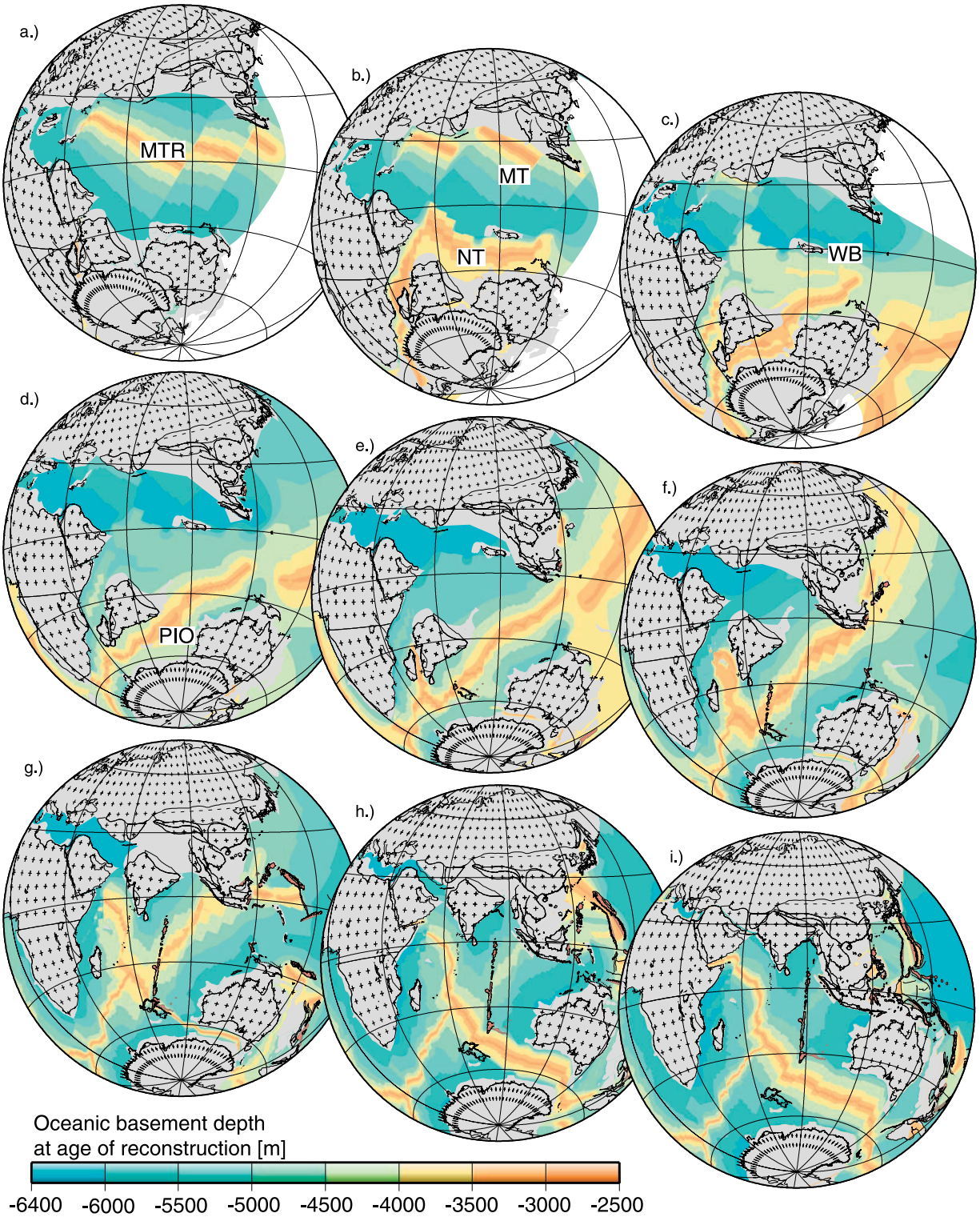
Oceanic basement depth
at age of reconstruction [m]

-6400   -6000   -5500   -5000   -4500   -4000   -3500   -3000   -2500

Plate 2. Paleo depth to basement grids for the time from 160 Ma to present in 20 My steps. a - 160 Ma; b - 140 Ma; c -120 Ma; d - 100 Ma; e - 80 Ma; f - 60 Ma; g - 40 Ma; h - 20 Ma, i - present day. Colours show depth to oceanic basement at a given reconstruction time. Tectonic blocks are outlined in black, continental and assumed shelfal areas in grey. Abbrevia-

Pacific with the eastern and central Tethys. In Santonian/Coniacian times (85–80 Ma) the West Burma continental terrane was accreted to the Southeast Asian mainland in the vicinity of present day western Thailand, while the active spreading ridge of the Wharton Basin began to be subducted beneath Southeast Asia from approx. 70 Ma onwards. At the same time, the Proto-Indian Ocean gateway reached its maximum width (Plate 2e–f). but the active mid-ocean ridge in the Wharton Basin might have acted as a bathymetric barrier for the water circulation between the Pacific and/or Atlantic and the Neotethyan oceans and affected the salinity of these basins. *Kutzbach et al.* [1990] simulated a strong east–west flow along the Equator in the absence of such a barrier. As this barrier deepened through time, deep and intermediate ocean circulation would have encountered other obstacles, like the newly formed mid ocean ridges in the Indian basin (Plate 2g).

Increasing spreading rates between Australia and Antarctica contributed to the opening of the circum-Antarctic gateway that started to play a major role in the ocean circulation and sedimentation patterns in the Indian Ocean. Shallow waters common in the incipient Indian ocean (Plate 2e, f) are replaced by deeper waters and as a result carbonate sedimentation gave way to detrital sediments [*Davies and Kidd,* 1977] which were heavily eroded once the Antarctic Circum Current was established triggered by the opening of the Drake Passage in the Oligocene. Old, deep basins situated north of Australia in the Eocene have been gradually replaced by shallower water that covered the newly formed backarc basins (Caroline and Solomon seas). A deep water passage (around 4500 m), that connected the Indian and Pacific oceans might have existed northwest of the Caroline basin until about 20 Ma when the renewing of the clockwise rotation of the Philippine and Caroline sea led to almost complete subduction of the Molucca Sea, a remnant of the Pacific abyssal plain [*Gaina and Müller,* in press]. Narrowing of the Indonesian gateway greatly influenced the heat transfer between the Pacific and Indian oceans by restricting the amount of water volume. According to our reconstructions, more than 3000 km of shortening occurred between Australia and Sundaland since Late Eocene. The closure of the Indonesian gateway by the collision of the Australian plate with the SE Asian margin around 3–4 Ma is regarded as cause for the aridification of East Africa and believed to have major impact on the global climate as it switched off the source of flow of warm South Pacific waters causing a decrease of Indian Ocean surface temperatures [*Cane and Molnar,* 2001].

5. CONCLUSIONS

The paleo-age and paleo-depth to oceanic basement maps shown here for the Tethyan Ocean help to correlate tectonic events such as compression, extension and anomalous heating on the overriding southern Eurasian margin with the evolution and subduction history of the Tethyan Ocean along the Sundaland trench and its successors. The model will significantly improve the understanding of the interactions between subduction of Tethyan Ocean lithosphere and the overriding SE Asian platelets in terms of basin formation, sedimentation patterns and uplift. Using this approach it might be possible to create a refined plate tectonic framework for the Mesozoic-Cenozoic tectonic evolution of Southeast Asia relating.

Our new plate model also has implications for paleoclimate modelling and reconstruction of sedimentation patterns within the Tethys and Indian Ocean and provides improved boundary conditions for the modelling of paleoceanic currents as it is possible to investigate the effect of spreading ridges acting as bathymetric barriers within the Tethys. The paleo-depth to basement grids can also be used for constraining the evolution and migration of floral and faunal regions.

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