Outcomes

REVISED INDIAN OCEAN MODEL

In the Jurassic, Eurasia's southern margin was composed of the Karakoram, West Qiangtang and Lhasa terranes, which were all derived from East Gondwana. Argoland formed East Gondwana's northern margin. East Gondwana and Eurasia were separated by the ~7000 km-long MesoTethys Ocean. A subduction zone spanned the southern Eurasian margin.

At ~155 Ma, Argoland began migrating north from Gondwana, creating the CHRISP Jurassic oceanic crust (J, Fig. 3.6) by the crust that would become the Zenith and Wallaby Plateaus (ZP and WP, Fig. 3.6), off West Australia. Meanwhile, the Lhasa terrane (L, Fig. 3.6) migrated west from the West Qiantang terrane (Q, Fig. 3.6) and beneath it, an intra-oceanic arc (IA, Fig. 3.6) and subduction zone (thick dashed blue line, Fig. 3.6) advanced towards the equator. This new spreading regime was isolated from the western MesoTethys (north of Africa) by a major transform fault, stretching roughly from East Africa to Iran. The central MesoTethys spreading ridge became extinct (light blue line, Fig. 3.6a) due to the initiation of the new spreading centre (thick grey line, Fig. 3.6a). The subduction zone was still located south of the Lhasa terrane.

At ~135 Ma (Fig. 3.6b), the Lhasa terrane was still migrating southwest, creating a fore-arc (Xigaze) and back-arc basin (Kohistan-Ladakh arc) between Lhasa and Karakoram-Qiangtang terranes. Argoland and the oceanic arc were approaching the equator. The two subduction zones were still operating south of the oceanic arc and south of the Lhasa terrane. Starting from a triple junction off NW Australia, Greater India and its northern indenter, the Gascoyne block, began to unzip from Gondwana.

At ~125 Ma (fig. 3.6c), West Argoland collided with the western portion of the oceanic arc causing the arc and Lhasa terrane to retreat back to the Eurasian margin. One subduction zone was located south of the Qiangtang terrane, subducting the back-arc basin to the Lhasa terrane as it advanced back towards Eurasia. The other subduction zone was located south of the oceanic arc, and was subducting the MesoTethys between Argoland and the arc. Several Indian micro-blocks were transferred to Australia, including the Naturaliste (NP, Fig. 3.6), Wallaby and Zenith Plateaus, and Batavia and Gulden Draak Knolls (GBK, Fig. 3.6) at ~128, 127, 124 and 108 Ma, respectively. The CHRISP Jurassic crust was temporarily transferred along with the Zenith Plateau to the Australian plate. Sri Lanka (SL, Fig. 3.6) had just detached from the West Enderby margin and began to rotate from India until ~115 Ma, when the Elan Bank, along with most of the Enderby Basin, was transferred to Antarctica by a northward ridge jump.

By ~95 Ma (Fig. 3.3d), the Lhasa terrane had accreted to Eurasia, forming the BNS ~100 Ma. The south Lhasa terrane subduction zone was obliquely subducting the oceanic crust formed by the oceanic arc while the subduction zone south of the arc was now obliquely subducting both the NeoTethys and MesoTethys, either side of Argoland. Greater India began relative motion from Madagascar ~98 Ma as India began to advance north towards the arc. Seafloor spreading progressing from south to north, separating India from Madagascar between 94-84 Ma. The ~98 Ma change in India's motion formed the curved Kerguelen and Wharton Basin fracture zones, and the prominent conjugate 85°E Ridge and Kerguelen Fracture Zone, as a leaky transform fault. The Marion hotspot formed the conjugate Conrad and Madagascar Rises and the

CHRISP Jurassic sliver was also transferred to the Wharton Basin at this time. The ANS were created ~74 Ma by the Conrad hotspot.

At ~55 Ma (Fig. 3.6e), Greater India collided with the oceanic arc, terminating Argoland and the subduction zone south of the arc. The subduction zone south of the Lhasa terrane continued to operate as India progressed north. The Gascoyne block (GB, Fig. 3.6e) collided with the arc or with Myanmar, depending on the geometry of the arc.

At ~35 Ma (Fig. 3.6f), Greater India (and arc) collided with the Eurasian margin, starting at Iran and Myanmar ~40 Ma, and began to shift West Myanmar northwards to its current location, southeast of the Lhasa terrane. Greater India reached the Kohistan-Ladakh arc ~35 Ma, and continued to suture eastward along the curved southern margin of the Lhasa block until it reached Nagaland ~10 Ma.

CONCLUSIONS

This study has assembled a plate kinematic model for the Indian Ocean that builds on previous reconstructions, which have suffered inconsistencies due to diverse methodology, localised frameworks and a lack of data, including the subduction of seafloor along the Java-Sunda trench. The Eurasian and Antarctic margins are not easy to sample, nor are submarine plateaus and abyssal plains but the advent of new technology and continued efforts to gather data have helped overcome such adversities. New data gathered offshore West Australia, and an iterative approach of combining potential field interpretations with regional-scale plate kinematic models, has forced this study to abide by many more tectonic constraints, from different areas of the Indian Ocean. Our model can now reconstruct most of the major tectonic features in the Indian Ocean, and match the geological observations from the Eurasian margin. The major problems this work has solved include:

Linking the Jurassic and Cretaceous seafloor corridors

We know that Argoland rifted north from East Gondwana in the Late Jurassic because most magnetic anomaly interpretations (including ours) for the Argo Abyssal Plain, off NW Australia, begin ~M25/155 Ma. However, there is disparity in how to link this Jurassic seafloor to the Cretaceous seafloor in the Gascoyne and Cuvier abyssal plains, off West Australia. One model suggested a triple junction, others a pseudofault. The most recent study proposed that the Jurassic anomalies continued into the Gascoyne Abyssal Plain, and also featured a southward ridge jump in the Argo Abyssal Plain ~136 Ma. Though our model does not continue the Jurassic spreading beyond the Argo

Abyssal Plain, it does incorporate the 136 Ma ridge jump and a triple junction off NW Australia so that Greater India could gradually 'unzip' from East Gondwana, stretching the Exmouth Plateau.

Greater India and the submerged plateaus

A Jurassic rock sample was dredged from the Cretaceous Wharton basin, ~1000 km offshore West Australia, during the IFM-Geomar CHRISP 2008 research cruise. Incorporating this into the model enforced a smaller extent for the part of Greater India, once conjugate to the Exmouth Plateau (the Gascoyne block), delaying its collisions. Greater India was even further reduced when portions of its crust were transferred back to Gondwana via ridge jumps during its early migration. These include the Wallaby, Naturaliste and Zenith Plateaus, which originally filled the gap between the Gascoyne block and remainder of India. They were transferred to the Australian plate ~128, 127 and 124 Ma, respectively. Seismic surveys and recent dredging of the Wallaby Plateau by Geoscience Australia support its continental origins but the Zenith Plateau has not yet been investigated. We also modelled the Gulden Draak and Batavia Knolls, located nearly 1500 km west of Perth, as Indian continental fragments, originally conjugate to the Naturaliste Plateau. These Knolls were transferred to the Australian plate ~108 Ma. Continental rocks were dredged from the Knolls in late 2011. We also model the Elan Bank, off East Antarctica, as an Indian fragment transferred to Gondwana ~115 Ma.

Linking the Antarctic and Australian spreading corridors

Previous studies have attempted to link the seafloor spreading corridors off West Australia and East Antarctica, a continuous margin at the time. The models based on seafloor spreading anomalies in the West Enderby basin, off East Antarctica, posed tectonic problems, including a ~500 km seafloor 'gap' in the Perth Abyssal Plain, off SW Australia, and ~600 km of two-way strike-slip motion between India and Madagascar. Greater India was still attached to Madagascar when it began migrating west from Gondwana, but it was essentially wedged between the Wallaby-Zenith fracture zone, off West Australia, and Madagascar. Our magnetic anomaly interpretations offshore West Australian and East Antarctica allow a slight anticlockwise 'unzipping' motion for Greater India from Gondwana. In this way, India could avoid excessive compression in the 'giant vice'. Our younger magnetic anomalies in the Enderby basin also ensure that similar amounts of oceanic crust formed in the Perth and Enderby basins, simultaneously avoiding excessive, two-way strike slip motion in between India and Madagascar.

The curved fracture zones and India-Madagascar separation

Our model is the first to accurately reconstruct the curved fracture zones in the Wharton and Enderby basins, off Australia and Antarctica, respectively. We determined that they are coeval and formed ~99 Ma. They formed as India, with the Seychelles and Laxmi Ridge continental fragments, began to migrate north, away from Madagascar, which remained fixed to Africa. Separation from Madagascar was gradual and progressed from south to north from ~94-84 Ma. The Marion and Crozet hotspots emerged southeast of

India ~105 Ma, which may have forced a boundary between India and Madagascar, allowing India to move north. This major change in plate motion also formed the Kerguelen fracture zone, in the Enderby basin, and its conjugate, the 85°E Ridge, offshore East India, likely as a spreading ridge, which transformed into a leaky transform fault. At this time, the Conrad Rise, Crozet and Marion hotspots were located near the Antarctic, Indian and Madagascan margins, respectively, and all less than 1000 km from the nascent Rodriguez triple junction. The Marion hotspot formed the Madagascar and Conrad Rise conjugate LIPS from ~100-80 Ma, and the Conrad hotspot formed the Afanasy Nikitin Seamounts, southwest of the 85°E Ridge, from ~74 Ma.

Evidence for collisions in Eurasia and SE Asia

Argoland accreted to an equatorial intra-oceanic arc ~126 Ma, which is evidenced by an obduction event recorded in zircons from ophiolites located in the Yarlung-Tsangpo suture zone, located between the Indian and Eurasian blocks. East Argoland accreted to Sumatra ~80 Ma, possibly re-attaching the Woyla Terranes back to its Sumatra's margin. West and Central Argoland, as relatively thin (~200 km-wide) continental ribbons, were likely destroyed along the island arc subduction zone, where Greater India also accreted ~55 Ma. Greater India's indenter, the Gascoyne block, reached West Burma and the eastern edge of the intra-oceanic arc ~50 Ma, as India continued to migrate north. Final collision between Greater India (accreted to the intra-oceanic arc) and Eurasia did not take place until ~35 Ma, which is supported by recent evidence of Upper Eocene marine sediments, located near Mount Everest.

Future work and relevance

This study is a first attempt at formulating a regional tectonic model for the Indian Ocean and only addresses the problem in a resolution suitable for that scope. Refining the model at a greater resolution would be more beneficial but arguably more difficult to achieve given that some of the plate tectonic constraints were hard to incorporate into even this limited resolution model. The study only addressed the pre-CNS seafloor spreading, which mainly formed the East Indian Ocean, so there is also scope to refine the Late Cretaceous-Cenozoic plate motions between Madagascar, the Seychelles, Laxmi and Chagos-Laccadive Ridges and India, as well as fine-tune the evolution of the Carlsberg, Central and Southwest Indian Ridges. We will be addressing these and other issues in the Australia-India Strategic Research Fund (AISRF) collaborative project between our group, the National Institute of Oceanography, Goa, India, and the Australian National University, Canberra, throughout 2012-2013.

The location of the continent-ocean boundary (COB) used in this model could also benefit from further investigation. This study did not encompass a detailed examination of seismic or potential field data, instead adopting COB outlines from a variety of published sources. The model will generally comply with COB variations of up to ~50 km but tectonic gaps/overlaps could arise depending on the location of the COB within the Mesozoic Gondwana reconstruction. For example, an increase in the COB between Southwest and Southeast India, East Madagascar, East Antarctica and Sri Lanka, which were in close proximity within Gondwana, could result in an overly tight initial fit. In contrast, the COB between the East Antarctica and East India has less overlap so a reduced COB would leave gaps and an equally incorrect initial fit. The COBs for the

West Australian plateaus were preliminarily outlined using the potential field data but under consideration of the initial fit, given that reasonable overlap must have preceded seafloor spreading. A more thorough investigation of all the associated COBs would certainly highlight the strengths or weaknesses of the model.

Developing a more accurate, regional plate tectonic model of the Indian Ocean is certainly of great benefit to petroleum prospectivity. Defining the continental margins and understanding their tectonic and thermal evolutions is of vital importance in assessing the quality and occurrence of potential hydrocarbon and mineral resources. This study has revised the age and thermal progression along several margin segments, including some from Australia and others from further afield. For example, the model now incorporates a westward ridge jump in the Perth basin, which reveals the thermal regime (migrating spreading centre) formed the depocentres south of the Wallaby-Zenith transform margin from ~135-108 Ma at a uniform rate of ~5 cm/yr, culminating at the Dirk Hartog Ridge (extinct spreading centre). Previous models were unable to fully account for the large size of the Perth basin and assumed that the seafloor simply progressing from east to west during the CNS, at an unknown rate. The Southern Gascoyne and Cuvier depocentres experienced three westward ridge jumps sequentially transferring the Wallaby, Quokka and Zenith Plateaus from 128-124 Ma, hence the northern portion of the Wallaby-Zenith transform margin differs drastically from its southern counterpart.

Our work also uncovers the potential existence of continental fragments in the Wallaby-Zenith transform margin. We proposed that the Batavia and Gulden Draak Knolls in the far west Perth basin were continental micro-fragments mainly they would have fit well as conjugate margins to the Naturaliste Plateau. This has since been proven correct. Submerged continental plateaus contain the richest potential hydrocarbon reserves and this study has revealed a minimum of two, each nearly the size of Tasmania. The Zenith Plateau is another continental candidate but is as yet untested. The Naturaliste Plateau in the southeast Perth basin was already considered a continental fragment but our model has shown that this feature rifted from Australia from ~136 Ma, helping to constrain the age and spreading/rifting sequence of the Mentelle Basin, located between the Naturaliste and southeast Australian margins.

As Greater India unzipped from the Australian and Antarctic margins from north (Exmouth Plateau) to south (Sri Lanka), the fastest spreading rates occurred in the northeast portion, near the Exmouth Plateau, where we propose a triple junction existed from ~136-120 Ma. This source of magmatism and heat could help explain the abundant volcanism and extension undergone by the northwest Australian margin in order to form the Exmouth Plateau (the Kerguelen hotspot, if active ~136 Ma, was located beneath Greater India, over 1300 km to the southwest). The 'unzipping' motion of India also reveals a ~3 million year younger age for the East Antarctic and Northeast Indian margins. The ~115 Ma northward ridge jump transferring the Elan Bank to Antarctica also formed the northeast Indian margin, though how far this pseudofault extended to the west remains unresolved as yet. Margin segmentation is often inherited from older structures in the continental basement and studies of the Indian east coast margin and continental structural trends may help reveal the distinction between the older (west) and younger (east) portions of the East Indian margins and seafloor. Such an age differentiation also has important implications for hydrocarbon exploration.