THE CLOSURE OF THE INDO-PACIFIC OCEAN GATEWAY: A NEW PLATE TECTONIC PERSPECTIVE

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Abstract

Reconstructions of the west Pacific, based on new palaeomagnetic results from east Indonesia show that there could have been no simple and direct Indian Ocean-Pacific Ocean pathway during the Neogene. Instead, for most of the Neogene there was a system of arcs and subduction systems at the Pacific margin extending southwards towards Australia that was probably similar in complexity to the present Pacific-Australia-SE Asian margins. Faunal and floral dispersion in this region during the Neogene must have been both hindered and aided by this configuration with its implications of short-lived volcanic islands and a complex oceanic circulation system.

Our reconstructions result from geological investigations, in particular palaeomagnetic studies, carried out in the eastern Indonesian islands of the north Moluccas. The palaeomagnetic results show that north of the Sorong Fault system there has been approximately 40° clockwise rotation accompanied by ~15° of northward motion since ~25 Ma. This region is currently part of the Philippine Sea Plate and geological similarities indicate that it has been part of the Philippine Sea Plate since at least the early Tertiary. There is an Early Miocene regional unconformity in eastern Indonesia that we interpret as the result of collision of a Philippine Sea Plate arc with Australia; an unconformity of the same age can be recognized throughout the whole of the New Guinea orogenic belt. Using this single geological assumption we have been able to demonstrate that the new east Indonesian palaeomagnetic data and all other palaeomagnetic data from the Philippine Sea Plate form part of a single coherent data set. Forward modeling of the data set shows that the entire plate has rotated clockwise since ~25 Ma and allows calculation of poles of rotation for the Philippine Sea Plate that permit accurate regional reconstructions. The tectonic gateway between the Indian and Pacific Oceans can be delimited by these reconstruction but more detailed geological, palaeomagnetic and faunal studies of the critical region in and around present-day east Indonesia are required to determine the exact timing of changes to the circulation system that linked the two oceans.

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Introduction

For some time it has been realized that the opening or closure of ocean gateways has had a profound influence on regional and global palaeoceanography, as pathways for faunal migrations, and perhaps most importantly, as an influence on global climate. The principal Tertiary gateway openings include Australia-Antarctica (late Cretaceous-early Paleogene), NE Atlantic-Arctic (Miocene), Drake Passage (Oligocene), Gibraltar (late Miocene). Important gateway closures include the Central America Isthmus (Pliocene), Indo-Pacific (Miocene), and west Mediterranean Tethys Seaway (middle Tertiary).

Even at the present-day, despite our knowledge of geography and bathymetry, the oceanic circulation system is still not fully understood suggesting that palaeoceanographic models will inevitably be over-simplifications. However, it should be possible to identify the major features of oceanographic circulation in the past and their relationship to tectonics; an understanding of the consequences of changing ocean circulation may even contribute to improvement of tectonic models. To assess the impact of a gateway opening or closing event requires a good palaeogeographic understanding, in particular an appreciation of the timing of relevant plate movements and configurations of plates. Hypotheses have been developed, tested (principally using the biotic record) and refined to produce models for each of the Tertiary gateways. Modeling the evolution of an ocean gateway is essentially limited by the initial assumptions regarding the plate tectonic framework. New evidence related to the plate tectonic development of the Indo-Pacific Gateway closure suggests that collision between the Philippine Sea-Australia Plates during the early Miocene and the subsequent westward (clockwise) motion of the Philippine Sea Plate relative to Sundaland played a critical role in the closure of the gateway.

The Indo-Pacific Gateway (Figure 1) is controlled by the interaction of three major plates: Indo-Australia, Eurasia and Philippine Sea Plates. The Tertiary motion history of two of these plates (Indo-Australia and Eurasia) is relatively straightforward and has been known for some time (e.g. Smith et al., 1981, Royer and Sandwell, 1989). The major problem with modeling of the Indo-Pacific Gateway has been the lack of information on the motion of the Philippine Sea Plate. An additional problem is that the three major plates do not join directly against one another; they are separated by oceanic and continental 'buffer' plates that occupy the region between New Guinea, Borneo and the Philippines. Until recently there have only been limited reliable palaeomagnetic data from east Indonesia; tectonic models for the region have been based primarily on comparing the stratigraphic records of crustal blocks at subregional scale (i.e. within areas of about 105 km²). As part of our studies of the Sorong Fault zone in east Indonesia we have acquired new geological (e.g. Hall and Nichols, 1990), biostratigraphic (Roberts, 1993; Roberts and Finch, 1993), and palaeomagnetic data (Ali and Hall, 1993; Hall et al, 1993a) from this critical region.
Palaeoceanographic Modeling of the Indo-Pacific Gateway

Edwards (1975) proposed one of the first models of Cenozoic Indo-Pacific palaeocirculation. The palaeogeographic basis for his model was limited; all of the oceanic (and continental) fragments that today occupy the region east of Sundaland were considered to have been fixed to Australia throughout the Cenozoic. In addition, Sundaland (including Borneo and west Sulawesi) was assumed to have maintained its present position since the early Tertiary. Edwards (1975, Figure 4) suggested that the Indo-Pacific gateway probably closed by the early middle Miocene.

The palaeoceanography of the Indo-Pacific Gateway was considered in a number of papers in the compilation edited by Kennett (1985). Many of these used Hamilton's (1979) reconstruction of the mid Tertiary evolution of the Indonesian archipelago. Although this was a thorough piece of work using all the available data at the time, subsequent studies have vastly increased our geological knowledge of this region. Using Hamilton's model, Kennett (1985) suggested that the Indo-Pacific Gateway was open until the late middle Miocene.

Based predominantly on DSDP cores from the Pacific Ocean, Kennett et al (1985) mapped the distribution of planktic foraminifera for three time slices in the Miocene: two in the early Miocene (22 and 16 Ma), and one in the late Miocene (8 Ma). The biogeographic patterns were plotted on global palaeogeographic maps of Sclater et al (1985); sampling localities were accordingly backtracked. The most significant change in the biogeographic distributions occurred between the 16 Ma and 8 Ma. During the early Miocene distinct east-west tropical Pacific faunal provincialism was seen. This provincialism had essentially vanished by the late Miocene. Based on Van Andel et al (1975), Kennett et al (1985) interpreted this change to reflect the initiation of the Equatorial Undercurrent during the middle Miocene (11-12 Ma) caused by the closure of the Indo-Pacific Gateway (Figure 2). The subsequent intensification of the tropical and gyral surface water circulation is recorded in cores far away from the Indo-Pacific Gateway in the north west and central north Pacific.

Romine and Lombardi (1985) examined Miocene radiolarian assemblages from DSDP Site 289 in the western equatorial Pacific. They conducted similar analyses as Kennett et al (1985) utilizing the same time slices and found that in the early Miocene two radiolarian species (Stichocorys wolffii and Calocyletta robusta) occurred in unusually high abundances. The species dominance may have been due to the development of a specific ecological niche. Rapid proliferation and decline of these species was noted and suggests that the niche was temporary, existing whilst certain threshold conditions were satisfied during progressive changes in the circulation patterns in the equatorial Pacific. The extinction of Stichocorys wolffii occurred in conjunction with the development of the characteristic late Miocene assemblage. This faunal event was coincident with the closure of the Indo-Pacific Gateway to significant westward flow from the Pacific (~12-10 Ma).

Clearly, many palaeoceanographers accept that closure of the Indo-Pacific
Gateway to have occurred at some time between the early and middle Miocene. How are the changes in faunas and inferred circulation system linked to regional tectonics?

Tectonic Modeling of the East Indonesian Region

Previous studies of ocean circulation between the Pacific and Indian Oceans were based on tectonic models available at the time (e.g. Edwards, 1975; Kennett et al, 1983) but as our geological knowledge of the east Indonesian region has increased more realistic models of the tectonic development of the region have been developed. Several plate tectonic models for the Indonesian Region have been proposed since the publication of Kennett (Jolivet et al 1989; Daly et al, 1991; Rangin et al, 1990; Hall et al, 1993b). The palaeoceanographic implications of the more recent tectonic models have not yet been utilized by oceanographers.

A New Tectonic Model: Summary

A tectonic model for the Philippine Sea and western Pacific area has recently been developed from new palaeomagnetic and geological information from east Indonesia (Hall et al, 1993 a, b; Ali and Hall, 1993) and published data from the north Philippine Sea Plate. The new model illustrates the Tertiary motion of the Philippine Sea Plate and its interaction with northern Australia, the key features of which are summarized in Figure 3. In addition there is new and important information relevant to the closure of the Indo-Pacific Gateway concerning the development of east Sundaland.

For the interval 23 to 40 Ma (and probably back to the Pacific plate reorganization at ~43 Ma) the Philippine Sea Plate was essentially static. During this interval Indian oceanic crust to the north of New Guinea was subducted beneath the Philippine Sea Plate as Australia advanced northwards towards the equator (Figure 3). An arc, possibly as long as 2000 km, was generated along the southern edge of the Philippine Sea Plate. Directly or indirectly the Philippine Sea-Australia arc must have been connected to the Indian Ocean-Sundaland arc. Prior to the early Miocene collision event the ocean floor north of continental Australia and south of the Philippine Sea subduction zone would have provided an open connection between the Indian and Pacific Ocean (assuming a Mesozoic age for this oceanic crust, it is likely that water depths there would have been in excess of 4000 m, cf. the NW Australia Basin today where the waters are > 5000 m). Between the early Miocene and early Pliocene the Philippine Sea Plate rotated clockwise at a little under 2°/m.y. about a Euler pole located at about 15°N, 160°E. The effect was to move the southern Philippine Sea Plate west along the north margin of New Guinea; for all of the Neogene a left-lateral strike slip transform separated the Australian and Philippine Sea Plates. The Halmahera arc
probably began activity at around 11 Ma (Hall et al., 1993a).

Sundaland forms the western side of the Indo-Pacific Gateway. Important new information from there concerns the source of the east Sulawesi ophiolite and the timing of its emplacement on to west Sulawesi. Palaeomagnetic studies of the east Sulawesi indicate an Indian (rather than Pacific) Ocean origin for the ophiolite (Mubroto and Briden, 1989; Mubroto et al., 1994). The work of Parkinson (1991) indicates that the East Sulawesi Ophiolite was emplaced at around 25 Ma.

Relative convergence between the Philippine Sea Plate and Sundaland has steadily reduced the gap separating the two areas. During the Neogene, as is the case today, this region was filled with fragments of both continental and oceanic origin. Since 22 Ma these blocks, plus volcanic arcs generated by the subduction of small areas of oceanic crust within this closing area between the Australian Plate, Philippine Sea Plate and Sundaland, have been shuffled within the ever-decreasing space. It is these blocks, moving in response to the convergence of the major plates, and the development of new volcanic arcs that eventually closed the gateway between the Indian and Pacific Oceans.

Implications for Palaeoceanographic Modelling

Based on the new tectonic model for east Indonesia/west Pacific we consider it is likely that the tectonics influencing the Indo-Pacific Gateway underwent a significant change sometime after the Australia-Philippine Sea Plate collision (22 Ma). Prior to this time there must have been a completely open equatorial seaway between the Indian and Pacific Oceans across both the south-west Philippine basin, and the ocean north of New Guinea. After 22 Ma the Indo-Pacific Gateway began to close gradually constricting the gateway and impairing the westward flow of equatorial waters. The link was probably completely closed by the initiation of the Halmahera Arc at 11 Ma at the western edge of the south part of the Philippine Sea due to subduction of the Molucca Sea Plate. Thus, the most important question facing palaeoceanographers working on the Indo-Pacific Gateway is what are the events (and their precise timing) that stopped circulation through the Indo-Pacific Gateway and led to the intensification of the north Pacific gyre? The answer to these questions will be provided by:

- Developing palaeomagnetically-based models for the fragments in and around the Banda and Molucca Seas.
- Obtaining precise age control of the biotic events that delineate the changes in the Indo-Pacific Gateway's development from sites in the Indian and Pacific Oceans and Indonesia.
- An understanding of volcanic arc history in the 'triangular' zone between Sundaland, the Philippine Sea Plate and Australia which decreased in size during the Neogene.
Figure 1: The area around the present-day Indian Ocean-Pacific Ocean gateway. Principal tectonic, bathymetric and magnetic features of the region. Solid squares indicate DSDP and ODP sites; important magnetic anomalies are numbered.

Figure 2: Inferred circulation patterns of surface and near surface waters in the Pacific Ocean at (a) 22 Ma, (b) 16 Ma, and (c) 8 Ma. Closed arrows indicate cold currents; open arrows indicate warm currents (Kennett et al., 1985). Palaeoreconstruction after Sclater et al. (1985)

Figure 3: Reconstruction of the position and approximate shape of the Philippine Sea Plate at 10 Ma, 25 Ma and 45 Ma based on Hall et al. (1993a, b). Sulawesi, the Philippines, the Philippine Trench and the Ryukyu Trench are fixed to Eurasia for reference only. Japan has been reconstructed using the model of Jolivet et al. [1991]. The position of the north Australian margin is based on Royer and Sandwell [1989]. No attempt has been made to portray the complex character of the western plate boundary. The known extent of the present plate is shown in black and white; subducted areas are shaded. At ~45 Ma the plate was rotating rapidly about the pole shown. At about this time subduction began at the NE margin of the plate. The West Philippine Central Basin was opening. All other marginal basins were closed; the character of the southern boundary of the plate is uncertain. Between 40 and 25 Ma there was no rotation and there was subduction of Indian Ocean lithosphere at the southern edge of the plate. At ~25 Ma the plate began rotating about the pole shown. Subduction ceased at the southern edge which subsequently became the Sorong Fault strike-slip boundary. The Mariana Trough is closed; the Shikoku Basin is beginning to open and the Parece Vela Basin is partly open. At 10 Ma the plate continued to rotate about the pole shown. Although Australia was moving north rotation of the Philippine Sea Plate allowed the southern boundary to remain a strike-slip system.

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