The Indian Promontory: A Bridge between Plate Tectonics and Life Evolution Models

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Abstract Since the 1970's, the Cretaceous–Cenozoic migration of the India subcontinent is fairly well-established. Seafloor magnetic anomalies in the Indian Ocean allow positioning the subcontinent during this time frame. India broke-up slowly from Antarctica in the Early Cretaceous, speed up (~18-20 cm/year) in the Late Cretaceous, and then slow down (~5 cm/year) in the early Cenozoic, a period for which geologists report the first evidences of the India–Eurasia collision leading to the formation of the Himalayan–Tibetan Orogen. However, fossil records as well as biogeography deduced from molecular phylogeny cast a doubt on the tectonicists' confidence on their palaeopositions, because faunal evidences support India as a 'biotic ferry' from its break-up from Gondwana in the Jurassic and then connectivity between Asia and India as early as the Cretaceous. The two types of observations can be reconciled if an Indian Promontory formed when India separated from Australia and Antarctica. In our plate tectonics model, the Indian Promontory drifted northward together with the Indian plate from the Cretaceous, but collided as early as the Campanian with Eurasia, *id est* about 40 Ma before the northern margin of 'Greater India' collide and form the Himalayas. The proposed Indian Promontory can therefore solve the paradox of having evidences for early land connectivity between India and Asia, the need of excluding unrealistic 'Greater India' (*i.e.* 4000-4500 km at *ca.* 80 Ma), and the need of having a plate tectonic scenario consistent with geological records (subsidence curves, exotic origin of terranes from the promontory), geophysical records (age and structure of the Argo Abyssal Plain), and geodynamical consideration about stress transmission of forces acting at plate boundaries.

Keywords Indian Promontory, Biotic Ferry, Faunal Connectivity, Argo, Andaman, Burma, Woyla

1. Introduction

Although the details of the Cretaceous–Cenozoic motion of India are still a matter of debate (*e.g.* [1-3]), the general migration of the subcontinent is established since the advent of the Plate Tectonics Theory [4]. Moreover, the definition of sea-floor magnetic anomalies in the Indian Ocean ([5-6]; and also [7-8]) has convincingly constrained the palaeo-position of the subcontinent though time, although information from the Argo Abyssal Plain (North-West of Australia) remains an issue (Fig.1 & 2). India broke-up slowly from Antarctica in the Early Cretaceous, speeded up (~18-20 cm/year; *e.g.* [1]) in the Late Cretaceous, and then slowed down (~5 cm/year) in the early Cenozoic until ~55-35 million years (Ma) ago, a period for which geologists report the first evidences of the India–Eurasia collision leading to the formation of the Himalayan–Tibetan Orogen.

Figure 1. Present-day localisation of the Argo-Andaman-Burma-Woyla terranes mainly constituting the proposed Indian Promontory.

Figure 2. The Indian and African plates 65 and 40 million years ago, after [53]-*op.cit.*fig.1. In this model, India is totally isolated from other land masses (*i.e.* a ‘biotic ferry’ as named by [39]) until the mid-Eocene Indian-Eurasia collision. In the Late Cretaceous therefore, no living beings can be exchanged between the various continents.

However, the palaeo-position of India has been questioned 1) relative to the extent of ‘Greater India’ (*i.e.* the various sizes given to what correspond to the grey area to the northern side of India in Fig.2) and the amount of subsequent shortening (up to 3000 km after [4]), 2) relative to the age of collision between India and Eurasia (*e.g.* discussion in [9]), and in particular 3) relative to biogeographic evidences indicating India with faunal connectivity as early as Late Cretaceous whereas the formation of the Himalayan-Tibetan Orogen is commonly regarded as Palaeogene in age (from, for instance, ~34 Ma after [9], to ~50-53 Ma after [10], to 58-60 Ma after [11]).

Using plate tectonic modelling, we suggest herein that the detachment of the Indian Promontory can solve all those paradoxes.

2. The Argo Abyssal Plain

From geophysical interpretation of magnetic sea-floor anomalies, a Late Jurassic age has been attributed to the Argo Abyssal Plain (anomaly M24A-M26; Kimmeridgian [12]). Moreover, radiometric dating of basalt from leg 765 and 766 had produced Jurassic (Kimmeridgian) ages [13]. Subsequently, all palaeogeographic reconstructions have represented the formation of the Argo Abyssal Plain prior to the rift and drift of India (*e.g.* [6,14-16]).

However, Ludden [13] acknowledged the inconsistency of the radiometric age with the late Berriasian age defined from biostratigraphic determination (*e.g.* [17]). Furthermore, magnetic anomalies were re-interpreted not only in terms of age but also in terms of orientation and disposition in the Gascoyne Abyssal Plain [18]. And Borel & Stampfli [19] noticed that the formation of the Argo Abyssal Plain prior to the India odyssey “*implies the definition of a tectonic plate in contradiction with the geodynamic environment*”.

Indeed, a Late Jurassic oblique opening of the Argo Abyssal Plain implies the formation of a plate boundary in-between India and Eurasia (*e.g.* such as in [6,20]), preventing slab pull to be transmitted. In such case, the necessary geodynamic force to move India northward would be annihilated. However, a plate boundary appears necessary to separate the Permian North Indian passive margin ([19,21]) from the Mesozoic West and North-West Australian passive margin ([18,21-22]).

3. Early Indian Ocean Opening

Controversies regarding the Argo Abyssal Plain must be related to the opening history of the Indian Ocean. While the history of the Mozambique Basin and Riiser Larsen Sea was reassessed these last years (in particular from [5] to [8]), the early opening between India and Antarctica remains poorly constrained. Gaina *et al.* [23] provided a solution for the EarthByte Group model (<https://www.earthbyte.org/>) that has been widely used since then and up to now (Fig.3; *e.g.* [6] up to [24-26]).

The solution of the EarthByte Group model has however a double flaw. First, the passive margin along Greater India and north-west Australia is the same (Fig.3). Consequently, the age of the north-western shelf of Australia should be Permian as is the Greater India passive margin, which is not the case. Second, the motion of India is accommodated by a sinistral fault between India and Madagascar for ages between *ca.* 135Ma and 100 Ma, and is followed by a dextral strike slip motion for ages between *ca.* 100 Ma and 84 Ma bringing Madagascar exactly back to its genuine position (blue arrows in Fig.3). Not only this round-trip is suspect but there is no field evidence for such major displacements prior to the India – Madagascar break-up.

Figure 3. The opening of the Indian Ocean after [23]-*op.cit.*fig.10. In this model, the Greater India passive margin is the same as along the north-western shelf of Australia (highlighted with a blue line), and must be older than at least 135 Ma. After the opening of the Mozambique Basin, the proposed separation of Indian from Antarctica leads a sinistral shear along Madagascar and Indian followed by a dextral shear bringing India back to its previous position (see blue arrows).

Figure 4. a) Late Cretaceous (65 Ma) reconstruction redrawn after [38]-*op.cit.*fig.3. Arrows indicate the directions of some vertebrate animal migrations; b) Late Cretaceous (66 Ma) reconstruction after [36]-*op.cit.*fig.7.3. Arrows indicates proposed routes for Maastrichtian tetrapodes dispersal.

4. Life Evolution Models

Since the 1980's (e.g. [27]), many palaeontologists suggest the existence of land bridges, *i.e.* faunal connectivity in the Cretaceous between India and both Africa – Madagascar – Seychelles on one side and Eurasia on the other side (Fig.4).

On the one hand, Sudamericidae – highly specialised mammals previously only known in South America – were reported in India and Madagascar in the Late Cretaceous [28]. Theropod dinosaurs, belonging to the family of Abelisauridae that are restricted to South America, Madagascar and India, were discovered in Late Cretaceous section of Madagascar [29].

From amphibians and reptiles on the other hand, Rage [30] suggested connectivity between India and Eurasia at least from the Maastrichtian. Connectivity prior to the main Himalayan–Tibetan orogeny is also supported by vertebrate fossils [31], freshwater Ostracoda [32], freshwater crabs [33–34], *etc.* Chatterjee & Scotese [35–36], in particular, provided a relative long list of fossils with affinities from the two sides. Late Cretaceous Indian – Asia connectivity is even suggested from anthropoids' evolution [37] and molecular-clocks studies of plants and animals (e.g. [38] and references therein).

However, Hedges [39] recalled that India was likely isolated at some times during the Cretaceous and acted as “a *‘biotic ferry’ with a passenger list of distinctive plant and animal groups*”. Similarly, Chatterjee & Scotese [36], in particular, quoted the Cretaceous endemism in India.

Without the Indian Promontory proposed herein (below) and whatever the size given to ‘Greater India’ — typically between 300 km and 3000 km in the literature — the India – Eurasia collision cannot occur before the Cenozoic according to the sea-floor magnetic anomalies and other palaeomagnetic records (e.g. example in Fig.2). Some authors have therefore suggested faunal connectivity through other routes, mainly through “jumps” from island to island along intra-oceanic island arc to the north, and through hypothetical emersion of oceanic plateaus to the south (Fig.4.b).

If such kind of connectivity cannot be excluded for a few species, the explanation cannot hold for all aforementioned living beings, in particular for freshwater animals or the emblematic giant frogs [40].

5. The Indian Promontory

The origin of Argo-Andaman-Burma-Woyla terranes is subject to questions (e.g. [41]) but in coherence with available geological information (stratigraphic, palaeontologic, tectonic...) at regional scale however, many authors (e.g. [15–16, 21, 42]) agree to place the terranes along the northern margin of ‘Greater India’ and Australia in the early Mesozoic. Now, the difference between the models mainly concerns the way the migration of the terranes towards south-east Asia occurred.

The solution suggested by Hall [16], for example, well reproduces the formation of the Argo Abyssal Plain (albeit with older age than anomaly M11 (Valanginian) in the Cuvier and Gascoyne Abyssal Plain as in [18]). Nevertheless, the Argo-Woyla terranes are, in his model, detached as ribbon from the northern margin of ‘Greater India’. Such configuration requires the formation of a subduction zone along the Argo-Woyla terranes and another plate boundary corresponding to a back-arc spreading axis in what he names the ‘Ceno-Tethys’ ([16]; *op.cit.* Fig.6–7 at 155–150 Ma). As for other models, those plate boundaries would likely annihilate most of the stress associated to slab pull, and appears in contradiction with the Early Cretaceous high velocity of the Indian Plate. In addition, the model subsequently supposes the formation of a major transform fault in the early Late Cretaceous, cross-cutting all structures of the mature lithosphere forming the ‘Ceno-Tethys’ (*op.cit.* Fig.19 at 90 Ma). Such tectonic accommodation appears dubious from a rheological point-of-view.

Having tested many configurations, we find that the location of the plate boundary (spreading ridge) must be south of the terranes so that slab-pull can be transmitted. As previously envisaged [19,21–22], we consider that detaching the Argo-Andaman-Burma-Woyla terranes from the western margin of Australia as part of the Indian Promontory provides the tectonic setting to have a passive margin north of the terrane (no plate boundary) and the plate boundary (ridge) to the south. The scenario is more consistent all together with age constraints (e.g. [17]), magnetic anomaly determination [18], thermal history of the Argo and surrounding basins [22], and the geodynamic configuration (*this study*).

6. The Plate Tectonic Model

The PANALEXIS plate tectonic model supersedes the plate tectonic model developed at the University of Lausanne (e.g. [43–44]). Entirely developed from scratch, PANALEXIS is a global plate tectonic model that aims to reconstruct 100% of the Earth surface from the Neoproterozoic to present-day. To date, the model is currently under development and covers the entire globe but only for the Mesozoic and Cenozoic Era. It uses the techniques and *savoir-faire* developed at the University of Lausanne (described in [45]; see also [43–44]), but is designed for further developments.

In the PANALEXIS model, the Cimmerian Blocks [43] correspond to a continental ribbon that detached from Gondwana in the Permian and collided with Eurasia in the Jurassic. This motion is primarily driven by slab-roll back, and led to closure of the PalaeoTethys Ocean forwards, and the opening of the NeoTethys Ocean backwards. After collision of the Cimmerian Blocks, the northern passive margin of the NeoTethys Ocean was reversed, and the newly created subduction zone consumed the ocean floor of the NeoTethys. Gondwana kept its unicity until the Upper Jurassic, when South America – Africa – Arabia to the west (West Gondwana) breakup from Madagascar – India –

Antarctica – Australia to the east (East Gondwana). In the model, the breakup is associated with stress changes related to the subduction of the ‘mid-oceanic spreading ridge’ of the NeoTethys Ocean to the north. However, faunal connectivity might have persisted between East and West Gondwana up to the latest Jurassic or earliest Cretaceous through the Mozambique Plateau and its magmatic activity between Africa and Antarctica.

In the Early Cretaceous, rifting occurs between Australia – Antarctica on one side and Madagascar – India on the other side. We propose the rift prolonged along the western flank of Australia, breaking up the Andaman – Argo – Burma – Woyla terranes (what we name the Indian Promontory) from main land Australia, together with the Indian plate. Because of the rotation of the Indian Plate in the model (Fig.5.a), the Indian Promontory detached earlier from Australia than the rest of India from Antarctica. We follow Robb *et al.* [18] to generate sea-floor at anomaly M11 (Valanginian) in the Cuvier and Gascoyne Abyssal Plain (Fig.5.a). Note that the transition from India and its Indian Promontory to the NeoTethys Ocean corresponds to a passive margin, so that the Indian tectonic plate extends from the mid-oceanic ridge separating India – Antarctica – Australia to subductions at the Eurasian margin and at the Kohistan-Spongtag intra-oceanic magmatic arc (see [21]). From a geodynamic point-of-view, stresses can thus be transmitted to the entire Indian Plate. The presence of a passive margin to the south of the NeoTethys Ocean and a double subduction to the north is also consistent with tomographic information ([46-47] and with the high Indian Plate velocity (*e.g.* [3]).

Contrary to some other models (*e.g.* [23]), PANALEXIS suggests slow and relatively minor motion between India and Madagascar up to the mid-Cretaceous. We assume therefore land connectivity to be possible between the two continental areas throughout the Lower Cretaceous (Fig.5.b), and potentially to the earliest Late Cretaceous if magmatism in the future Farquhar – Amirante Islands were then active between the Seychelles and Madagascar.

During most of the Late Cretaceous, India is viewed herein as a ‘biotic ferry’ [39] largely isolated from other landmasses.

The Indian Promontory collides obliquely with Eurasia as early as the Late Cretaceous. In our model, collision occurs at 78 Ma (Campanian). The land bridge between Asia and India is thus created (Fig.5.c).

Notwithstanding, the Indian plate kept moving northwards because of a double subduction to the north, one along the Eurasian margin, and a second related to the Kohistan – Spongtag intraoceanic arc. Around *ca.* 80 Ma, this arc splitted and left the Kohistan abandoned arc behind, while the Spongtag ophiolites obducted onto the Indian passive margin by *ca.* 65-60 Ma (*e.g.* [21,48]; but much of the geology was known already in the 1980’s: *e.g.* [49]). The main collision triggering the Himalaya and Tibetan Plateau occurred around the early Palaeogene — from *ca.* 51 Ma to the west to *ca.* 46 Ma to the east in our model — although some diachronicity (approximately ± 5 Ma) according to the

effective shapes and sizes of the ‘Greater India’ continental plateau and the Eurasian active margin may be possible. Hence, the India – Eurasia collision is proposed to start with a ‘soft’ phase in the Late Cretaceous and lasted until the main phase began in the early Palaeogene.

The age of the sea-floor is colour-coded from blue (old) to red (young) relative to the age of the reconstruction. The distinction between sea-floor and continents (brown) is related to the nature of the crust and not to palaeo-coast-lines. Abbreviations are: Mad., Madagascar, SAm, South America; Orthographic projection.

Figure 5. Reconstructions proposed herein (*this study*); **a)** Reconstruction at 130 Ma (Hauterivian): the Argo-Andaman-Burma-Woyla terranes are detached from Australia together with India, and form the ‘Indian Promontory’; **b)** Reconstruction at 100 Ma (Cenomanian): India is viewed as a ‘biotic ferry’ [39] largely isolated from other landmasses; **c)** Reconstruction at 70 Ma (Maastrichtian): the ‘Indian Promontory’ collides with Eurasia creating a land bridge. While the Kohistan arc is left behind (abandoned arc; [21]), the Spongtag-Incertus Arc is subsequently obducted onto the Indian Plate.

7. Conclusions

The solution proposed here of the existence of the Indian Promontory is therefore consistent with geologic, geophysics, geodynamic constraints on the one hand and with palaeontologic and biologic data on the other hand. It does not require a very extended 'Greater India' (e.g. [14,50]) implying shortening of up to 3000 km (e.g. [4]) during the Himalayan-Tibetan collision, which has great meaning for the study of orogenic processes (e.g. [51]). The early collision of the Indian Promontory can also relatively simply explain the slow-down of the Indian plate in the Eocene. Consequently, the interaction between the Deccan plume head and the slow-down of India inferred by [2] might just be apparent. The solution has also great implications for life evolution since the presence of animals in India prior to the Himalayan-Tibetan collision (Palaeogene) does not necessarily mean they originate from the sub-continent (e.g. [52]).

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