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Greater India

Jason R. Ali *, Jonathan C. Aitchison

Department of Earth Sciences, University of Hong Kong, Pokfulam Road, Hong Kong, China

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Abstract

"Greater India" is an 80-yr-old concept that has been used by geoscientists in plate tectonic models of the India–Asia collision system. Numerous authors working on the orogen and/or plate models of the broader region have added various sized chunks of continental lithosphere to the now northern edge of their reconstructed Indian plate. Prior to plate tectonic theory, Emile Argand (1924) [Argand, E., 1924. La tectonique de l' Asie. Proc. 13th Int. Geol. Cong. 7 (1924), 171–372.] and Arthur Holmes (1965) [Holmes, A., 1965. Principles of Physical Geology, Second Edition. The Ronald Press Company, New York, 1128.] thought that the Himalayan Mountains and Tibetan Plateau had been raised due to the northern edge of the Indian craton under-thrusting the entire region.

Since the advent of plate tectonic theory, Greater India proposals have been based principally on three lines of logic. One group of workers has added various amounts of continental lithosphere to India as part of their Mesozoic Gondwana models. A second form of reconstruction is based on Himalayan crustal-shortening estimates. A third body of researchers has used India continent extensions as means of allowing initial contact between the block and the Eurasian backstop plate in southern Tibet to take place at various times between the Late Cretaceous and late Eocene in what we call "fill-the-gap" solutions. The Indian craton and the southern edge of Eurasia were almost invariably some distance from one another when the collision was supposed to have started; extensions to the sub-continent were used to circumvent the problem. Occasionally, Greater India extensions have been based on a combination of fill-the-gap and shortening estimate arguments.

In this paper, we exhume and re-examine the key Greater India proposals. From our analysis, it is clear that many proponents have ignored key information regarding the sub-continent's pre break-up position within Gondwana *and* the bathymetry of the Indian Ocean west of Australia, in particular the Wallaby–Zenith Plateau Ridge and the Wallaby–Zenith Fracture Zone. We suggest that the Indian continent probably extended no more than 950 km in the central portion of the Main Boundary Thrust, up to the Wallaby–Zenith Fracture Zone. At the Western Syntaxis, the extension was about 600 km. These estimates are broadly compatible with some of the geophysically-derived models depicting subducted Indian lithosphere beneath Tibet, as well as estimates of Himalayan shortening. Models requiring sub-continent extensions >9° ahead of the craton are probably wrong. We also suggest that northern India did not have a thinned rifted passive margin due to the earlier rifting of blocks away from it when it formed part of Gondwana. Instead, the boundary developed as a transform fault

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* Corresponding author. Tel.: +852 2857 8248; fax: +852 2517 6912.
E-mail address: jrali@hku.hk (J.R. Ali).

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and probably had a very narrow ocean–continent transition zone (5–10 km wide), similar to the Romanche Fracture Zone offshore of Ghana, West Africa.

Keywords: Gondwana; Indian Ocean; Tethys; Wallaby Plateau; Palaeogeography

1. Introduction

The most important advances in the earth sciences came about following the widespread acceptance of plate tectonic theory in the late 1960s. The paradigm best explains why the Himalayan chain to the north of the Indian craton has Earth's greatest collection of high peaks, and the Tibetan Plateau immediately to the north forms the planet's largest–highest elevated surface. The Indian sub-continent slammed into Eurasia sometime in the last 70 million yr (c.f. Yin and Harrison, 2000, who suggest collision started possibly as early as ~70 Ma with Aitchison and Davis, 2004, who argue that the event started in the late Oligocene–early Miocene) and has since continued indenting in the backstop plate thus creating this gigantic topographic feature.

Since the 1970s, a large number of geologists have proposed "Greater Indias," that is, the Indian sub-continent plus a postulated northern extension. One type of proposal has been based on the need for the sub-continent's collision with Asia to take place at the right time and/or place (Fig. 1). Other forms of model have been based on reconstructions of Gondwana in the Mesozoic, or estimates of shortening in the Himalayas, between the Indian craton and the Yarlung Tsangpo suture zone. It is important to note, however, that "Greater India" is much older than plate tectonic theory. Emile Argand's groundbreaking (literally and figuratively) work in the mid-1920s argued for what we would now call continental plate extending north from the Indian craton beneath the entire Tibetan Plateau region, in order to raise the huge tract of land such that its average elevation is ~5 km (see below).

Reviews of Greater India have been carried out previously, e.g., Powell and Conaghan (1975) Harrison et al. (1992) Le Pichon et al. (1992) Packham (1996); Matte et al. (1997) DeCelles et al. (2002). The work presented herein stems from the fact that after 15 yr of researching different aspects of the evolution of the eastern Asia–western Pacific, and 8 yr of looking specifically at the geology of Tibet, we were utterly confused with the vast body of opinions and ideas regarding the size of India prior to its collision with Asia, as well as where and when the process started. Indeed, it is our contention that future historians of science will view "Greater India" as one of the geoscience community's most fascinating and flexible concepts. We hope this review will (1) explain how the concept of "Greater India" has developed, (2) present some of the important reconstructions and (3) provide some constraints on how big India was in the Cretaceous, prior to its collision with Asia. It should thus be useful both to those modeling this key continent–continent collision system, and to those studying the Cenozoic evolution of the broader region.

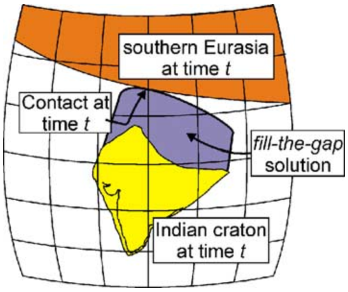

Fig. 1. Schematic diagram summarizing the rationale behind "fill-the-gap" Greater India proposals. The image is clipped from an orthogonal projection in which the latitudes and longitudes are spaced at 10° intervals and is viewed from 20°N. An extension to the Indian plate fills the void between the northern edge of the Indian craton and the southern edge of Eurasia at the time when the two continents are believed to have made initial contact. As the 100–0 Ma motion history of India has been well-defined for the past two decades (e.g., Besse and Courtillot, 1988; Acton, 1999; see also Fig. 3), early collision events have tended to result in modellers proposing large Greater India extensions. Conversely, models assuming late collision result in small Greater Indias.

2. Present-day Indian plate

Indian plate rocks can be divided into two types: those currently attached to the craton, i.e., south of the Main Boundary Thrust, and those north of the fault and south of the Indus River–Yarlung Tsangpo suture zone (Fig. 2). The latter occupy a band ~3° S–N which is defined by the Himalayas. North of the Yarlung Tsangpo suture are three major crustal blocks forming Tibet: Lhasa, Qiangtang and Songpan–Qaidam, which are separated respectively by the Banggong and Jinsha sutures (e.g., DeCelles et al., 2002).

3. Motion history of the Indian plate since the Late Cretaceous

Apart from its key role in creating Earth's most spectacular orogen, the Indian continent is famous for the speed it attained during the Late Cretaceous–early

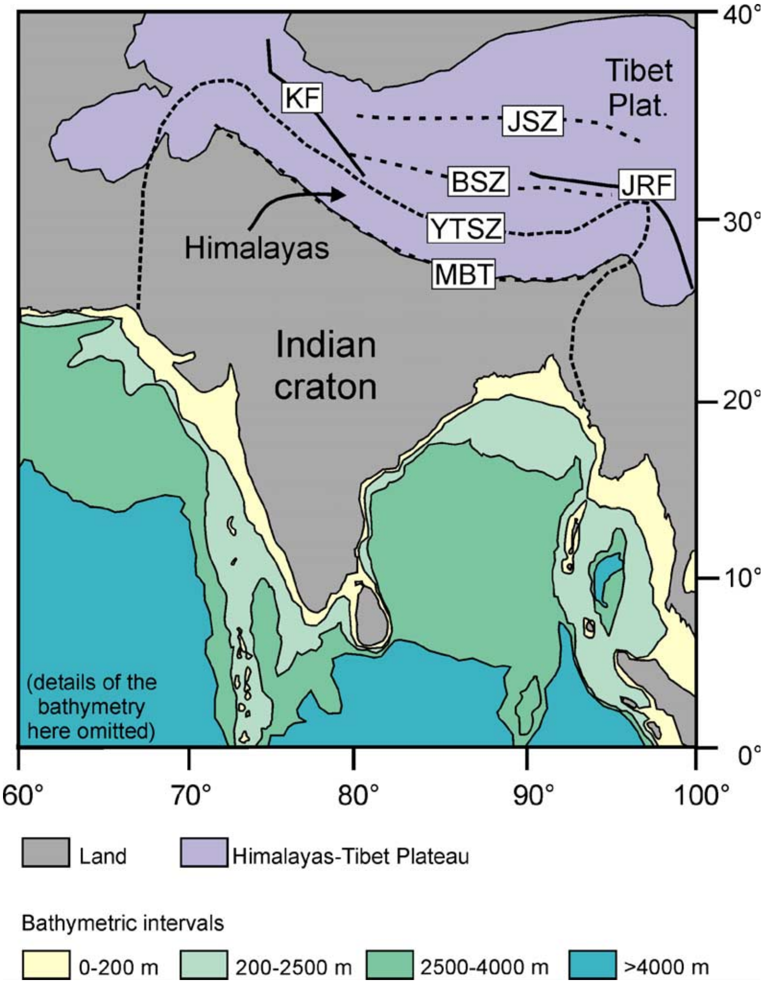

Fig. 2. Simplified tectonic map of the northern Indian Ocean and southern Asia. The Indian craton terminates at the Main Boundary Thrust (MBT). Indian plate-derived rocks are exposed between the thrust and the Indus River–Yarlung Tsangpo suture (YSTZ) where they form the Himalayas. BSZ is the Banggong Suture, between Lhasa (S) and Qiangtang (N) blocks; JSZ is the Jinsha suture, separating the Qiangtang (S) and Qaidim–Songpan Ganze (N) terrains; KF and JRF are the Karakoam and Jiali-Red River Faults respectively. The base map has been drawn over an image generated using the GEBCO Digital Atlas (2003). Details of the bathymetry in the Carlsberg Ridge area, SW of India, are not shown.

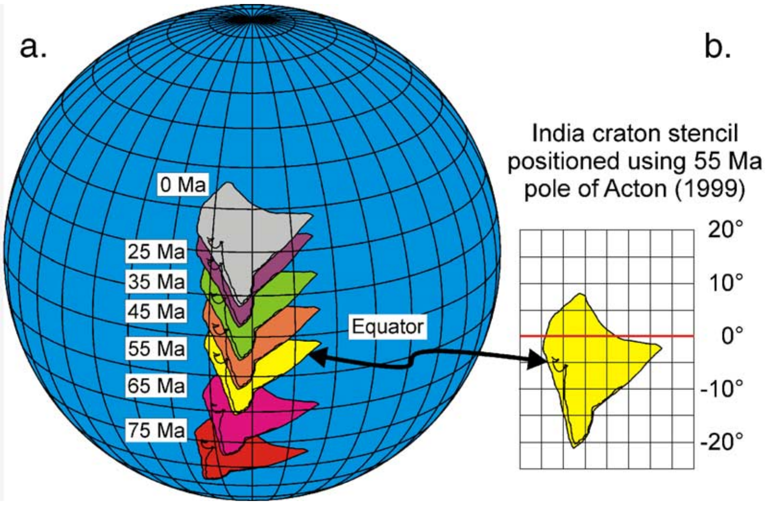

Fig. 3. Indian craton's motion history since 75 Ma (a) based on Acton (1999). The stencil for the Indian craton using Acton's 55 Ma pole is also shown (b) and is drawn using the GMAP computer program (Torsvik and Smethurst, 1999). The latter is used in all of the Greater India redrafts (Figs. 5b, 8, 10, 11).

Palaeogene when it was traveling, relative to the spin axis, at the almost phenomenal rate of 16–20 cm/yr (Patriat and Achache, 1984; Besse and Courtillot, 1988; Klootwijk et al., 1992; Lee and Lawver, 1995). The most detailed analysis of India's motion history appears to have been provided by Gary Acton (1999). Using his suite of poles, the sub-continent's path for the period 75–25 Ma is shown in Fig. 3a. The adjacent figure (Fig. 3b) also shows the Indian craton plotted on a Galls projection at 55 Ma. It is this image which forms the basis for the later comparison of the key Greater India proposals.

4. India in Gondwana: key information from the southeastern Indian Ocean

Before commencing our review of past Greater Indias, it is first useful to consider the probable size of the continent. A key piece of information apparently neglected by many is the position and shape India occupied when it formed part of eastern Gondwana (prior to the Early Cretaceous). During the 1970s, various solutions were proposed for fitting India back into the southern supercontinent. Three decades on, some of these proposals looked distinctly odd, for example Veevers (1971) and Veevers et al. (1971) used the apparent similarities in the stratigraphic records of eastern India and western Australia to align the two margins against one another (Fig. 4). This contrasted with a large body of authors who favoured positioning the southeast-facing coast of India against Antarctica (e.g., Du Toit, 1937; Smith and Hallam, 1970; Larson, 1977). It was the 1988

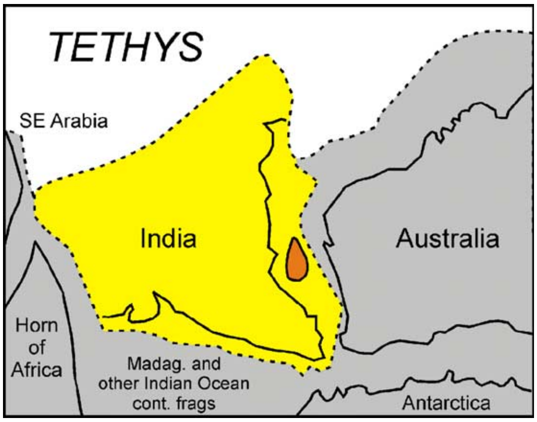

Fig. 4. East Gondwana reconstruction by John Veevers et al. (1971), one of many that appeared shortly after plate tectonic theory was introduced. Note the position of Sri Lanka. The edges of the continents south of Australia–Antarctica and east of Africa and southern Arabia are not shown but are only a short distance seaward of the present-day coastlines. Note that a SE-facing margin of India against Antarctica is now preferred by most workers e.g., Smith and Hallam (1970); Powell et al. (1988), see Fig. 5.

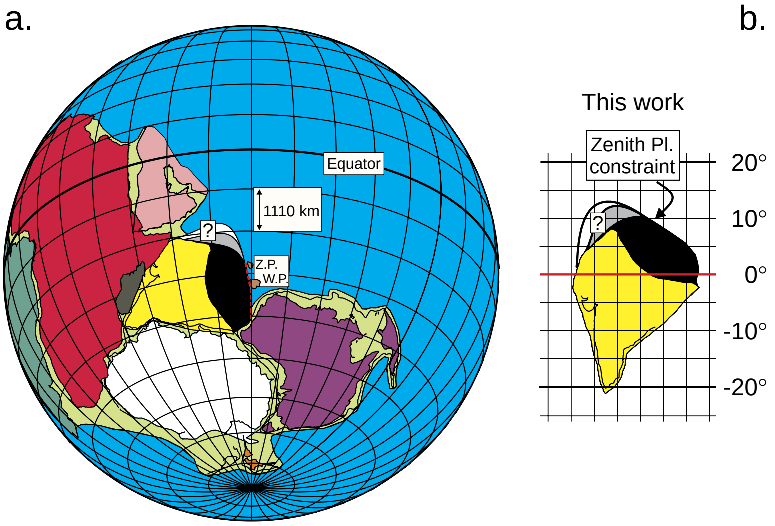

Fig. 5. (a) Gondwana in the Middle Jurassic (~160 Ma) immediately prior to the rifting/drifting which separated South America–Africa from the eastern part of the continent. The figure has been created using the "Gondwana" stencil in the GMAP programme (Torsvik and Smethurst, 1999, and references therein, in essence following the India–Australia–Antarctica positioning proposal of Powell et al., 1988). Gondwana is positioned using the 160 Ma pole for South Africa in the Besse and Courtillot compilation (2002, corrected 2003) at 259.9°E, 55.1°N ($A_{95}=5.1°$). Note the Wallaby and Zenith Plateaus and the Wallaby–Zenith Fracture Zone (red dash line) immediately to the west of Australia (see Fig. 6). The West Burma block, which rifted off NW Australia ~156 Ma (Heine et al., 2004) is not shown. The Himalayan chain, which comprises rocks of Indian plate affinity, is not shown. (b) Proposed Greater India shown as it would fit into eastern Gondwana at 160 Ma, and relative to the Indian craton at 55 Ma using Acton's (1999) pole (see text for details).

Tectonophysics paper by Powell, Roots and Veevers that provided us with both the fit and break-up history that is widely accepted today (Fig. 5a). Interestingly, on the basis of stratigraphic records and outcrop patterns in India and Australia, Luc-Emmanuel Ricou was still arguing against this type of proposal in the mid-1990s (Ricou, 1994, see also Ricou, 2004: Fig. 2). He matched the southeast-facing margin of India with the west-facing coast of Australia as Veevers et al. (1971) had earlier suggested, but later abandoned (Veevers et al., 1975; Powell et al., 1988).

Prior to its separation from Gondwana, India was sandwiched between Africa–Madagascar, Antarctica and Australia. Immediately to the "north" of India and northern West Australia lay Neotethys. Starting in the Middle to Late Jurassic and taking place over about 40 million yr, India became isolated from the major Gondwana blocks. Initially this was caused by the break-up of South America–Africa from eastern Gondwana (c. 170 Ma: Reeves and de Wit, 2000; 155–160 Ma: Schettino and Scotese, 2001). Around 140 Ma, the sub-continent began separating from western Australia (Powell et al., 1988; Müller et al., 2000) subsequently unzipping from Antarctica ~120 Ma. The India we know came into being when it split from Madagascar in the Late Cretaceous (85–90 Ma: Storey et al., 1995; ~83 Ma: Torsvik et al., 2000), by which time the central part of the continent was ~40°S (e.g., Reeves and de Wit, 2000).

It is the present-day southeast Indian Ocean which provides critical data as to the maximum size Greater India could have been, at least in the east and central parts (Fig. 6). The east/southeast Indian Ocean is notable (e.g., Schlich, 1973: Figs. 2 and 9; Powell et al., 1988: Fig. 5; Brown et al., 2003; GEBCO Digital Atlas, 2003) for a number of submerged bathymetric promontories that extend out from Australia's western- and northwestern-facing coasts. Progressing clockwise around Australia, these are the Naturaliste Plateau, the Wallaby–Zenith Plateaus and the Exmouth Plateau. We believe that the middle feature, i.e., the Wallaby–Zenith Plateau Ridge, is critical for constraining Greater India proposals.

With highs of ~2460 and ~1960 m below sea level respectively (GEBCO Digital Atlas, 2003), the Wallaby and Zenith Plateaus (along with the Natur-

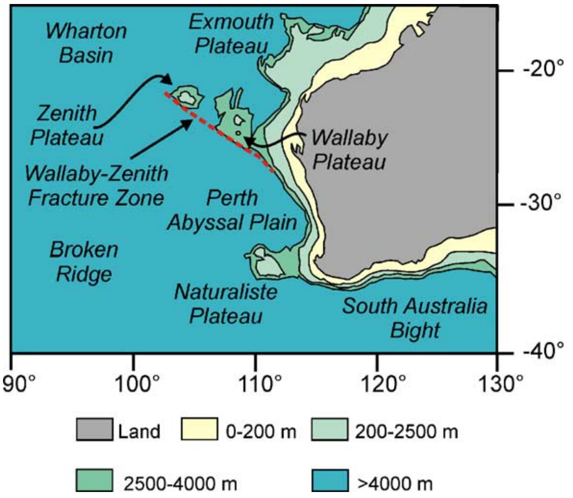

Fig. 6. Key bathymetric features in the southeast Indian Ocean. Note the Wallaby–Zenith Ridge extending WNW from the western coast of Australia. The Wallaby and Zenith Plateaus are blocks of thinned continental crust. The Wallaby–Zenith Fracture Zone is shown by the red dash line. South of the fracture zone, the oldest ocean floor in the Perth Abyssal Plain is ~131 Ma (M11 age). The area between the Wallaby–Zenith Plateau Ridge and the Exmouth Plateau is believed to be the site where either the basement of east Java or the Woyla terranes, southwestern Sumatra, originated—see text. The map has been drawn over an image generated using the GEBCO Digital Atlas (2003).

aliste and Exmouth Plateaus) have long been considered thinned rafts of the Australian margin (Schlich, 1973; Veevers, 1973a,b; Larson, 1977). Mihut and Müller (1998), however, suggested that the two linked features were volcanic edifices that had formed on top of the southeast Indian Ocean floor, the implication being that they played no role in constraining the northern limit of Greater India. However, the recent paper by Brown et al. (2003), which featured Dietmar Müller and Phil Symonds as co-authors, followed Symonds et al. (1998) in interpreting the Wallaby and Zenith Plateaus as being of continental origin. Brown et al. (2003) also argued that the Wallaby and Zenith Plateaus were separated by short sections of Early Cretaceous (131–130 Ma) ocean floor.

Immediately southwest of the Wallaby–Zenith Plateau ridge is the Wallaby–Zenith Fracture Zone, which extends northwest from the margin of Australia at around 113°E/31°S to about 103°E/22°S in the Indian Ocean. South of the fracture zone is oceanic crust, which records India's break-up (131–130 Ma; Brown et al., 2003: Fig. 8) from Australia and the early stages of drifting. We thus believe that the Wallaby–Zenith Plateau ridge, even when its telescoped length is restored, controls how far north Greater India could have existed, at least in the center and east.

Our proposed Greater India is thus shown in Fig. 5b. The sub-continent's longest N–S extension is approximately 8.5° along a great circle, equating to about 950 km, and concerns the area north of the central Main Boundary Thrust. Based on the form of the Perth Abyssal Plain, the eastern end of the continent curved around to a point marked by the tip of the Eastern Syntaxis. The E–W width of the extension is somewhat imprecise because of lack of control in the area immediately to the west of the Western Syntaxis. However, because the Himalayan belt (Main Boundary Thrust to the Yarlung Tsangpo suture in an arc-normal direction) is of uniform width, the extrapolation shown in this area is probably sensible (i.e., the extension north of the feature was probably ~600 km).

An important implication from this proposal is that the boundary separating "northern" India and the Wallaby–Zenith Plateau Ridge was at one time a dextral transform fault. The most appropriate example of this type of ocean–continent boundary is provided by South America's northeast-facing margin, offshore of Brazil, and its conjugate immediately to the south of Ghana, West Africa (Mascle et al., 1997; Edwards, 1997). Therefore, when India collided with Eurasia, the sub-continent's leading edge would have been marked by a sharp ocean–continent transition zone, probably only 5–10 km wide. Critically, the margin would not have been excessively extended as in the Atlantic west of Iberia (Whitmarsh et al., 2001).

Before concluding this section, we note that the ocean floor between the Wallaby–Zenith Plateau Ridge and the Exmouth Plateau to the northeast is also marked by Early Cretaceous crust. We consider the fragment(s) which rifted off this sector of the Australian margin may at a later date have accreted to SE Asia. Possibly they form the continental basement beneath the Woyla terranes (Metcalfe, 1996; Barber, 2000), which today form the southwestern flank of Sumatra, western Indonesia (Barber and Crow, 2003). Alternatively, based on recent zircon age-dating studies by London University's Helen Smyth and Robert Hall, the crustal blocks could be beneath east Java (Robert Hall, personal communication, 2005).

5. Summary of key Greater Indias

The following discussions and figures summarize some of the key Greater India reconstructions. For ease of comparison, we have positioned the Indian plate at 55 Ma (using the Indian continent pole compilation of Acton, 1999), as this is when many consider India's collision with Asia to have begun (DeCelles et al., 2002; Guillot et al., 2003). The proposed northern appendages have then been added to the stencil.

At some basic level, scientific thought evolves (although as with biological evolution often not in a simple linear fashion), so the proposals are discussed generally in chronological order. The models are grouped at a higher level into (a) pre-plate tectonic theory models; (b) 1970s models ("early" plate tectonic theory works); and (c) models from the 1980s onwards. A fourth category has been included which deals with information deduced from recent geophysical investigations in Tibet, their focus being to establish the nature and position of the India continental lithosphere beneath the region. These studies have not really aimed at defining the original extent of Greater India, but they do provide critical independent insights. Many of the models presented in the original works provide robust aerial controls (e.g., Powell et al., 1988, Le Pichon et al., 1992). For others, the Greater Indias are more sketch-like. Another issue related to the redrafting process concerns the switching between different map projections. However, we have attempted to reproduce each reconstruction (as a Galls projection) in a form that best reflects the original. In most cases, errors in defining the limits of each Greater India are generally within a degree in both the N–S and E–W directions.

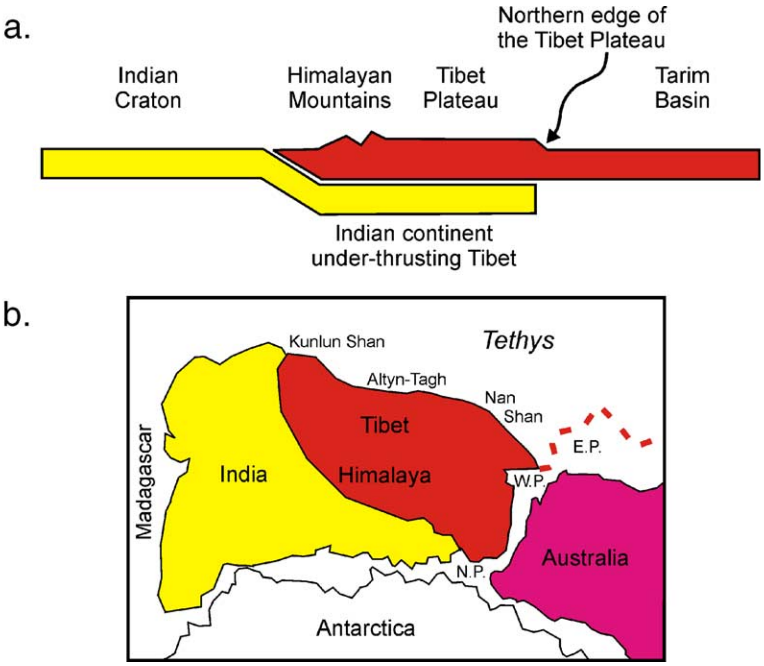

Fig. 7. Greater India reconstructions: (a) Under-thrusting model of Argand (1924: Fig. 13) and Holmes (1965: Figs. 7–9); (b) redrafting of the Veevers et al. (1975: Fig. 1) "under-rafting" model in which the Himalayas and Tibet Plateau are considered to be underlain by Indian continental crust. N.P., W.P. and E.P. are respectively the Naturaliste, Wallaby and Exmouth Plateaus. The Zenith Plateau was not shown in the original figure. Additionally the alignment of the Wallaby–Zenith Fracture Zone was slightly wrong.

6. Pre-plate tectonic models

6.1. Argand's (1924) model

Emile Argand's classic 80-yr-old monograph (Argand, 1924) provides us with the foundations for understanding the Himalaya–Tibet region. The collision zone was marked by Indian, Tethyan and Asian "crust," the E–W boundary between the latter two subdividing Tibet into southern and northern halves. Argand had an Indian continent with a hidden extension that had under-thrust the entire elevated area defined by the Himalayan Mountains and the Tibetan Plateau (Figs. 7a and 8a). Although the proposal would work for the western end of the Indian–Asia collision zone, the required extensions in the center and east get progressively larger (up to >1400 km) and are thus well in excess of the guide limit provided by the Wallaby–Zenith Fracture Zone.

6.2. Holmes' (1965) model

The second edition of Arthur Holmes' *The Principles of Physical Geology* (1965, the year of his death) included a "new" section on orogeny and the Himalayan–Tibet region in particular (see pages 1097–1100). By the mid-1960s, Holmes had access to the growing palaeomagnetic data-set, which was confirming Alfred Wegner's idea that the continents had moved relative to both the spin axis and one another. The second edition of *Principles* showed Holmes grappling with theories that might unify the observations. Unlike Argand, Holmes' general view of Tibet can be considered modern. Between the India craton and the Yarlung Tsangpo suture zone lay deformed rocks that prior to the collision had formed northern part of India; and shortening between India and Asia was accommodated on thrusts marking the southern boundary of the Himalayas. Like Argand, he thought that the Indian plate underlay the elevated parts of southern Asia (Figs. 7a and 8a). For the reason described in the preceding section, that part of his interpretation was probably wrong.

7. Models from the 1970s

7.1. Macquarie University group's models

In the 1970s, Chris Powell, John Veevers, David Johnson and Pat Conaghan were authors on a number of Himalaya–Tibet–Greater India-related papers (e.g., Veevers et al., 1971, 1975; Powell and Conaghan, 1973, 1975). All those researchers were then based at Macquarie University, Sydney. Some works dwelt on India's site within Gondwana, while others focused on the plate's collision with Asia. The group favoured a model in which the Indian continental lithosphere underlay the Himalayas and Tibet, and showed an

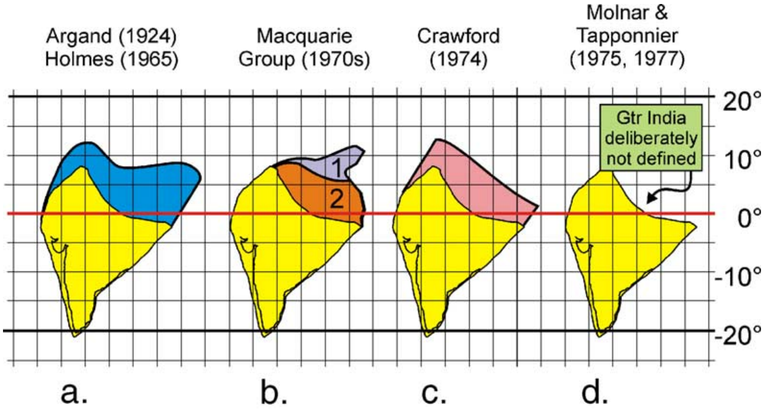

Fig. 8. Greater India reconstructions: (a) Under-thrusting/-plating model relative to the Indian craton at 55 Ma (Argand, 1924; Holmes, 1965); (b-1) Macquarie Group, mid-1970s; (b-2) Powell (1979); (c) redraft of Crawford's (1974) proposal; (d) Molnar and Tapponnier's model (1975, 1977).

interesting reconstruction in which the Indian plate plus the Himalayas and Tibet were repositioned against Antarctica and western Australia (Fig. 7b). However, as mentioned above, the main problem with such a model (Fig. 8b-1) is the misfit that occurs in eastern Tibet, with India's extension going beyond the Wallaby–Zenith Fracture Zone. Another point is that there is no crust to the north and west of the Western Syntaxis when there probably should be.

Powell's later proposal (Powell, 1979) adopted a slightly smaller Greater India, explicitly using the Wallaby Plateau as a guide in the east. A line (concave south) which delineated the edge of the continent was then drawn parallel to the Himalayan Front (Fig. 8b-2). At the western end, the line connected up with the Western Syntaxis. This Greater India would fit within a Gondwana reconstruction but is probably too small because it leaves a small unfilled strip, which widens to the west, from the edge of the sub-continent to the Wallaby–Zenith Fracture Zone.

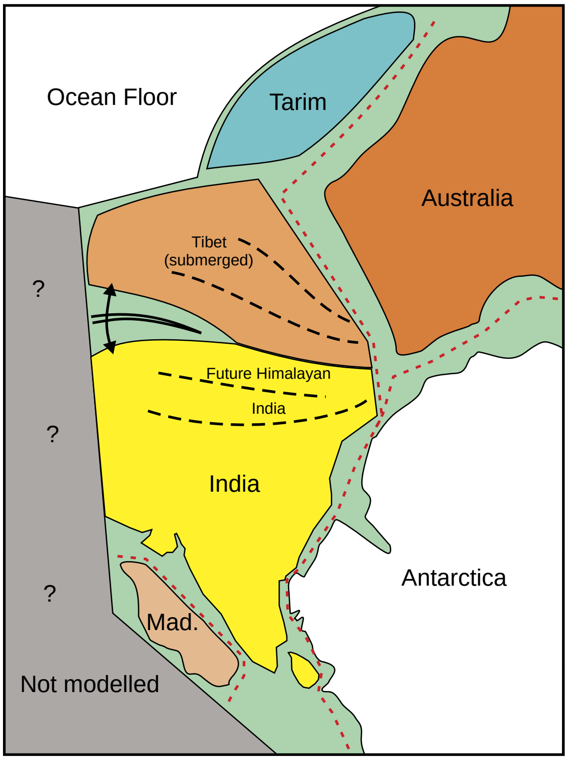

Fig. 9. A.R. Crawford's (1974) reconstruction of eastern Gondwana (see text for details).

7.2. Contribution of A.R. Crawford

Ray Crawford wrote an interesting paper in *Science* (1974) explaining the relationship between Australia, India, Neotethys, Tibet and the Tarim block. The root of his reconstruction proposal (Fig. 9) was the need to accommodate the "extraordinary distribution of the cladoceran *Daphniopsis*, recorded only in Kerguelen, Antarctica, Australia, Tibet and inner Mongolia (Tarim block)." Crawford positioned the southeast-facing margin of India against Antarctica, and to the "north" of the sub-continent added portions of ground for the future Himalayas and Tibet. Neotethys, the ocean between the Himalayas and the Lhasa block in Tibet, opened in Permo-Triassic times as a scissor-like basin about a rotation pole in SW Australia. Crawford's Neotethys then closed as India broke away from Gondwana in the Late Jurassic (or more probably, in the light of new information, in the Early Cretaceous). The Himalayas developed much later due to compression acting upon the pre-existing structural weaknesses within the northern Indian plate. The model assumed no under-thrusting of India beneath Tibet. The flaws in this model are now apparent in the light of 30 yr of subsequent research. First, by the Late Jurassic–Early Cretaceous, the Lhasa block had already accreted to southern Asia (Allegre et al., 1984; Yin and Harrison, 2000), and Neotethys was several thousand kilometers wide. Second, Tarim was not positioned directly adjacent to northwest Australia in the Permo-Triassic. It had rifted off Gondwana sometime in the Paleozoic and had already accreted to Eurasia at this time (e.g., Enkin et al., 1992). Third, immediately adjacent to the NW-facing coast of Australia in the Middle Jurassic lay the West Burma block, which separated from Gondwana at ~156 Ma (Heine et al., 2004). Crawford's Greater India has been redrafted (Fig. 8c), although it is based on a rather sketchy figure.

7.3. Peter Molnar and Paul Tapponnier models from the 1970s

In the mid- to late 1970s, Peter Molnar and Paul Tapponnier co-authored a number of influential papers on the India–Asia collision system (e.g., Molnar and Tapponnier, 1975, 1977). The works focused on the deformation processes associated with continent–continent collision. As part of their analyses, they reconstructed India's past position at several key times back to the Late Cretaceous (Molnar and Tapponnier, 1975, Fig. 1). They deliberately avoided delineating the northern margin of the sub-continent, portraying the craton only, "We do not know the northern boundary of the Indian continent before the collision and do not mean to imply that it was as drawn." A conspicuous feature of Tapponnier's India–Asia collision publications over the past three decades (e.g., Molnar and Tapponnier, 1975; Replumaz and Tapponnier, 2003) is the noticeable angular offset of the India continent in the early Palaeogene (~13° clockwise at 55 Ma) as compared with the more typical India reconstructions (e.g., Besse and Courtillot, 1988, 2002; Acton, 1999). However, the India depicted in Fig. 8d uses Acton's (1999) 55 Ma pole.

8. Models since 1980

8.1. Barazangi and Ni (1982)

Barazangi and Ni (1982) used seismic waves travelling beneath Tibet and the adjacent region to test the under-thrusting/-rafting model proposed by Argand (1924), Holmes (1965) and the Macquarie Group (e.g., Powell and Conaghan, 1975; Veevers et al., 1975). The gist of their conclusion was that Indian continental crust probably existed directly beneath a large portion of Tibet and surrounding regions, although in central Tibet, beneath the Qiangtang block, a distinct patch of ground marked by the inefficient transmission of seismic waves was identified. The area of "efficient" seismic wave transmission, which was used by Barazangi and Ni to infer the existence of Indian crust beneath Tibet, is shown added to a 55 Ma restored India in Fig. 10a. An obvious problem with this proposal is the extent of the lithosphere to the north and northeast of the Indian craton. Such protrusions would make it impossible to relocate the sub-continent in a Gondwana reconstruction.

8.2. Besse and Courtillot (1988)

Jean Besse and Vincent Courtillot, from the Institut de Physique du Globe de Paris, were the first to rigorously model the past positions of the continents rimming the Indian Ocean basin (Besse and Courtillot, 1988). They presented a series of reconstructions at key times going back to the Early Jurassic. Drawing upon a considerable body of palaeomagnetic data that had then been assembled for the continents of this vast region, the information was integrated with magnetic anomaly data-sets that had been generated for the Indian and Southern Oceans. Besse and Courtillot's Greater India extension estimate was a classic "fill-the-gap" approach. Collision of the plate occurred at 50 Ma, based on an inferred slowdown in India's northward motion (Patriat and Achache, 1984; Besse and Courtillot, 1988). The southern margin of Eurasia was fixed at ~11°N, based on two palaeomagnetic results from southern Tibet. Material was then added to western north India at Anomaly 24 times (then 53 Ma, now 55 Ma) thereby bridging a 5° S–N gap (Besse and Courtillot, 1988; Fig. 7). The Besse and Courtillot reconstruction is shown in Fig. 10b.

8.3. Powell et al. (1988)

The Macquarie Group's next major contribution was their 1988 paper in *Tectonophysics* (Powell et al., 1988). The work is important because, barring minor details, their eastern Gondwana reconstruction and the India–Australia–Antarctica break-up story is the one that most workers today would consider definitive. However, their postulated Greater India (Powell et al., 1988, Fig. 6) extended up to the Cape Range Fracture Zone, the SW edge of the Exmouth Plateau. The reconstruction is thus similar to that presented by this group in the mid-1970s (Fig. 8b-1) and, for the reasons described, was probably incorrect.

More recently, Zheng-Xiang Li and Chris Powell published a major review of the Australian plate's tectonic evolution back to 1 Ga (Li and Powell, 2001). Their Mesozoic reconstructions included a Greater India, and they also showed the approximate sites at which the Lhasa, Sibumasu and West Burma blocks were located prior to their rifting (to the NW of Australia and north of Greater India) from Gondwana and their translation across Tethys. Although portions of their Mesozoic models are somewhat sketchy, the Greater India they proposed essentially

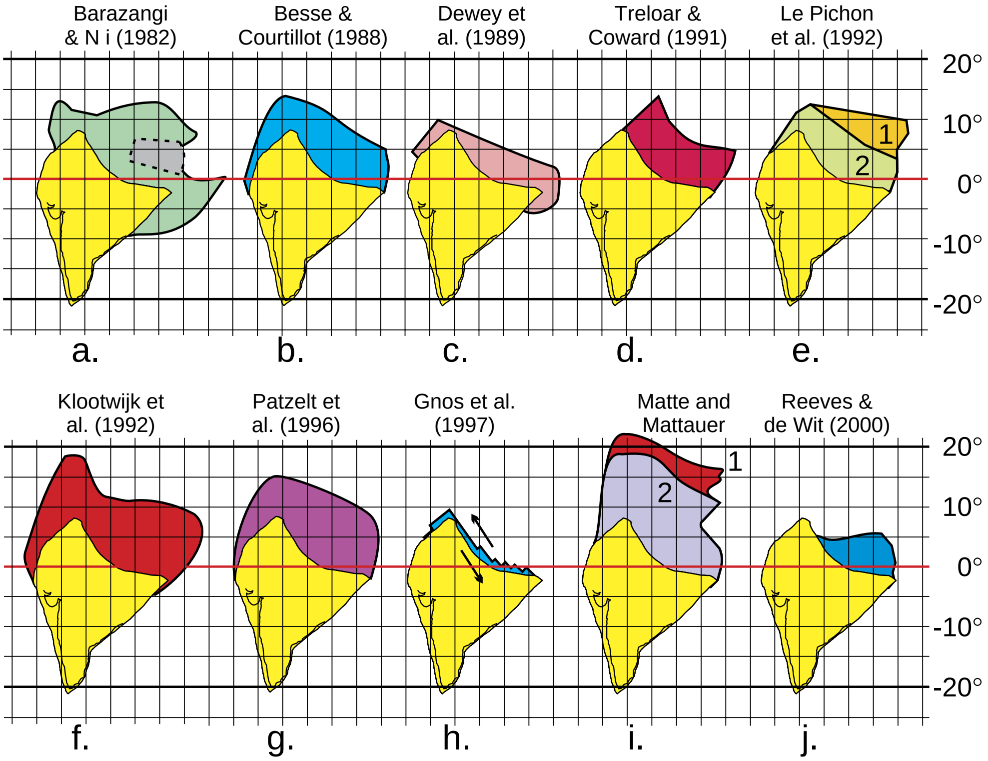

Fig. 10. Greater India reconstructions: (a) Barazangi and Ni (1982); (b) Besse and Courtillot (1988); (c) Dewey et al. (1989); (d) Treloar and Coward (1991); (e) Le Pichon et al. (1992); (f) Klootwijk et al. (1992); (g) Patzelt et al. (1996); (h) Gnos et al. (1997); (i) Matte et al. (1997) and Mattauer et al. (1999); (j) Reeves and de Wit (2000). The grey patch in the Barazangi and Ni model reflects a seismically anomalous zone marked by the inefficient transmission of seismic waves.

follows that of the Macquarie Group (mid-1970s) and Powell et al. (1988).

8.4. *Dewey et al. (1989)*

Dewey et al. (1989) produced an influential paper on the India–Asia collision system. It is clear that they were irked by some of the models that had been proposed for the region. They were anti-major under-thrusting and large-scale eastwards extrusion, and pro large-scale northward indentation (at least 1500 km absorbed by the Eurasian plate). They favoured a relatively small Greater India. Based on a change in India's motion (movement direction and motion rate), it was assumed that collision occurred ∼45 Ma. Palaeomagnetic results from the Lhasa block were used to position the southern edge of Eurasia at low latitudes (60°E/25°N, 70°E/20°N, 80°E/14°N and 90°E/4°N). Based on Dewey et al. (1989, Fig. 5), it is estimated that the sub-continent had a 1° extension north of the Western Syntaxis, and a 5° extension in the central northern and eastern northern parts of the sub-continent (Fig. 10c). Their proposed extension is probably too small.

8.5. *Treloar and Coward (1991)*

Treloar and Coward's (1991) Greater India assumed there had been 200–300 km of under-thrusting of the India beneath Tibet north of the Yarlung Tsangpo suture zone. Based on the 50% shortening estimate Dewey et al. (1989) proposed for the Himalayas, they also advanced the suture zone northwards. This would mean that the plate extended 800–900 km north from the Main Boundary Thrust (Fig. 10d), enabling their Greater India to be fitted back into Gondwana.

8.6. Le Pichon et al. (1992)

Xavier Le Pichon et al. (1992) favoured collision at 45 Ma. In a detailed analysis, they proposed maximum and minimum Greater Indias. Their minimum model is based simply on shortening estimates that had been made for the Himalayas, the extensions ranging from about 1000 km in the center to ~670 km at in both the east and west (Fig. 10e-1). Allowing for a number of uncertainties, this Greater India would just about fit back in Jurassic Gondwana. With the maximum model, the extension is asymmetrical, the eastern end being based on the Powell et al. (1988) proposal, the western end corresponding to that in their minimum estimate model (Fig. 10e-2). As for the reasons discussed in the section dealing with the Macquarie Groups' proposals, this configuration is probably wrong.

8.7. Chris Klootwijk and associates

Chris Klootwijk's name is synonymous with "Greater India." Between the late 1970s and mid-1990s, he and several colleagues published the results of many palaeomagnetic-based investigations of the India–Asia collision, the main focus being the timing of the event and the original size of sub-continent (e.g., Klootwijk and Peirce, 1979; Klootwijk and Bingham, 1979; Klootwijk, 1984; Klootwijk et al., 1985, 1992). His earlier works favoured initial contact at 60–50 Ma (Klootwijk et al., 1979, 1981, 1986). Later papers argued for an earlier collision, 68–65 Ma (Klootwijk et al., 1992, 1994). Klootwijk argued consistently for diachronous suturing (taking place over several million years), the northwestern tip of the craton making the initial contact with Eurasia. The Greater India shown in Fig. 10f is a redraft of that shown in Klootwijk et al. (1992), which is based upon (1) collision-induced overprint magnetizations in NW India and southwest Tibet (Eurasian plate) to position the NW tip of the sub-continent at a sub-equatorial (0–5°N) location ~65 Ma, (2) a Himalayan shortening restored northern India, (3) motion-change data for India derived from palaeomagnetic studies. The resultant Greater India has extensions in the east ~12° (>1300 km), while north of the Western Syntaxis the value is ~10° (>1100 km).

8.8. Patzelt et al. (1996)

Patzelt et al. (1996) conducted a palaeomagnetic study of mid-Cretaceous through Palaeocene sedimentary rocks of Indian plate affinity in the Tethyan Himalayas at Gamba (88.5°E, 28.3 °N) and Duela (89.2°E, 28.0°N). A primary magnetization identified in a sub-set of sites from late Maastrichian and middle–late Palaeocene units was then used to locate the northern part of India at the time the rocks formed. Based on a fill-the-gap argument, the sub-continent in the Western Syntaxis area was given an extension of ~7°, the southern edge of Eurasia at the collision point being located at ~11°N. The addition to the Indian plate was wider in the east with an extension ~12° (Fig. 10g).

8.9. Gnos et al. (1997)

The relatively recent paper by Edwin Gnos et al. (1997) includes what is probably the smallest Greater India extension. The 130 Ma cartoon in Gnos et al. (1997) has a spreading system which rifts-off a continental fragment (Fig. 10h) from the area north of India and west of Australia (now marked by the Perth Abyssal Plain). The paper does not indicate where this unnamed block ended up. This proposal is wrong on at least two counts. First, the Himalayas record considerable shortening of Indian continental rocks north of the craton. Second, geophysical evidence (see later) suggests that a substantial volume of India continental lithosphere is present in the mantle beneath southern and central Tibet.

8.10. Matte et al. (1997), Mattauer et al. (1999)

Colleagues Maurice Mattauer and Philippe Matte produced two Greater India proposals in the late 1990s. Based on the PhD thesis by M. Sahabi (1993), Matte et al. (1997) added a huge appendage to the sub-continent; its N–S dimension was the same size as the present-day Indian craton (Matte et al., p. 267) (Fig. 10i-1). The extension was so large that its northeastern corner would have sat adjacent to the most northerly point of the Exmouth Plateau. As a result, this proposal is unlikely to be correct. The later paper by Mattauer et al. (1999, Fig.

3) had a slightly smaller extension, this time reaching to the southern edge of the Exmouth Plateau (Fig. 10i-2). Again, such a reconstruction would make it impossible to fit India back into Gondwana.

8.11. Scotese et al. (1999)

Christopher Scotese has played a leading role in deciphering the Phanerozoic palaeogeography of Earth's plates (e.g., Scotese et al., 1979; Scotese, 1991). A recent Gondwana-focused work included a Greater India (Scotese et al., 1999). The proposal has an extension that reached up to the southwestern edge of the Exmouth Plateau, beyond the line of the Wallaby–Zenith Fracture Zone, and is thus similar to the Macquarie Group's mid-1970s model and to Powell et al. (1988).

8.12. Reeves, de Wit and Kobben (2000)

Colin Reeves and Barend Kobben produced a detailed Atlas program (Cambridge Paleomap Services, 1993) based computer animation of the Indian Ocean's evolution since 200 Ma (Reeves and de Wit, 2000). The eastern end of their Greater India is identical to the one proposed in this work, being fixed by the SE Wallaby–Zenith Plateau Fracture Zone (Fig. 10j). However, in the center and west the extension to the continent cuts back south to the edge of the present-day craton. We therefore suggest that India's appendage in these parts is too small.

8.13. Rotstein et al. (2001)

Although somewhat sketchy, the Rotstein et al. (2001, Fig. 10) Greater India shows the largest subcontinent extension so far proposed. The pre-break-up reconstruction (132 Ma) has an appendage that hugs the shoreline of West Australia to a point on the NW-facing coast at 120°, >2800 km from the central part of the Main Boundary Thrust (Fig. 11a-1). The reconstruction ignores the various submarine promontories that extend out the Australian continent. From this point, it then connects as a straight line to the Western Syntaxis. The 96 Ma model actually differs considerably from the Early Cretaceous proposal, the extension from the NE tip of the block running along an E–W line (Fig. 11a-2), rather than to the SW as with the 132 Ma model. As such, neither proposal carries much credibility.

8.14. Dietmar Müller and colleagues

Dietmar Müller is associated with ocean floor history maps and plate reconstructions in which the continents are refitted by the progressive removal of ocean floor (e.g., Müller et al., 1997). With various colleagues, he has published a number of works dealing with the Meso-Cenozoic evolution of the Indo-Australian plate (e.g., Gaina et al., 1998; Mihut and Müller, 1998; Müller et al., 2000; Brown et al., 2003; Heine et al., 2004). Over the years, Müller and his colleagues' portrayals of Greater India have varied considerably. In the early 1990s (Müller et al., 1993), they showed India with an extension that would at its eastern side have wrapped around the northwest-facing edge of the Exmouth Plateau (Fig. 11b-1). More recently their reconstructions (e.g., Fig. 11b-2 and b-3) have ranged from very small (e.g., 0–400 km: Kent et al., 2002, Fig. 4; Gaina et al., 2003, Fig. 4) to very large, ~2000 km N–S (O'Neill et al., 2003; Heine et al., 2004, Plate 1). The paper by Mihut and Müller (1998) complicates matters because they introduced a North India continental plate, roughly equivalent in size to the largest (O'Neill et al., 2003) minus the smallest (Kent et al., 2002) reconstructed India. None of the proposals use the Wallaby–Zenith Fracture Zone as a guide, and for this reason, we feel that the various versions (large and small) presented by Müller and his colleagues of Cretaceous India are wrong.

8.15. Hall (2002)

For nearly a decade, Robert Hall's Cenozoic reconstructions and computer animations of SE Asia have influenced many workers investigating the region. On all of his models, India appears at the western edge of the reconstructions. For this work, Hall very kindly provided the 55 Ma snapshot in his 2002 paper (Hall, 2002) as a cylindrical projection centered on India (rather than an orthogonal projection looking directly down onto 135°E, 10°S (present-day Arafura Sea, north of Australia). The model has a Greater India that extends 13–14°

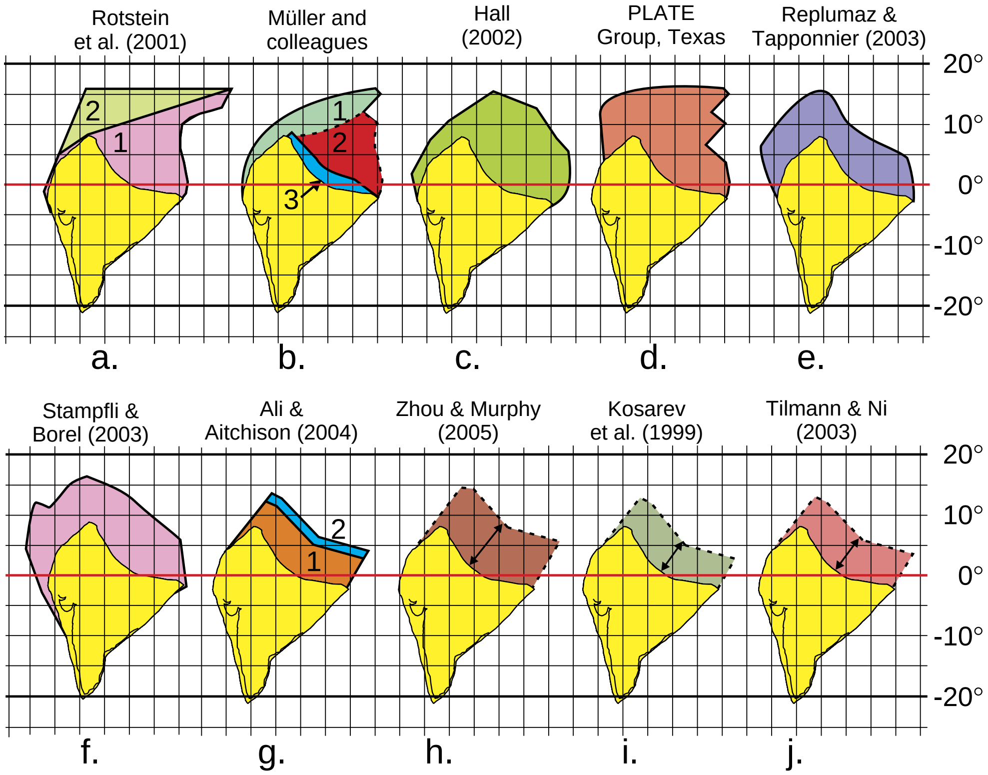

Fig. 11. Greater India reconstructions: (a-1 and a-2) Rotstein et al. (2001) at 130 Ma and 96 Ma respectively; (b-1) Müller et al. (1993), O'Neill et al. (2003); (b-2) Heine et al. (2004); (b-3) Kent et al., 2002, Gaina et al. (2003); (c) Hall (2002); (d) Lee and Lawver (1995) and Lawver and Gahagan (2003); (e) Replumaz and Tapponnier (2003); (f) Stampfli and Borel (2003); (g) Ali and Aitchison (2004); (h) Zhou and Murphy (2005); (i) Kosarev et al. (1999); (j) Tilmann and Ni (2003). For Ali and Aitchison, 1 and 2 are based respectively on the 55 Ma and 57 Ma positions of India using the poles of Acton (1999)—see text. For panels (h–j), the key issue is the arrow length denoting the extent of continental lithosphere ahead of the Indian craton, minimum values being shown.

northeast from the central portion of the Main Boundary Thrust, and ~9° north–northeast from the Western Syntaxis (Fig. 11c). Hall's modeling was designed such that Greater India in the west collided with the southern edge of Eurasia in the latter part of the early Eocene, around 50 Ma based on Rowley's (1996) estimate of the initial age of collision. The Hall (2002) Greater India would not fit into a Gondwana as it would extend beyond the Wallaby–Zenith Plateau Fracture Zone by 300–400 km at its widest part (in the middle).

8.16. Plate Group, University of Texas

In recent years, the global and regional Phanerozoic plate reconstructions by Larry Lawver and his Plate Group colleagues from the University of Texas at Austin have featured prominently in the literature. Lee and Lawver (1995) and Lawver and Gahagan (2003) adopted large Greater Indias with extensions north from the Main Boundary Thrust of ~16° (Fig. 11d). Again, with such a large appendage, it would be impossible to fit India back into Gondwana.

8.17. Replumaz and Tapponnier (2003)

Paul Tapponnier of the Institut de Physique du Globe de Paris is associated with several seminal papers on the India–Asia collision system (e.g., Molnar and Tapponnier, 1975; Tapponnier et al., 1982). A recent publication with Anne Replumaz shows India in the middle Cenozoic with a well-defined northern appendage (Replumaz and Tapponnier, 2003: Fig. 7). The ~600 km N–S extension (Fig. 11e) is based essentially on a fill-the-gap argument. Following collision, Replumaz and Tapponnier argue for a substantial body of Asian crust being extruded southeastwards, similar to that predicted in the famous plasticene experiment (Tapponnier et al., 1982).

8.18. Stampfli and Borel (2003)

Gerard Stampfli and his colleagues at Lausanne have published many papers on the evolution of Tethys, particularly the western part of the system. Stampfli and Borel (2003, Fig. 9) included one of the more unusual Greater Indias. The eastern and central portions of the sub-continent's northern margin had what we consider to be sensible extensions. The western part was, however, marked by a major chunk of continental plate that would have extended well across present-day Pakistan, probably into central Afghanistan (Fig. 11f). Such a model could be accommodated within a Gondwana reconstruction but would probably create problems with the way we generally view how NW India indented into Eurasia.

8.19. Meert (2003)

A late Proterozoic–Palaeozoic reconstruction history for Gondwana was recently published by Joe Meert (2003). He includes a sketch-like model of Greater India (Meert, 2003: Fig. 2) which is effectively identical to that proposed by Powell et al. (1988), see Fig. 8b-1.

8.20. Ali and Aitchison (2004)

Having scrutinized the key Greater India models, it is appropriate that we account for our own proposals (e.g., Ali and Aitchison, 2004; Abrajevitch et al., 2005). Using ocean lithosphere Slabs III and II of Van der Voo et al. (1999), defined at the 1325 km depth but reduced in width to allow for their "back projection" up to the Earth's surface, an estimate for the India extension can be made by measuring the distance between the craton and the northern edges of the two subducted slabs. Our 55 Ma reconstruction yields an extension of 500–700 km, while the 30 Ma proposal gives values of 400–600 km (Fig. 11g-1). While these estimates are probably too low by 200–500 km, it is worth remembering that the data are based on the Van der Voo et al. (1999) tomography study, and the Acton (1999) Indian plate motion analysis. Indeed if the conspicuous slowdown in India's motion at 57 Ma (Lee and Lawver, 1995; Acton, 1999) is taken to mark collision with an intra-oceanic arc (e.g., Aitchison and Davis, 2004), the extension to India (based on the 55 Ma reconstruction) would increase by approximately 150 km as the India plate is positioned a little further to the south (Fig. 11g-2).

8.21. Recent geophysical probing of India beneath Tibet

In recent times, geophysical techniques have been used to image the lithosphere beneath Tibet and the adjacent areas, essentially to see if Indian continental material is present, although in most cases, the investigations have not focused on deducing the original form of Greater India. Two approaches have been used: seismic tomography and seismic refraction. The first involves assessing the slight perturbations in the travel times of earthquake-induced seismic waves passing through the mantle to infer the presence of subducted lithosphere (such waves are considered to travel slightly faster through subducted oceanic and continental lithosphere than would be the case for "uncontaminated" mantle). The current resolution of the technique (in which anomalies have travel-time velocities ~0.5–3.0% above the background level) produces distinctly blurred images where approximately cubic "pixels" of the mantle, with sides several tens of kilometers long, are assigned averaged velocity values. In contrast, the seismic refraction technique is more focused. It has entailed setting up along a number of N–S oriented profiles in Tibet a series of seismic "listening" stations. Using a complex processing technique applied to the incoming wave trains from both earthquakes and/or shot triggered events, it has been possible to resolve extremely deep (to several hundred kilometers) features present beneath the region.

Another minor issue related to the imaging of subducted India is that shortening of the continent must have been experienced when it first collided with an island arc and then Asia (Aitchison et al., 2000; Abrajevitch et al., 2005). The sub-continent today cannot be larger than when it left Gondwana in the Early Cretaceous, though we surmise that the shortening is probably less than several tens of kilometers.

8.22. Van der Voo et al. (1999) seismic tomography study

The seismic tomography study of Van der Voo et al. (1999) involved trying to identify lithospheric slabs within the mantle across a vast area stretching from Central Asia (N) to the central Indian Ocean (S), and from SE Asia (E) to eastern Europe (W). A key finding was the presence of several high velocity zones beneath the India–Tibet region, one of which was used to infer the presence of an intra-Neotethyan subduction system (see also Aitchison et al., 2000). The study also provided information on the nature of the northern India. Van der Voo et al. suggested that the continent was sinking into the mantle almost directly beneath the Yarlung Tsangpo suture zone in Tibet, where it had been dragged down with the oceanic lithosphere that was once attached to its northern passive margin prior to its consumption beneath Tibet.

8.23. Replumaz et al. (2004) seismic tomography study

The recent study of Replumaz et al. (2004) essentially confirmed the findings of Van der Voo et al. (1999) as regards the Indian plate being drawn into the mantle. The authors were very much against any significant under-thrusting of the sub-continent beneath Tibet.

8.24. Zhou and Murphy (2005) seismic tomography study

Zhou and Murphy (2005) carried out a geographically more focused seismic tomographic study of the northern India–Tibet region. Contrary to Van der Voo et al. (1999) and Replumaz et al. (2004), their modeling indicated that a substantial length of India extends at shallow depths beneath Tibet: ~570 km NNE of the Yarlung Tsangpo suture (another 300 km from the Main Boundary Thrust). At around 82–84°E, the subducted continent dips at a relatively low angle reaching as far north as the Jinsha suture, with a thin wedge of Asian asthenosphere separating the upper lithosphere surface of India from the lower lithosphere band of Tibet. Further east (85–93°E), the plate dips at a moderate angle into the mantle, although if this part of the plate was "straightened," it would give a similar length of subducted continental slab to that thought to be present in the west (Fig. 11h). As such, the reconstructed continent would just about fit back into Gondwana.

8.25. Kosarev et al. (1999)

Using teleseismic waves along a NNE–SSW oriented receiver network in eastern Tibet (~89°E, 28°N to ~95°E, 36°N), Kosarev et al. (1999) were able to infer the presence of low-dipping Indian lithosphere beneath a large tract of the plateau up to the line of the Banggong suture (~33°N). The data indicate that Greater India extends north from the Main Boundary Thrust by at least 550 km (Fig. 11i).

8.26. Tilmann and Ni (2003)

Again using earthquake seismic wave arrivals beneath Tibet, Fred Tilmann and James Ni were able to generate an image of the India plate beneath Tibet. The modeling shows a low dipping wedge of Indian lithosphere present to the line of the Banggong suture. North of the suture, the slab dips steeply into the mantle. From their Fig. 3, it is possible to infer that India extends north from the Main Boundary Thrust by about 800 km (Fig. 11j).

9. Conclusions

India's collision with southern Asia sometime in the relatively recent geological past has created the planet's most spectacular orogenic belt. A key assumption in models of the system is the idea that the sub-continent was larger than the present-day craton before this collision, hence the concept "Greater India." The earliest Greater Indias were based upon the idea that continental lithosphere ahead of the Indian craton had been thrust under Asia, thereby jacking up, to an average elevation of ~5 km, a huge portion of central southern Asia (e.g., Argand, 1924; Holmes, 1965; Powell and Conaghan, 1973, 1975; Veevers et al., 1975). Later models tended to have different objectives. One lot of extensions were designed to bridge a large physical gap between the cratonic part of the sub-continent and the southern margin of Tibet to allow collision with Eurasia at a particular time and site (e.g., Besse and Courtillot, 1988; Patzelt et al., 1996; Klootwijk et al., 1994). Alternatively, Greater India proposals were based either on reconstructions of eastern Gondwana back in the Mesozoic (e.g., Lee and Lawver, 1995; Müller et al., 2000), or estimates of crustal shortening in the Himalayas (e.g., Treloar and Coward, 1991).

Based on the Powell et al. (1988) fitting of India-in-Gondwana, and an analysis of bathymetric features in the eastern Indian Ocean, we suggest that there are very definite limits as to how big Greater India was. In the central part, the extension up to the Wallaby–Zenith Plateau Fracture Zone could only have been about 950 km. In the east and west, the extensions were less, about 500 km and 600 km respectively (Fig. 5). In future, models of the India–Asia collision system may wish to accommodate this control. Interestingly, geophysical studies of the Indian continental lithosphere beneath Tibet are generally supportive of this conclusion, as are shortening estimates for the Himalayan belt (670 km from Pakistan to Sikkim: DeCelles et al., 2002). We also draw attention to the nature of India's northern edge. It formed as a transform fault, thus we might expect the associated ocean–continent transition zone to be very sharp, probably only 5–10 km wide.

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