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The collision of India with Asia

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The collision of India with Asia

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Abstract

We review the relative motion of India and Asia for the last 100 million years and present a revised reconstruction for the India-Antarctica-Africa-NorthAmerica-Eurasia plate circuit based on published motion histories. Deformation of these continental masses during this time introduces uncertainties, as does error in oceanic isochron age and location. Neglecting these factors, the data *ipso facto* allow the inference that the motion of India relative to Eurasia was distinctly episodic. Although motion is likely to have varied more smoothly than these results would allow, the geological record also suggests a sequence of distinct episodes, at about the same times. Hence we suggest that no single event should be regarded as the collision of India with Asia. The deceleration of the Indian plate commencing at ~65 Ma is matched by an equally significant prior acceleration and this aspect must be taken into account in geodynamic scenarios proposed to explain the collision of India with Asia.

Keywords: India, Himalaya, collision, orogen, reconstruction, tectonics, Tethys

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1. Introduction

The motion of the Indian plate relative to Eurasia led to the formation of the Himalayan mountain belt [Dewey and Bird, 1970; McKenzie and Sclater, 1971]. Information as to the history of the collision between India and Eurasia (i.e. when the last oceanic lithosphere was subducted and, continental lithosphere comes into contact with other continental lithosphere) can be extracted by examining the timing of deformation, metamorphism, erosion and sedimentation within the collisional belt [Aitchison et al., 2007; Guillot et al., 2003; 2008; Searle et al., 1987; 1988]. Some authors suggest that the evolution of the orogen involved several distinct accretion events [Aitchison et al., 2007; Lister et al., 2001], while others suggest a single collision event was followed by a protracted history [Beaumont et al., 2001; 2004; Jamieson et al., 2006; Leech, 2008; Noble et al., 2001; Searle et al., 1992; 1999; Vance and Harris, 1999; Walker et al., 2001]. Resolution of this controversy could be achieved by increased detail in terms of the analysis of what geochronological and structural data within the orogen imply in terms of the evolution of its tectono-metamorphic stratigraphy, and of its architecture. Alternatively, the impact of individual accretion events might be evident in plate reconstructions of the relative motion of India to Eurasia using ocean floor magnetic anomaly data.

Several different interpretations of India's relative motion have been published. All of these rely on the motion of Africa relative to North America, and North America relative to Eurasia [e.g., Gaina et al., 2002; Müller et al., 1999; Rosenbaum et al., 2002]. The aim of this paper is to update the India-Antarctica-Africa-North America-Eurasia plate circuit, and reassess earlier interpretations in the light of this improved understanding as to the timing and location of oceanic isochrons. Each difference in the interpretation of any component of the plate circuit [e.g., Copley et al. 2010; van Hinsbergen et al., in press] must be propagated through the entire plate assemblage, leading to changes in inferred relative velocity. In addition, as noted by Cande et al. [2010], the method of interpolation used to obtain relative motion at specific times in individual plate circuits must also be considered, as well as uncertainty.

The relative motion of each plate is dependent on a series of Euler rotations, derived from multiple sources, with differing error and uncertainty. For the purposes of this paper, data is taken as provided by the authors and we do not independently attempt to propagate a quantitative analysis of error and uncertainty. While we agree that error and uncertainty in each component of a plate circuit adds complexity and increases the potential error in any reconstruction [e.g., see analyses in Copley et al., 2010, Molnar and Stock, 2009; van Hinsbergen et al., in press] we did not repeat calculations already published and/or taken into account by previous researchers (we will further discuss our rationale for this below).

2. Relative motion histories for the Indian Plate

The Indian plate consists of the Indian craton, as well as a significant portion of the Indian Ocean seafloor. The plate is bounded to the southeast by the Australian plate, to the southwest by the African plate and to the north and northeast by the Eurasian plate. To the north it terminates somewhere beneath Tibet and the Pamir. This northern boundary is currently considered as marked by the Indus-Zangpo Suture Zone [Thakur and Misra, 1984] (Figure 1).

Insert Figure 1.

The earliest work on the relative motion history of the Indian plate was presented during the advent of plate tectonic theory [Heirtzler et al., 1968; Le Pichon, 1968; Le Pichon and Heirtzler, 1968; McKenzie and Sclater, 1971; Molnar and Tapponier, 1975; Norton and Sclater, 1979; Sclater and Fisher, 1974]. As higher resolution data became available, these earlier models were refined, and new interpretations of magnetic data and bathymetry were produced [Dewey et al., 1989; Molnar et al., 1988; Patriat and Achache, 1984; Patriat and Segoufin, 1988). These efforts continue as relative motion in various parts of the plate circuit becomes better understood [Cande et al., 2010; Copley et al., 2010; DeMets et al., 1994; 2005; Gaina et al., 2002; Gordon et al., 1990; 1998; Lee and Lawver 1995; Merkouriev and DeMets, 2006; Molnar and Stock, 2009; Rosenbaum et al., 2002; Royer and Chang, 1991; Royer et al., 1997; van Hinsbergen et al., in press; Wiens et al., 1985; 1986].

3. Establishing the timing of collision from plate reconstructions

Plate reconstructions of India's motion relative to Eurasia are one the key pieces of evidence used to establish when the collision of the two continents occurred. Molnar and Tapponnier [1975] were the first to suggest that a decrease in the rate of northward motion of India from 100-112 mm/yr to 45-65 mm/yr at ~40 Ma represented the collision of India and Eurasia. Subsequent plate reconstructions also observed a decrease in the relative motion of India relative to Africa, Antarctica and Eurasia [Dewey et al., 1989; Molnar et al., 1988; Patriat and Achache, 1984; Patriat and Segoufin, 1988] (Figure 2 and Figure 3). While there were differences in each of these models, they all attribute the deceleration of the Indian plate between 55-36 Ma to the collision of India and Asia. This is consistent with geological observations that suggest substantial changes occurred in the Himalayan orogen during this time period [e.g., Rowley, 1996; Guillot et al., 2003].

Recent work [van Hinsbergen, in press] suggests the deceleration of India relative to Eurasia may be related to something other than the collision of the two continents. These workers highlighted that India's motion increased at ~90 Ma and between ~65-50 Ma. They suggested that plate acceleration and deceleration could be related to plume head arrival and increasing continent-plume distance respectively.

4. Episodic versus smooth motion

Several reconstructions of the Indian plate have shown that its motion has sporadically accelerated and decelerated during the past 100 Ma. Whilst this is not necessarily noticeable in all reconstructions of India relative to Eurasia [e.g., Copley et al., 2010; Dewey et al., 1989; Molnar and Stock, 2009; Patriat and Achache, 1984] (Figure 2 and Figure 4), such changes are observed in other parts of the plate circuit. For instance Patriat and Segoufin [1988] suggest India's motion relative to Africa is much more sporadic than the reconstruction of Molnar et al., [1988](Figure 3). There are also subtle differences between the relative motion of Africa's motion relative to North America, and North America's motion relative to Eurasia [Gaina et al., 2002; McQuarrie et al., 2003; Rosenbaum et al., 2002] (Figure 5). Some of this variation is no doubt due to the uncertainty associated with each reconstruction. However, the question of whether plate motion is relatively smooth, or episodic remains unresolved despite considerable improvement to our understanding of different parts of the plate circuit [Cande et al., 2010; Copley et al., 2010; DeMets et al., 1994; Gordon et al., 1998; Lee and Lawver, 1995; Merkouriev and DeMets, 2006; Molnar and Stock, 2009; Royer and Chang, 1991; Royer et al., 1997; van Hinsbergen, in press]. Data from high-resolution studies of 0-20 Ma magnetic isochrons also indicates that plate motion occurs in episodic pulses in the Indian Ocean [Merkouriev and DeMets; 2006], and these pulses have been attributed to the crustal mechanics associated with the Himalayan orogeny [e.g., Merkouriev and DeMets, 2006; Molnar and Stock, 2009].

It is important to note that oceanic isochron data produces samples of relative displacement at discrete time intervals, and since these time intervals differ from one part of the plate circuit to another, the multiplicative effect in a plate circuit produces sharp changes in velocity. These are data artifacts and they should not be interpreted to imply rapid (i.e. <0.1 Ma) changes in velocity. In the real world, rheology would smooth any localized rapid change, but to remove such fluctuations by introducing smoothing and interpolation methods in a scientific paper runs the risk of inextricably mixing model and assumptions in a way that obscures the actual data. Therefore we have not done this. More importantly, since plate reconstructions that are based on oceanic isochrons *a priori* assume rigid lithosphere, we decided instead to consider the implications of the changes in velocity that can be inferred based on the observed data. We therefore propagate these datasets through the plate circuit in a way that is faithful to the rigid-plate assumption.

Insert Figure 3.

Insert Figure 4.

Insert Figure 5.

5. Towards an integrated model

In a mathematical sense, every tectonic reconstruction of the Earth's past is based on a set of instructions (e.g., Euler rotations). These instructions are used to transform the architecture of the modern day world back to some ancient configuration (i.e., a "Virtual World"). Different choices as to Virtual World architectures are related to the availability of data (e.g., Euler poles derived from seafloor fracture zones and magnetic isochrons), or to different selections of the available data. In particular, different hypotheses originate by virtue of a sequence of linked assumptions, made through space and time. In consequence, as outlined above, as more and more data becomes available, the data and decisions that are employed in each reconstruction become increasingly difficult to compare with others. Therefore, we propose a more systematic approach, utilizing what we refer to as a "Didactic Tree". The purpose of a Didactic Tree is to document the data, decisions and assumptions made in a given reconstruction and to graphically convey this information to the reader (Figure 6). The Didactic Tree is therefore a data construct that represents the knowledge/interpretation paths taken between the modern Earth and a particular Virtual World. This method therefore allows us to document, understand and easily access and assess the differences between different interpretations as to ancient Earth configurations.

Insert Figure 6.

We used this technique to systematically record the data, decisions and assumptions from rigid-plate reconstructions of the Indian plate based on magnetic seafloor anomaly and fracture zone data (see Auxiliary Data [A1]). This technique allowed us to identify the lineage of data that was used in each reconstruction of the Indian plate, as well as the decisions and assumptions behind each tectonic reconstruction. We used the method to assess the relevance of specified Euler poles describing motion at any specific time, for any given plate. This allowed us to identify, for example, which Euler poles needed to be adjusted according to proposed changes in the geological timescale [Gradstein et al., 2004].

Each Didactic Tree was created using the open source software XMind (www.xmind.net).

This approach enabled systematic revision of relative motion of the Indian plate relative to Eurasia using already published rotation data (see Auxiliary Data [A2]). The ages of each Euler pole that were used in this reconstruction have been updated according to the most recent magnetic anomaly timescale [Gradstein et al., 2004]. However, we were unable to update the timescale of any of the Euler poles derived from Müller et al., [2008] as these workers report ages from their digital isochron map.

Our reconstruction is based on a plate circuit of India → Antarctica → Africa → North America → Europe between 84 – 0 Ma. Between 100 – 84 Ma we move India → Australia → Africa → North America → Europe. The Euler poles for the motion of North America → Eurasia were derived from Gaina et al. [2002], Merkouriev and

DeMets [2008] and Rosenbaum et al. [2002] (see Auxiliary Data [A2]). The Euler poles for the motion of Africa → North America were taken from the data presented in Müller et al. [1999] and Rosenbaum et al. [2002]. The motion histories for North America relative to Eurasia [Gaina et al., 2002; McQuarrie et al., 2003; Rosenbaum et al., 2002] and North America relative to Africa [McQuarrie et al., 2003; Müller et al., 1999; Rosenbaum et al., 2002] are similar (Figure 5). However, each paper presents a number of rotation poles, where one may have a better resolution at a given time [e.g., Gaina et al., 2002 compared to Rosenbaum et al., 2002]. We therefore amalgamated the Euler poles to build a comprehensive dataset (see Auxiliary Data [A2]).

We also combined the rotation data of several papers for Antarctica's motion relative to Africa [Bernard et al., 2005; Jokat et al., 2003; König and Jokat, 2006; Lemaux et al., 2002; Patriat et al., 2008]. The Euler poles that were used to rotate India relative to Antarctica between 84 and 0 Ma were derived from Patriat [1987] and Patriat and Segoufin [1988]. The Euler poles that were used to rotate India relative to Australia between 100 – 84 Ma were derived from Müller et al. [2008]. In the reconstruction, we also restore the position of Australia, Iberia, Greenland and Madagascar according to the Euler poles presented in the Auxiliary Data [A2]. No significant overlaps were observed when all of the data was rotated back to 100 Ma. All of this information is summarized in Figure 7.

Insert Figure 7.

We chose to rotate India relative to Antarctica, rather than India relative to Somalia. While there is much higher resolution data available for part of the latter plate circuit, there is also considerable uncertainty in terms of constraints as to the magnitude of crustal extension in the East-African Rift System. For example our investigation of the various reconstructions that rotate India relative to Somalia [e.g., Chu and Gordon, 1999; Horner-Johnson et al., 2007; Lemaux et al., 2002; Royer et al., 2006] highlighted that there was contradiction between what these models proposed for the timing and geometry of crustal extension in the East-African Rift System (11 – 0 Ma), compared to field observations that suggest crustal extension began at ~32 Ma [Joffe and Garfunkel, 1987]. This discrepancy indicates that the problem in the India-Somalia plate circuit cannot simply be resolved, e.g., by changing the age of the 11 Ma Euler pole to 32 Ma.

6. Reconstructing the motion history of the Indian plate

Each reconstruction discussed in this paper was created with Pplates (version 2.0) deformable reconstruction software (downloadable from: http://rses.anu.edu.au/tectonics/programs/). The tracking point feature of this program was used to determine the velocity of the Indian plate relative to the Eurasian plate at 0.001 Ma increments. This does not mean that we have an Euler pole at each 0.001 Ma increment, but that we sample India's velocity at 0.001 Ma increments to ensure that we account for each Euler pole within the plate circuit. Pplates determines the location of a point to be tracked by applying all known Euler pole rotations to produce a discrete set of known positions ($P_1, P_2, ..., P_n$), $P_i = (x_i, y_i, z_i)$ with corresponding times ($t_1, t_2, ..., t_n$), where P_1 is the initial position of the tracking point, and $t_1 = 0$ Ma.

Using this feature, three tracking points were created on the Indian plate at 0 Ma (Western point = 26°N / 70°E; Central point = 28°N / 83°E and Eastern point = 26°N / 92°E). These points were then rotated back in time according to the Euler poles used in the reconstruction. Only the central tracking point is shown in Figure 8.

Insert Figure 8.

These results imply that the Indian plate accelerated in several steps between 85-64 Ma, with several minor decelerations in between (Figure 8). The period of net acceleration between 85-64 Ma was followed by rapid deceleration between 64-62 Ma. The fluctuations in velocity continued after this point. Subsequent periods of plate acceleration occurred between 62-61 Ma, 55-52 Ma, 47-45 Ma, 20-19 Ma, 18-16 Ma, 14-13 Ma and 11-10 Ma. Subsequent periods of deceleration occurred between 60-58 Ma, 52-51 Ma, 48.5-47 Ma, 45-39.5 Ma, 26.5-25 Ma, 19-18.7 Ma, 15.5-14.5 Ma, 12-11 Ma and 9.8-5.5 Ma (Figure 8). The Indian plate essentially had a steady-state northward motion of ~55-60 mm/yr between 39.5-20 Ma. After 20 Ma, there were another series of rapid changes in acceleration and deceleration until ~9.8 Ma where the velocity gradually slowed from ~64 mm/yr to ~50 mm/yr at present.

7. Discussion

The simplest interpretation of the results above is to suggest that the Indian plate accelerated and decelerated several times during its northward progression between 100 Ma and 0 Ma. We have already stated, however, that some of these rapid fluctuations in velocity may be data artifacts (see §4 where we discuss the implications of episodic versus smooth motion). We agree that these variations can be removed by smoothing, although note that by under-sampling (see Figure 4) some authors have made the variation of velocity smoother than the actual data would allow. We also emphasize that there is a degree of circular logic in requiring data to be smoothed and thereafter concluding that India has moved smoothly northward without episodic variation in velocity. Modern geodynamic theory makes it well possible that the motion record reflects episodic variation in velocity, with each episode reflecting individual accretion events as India ploughed northwards towards Eurasia, across a seascape littered by continental ribbons, intra-oceanic arcs, and other bathymetric features.

It is beyond the scope of this paper to review the timing of each geological event in the Alpine-Himalayan orogen and how these might possibly relate to our reconstruction. However, it is worth considering whether the episodic velocity of India might correspond with specific geological events. For instance, the Ladakh arc is thought to have accreted to the northern margin of India by ~45 Ma [Rowley et al., 1996]. This accretion event might therefore correspond to any of the decelerations prior to ~45 Ma (e.g., 64-62 Ma, 60-58 Ma, 52-51 Ma, 48.5-47 Ma and potentially 45-39 Ma). We note that other authors state that the Ladakh arc accreted to Eurasia before India arrived [Aitchison et al., 2007; Baxter et al., 2010; Guillot et al., 2003; 2008; Petterson and Windley 1985; Rolland et al., 2000; 2002; Weinberg et al., 2000;] and thus that there is no consensus.

The debate as to which continental ribbon or island arc chain accreted to what is dependent on how complex each worker envisages the Tethyan palaeogeography. For instance, Khan et al. [2009] suggest that the Ladakh-Kohistan arc accreted to the northern margin of India because they classify the Spongtang massif and Ladakh-Kohistan arc as the same system [Baxter et al., 2010]. Other workers consider these to be different terranes, stating the Spongtang massif accreted to the northern margin of India and the Ladakh-Kohistan arc accreted to the southern margin of Eurasia [Aitchison et al., 2007; Baxter et al., 2010; Petterson and Windley 1985]. The arguments that surround the obduction age of continental ribbons such as the Spongtang massif [Baxter et al., 2010; Corfield et al., 2001; Pedersen et al., 2001] preclude objective analysis as to whether a particular accretion event relates to a particular deceleration. Nevertheless, if we do accept that Tethys had a complex palaeogeography [Aitchison et al., 2007] and that the Indian plate can decelerate due to the effects of crustal accretion [e.g., Molnar and Tapponnier 1975] it is reasonable to assume that the Indian plate slowed more than once, and that each deceleration might relate to the accretion of a continental ribbon and/or associated volcanic or magmatic arcs.

The debate becomes murkier when along strike variation in palaeogeography is considered. For example some components of the Kohistan-Ladakh arc evolved in an island arc setting, while other components (e.g., in eastern Ladakh) evolved from an island arc system into a continental arc [Rolland et al., 2000; 2002].

Stratigraphic relations and the interpretation of geochemical analyses and geochronological data can provide constraints as to the timing of accretion events. The presence of 60 ± 10 Ma granitoids north and south of the Karakorum Thrust and Karakorum Fault can be interpreted to suggest that the Dras-Kohistan island arc had accreted to Eurasia by this time [Weinberg et al., 2000]. Perhaps this accretion event is marked by deceleration of the Indian plate between 64-62 Ma or 60-58 Ma. However, if this island arc accreted before 60 Ma, it suggests that the <60 Ma volcanics and granitoids associated with the Ladakh-Kohistan arc were emplaced in a continental margin setting, contradicting the interpretation of geochemical data that suggests they were emplaced in an island arc setting [Weinberg and Dunlap 2000].

Several workers have suggested that the timing of the India-Asia collision is constrained by the timing of high-pressure metamorphism. For instance, de Sigoyer et al., [2000] suggest the Indian crust locally passed through eclogite facies metamorphic conditions at 55 Ma ± 7 Ma and was exhumed by 48 ± 2 Ma. The Tso Morari eclogite might therefore correspond with deceleration of the Indian plate at 60-58 Ma and/or 52-51 Ma. However, the eclogite and other high-pressure metamorphic assemblages do not necessarily indicate subduction of continental lithosphere [Lister and Forster 2009]. These rocks may instead represent the timing of an accretion event as a slice of rock that has undergone high-pressure metamorphism beneath a lithospheric scale megathrust and then exhumed during subsequent lithosphere-scale extension.

In any case many different ages are found for the formation and subsequent exhumation of different terranes containing high-pressure rocks in the Himalaya, as well as along the length of the Alpine-Tethyan orogen [79-75 Ma, 70-65 Ma Sesia zone, Italian Western Alps: Rubatto et al., 2011]; [53-49 Ma, 44-38 Ma and 35-30 Ma Cycladic Eclogite-Blueschist, Greece: Forster and Lister 2005]; [47-46 Ma Kaghan Valley eclogite, Pakistan: Wilke et al., 2010] and these data can be interpreted as representing evidence of multiple, episodic accretion events as Tethys closed [Lister et al., 2001; Lister and Forster 2009].

If high-pressure metamorphism reflects accretion events rather than terminal collision, it follows that the collision of India and Eurasia might not have occurred by ~50 Ma. A growing body of work suggests India-Eurasia collision may not have occurred by ~50 Ma and possibly occurred as late as ~34 Ma [Aitchison et al., 2007; Bera et al., 2008; Henderson et al., in press]. We therefore consider that the deceleration of India between 45-39.5 Ma might reflect a period crustal shortening that led to the closure of an ocean basin at ~34 Ma (as determined from the oldest evidence of marine sedimentation in the Pengqu Formation, Qomolangma Tibet) [Aitchison et al., 2007; Wang et al., 2002]. As new data emerges from geological studies within the orogen itself greater clarity as to the significance of the velocity changes reported here will emerge.

7.1 Uncertainty in Plate Reconstructions

Many workers propose that they can provide a precise estimate of the uncertainty associated with Euler poles [e.g., Cande et al., 2010; Royer and Chang 1991] but we argue that the true uncertainty of a reconstruction involves many more factors than are currently taken into account. These include: (1) deformation within the plate circuit; (2) the uncertainty associated with the age of each of the sample that is used to define each magnetic isochron; (3) variations in different geological timescales [e.g., Cande and Kent, 1995; Gradstein et al., 2004]; (4) the precision and accuracy used to locate the survey vessel; (5) the precision and accuracy used to locate the dredge/drill sample site below the survey vessel; (6) the precision and accuracy used to locate of the geophysical data collected below the survey vessel; (7) the precision and accuracy of GPS measurements, and (8) the precision and accuracy of pre-GPS measurements. We argue that if each of these factors were considered the uncertainty would be greater than is currently portrayed in plate reconstructions. This said, a completely different set of rules comes into play when considering the implications of the inferred time variation of velocity in individual parts of a plate circuit. For example, it may not be the case that uncertainty with respect to absolute velocity translates directly into uncertainty as to the magnitude of temporal changes in velocity.

Some of the methods of calculating uncertainty of individual Euler poles are based on rough estimates. For example Cande et al. [2010] write (pp 6-7) "*Although it is possible to assign a separate error estimate to each data point, varying it, for example, for the type of navigation, this level of detail was beyond the scope of this study. Instead, based on our experience with other data sets, we generally assigned an estimate of 3.5 km for all magnetic anomaly points and 5 km for all fracture zone crossings. One major exception to this rule was that we assigned an error estimate of 5 km to anomaly points older than anomaly 24o on the SWIR west of the Bain fracture zone where data coverage is particularly sparse and anomaly identifications are difficult due to the slow spreading rates.*"

We acknowledge that the changes in India's velocity produced in our plate reconstruction might be related to errors due to the propagation of uncertainty within the plate circuit. However, in spite of considerable pressure exerted on us during the review process to ameliorate our views, our position remains that until we can reliably assess the true uncertainty of the system we choose to interpret the velocity curve at face value (Figure 8). In other words the data is taken as it has been published, and the implications of these revisions to the temporal history of motion in individual parts of the plate circuit are propagated to produce the velocity curve *ipso facto* as it is presented in Figure 8.

7.2 Deceleration of the Indian plate

Other reconstructions suggest that the Indian plate decelerated only once between 55 Ma and 35 Ma [e.g., Copley et al., 2010; Molnar and Stock 2009; Patriat and Achache 1984; Tapponier and Molnar 1975]. The differences in interpretation can be attributed in part to the different Euler poles, plate circuits and timescales adopted in each reconstruction. These differences are summarized in the Didactic Trees that were compiled from each reconstruction (Auxiliary Dataset [A1]).

Another contrast between our results and some reconstructions relate to the time interval that is sampled during a reconstruction. Figure 4 (continuous line) shows the variation of India's velocity over time according to Copley et al. [2010], and implies smooth and continuous changes in velocity. However, if we use the Euler pole data for India relative to Eurasia as it is presented in Copley et al. [2010] we find that the velocity curve that they propose (black line) does not match the input data (dotted line). The reason for this is because Copley et al. [2010] sampled India's velocity at arbitrary time points (i.e. 2.5 Ma intervals between 30 Ma and 0 Ma, and 5.0 Ma intervals between 75 Ma and 30 Ma) and simply joined the dots. The problem is that this artificially smoothed curve (black line) is not consistent with the data input (dotted line) as it can only be produced through the omission of the full set of linearly interpolated velocities (Figure 4).

Previous reconstructions of the Indian plate relative to the Eurasian plate suggest that India decelerated between ~50 Ma and 36 Ma [Copley et al. 2010; Dewey et al. 1989; Lee and Lawver 1995; Molnar and Stock 2009; Patriat and Achache 1984; van Hinsenberg et al., in press]. This single deceleration episode is often interpreted to represent the time when Indian and Eurasian continental crust collided [Molnar and Tapponier 1975; Patriat and Achache 1984]. However, our reconstruction suggests that India's velocity accelerated and decelerated several times over the past 100 Ma. We therefore consider the possibility that the timing of each deceleration might indicate a separate accretion event during India's northward progression between 100 Ma and 0 Ma. This would imply that accretion events occurred at 64-62 Ma, 60-58 Ma, 52-51 Ma, 48.5-47 Ma, 45-39.5 Ma, 26.5-25 Ma, 19-18.7 Ma, 15.5-14.5 Ma, 12-11 Ma and 9.8-5.5 Ma. Some of these ages broadly correspond with ages that have been proposed for the collision of India and Asia [e.g., 35-34 Ma: Aitchison et al., 2007; 55-50 Ma: Searle et al., 1987 and ~70 Ma: Yin and Harrison, 2000].

7.3 Acceleration of the Indian plate

Most interpretations of changes in the velocity of the Indian plate have focused on the deceleration of the Indian plate relative to Eurasia. We [and Van Hinsbergen et al., in press] argue that geodynamic explanations for India's motion must include the reasons for both plate acceleration and as well as plate deceleration.

Our reconstruction suggests that the Indian plate accelerated several times during the past 100 Ma (85-64 Ma, 62-61 Ma, 55-52 Ma, 47-45 Ma, 20-19 Ma, 18-16 Ma, 14-13 Ma and 11-10 Ma). These results suggest the Indian plate accelerated at different times than the reconstruction of van Hinsbergen et al. [in press]. The differences probably relate to the different plate circuits and data adopted in each reconstruction.

Whilst it seems logical that India's deceleration would relate to the collision of India and Asia, there are other geodynamic explanations that may explain India's velocity over time [van Hinsbergen et al., in press]. For instance, van Hinsbergen et al. [in press] attributed a period of acceleration at ~90 Ma to the arrival of the Morondova mantle plume. However, these workers also discovered that the driving forces of a plume-head could not alone account for a period of rapid acceleration between 65-50 Ma.

Other factors that might impact on the geodynamic torque balance could include acceleration because of the existence of more than one subduction system operating in Tethys when the Indian plate rapidly accelerated. If multiple synchronous subduction systems existed, this would mean that at least twice as much material could be subducted and greater slab-pull forces that operated during specific intervals. If this were the case, it follows that plate deceleration might be associated with accretion events jamming one (or more) of the subduction zones, or the cessation of the operation of other subduction zones elsewhere in the plate circuit.

Another explanation for these episodes of rapid plate motion may be that periods of deceleration represent times of strain accumulation within the plate circuit, and the periods of acceleration represent the timing of failure during motion of an indentor. Periods of rapid acceleration may therefore indicate the timing of fault movement within the plate circuit. The timing of these accelerations may therefore correspond with episodes of movement on major crustal strike-slip such as the Karakorum Fault or the Oligo-Miocene Altyn-Tagh Fault [Robinson 2009; Yue et al., 2001].

The timing of movement of the Karakorum Fault is constrained by U/Pb SHRIMP dating of zircons from deformed granitoid dykes in Tangste that indicate deformation occurred after ~18 Ma [Searle et al., 1998]. This age is consistent with 149-167 km of displacement determined from tie-points of the Aghil Formation and slip rates between 6.1-12.1 mm/yr [Robinson 2009]. Other workers suggest that these dykes are 16 Ma and were emplaced synchronously with deformation [Leloup et al., 2011; Rolland et al., 2009]. The Altyn-Tagh fault initiated during the latest Oligocene to earliest Miocene [Yue et al., 2001]. We therefore accept that the rapid changes in plate velocity at times <20 Ma might be reflected by movement on the major indentor-bounding strike-slip faults that developed during the ingress of the indentor.

7.4 Other factors to consider

We must also consider that the changes in the velocity of the Indian plate are related to geological events in other parts of the India-Eurasia plate circuit. For example, as we use the motion of the African plate to determine the motion of India relative to Eurasia, any time that Africa accelerates or decelerates this motion will be expressed in India's motion. It is interesting to note that the timing of several decelerations (64-62 Ma, 60-58 Ma, 52-51 Ma, 48.5-47 Ma, 45-39.5 Ma, 26.5-25 Ma, 19-18.7 Ma) correspond with major accretion events identified along the length of the Alpine-Tethyan orogen [Lister et al., 2001].

Mechanical torque balancing occurs at all times between all tectonic plates. If the ancient Tethys Ocean had a complex palaeogeography and its demise involved multiple accretion events [Aitchison et al., 2007; Lister et al., 2001], it follows that there must have been times when certain plates lock-up and others move or deform. The state of the global lithospheric stress would no doubt be expressed in the fracture zones and magnetic anomalies at mid-ocean ridges (the key data input to tectonic plate reconstructions). If this were the case, it would mean that spreading velocity in the world's oceans is more an outcome of global torque balancing, rather than one particular orogen such as the Himalaya.

8. Conclusion

Revised plate reconstructions of the Indian plate relative to the Eurasian plate indicate that the velocity of the Indian plate changed several times during the past 100 million years. These results differ to those of earlier reconstructions, but the differences can be attributed to different input data, different plate circuits and in some instances under sampling the time intervals that were used to produce velocity/time curves of the Indian plate. If previous workers attribute a major deceleration of the Indian plate at c. 50 Ma, it follows that multiple episodes of acceleration and deceleration could be indicative of several accretion events. This hypothesis is supported by observations of multiple episodes of deformation, magmatism and metamorphism observed along the Alpine-Himalayan orogen, not simply at c. 50 Ma. However, there are several other geodynamic explanations as to why the velocity of the Indian plate changed over the past 100 Ma. The alternative explanations suggest such changes in velocity might relate to mantle-plumes, other parts of the India-Eurasia plate circuit or mechanical torque balancing between the world's tectonic plates. We therefore suggest that independent geological observations and geochronological data are the best constraints to determine the complex tectonic history of the Himalayan orogen; at least until higher resolution reconstruction data becomes available.

9. Acknowledgements

This research utilized the *Pplates* deformable plate global tectonic reconstruction software (http://rses.anu.edu.au/tectonics/programs/). We thank Sam Hart for writing the computer code that made this study possible. Lloyd White is grateful for the support of the John Conrad Jaeger Scholarship provided by the Research School of Earth Sciences and an Australian Postgraduate Award provided by the Australian Government. Research support was provided Australian Research Council Discovery Grant DP0877274 "Tectonic mode switches and the nature of orogenesis". We thank Dietmar Müller, Jason Ali and Jonathan Aitchison for providing constructive feedback prior to the submission of this manuscript. We also thank the editor Yann Rolland, as well as Douwe van Hinsbergen and an anonymous reviewer for their comments.

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FIGURE CAPTIONS

Figure 1. Topographic and bathymetric map of Indian ocean showing the location of the boundaries of the African, Arabian, Antarctic, Australian, Indian and Eurasian tectonic plates. The image was derived from NOAA's ETOPO1 global relief model [Amante and Eakins 2009]. The location of plate boundaries was modified from Bird [2003].

Figure 2. Velocity (mm/yr) vs. time (Ma) plot of the Indian plate relative to the Eurasian plate according to; (a) Patriat and Achache [1984]; (b) Dewey et al. [1989], and; (c) Molnar and Stock [2009]. The timescales used in these plots are the same as was originally quoted in each reference, including a misquoted age of anomaly 22, in Dewey et al. [1989]. The velocity of the tracking point was recorded at 1 Ma intervals with Pplates (v2.0).

Figure 3. Velocity (mm/yr) vs. time (Ma) plot of the Indian plate relative to the African plate according to: (a) Patriat and Segoufin [1988] and (b) Molnar et al., [1988]. The timescales used in these plots are the same as was originally quoted in each paper. The velocity of the tracking point was recorded at 1 Ma intervals with Pplates (v2.0).

Figure 4. Velocity (mm/yr) vs. time (Ma) plot of the Indian plate relative to the Eurasian plate according to Copley et al. [2001]. These workers used a 2.5 Ma time interval between 30 - 0 Ma and a 5 Ma time interval between 75 - 30 Ma and produced a reasonably smooth curve of India's deceleration at ~50 Ma. However, using the same Euler poles for India relative to Eurasia with 1 Ma increments shows

the effect of under sampling/smoothing the data. The widely accepted deceleration of India at ~50 Ma may be associated with unintentional smoothing of results by interpolating tracking points with too broad a time interval. The timescale used in this plot is the same as was originally quoted in Copley et al. [2001].

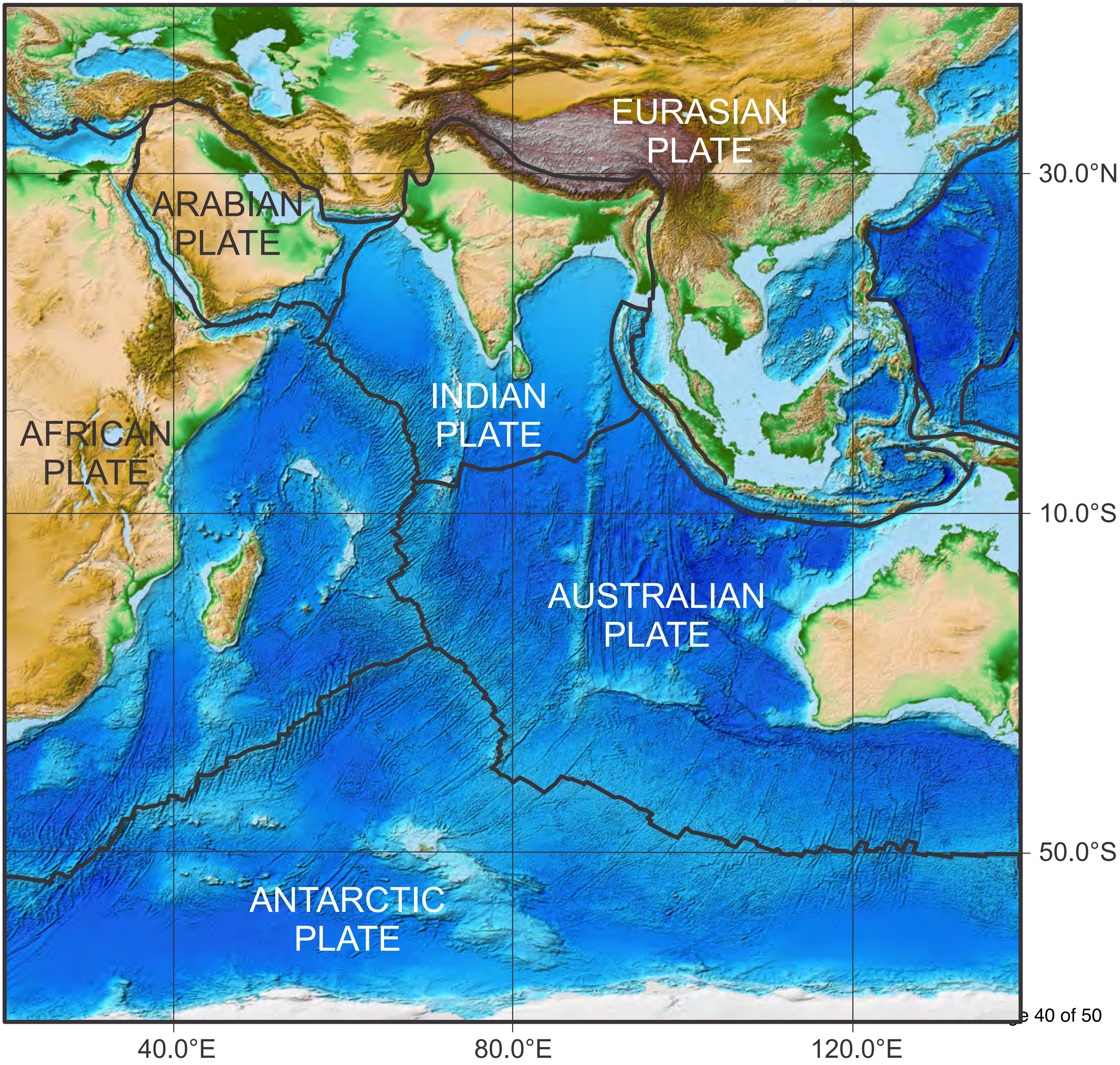
Figure 5. Comparison of the motion of the African plate relative to the North American plate according to: (a) Müller et al. [1999]; (b) Rosenbaum et al. [2002], and; (c) McQuarrie et al. [2003], as well as a comparison of the velocity of the North America plate relative to the Eurasian plate according to: (d) Gaina et al. [2002]; (e) Rosenbaum et al. [2002], and; (f) McQuarrie et al. [2003]. The timescale used in these plots is the same as was originally used in each respective paper. The velocity of the tracking point was recorded at 1 Ma intervals with Pplates (v2.0).

Figure 6. A fictional example of a Didactic Tree showing two models (1 and 2). This suggests that the worker who proposed Model 1 assumed that all plates are rigid, whilst the worker who proposed Model 2 assumed that all plates are deformable. Examining the Didactic Tree further we can identify that the timescale adopted in Model 1 was updated in 1972, whilst the timescale that was adopted in Model 2 was updated in 2004. This tree also informs the reader that both Model 1 and 2 are based on the same plate circuit. However, Model 1 is clearly based on much more magnetic seafloor anomaly data than Model 2. A future reconstruction may therefore use the detailed magnetic seafloor anomaly data of Model 1 in a deformable plate reconstruction, but update the ages of each anomaly according the most recent timescale that was adopted in Model 2.

Figure 7. The Didactic Tree according to the data, decisions and assumptions that were used our reconstruction of the motion history of the Indian plate relative to the Eurasian plate. Information about which Euler poles were used for a given time can be obtained from Auxiliary Dataset (A2).

Figure 8. Velocity vs. time plot of the Indian plate relative to Eurasia according to our reconstruction [Auxiliary Dataset (A2)]. This plot shows that the velocity of the Indian plate was episodic and that there was more than one period of acceleration and deceleration. The plot was generated by rotating a point at 0 Ma (28°N / 83°E) according to the Euler poles adopted in this study. The position and velocity of the point were calculated at 0.001 Ma intervals with Pplates (v2.0).

Figure 1(colour)



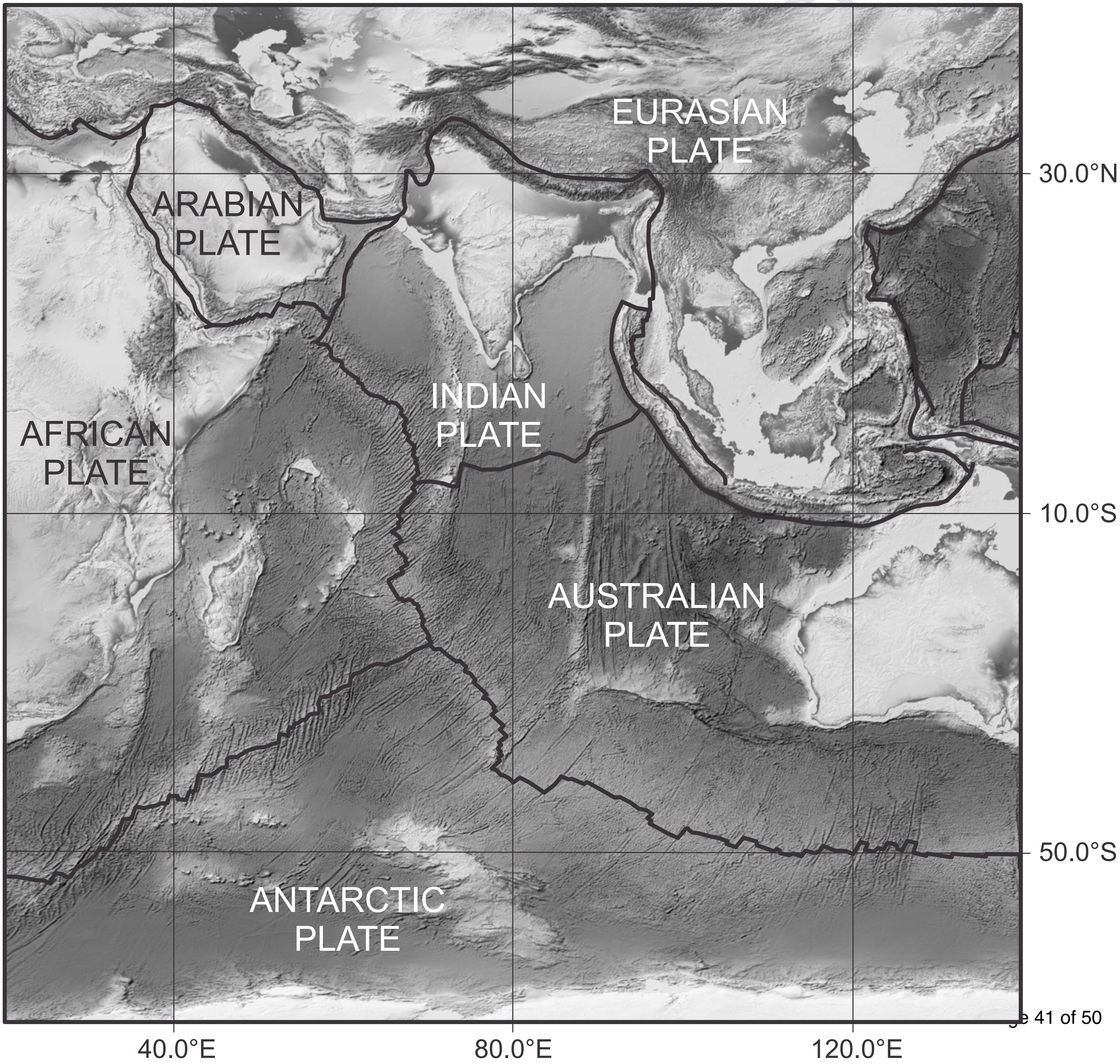
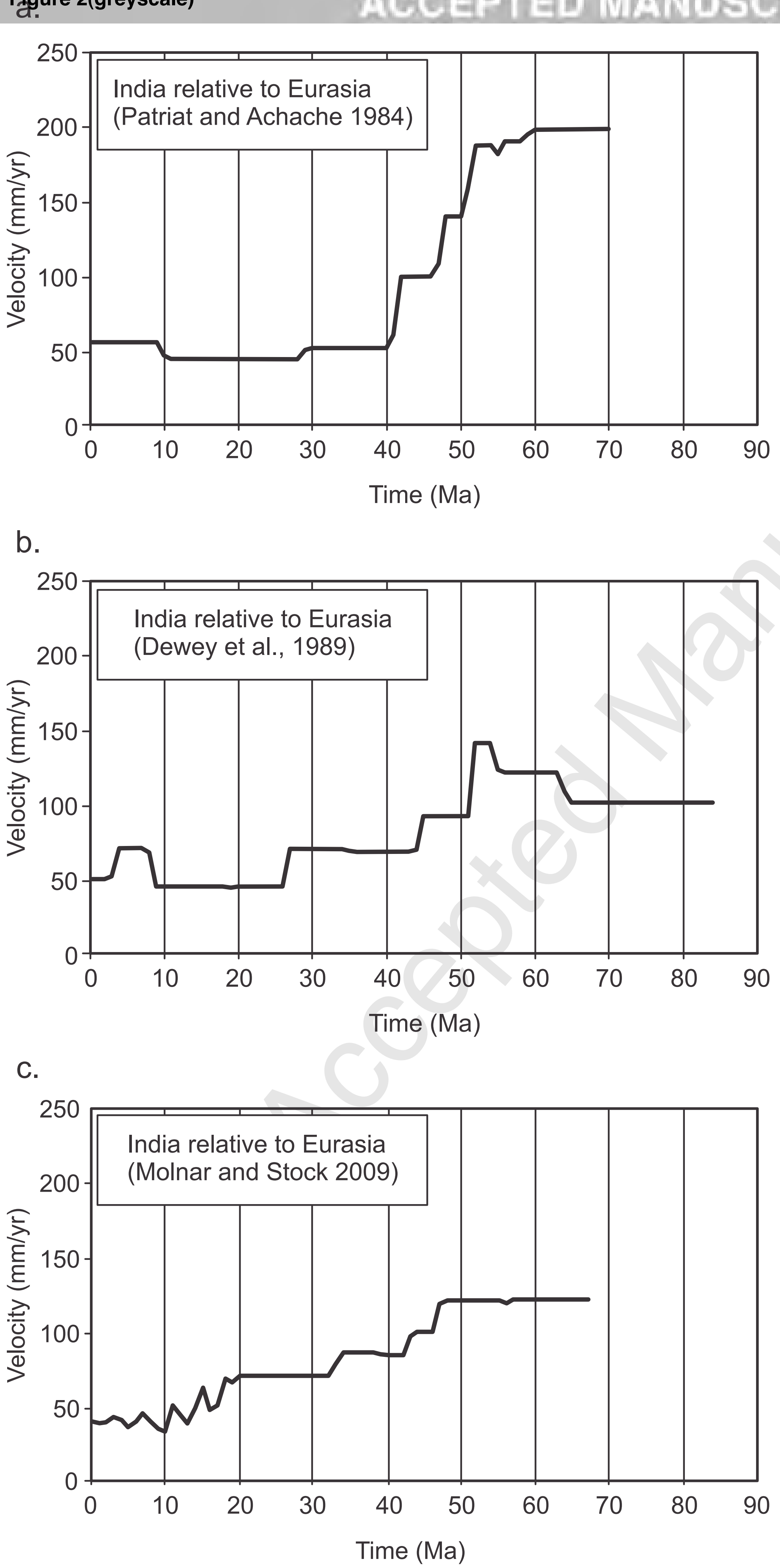
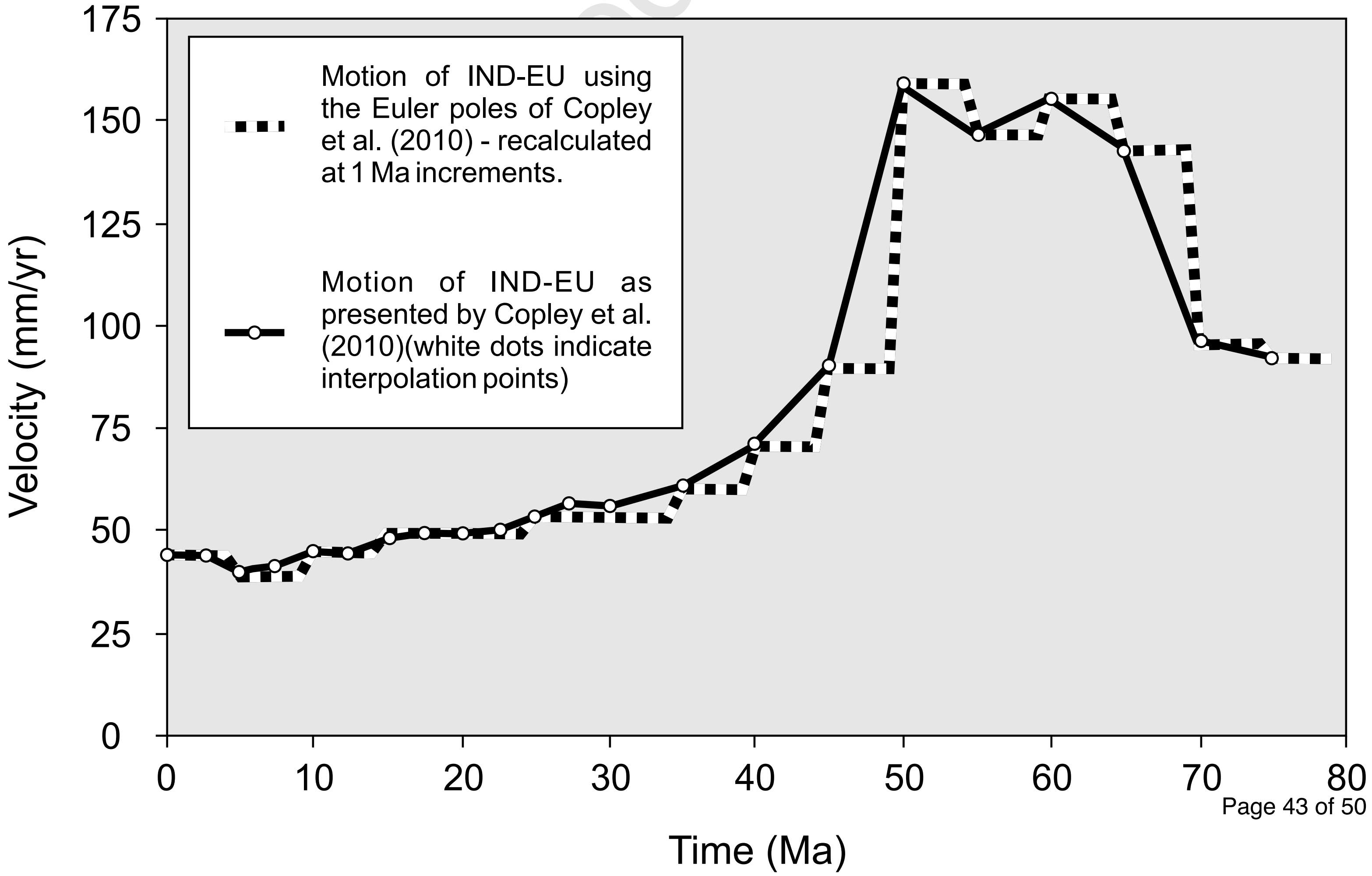
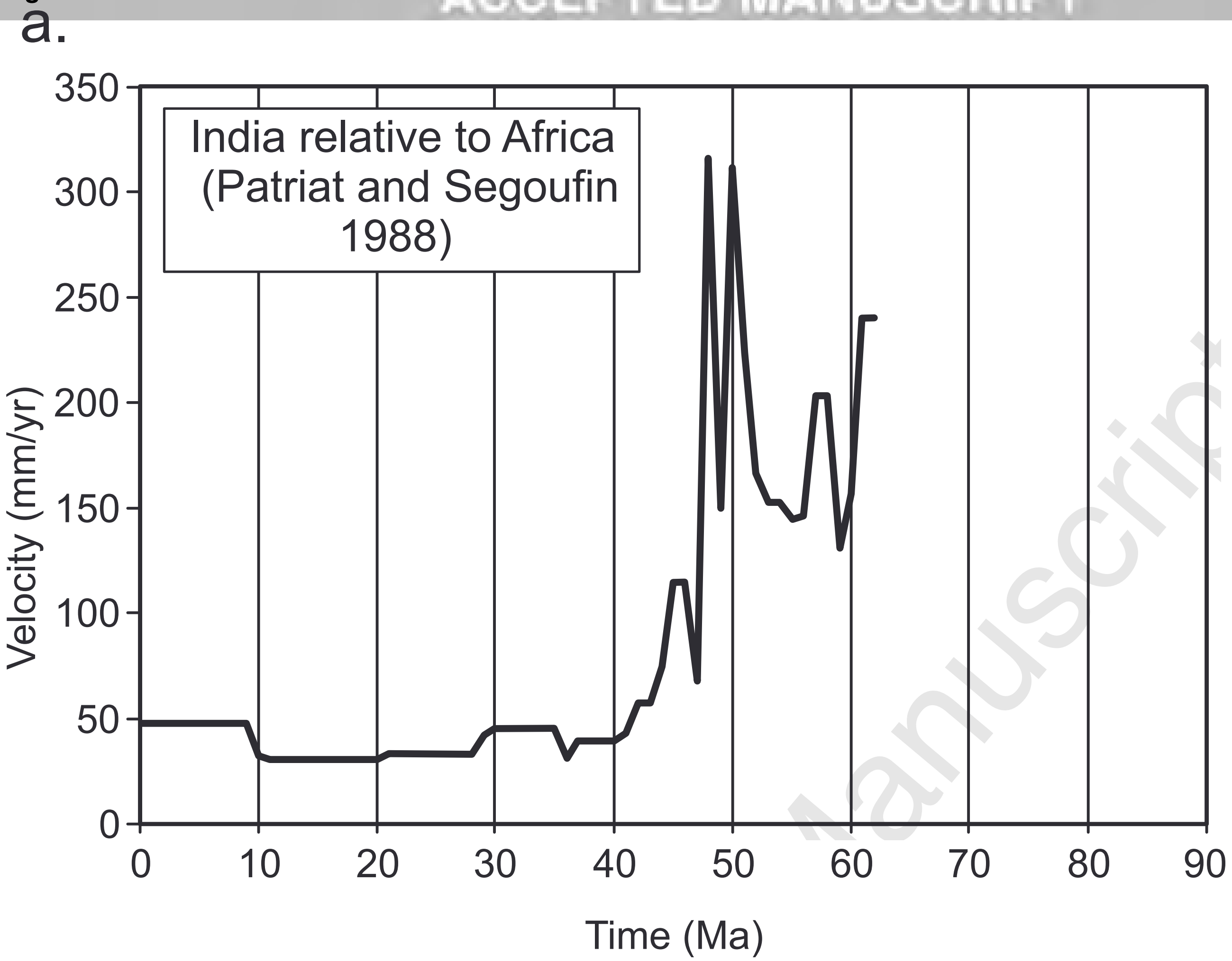

EURASIAN PLATE
ARABIAN PLATE
INDIAN PLATE
AFRICAN PLATE
AUSTRALIAN PLATE
ANTARCTIC PLATE
30.0°N
10.0°S
50.0°S
40.0°E
80.0°E
120.0°E

Figure 2(greyscale)




Velocity (mm/yr)
175
150
125
100
75
50
25
0
0
10
20
30
40
50
60
70
80
Time (Ma)
Motion of IND-EU using the Euler poles of Copley et al. (2010) - recalculated at 1 Ma increments.
Motion of IND-EU as presented by Copley et al. (2010)(white dots indicate interpolation points)


a.
India relative to Africa (Patriat and Segoufin 1988)
Velocity (mm/yr)
Time (Ma)
0
50
100
150
200
250
300
350
0
10
20
30
40
50
60
70
80
90

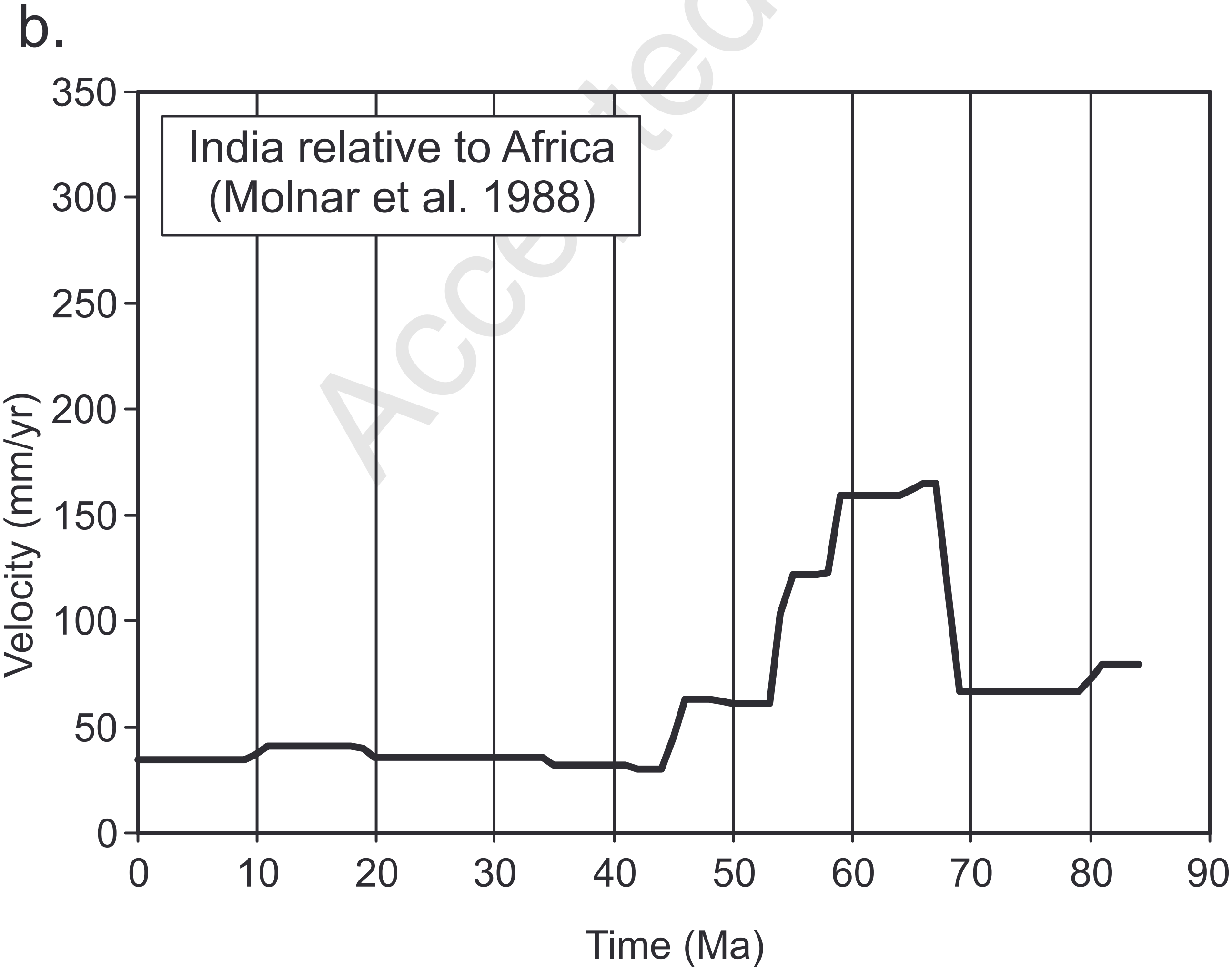
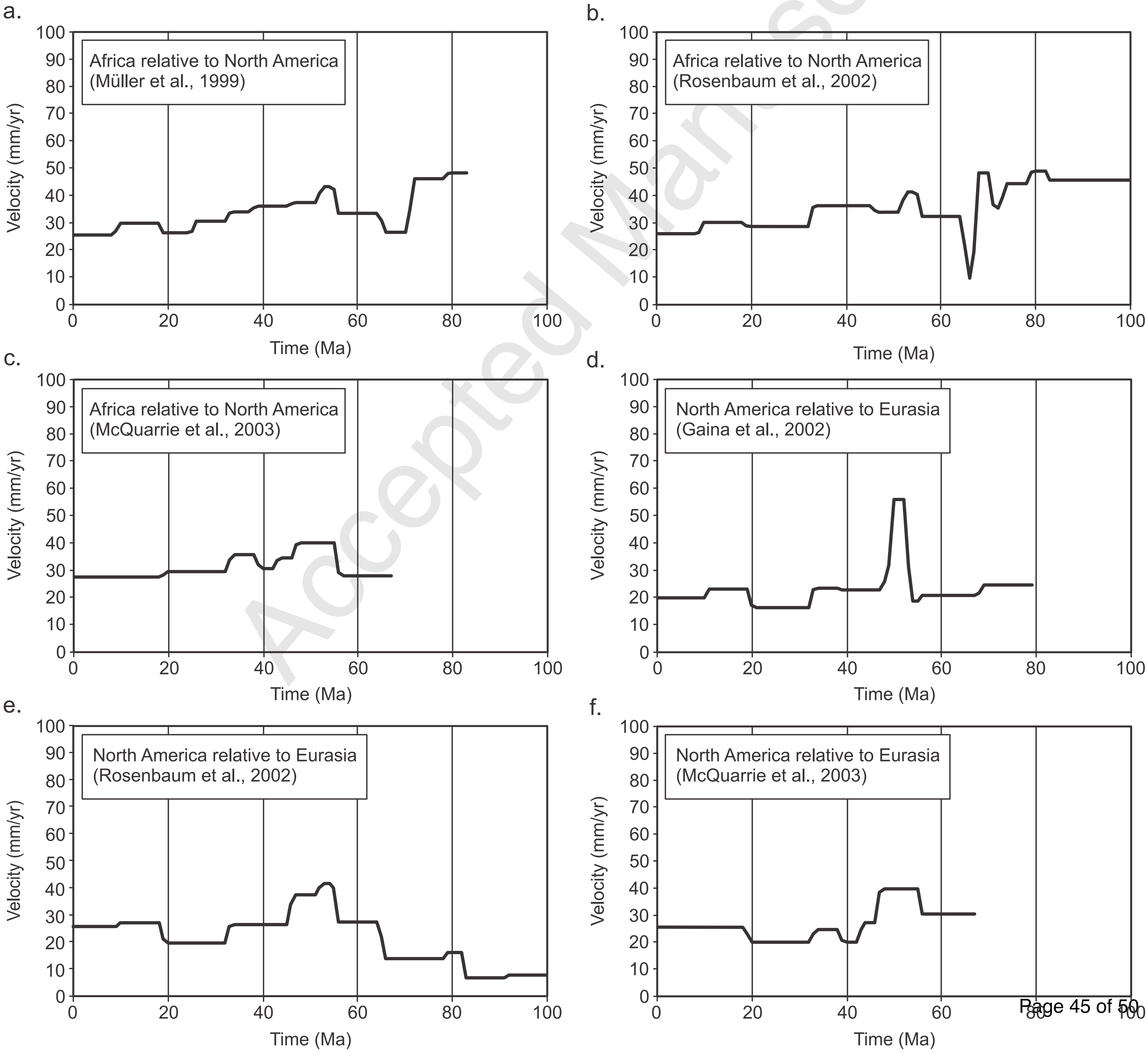

b.
India relative to Africa (Molnar et al. 1988)
Velocity (mm/yr)
Time (Ma)
0
50
100
150
200
250
300
350
0
10
20
30
40
50
60
70
80
90

Figure 5


a.
Africa relative to North America
(Müller et al., 1999)
b.
Africa relative to North America
(Rosenbaum et al., 2002)
c.
Africa relative to North America
(McQuarrie et al., 2003)
d.
North America relative to Eurasia
(Gaina et al., 2002)
e.
North America relative to Eurasia
(Rosenbaum et al., 2002)
f.
North America relative to Eurasia
(McQuarrie et al., 2003)
Velocity (mm/yr)
0
10
20
30
40
50
60
70
80
90
100
Time (Ma)
0
20
40
60
80
100

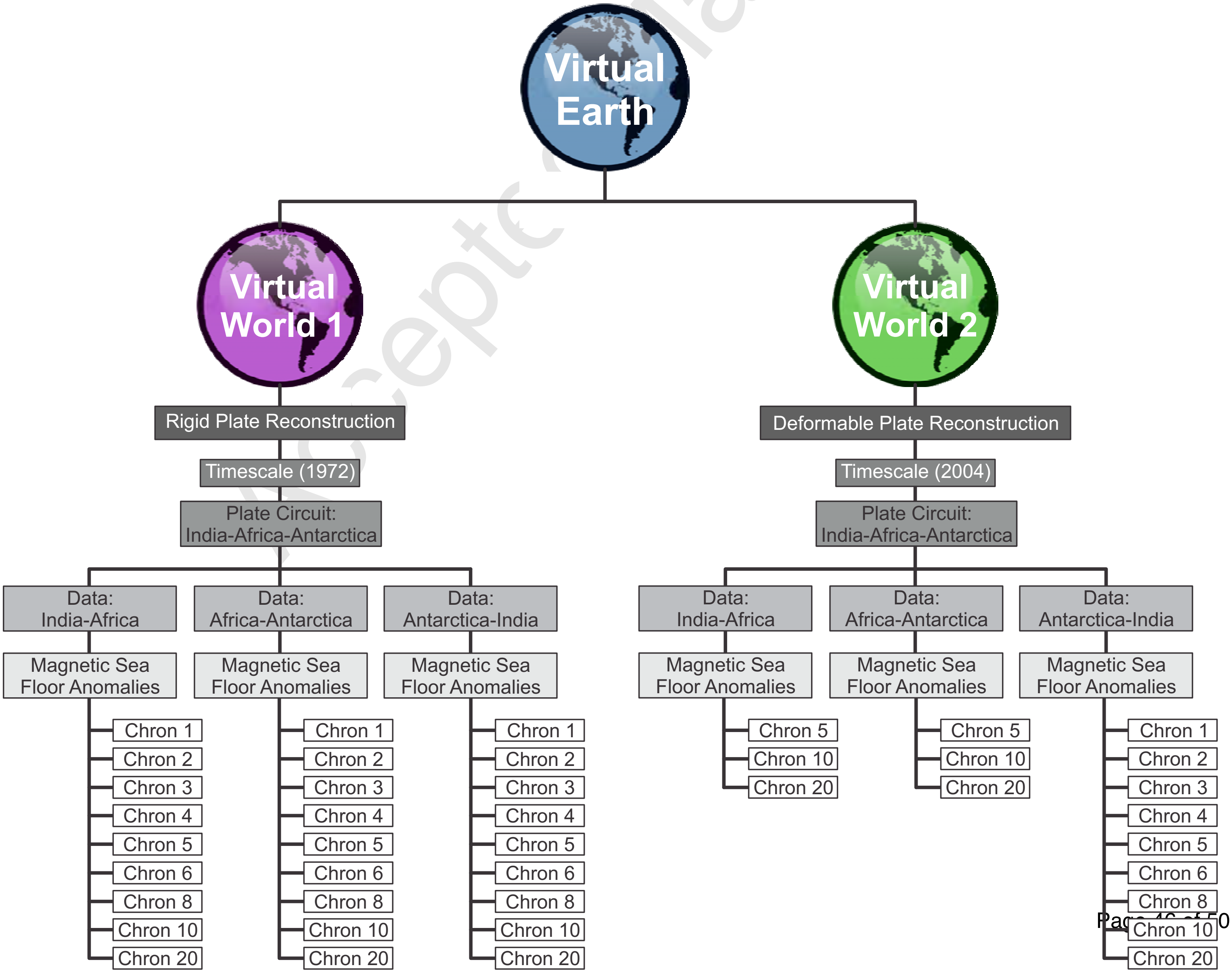

Virtual Earth
Virtual World 1
Virtual World 2
Rigid Plate Reconstruction
Timescale (1972)
Plate Circuit: India-Africa-Antarctica
Data: India-Africa
Magnetic Sea Floor Anomalies
Chron 1
Chron 2
Chron 3
Chron 4
Chron 5
Chron 6
Chron 8
Chron 10
Chron 20
Data: Africa-Antarctica
Magnetic Sea Floor Anomalies
Chron 1
Chron 2
Chron 3
Chron 4
Chron 5
Chron 6
Chron 8
Chron 10
Chron 20
Data: Antarctica-India
Magnetic Sea Floor Anomalies
Chron 1
Chron 2
Chron 3
Chron 4
Chron 5
Chron 6
Chron 8
Chron 10
Chron 20
Deformable Plate Reconstruction
Timescale (2004)
Plate Circuit: India-Africa-Antarctica
Data: India-Africa
Magnetic Sea Floor Anomalies
Chron 5
Chron 10
Chron 20
Data: Africa-Antarctica
Magnetic Sea Floor Anomalies
Chron 5
Chron 10
Chron 20
Data: Antarctica-India
Magnetic Sea Floor Anomalies
Chron 1
Chron 2
Chron 3
Chron 4
Chron 5
Chron 6
Chron 8
Chron 10
Chron 20

Figure 6(greyscale)

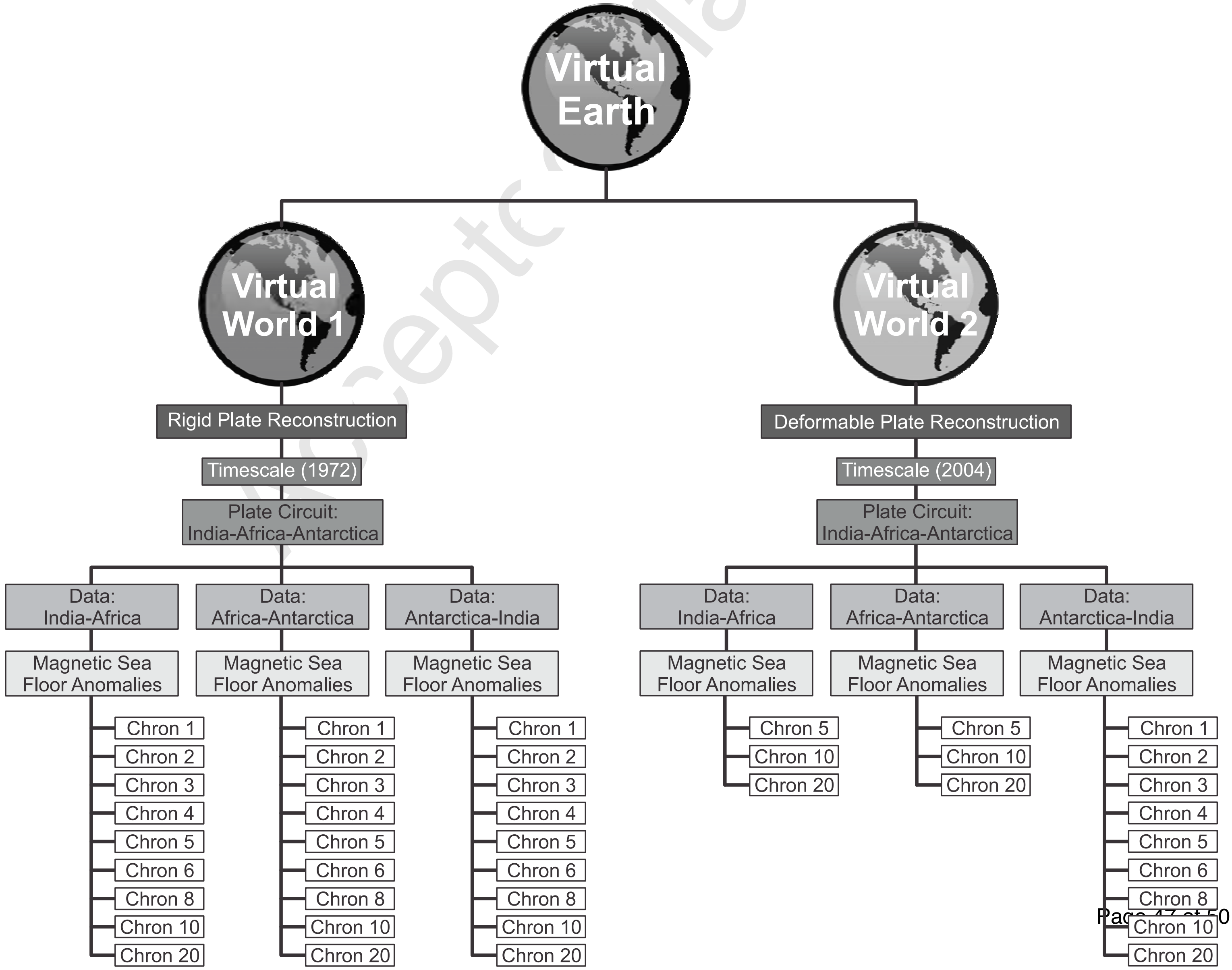
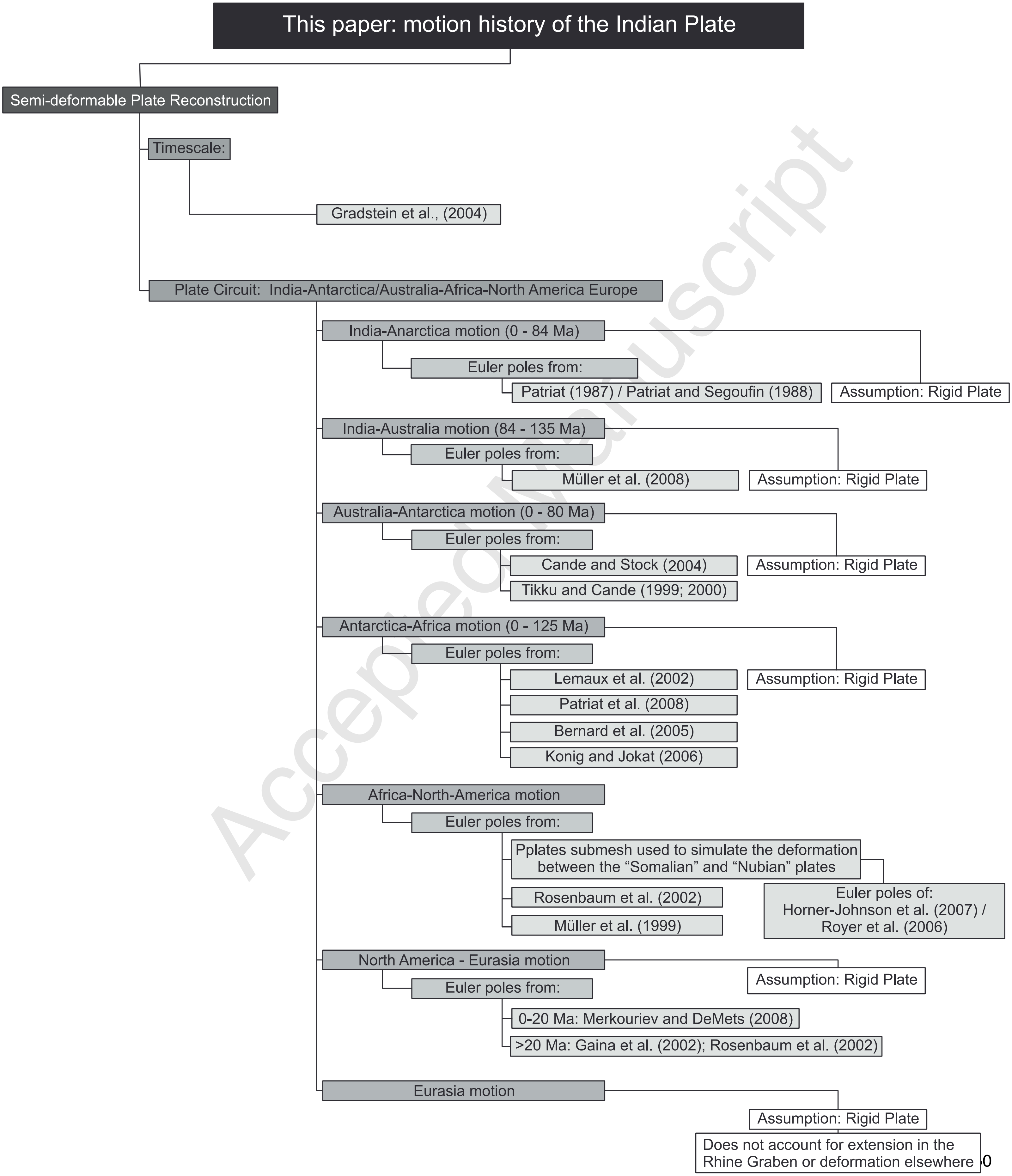
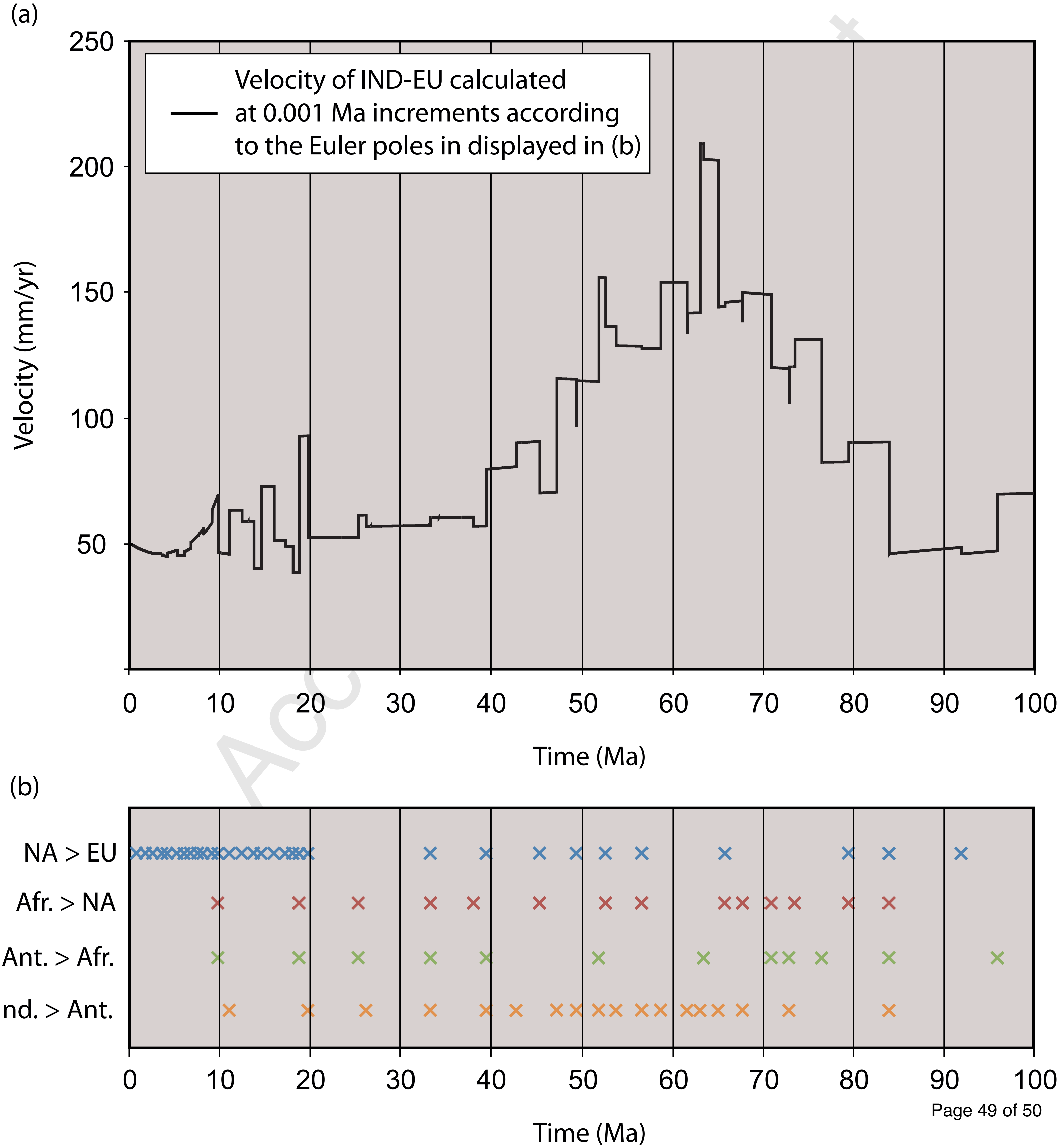
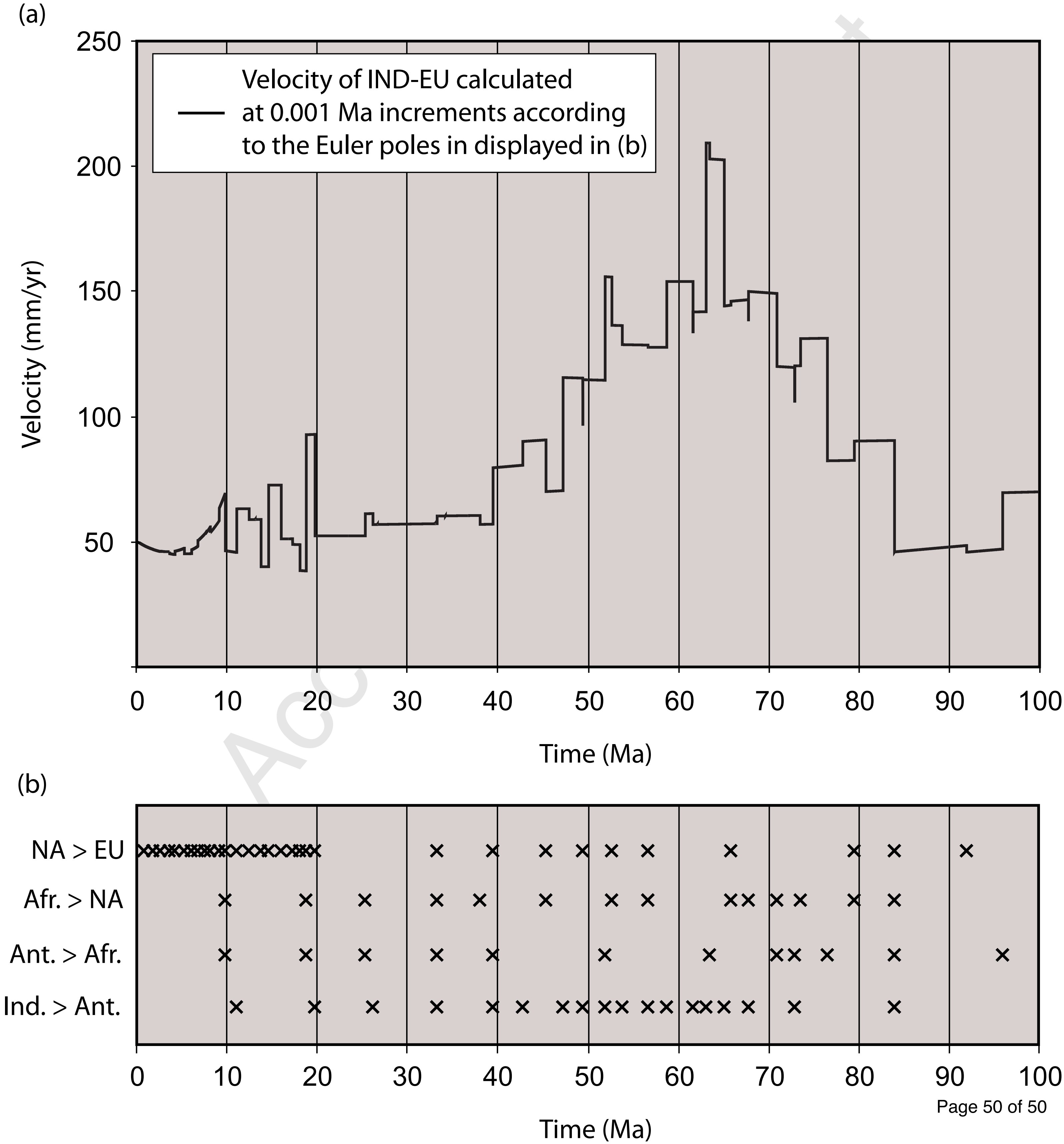


Figure 7


This paper: motion history of the Indian Plate
Semi-deformable Plate Reconstruction
Timescale:
Gradstein et al., (2004)
Plate Circuit: India-Antarctica/Australia-Africa-North America Europe
India-Anarctica motion (0 - 84 Ma)
Euler poles from:
Patriat (1987) / Patriat and Segoufin (1988)
Assumption: Rigid Plate
India-Australia motion (84 - 135 Ma)
Euler poles from:
Müller et al. (2008)
Assumption: Rigid Plate
Australia-Antarctica motion (0 - 80 Ma)
Euler poles from:
Cande and Stock (2004)
Tikku and Cande (1999; 2000)
Assumption: Rigid Plate
Antarctica-Africa motion (0 - 125 Ma)
Euler poles from:
Lemaux et al. (2002)
Patriat et al. (2008)
Bernard et al. (2005)
Konig and Jokat (2006)
Assumption: Rigid Plate
Africa-North-America motion
Euler poles from:
Pplates submesh used to simulate the deformation between the "Somalian" and "Nubian" plates
Euler poles of: Horner-Johnson et al. (2007) / Royer et al. (2006)
Rosenbaum et al. (2002)
Müller et al. (1999)
North America - Eurasia motion
Euler poles from:
0-20 Ma: Merkouriev and DeMets (2008)
>20 Ma: Gaina et al. (2002); Rosenbaum et al. (2002)
Assumption: Rigid Plate
Eurasia motion
Assumption: Rigid Plate
Does not account for extension in the Rhine Graben or deformation elsewhere


(a)
250
200
150
100
50
Velocity (mm/yr)
Velocity of IND-EU calculated at 0.001 Ma increments according to the Euler poles in displayed in (b)
0
10
20
30
40
50
60
70
80
90
100
Time (Ma)
(b)
NA > EU
Afr. > NA
Ant. > Afr.
Ind. > Ant.
0
10
20
30
40
50
60
70
80
90
100
Time (Ma)


(a)
Velocity of IND-EU calculated at 0.001 Ma increments according to the Euler poles in displayed in (b)
Velocity (mm/yr)
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90
100
Time (Ma)
(b)
NA > EU
Afr. > NA
Ant. > Afr.
Ind. > Ant.
0
10
20
30
40
50
60
70
80
90
100
Time (Ma)