Paleomagnetic Constraints on Neoproterozoic 'Snowball Earth' Continental Reconstructions

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Abstract

The Neoproterozoic glacial intervals represent one of the most curious expressions of Earth's climate. Despite the popularity of the hard "Snowball" hypothesis in the popular press, the scientific community remains divided over the extent of the Neoproterozoic glaciations, the age of the glaciations, the number of glacial events and the triggering mechanism for the glaciations. A major, and yet unresolved issue, is knowledge of the exact paleogeography during the so-called Sturtian and younger Vendian glaciations. The problem stems from the paucity of the Neoproterozoic paleomagnetic database, in particular the interval from 600-720 Ma along with the varied interpretations of those data. Here we present 4 scenarios for the paleogeographic setting in the Neoproterozoic. The first two paleogeographies are thought to be representative of the Sturtian (700-800 Ma) glaciations and the younger reconstructions represent possible extremes for the Vendian glacial events. The paleogeographies presented here have important implications for the posited triggering mechanisms for the Neoproterozoic glacials.

Introduction

In 1959, W.B Harland and D.E.T. Bidgood completed a paleomagnetic study of the Moelv tillite and associated sedimentary rocks in the Sparagmite district of central Norway (Harland & Bidgood, 1959). Those results, conducted without demagnetization, indicated a depositional paleolatitude of ~11 degrees. Harland and Bidgood (1959) suggested that the evidence suggested that the Precambrian glaciations were far more severe and widespread than the Phanerozoic glaciations and they further suggested that the end of these glaciations led to the explosion of life in the Cambrian. The notion of a severe 'anti-greenhouse' effect in the Neoproterozoic was also discussed, in seldomly cited papers, by J.D. Roberts (1971, 1976). Roberts (1971) based his arguments on the ubiquitous presence of dolomitic rocks in pre and post-glacial successions and concluded that CO_2 drawdown, via carbonate sedimentation, was likely the trigger for globally synchronous glaciations in the Neoproterozoic. In 1976, Roberts expanded on the anti-greenhouse concept and discussed a variety of other possible explanations for the presence of similar-age tillites on a global scale. A number of other possible

explanations for the Neoproterozoic glaciations have been argued through the years (see Meert and Van der Voo, 1994 and Evans, 2000 for a review; Hoffman et al., 1998). Although the exact nature and severity of the Neoproterozoic glacial epochs is controversial, it is clear that paleomagnetic studies have played, and will play, a crucial role in determining the best explanation for the apparently enigmatic latitudinal distribution of tillites.

The aim of our contribution is relatively simple. We wish to summarize the paleogeographic constraints on the Neoproterozoic glaciations. The paleomagnetic database for this interval of time is both scarce and controversial (Meert and Powell, 2001; Meert and Torsvik, in press). Nevertheless, knowledge of paleogeography has proved useful in evaluating potential climatic triggers for the Neoproterozoic glaciations and testing alternative hypotheses (Donnadiue et al., 2002; Donnadiue et al., 2003). We express our prejudice clearly in this paper, but acknowledge that a single new pole can result in a radical change in reconstructions. Thus, we present 4 models (low-latitude 750 Ma supercontinent, low-latitude 750 Ma dispersed model, 580 Ma polar supercontinent, 580 Ma low-latitude supercontinent) and provide the evidence/counterevidence for these models. These 4 models are not meant to be exhaustive, but appear to cover the extremes of possible configurations.

750 Ma Reconstructions (Sturtian Glaciations)

Meert and Torsvik (in press) provide a summary of the historical development of paleogeographic models for the Rodinia supercontinent. Despite disagreements over the exact makeup of the supercontinent, the evidence for some form of large continental aggregate is substantial (see Dalziel 1997; Meert and Powell, 2001). One of the more important issues regarding paleogeography and Neoproterozoic glaciations relates to the exact timing of the glaciations. Typically, the 'Sturtian' glacial epoch is defined somewhere between 700-800 Ma (Evans, 2000) although most Neoproterozoic glacial episodes are poorly constrained by absolute ages. As shown by Meert and Powell (2001), there is a paucity of paleomagnetic data for the time interval from 600-720 Ma and therefore, the best picture we can provide for the Sturtian glacial episode is at 750 Ma. The most popular Rodinia model of the middle 1990's had Laurentia at the core of the supercontinent surrounded on its present-day western side by East Gondwana, along

its present-day arctic margin by Siberia and South China and along the present-day eastern and northeastern margin by Baltica, Amazonia and Rio de la Plata cratons. The Congo, Kalahari and West African cratons were generally placed in close proximity to the Amazonian and Rio de la Plata blocks (Torsvik et al., 1996; Dalziel, 1997; Weil et al., 1998). Figure 1 shows the archetypal Rodinia model based on paleolatitudes provided from Laurentia (see Torsvik et al., 1996). This model assumed that the breakup of Rodinia commenced shortly after 750 Ma. More recent data seriously challenge this configuration for Rodinia (see summary in Meert and Torsvik, in press) and the argument is forwarded that Rodinia, whatever its configuration, had begun to disaggregate prior to 750 Ma.

Figure 2 shows the dispersed continental configuration for the onset of the Sturtian glacial epoch. This model is adapted from many studies outlined in Meert and Torsvik, in press). Wingate et al. (2002) suggested that Australia and Antarctica were positioned of the extreme southwestern edge of Laurentia around 750 Ma (AUSMEX). 750 Ma paleomagnetic data from the Seychelles and India (Torsvik et al., 2001a, 2001b) indicated that East Gondwana was not a coherent entity at 750 Ma. Tohver et al. (2002) presented a reconstruction for Amazonia of the Llano region of southwestern Laurentia for an earlier time period (~1100 Ma). It is argued that sinistral strike-slip motion might have moved Amazonia to a position off present-day eastern Laurentia by 750 Ma (Tohver et al., 2002). The exact configuration of the continents during the Sturtian glacial events has important implications for climate models. For example, Donnadiue et al. (2003) used a coupled Climber 2.3 global climate model and COMBINE global geochemical model to assess the effects of continental dispersal on global climate. The results indicate that substantial CO_2 drawdown (1000 ppm) would contribute to overall global cooling. While continental dispersal, in and of itself, would not cause severe glaciations, it would serve to decrease the overall global mean temperatures.

600-700 Ma Reconstructions

As noted by Meert and Powell (2001), little is known about the paleogeography for the interval of time from 600-700 Ma. It is possible to assume a starting paleogeography at 750 Ma and estimate an approximate paleogeography at 650 Ma. This would require well-constrained end points (for example a well-resolved 600 Ma

paleogeography) and some knowledge of the tectonic and geodynamic conditions of the planet during that interval. For example, it is fairly well-documented that the Gondwana continent was assembled during the interval from 700-530 Ma (Meert, 2003; Powell and Pisarevsky, 2002; Stern, 1994) and that the Iapetus Ocean opened between Laurentia and Gondwana sometime during the 600-530 Ma (McCausland and Hodych, 1998; Cawood et al., 2001). These observations might allow us to estimate the approximate positions of the various Gondwana elements by assuming plate velocities. However, several authors have discussed the possibility of rapidly changing paleogeographies during the Neoproterozoic (Evans, 2003; Meert and Tamrat, in press). Therefore paleogeographies during the interval of time leading up to, and including the onset of the Varangian-Vendian-Marinoan glaciations are highly speculative.

600-560 Ma Reconstructions (Vendian Glaciations)

The vestiges of the Rodinia supercontinent broke apart during the terminal Neoproterozoic and the timing of that breakup is broadly synchronous with the assembly of Gondwana (Meert, 2003; Powell and Pisarevsky, 2002; Boger et al., 2002; Meert, 2001; Torsvik et al., 1996). The existence of a younger, ephemeral supercontinent called Panottia is dependent on the time of rift-drift transition between Laurentia and the elements of western Gondwana (traditionally Amazonia-Rio Plata) and the final assembly of Gondwana. A number of authors have discussed the timing of final Gondwana assembly from a number of perspectives. Meert (2001) suggested, on the basis of paleomagnetic data, that final Gondwana assembly did not occur until sometime in the 550-530 Ma interval. This is consistent with a number of new geologic findings dividing East Gondwana into several different blocks (Fitzsimons, 2000; Boger et al., 2002; Meert, 2003). Figure 3 is adopted from Meert (2003) and shows the position of the major continental blocks at 580 Ma. This option, is known as the 'high-latitude' Laurentia option and is based on paleomagnetic data from the Catoctin volcanics (Meert et al., 1994) and the Callander Complex (Symons and Chiasson, 1991). We note that in our reconstruction neither Australia nor the Mawson continent (East Antarctica, see Fitzsimons, 2000) have joined greater Gondwana and are separated from elements of eastern Gondwana by the Mawson Sea. Baltica and Siberia are shown in a slightly modified configuration advocated by Torsvik & Rehnström (2001), Rehnström and

Torsvik. (2003) and Hartz and Torsvik (2002). All of the models are critically dependent on the location of the Amazonian and Rio-Plata cratons whose positions are largely unconstrained by paleomagnetic data although the model advocated by Tohver et al. (2002) would require a significant change to the paleogeography shown in Figure 2 (requiring more than 4500 kilometers of sinistral offset).

There are a number of alternative reconstructions posited for the Vendian glacial interval. These alternatives can be divided into two camps. Kirschvink et al. (1997) posited a rapid episode of inertial interchange true polar wander (ITTPW) during the early Cambrian and assumed a continental configuration similar to the high-latitude option discussed above for the Vendian interval. Evans (2003) expanded on the IITPW idea and suggested a series of TPW episodes during the interval of the Vendian glaciations. Unfortunately, Evans (2003) did not detail any proposed paleogeography such that the model is difficult to test. However, Meert and Lieberman (2002) analyzed the distribution of trilobites and concluded that their paleobiogeographic distribution was not consistent with models involving multiple and rapid episodes of TPW.

The second alternative is based on the premise that Laurentia occupied low latitudes during the Vendian (Pisarevsky et al., 2000). The low-latitude Laurentia model is shown in Figure 4 and is adapted from Meert and Lieberman (in review) and Meert and Van der Voo (2001). Pisarevsky et al. (2000) argued that paleomagnetic data from Laurentia can be interpreted as supporting a low-latitude position for Laurentia at ~580 Ma. The low-latitude model was favored because it allowed for a close relationship between Siberia and the arctic margin of Laurentia until ~550 Ma (see also Pelechaty, 1996). New data from Baltica (Popov et al., 2002) contrast with previously published results from the Fen Central Complex (Meert et al., 1998). The new results from the Winter Coast of Russia indicate a low paleolatitude for Baltica during the Vendian glacial epoch and differ considerably from the Fen Complex pole. Popov et al. (2002) argued that the Fen Complex was remagnetized during the Permian. The possibility of remagnetization for the Fen Complex was originally noted by Meert et al. (1998). However, paleomagnetic data from early and late Cambrian sediments from northern Norway and Sweden (Torsvik and Rehnström, 2001 and Rehnström and Torsvik, 2003) indicate relatively slow motion from 580 Ma to 500 Ma. Furthermore, a recent re-

analysis of the Alno Complex in Sweden (Walderhaug et al., 2003) indicates a pole statistically indistinguishable in both age and position from the Fen Complex pole. Trindade et al. (2003 and personal communication) provide new paleomagnetic data from the Vendian cap carbonate sequence in Amazonia (Puga Cap, Brazil) indicating a low paleolatitude for Amazonia (~22°). The age constraints on this glaciation are poor, but suggested to be ~580 Ma (Trindade, personal communication 2003). If the pole is primary then the paleoposition implied by these data indicate that (a) the Iapetus Ocean had opened between Laurentia and Amazonia prior to 580 Ma (assuming that Figure 3 is correct) or (b) it provides additional support for the low-latitude Laurentia model. Additional data from both Laurentia and Amazonia for this critical interval are needed to distinguish between the two models.

If the low-latitude Laurentia model is correct, then this would imply that both the Sturtian and Vendian glaciations occurred as the continents were located in low latitudes. This has interesting climatic implications. Besides the snowball earth hypothesis, one other mechanism for generating low-latitude glaciations has garnered attention. The high obliquity model (Williams, 1975) posits that the earth's obliquity was $\geq$ 56° during the Neoproterozoic glacial intervals. In the case of the high obliquity model, lower latitude regions ($\leq$ 45 degrees) would be preferentially glaciated.

If the low-latitude Vendian supercontinent model proves correct, then such a configuration would hinder our ability to distinguish between the high obliquity model and the snowball earth model via paleomagnetic methods. However, Donnadiue et al. (2002) have shown that a high-latitude supercontinent, coupled with a high obliquity earth is incapable of generating extensive glaciations and thus, if this model proves correct, then the high-obliquity model is negated.

Other Paleogeographies

Evans (2003) suggested that the Neoproterozoic Earth underwent a series of rapid paleogeographic changes due to true polar wander. This suggestion is highly dependent on the choice of paleomagnetic poles (Meert, 1999) and the fact that the current database is too sparsely populated to test such a hypothesis. Evans (2002,2003) was careful to note that such rapid true polar wander transitions were not designed to explain the rapid climatic changes indicated by the 'cap-carbonate'/tillite stratigraphic relationships.

Nevertheless, rapid paleogeographic changes would also result in rapid climatic shifts. If rapid true polar wander did occur in the manner proposed by Evans (2003), it would likely hinder our ability to distinguish between the high-obliquity and snowball earth models using paleomagnetic methods.

Conclusions

Climatic models for the Neoproterozoic glaciations depend upon numerous factors including, but not limited to, the paleogeographic setting. Current knowledge of Neoproterozoic paleogeography is hindered by the rather limited dataset, particularly for the interval from 600-720 Ma (Meert and Powell, 2001). Current paleogeographic models for the Sturtian glaciations, defined here as the interval from 700-800 Ma, are more robust than the younger Vendian glaciations. The most robust paleomagnetic data indicate that the supercontinent of Rodinia had begun to disperse. Climate models suggest that continental rifting may lead to an overall cooling trend that may have facilitated the climatic conditions necessary for an icehouse planet. The low-latitude position of this supercontinent (or fragments of the supercontinent) is also compatible with the high-obliquity model. The younger Neoproterozoic glacial epoch (Vendian-Varangian) has a less certain paleogeography (Meert and Torsvik, in press). The 'high-latitude' model is favored here, but the configuration is not without critics (Pisarevsky et al., 2000). If the high-latitude model proves correct, then the high-obliquity scenario is invalidated. If the low-latitude model is correct, then both the high-obliquity model and the severe icehouse models would be untestable for this interval of time.

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Figure Legends

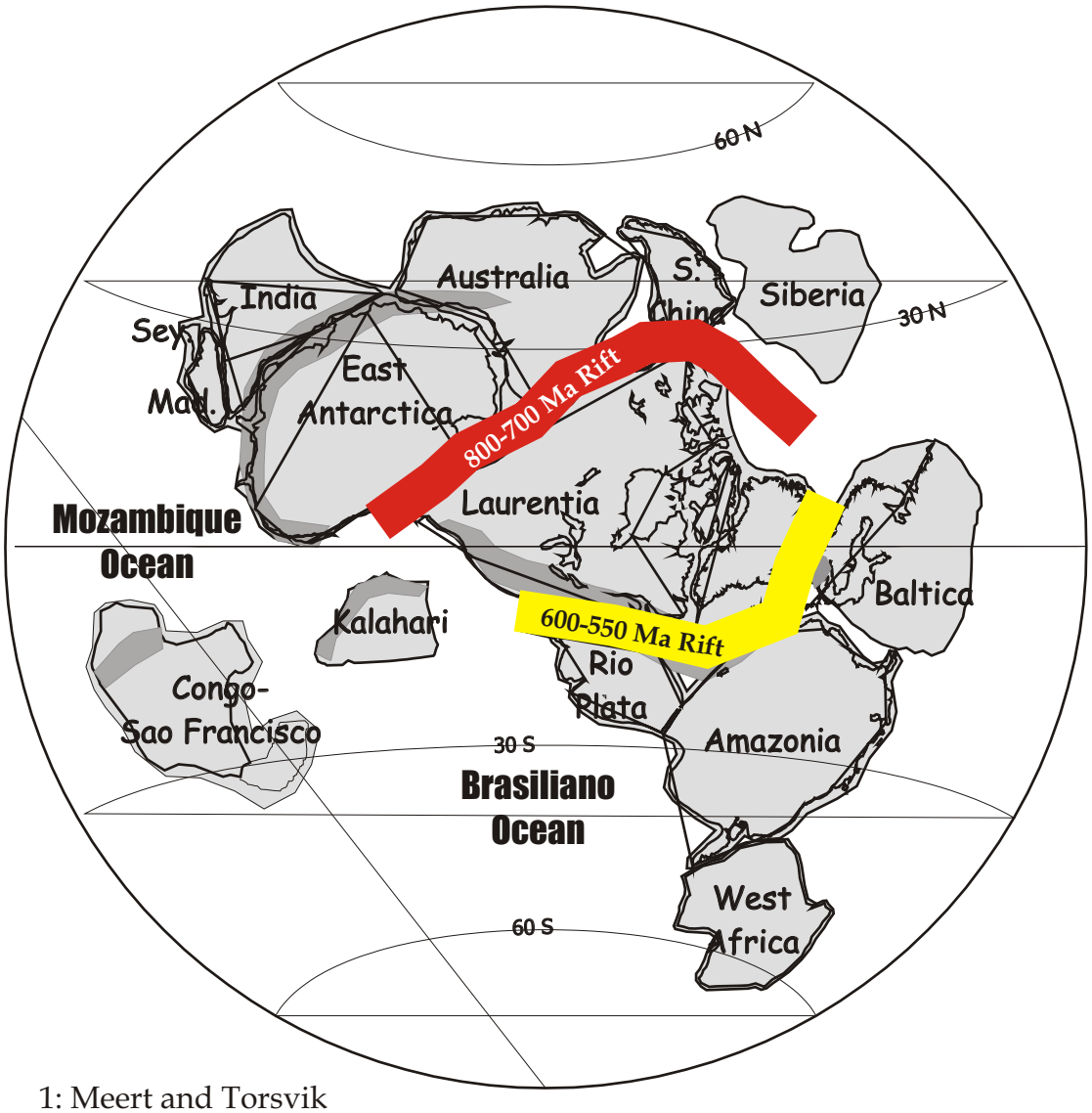
Figure 1: The 'traditional' model of Rodinia adopted from Dalziel (1997) and Torsvik et al. (1996). The model posits two rifting events, one along the present-day western margin of Laurentia sometime between 800-700 Ma, and a second along the present-day eastern margin of Laurentia between 600-550 Ma.

Figure 2: (a) 750 Ma reconstruction modified from Meert (2003) showing the western margin breakup of the Rodinia supercontinent. In this reconstruction, eastern Gondwana is broken up into two large segments and (b) 750 Ma reconstruction based on the model of Hartz and Torsvik (2002) showing the relationship of landmasses along the eastern margin of Laurentia.

Figure 3: (a) The high-latitude Laurentia option places the present-day eastern margin of Laurentia at the south pole adjacent to the Amazonian and Rio Plata cratons at 580 Ma. Baltica has rifted from NE-Laurentia opening the Iapetus Ocean. Siberia is positioned according to the suggestion in Hartz and Torsvik (2002). (b) Figure 1a is rotated to show the final stages of Gondwana assembly and closure of the Mawson Sea between Australo-Antarctica and the rest of Gondwana.

Figure 4: (a) The low-latitude Laurentia model of Pisarevsky et al. (2000). This reconstruction maintains the relationship of the South American cratons with eastern

Laurentia and places Siberia rifted from the present-day arctic margin of Laurentia. (b) Figure 2a is rotated to highlight the relationship of Australo-Antarctica to the rest of Gondwana (see also Meert and Van der Voo, 2002).



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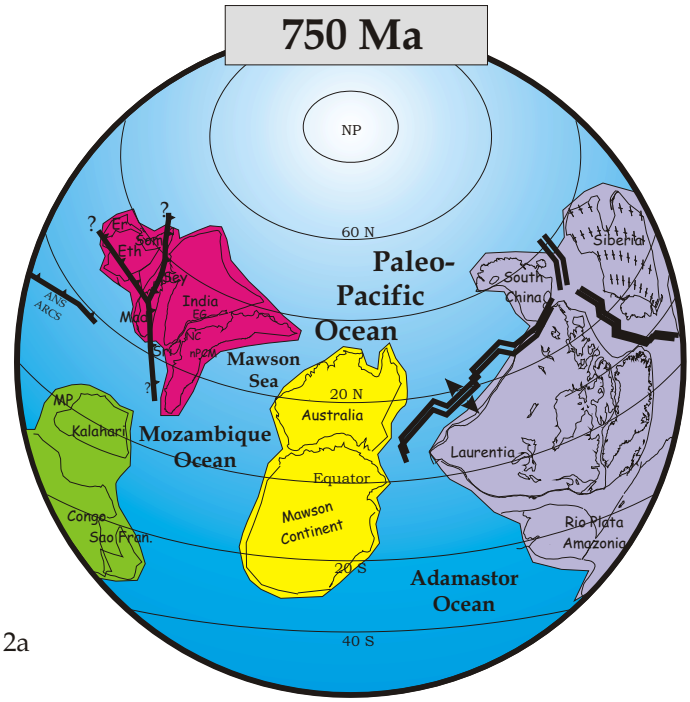

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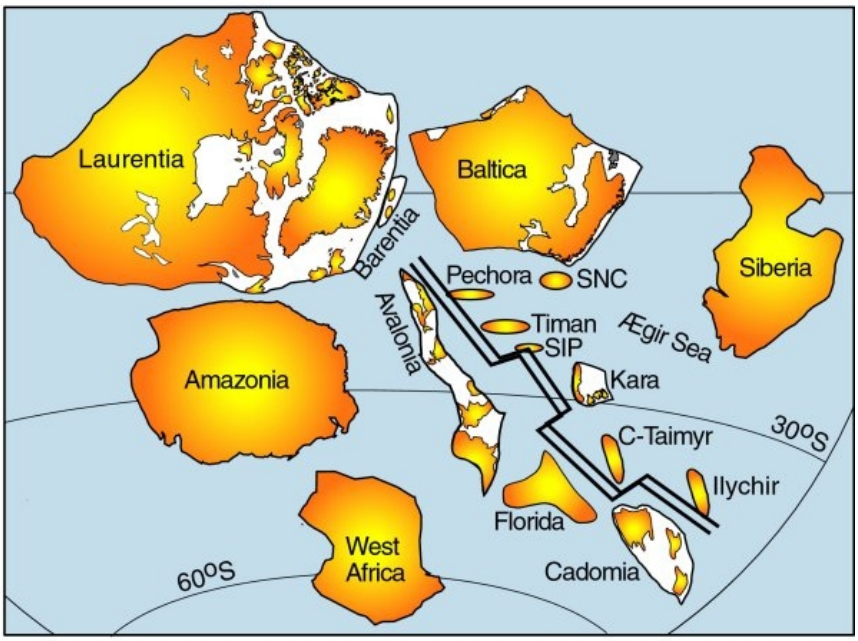

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Figure 2: Meert and Torsvik

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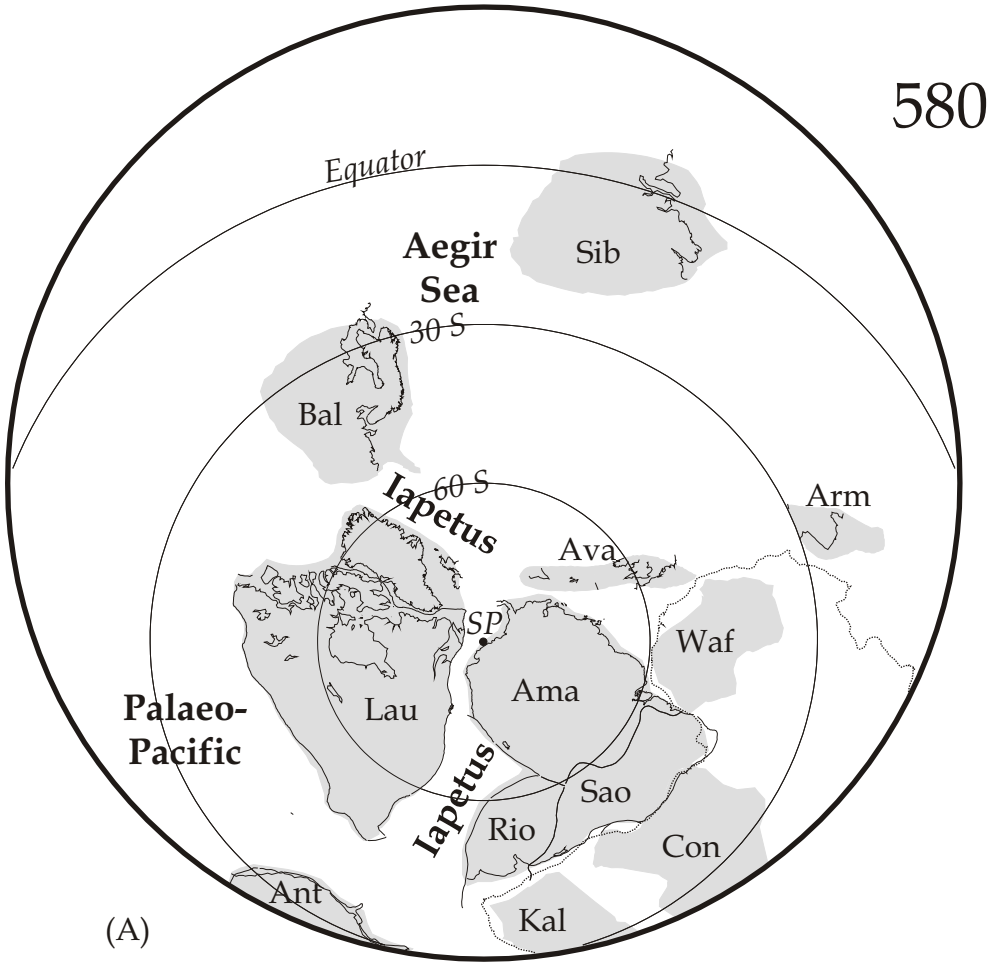
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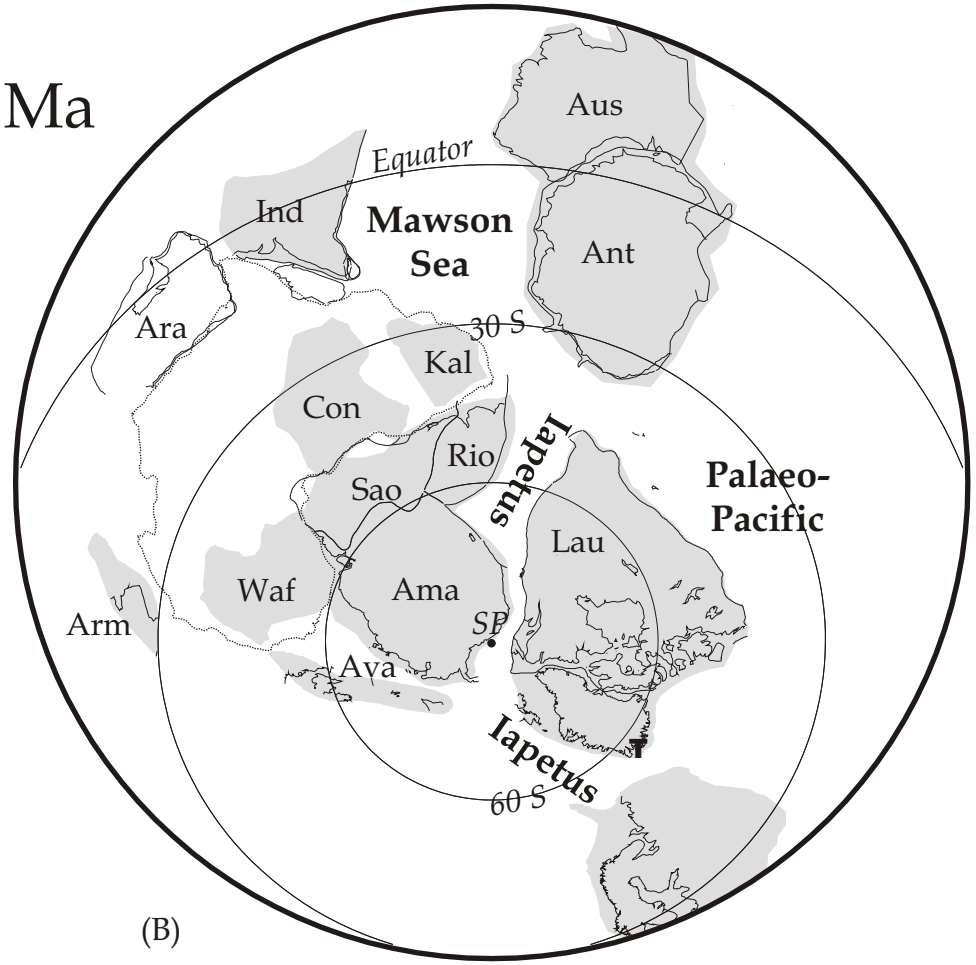
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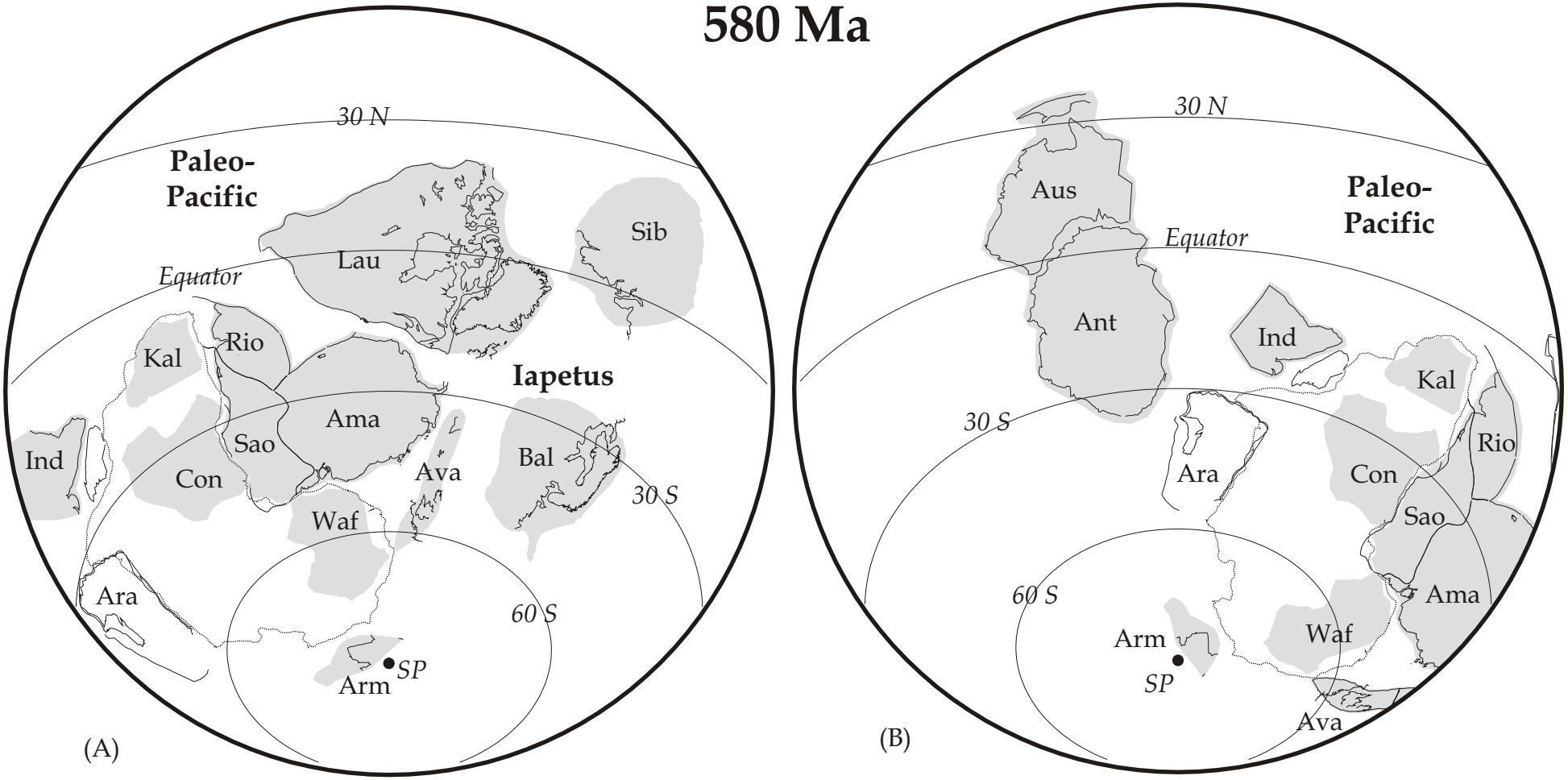
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