Tectonics and geodynamics of the eastern Tethys and northern Gondwana since the Jurassic

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SUMMARY

Southeast Asia experienced a complex tectonic and geodynamic history related to the subduction of the eastern Tethyan ocean basins, resulting from the long-term convergence between the Indo-Australian, Eurasian, and Pacific plates since Pangea breakup. The complex collage of continental and island arc terranes can be reconstructed into an estimated ancient arrangement using plate tectonic reconstruction approaches based on a synthesis of continental and marine geological and geophysical data. We use the open-source and cross-platform software *GPlates* (www.gplates.org) to refine the evolution of the eastern Neo-Tethys since the latest Jurassic rifting episodes along northern Gondwana. We apply the resulting plate motions to drive numerical models of mantle flow in order to predict the evolving mantle structure. New Guinea's northward motion over subducted slabs, related to the Sepik back-arc basin and the Maramuni subduction system, resulted in long-term flooding of the margin since ~20 Ma, despite falling long-term global sea levels. The Sundaland continental promontory experienced dynamic uplift in the latest Cretaceous to Eocene times due to the accretion of the Woyla Arc at ~80 Ma, leading to slab breakoff and a temporary interruption of subduction. However, renewed subduction along the Sunda margin resulted in renewed dynamic subsidence from ~30 Ma, which was amplified by regional basin rifting events. In addition, the sinking Sunda slab likely triggered a mantle slab avalanche, resulting in a counterintuitive combination of contemporaneous basin inversion and strong dynamic subsidence from ~15 Ma. The evolution of the eastern Tethyan oceanic gateway provides an important framework for understanding the role of plate tectonics in controlling long-term oceanic circulation and climate, as well as shedding light on the complex interplay between deep Earth and surface processes in driving basin formation and evolution. These results provide new avenues for reconciling stratigraphic and tectonic processes, as well as contributing new approaches for basin analysis and hydrocarbon exploration.

Key words: Tectonics, Geodynamics, Dynamic Topography, Mantle Convection, Tethys

INTRODUCTION

The eastern Tethys, representing the Java-Sunda subduction system and eastward to the New Guinea margin, records the long-term tectonic convergence between the Eurasian, Indo-Australian, and Pacific plates since Pangea breakup. The mosaic of continental and island arc terranes sutured onto Southeast Asia and New Guinea represent the opening and closure of multiple ocean basins (Metcalfe, 1988; Metcalfe, 1994), which have been lost to subduction. This complex tectonic and geodynamic history has important implications for ocean circulation and climate (Gaina and Müller, 2007; Hall et al., 2011), but is also crucial in understanding basin evolution and hydrocarbon systems in the region (Doust and Sumner, 2007). Our recent work synthesises the marine and continental geological record to provide insights into the interaction between mantle and surface processes in this region (Zahirovic et al., 2016a; Zahirovic et al., 2016b), with broader implications for the interpretation of subsidence and compressional events from the stratigraphic record. Using numerical models of plate tectonics and mantle convection, the role of sinking slabs in the mantle has been shown to impart a regional signal of 'dynamic' subsidence in this region during the post-Pangea timeframe (DiCaprio et al., 2011; Harrington et al., 2017; Zahirovic et al., 2016a). However, recent numerical models indicate that mantle 'slab avalanches' drive surface subsidence, as well as contemporaneous compression and basin inversion in the absence of collisional events (Yang et al., 2016a; Yang et al., 2016b).

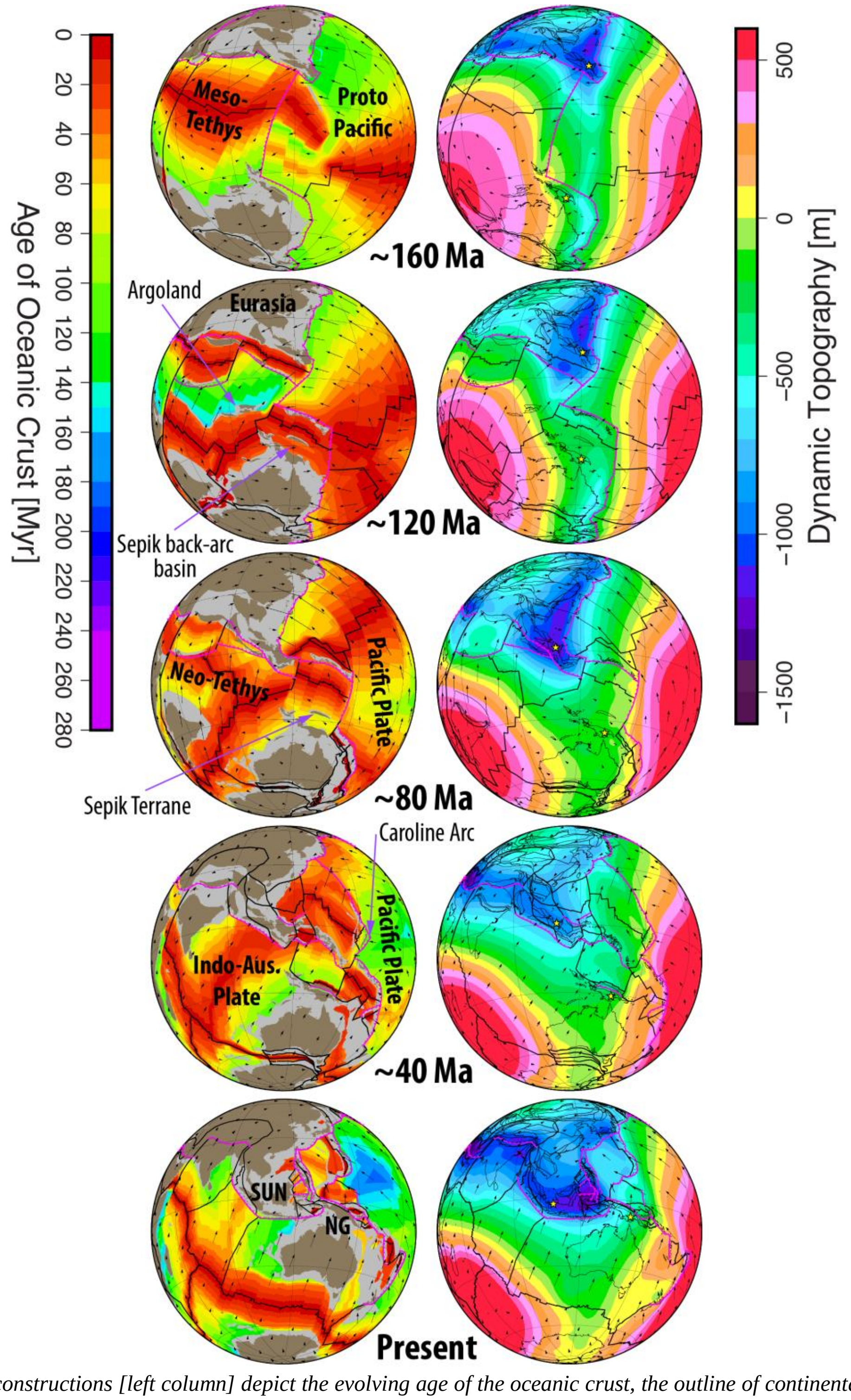

Figure 1: *Plate reconstructions [left column] depict the evolving age of the oceanic crust, the outline of continental crust (grey), and the reconstructed present-day coastlines (brown). Mid-oceanic ridges, transforms, and deforming regions of continental crust are plotted as thick black lines, while teethed magenta lines represent subduction zones and their polarities. Arrows represent plate velocities. The dynamic topography resulting from mantle flow [right column] highlights regions of mantle upwellings (warm colours) and downwellings (cold colours), dominated by the post-Pangea girdle of subduction, and the African and Pacific mantle superswells. It is important to note that continents override different mantle domains through time, which results in an ephemeral dynamic topography signal acting on the surface. Yellow stars indicate dynamic topography sampling locations in Fig. 2. SUN, Sundaland; NG, New Guinea.*

New Guinea

The New Guinea margin represents the eastern termination of the Tethyan system, with a tectonic and geodynamic complexity owing to the nature of the complex convergence between the Australian and Asian margins (van Ufford and Cloos, 2005), which consumed most of the equatorial oceanic gateway in the Cenozoic. The history of volcanism, basin evolution, and ophiolite formation and obduction provides some insight into the evolving plate configurations, and the role tectonics and mantle flow beneath the lithosphere plays in modulating the formation of ore deposits and hydrocarbon resources. The New Guinea margin was an active margin with south-dipping subduction in the Late Jurassic, with granites from this system preserved in the Bena Bena Terrane (Davies, 2012). Slab rollback in the latest Jurassic likely caused the opening of the Sepik back-arc basin, with supra-subduction zone ophiolites dated to ~157 ± 16 Ma in the Central Ophiolite Belt (Permana, 1998) between the Sepik composite terrane and Australian continental crust. The north-south extent of this back-arc basin is uncertain, with a minimum size of 300 to 500 km (akin to the Japan Sea) estimated using numerical mantle flow modelling (Zahirovic et al., 2016b). This back-arc basin was subsequently subducted northward along the Sepik composite terrane, with subduction initiating sometime in the Late Cretaceous and generating the Eocene age volcanics of the Sepik Arc, and continent-arc collision occurring in the Oligocene (Davies and Jaques, 1984). However, the size of the Sepik back-arc basin, the timing of arc-continent collision, and the response of New Guinea topography requires further testing and investigation. Following the docking of the Sepik Arc to New Guinea, the eastward continuation of the Molucca Sea Plate was subducted southward along New Guinea to produce the Maramuni Arc (~18 to 8 Ma), and northward along the Caroline Plate to produce the Halmahera and Caroline arc systems (~25 Ma to 8 Ma) (Hill and Hall, 2003). Australia's rapid northward motion from Eocene times resulted in the northern portion of the continent, including parts of New Guinea, overriding subducted slabs from the closure of the equatorial oceanic gateway. Sinking slabs result in mantle downwelling and associated dynamic subsidence of the overriding plate – typically with amplitudes of several hundred meters, over a region of many hundreds to thousands of kilometres (Flament et al., 2013; Lithgow-Bertelloni and Gurnis, 1997). Previous work has implicated these sinking slabs in contributing to the subsidence of the northern Australian margin and the tilting of the Australian continent (DiCaprio et al., 2009; DiCaprio et al., 2011), as well as contributing to the flooding of New Guinea during south-dipping subduction associated with the Maramuni Arc (Harrington et al., 2017). This highlights the importance of understanding both the nature and chronology of tectonic events to produce tectonic topography (e.g., basins, orogens, etc.), as well as considering the role of the deep Earth in modulating these regional topographic signals through dynamic topography.

Sundaland

The Sundaland continental promontory has grown through multiple accretions of terranes originating from the Tethyan tectonic conveyor that transferred blocks from northern Gondwana towards Southeast Asia (Fig. 1). The Late Jurassic marks the opening of the Neo-Tethyan ocean basin, at the expense of the older Meso-Tethyan basin that was subducted northward along the southern Eurasian active margin (Gibbons et al., 2015). In the Sundaland segment of the eastern Tethys, northward subduction beneath Sumatra and the Southwest Borneo core initiated by ~170 Ma (McCourt et al., 1996), with the slab pull propagating across the Meso-Tethyan plate and resulting in rifting initiation along the passive margin of the Northwest Shelf in Australia and Greater India. The earliest seafloor spreading occurred by 155 ± 3.4 Ma in the Argo Abyssal Plain (Gradstein and Ludden, 1992), and likely detached the East Java, south-eastern Borneo, and West Sulawesi continental fragments during the initial opening of the Neo-Tethys (Zahirovic et al., 2016b). Ongoing subduction along Sundaland likely led to slab roll-back to open the Woyla back-arc basin, and the establishment of the Woyla intra-oceanic arc system (Barber, 2000). The Tethyan continental terranes likely first collided with the eastward continuation of the Woyla Arc by ~100 Ma, with complete suturing of the Woyla Arc and the continental terranes to Sundaland complete by ~80-75 Ma. The suturing interrupted subduction along the southern Sunda margin, resulting in a magmatic gap between ~75 and 62 Ma on Sumatra (McCourt et al., 1996). Subduction of the Indian Ocean basin started by ~62 Ma and has continued to present-day, resulting in the unbroken Sunda Slab beneath Borneo and Sumatra to depths of ~1,500 km (Li et al., 2008) with an implied average slab sinking rate of ~2.5 cm/yr. Widespread rifting occurred in many Sundaland basins largely in the Eocene and Oligocene (~56 to 23 Ma), with a major pulse of compression, basin inversion, and continued subsidence occurring from the Early Miocene (~17 Ma) to the present (Doust and Sumner, 2007). The conventional interpretation of these inversions is the combination of extrusion tectonics and collision of Australia with eastern Sundaland. However, numerical modelling suggests that the contemporaneous regional basin inversion and subsidence may be explained through the effects of a mantle slab avalanche, which causes synchronous dynamic subsidence, trench advance, and compression in the overriding plate (Yang et al., 2016a; Yang et al., 2016b). These results also highlight the need to consider the role of mantle processes when interpreting basin histories, especially in explaining anomalous subsidence (or uplift) and basin inversions in the absence of major tectonic collisions.

METHOD AND RESULTS

Plate tectonic reconstructions provide an important framework for understanding the chronology and geodynamic mechanisms of major events preserved in the geological record. We use the open-source and cross-platform *GPlates* (www.gplates.org) plate reconstruction software (Boyden et al., 2011), and synthesise the continental and marine geological and geophysical records to propose a scenario of eastern Tethyan evolution since the Late Jurassic. The reconstructions are refined for this region and described in Zahirovic et al. (2016b). The global plate reconstructions (Fig. 1) are used as surface boundary conditions to drive numerical models of mantle flow using the finite element code *CitcomS* (https://geodynamics.org/cig/software/citcoms/). Plate velocities are extracted using evolving plate topologies (Gurnis et al., 2012), and subduction zone locations and slab polarities are assimilated into the numerical models to maximum depths of 350 km at 1 Myr intervals (Bower et al., 2015). In addition, the thermal lithosphere thickness is generated using the seafloor age-grids for oceanic crust, while tectonothermal ages of continental crust is used to infer continental lithosphere thickness. The mantle flow models are run forward in time, and the present-day predicted mantle structure is qualitatively validated using P- and S-wave seismic tomography, which is described in Zahirovic et al. (2016b), along with the details of the model set up and parameters (Case 4). Dynamic topography represents the vertical motion of the surface resulting from flow in the mantle. We remove lateral viscosity variations and sources of buoyancy in the shallowest 350 km of the mantle as this represents the maximum depth to which mantle structure is imposed, and we compute the radial stresses on the surface resulting from mantle flow for a free-slip boundary. The dynamic topography h is obtained by scaling the total normal stress σ_{rr} on the top model surface following:

$$h = \frac{\sigma_{rr}}{\Delta\rho g_0}$$

where $\Delta\rho$ is the density difference between the shallow mantle (ρ_{um} = 3340 kg m^{-3}) and air (ρ_a = 0 kg m^{-3}), R_0 is the radius of the Earth, and g_0 gravitational acceleration. Dynamic topography is plotted regionally in Fig. 1, and extracted for a location in Sundaland (near Belitung/Billiton Island) and New Guinea (near the Gulf of Papua) since the Late Jurassic (Fig. 2). Although amplitudes of dynamic topography are more difficult to constrain, the trends provide meaningful insights into episodes of dynamic uplift and subsidence as the continents move across mantle upwellings and downwellings, respectively.

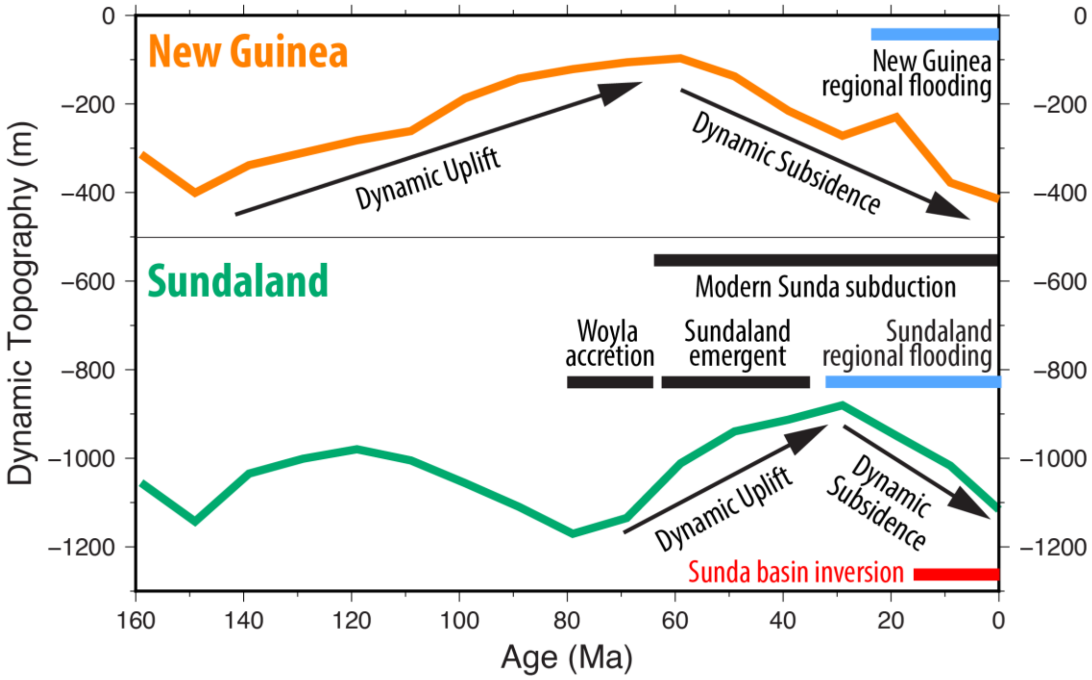

Figure 2: *Dynamic topography extracted for a point on Sundaland (near Belitung Island) and New Guinea (near the Gulf of Papua) since the Late Jurassic (see Fig. 1 for locations). Dynamic uplift occurs when subduction is interrupted (such as the accretion of the Woyla Arc onto Sumatra) or when slab rollback results in a greater distance between the overriding continent and the subducting material (such as the opening of the Sepik back-arc basin along New Guinea). New Guinea flooding timing is adapted from the paleogeographic constraints in Harrington et al. (2017), the emergence of Sundaland in the Eocene is from the paleogeographic reconstructions in Zahirovic et al. (2016a), and the timing for Sundaland basin inversion is from Doust and Sumner (2007).*

New Guinea experiences dynamic subsidence in the Late Jurassic, largely due to the proximity of the south-dipping proto-Pacific slab. However, slab roll-back to open the Sepik back-arc basin results in a subdued dynamic subsidence signal, as the locus of subduction shifts oceanward. This trend continues until ~60 Ma, when dynamic subsidence becomes stronger largely from the initiation of Sepik back-arc basin subduction, and New Guinea's northward motion over these subducted slabs. The south-dipping subduction system related to the Maramuni Arc between ~18 and 8 Ma results in strong subsidence of the New Guinea margin, leading to regional flooding despite falling long-term sea levels (Harrington et al., 2017), which is also amplified by the flexural response of the plate from orogenic loading.

The dynamic subsidence acting on Sundaland is interrupted in the Late Cretaceous with the docking of the Woyla Arc at ~80 Ma, leading to a temporary cessation in subduction. This leads to slab break-off and relative dynamic uplift of Sundaland through the Paleocene and Eocene. However, subduction along the Sunda margin produces renewed strong dynamic subsidence from ~30 Ma, which is amplified by basin rifting across the region (Doust and Sumner, 2007). Many Sundaland basins underwent compression and basin inversion by ~17 Ma, despite a large distance to the eastern Australia-Sunda collision system. The numerical models of Yang et al. (2016a) and Yang et al. (2016b) (Fig. 3) suggest that the contemporaneous basin inversions and regional flooding represents the effects of a mantle slab avalanche, resulting from trench advance (leading to compression) and the large volume of sinking slabs in the mantle (leading to dynamic subsidence). However, although the regional signal is dominated by dynamic subsidence, areas of the continental crust where deformation is focused may become emergent due to the effect of isostatic topography (namely thickening and uplift of continental crust). It is therefore also important to consider the interplay and time-evolving competition between dynamic topography (mantle origin), isostatic topography (largely crustal origin), and flexural components (largely lithospheric in origin) when interpreting orogenic and basin histories.

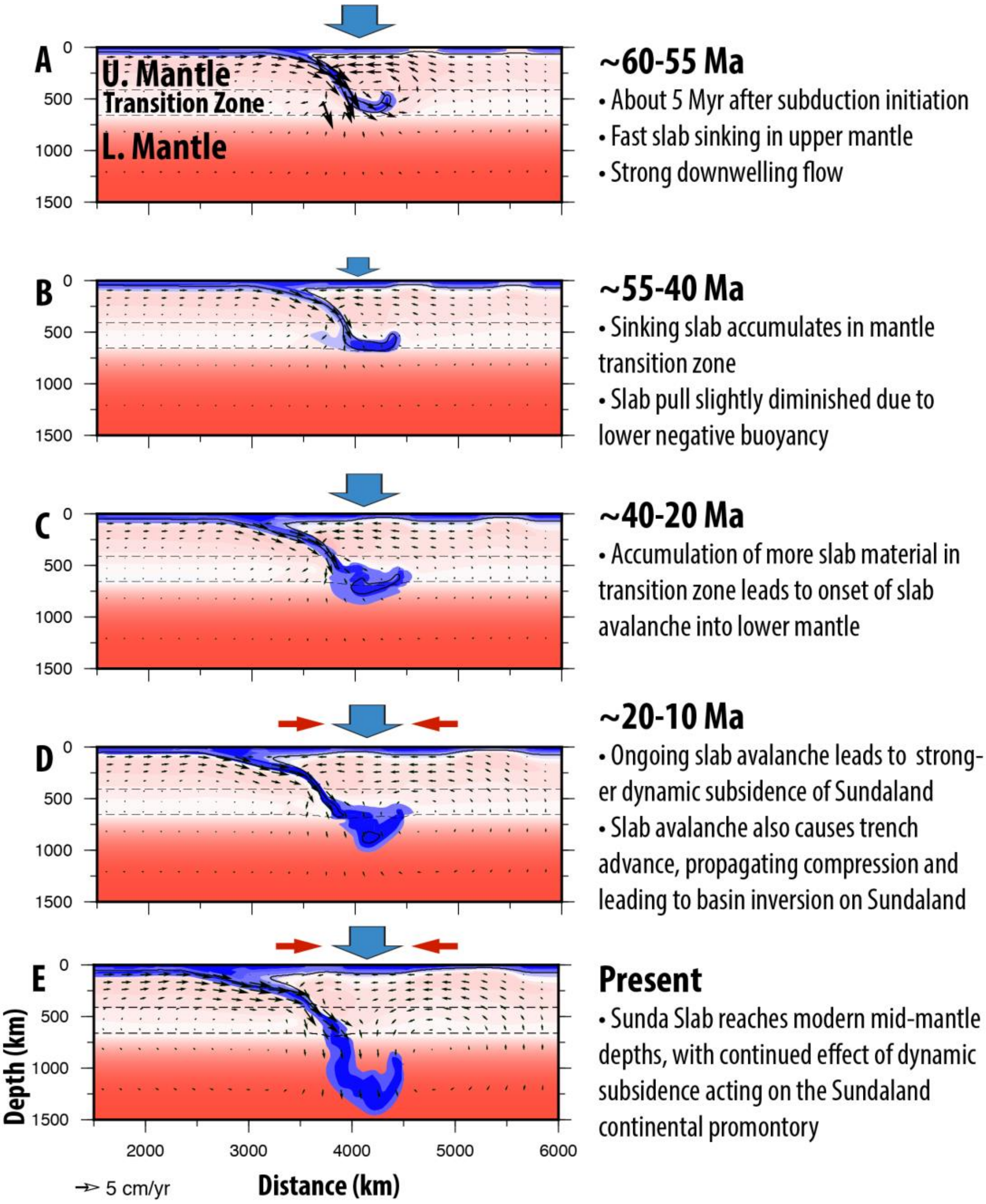

Figure 3: *Summary figure from 2D numerical models of mantle flow described in Yang et al. (2016b). Following subduction initiation (A), the slab sinks through the low-viscosity asthenosphere, imparting strong dynamic subsidence on the overriding plate. However, the slab reaches the mantle transition zone (410 to 660 km), where the slab's descent is impeded, leading to slower sinking velocities. Continued subduction leads to the accumulation of slab material in the transition zone (C), leading to a slab avalanche where the slab material enters the lower mantle (D). During this time the trench advances and imparts compression (including basin inversion) in the overriding plate, which is contemporaneous to strong dynamic subsidence (D-E). This slab avalanche phenomenon explains the contemporaneous long-term flooding of Sundaland (despite long-term falling sea level) and basin inversions (in the absence of major tectonic collisions) in the last ~15 to 20 million years.*

CONCLUSIONS

We present a summary of the latest plate reconstructions for the eastern Tethyan region (Zahirovic et al., 2016b), and describe the resulting evolution of dynamic topography from these regionally-refined reconstructions. The plate tectonic reconstructions provide a crucial framework for studying regional and global geodynamics, and the influence of deep Earth processes on basin formation and evolution. In addition to better understanding the mechanisms and chronology of tectonic events (such as rifting or collisions), the plate reconstructions and numerical models of mantle flow provide a 4D perspective on the vertical motions affecting continents as they traverse over mantle upwellings and downwellings. Although Sundaland and New Guinea have been under the influence of mantle downwellings for most of the post-Pangea timeframe, the relative strength and changes in this mantle signal has first-order implications for the long-term flooding and emergence of these regions. New Guinea experienced a weakening dynamic subsidence signal from the Early Cretaceous, due to the roll-back of the proto-Pacific slab, which caused the opening of the Sepik back-arc basin. However, renewed subduction of this basin in the Late Cretaceous, and Australia's northward motion, led to New Guinea overriding these subducted slabs. These ancient sinking slabs, in addition to the younger slab related to Maramuni subduction (~18-8 Ma) led to the most recent phase of strong dynamic subsidence, and long-term flooding of the region in the last ~20 Myr (Harrington et al., 2017). For Sundaland, a Late Cretaceous interruption in subduction led to dynamic uplift of the region, and long-term emergence of the continent during the Paleocene and Eocene. However, renewed subduction resulted in strong dynamic subsidence from ~30 Ma, amplified by widespread basin rifting. The sinking Sunda slab also likely triggered a mantle slab avalanche at this time, resulting in trench advance (with compression and basin inversions in the overriding plate) from ~15 Ma, and a counterintuitive and contemporaneous strong dynamic subsidence resulting from mantle flow beneath Sundaland. The strong coupling between deep Earth and surface processes highlight the need to comprehensively evaluate the mechanisms for basin formation and evolution, and provide a new framework for basin analysis in hydrocarbon exploration.

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