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What drives the continued India-Asia convergence since the collision at 55 Ma?

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What may drive the India-Asia convergence has been puzzling and has in fact puzzled many. According to the theory of plate tectonics and the concept of Wilson Cycle, continental collision means the loss of seafloor subduction and thus the disappearance of slab pull for driving plate motion [1–3], yet the India-Asia convergence has continued to this day at a rate of ~40 mm/a [4] since the collision ~55 million years ago [5]. This apparent puzzle has made some to question the validity of the Wilson Cycle concept and to raise doubts about slab pull being the primary driving force for plate motion [1–3]. Ridge push, which is well-understood as a secondary force, has thus been emphasized by some; the idea of mantle plumes as driving force has also been reinvoked; and subduction of the Indian mantle lithosphere itself has been claimed as being adequate to drive the India-Asia convergence [6].

Given the fundamental importance of the question towards complete understanding of global tectonic processes in general and the origin and evolution of the Tibetan Plateau in particular, it is necessary to resolve the puzzle. In this short paper, I do not wish to enter debates on many details but offer the results of my objective analysis on observations in terms of simple physics and readily understandable geological concepts and principles. To ensure better appreciation of my analysis, I first summarize my solution to the puzzle as follows:

The continued India-Asia convergence since the collision ~55 million years ago has been driven by the subducting slab pull of the giant Indo-Australia plate at the Sumatra-Java trench. The convergence will cease to continue once the Indo-Australia plate disintegrates into several smaller plates in the future.

As we understand, the primary assumption of the plate tectonics theory is that the surface plates are rigid and do not deform internally but can move relative to one another along plate boundaries [2,3]. Fig. 1a is a portion of the present-day global plate tectonics map with named plates being some of the original 12 rigid plates identified 45 years ago [1]. The giant Indo-Australia plate is one of these rigid plates. Recent studies have shown that most of the plates are strictly speaking not quite rigid [7], but the "rigid" assumption remains a valid approximation [3]. For example, the colored localities in the giant Indo-Australia plate indicate the non-rigid property with seismicity [7] seen in Fig. 1b. Nevertheless, there exist no "plate boundary" features in the interiors of the giant Indo-Australia plate such as "spreading ridges", "trenches" and "transform faults" with obvious displacement. Therefore, correctly-speaking, the giant Indo-Australia plate is a not-perfectly rigid, but coherent single plate with its edges bounded by ridges (Central Indian Ridge to the west and Southeast Indian Ridge to the south), trenches (Sumatra, Java, New Hebrides, Tonga and Kermadec to the north and east), large transforms (with the Arabic plate to the northwest and with the Pacific plate along the Macquarie ridge to the southeast) and collision zone with the Eurasia plate along the Himalaya (Fig. 1).

Fig. 1 shows that in the absolute plate motion (APM) reference frame, the eastern part (Australia and the vicinity) of the giant Indo-Australia plate is moving northward at the rate of >70 mm/a while the western part (India and the vicinity) is moving only at the rate of ~40 mm/a because of the impediment at the Himalaya as the result of the India-Asia "collision" and convergence. The fact that the Antarctic plate is essentially stagnant in the APM framework (Fig. 1) means that the opening of the Southeast Indian Ocean is simply and entirely caused by the northward moving of the Indo-Australia plate pulled into the Sumatra-Java-New Hebrides trench to the north. The continued northward slab-pull into the >4000 km long Sumatra-Java Trench can readily carry northward movement of the Indian continental lithosphere of the same giant Indo-Australia plate, making the continued India-Asia convergence possible and thus the continued Himalayan orogenesis. So, the continued slab pull at the Sumatra-Java trench and the continued resistance along the Himalaya make the giant Indo-Australia plate under increased shearing stress, which is in fact well expressed as intraplate seismicity indicated in colored localities (Fig. 1b), where the largest intraplate strike-slip earthquake of magnitude 8.6 M_w occurred on 11 April 2012 at 2.311°N, 93.063°E [8].

From the above observations and analysis, we cannot avoid the conclusion that the giant Indo-Australia plate will in no distant future break up because of the accumulated shear stress caused by slab pull at the Sumatra-Java trench and the impediment of the Indian continent along the Himalaya. Once this plate breaks up into smaller plates with the presumed Capricorn plate

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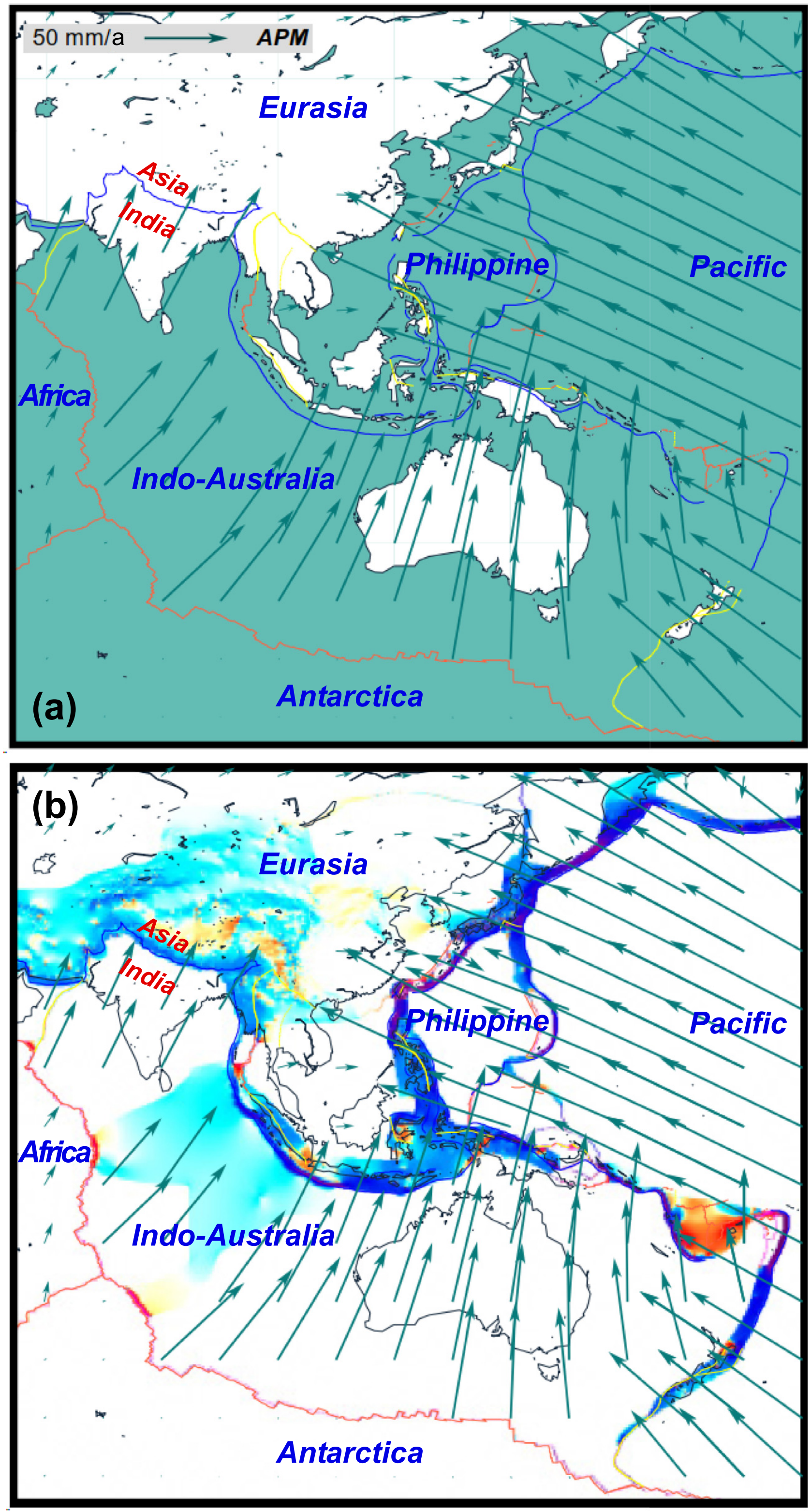

Fig. 1. Indo-Pacific conjunction portion of the global plate tectonics map using the absolute plate motion (APM) reference (http://jules.unavco.org/Voyager/GEM_GSRM). (a) shows the giant Indo-Australia composite plate consisting of continental (India and Australia) and oceanic lithosphere. This plate is one of the 12 rigid plates globally recognized 45 years ago [1] and is still considered a single plate today as there is no within-plate plate boundary feature (e.g., spreading center, subduction and transform) with displacement. The India-Asia continental collision suture is indicated. The reason why the India-Asia convergence continues is understood here as the Indian plate being passively dragged by subduction of the same giant Indo-Australia plate due to slab pull under gravity into the Sumatra-Java Trench [3]. (b) is the same plate tectonics map as above with color-coded areas recently discovered to show seismicity, suggesting that many plates are not rigid but do deform, which is true in much of the continental China, especially the Tibetan Plateau and within the giant Indo-Australia plate. These non-rigid regions (narrow or areal) have been termed diffuse plate boundaries [7]. Note that the colored areal region in the giant Indo-Australia plate means that this plate is being torn and will break up, and the predicted "Capricorn" plate may separate in the future. This will end the India-Asia convergence and the Himalayan orogenesis will give rise to orogenic collapse [3].

completely separated, the India-Asia convergence will cease to continue and the Himalayan orogenesis will give rise to orogenic collapse [3]. Fig. 2 summarizes my understanding discussed above. I fully realize the century-long and continued debate on the origin, evolution and lithospheric structure of the Tibetan Plateau [9–14], but I argue below why the presentation in Fig. 2 is a highly likely scenario in terms of straightforward physics and geology.

Fig. 2b (bottom) shows cross sections of the present-day downgoing slab at the Sumatra [***b***] and Java [***c***] trench [11], which exerts primary force pulling the northeastward movement of the giant Indo-Australia plate. Fig. 2b (top) shows the cross-section [***a***] of the present-day topography and my envisioned lithosphere structure of the Tibetan Plateau. The Indian plate here refers to its mantle lithosphere and portions of its deep crust. The original Tethyan seafloor lithosphere has long detached and sunk into the mantle at depths of >1000 km (detected from ~1000 to 2200 km depths) at ~21°N beneath India [15]. Assuming its sinking speed of 24 mm/a [15], the shallowest depth of ~1000 km for the very last bits of the sinking Tethyan oceanic lithosphere means that the complete slab breakoff took place at ~40 Ma, which is later than suggested in the literature, and is about ~15 Myrs after the India-Asia collision. This “delayed” breakoff (relative to the time of collision) is physically more likely because slab breakoff can only take place when the shear tress associated with the buoyancy contrast between the dense sinking oceanic lithosphere and the buoyant “rising” continental lithosphere exceeds the lithospheric strength (see below). Consequently, the subducting Tethyan seafloor lithosphere leads the way for the Indian continental lithosphere to underthrust beneath the Asian plate (Fig. 2) before the seafloor slab breakoff (not show).

Because continental mantle lithosphere of Precambrian age as a result of prior melt extraction is compositionally depleted and physically buoyant relative to the asthenosphere [13,16,17], it cannot subduct and sink into the asthenosphere. Hence, it is physically straightforward why the Indian lithosphere will underthrust beneath the Asian plate rather than sinking in the asthenosphere (Fig. 2). However, this continental underthrusting would not have happened in the first place without the lead of the dense Tethyan seafloor lithosphere subduction as elaborated above. Based on the above analysis and the concept of the isostasy, I argue that the Tibetan Plateau has double lithosphere with the Indian lithosphere thrusting beneath the Asian lithosphere, a scenario similar to the century-old idea by Argand [9] although the latter offered no mechanism. The Argand model, however, has been rejected or “ruled out” because (1) it is too old and too simple and (2) decades of multidisciplinary studies by the international communities with voluminous publications have shown extraordinary complexities beyond any single model. But these reasons are not convincing. Saying “complex” reflects a sense of lacking confidence. It is my understanding that large scale Earth processes are likely very simple, but the key skill to discover the simplicity is to correctly identify the primary variables that control the processes. This methodological statement is proven by the simple and elegant

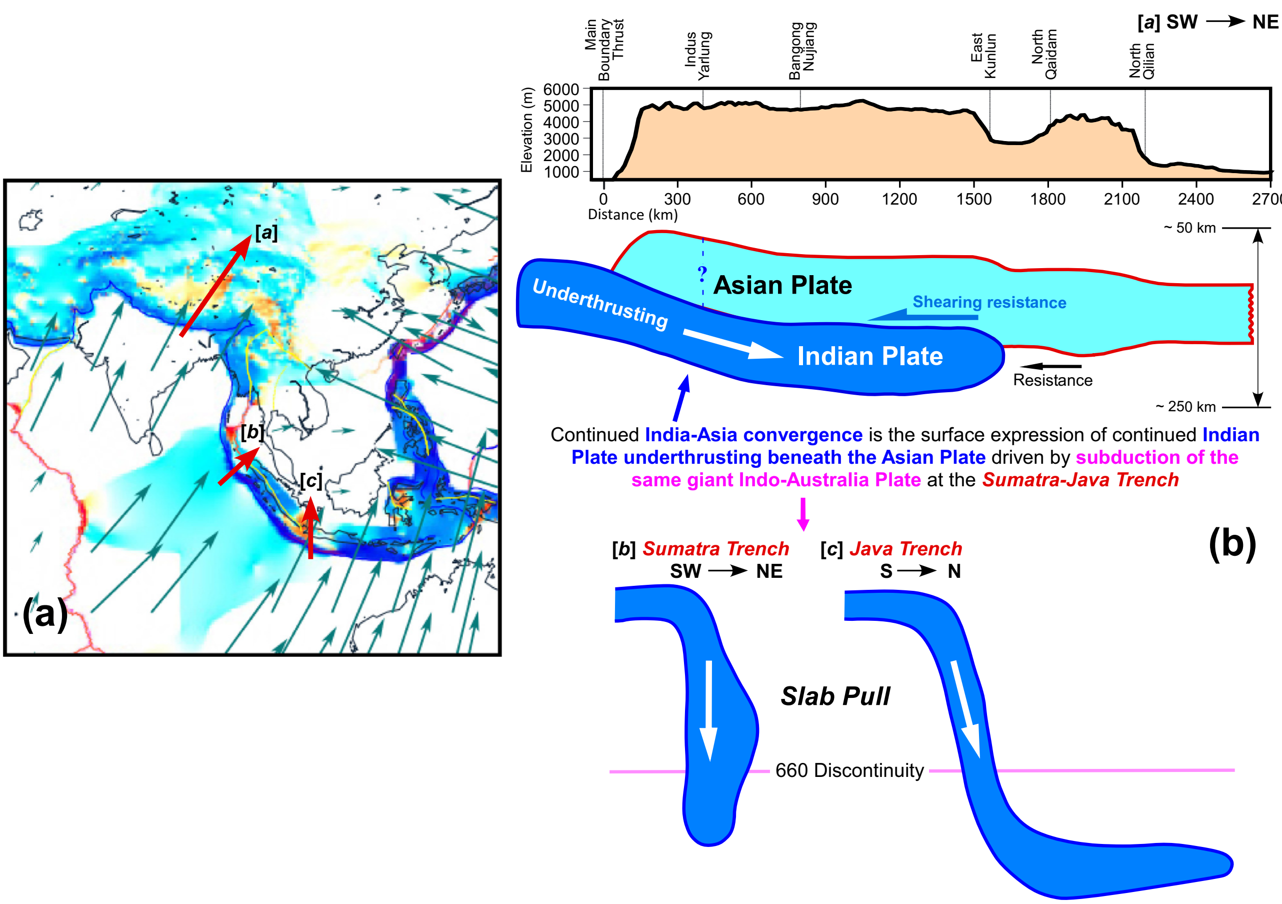

Fig. 2. Geological interpretation of the Indo-Pacific conjunction region. (a) is a small portion of Fig. 1b, indicating the localities of the three cross-sections [***a***], [***b***] and [***c***] to show in (b). [***a***] shows the underthrusting of the Indian lithosphere beneath the Asian (Tibetan) lithosphere, passively driven or dragged by subduction and slab pull of the same giant Indo-Australia plate into the Sumatra [***b***] and Java [***c***] trench (slab geometries after [11]). The interpretation offered here differs from all the many different models of varying sophistication but is consistent with the grand regional geology and physics, including the origin of the Tibetan Plateau. Note, the Indian plate underthrusting model agrees with the idea by Argand [9], but has more efficacies in explaining many specific details, especially isostasy.

theory of plate tectonics that explains much of the global geology on all scales at least since the Proterozoic. Then, what is the primary variable that controls the Tibetan Plateau formation? To me, it is the isostasy, the thickened and buoyant double lithosphere (Fig. 2b) and thus the plateau elevation. That is, the plateau is the surface expression of the thickened (doubled) lithosphere with intrinsic buoyancy (Fig. 2b, top).

I expect that many will continue to disagree on the above analysis and conclusion because different images of seismic tomography can be interpreted differently [12–14], but I agree that (1) the INDEPTH seismic profile is not representative [12] and (2) the Tibetan Plateau has excessively thickened lithosphere throughout [13], which is manifested by the broad plateau surface elevation because of the isostasy (Fig. 2b, top). The idea of lithosphere thinning by convective removal, delamination or foundering has been popular in explaining the origin of the elevated Tibetan Plateau, but this popular idea has obvious difficulties: (1) the compositionally depleted continental mantle lithosphere is physically buoyant [13,16,17] and cannot sink into the dense asthenosphere; (2) if the lithospheric mantle could indeed be thinned by convective removal, the top interface of the dense asthenosphere will rise accordingly through isostatic adjustment, which, according to Airy isostasy will not favour plateau formation, but can in fact cause instability and even tend to destroy the existing plateau like eastern continental China in the Mesozoic; (3) in fact, recent shear wave velocity data and models that apply globally on fine structures show a clear picture of the thickened Tibetan Plateau lithosphere [13] in support of my understanding in Fig. 2.

In summary, I present my analysis and understanding here to (1) emphasize that the continued India-Asia convergence does not negate but further confirms that subducting slab pull is the very primary force that drives plate motion and plate tectonics; and to (2) advocate re-evaluation of the merit of the century-old Argand idea with new data and using simple physics and geological understanding.

Conflict of interest

The author declares that he has no conflict of interest.

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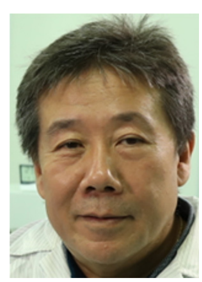

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