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On the cause of continental breakup: A simple analysis in terms of driving mechanisms of plate tectonics and mantle plumes

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ABSTRACT

Earth's continents can come together to form supercontinents and the supercontinents can break apart into fragments of varying size scattering around the globe through a hypothetical process called continental drift. The continental drift hypothesis had survived after ~60 years debate and evolved into the powerful theory of plate tectonics with unquestionable and irrefutable lines of evidence. This narrative statement is familiar and acceptable to everyone in the scientific community, but scientists differ when talking about the cause of continental breakup. Some advocate mantle plumes, especially superplumes, as the cause ("bottom up"), whereas others emphasize plate tectonics to be the cause ("top down") and still some believe both are needed. In this short paper, I do not wish to enter the debate, but offer a readily understandable geological analysis on the likely driving mechanisms of plate tectonics and mantle plumes, which leads to the conclusion that continental breakup is a straightforward consequence of plate tectonics without requiring mantle plumes. Mantle plumes, if needed, may be of help at the early rifting stage, but cannot lead to complete breakup, let alone to drive long distance dispersal of broken continents. Superplumes invoked by many do not exist. The debate may continue, but I encourage enthusiastic debaters to consider these straightforward concepts and principles of geology and physics given in this objective analysis.

1. Introduction

Formation of supercontinents and their breakup seem to have been cyclic through Earth's history (e.g., Nance et al., 1988, 2014; Rogers and Santosh, 2002; Zhao et al., 2004; Oriolo et al., 2017; Li et al., 2019a,b). Among the several supercontinents recognized, *Pangea* (~250 Ma) and *Rodinia* (~800 Ma) are best studied and understood to have included almost all the landmasses on Earth (Li et al., 2019a,b; Torsvik, 2003; Zhao et al., 2018; Fig. 1). The word *Pangea*, meaning *all land*, was used by Wegener (1912) to illustrate his hypothesis of continental drift (Wegener, 1929), which has by now become self-evident, but was highly controversial in his time and subsequent years. In this hypothesis, Wegener argued that all the continents had once formed a single land mass, *Pangea*, before breaking apart and drifting to their present-day locations, and that mountains were the results of continents colliding and crumpling, insightfully citing the example of India colliding into Asia to uplift the Himalayas (see Powell, 2015). The continental drift hypothesis had survived after ~60 years debate and evolved into the powerful theory of plate tectonics with unquestionable and irrefutable evidence (see Frankel, 2011). That is, the plate tectonics theory not only confirms continental drift but has been discovered to offer an effective mechanism on why and how continents move in subsequent studies (see Forsyth & Uyeda, 1975; Davies & Richards, 1992; Niu, 2014). This story is familiar and acceptable to everyone in the scientific community, yet scientists differ when talking about the cause of continental breakup and dispersal (e.g., Storey et al., 1992; Storey, 1995). Some advocate mantle plumes, especially superplumes, as the cause ("bottom up"; e.g., Richards et al., 1989; Hill, 1991; Hill et al., 1992; Li et al., 1999, 2003; Condie, 2004; Zhong et al., 2007; Buiter & Torsvik, 2014; Zhang et al., 2018), whereas others emphasize plate tectonics to be the cause ("top down"; e.g., Coltice et al., 2007; Gutierres-Alonso et al., 2008; Cawood et al., 2016; Wan et al., 2019) and still some believe both are needed (e.g., Murphy & Nance, 2013; Buiter & Torsvik, 2014; Wolstencroft & Davies, 2017). All these are commendable efforts based on geological observations, petrological and geochronological data, rigorous analysis and quantitative modeling, but the debate remains. A consensus is needed if possible.

In this contribution, I do not wish to enter the debate but offer an

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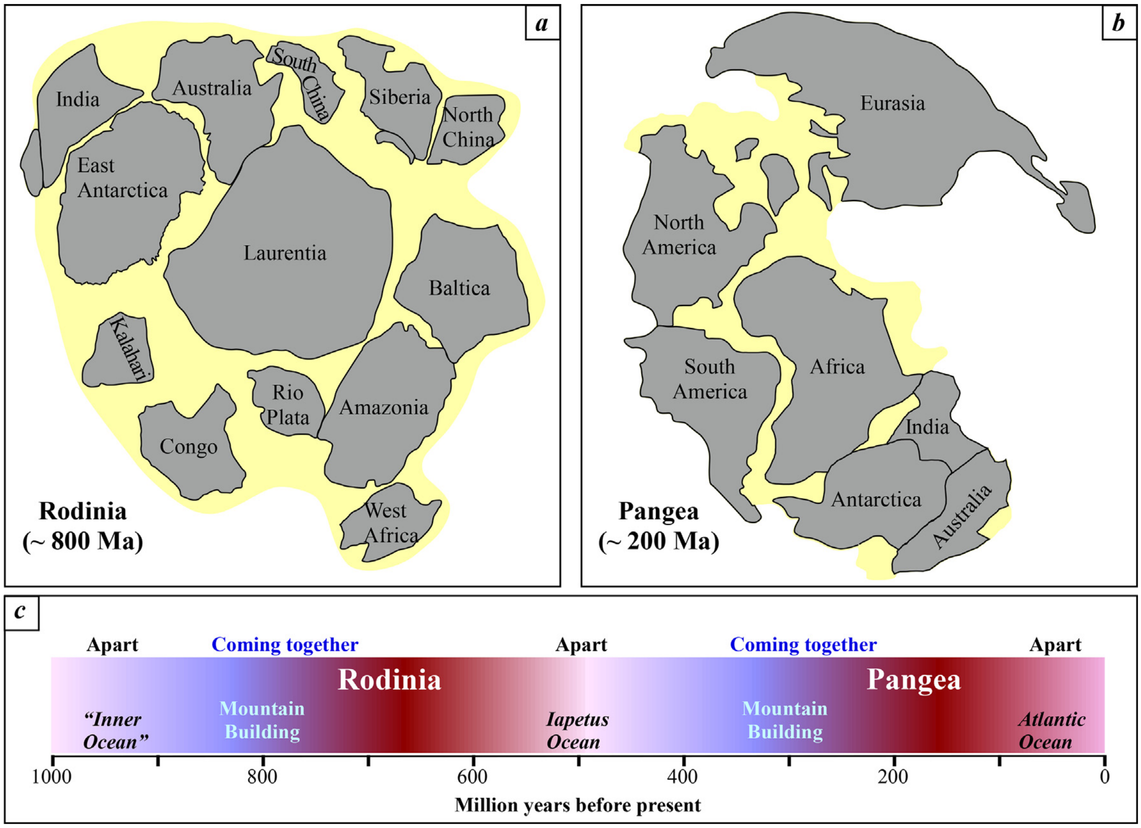

Fig. 1. Schematic illustration of the two supercontinents Rodinia (*a*) and Pangea (*b*) in the geological history with relative timing given in *c*, simplified from Torsvik (2003), Wikipedia (Pangaea, https://en.wikipedia.org/wiki/Pangaea) and Wikimedia commons (https://commons.wikimedia.org/wiki/User:Hgrobe/platetectonics).

objective and readily understandable analysis on the likely driving mechanisms of plate tectonics and mantle plumes. This analysis leads to the conclusion that continental breakup is a straightforward consequence of plate tectonics without requiring mantle plumes. Mantle plumes, if needed, may be of help at the early rifting stage, but cannot lead to complete breakup, let alone to drive long distance dispersal of broken continents. In order to help readers to share my analysis, whether agree or disagree, I begin by illustrating the scientifically well-understood but not necessarily widely informed geological concepts and physical principles. The debate may continue, but I encourage enthusiastic debaters to consider the basic concepts and principles given in this objective analysis.

2. Heat loss drives earth processes

We often say that Earth's internal heat powers most geological processes, but precisely speaking the powering mechanism is Earth's *heat loss to surface*. This can be understood because relative to Earth's deep interiors, the shallow mantle loses heat readily, making the shallow mantle material cool, dense, and tend to sink due to gravity, while displacing the warm deep mantle material to rise due to thermal buoyancy, forming the classic mantle convection current circuit proposed by Arthur Holmes (Holmes, 1931). Although this convection current picture is too simplistic and is likely incorrect as we understand today, it nevertheless correctly depicts the concept of thermal convection as the result of Earth's cooling.

Convection is a phenomenon of mass in motion driven by pressure difference. In the grand gravitational field in the Earth, the pressure difference is dominated by buoyancy contrast due to density contrast at any given depth. Both compositional difference and temperature difference can create density difference and thus buoyancy contrast, responsible for mantle convection on various scales. Thermal convection requires thermal boundary layers (TBLs) across which large temperature contrast exists. Our current understanding is that there are two thermal boundary layers in the Earth (Fig. 2). The top cold thermal boundary layer (TCTBL) is the lithospheric plates, which cools the mantle and drives plate tectonics. The basal hot thermal boundary layer (BHTBL) is at the core-mantle boundary, which cools the core and is responsible for mantle plumes (Davies & Richards, 1992; Davies, 1993, 1999; Bercovici et al., 2000; Niu, 2005a, 2014, 2018). Some may consider the 660-km seismic discontinuity (i.e., 600-D), which is the lower-upper mantle boundary, as a TBL, but this is unlikely because heat transfer (or thermal "homogenization") across the 660-D is effectively accomplished through "convective" processes as globally evidenced by penetration of many subducting slabs into the lower mantle. Likewise, mass-balance requires the same amount of lower mantle material rising into the upper mantle (see Niu, 2018). Hence, the 660-D is not a TBL. Stagnation of slabs in the mantle transition zone above the 660-D in some places may prevent localized mass and heat exchange across these slabs, but they are not permanent features and they are certainly not heat source, but heat sink (Fig. 2; see Niu et al., 2017). Hence, the 660-D is not a TBL to generate anomalously hot plumes.

The above concepts are illustrated in Fig. 2. In this context, we should note that the Earth has been cooling over its history and will continue to cool for some long time. Hence, plate tectonics will continue to operate. The total heat loss of the Earth to the surface is estimated to be ~47 TW (Davies and Davies, 2010), coming from primordial heat associated with Earth's assembly and radiogenic heat resulting from radioactive decay (^{40}K-^{235}U-^{238}U-^{232}Th) although large uncertainty exists on relative importance of each of the two sources and especially radiogenic heat contribution because of not-yet-fully-constrained Th/U in the deep mantle (McDonough and Sun, 1995; Šrámek

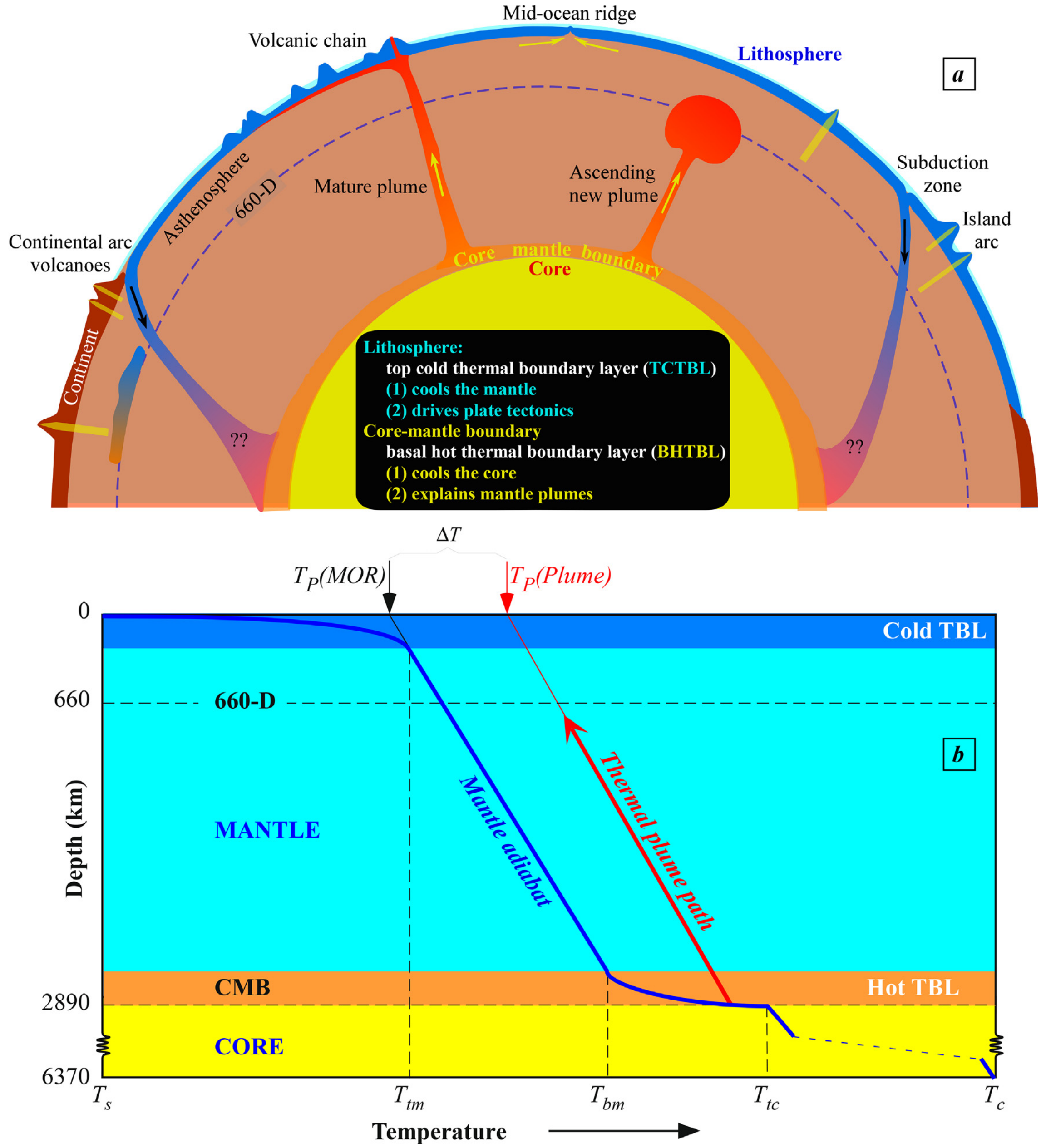

Fig. 2. *a* An across-earth cartoon simplified from various forms in the literature to illustrate the state-of-the-art conceptual understanding of plate tectonics theory and mantle plume hypothesis. The solid earth dynamics is driven by the two thermal boundary layers as illustrated in *b*. The top cold thermal boundary layer (TCTBL), which is the lithospheric plates, cools the mantle and drives plate tectonics. The basal hot thermal boundary layer (BHTBL), which is at the core-mantle boundary, cools the core and is responsible for mantle plumes (Davies & Richards, 1992; Davies, 1993, 1999; Niu, 2005a, 2014).

et al., 2013; Wipperfurth et al., 2018). The ~47 TW heat loss of the Earth is rather small, ~ 0.03% of Earth's total energy budget at the surface, which is dominated by the 173,000 TW of incoming solar radiation (e.g., Archer, 2011). The latter is, on average and over a long term, balanced out at the top of the atmosphere through reflection of sunlight and emission of infrared radiation (e.g., Loeb et al., 2009), but its significance on Earth's surface geology has been known to be important. This will not be discussed here.

3. Plate tectonics and mantle cooling

The ocean crust forms at ocean ridges as the underlying asthenosphere rises in response to plate separation and undergoes decompression melting (e.g., McKenzie & Bickle, 1988). The basaltic melts so produced, when extracted, build the ocean crust with the peridotitic residues left in the mantle, accreting new growth to oceanic lithospheric plates (e.g., Niu, 1997). The movement of these plates, their subsidence and thickening with time by thermal contraction, and their eventual recycling into the Earth's deep interior through subduction zones provide an efficient mechanism to cool the mantle, which is how plate tectonics works, and is also understood as the primary driving force for thermal convection of the mantle (e.g., Forsyth & Uyeda, 1975; Parsons & McKenzie, 1978; Davies & Richards, 1992; Stein and Stein, 1992; Niu & Green, 2018). While this is physically well understood, different views still exist when discussing actual forces that drive seafloor spreading and plate tectonics largely influenced by old textbooks as pointed out by Niu (2014). In fact, the observational data by Forsyth and Uyeda (1975) are adequately informative although these data have not been fully appreciated. I plot these data in Fig. 3 to illustrate the significance of these data in terms of the probable major/

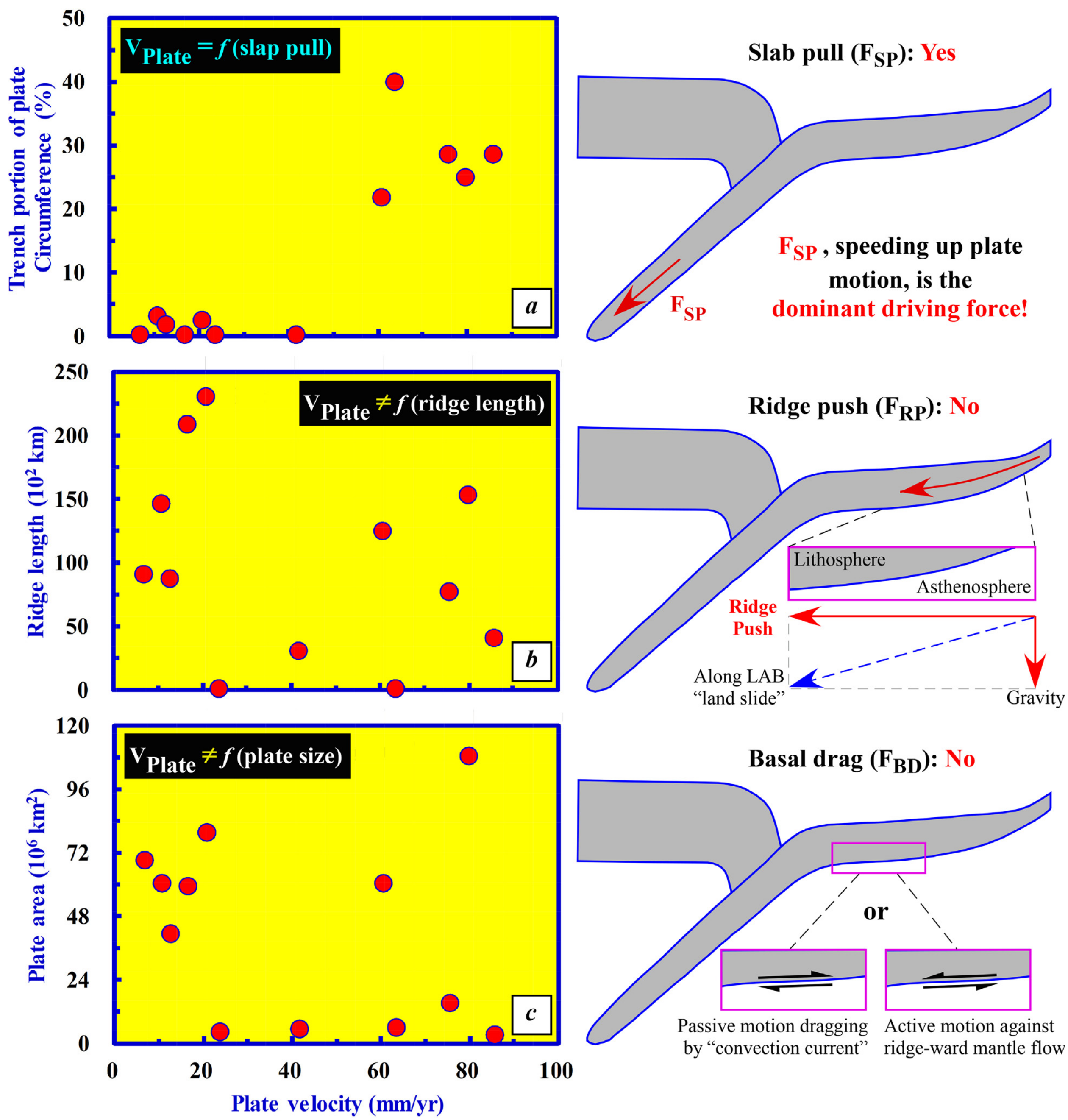

Fig. 3. *a–c* plots of the data by Forsyth & Uyeda (1975) to show that the average absolute velocity of the then recognized 12 plates (from left to right: Eurasia, North America, South America, Antarctica, Africa, Caribbean, Arabia, India-Australia, Philippines, Nazca, Pacific and Cocos) correlates well with the trench portion of a plate circumference (*a*), but is independent of ridge length (*b*) and plate size (*c*). *a* is used to argue that slab pull due to gravity is the primary force driving plate motion (F_{SP}). The plate velocity data have been revised since then (e.g., DeMets et al., 1990), but the co-variation plots *a-c* remain essentially unchanged. Cartoons on the right are my interpretations to show that ridge push (F_{RP}) and basal drag (F_{BD}), which, considered two other important forces, are in fact unimportant or less important if any for plate motion.

primary forces that may drive plate motion and plate tectonics, i.e., the slab pull (F_{SP}), ridge push (F_{RP}) and plate basal drag (F_{BD}). The significance of Fig. 3a is better appreciated, but the significance of Fig. 3b-c is not as discussed below.

3.1. Slab pull (F_{SP}) into subduction zones drives seafloor spreading and plate tectonics

Fig. 3a shows that the average absolute velocity of the then recognized 12 plates correlates well with the trench portion of a plate circumference. This correlation has been used to argue that *Slab Pull* (F_{SP}) due to gravity into subduction zone is the primary driving force for plate motion, which has been verified subsequently by many observations (e.g., Zoback et al., 1989; Zoback, 1992), quantitative modeling (e.g., Davies and Richards, 1992; Bercovici et al., 2000) and the demonstration that ocean ridges are passive features (e.g., McKenzie and Bickle, 1988) in response to seafloor spreading ultimately caused by slab pull as shown schematically on the right of Fig. 3a.

Despite the consensus above, we also note different views on what may drive plate motions, including the ideas of "eclogite engine" (Anderson, 2007) developed on the basis of eclogite sinking as a

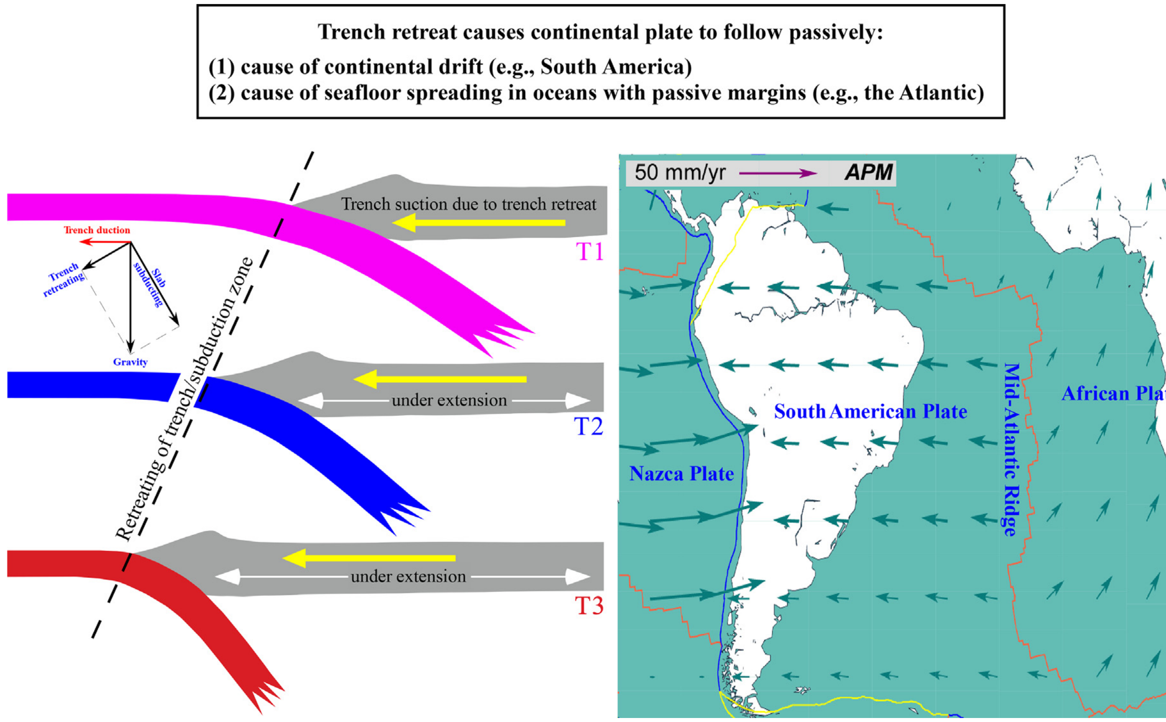

Fig. 4. *Left* Cartoon illustrating that trench retreat is the very cause of continental drift (modified from Niu, 2014). Under gravity, the subducting slab not only rolls back, but its bending hinge necessarily moves seawards, which is described as "trench retreat", hence the subduction-zone retreat. The dashed line indicates the newer position of the trench/subduction zone with time: T1 → T2 → T3. Consequently, the overriding continental plate passively follows the retreating trench, which is the action of continental drift towards left. This concept is demonstrated, on the *right*, by the eastward subduction of the Nazca Plate beneath the South American continent, westward trench retreat, westward continental drift of South America, and hence the seafloor spreading and the growth of the Atlantic Ocean (using the absolute plate motion reference: http://jules.unavco.org/Voyager/GEM_GSRM).

potential driving force (Holmes, 1931), "magma engine" (Sun, 2019), "six geospheric poles" (Li et al., 2019a,b) and perhaps many others, but the physical and geological validity and rigor of these ideas need comprehensive testing. At the time of this writing, I accept the theory of plate tectonics as we understand today including the driving mechanisms because this theory has undergone hot debate and scrutiny of over a century, including the ~60-year "continental drift" debate and over 50-year improvements since its acceptance (e.g., Wilson, 1963a,b, 1965, 1966; McKenzie & Parker, 1967; Sykes, 1967; Morgan, 1968; Isacks & Oliver, 1968; Le Pichon, 1968). Some raise doubt about slab-pull being the primary driving force because, for example, the India-Asia convergence has continued since the collision some ~55 million years ago without slab-pull, but this apparent "puzzle" in fact supports the understanding that subducting slab-pull is indeed the primary driving force for plate motion and plate tectonics. The continued India-Asia convergence since the collision has been actually 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 (Niu, 2014, 2020).

In this context, I may emphasize that it is my long-held view that geological research all ends up with models. Multiple models or multiple hypotheses are "intermediate ideas" towards the unifying theory. A new model is needed if and only if existing models do not work. That is, representing the Earth Science revolution, the plate tectonics theory explains much of the global geology on all scales at least since the Proterozoic although its full efficacies remain to be further explored (Niu, 2014, 2002). Hence, I do not see the need of any other "theories" as elegant and powerful as plate tectonics in the foreseeable future, but continue to (1) better understand this theory, (2) explore its efficacies, and (3) improve its power of further predictions.

3.2. *Ridge push (F_{RP}) is not a primary force driving seafloor spreading*

As illustrated in the cartoon on the right of Fig. 3b, ridge push (F_{RP}) is essentially the "land slide" of the young (< 70 Ma) lithosphere along the lithosphere-asthenosphere boundary (LAB). F_{RP} has been considered by many to be primary force driving seafloor spreading and plate motion. If so, the plate velocity should be proportional to ridge length, but this is not observed (Fig. 3b). Hence, F_{RP} push is not the primary driving force for plate motion although it is not negligible (about one order of magnitude less than F_{SP} (Turcotte & Schubert, 2002; Niu, 2014).

3.3. *Plate basal drag (F_{BD}) contributes little to plate motion*

Shown in the cartoon on the right of Fig. 3c is the idea of plate basal drag force (F_{BD}), which concerns the nature of coupling at the LAB (see Niu & Hékinian, 2004). The traditional view is that the plate motion is passively dragged by the "convection current" in the asthenosphere (e.g., the Arthur Homes "convection current circuit"; see above), which has been proven to be incorrect yet remains misguiding in many textbooks. If plate motion is driven by F_{SP} (see above), then there would be shear resistance at the LAB, and this resistance would increase with increasing the size of the plate (the size of the basal contact area of the plate at the LAB). If this is true, the plate velocity should decrease with increasing plate size, but this is not observed as there is no inverse correlation (Fig. 3c). In fact, the resistance at the LAB is minimal because the LAB is a petrological phase boundary (Niu & Green, 2018) and there is a melt rich layer close beneath the LAB atop the asthenosphere (Niu & O'Hara, 2009; Kawakatsu et al., 2009).

3.4. Trench retreat drives the Atlantic-type seafloor spreading and continental drift

The above analysis demonstrates our current understanding that subducting slab pull is the primary force driving seafloor spreading and plate tectonics. This is straightforward for the Pacific-type seafloor spreading because of the active seafloor subduction and slab pull in the western, northern and eastern Pacific, but it is not obvious what may cause the seafloor spreading in ocean basis with passive continental margins without subduction zones like the Atlantic. The answer is straightforward because of trench retreat in the Pacific (Niu, 2014). Fig. 4 shows the subduction of the Nazca plate towards beneath the South American continent. Under gravity, the subducting slab will necessarily roll back (slab getting steeper from T1 to T3), but what is far more important is the trench retreat (Fig. 4; Niu, 2014).

The trench retreat causes the overriding South American continental plate to follow passively and drift towards west (Fig. 4). That is, the very mechanism that drives continental drift is its passive response to trench retreat in ocean basins with subduction zones like the Pacific (Fig. 4). The eastern Eurasian continent has drifted towards east for over 2000 km since the Cenozoic, which is also a consequence of western Pacific trench retreat towards east (Niu, 2014; Niu et al., 2015). We should also note that the South American plate is a composite "continent + ocean" plate, and the South American continental drift in response to the trench retreat is in fact the very mechanism that drives the Atlantic-type seafloor spreading (Niu, 2014).

We can thus conclude that (1) slab pull drives the Pacific-type seafloor spreading; (2) continental drift and Atlantic-type seafloor spreading are passive response to trench retreat, as reiterated in Fig. 5 using the plate tectonic map of the southern oceans and continental masses.

Fig. 5 shows, in an absolute plate motion framework, the Antarctic plate essentially stands still because it has passive continental margins all around and is surrounded by ridges with all other plates beyond these ridges moving away from it directly and indirectly towards distal subduction zones. This map demonstrates in simple clarity that seafloor spreading, and continental drift/dispersal all require subduction zones. That is, *continental breakup and dispersal cannot happen without plate tectonics that is driven by seafloor subduction.*

4. Mantle plumes and core cooling (?)

The mantle plume hypothesis arose from the need to explain magmatism occurring in plate interiors such as the Hawaii volcanism that cannot be explained by the plate tectonics theory. Wilson (1963) first called the intraplate volcanoes like Hawaii as "hotspots" with a relatively fixed deep source, deeper than and thus unaffected by the moving Pacific plate. Morgan (1971) proposed further that the hotspots are surface expressions of thermal mantle plumes coming from the core mantle boundary (CMB). The mantle plume hypothesis has since been widely accepted to explain intraplate magmatism, in particular since the experimental (e.g., Campbell & Griffiths, 1990) and numerical (Griffiths & Campbell, 1990) simulations, and the recognition of large igneous provinces (LIPs) as the products of giant plume heads initiated at the CMB and accreted during ascent (see Figs. 2, 6; Duncan & Richards, 1991; Coffin & Eldholm, 1994). The plume-produced LIPs are oceanic plateaus in ocean basins and flood basalts on land. We should note, however, that a great debate continues on whether mantle plumes indeed exist as a result of Earth's cooling or whether their existence is purely required for convenience in explaining certain Earth phenomena (Anderson, 1994, 2004; Foulger & Natland, 2003; Niu, 2005a; Davies, 2005; Foulger, 2005, 2010; Campbell, 2005; Campbell & Davies, 2006). With the hope of settling this debate, Niu et al. (2017) proposed that the effective way to test the mantle plume hypothesis is to find out the makeup of the Kamchatka-Okhotsk Sea basement by drilling at ideal sites. This is because if a mantle plume is indeed originated from the CMB as proposed, a giant plume head is required to carry the material from the deep mantle to the surface (Fig. 6). However, the classic Hawaiian mantle plume does not seem to have a genetically associated plume head product such as a LIP. There is the high probability that the Kamchatka-Okhotsk Sea basement may prove to be the Hawaiian plume head product (Niu et al., 2003). It is worth to mention this debate here, but we focus below on the basic assumptions and physical foundation of the mantle plume hypothesis so as to informatively assess whether mantle plumes may be essential in causing supercontinent breakup and dispersal.

4.1. Mantle plume hypothesis and its predictive efficacies

Campbell (2005, 2007) summarized the key elements of the mantle plume hypothesis. Mantle plumes are columns of hot, solid material that originate from the CMB (Figs. 2, 6a–c). Laboratory and numerical models (Fig. 6d–e) replicating conditions appropriate to the mantle show that mantle plumes have a regular and predictable shape that allows predictions: new mantle plumes consist of a large head, 1000 km in diameter, followed by a narrower tail (Fig. 6). Initial eruption of basalt from a plume head should be preceded by ~1000 m of domal uplift (Fig. 6f). High-temperature magmas are expected to dominate the first eruptive products of a new plume and should be concentrated near the center of the volcanic province (Fig. 7). Decompression melting of the plume heads produces LIPs with thick basaltic crust and thickened lithospheric mantle residues (Fig. 6a–b; Niu et al., 2003, 2017), and the sustained material supply and decompression melting produces and leaves volcanic chains such as the Hawaiian-Emperor seamounts chains in the Pacific if the plate is moving fast relative to the more fixed plume source (Fig. 6a–c).

Fig. 7 shows three representative scenarios perceived by the mantle plume community to take place when the rising plume head impinges the continental lithosphere. In addition to the flattening and decompression melting of the plume head and complexities of magmatism (e.g., CMB derived plume melts, plume melts of entrained mantle materials, crustal extension, crustal melting and assimilation etc.), Fig. 7c (Campbell, 2007) emphasizes crustal doming and uplift, continental breakup, opening of a new ocean basin and volumetrically significant flood basalts (e.g., SWDRs) well exposed on both sides of the North Atlantic passive margins (e.g., East Greenland and British Tertiary basaltic province) interpreted to be associated with the ancestral Iceland plume and the opening of the North Atlantic (White & McKenzie, 1989; Saunders et al., 1998; Larsen et al., 1999). Whether the Iceland plume triggered opening of the North Atlantic or the latter allowed the Iceland plume to surface has been debated (e.g., Saunders et al., 1998; Storey et al., 1992; White, 1992). This debate, together with some earlier views (Dewey and Burke, 1974; Nance et al., 1988), has led to the strong view on a global scale that continental breakup could indeed be caused by mantle plume heads and associated magmatism although further research is needed (Hill, 1991; Storey, 1995; Li et al., 1999, 2008; Condie, 2004, 2005). Superplumes derived from the CMB have been particularly favored as the ultimate cause of continental breakup (e.g., Condie, 2004, 2005; Zhong et al., 2007; Li & Zhong, 2009; Santosh, 2010; Nance et al., 2014; Zhang et al., 2018) because there appears to be a seismic low-velocity channel connecting the East African Rift with one of the large low shear wave velocity provinces (LLSVPs) at the base of the mantle (Romanowicz & Gung, 2002).

4.2. Can mantle plumes breakup supercontinents?

This is contentious as discussed above and is the very focus of this paper. The logical approach to addressing this issue is to examine well preserved and better studied LIPs in continental settings to assess their possible influence on continental breakup at the time of their emplacement regardless of whether their hotspot tails remain active or not. Examining the long list of hotspots and LIPs (e.g., Courtillot et al., 2003;

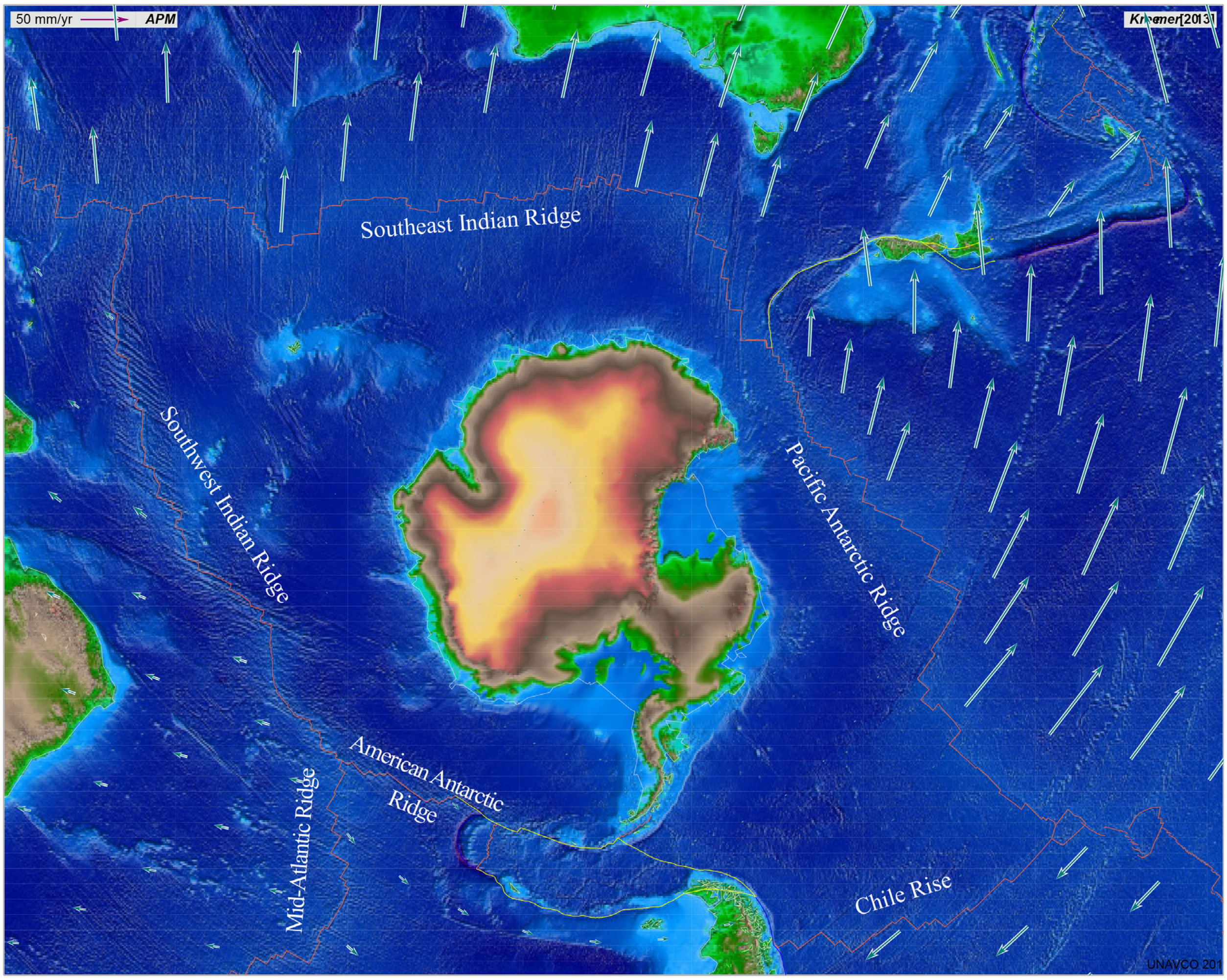

Fig. 5. Plate tectonics map of the southern oceans viewed from Antarctica (using the absolute plate motion reference: http://jules.unavco.org/Voyager/GEM_GSRM) to show that the Antarctic continental plate essentially stands still because it has passive continental margins all around and is surrounded by ridges with all other plates beyond these ridges moving away towards distal subduction zones.

Foulger, 2010; Ernst, 2014), one can find the following well preserved and better studied LIPs:

(1) The ~260 Ma LIP Emeishan is estimated to have an areal extent of ~0.25 million km^2 (Ernst, 2014), which recorded a prominent pre-eruption doming uplift (He et al., 2003), but did not cause continental breakup.
(2) The ~250 Ma LIP Siberian Traps is the largest known continental flood basalt province on Earth (Saunders & Reichow, 2009) with an areal extent in excess of ~7 million km^2 and an erupted volume of ~4 million km^3 (Ernst, 2014). If this LIP has indeed resulted from a rather large mantle plume head and its melting, we can conclude that this plume head had not caused breakup of the Eurasian continent.
(3) The ~200 Ma LIP CAMP (Central Atlantic Magmatic Province) has been recognized by contemporaneous dyke swarms widespread in the eastern North America, western Africa, northern South America and Europe, predicted to be coeval with the splitting of these continents (Hill, 1991; White & McKenzie, 1989). The magmatic output volume is difficult to estimate, but the areal distribution appears to be vast, ~10 million km^2 (Ernst, 2014). This would be a good case for a possible link between a mantle plume and continental breakup although the cause-and-effect relationship needs understanding.
(4) The ~130 Ma LIP Parana-Etendeka on both sides of the South Atlantic with a combined areal extent of ~2.0 million km^2 (Ernst, 2014) is thought to be the plume head product of the present-day active Tristan hotspot near the South mid-Atlantic Ridge (Storey, 1995). This would be another case for a possible link between a mantle plume and continental breakup, but the cause-and-effect relationship again needs understanding.
(5) The ~65 Ma LIP Deccan Trap (Fig. 7b) with an areal extent of ~1.8 million km^2 (Ernst, 2014) is thought to be the plume head product of the present-day active Reunion hotspot (White & McKenzie, 1989). At ~65 Ma, the sub-Indian continent was drifting on its way to collide with Eurasia in the next ~10 Myrs, so the stress condition may not permit continental breakup, although it is possible that the Reunion plume head may have separated the Seychelles from India (Storey, 1995).
(6) The ~60 Ma LIP NAIP (North Atlantic Igneous Province) is remarkable with volumetrically significant basalts cropping out on both sides of the North Atlantic (Greenland, northern Canada, and Scotland) with strong SWDRs at subsurface widely believed to be plume head product of the Iceland hotspot uniquely centered on the North Mid-Atlantic Ridge at present (e.g., White & McKenzie, 1989; Larsen et al., 1999; Storey et al., 2007). The coeval of the NAIP and the opening of the North Atlantic indeed points to a genetic link between the two.
(7) The ~30 Ma LIP Ethiopian Flood Basalt distributes over an areal extent of ~2 million km^2 and is thought to be the plume head product of the presently active Afar hotspot (Ernst, 2014). The Afar

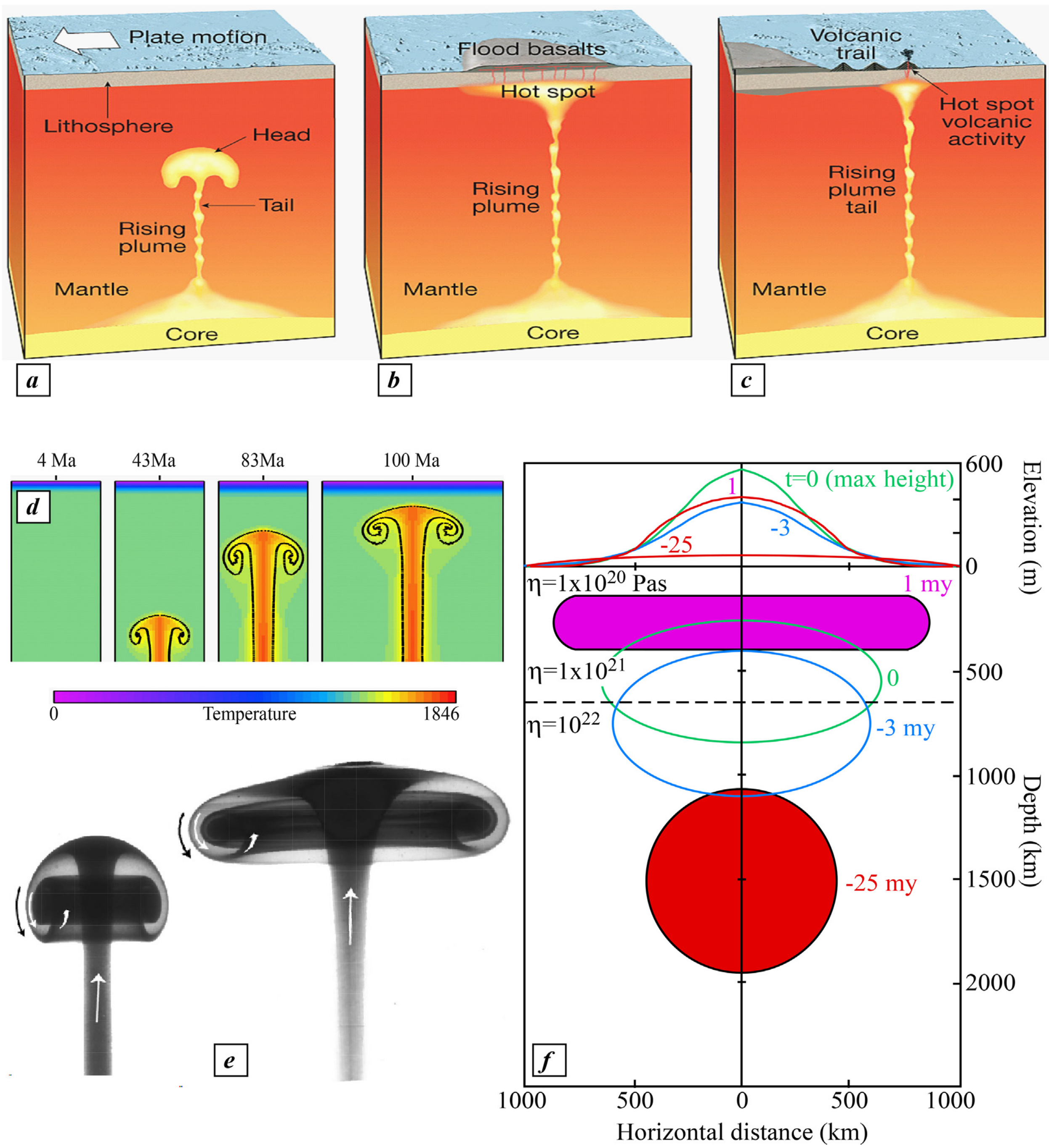

Fig. 6. Illustrations of the concept of mantle plumes, their initiation, growth and consequences. *a-c* illustrate the mantle plume hypothesis: plume initiation at the core mantle boundary, rise of the plume with the head being fed by the plume tail, decompression melting of the head producing a large igneous province (LIP; flood basalts on land and oceanic plateaus in ocean basins), and an age-progression volcanic trail (a seamount chain) left on the LIP-carrying moving plate (adapted from Tasa Graphic Arts, Inc). *d* shows theoretical simulation of thermal mantle plume development at the CMB, its rise/growth and the timeframe of ~100 Myrs required to reach the lithosphere (after Davies, 2005). *e* shows tank-syrup simulation of thermal plume development (after Campbell & Griffiths, 1990; Campbell, 2007). *f* is the quantification of *e*, showing the evolution of plume head during ascent from a sphere to a flattened disk towards the upper mantle while causing surface uplift of up to 600 m in its last ~25 Myrs (taken from Campbell, 2007).

hotspot/plume may have indeed caused the continental breakup and the formation of the triple junction shared by the Red Sea, Gulf of Aden and East African Rift (Schilling, 1973; Ebinger & Casey, 2001; Furman et al., 2004; Bastow et al., 2018).

(8) The ~16 Ma LIP Columbia River Basalt with an areal extent of ~0.24 million km^2 is considered as the plume head product of the presently active Yellowstone hotspot (Courtillot et al., 2003; Ernst, 2014). There is no indication that this plume would cause continental breakup.

The above analysis indicates explicitly that the inferred giant (e.g., represented by the Siberian LIP), large (e.g., the Deccan LIP), and small (e.g., the Emeishan and Columbia River LIPs) mantle plumes and plume heads did not cause continental breakup.

The Afar plume offers a good case in causing continental breakup such as the opening of the Red Sea, Gulf of Aden and East African Rift. The opening of the Red Sea and the northeastward movement of the Arabia plate at present may be driven by its subduction beneath and collision with the Eurasian continent, rather than driven by the Afar

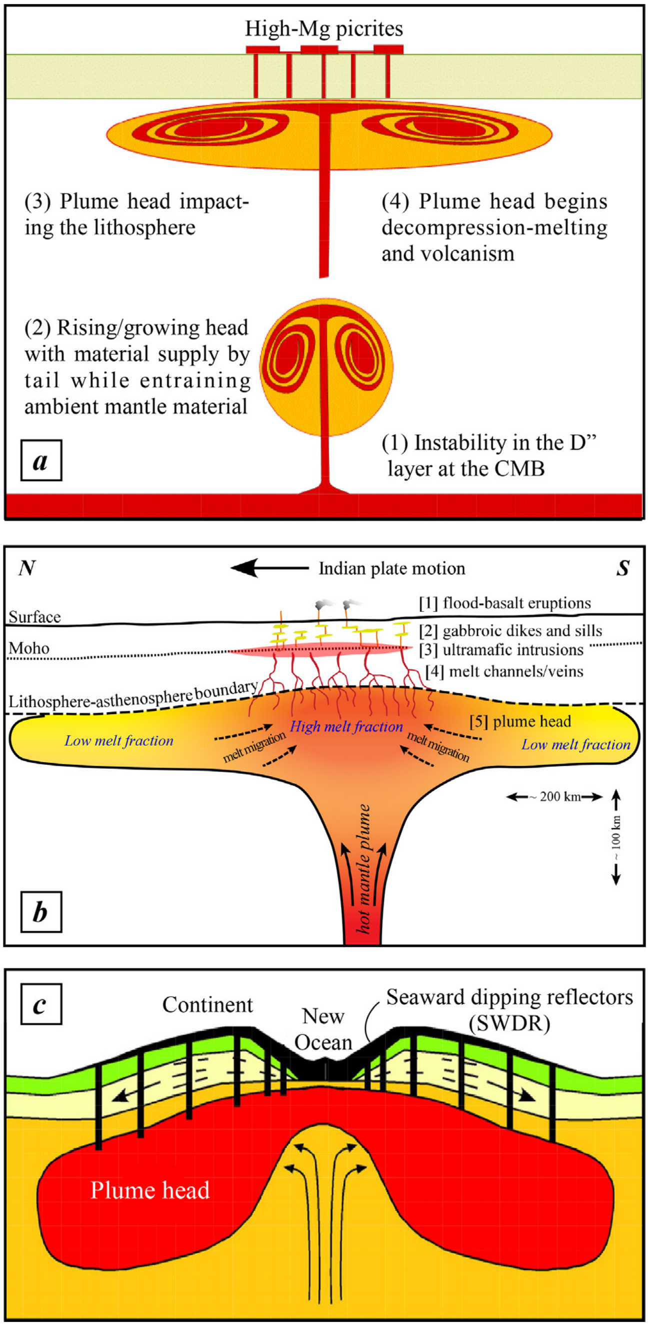

Fig. 7. Examples of three schematic variations of mantle plume heads upon impinging the continental lithosphere and the varying consequences. *a* Flattening and decompression melting (Saunders et al., 1992). *b* Reunion plume head impacting the north-drifting Indian continent and forming the Deccan LIP (Richards et al., 2015). *c* An advanced scenario (Campbell, 2007), where a plume head of ~1000 km diameter rises "beneath continental crust", flattens and melts by decompression to form a flood basalt province. "Arrival of the plume head also leads to uplift, which places the lithosphere under tension, as shown by the arrows." The final diameter of the flattened plume head is claimed to reach 2000–2500 km. "Tension introduced by the plume head can lead to run-away extension and the formation of a new ocean basin", drawing the hot plume head into the spreading center leading to the formation of thickened oceanic crust represented by the seaward dipping (seismic) reflectors (SWDRs) seen on both sides of the North Atlantic ocean genetically associated with the Iceland plume (White & McKenzie, 1989; Saunders et al., 1998; Larsen et al., 1999) and many other passive continental margins (Storey et al., 1992; Coffin & Eldholm, 1994; Ernst, 2014).

plume. A continental rift, such as the East African Rift, represents the earliest stage of an ocean basin formation as per the Wilson Cycle concept, yet there seems to be no prospect that this rift will evolve into an ocean basin because the African plate is surrounded by ocean ridges and the Central Indian Ridge will likely prevent the rifting from extending further apart to the east.

The coincidental happenings of LIP emplacement and opening of the central (~200 Ma CAMP), south (~130 Ma Parana-Etendeka) and north (~60 Ma NAIP) Atlantic do indicate a genetic link between the two. The question is thus to correctly understand the cause-and-effect relationship, as analyzed in the context of Gondwana breakup by Storey (1995). The locations of St Helena, Tristan, and Iceland plumes may contribute to approximately where and even when continental breakup may begin locally (Morgan, 1983;White & McKenzie, 1989; Hill, 1991; Storey, 1995), but complete breakup requires continental scale tension forces most likely driven by plate tectonics. For example, in an absolute plate motion framework, both Eurasian and African plates move very slowly (< ~5 mm/yr), but much of the growth of the Atlantic ocean and plate separation along the mid-Atlantic Ridge largely results from westward drift (~20–30 mm/yr) of Greenland, North American and South American plates because of trench retreat in the eastern Pacific (see Fig. 1 and discussion of Niu, 2014). This means that the full-scale opening of the Atlantic must have resulted from continental drift of American plates towards west. In response to the opening is the rifting, lithosphere thinning, decompression melting and the formation of volcanic passive margins over much of both sides of the Atlantic, around the African continent, and significant portions of the both eastern and western Australian continent and portion of the Antarctic.

All these, together with the fact that the giant mantle plume head inferred from the vast Siberian Traps did not cause breakup of the Eurasian continent, suggest that mantle plumes mostly do not cause continental breakup. That is, mantle plumes alone cannot cause complete continental breakup, let alone to drive long distant dispersal of fragmented continental masses, which has been the very heart of continental drift hypothesis debate, and this very debate has been finally settled because of the plate tectonics theory.

4.3. A widely overlooked difficulty of plume head melting in the context of continental breakup

Seismology has long informed us that the Erath's entire mantle is solid with no magmas detectable at any depth and on any scale. The volcanism occurs along global ocean ridges, above subduction zones and in isolated localities away from these plate boundaries in ocean basins and on land are all shallow phenomena where the physical conditions allow the solid mantle to partially melt. Apart from subduction settings where magmas form as the result of slab-dehydration induced mantle wedge melting, mantle melting elsewhere results from decompression when the adiabatically ($[dT/dP]_{ADIABA}$) upwelling asthenospheric mantle intersects the solidus (P_o; $[dT/dP]_{SOLIDUS} > [dT/dP]_{ADIABA}$) as shown in Fig. 8a (Niu, 2005b). Mantle compositional variation may slightly alter the solidus in this pressure-temperature space, but the solidus shown in Fig. 8a based on many experimental studies (McKenzie & Bickle, 1988) is adequately correct for the discussion here. The normal mantle beneath ocean ridges is considered relatively cool and has a potential temperature of $T_P = 1350\,°C$ (McKenzie et al., 2005; Niu et al., 2001), but mantle potential temperatures can be variably and significantly hotter with $T_P = 1550\,°C$ (Herzberg & O'Hara, 2002) for mantle plumes. For the sake of conservative discussion, we can assume a very hot mantle plume head with $T_P = 1600\,°C$ (Fig. 8a). As we understand, the hotter the mantle is, the deeper the upwelling mantle intersects the solidus to begin melting (P_o). The extent of melting (F) is proportional to the decompression interval between P_o (~140 km) and the depth of melting cessation P_f, which is the LAB (i.e., $F \propto P_o - P_f$; Fig. 8b).

Fig. 8b shows three scenarios of flattening mantle plume head

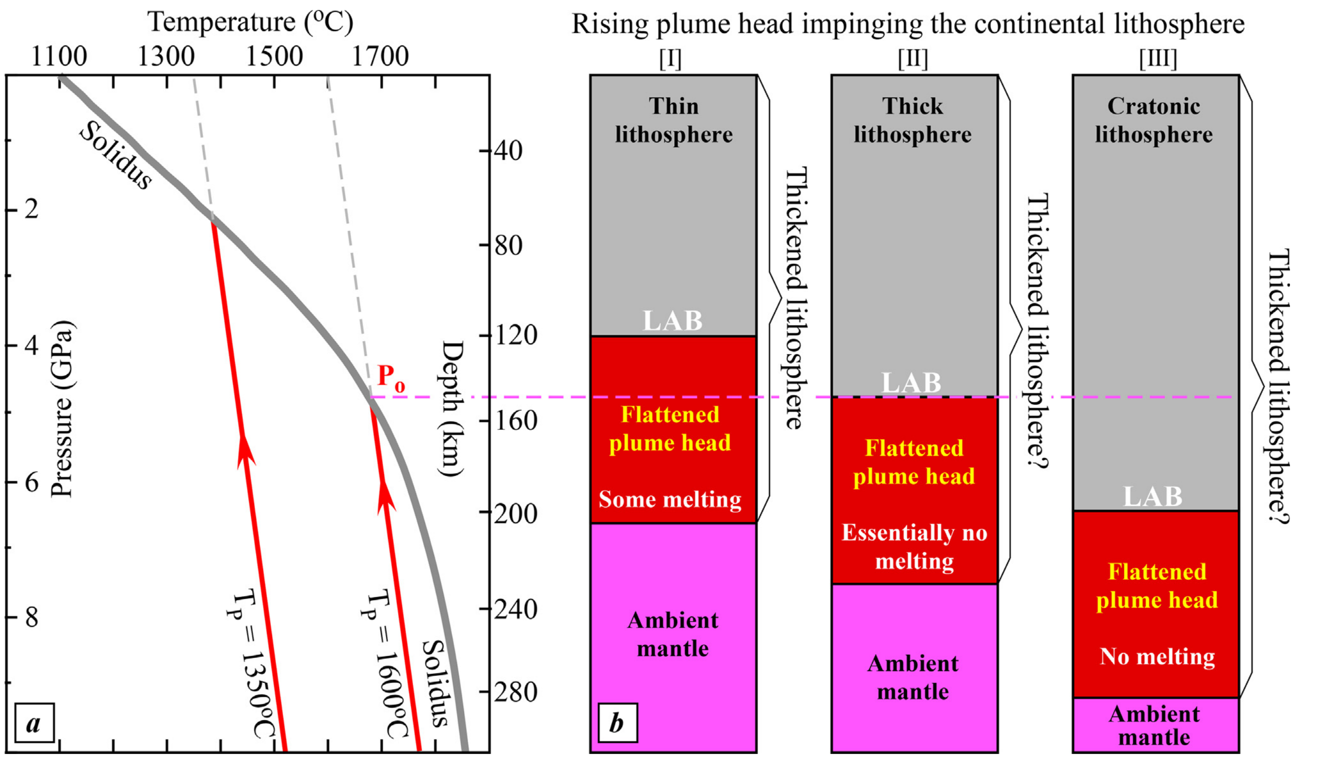

Fig. 8. *a* Showing in P-T space mantle solidus and adiabat (McKenzie & Bickle, 1988) for two scenarios with mantle potential temperature of T_P = 1600 °C probably excessively hot and hotter than most assumed mantle plumes of dynamic upwelling and T_P = 1350 °C appropriate for passive upwelling beneath ocean ridges for comparison. *b* Showing three scenarios of varying thickness of continental lithosphere when impacted by a rising mantle plume head. The key concepts are: (1) mantle melting takes place by decompression when adiabatically rising mantle plume head intersects the solidus at P_o ≈ 140 km; (2) melting begins in the asthenosphere at P_o, ceases to continue at P_f, the LAB (lithosphere-asthenosphere boundary) and cannot happen in the lithosphere; (3) a spherical plume head 1000 km across (R = 500 km) that flattens to a disk 2000 km across (r = 1000 km) when reaching the lithosphere (Fig. 6f; Campbell, 2007) will have a thickness of ~167 km (h = 4/3 * R^3/r^2); (4) To be conservative, the flattened lithosphere in *b* is only half of the thickness of ~84 km by using the scale in Fig. 7b (Richards et al., 2015); (5) whether melting actually occurs or not and to what extent strictly depends on the lithospheric thickness (Niu et al., 2011) as rigorously quantified (Watson & McKenzie, 1991; White & McKenzie, 1995); (6) No matter how hot the mantle plume head may be, melting cannot happen beneath the thickened lithosphere like scenarios [II] and [III], but can take place beneath the thin lithosphere like scenario [I]; (7) the extent of melting beneath the thin lithosphere (scenario [I]) is likely very low (no more than ~5%), and with H_2O-dominated volatiles entering the melt, the viscosity of the residual plume head becomes significantly elevated and becomes accreted new lithosphere, which thickens (vs. thins) the lithosphere from the prior ~120 km to ~200 km. Despite the uncertainties, this simple and objective analysis is informative and indicates that the effect of plume head arrival will make the lithosphere thickened, not thinned, against common perception let along to cause lithosphere breakup. (8) Because melting cannot take place beneath thickened lithosphere (scenarios [II] and [III]), the physical effect of plume heads on the existing lithosphere is limited, thus unlikely causing lithosphere breakup. Because of the hot plume head, H_2O-CO_2-rich low-degree (~1% or lower) melt may be produced, but such minute melt can metasomatize the overlying lithosphere, yet inadequate to produce LIPs. (9) Lithosphere uplift or doming (Fig. 6f) can take place, but this will not change the LAB depth without surface erosion (or exhumation). A maximum uplift and erosion of 600 m is rather small and even 2000 m is still too small to affect the LAB at great depths (~120 km, ~ 150 km, and ~200 km scenarios [I], [II] and [III]). (10) Hence, mantle plume heads would have very limited impact on the mature and thickened lithosphere without melting but can have large impact on thin or thinned lithosphere by melting with the extent of impact increasing with decreasing lithosphere thickness. (11) This suggests that the mantle plume head effect is best observed beneath thin or thinned lithosphere such as beneath prior between-craton sutures, especially extensional settings like continental rifts and spreading centers in ocean basins (Niu & Hékinian, 2004).

impinging the continental lithosphere of varying thickness. For a spherical plume head 1000 km across (R = 500 km; Fig. 6f) that flattens to a disk of 2000 km (r = 1000 km), it would have a thickness of 167 km. To be conservative for discussion, Fig. 8b only shows half of this thickness of ~84 km as shown in Fig. 7b (Richards et al., 2015). Analysis of Fig. 8 correctly tells us the following:

Scenario [I]: For a thin continental lithosphere of 120 km thick (i.e., LAB depth of 120 km), there would be about ~20 km ($P_o - P_f$) decompression and up to 5% melting. There are three important implications. (1) With such low extent of melting, incompatible elements and volatiles such as water would have entered the melt. Consequently, the "dry" melting residue becomes too viscous to flow, making the lithosphere thickened, at least 120 + 20 = ~ 140 km (If not up to 200 km), rather than thinned. It follows that mantle plume head melting will not weaken and break the continental lithosphere, but rather will make the lithosphere thicker and stronger. (2) Note that T_P = 1600 °C is likely exaggerated for the sake of conservative discussion. If T_P = 1550 °C or less, there would be little or no melting because P_o = ~120 km, which is the depth of the LAB. Therefore, there would be no melting products as LIPs. (3) The ~1000 m surface uplift, if any, will have negligible effect on mantle melting processes.

Scenario [II]: For a slightly thicker continental lithosphere of ~140 km with the LAB ≈ P_o, there will be no decompression melting, and thus no LIP basaltic magmatism. The lithosphere will not be thinned, if not thickened. Without the presence of melt, thermal erosion would have limited effect (Lavecchia et al., 2017) on the lithosphere through thermal conduction unless the lithospheric mantle had been previously metasomatized with materials of lower solidus (McKenzie & O'Nions, 1995; Niu & O'Hara, 2003; Niu, 2018).

Scenario [III]: For a thick cratonic lithosphere of ~200 km (if not thicker) with the LAB about 60 km deeper than the solidus P_o = 140 km, there is absolutely no plume head decompression melting at all, and thus no LIP basaltic magmatism. Hence, no matter how big and how hot the plume head may be, the cratonic lithosphere will be

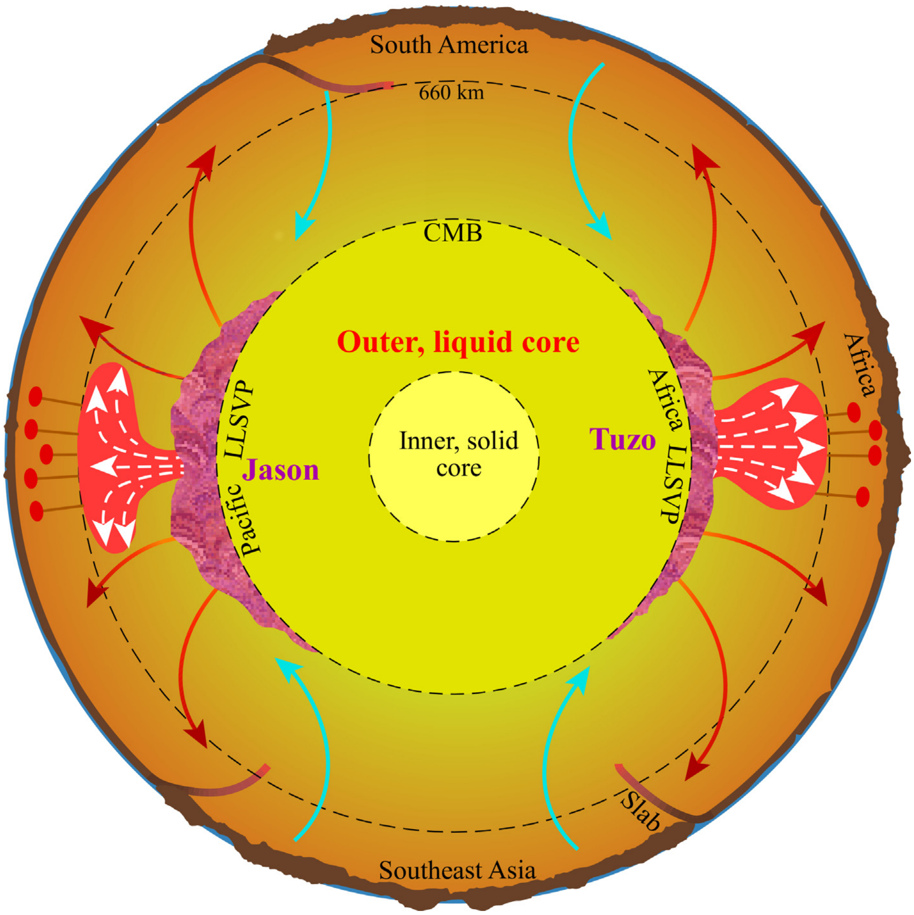

Fig. 9. Cartoon reconstructed from the literature (Courtillot et al., 2003; Torsvik et al., 2014; Romanowicz, 2017) to show the common perception of superplumes genetically associated with the two large low shear-wave velocity provinces (LLSVPs) at the base of the mantle beneath the Pacific and Africa (e.g., McNutt, 1998; Romanowicz and Gung, 2002; Courtillot et al., 2003; McNamara and Zhong, 2004; Condie, 2004; Thorne et al., 2004; Schmerr et al., 2010; Torsvik et al., 2014) although Burke and co-authors show that LIPs and mantle plume sites over the last ~300 Myrs are associated with edges of the LLSVPs (Burke & Torsvik, 2004; Burke et al., 2008; Torsvik et al., 2010, 2014). However, the LLSVPs are not simple thermal anomalies because they have sharp boundaries with, and greater density (~2–5%) than, the ambient mantle (Becker & Boschi, 2002; Ni et al., 2002; Ni & Helmberger, 2003; Wang & Wen, 2004; To et al., 2005; Ford et al., 2006; Garnero et al., 2007; Lau et al., 2017), indicating that they are too dense to rise as hot plume sources, but are more consistent with the subducted and stored ocean crust accumulated over earth's history (Niu et al., 2012; Niu, 2018) or ancient residual materials associated with core separation (Garnero et al., 2007; Hirose & Lay, 2008; Garnero et al., 2016). Hence, superplume sources do not exist and superplumes are a hypothetical concept with no evidence. To emphasize the stable nature of the two LLSVPs, Burke (2011) named the LLSVP beneath Africa as Tuzo (abbreviated from The Unmoved Zone Of Earth's deep mantle) in honor of Tuzo Wilson and the LLVSP beneath the Pacific as Jason (abbreviated from Just As Stable ON the opposite meridian) in honor of Jason Morgan.

largely intact.

The above analysis with illustrations (Fig. 8) tells us in simple clarity that decompression melting of mantle plume heads upon impinging the continental lithosphere is highly restricted, depending on the thickness and, of course, cohesion of the continental lithosphere. This can be elaborated below:

(1) No matter how hot a mantle plume head may be, melting cannot happen beneath typical continental lithosphere with thickness > 140 km if T_P = 1600 °C or > 130 km T_P = 1550 °C (Fig. 8).
(2) Thermal erosion of the existing lithosphere by hot mantle plume head is possible, but likely highly restricted, depending on the abundances and distribution of the prior enriched metasomatic dykes and veins with lower solidus in the lithosphere, whose melt so produced may or may not surface, depending on the quantity, but cannot develop into an LIP.
(3) A plume head may produce volumetrically tiny CO_2-H_2O-rich melt, which, if extracted, can metasomatize the overlaying lithosphere to form metasomatic dykes or veins or absorbed.
(4) It is possible, in any of the three scenarios above (Fig. 8b: I, II and III), that a plume head may indeed cause surface uplift and localized rifting and extension, but the latter cannot develop into an ocean basin without horizontal forces such as seafloor spreading and trench retreat that pull apart and move away the rifted continental mass fragments (Figs. 4, 5).
(5) Because decompression melting of mantle plume heads cannot happen beneath thick lithosphere (> 130 km), let alone beneath thickened cratons (Fig. 8) as demonstrated (e.g., Watson & McKenzie, 1991; White & McKenzie, 1995), we can thus reason that all the known LIPs, if they are indeed decompression melting products of mantle plume heads, must indicate thin or thinned continental lithosphere at the time of the LIP magmatism.
(6) It follows that if mantle plumes do contribute to continental breakup, the loci of continental breakup must be existing zones of weakness of prior continental suture zones, which seems to be the case as shown in recent studies (McKenzie et al., 2015; Whalen et al., 2015; Petersen and Schiffer, 2016). The fact that many cratonic cores considered to be major constituents of the ~1600 Ma supercontinent Columbia (e.g., Amazonia, East Antarctica, West Africa, West Australia, Baltica, North China, South China, India, Greenland, Kalahari, Siberia etc.; see Rogers & Santosh, 2002; Zhao et al., 2004, 2018) have been identified in the ~800 Ma supercontinent Rodinia, in the ~250 Ma Pangea, and still have their identities at present confirms this reasoning.
(7) Hence, volumetrically significant basalts over much of both sides of the Atlantic margins, around the African continent, around the Greenland, India, west and east Australia all result from rifting and significant extension induced decompression melting beneath the thinned continental lithosphere.
(8) This analysis leads to the suggestion that the opening of the Atlantic may have allowed the existing mantle plumes to surface. This provides a simple and logical solution to the chicken-and-egg debate on whether the Iceland Plume triggered the opening of the North Atlantic or the opposite. The ODP Legs 152 (1993) and 163 (1995), in which I was a participant, attempted but failed to resolve the debate by drilling the seafloor between Iceland and Greenland.

4.4. Can a superplume cause continental breakup? What is a superplume, what is its origin? Does it exist?

Larson (1991a,b) was the first to invoke superplume or superplumes to explain the globally significant volcanic output, long period of geomagnetic quiescence, increased surface temperature, deposition of black shales, oil generation and eustatic sea level in the mid-Cretaceous (124–83 Ma). He continued that these superplumes originated just above the core-mantle boundary, significantly increased convection in the outer core, and stopped the magnetic field reversal process for 41 Myrs. There have been at least 101 papers published since then with superplume/s appearing in the titles to discuss the origins of superplumes and their geological consequences, including supercontinent breakup (Condie, 2000, 2004; Li et al., 2003, 2006; Maruyama et al., 2007; Li & Zhong, 2009; Yukio, 2009).

By accepting that mantle plumes are initiated at the CMB, it is logical to reason that superplumes must also originate at the CMB as originally proposed (Larson, 1991b). The evidence for superplumes comes from the two large low shear-wave velocity provinces (LLSVPs) at the base of the mantle beneath the Pacific and Africa (see Fig. 9; e.g., Romanowicz & Gung, 2002; Courtillot et al., 2003; McNamara and Zhong, 2004; Condie, 2004; Thorne et al., 2004; Schmerr et al., 2010; Torsvik et al., 2014), corresponding to the Pacific superswell and the higher-than-expected elevation of the African continent (e.g., McNutt, 1998; Burke, 2011). The slow shear wave velocity at the base of the mantle above the core would be consistent with the LLSVPs being hot thermal anomalies and they should also have low viscosity because low shear wave speed means low shear modulus (μ; $Vs = (\mu/\rho)^{1/2}$) and low μ means low viscosity (Niu & Hékinian, 2004). So, it is logical to suspect the LLSVPs to be sources of superplumes. However, seismic velocity and waveform analysis indicate that the LLSVPs have sharp boundaries with, and higher density (~2–5%) than, the surrounding mantle (Becker & Boschi, 2002; Ni et al., 2002; Ni & Helmberger, 2003; Wang & Wen, 2004; To et al., 2005; Ford et al., 2006; Garnero et al., 2007; Sun et al., 2007). The recent tidal tomography study (Lau et al., 2017) confirms the results of seismic tomography that the LLSVPs are chemical anomalies denser than the ambient mantle, but argues for only 0.5% denser, which is less than previous estimates, suggesting large uncertainties exist for further improvements. The sharp boundaries mean that the LLSVPs are unlikely to be simple thermal anomalies because thermal conduction/diffusion would make the boundaries gradual, not sharp. Also, the higher densities mean that the LLSVPs are compositionally different from the ambient mantle. Hence, the LLSVPs are compositional anomalies, whose origin remain to be understood. Some studies suggest the possibility that the LLSVPs could be Fe-rich materials from the core or residues of the core separation in Earth's early history because of the high density (e.g., Garnero et al., 2007; Hirose & Lay, 2008; Garnero et al., 2016; Lau et al., 2017), but how to test this hypothesis may be forever challenging (Niu, 2018). Based on studies of global seafloor petrogenesis, Niu and co-authors (Niu et al., 2012; Niu, 2018) argue that the LLSVPs are most consistent with piles of subducted ocean crust accumulated over Earth's history, which explains why the LLSVPs have sharp boundaries with, and greater densities than, the surrounding mantle under lower mantle conditions. The LLSVPs of subducted ocean crust origin act as thermal insulators only to allow the core heating concentrated at edges of the LLSVPs, which explains why most LIPs over the last 300 Myrs were associated with edges of the LLSVPs (Burke et al., 2008). Furthermore, the antipodal positioning of the two LLSVPs represents the optimal moment of inertia, which explains why the LLSVPs are stable in the spinning Earth (Niu, 2018; Dziewonski et al., 2010).

The most important point here is that the LLVPS are not simple thermal anomalies, but compositional anomalies. It is possible that they could be warmer or hotter than the ambience because subducted ocean crust (OC; Niu & O'Hara, 2003) has higher heat-producing element (e.g., K, Th and U) abundances than the primitive mantle (PM; Sun & McDonough, 1989) with $K_{OC/PM} = \sim 3.29$, $Th_{OC/PM} = \sim 1.18$ and $U_{OC/PM} = \sim 2.43$. Nevertheless, because they have significantly higher densities than the ambient mantle, the LLSVPs cannot rise and cannot be the widely perceived plume materials. Hence, LLSVPs are not superplumes or sources of superplumes. Superplumes do not exist in Earth.

5. Summary

(1) Continental breakup and dispersal (drift) are straightforward consequence of plate tectonics without needing mantle plumes.
(2) Mantle plumes could facilitate continental rifting as many believe, but tectonic evolution from rifting to complete breakup requires that the rifted/broken continental fragments be pulled away or moved far apart. The latter is the conceptually familiar phenomenon or process of "continental drift", which can only be driven by plate tectonics.
(3) The way in which plate tectonics drives continental drift is the passive movement of continents in response to trench retreat (i.e., seaward migration of subduction zones under gravity). This is well illustrated in simple clarity by the present-day shrinking of the Pacific Ocean basin because of the trench retreat in eastern, western and northern Pacific. The eastward trench retreat of the western Pacific subduction zones has induced eastern Eurasian continent to drift eastward for over 2000 km since the Cenozoic. The westward trench retreat of the eastern Pacific subduction of the Explorer, Juan de Fuca and Gorda plates (remnants of the larger Farallon plate) in the north and of the Nazca plate in the south has caused the North and South American continents to drift westward.
(4) The westward drift of the North and South American continents has in fact been the very driving mechanism for the growth of the Atlantic Ocean basin although its timing of opening seems to be coeval with the recognized mantle plumes, i.e., the opening of the central Atlantic at ~200 Ma represented by the LIP CAMP, the South Atlantic at ~130 Ma represented by the LIP Parana-Etendeka and the North Atlantic at ~60 Ma represented by the LIP NAIP.
(5) The aforementioned three plumes could be argued to have caused the continental rifting, but we cannot avoid the conclusion that the continued growth of the Atlantic would not happen without westward drift of American continents as a passive response to westward trench retreat in the eastern Pacific as elaborated above.
(6) The coincidence of the Atlantic opening and the three plume activities is consistent with the lithosphere thinning that allows potential plumes to rise and "surface". This is because our understanding of these mantle plumes is entirely based on LIPs that are thought to decompression melting products of mantle plume heads, which cannot melt to produce LIPs without thin or thinned overlying continental lithosphere.
(7) Hence, mantle plumes, no matter how hot and how big a plume head may be, cannot melt by decompression to produce LIPs beneath thickened cratonic lithosphere. That is., continental rifting and breakup cannot take place within thickened and physically coherent cartons by mantle plumes. On the other hand, cratonic lithosphere can be thinned and destructed through basal hydration weakening as was the case in eastern continental China in the Mesozoic (Niu, 2005b).
(8) Thus, LIPs genuinely reflect the prior thin or thinned continental lithosphere. It follows that if there are/were many more mantle plumes and plume heads beneath continents at present and probably also in Earth's history, only those arriving beneath thin or thinned lithosphere could be recognized through LIPs. This further means that it is the size, thickness and strength of the continental lithosphere that determines whether a mantle plume can surface and whether a mantle plume can break up the continents, not the other way around.
(9) Even if the pre-existing lithosphere is thin enough to allow decompression melting of the arriving mantle plume heads to produce LIPs, because the extent of melting is no more than ~5% with essentially all the volatiles extracted, the ~95% mass of

melting residues would become too viscus to flow, and thus resulting in thickened and accreted new continental lithosphere. That is, the effect of mantle plumes and mantle plume heads is not to thin and break, but rather to thicken and strengthen the continental lithosphere, contrary to the general perception.

(10) The fact that many cratonic cores considered to be major constituents of the ~1600 Ma supercontinent Columbia (e.g., Amazonia, East Antarctica, West Africa, West Australia, Baltica, North China, South China, India, Greenland, Kalahari, Siberia etc.) have been identified in the ~800 Ma supercontinent Rodinia, in the ~200 Pangea, and still have their identities at present means that continental breakup takes place along the prior zones of weakness such as sutures over Earth's history.

(11) It is worth to stress that the widely perceived superplumes initiated from the two LLSVPs at the base of the mantle beneath the Pacific and Africa do not exist. This is because they are compositional anomalies with sharp edges and greater density than the ambience. They are too dense to rise.

(12) The debate on the cause of continental breakup may continue, but I encourage enthusiastic debaters to consider the rigorous and objective analysis given here based on straightforward concepts and principles of geology and physics.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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I am honored to write this paper in commemoration of Professor Shu Sun for his dedication and significant scientific contributions to our science, and in expressing my gratitude to him for his encouragement and support of my effort in research on Chinese geology and in fulfilling my dream of building a state-of-the-art geology program at Lanzhou University and a modern geochemistry laboratory in the Institute of Oceanology in Qingdao. It is my pleasure to record in printed form a brief communication from him in response to my two papers concerning the continental rift origin of the Yellow Sea (Niu & Tang, 2016) and the exotic origin of the Chinese continental shelf (Niu et al., 2015): "*Yaoling, The similarity of the coastlines on both sides of the Yellow Sea once aroused my imagination that the Yellow Sea could be pulled apart, but I had to give up on this because I could not find evidence from my own specialty. Sanya, Hainan Island, has Middle Cambrian strata, which contain phosphorites and fossils similar to those in Australia and completely different from those in mainland China, which we paid attention to in the past but have never resolved it. Sun Shu*" (Email communication from Professor Shu Sun to Yaoling Niu on July 14, 2016).

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