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Role of Large Igneous Provinces in continental break-up varying from "Shirker" to "Producer"

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Traditionally, the emplacement of the Large Igneous Provinces (LIPs) is considered to have caused continental break-up. However, this does not always seem to be the case, as illustrated by, for example, the Siberian Traps, one of the most voluminous flood basalt events in Earth history, which was not followed by lithospheric rupture. Moreover, the classical model of purely active (plume-induced) rifting and continental break-up often fails to do justice to widely varying tectonic impacts of Phanerozoic LIPs. Here, we show that the role of the LIPs in rupture of the lithosphere ranges from initial dominance (e.g., Deccan LIP) to activation (e.g., Central Atlantic Magmatic Province, CAMP) or alignment (e.g., Afar LIP). A special case is the North Atlantic Igneous Province (NAIP), formed due to the "re-awakening" of the Iceland plume by the lateral propagation of the spreading ridge and the simultaneous approach of the plume conduit to adjacent segments of the thinner overlying lithosphere. The proposed new classification of LIPs may provide useful guidance for future research, particularly with respect to some inherent limitations of the common paradigm of purely passive continental break-up and the assumption of a direct link between internal mantle dynamics and the timing of near-surface magmatism.

Large Igneous Provinces (LIPs) are defined as large volumes of predominantly mafic rocks characterized by a high rate of magma accumulation and unrelated to plate-tectonic processes, i.e., formed far away from plate boundaries within intraplate tectonic environments[1–3]. Within continents, such a sudden occurrence of continental flood volcanism is usually preceded by a rapid uplift of the surface topography of 0.5–2 km within a few Myr[4,5]. Most commonly, both the transient dome-shaped surface uplift[6] and the subsequent intraplate magmatic activity[7] are attributed to mantle plumes[8], seismically detected thermal[9,10] or thermal–chemical[11,12] anomalies in the Earth's mantle[13,14]. Importantly, these upwelling structures are not limited to the classic ("primary") Morgan-type plumes[15] that rise from the mantle–core boundary (~2900 km) throughout the entire mantle but also include so-called "secondary" plumes[16] rooted in the upper-lower mantle transition zone (MTZ: ~410–660 km)[17]. Such small-scale anomalies in the upper mantle (also called "baby" plumes)[18] could originate from "primary" (super)plumes ponding at the 660 km phase change boundary[19] or be the result of deep dehydration of oceanic slabs stagnating in the lower part of the MTZ[20–22].

Although the formation of LIPs is by definition not causally linked to plate-tectonic processes, Precambrian records in southern Africa show that LIPs may occur during supercontinental assembly[23] through thermal blanketing beneath the growing continent[24] and without support from mantle plumes[25]. In contrast, most Phanerozoic plume-related LIPs are known to be associated with the break-up of continents and the subsequent opening of large oceanic basins. This is evidenced by the spatial and temporal correlation between the major continental flood basalts formed in the last 300 Myr and the different phases of fragmentation of Pangea, the youngest supercontinent in Earth's history[26] (see also Table 1). In addition, recent compilations

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Table 1 Break-up-based classification of Large Igneous Provinces (LIPs).

LIP type	Examples		
	LIP and timing of emplacement	**Separated continents and timing of break-up**	**Timing of pre-, syn-, and post-LIP continental rifting (or of attracted oceanic spreading)**
LIP-Shirker	Siberian Traps [~250 Ma][40]	–	West Siberian rift system[a] [~250–240 Ma][42]
	Emeishan LIP [~260 Ma][47]		Panxi rift[a] [~260–250 Ma][48]
LIP-Producer	Madagascar LIP [~93–90 Ma][56]	India–Madagascar [~84 Ma][66]	Amirante pull-apart basin[b] [~95–85 Ma][74]
	Deccan LIP [~66–64 Ma][57]	India–Seychelles [~63 Ma][67]	Cambay Basin, Kutch Basin, Narmada-Zone Rift[b] [~98.9–75 Ma][75–77]
LIP-Trigger	Central Atlantic Magmatic Province (CAMP) [~201 Ma][98]	Africa–North America [~190 Ma][107]	Central Atlantic rift system[c] [since ~225 Ma][104]
	Karoo LIP [~184–182 Ma][99]	Africa–Antarctica/Madagascar [~168–164 Ma][108]	Karoo rift system[c] [since ~190 Ma][106]
LIP-Attractor	Afar LIP [~30 Ma][121]	Africa–Arabia [~19-17 Ma][119]	Carlsberg Ridge[d] [since ~63 Ma][67]
	Paraná-Etendeka LIP [~134–132 Ma][126]	Africa–South America [~133–125 Ma][125]	South Atlantic Ridge[d] [since ~133 Ma][125]
LIP-Dornröschen	North-Atlantic Igneous Province (NAIP)[e] [~62–58 Ma][142]	North America–Greenland [~64–56 Ma][143,144]	Labrador Sea Ridge[d] [since ~64 Ma][143]
		Greenland–Europe [~54–53 Ma][145]	Norwegian–Greenland Sea rift[c] [since >300 Ma][166]
LIP-Sleeper	Manus Basin (Western Pacific)[172]	–	–

[a]LIP-induced aborted rift(s).
[b]Pre-LIP extensional basin/rift oblique to future syn-LIP magmatic break-up trend.
[c]Pre-LIP rift system evolving into break-up after LIP emplacement.
[d]Remote center of oceanic spreading propagating toward LIP-induced lithospheric soft point.
[e]LIP emplacement delayed by several tens Myr in relation to plume arrival time.

of continental and oceanic LIPs (including those found not only on the present-day seafloor but also in ophiolites) have shown a statistical correlation between the number of mantle plume events and supercontinental cycles since >1000 Myr[27].

However, the concept of plume-induced continental rupture can be challenged by the following observations: (1) long-lasting (up to ~200 Myr) phases of near-amagmatic rifting preceding emplacement of LIPs[28] and (2) the coincidence of the location and orientation of break-up axes with pre-existing suture zones[29]. In conjunction with arguments in favor of low (50–100 K) potential temperature anomalies beneath commonly accepted mantle plumes, such as the Iceland plume[30], not only has the active role of LIPs in Pangea break-up[31] been questioned, but even the existence of mantle plumes themselves[32,33]. It should be noted that all of these “anti-plume” views are generally at odds with deep mantle geochemical signatures of the LIPs[34] and other volcanic hotspot lavas[35].

To reconcile these apparent contradictions between active (driven by mantle plumes) and passive (driven by far-field tectonic forces) mechanisms of continental rifting and subsequent break-up, attempts have been made to develop transitional[36] or combined[37–39] passive-active scenarios. More recently, intermediate types of rifting-to-break-up systems (such as the so-called “semi-active” and “semi-passive”) have also been identified[18]. With this in mind, we examine major continental LIPs emplaced since the Late Paleozoic and propose a new classification consistent with their relationship to the disintegration of Pangea.

LIPs without break-up (*LIP-Shirker*). We begin our overview of Phanerozoic LIPs with two examples that, contrary to common expectations, are completely ineffective in terms of continental break-up and subsequent onset of oceanic spreading. Therefore, we refer to this type of LIP as *LIP-Shirker*.

The Permo-Triassic Siberian Traps (~250 Ma[40]) is an archetypal example of a continental LIP (Fig. 1a), best known for its proven impact on the largest known mass extinction event[11,41]. Despite the concurrent development of a rift system beneath the West Siberian Basin[42,43], one of the largest hydrocarbon provinces in the world[44,45], the Siberian Traps did not result in plate rupture and subsequent formation of an ocean basin.

Coincidence or not, another *LIP-Shirker* developed around the same time: the Late Permian (~260 Ma) Emeishan LIP was emplaced on the western margin of the Yangtze Cratonic block of South-West China[46,47]. Similar to the Siberian Traps, the Emeishan LIP was accompanied by plume-induced continental rifting[6,48], which took place in the Panxi region above the plume head[49], possibly also in the presence of far- and near-field tectonic stresses[50].

These two examples document that without appropriate geodynamic conditions (e.g., the presence of a pre-existing weak zone at the site of LIP emplacement and/or high-level and long-lasting far-field extensional stresses), even the most voluminous extrusions of flood basalts are insufficient to cause continental break-up with their impact limited to aborted rift systems.

Although the criteria for defining LIPs are not quite met, the Tertiary volcanic provinces of western and central Europe are probably another example of a “*Shirker*”. In this case, the European Cenozoic Rift System (ECRIS) was likely activated during the Paleogene[51] by a mantle plume or a system of small (“secondary”) plumes that have been magmatically active since the Paleocene[52] and can still be detected through seismic tomography[53,54]. The change in geodynamic regime at ~35 Ma

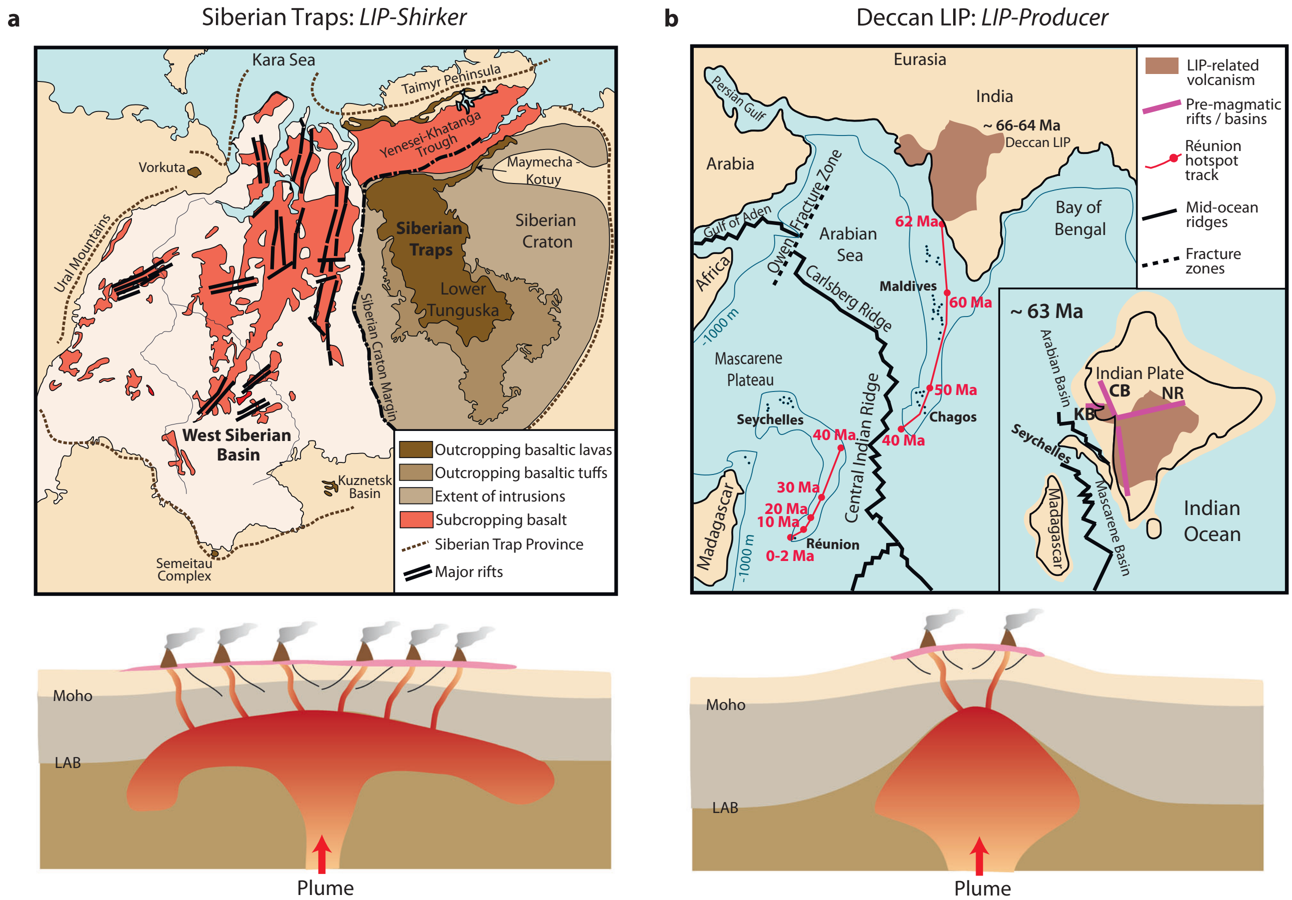

Fig. 1 End-member LIP types. a Siberian Traps as an example of *LIP-Shirker*. Hot upwelling material spreads laterally below the lithosphere-asthenosphere boundary (LAB) to form a mushroom-shaped plume head feeding widespread magmatic activity over an area of up to ~5.0×10^6 km^2. Plume-induced continental rifting (the West Siberian rift system) terminated in ~10 Myr during the Middle Triassic[42] without rupturing the lithosphere. Geological map is modified from ref. [40]. **b** Deccan LIP as an example of *LIP-Producer*. Rapid penetration of the mantle plume through the lithospheric mantle, which is progressively thinned in the active-passive mode[37,79], leads to continental break-up shortly after (in a few Myr) emplacement of LIP-related volcanism, which in this case is much more spatially restricted, covering an area of ~1.5×10^6 km^2. Réunion hotspot track is after refs. [70,71]. Paleo-position of the Seychelles microcontinent at ~63 Ma is after ref. [67]. Note the oblique orientation of the pre-magmatic rifts/basins (CB—Cambay Basin; KB—Kutch Basin; NR—Narmada-Zone Rift)[75–77] with respect to the break-up axis (future Carlsberg Ridge) between the Indian Plate and the Seychelles[78].

(transition from progressive closure of the Neo-Tethys Ocean to development of back-arc basins over retreating slabs)[55] has aborted the ECRIS and made the European volcanic province an equivalent counterpart to the more voluminous *LIP-Shirkers* discussed above.

LIPs with break-up. In contrast to the *LIP-Shirker* end-member, most cases of LIP emplacement result not only in rifting but also in rupture of the continental lithosphere[26]. Considering the relative role of mantle plumes associated with LIPs in the break-up process, we introduce the following types: *LIP-Producer, LIP-Trigger*, and *LIP-Attractor*. Their characteristic features are described below along with the natural examples and the criteria for distinguishing them.

LIP-Producer. The *LIP-Producer* corresponds to a scenario in which plume emplacement determines the location and timing of continental rupture. Prominent examples are the Madagascar and Deccan LIPs (Fig. 1b), where the rapid eruption of intraplate flood basalts occurred at ~93–90[56] and ~66–64 Ma[57], respectively. The continental lithosphere overlying the corresponding mantle plumes was therefore effectively weakened by basal thermo-mechanical erosion[58–60] and the reduction in the long-term brittle strength of rocks exposed to melt percolation[61–63]. In addition, this weakened lithosphere was subjected to slab pull forces by the continuous subduction of the Neo-Tethys Ocean floor[64], sometimes enhanced by a double subduction with two nearly parallel, north-dipping subduction zones between the Indian and Eurasian plates[65]. Under such favorable conditions, corresponding to the active-passive scenario when the mantle plume is combined with far-field tectonic extension[37–39], the continents were broken-up in only a few Myr after the formation of the Madagascar and Deccan LIPs, resulting in the successful separation of Madagascar and India at ~84 Ma[66] and India and the Seychelles at ~63 Ma[67]. Consistent with the classic concept that flood basalts represent the “head” of the plume and that continued magmatism along hotspot tracks is associated with the remaining plume “tail”[68], the Madagascar and Deccan LIPs mark the spatial and temporal beginning of well-known oceanic hotspot tracks that terminate at the current position of the Marion[69] and Réunion[70–72] plumes, respectively. It is also important that the Mesozoic extensional basins that preceded the emplacement of both the Madagascar[73,74] and Deccan LIP[75–77] are characterized by a strong obliquity with respect to the future break-up axis[78].

As evident from these examples, on the one hand, the role of the *LIP-Producer* is dominant because plate-tectonic forces alone (e.g., slab pull by long-lived subduction since the Paleozoic)[64] were not sufficient to localize rifting at the site and with the same orientation as the axis of eventual break-up. On the other hand, as shown by contrary *LIP-Shirker* end-member cases (Siberian Traps and Emeishan LIP), complete rupture of the lithosphere would not be possible without appropriate (extensional) far-field stresses determining the orientation of the break-up axis[79,80]. Paradoxically, the East African Rift System (EARS) could be an example of both end-members. The ongoing purely active rifting in its Eastern Branch, established in the Miocene[81] after the emplacement of the Kenya plume[82–85] at ~40–45 Ma[86], did not yet evolve into the rupture of the African Plate. Obviously, this is due to an unfavorable tectonic setting with regional far-field compression by mid-ocean ridges surrounding the African continent[87–89]. In the absence of a plate-tectonic reorganization, the EARS will be aborted, similar to the fate of the ECRIS and other rift systems associated with *LIP-Shirkers*. In an opposite scenario where a switch in the tectonic regime can make break-up possible, the East African volcanic province will be an equivalent of *LIP-Producer*.

Importantly, mantle plume impingement can produce not only (super)continent rupture, but also the separation of relatively small continental ribbons or microcontinents[90,91]. In particular, several continental fragments are known to have drifted away from northern Gondwana during the Paleozoic (the Avalonia terranes and the Cimmerian blocks)[92] and Mesozoic (the Apulian microcontinent)[93], possibly due to the combined effect of slab pull by continuous subduction of paleo-oceans (from Proto-Tethys to Neo-Tethys)[94] beneath the active margin of opposing continents (from Laurentia to Laurasia)[95] and mantle plumes periodically arriving at the base of the African lithosphere[96].

LIP-Trigger. In contrast to the *LIP-Producer* scenario, where thermal and magmatic weakening caused by a mantle plume leads to initial localization of pre-break-up deformation in the lithosphere, the magmatic activity associated with an *LIP-Trigger* is preceded by continental rifting, situated in the area of future lithospheric rupture and, crucially, of the same orientation as the final break-up axis[78]. Prominent examples are the Central Atlantic Magmatic Province (CAMP) and the Karoo LIP, emplaced at ~201[97,98] and ~184–182 Ma[99–102], respectively. In these cases, the role of the corresponding plumes was limited, only enhancing the ongoing localized extension related to pre-magmatic rifting which in both regions was already operating for several tens[103,104] to several[105,106] Myr. Therefore, the CAMP and the Karoo LIP activated (but did not cause!) lithospheric rupture that occurred relatively soon (~10–15 Myr) after their emplacement, opening the Central Atlantic at ~190 Ma[107] and separating South Africa from Antarctica and Madagascar at ~168–164 Ma[108].

We dub this type of LIP as *LIP-Trigger* because in this case pre-LIP localized deformation (rifting) could ultimately be terminated by a break-up of the continent, even without the involvement of a plume that merely accelerates (or triggers) this process without playing a dominant role. Coincidence or not, both *LIP-Triggers* (the CAMP and the Karoo LIP) lack hotspot tracks, unlike the *LIP-Producers* (the Deccan and Madagascar LIPs), which, as described above, have a clear expression in the form of tracks imprinted by deep-seated Réunion and Morion plumes. Therefore, *LIP-Triggers* seem to be preferably associated with bundles of "secondary" plumes rather than with individual "primary" plumes (Fig. 2a). This assumption is indirectly supported by (1) the presence of numerous small plumes in the central Atlantic Ocean (Azores, Canary, and Cape Verde)[109], which are obviously much younger (Cenozoic) in age[110,111], but could indicate a "secondary" plume fabric, that established in the region during the Late Triassic–Early Jurassic and is still in operation; (2) a larger area of scattered magmatism associated with *LIP-Triggers* (e.g., ~3×10^6 km^2 for the Karoo LIP) than in the case of a spatially more concentrated magmatic area typical of *LIP-Producers* (e.g., ~1.5×10^6 km^2 for the Deccan LIP); and (3) strong multivariance in proposed positions for the center of the Karoo plume[112]. We should note, however, that despite our hypothesis of numerous "secondary" plumes below the CAMP and the Karoo LIP this is not a general requirement for the *LIP-Trigger*, which in principle can also develop with a single "primary" plume, as exemplified by the Kerguelen oceanic plateau formed in the Early Cretaceous as a LIP over the Kerguelen hotspot[113]. The first magmatism associated with the Kerguelen plume has been dated to ~130 Ma in southwestern Australia[114] and ~132 Ma in southeastern Tibet[115], roughly contemporaneous with the initial break-up of India–Antarctica[116] and India–Australia[117], which in turn was preceded in both cases by continental rifting since ~160 Ma[118], consistent with the *LIP-Trigger* scenario.

LIP-Attractor. For both *LIP-Producer* and *LIP-Trigger*, continental break-up always occurs first above the plume emplacement area, forming volcanic passive margins (VPMs), and then propagates laterally, developing non-volcanic passive margins (NVPMs), which are usually abruptly separated from volcanic counterparts by transform faults[78]. On the contrary, in the case of the Afar LIP (Fig. 2b), the NVPMs at the eastern tip of the Gulf of Aden began to develop much earlier (~19–17 Ma[119]) than the VPM formation within the Afar triple junction (~1 Ma[120]). This spatial and temporal evolution of the break-up of the Gulf of Aden could be explained as follows: a domain of the continental lithosphere, that was rheologically weakened by the massive melting event of the Afar plume at ~30 Ma[121,122], directed the westward lateral propagation of seafloor spreading from the mid-oceanic Carlsberg Ridge, which had already been active since ~63 Ma[67] and then approached this thermal sublithospheric anomaly acting as a soft point[123]. We, therefore, dub this type of LIP as *LIP-Attractor*.

In the South Atlantic[124], break-up at 133–125 Ma[125] also propagated (in this case from south to north) toward the Paraná-Etedeka LIP, which erupted almost simultaneously at ~134–132 Ma[126]. This sequence has been hypothesized as evidence for a non-plume mechanism of South Atlantic opening[127] and Pangea fragmentation in general[31]. However, it is more likely that we are dealing here with another *LIP-Attractor*, where the influence of the plume is restricted to directing the propagation of oceanic spreading that is already operating.

It should be mentioned that from the perspective of the opening of the Red Sea, the Afar LIP can also be considered as *LIP-Producer*. In this case, initial continental rifting occurred almost simultaneously with plume emplacement[119], while the break-up was considerably delayed until ~4 Ma at the southern tip, without yet reaching the northern segments of the Red Sea[128]. This delay between the LIP formation and the resulting plate rupture (not typical of the classic *LIP-Producers*, where break-up usually develops much more rapidly) may be due to a much reduced Neo-Tethys slab pull since the onset of the progressive collision between the Arabian and Eurasian Plates in the Bitlis suture zone at ~40–30 Ma[129]. Consequently, it appears that in the classic active–passive scenarios corresponding to the *LIP-Producers*, the time interval between LIP emplacement and final break-up is controlled primarily by a combination of the efficiency of lithosphere weakening by magmatism (volume, temperature, and water content of plume material) and the level of external extensional forces.

"Re-awakened" and "dormant" LIPs (*LIP-Dornröschen* and *LIP-Sleeper*). Despite decades of extensive study and the

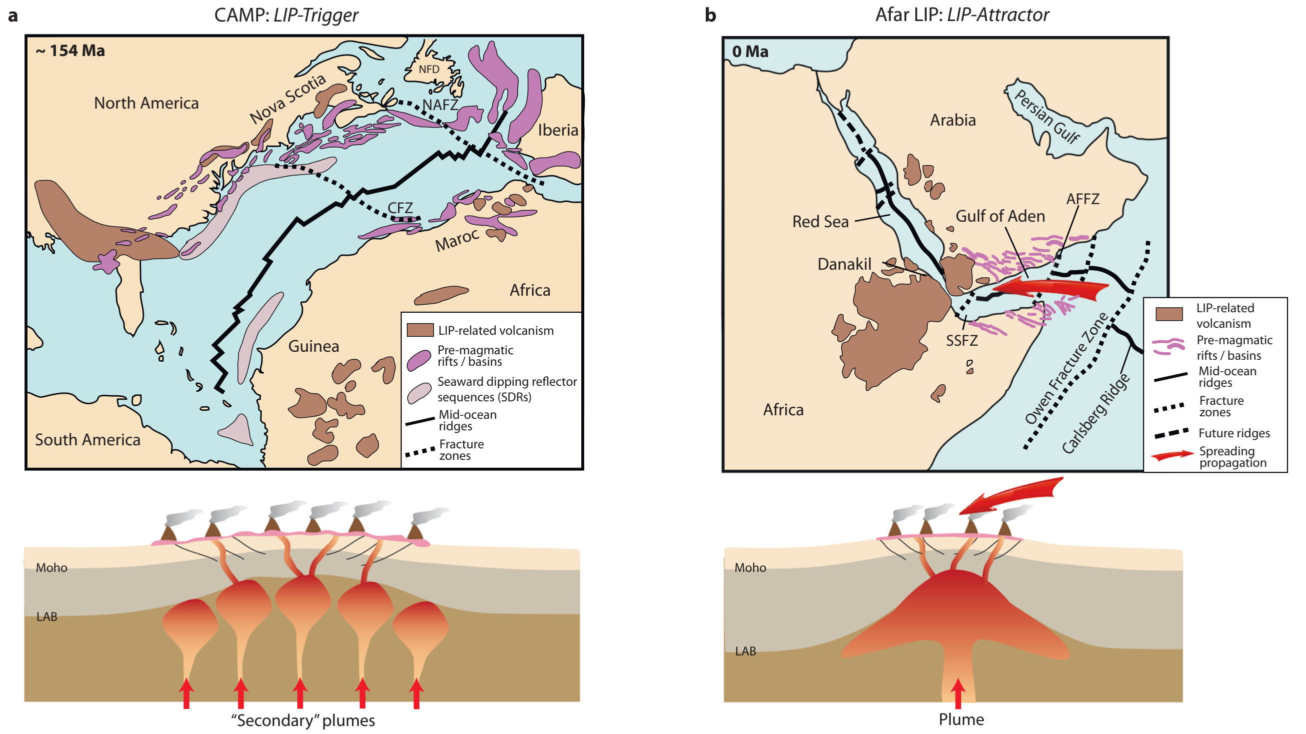

Fig. 2 Other types of LIPs associated with break-up. a Central Atlantic Magmatic Province (CAMP) as an example of *LIP-Trigger*. Simultaneous emplacement of numerous "secondary" plumes[16] at the base of the pre-thinned lithosphere results in scattered magmatism that is relatively quickly followed (in ~10 Myr) by plate rupture. Concentrated volcanism coincident with plume-related lithospheric break-up forms large and thick wedges of so-called seaward dipping reflector sequences (SDRs) that mark volcanic passive margins (VPMs), in contrast to adjacent non-volcanic passive margins (NVPMs) without SDRs that presumably develop as part of a purely passive rifting-to-break-up system. Note that the VPMs of the Central Atlantic are separated from the NVPMs between Newfoundland and Iberia by a series of major transform faults. CFZ Canary Fracture Zone, NAFZ Newfoundland-Azores Fracture Zone, NFD Newfoundland. **b** Afar LIP as an example of *LIP-Attractor*. Soft point in the lithosphere created by plume-induced thermal anomaly at ~30 Ma[121,122] controls the direction of horizontal propagation from the Carlsberg Ridge, which causes progressive break-up in the Gulf of Aden from the east (~19–17 Ma)[119] to the west (~1 Ma)[120]. AFFZ Alula-Fartak Fracture Zone, SSFZ Shukra El Sheik Fracture Zone. Two maps in **a** and **b** are modified from ref. [78].

accumulation of a vast amount of geologic and geophysical data[130], the North Atlantic Igneous Province (NAIP) and the associated evolution of lithospheric rupture and oceanic spreading are still the subject of vigorous debate about the mechanisms that favor either plume-induced[131,132] or purely passive rifting and break-up[133].

To reconcile ongoing controversies about the actual causes of the emplacement of voluminous magmatism in the NAIP, the following key elements of the evolution and structure of the North Atlantic realm should be taken into account as constraints: (1) the spatial variation in the thickness of the continental lithosphere[134–136]; (2) the relative motion trajectory of the Iceland plume since the Cretaceous[137–139]; (3) the timing and spatial distribution of the magmatism related to the NAIP[140–142]; and (4) the timing of the opening of the Labrador Sea/Baffin Bay[143,144] and the North Atlantic[145,146]. According to these data, the lithosphere is thinned beneath the central part of Greenland, as evidenced by low seismic velocities in the mantle[134–136]. This seismically detected zone of relatively thin lithosphere crossing Greenland from west to east is also reflected in high measured[147] and predicted[148] heat flow, intense basal ice melt[149], and increased crustal thickness due to magmatic underplating[150] and intrusions in the middle and lower crust[151]. Given the spatial correspondence with the reconstructed paths of the Iceland hotspot[137–139], most recent studies interpret these features as relict signatures of the passage of the Iceland mantle plume beneath Greenland from at least 90 to ~60 Ma[148–151]. In contrast, according to more traditional views, the Iceland plume was emplaced on the eastern edge of Greenland, as supported by observations of radiating and circumferential dyke swarms[152], whereas part of its large, flattened head rapidly extended into western Greenland[153], causing the quasi-simultaneous magmatic activity (the NAIP) on both sides of Greenland around 60 Ma[140–142]. However, the relatively close location of the reconstructed position (~130–120 Ma) of the so-called High Arctic Large Igneous Province, which includes the exposed components on Ellesmere Island, Spitsbergen, and perhaps northern Greenland[154], and the corresponding segment of the hotspot track[132] is indicative of the Iceland plume, which is more than twice as old as the NAIP[137]. Furthermore, the Iceland hotspot can even be traced back to West Siberia in the Late Permian–Early Triassic[155], so that the Siberian Traps (~250 Ma[40]) could hypothetically be the very first magmatic manifestation of the Iceland plume.

In view of the above, magmatic activity in Baffin Island and Western Greenland during the Paleocene was probably triggered by spreading axis propagation from the Labrador Sea toward the Baffin Bay, where continental break-up was progressively initiated from ~64 Ma[143] to ~56 Ma[144], respectively. The overlap of the propagating spreading ridge with the ~100–80 Ma-dated segment of the Iceland hotspot track near the West Greenland passive margin[139] (Fig. 3a) enlivened the hot material that had resided there already for ~20–40 Myr without signs of excessive volcanism. The simultaneous approach of the actual "tail" of the Iceland plume to the eastern edge of thick Greenland lithosphere[139] allowed horizontal flow of the plume material

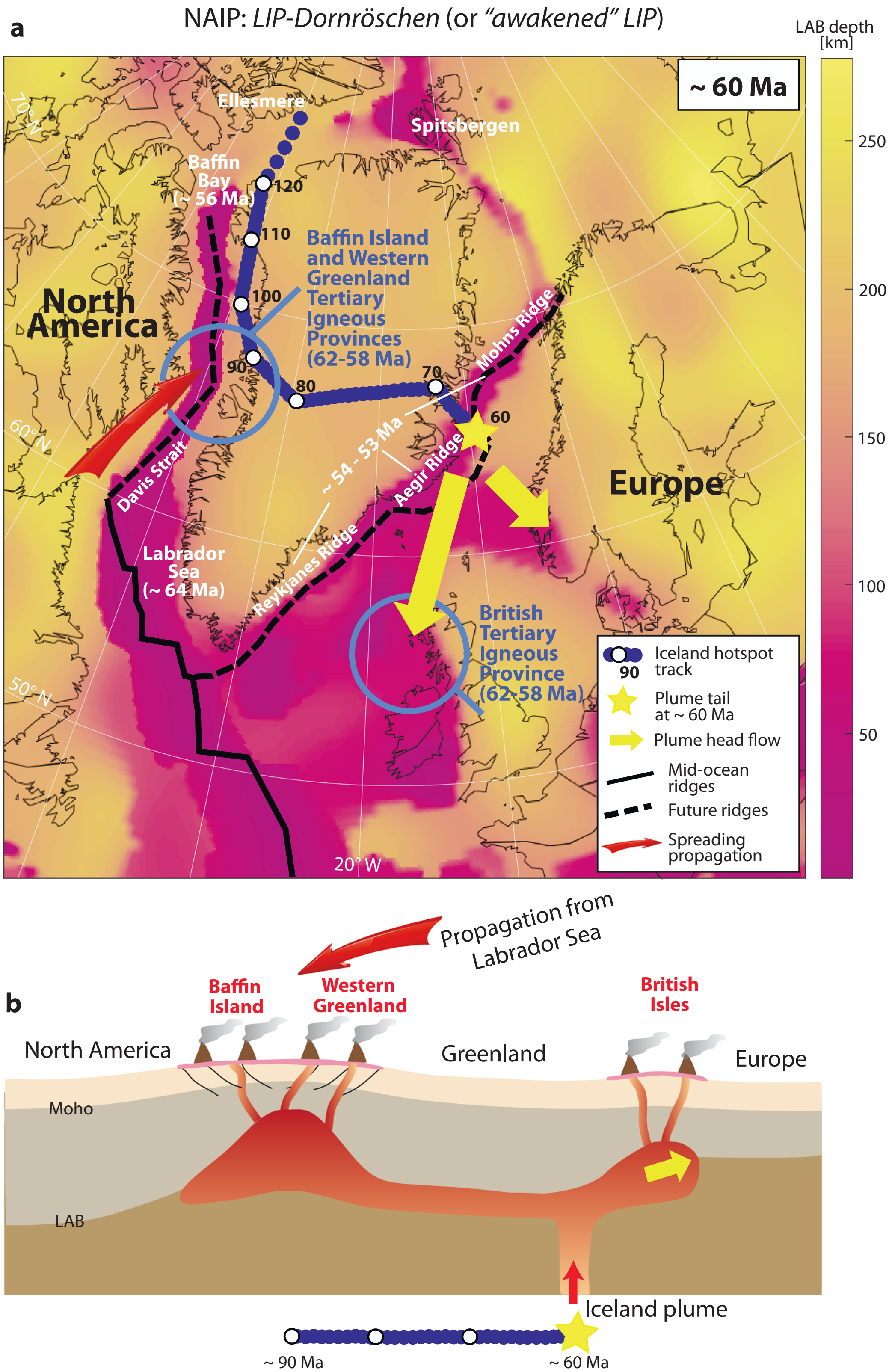

Fig. 3 North Atlantic Igneous Province (NAIP) as an example of *LIP-Dornröschen* (or *"re-awakened" LIP*). a Thickness of continental lithosphere (LAB depth), based on seismic tomography model by ref. [135]. A ~60 Ma plate reconstruction and the Iceland plume trajectory are based on the global moving hotspot reference frame of ref. [139]. Blue circles indicate the approximate location of two NAIP regions. **b** Schematic profile showing: (1) "re-awakening" of plume material seeded since ~90 Ma on the western edge of Greenland by propagation of the spreading axis from the Labrador Sea, and (2) flow of hot material delivered from the plume source on the eastern edge of Greenland toward the thinner lithosphere of Europe. These independent but coincident events led to the simultaneous (at ~62–58 Ma)[142] emplacement of the Baffin Island/West Greenland and British Tertiary Igneous Provinces, which together form the NAIP. Note that the vertical scale is exaggerated on this and other (Figs. 1 and 2) schematic profiles. Map in **a** is modified from ref. [132].

along the adjacent thin-lithosphere corridors[135] connecting the eastern edge of Greenland with the Southern Scandinavia and Scotland/Ireland[156,157]. A similar mechanism of propagation of hot plume material toward areas distant from its original emplacement along the elevated lithosphere–asthenosphere boundary[158–160] has been proposed for Late Mesoproterozoic mafic magmatism in the southwestern USA (the Keweenawan LIP and the Southwest Laurentia LIP)[161] and Cenozoic alkaline volcanism in Africa[162] and Arabia[163,164]. The arrival of Iceland plume hot material beneath thin European lithospheric segments has led to intense plume-related magmatism in the British Isles area[165], quickly followed by the break-up in the North Atlantic *sensus stricto* (i.e., between Greenland and Europe) along the Reykjanes–Aegir–Mohns Ridge at ~54–53 Ma[145], preceded by the most long-lasting rifting since the Late Paleozoic[166,167]. The contemporaneous (~62–58 Ma) magmatism over a vast area from Baffin Island to the British Isles[142] is thus driven by these two independent processes—spreading axis propagation and plume conduit motion—which happen to coincide in time (Fig. 3b).

The evolution of the North Atlantic region shows that a thermal anomaly hidden for a while beneath thick lithosphere can be "re-awakened" (or "re-initialized") by the lateral propagation of spreading ridges or by tapping its source under thinner segments of overlying lithosphere due to horizontal plate movements. We dub this type of LIPs as *LIP-Dornröschen* (*"re-awakened" LIP*). We expect that the term *LIP-Dornröschen* (*LIP-Sleeping Beauty*) may be applicable to a broad family of LIPs, including those from the Precambrian. For example, several LIP pulses in the period 1800–1600 Ma, which formed on the supercontinent Columbia during ancient plate motion over a single stationary Xiong'er plume in the North China Craton[168], can be regarded as the earliest known manifestation of a *LIP-Dornröschen*-like scenario in Earth history. On the contrary, the youngest case of delayed LIP outpouring might be the Columbia River Basalt LIP (~17–16 Ma[169]) associated with the Yellowstone mantle plume[170], with a history appearing to extend to at least ~56 Ma, as indicated by offshore volcanism on the Siletzia oceanic plateau[171].

Interestingly, the western (Baffin Island and Western Greenland) and eastern (British Isles) components of the North Atlantic "Sleeping Beauty" show some similarities to the *LIP-Attractor* and the *LIP-Trigger*, respectively (see Fig. 3 and Table 1), so a multilevel classification for these and/or other LIPs (and/or LIPs components) could probably be developed in the future.

The mantle plume underlying the Manus back-arc basin (Western Pacific Ocean), which was discovered by seismic tomography without showing up as an evident hotspot[172], is likely a good example of a possible future *LIP-Dornröschen* that is currently still "dormant" (*LIP-Sleeper*). Future high-resolution seismic tomographic studies in continental and oceanic lithospheric environments will be of particular importance in discovering new "dormant" plumes or hidden hotspots[173], which may provide additional constraints on plate motion history[174] and will likely help uncover new aspects in the geodynamics of mantle-lithosphere interactions.

Conclusions and future outlooks. For more than 25 years, the prevailing view of the scientific community on the causal links between mantle plumes and the break-up of (super)continents has changed considerably. Traditionally, it was postulated that the emplacement of LIPs played a key role in Pangea fragmentation[26]. However, recognition of certain limitations of this concept[28,29] has gradually led to a fundamental reassessment of the causes of continental break-up[31], which ultimately rules out the necessity[175] and even the existence of a mantle plume component[32,33]. As a consequence, purely passive continental rifting models are now even being applied to regions such as East Africa[176–179], where both geophysical[83,85] and geochemical[82,84] observations unequivocally indicate the presence of mantle plumes, rooted in a common large-scale source corresponding to a first-order mantle structure such as the African superplume[180,181].

To prevent further counterproductive discussions advocating end-member views of classic "passive versus active" rifting debate[182], a parallel of the more general "plates versus plumes" controversy[32,33], we propose here a new classification of LIPs that illustrates the variability in the possible role of mantle plumes in the process of continental break-up (in addition to the well-known diversity in geochemically based classifications)[23,183]. In particular, we demonstrate that, on the one hand, LIPs indeed cannot always be causally linked to lithospheric rupture. As the geologic records of the Siberian Traps and the Emeishan LIP (*LIP-Shirkers*) show, even very voluminous magmatism associated with active rifting does not always by itself lead to continental break-up in the absence of favorable tectonic conditions. On the other hand, regional far-field extension alone also does not act as an efficient break-up mechanism, as most non-volcanic passive margins (e.g., Newfoundland–Iberia, Equatorial Atlantic) are the result of horizontal propagation from adjacent areas of plume-activated spreading[78]. This highlights the key role of combined active–passive mechanisms[38,184], where the site of localized deformation is determined by the plume, while the orientation of the rift and spreading axis is controlled by the direction of external extension. This active-passive scenario corresponds to the *LIP-Producer* exemplified by the Deccan and Madagascar LIPs.

In addition, plumes can play a limited, yet important and sometimes even definitive role in the dynamics of plate rupture. These include (1) initiating break-up when rifting is already underway, thereby determining the timing of lithospheric rupture (*LIP-Trigger*, e.g., the CAMP and the Karoo LIP), and (2) creating mechanically soft zones in the lithosphere that spatially control the direction of propagation of oceanic spreading (*LIP-Attractor*, e.g., the Afar and Paraná-Etedeka LIPs).

Two remaining types of LIPs are *LIP-Dornröschen* (Iceland plume) and *LIP-Sleeper* (Manus basin). This implies that interpretation of the timing of LIP emplacement made from a mantle dynamics perspective[27] should be handled with caution because of possible delays between the timing of upwelling in the mantle and its detectable magmatic manifestation at or near the Earth's surface.

Although our classification is currently based on the best-known examples of continental Phanerozoic LIPs (Table 1), it should also be relevant to the future study of other LIPs (including Precambrian and oceanic), providing a generic guide for further studies of intraplate magmatism in terms of its relationship to plate rupture.

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