News & Views

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Slab breakoff: A causal mechanism or pure convenience?

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The idea of lithosphere delamination has long been conceived as a mechanism to cause tectonic uplift, metamorphism and magmatism in active orogenic belts [1-3]. Since the publication of the two seminal papers by Davies and von Blanckenburg [4,5], the idea of slab breakoff has been better accepted over the last ~ 20 years as the favored mechanism to cause collision zone magmatism and exhumation of subduction-zone metamorphosed rocks. These two papers demonstrated the physical probability of slab-breakoff during continental collision and illustrated the geological consequences using the Alpine geology as an example. Currently, slab-breakoff seems to have been axiomatically accepted as the causal mechanism in studies of continental collision-related magmatism. In this short communication, I do not intend to deny the probability of slab breakoff nor the possible geological consequences, but emphasize that caution must be exercised when invoking “slab-breakoff” as a causal mechanism without physical and geological justifications or if evidence clearly indicates otherwise.

Figure 1 is a set of histograms using the data from the Web of Science. Fig. 1a shows the number of papers on “slab breakoff” published each year since 1995 (blue histogram) and the total number of papers published on the subject up to each of these years (red cumulate curve). Fig. 1b shows the citations of these papers and reads accordingly. Fig. 1c-d gives the same type of the information on papers that invoke slab breakoff as the mechanism causing observed magmatism. Fig. 1e-f shows the similar on papers that consider slab breakoff as a possible or probable mechanism responsible for the exhumation of subduction-zone metamorphosed rocks (blueschist and eclogite facies rocks). From the increasing trend over the years, it is expected that the number of papers and citations both will continue to rise. It is possible that such increase and rise may indeed reflect more research that offers support or verification of the breakoff related interpretations, but it could also be a bandwagon effect because of the increasing popularity and convenience. While slab breakoff may indeed take place [6], and this could in some way facilitate magmatism and ease tectonic exhumation [7-11], we can readily see, however, that the effect of the “slab-breakoff” is likely overstretched in the current literature.

Figure 2 shows a few examples from the literature that use slab-breakoff to explain geological observations. Fig. 2a invokes slab-breakoff to explain the exhumation of high- and ultra-high-pressure eclogites produced from subducted passive margin crustal lithologies. But slab-breakoff may not be required because the eclogites are volumetrically minute (< 10 %) hosted in the volumetrically significant granitic gneisses (> 90%), whose bulk density (~ 2.8 g cm^{-3}) is much smaller than that of the subducting/subducted mantle lithosphere (> 3.2 g cm^{-3}). The large buoyance contrast and the weak contact between the buoyant crust and dense mantle section of the slab can readily separate. The straightforward point is that the eclogite-hosting granitic gneisses exhume, but the lithologies of mantle section of the slab do not. The latter will not exhume unless they are highly serpentinized with added buoyancy. The inference here is that serpentine diapirs could be important in the exhumation of some blueschist and eclogite fragments. Fig 2b-d invokes slab-breakoff to allow hot asthenosphere to enter the mantle wedge, providing both materials and heat for magmatism, as if the mantle wedge is “vacuum” with below-slab asthenosphere freely flowing into the mantle wedge. This is physically unlikely (see below). Fig 2e is a highly-exaggerated scenario, which is even more difficult unless there is rather significant overlaying plate extension that permits passive upwelling and decompression melting such as beneath extensional settings (e.g., ocean ridges, back-arc spreading centers and continental rifts). Fig 2f invokes ridge subduction to explain the Mesozoic granitoid magmatism and associated mineralization in eastern China. Ridge subduction is known to take place at present (e.g., the Chilean Rise subducting beneath South America), but subducting ridges are at high angles with the trench to ensure well-maintained slab pull. If the ridge is parallel or sub-parallel to the trench, there would be no slab pull for continued subduction because the ridge lithosphere is the thinnest and weakest without cohesion. These are the few examples of many that seem to follow the crowd without analyzing the likelihood in terms of basic geology and physics. There are also many good examples of researchers who revise their thinking when they have discovered their original creative ideas, despite being popular, are no longer supported by the new observations. I discuss and illustrate the obvious problems as follows:

Slab-breakoff is expected not to produce voluminous magmatism

Figure 3a is an ideal scenario of seafloor subduction beneath active continental margin (e.g., the Andean-type), where subducting-slab dehydration induced mantle wedge melting produces basaltic magmas parental to arc magmatic rocks. Mantle wedge corner flow as indicated by the arrowed lines is a consequence of down-going slab dragging. This corner flow convection cannot be directly observed, but must be true because of seismic anisotropy, dynamic modeling, and the required supply of fertile mantle material to maintain the longevity of subduction-zone magmatism. The latter is further supported by the fact that arc magmas are geochemically more depleted if the mantle-wedge material has been previously depleted beneath a back-arc basin (vs. settings without back-arc spreading). Subduction would stop (or stop shortly) upon continental collision [8,12]. It follows that mantle wedge corner flow would diminish and flux-melting would also diminish if they do not stop immediately. Slab-breakoff may happen, but if it does, the “gap” or “void” created (Fig 3b) is *where* the only volume is made available to be filled by *adjacent* asthenospheric material from both *above* and *below*. There is no “vacuum” or free space available in the mantle wedge for voluminous hot asthenosphere to flow from beneath the slab and fill the wedge above the slab, contrary to the speculative scenarios in Fig. 2. Hence, it is physically unlikely to have the speculated voluminous asthenosphere decompression melting as the heat source to cause melting of the overlaying continental plate as popularly interpreted (Fig. 2). We should note, however, that the subducting/subducted upper ocean crust can melt, but this is not caused by slab breakoff [7].

Observations that do not support slab-breakoff

von Blanckenburg & Davies [5] made a classic case of slab-breakoff as the cause for syncollisional magmatism and tectonics in the Alps. However, the recent high-resolution P-wave tomography study [13] demonstrates that the Alpine slab is in fact continuous without breakoff, questioning the validity of previous interpretations of syncollisional magmatism as the result of successive slab breakoffs along the Alpine-Zagros-Himalaya orogenic belt, also ruling out slab-breakoff as a possible mechanism for Alpine topography. Kohn & Parkinson [14] and many others invoke slab-breakoff during India-Asia collision to explain the exhumation of eclogites and widespread syncollisional granitoid magmatism in southern Tibet. While the slab-breakoff model has gained wide acceptance, it remains unclear if slab-breakoff indeed took place during this collision because there is thus far no smoking-gun evidence in support of the breakoff interpretation. Existing tomographic studies (seismic Vp), as exemplified in Fig. 4a [15,16], seem to show that the Indian plate remains continuous beneath the Greater Tibetan plateau, suggesting that complete slab breakoff may not happen. Although the validity of this tomographic interpretation needs verifying, we should not neglect these studies in explaining the syncollisional granitoid magmatism in southern Tibet.

Figure 4b shows the mantle seismic shear velocity (Vs) structure beneath the Greater Tibetan Plateau [17]. The high Vs layer of ~ 100 km thick at depth of ~ 100 - 200 km extends continuously from beneath India northward throughout the Tibetan plateau, which is most consistent with the underthrust of the Indian continental lithosphere beneath the Tibetan plateau lithosphere [16]. This offers evidence against slab-breakoff model, suggesting that alternative interpretations need considering on the origin of the syncollisional magmatism preserved in southern Tibet [7]. Importantly, this recent study [17] also emphasizes that the lithospheric mantle beneath the Tibetan Plateau has not been thinned through the process of "delamination" or "convective removal" as popularly favored [1-3], but rather has been thickened, suggesting that continental collision zones may be potential sites of cratonic lithosphere nucleation [17]. This totally reversed interpretation, "thickened" [17] vs. "delaminated and thinned" [2] lithosphere beneath the Tibetan plateau results from new seismic observations and the objective and open-minded thinking. We should also note the low Vs layer underneath the crust and atop the mantle lithosphere beneath the Tibetan Plateau (Fig. 4b) is consistent with radiogenic heat accumulation [17], which can effectively explain the volumetrically small but widespread Cenozoic high potassic volcanism on the Plateau [18].

A recent study on a gabbro (vs. basaltic melt composition) with ocean island basalt signature from southern Tibet is interpreted as solid evidence for slab breakoff at ~ 45 Ma [19], which, together with an earlier interpretation of tectonic exhumation at northwestern Himalaya [14], is used to argue for almost synchronous slab breakoff along the whole length (>2500 km) of the India-Asia collision zone. We should note that (1) this is *not* evidence, but an interesting speculation; (2) if slab breakoff is indeed a primary cause for volumetrically significant syncollisional magmatism, such "smoking-gun" evidence [19] should be widespread along the whole length of the > 2500 km collisional zone, but this is not the case; (3) The interpreted synchronous breakoff time of ~ 45 Ma [19] in fact postdates the volumetrically significant syncollisional granitoid batholiths (~ 51±5 Ma) and volcanic rocks (> 52 Ma) in southern Tibet [9]; (4) any attempt to invoke slab breakoff model for syncollisional magmatism should address the difficulties elaborated above (Fig. 3).

Indeed, the lack of tomographic evidence for slab breakoff at present in Fig. 4 cannot be used to argue against its possible happening some ~ 50 Myrs ago, but if it did happen, the broken slab fragments of volumetric significance should be seismically observed in mantle sections beneath the greater Indian-Tibetan region [15], but these are not observed [16]. In this context, it is necessary to emphasize the particularity of the India-Asia collision that took place ~ 55 Ma, but the convergence has continued to this day. The subduction is expected to stop and slab pull as the driving force must disappear upon continental collision. The continued India-Asia convergence since the collision is actually a consequence of active subduction of different parts of the same giant "rigid" Indo-Australia plate [12]. The active subduction of the same "rigid" plate at the Sumatra-Indonesia trench drags the India-Asia convergence, thus the continued underthrusting of the Indian mantle lithosphere beneath the Tibetan lithosphere [12], which also explains why the position of the India-Asia suture has migrated northward from ~ 21°N at ~ 50 Ma to ~ 29°N at present [20]. The Indian + Tibetan mantle lithosphere doubling explains the thickened lithosphere and high elevation beneath the greater Tibetan plateau (Fig. 4). The Himalaya mountain range is largely made of piles of scraped Indian crust in response to the continued convergence.

In summary, I do not take position for or against slab breakoff as a causal mechanism to explain the collisional processes, but I emphasize the importance of objective evaluation of existing observations and open-minded thinking, which will help us to make logical interpretations whether slab breakoff can indeed happen during continental collision and if so whether it is required or sufficient to cause the speculated tectonic exhumation and volumetrically significant syncollisional magmatism. If not, alternatives should be sought to truly advance our science and our scientific understanding on how the Earth works.

Acknowledgments

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Fig. 1 Histograms showing number of papers published each year since 1995 on slab breakoff (**a**) used to explain orogenic magmatism (**c**) and tectonic exhumation (**e**). Panels (**b**), (**d**) and (**f**), respectively, show number of citations of these papers up to each of these years as shown. The data are from Web of Science as of November 15, 2016.

Fig. 2 Selected cartoons from the literature that use slab breakoff to explain tectonic exhumation of ultrahigh pressure eclogites (**a**[21]), syncollisional magmatism (**b**[22]**, c**[10]**, d**[23]**, e**[24]) and ridge subduction and mineralization (**f**[25]).

Fig. 3 a, Cartoon showing the general perception on slab-dehydration induced mantle wedge melting and induced crustal magmatism at active continental margin (e.g., the Andean-Type), where slab-dragged mantle wedge corner flow is important. **b**, Cartoon illustrating that if slab breakoff may indeed take place during continental collision, the breakoff related asthenospheric upwelling is limited to the “gap” or “void” made available in space and volume because of the breakoff and it is not possible to have volumetrically significant hot asthenosphere to upwell and cause the claimed magmatism as shown in Fig. 2b-f.

Fig. 4 a, Topographic elevation and mantle seismic (Vp) tomography of the Tibetan Plateau (modified from [15]). **b**, Topographic elevation, crust and mantle seismic (Vs) tomography of the Tibetan Plateau (modified form [17]).

俯冲板片断离：地质过程的诱因还只是流行观点？

过去 20 多年来俯冲板块断离被广泛用来解释大陆碰撞带高压-超高压变质岩折返和同碰撞岩浆作用的诱因。本文在地质观察和对地质学、物理学基本概念分析的基础上认为，(1) 俯冲带变质岩的折返不需要板块断离机制；(2) 用板块断离来解释同碰撞带大规模岩浆作用有诸多困难；(3) 同碰撞带岩浆作用的成因机理急需进一步客观深入的分析和研究。

Figure 1 (Niu, 2016)

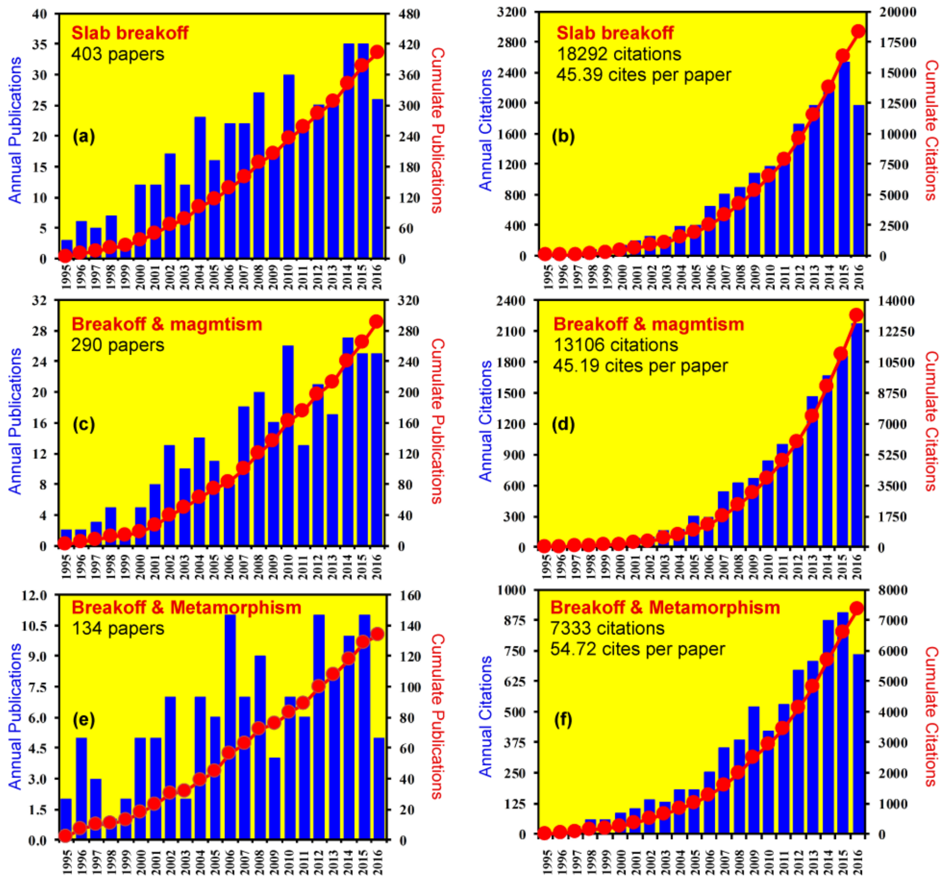

Figure 2 (Niu, 2016)

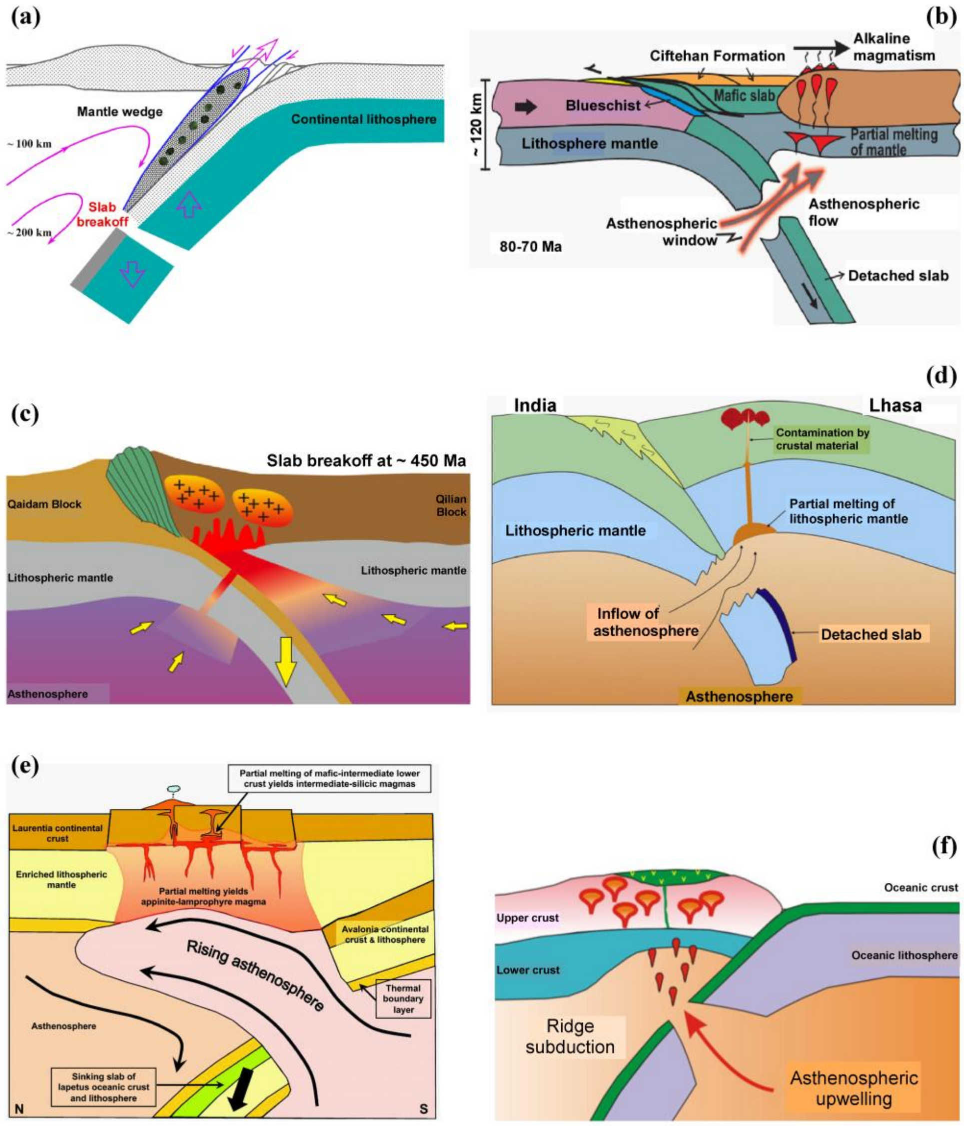

Figure 3 (Niu, 2016)

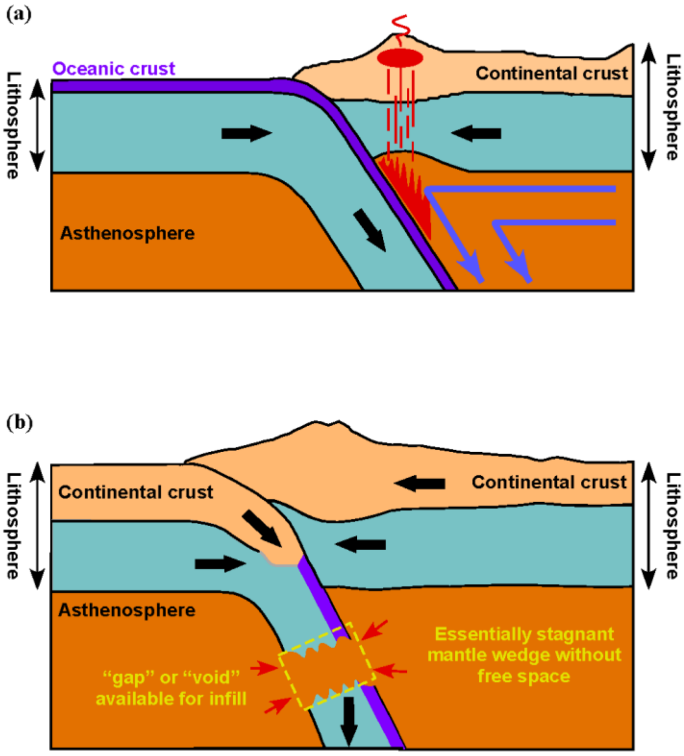

Figure 4 (Niu, 2016)