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Seismic evidence for the existence of an entrained mantle flow coupling the northward advancing Indian plate under Tibet

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Abstract: The Tibetan Plateau, known as "the roof of the world" and "the third pole of the earth", is a product of the collision between India and Asia during the last ~50 Ma. The regional tectonics–in particular, growth and expansion of the plateau–has been attributed primarily to deformation within the lithosphere. The role and pattern of the underlying asthenospheric flow, however, remain mostly unaddressed. In light of recent seismic tomographic images and published seismic anisotropic descriptions of the upper mantle, here we propose that an entrained mantle flow is likely to exist under Tibet, induced by the northward advancing Indian plate. The direction of mantle flow is characterized by a gradual rotation from northward in the south to eastward in the north as a result of deflection by the deep root of the Tarim block. The presence of an underlying mantle flow is not only able to account for the west-east oriented fast-axis of seismic anisotropy in northern Tibet, but can also adequately explain the sporadic null splitting in southern Tibet. Specifically, the null splitting results, at least in part, from upwellings of asthenospheric flow through tears of the underthrusting Indian plate that have been revealed by various seismic observations. The mantle flow may in turn promote the block extrusion under Tibet that has been observed in GPS measurements; hot asthenospheric upwellings may also lead to widespread post-collisional magmatism in southern Tibet.

Keywords: Tibet; seismic anisotropy; mantle flow; null splitting; upwelling

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1. Introduction

It is widely accepted that the Tibetan Plateau, the highest and largest topographic plateau on earth, forms as a direct consequence of the collision of India with Asia that began during the Cenozoic. The plateau thus represents a natural laboratory to study continent-continent collision orogenesis on the Earth (e.g., Yin A and Harrison, 2000; Chung SL et al., 2005). Mantle dynamics beneath the plateau may also play an important role in altering regional and global climates (Molnar et al., 1993). Our current understanding of the regional tectonics has greatly benefitted from numerous seismological investigations, and many achievements have been obtained; e.g., an inefficient Sn and low Pn zone has been seen in the Songpan-Garzê terrane (Barazangi and Ni, 1982), which may suggest removal of lower lithosphere in response to the Indian plate's northward indention (Owens and Zandt, 1997). The subducting Indian plate has been intensely fragmented, leading to tearing of the lithosphere (e.g. Chen Y et al., 2015; Liang XF et al., 2016; Li JT and Song XD, 2018). A low-velocity layer exists pervasively in the crust (e.g., Shapiro et al., 2004; Guo Z et al., 2009), which may be a manifestation of crustal flow, promoting expansion of the plateau (e.g., Royden et al., 1997; Liu QY et al., 2014).

In particular, the characteristics of lithospheric deformation under Tibet have been largely revealed by constraining the seismic anisotropy (e.g., McNamara et al., 1994; Hirn et al., 1995; Lavé et al., 1996; Fu et al., 2008; Heintz et al., 2009; Chen WP et al., 2010; Zhao JM et al., 2014; Wu J et al., 2015; Wu CL et al., 2015; Singh et al., 2016)—the directional and polarizational dependence of seismic wave speeds, which is a consequence of strain-induced lattice-preferred orientation (LPO) of mineral in the Earth's mantle (Zhang SQ and Karato, 1995). The most important process producing the LPO is simple shear due to flow gradients existing in the asthenosphere, leading to a fast direction that exhibits parallel to the flow direction, whereas lithospheric compression causes anisotropy with a fast direction parallel to the strike of mountain belts. Measurement of seismic anisotropy thus represents perhaps the best tool available to directly probe the past and present patterns of deformation at depth (Long and Silver, 2009). Specifically, a change in deformational style–from simple shear on the Tibetan Plateau, transitioning to pure shear in surrounding regions–has been suggested by jointly analyzing seismic anisotropic measurements and GPS observations (Wang CY et al., 2008). Depth-variant azimuthal anisotropy in Tibet has been revealed by surface wave tomography (Pandey et al., 2015). Co-existing chan-

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nel flow and pure-shear crustal thickening have been suggested by surface-wave dispersion analysis (Agius and Lebedev, 2017). It is worth mentioning that shear-wave splitting has a high lateral resolution, but is subject to poor depth resolution, whereas surface-wave study has high depth resolution, but suffers from lateral smearing, leading to poor horizontal resolution. Body wave anisotropic tomography seemingly can provide good resolution in lateral and vertical directions simultaneously; it has also been employed to explore internal deformation of the lithosphere (Zhang H et al., 2016, 2017). In addition, two layers of anisotropy beneath western Tibet and the southern Lhasa Terrane have been observed by shear-wave splitting analysis, suggesting existence of crustal flow as the cause of the upper layer anisotropy (Gao SS and Liu KH, 2009; Wu J et al., 2015). It is worth noting that receiver function analysis has shown its importance in resolving features of anisotropic structure in the crust–in particular, in regions subject to strong crustal deformation, such as Tibet (e.g., Levin et al., 2008; Liu Z and Park, 2017). However, previous studies have tended to focus on lithospheric deformation (e.g., Zhao JM et al., 2010), leaving the underlying asthenospheric flow mostly unaddressed. Moreover, a recent dynamic model of the India-Asia collision emphasizes the role of asthenospheric flow underneath continents (Jolivet et al., 2018). Hence, understanding mantle flow may offer improved explanations of tectonic processes (Jolivet et al., 2018).

Observations of a W-E fast-axis of anisotropy in the upper mantle have suggested that an eastward flow takes place in northern Tibet (e.g., Owens and Zandt, 1997). However, the origin of such a W-E-oriented mantle flow has not been discussed. In addition, the null splitting in southern Tibet has often been attributed to downwelling of the Indian plate (e.g., Sandvol et al., 1997), but it is very unclear how the fossil fabric in the Indian mantle lithosphere (IML) could produce sporadic occurrences of null splitting and a gradual rotation of fast-axis of non-null splitting from northward to eastward. Therefore, we suggest existence of other causes, which, if not completely explaining, may be major factors in the widespread null splitting observed in southern Tibet.

To address these questions of upper mantle anisotropic signatures, we collect previous seismic anisotropic measurements and compare them to recent tomographic images. Results of this analysis leads us to propose a mantle flow model to explain the anisotropic observations; we also discuss the related tectonics and dynamics in Tibet.

2. Tectonic Setting in Tibet and Tearing of the IML

The Tibetan plateau is separated from the Himalayas by the Yarlung-Zangbo suture (Figure 1). The plateau consists primarily of three terranes that are, from south to north, the Lhasa, Qiangtang, and Songpan-Garzê terranes, separated from each other by the Bangong-Nujiang and Jinsha sutures, respectively (Figure 1). The plateau is characterized by high elevations and remarkable crustal thickness that is twice that of normal continental crust (Molnar et al., 1993).

Our current understanding of the present-day lithospheric structure of the Tibetan plateau has been greatly advanced by a series of projects like the INDEPTH (Nelson et al., 1996), INDEPTH III (Haines et al., 2003; Tilmann et al., 2003); for instance, a partially molten zone in the middle crust of southern Tibet has been detected (e.g., Owens and Zandt, 1997; Yuan XH et al., 1997). In the southern plateau, it is often believed that the IML has underthrust

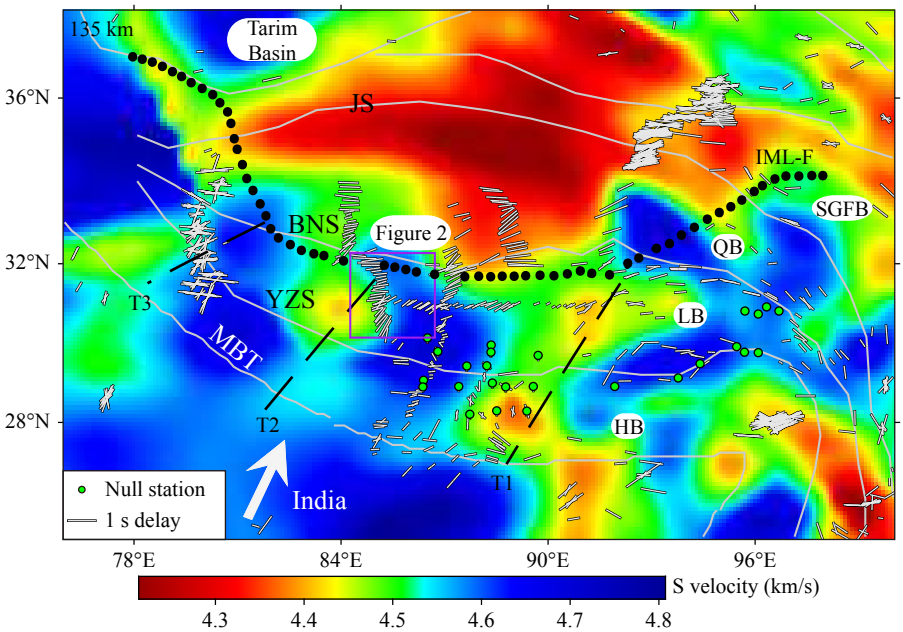

Figure 1. Comparison of S-velocity image at 135-km depth from surface-wave tomography (Bao XW et al., 2015) and previous shear wave splitting measurements (from http://splitting.gm.univ-montp2.fr/DB/public/searchdatabase.html). Circles show null measurements. The black dotted line denotes the approximate location of the northern frontier of the Indian mantle lithosphere (IML-F). The black dashed lines denote the locations of the three possible tears (T1 to T3) of the IML. The arrow indicates the Indian plate motion. BNS, Bangong-Nujiang suture; HB, Himalaya block; JS, Jinsha suture; LB, Lhasa block; QB, Qiangtang block; SGFB, Songpan-Garzê fold belt; YZS, Yarlung-Zangbo suture.

Asia to as far north as the Bangong-Nujiang suture (e.g., Zhao JM et al., 2010) and the lithospheric mantle root seems to be mostly lost (e.g., Kind et al., 2002). In the north, a thin but complex lithospheric lid is situated beneath the Qiangtang and Songpan-Garzê terranes; meanwhile, the Asian lithospheric mantle, too, seems to underthrust the northern margin of the plateau (e.g., Kind et al., 2002; Zhao WJ et al., 2011).

North-south trending rifts are widespread in southern Tibet and Himalaya. Yin A (2000) was first to propose that the mantle lithosphere must have been involved in east-west extension. Recent seismological studies have proven that tearing occurs in the IML (e.g., Liang XF et al., 2012; Chen Y et al., 2015; Liang XF et al., 2016; Li JT and Song XD, 2018). Specifically, the subducted IML has been torn into at least four pieces with different angles and northern limits; in the east and west sides, the IML is shallower and extends further, while in the middle is it steeper (Li JT and Song XD, 2018).

3. Spatial Variations of Splitting Parameters

We collected a total of 1244 measurements from previous studies (Figure 1) and divided the study area into two regions based on the characteristics of splitting measurements and also the tomographic images at the depth of 135 km. The two regions, roughly north Tibet and south Tibet, are separated approximately at 32°N. The measurements in the north are from 664 stations, while those in the south are from 580 stations.

The synthesis of fast-axis data demonstrates that the W-E direction is abundant in northern Tibet, whereas a complex pattern is seen in southern Tibet (Figure 1). Specifically, null splitting and ambiguous polarization are widespread in south Tibet and the Himalayas. A fast-axis rotation from N-S to W-E is noticeable in the central Lhasa block (Figure 2). The splitting times in northern Tibet are strikingly larger than those in southern Tibet (Figure 3). The dominant splitting times in the north are in the 1–1.5 s. range; in the south, times of 0.5–1 s. occur frequently. The former are much

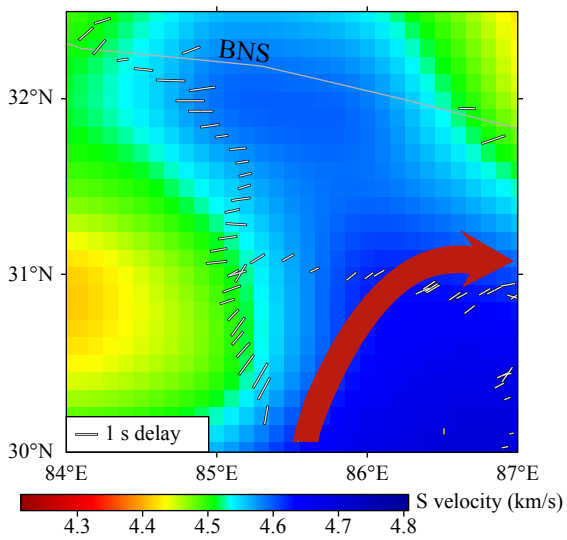

Figure 2. A close-up view of splitting results in the central Lhasa block, south Tibet. A gradual rotation of the fast-axis from northward to eastward is clearly evident, as indicated by the large red arrow.

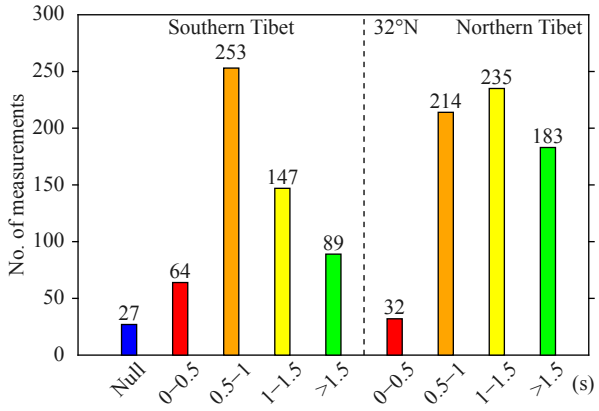

Figure 3. Histograms showing a comparison of splitting times between northern Tibet and southern Tibet.

larger than the global average of 1.0 s (Silver, 1996); the latter are significantly smaller. It appears that underplating of the Indian plate significantly lowers the splitting times and complicates the fast direction pattern. More precisely, simple and coherent splitting parameters are abundantly distributed beyond the lithospheric front of the Indian mantle (IML-F).

In addition, spatial correspondence between shear-wave splitting times and shear-wave velocity images at the 135 km depth clearly demonstrates that larger shear-wave splitting times preferentially occur beyond the IML-F, while smaller values abundantly locate within the IML-F, which is perhaps further indication that underplating of the Indian plate significantly lowers the splitting times, and that splitting times are substantially enhanced by existence of a single anisotropic layer with asthenospheric flow (Figure 4).

4. Discussion

4.1 Null Splitting in Southern Tibet

The null splitting in southern Tibet has often been attributed to downwelling of the Indian plate (e.g., Sandvol et al., 1997). However, if the null splitting is indeed due to Indian plate downwelling, we should observe clustered occurrence in the locus of downwelling instead of sporadic distribution; moreover, if the fast-axis's rotation truly occurs in the lithosphere, what deformation mechanism can account for such rotation (Figure 2)? Hence, we conclude that the source of anisotropy occurring in southern Tibet is primarily from the underlying asthenosphere, even though we cannot fully exclude contributions from downwelling of the IML.

Accordingly, we suggest that the null splitting was developed by upwellings of hot asthenosphere through tears. In other words, in addition to the three major tears (T1 to T3 in Figure 1), there may have been a large number of small tears within the underthrust Indian plate (i.e., we propose that the IML has been fragmented more intensely than envisaged by Liang XF et al. (2016)), because the small fragments have escaped detection by seismic tomography due to their size; such fragmentation could readily induce hot upwelling, leading to sporadic null splitting under south Tibet. This suggestion is supported by the spatial distribution of null splittings, which shows that they seem to occur not only near the major tears, such as T1, but also substantially far from the major

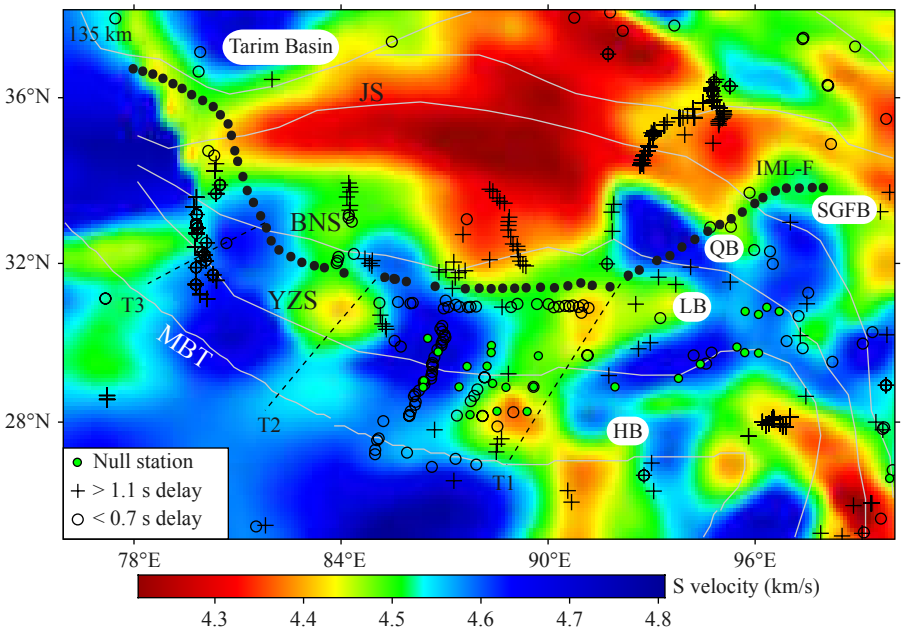

Figure 4. Spatial correspondence between shear-wave splitting time and shear-wave velocity at 135 km depth. The larger shear-wave splitting times (pluses) are found substantially beyond the IML-F, while the smaller values (circles) are located mostly within the IML-F, perhaps indicating that underplating of the Indian plate significantly lowers the splitting times and that the existence of a single asthenospheric flow enhances the splitting times.

tears (Figure 1). (Lack of detection, so far, of null splittings near T2 and T3 may be due to limited spatial coverage of stations.) Moreover, the hot upwellings may also concurrently contribute to widespread post-collisional magmatism in southern Tibet (e.g., Chung SL et al., 2005).

The null splitting is thus a direct consequence of upwellings. By constrast, the large number of non-null splittings, but with small delay times (< 1 s) in southern Tibet (Figure 4), are perhaps an integrated result of multiple layers with different oriented fast directions, as follows: the overriding Tibetan lithosphere at the top, the underplating IML in the middle, and the entrained asthenosphere at the bottom. Existence of multiple layers in southern Tibet has been suggested by various studies; for instance, two layers of anisotropy beneath western Tibet and the southern Lhasa Terrane have been observed by shear-wave splitting analysis, suggesting existence of crustal flow as the cause of the upper layer anisotropy (e.g., Gao SS and Liu KH, 2009; Wu J et al., 2015). The Tibetan multi-layer anisotropic structure has also been revealed by surface wave tomography (e.g., Pandey et al., 2015; Agius and Lebedev, 2017) and P-wave azimuthal anisotropic tomography (e.g., Zhang H et al., 2017). Overall, these observations support the conclusion that a complex anisotropic structure has been developed due to the northward indenting of Indian plate under Tibet. The small-scale anisotropic signatures will not be characterized until shear-wave splitting analysis is performed in conjunction with body-wave and surface-wave anisotropic tomography.

4.2 W-E Oriented Fast-Axis of Anisotropy in Northern Tibet

The W-E fast direction with large delay times (>1 sec.) in northern Tibet (Figure 4) has been attributed to squeezing of the asthenosphere by the northward IML beneath northern Tibet (e.g., Owens and Zandt, 1997; Liang XF et al., 2012). A gradual fast direction rotation from northward to eastward is seen near the IML-F (Figure 2), but the lithosphere is too rigid to produce such a fast-axis rotation, leaving the asthenosphere as the most likely candidate. Hence, the asthenospheric materials in northern Tibet are thought to be connected dynamically to the underlying flow below the northward Indian plate. The flow system in Tibet is hence a result of interaction of entrained flow with the flow in northern Tibet, and the interaction occurs primarily near the IML-F (Figure 5).

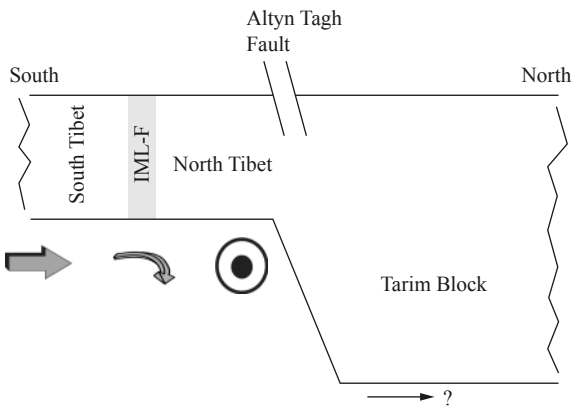

Figure 5. A sketch showing mantle flow deflected by the southern Tarim root, leading to a rotation from northward to eastward. The circle with a dot represents eastern moving flow, the straight arrow indicates the un-deflected flow, and the bent arrow represents the deflecting flow. The shadow zone depicts the IML-F where the fast direction is rotating.

Geodynamic modeling has suggested that mantle flow associated with the India-Asia collision may play an important role in tectonic processes below East Asia. Indian mantle flow may have reached the Pacific border (Jolivet et al., 2018). It has been suggested that Cenozoic rifting and volcanism in eastern China links with the lateral extrusion of the Indian asthenospheric mantle (Liu M et al., 2004). Eastward Tibetan asthenospheric flow has been seen around the southern Orods (Yu YJ and Chen Y, 2016), and the lateral flow beneath the South China craton is thought to be driven by both Pacific plate subduction and the India-Eurasia continental collision (Gong JF and Chen YJ, 2013), though no direct correlation of mantle flow beneath the North China craton to the India-Eurasia collision has been suggested by SKS wave splitting measurements (Zhao L et al., 2011).

The Tibetan block's eastward extrusion in response to the indention of the Indian plate has long been suggested by simple experiments with plasticine (Tapponnier et al., 1982). Relative to Eurasia, GPS observations show that material within the plateau interior moves roughly eastward with speeds that increase toward the east (e.g., Zhang PZ et al., 2004). Existence of eastward flow in north Tibet may thus promote eastward motion of the block.

4.3 Entrainment of Flow Driving by the Northward Indian Plate

Existence of asthenospheric flow entrained by the down-going oceanic slab has been suggested by sub-slab seismic anisotropy observations (e.g., Song and Kawakatsu, 2012), a suggestion supported also by geodynamic simulations (e.g., Liu LJ and Zhou Q, 2015). However, such a scenario in a continental subduction environment has not often been studied. Here, we propose that, initially, the entrained flow coupled with the down-going Neo-Tethyan slab. After break-off with India, the Indian plate took over the entrainment to drive continuous downward movement of the underlying flow. The shallow subduction and existence of tears promote voluminous northward flow (Figure 6). The northward flow interacts with the flow deflected by the Tarim deep root, resulting in a gradual rotation from northward to eastward, occurring near the IML-F. It is worth mentioning that a flow system entrained between the subducting Tarim lithosphere and the thick Kazakh lithospheric root has been proposed by Cherie et al. (2016), based on shear-wave splitting analyses in Tian Shan. This scenario seems to resemble the northern Tibet flow system, supportingt the hypothesis that the asthenosphere plays an important role in explaining the observed azimuthal anisotropy in continent-continent collisional settings.

4.4 Implications for Post-Collisional Magmatism in Southern Tibet

Post-collisional magmatism is widespread in Tibet, and its cause has been attributed primarily to convective removal of Tibetan lithospheric root and break-off from the Neo-Tethyan slab (e.g., Chung SL et al., 2005). However, post-collisional magmatism in the Himalayan and Lhasa blocks is thought to take place coevally during the late Oligocene to Miocene (e.g., Chung SL et al., 2003; Hou ZQ et al., 2004; Liu XC et al., 2016; Miller et al., 1999; Pan FB et al., 2012; Searle et al., 1997; Zhang HF et al., 2004). This period's igneous rocks in the Himalaya are composed of crust-derived leucogranites (e.g., Searle et al., 1997; Zhang HF et al., 2004), while the coeval igneous rocks in the Lhasa block mainly comprise mantle-derived ultrapotassic to potassic volcanics and crust-derived adakite-like porphyrys and dykes (e.g., Chung SL et al., 2003; Hou ZQ et al., 2004; Miller et al., 1999; Pan FB et al., 2012; Chen M et al., 2017; Sun X et al., 2018). More importantly, the post-collisional magmatism in the Lhasa block appears to be locally controlled by NS-striking normal faulting systems (Hou ZQ et al., 2004), which are suspected to associate with tears of the IML (Yin A, 2000). Hence, hot asthenospheric upwellings through IML tears (Figure 6) are thus able adequately to explain post-collisional magmatism in the Lhasa block. The widespread null splitting attributed to hot upwellings in the Lhasa block thus in turn supports this notion. It is worth mentioning that hot asthenospheric upwellings through slab windows or tears have also been suggested to produce intraplate volcanism in other tectonic settings (e.g., Thorkelson et al., 2011; Tang YC et al., 2014).

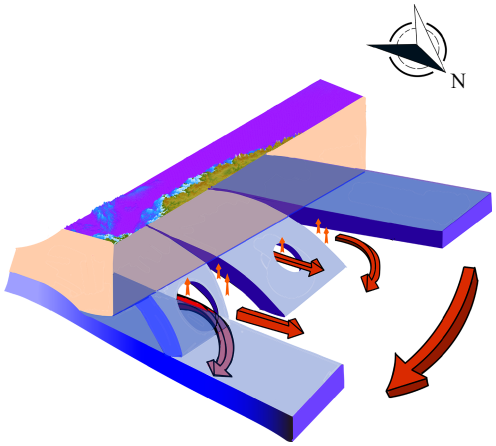

Figure 6. A cartoon illustrating the tearing of the IML along with entrained and deflected flow under Tibet. The large red arrows imply flow in the asthenosphere, and the small pink arrows depict hot asthenospheric upwellings. The thicknesses of overriding lithosphere and underplating IML are not to scale. The small tears (perhaps not seen by tomographic images due to limited resolutions) within the segments of IML are exaggerated. The tearing model of the IML is taken from the work by Li JT and Song XD (2018).

5. Conclusion

In this study, we compare previously published shear-wave splitting measurements and a recent seismic tomographic image of upper-mantle under Tibet, and suggest that an entrained flow, driven by the northward indenting Indian plate, occurs perhaps vigorously under Tibet. We propose that this flow suffers from a deflection by the deep root of the Asian lithosphere, leading to a rotation from northward to eastward. We further suggest that asthenospheric flow may play an appreciable role in facilitating block extrusion and creating post-collision magmatisms in orogenic environments such as Tibet, due to continent-continent collision. A future numerical modeling is necessary to validate our predicted flow model under Tibet.

Acknowledgments

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