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Post-ridge-subduction acceleration of the Indian plate induced by slab rollback

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Abstract

The driving forces of plate motion, especially that of its sudden change over time, has long been debated. During the closure of an old ocean, the subduction process of the mid-ocean ridge provides valuable clues to quantitative evaluation of the driving forces of plate tectonics. Here we show that the drifting rates of the Indian plate were correlated with a Late Cretaceous adakitic event hosting abundant adakites and adakitic charnockites in the Gangdese belt, southern Tibetan Plateau. While adakites form through slab melting, the ultra-high temperatures and dry nature of charnockites indicate major disturbance of the hot asthenosphere. Temporally, the oldest adakite corresponds to the initiation of the ridge subduction, whereas the youngest adakitic charnockite marks the onset of post-ridge-subduction slab rollback (steepening). Geodynamic modeling suggests that the initiation of the ridge subduction was facilitated by the Morondova mantle plume, corresponding to the lowest drifting rate of the Indian plate. Our analyses further show that the post-ridge-subduction slab rollback pushed the asthenospheric mantle backward, meanwhile it dramatically reduced the ridge-arc interaction force, leading to the first abrupt acceleration of the Indian plate. Slab rollback contributed ~3.5 cm/yr but lasted for only ~5 Ma, while slab pull, ridge push together with plume contributed ~5 cm/yr to the acceleration of the Indian plate. Our study, therefore, provides evidence for a new type of driving forces of Indian plate acceleration during the Late Cretaceous Neotethys ridge subduction.

Keywords: Ridge subduction; Slab rollback; Adakite; Tibet; Driving force

1. Introduction

The driving forces of plate tectonics have been debated for decades. Mantle convection (Bokelmann, 2002; Eaton and Frederiksen, 2007; Holmes, 1933), ridge push (Sun et al., 2007), slab pull (Capitanio et al., 2010; Chatterjee et al., 2013; Conrad and Lithgow-Bertelloni, 2002; Elsasser, 1969; Forsyth and Uyeda, 1975; van Summeren et al., 2012), and the effects of mantle plumes (Eagles and Wibisono, 2013; Gerya et al., 2015; Griffiths and Campbell, 1991; van Hinsbergen et al., 2011) as well as subsidence of dense lithosphere (Arculus et al., 2015; Niu, 2016; Niu et al., 2003) have all been proposed as driving forces of plate tectonics, but their relative contributions to plate motion, especially to its spatial–temporal variations, have not been well determined. Part

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of the reason is the lack of direct comparison among these forces. Closure of the Neotethys Ocean during the Late Cretaceous involved a phase of ridge subduction, plume emplacements, coupled with dramatic plate velocity variations and arc magmatism (Ji et al., 2014; Jiang et al., 2015; Ma et al., 2013, 2015; Wu et al., 2015; Xiong et al., 2016; Xu et al., 2015). Here we show that the drifting rate of the Indian plate was correlated with the subduction of the Neotethys spreading ridge and post-ridge-subduction slab rollback, providing an opportunity to evaluate the contributions of driving force to plate motions.

2. Materials and methods

We use a modified version of the finite element code CitcomS (Tan et al., 2006), where we incorporated a pseudo free surface in modeling subduction (Liu and Stegman, 2011) and a plastic overriding plate to properly simulate the subduction zone coupling. The 2D mesh covers a 5000 km east-west dimension and a 2000 km in depth. A spatially variable numerical resolution is adopted with a minimum local grid size of ~3 km within the subducting plate above 200 km depth (Fig. 1). The subducting Indian plate has a layered rheology with a strong dense core and a plastic buoyant crust (Stegman et al., 2006). The plate contains a ridge on both ends, which exert a northward push on the Indian plate after the northern end subducts. The Morondova plume is simulated with an excess temperature of ~200 °C and a diameter of ~150 km emplacing beneath the southern side, exerting an additional northward push.

Geochemical compositions of Gangdese adakite were analyzed in the State Key Laboratory of Isotope Geochemistry. Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The fresh and pollution-free samples for geochemical analyses were first ground to less than 200 mesh (0.5200 ± 0.0001 g), and then fluxed with $Li_2B_4O_7$ (1:8) to make homogeneous glass disks at 1250 °C using a V8C automatic fusion machine produced by the Analymate Company in China. The bulk rock major elements were analyzed using X-ray fluorescence spectrometry techniques (Rigaku 100e). The analytical errors for major elements were better than 1%.

The samples for trace element analysis (<200 mesh) were first dissolved using distilled HF + HNO_3 in screw-top Teflon

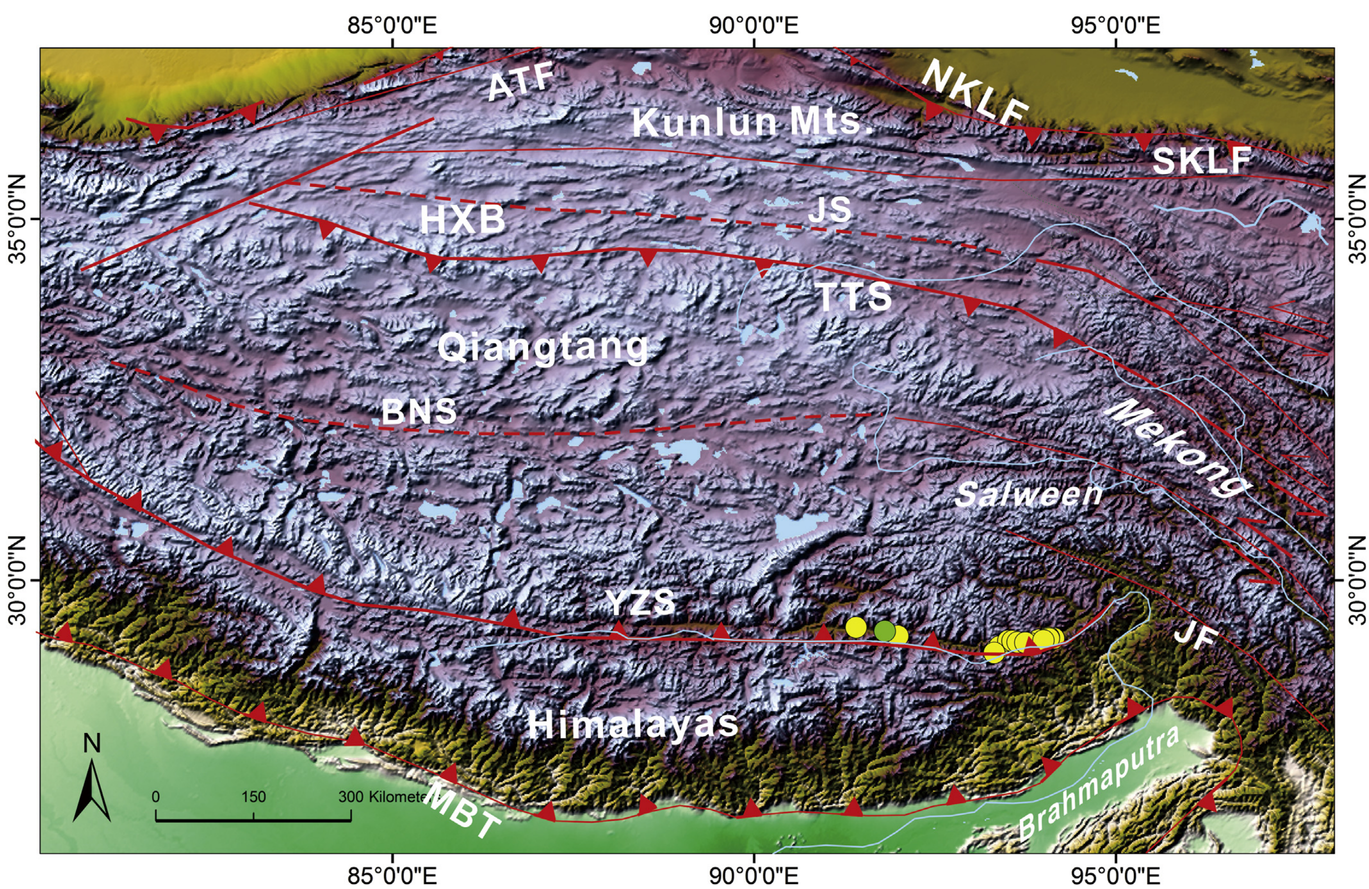

Fig. 1. Distribution of Late Cretaceous adakites and adakitic charnockites (circles) in the Gangdese belt, south Tibet (Ma et al., 2013; Wen et al., 2008; Zhang et al., 2010). Also shown are major tectonic units and rivers of the Tibetan Plateau. HXB, Hoh Xil basin; NKLF, north Kunlun fault; SKLF, south Kunlun fault; ATF, Altyn Tagh fault; TTS, Tanggula thrust system; JF, Jiali fault; JS, Jinsha suture zone; BNS, Bangong− Nujiang suture zone; YZS, Yarlung Tsangpo suture zone; MBT, main boundary thrust. Blue circle is the location of our own samples, where yellows are locations of literature samples.

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beaker for 7 days at 100 °C (Liu et al., 1996; Ling et al., 2014). Trace elements of those samples were analyzed by inductively coupled mass spectrometry (ICP–MS) at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, The Chinese Academy of Sciences, Guangzhou (Li et al., 2012; Lin et al., 2016). The analytical uncertainty of the elements examined here was better than 5% for ICP-MS analysis, except for a few samples with low contents of trace elements for which the uncertainty was about 10%. The obtained values of trace elements in the AGV-3 standard are all consistent with their recommended values.

3. Results

More and more Cretaceous adakites and adakitic charnockite have been reported in the Gangdese belt. Most of these adakite and adakitic charnockite plot in “slab melting” field (Figs. 2 and 3), which are closely related to subduction of young oceanic crust (Defant and Drummond, 1990; Sun et al., 2012). In contrast, some of the Cenozoic adakites from the same belt formed through partial melting of thickened continental crust (Fig. 3), which is attributed to the collision between the Indian and the Eurasia continents (Chung et al., 2009; Wang et al., 2005). Interestingly, adakitic charnockite is systematically older than those of normal adakite (Fig. 4). The most straightforward explanation is ridge subduction. The age and special distributions of Cretaceous adakite and adakitic charnockite (Figs. 1 and 4) provide constraints on the subduction history of the Neotethys spreading ridge, which correlates well with the drifting history of the Indian plate (Fig. 5).

We have simulated the ridge subduction process in a fully dynamic numerical model. Our results show that around 8 million years after the emplacement of the Morondova mantle

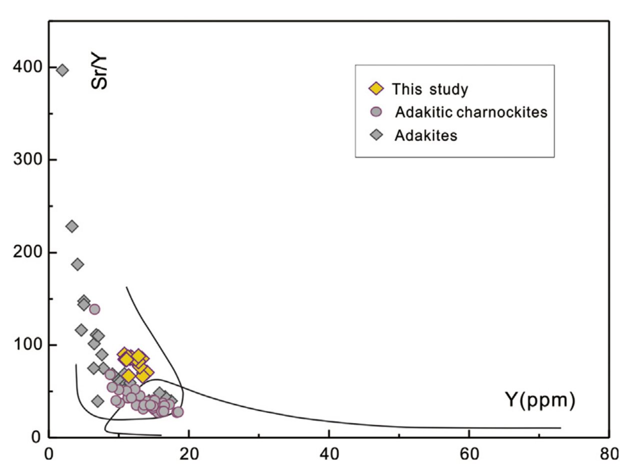

Fig. 2. Sr/Y versus Y diagram, which discriminates adakites from normal arc rocks after (Defant and Drummond, 1990; Sun et al., 2012). Late Cretaceous adakites and adakitic charnockites in the Gangdese belt, south Tibet plot in the adakite field. Data (Guan et al., 2010; Jiang et al., 2012; Kang et al., 2010; Ma et al., 2013; Wen et al., 2008; Zhang et al., 2010) are listed in Supplementary Table 1.

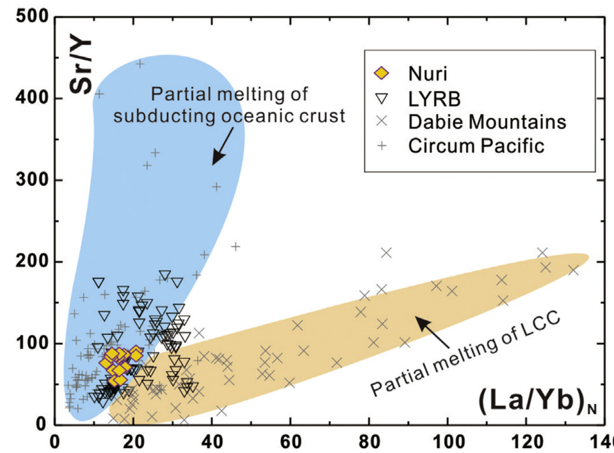

Fig. 3. Sr/Y versus $(La/Yb)_N$ diagram which discriminates adakites of different origins. The field defined by circum-Pacific adakites formed through partial melting of subducted oceanic slabs, whereas the field defined by adakites from the Dabie Mountains formed through partial melting of thickened lower continental crust. Most of the Cretaceous (78–100 Ma) adakites and adakitic charnockites of the Gangdese belt plot in the slab melting field, supporting a ridge subduction model.

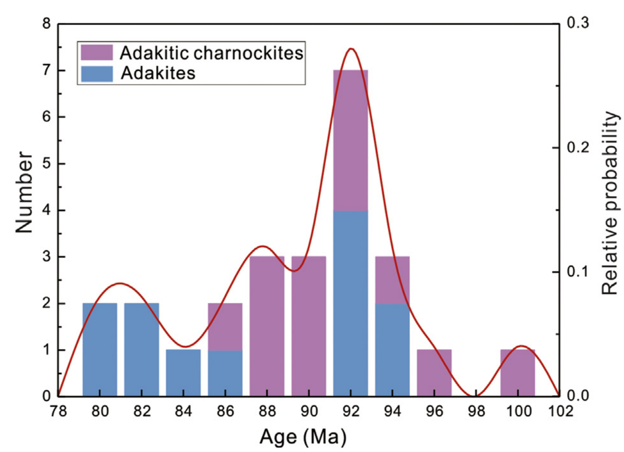

Fig. 4. Age distribution of Late Cretaceous adakites and adakitic charnockites in the Gangdese belt, south Tibet. Data are listed in Supplementary Table 1. Note the peak of adakitic charnochite is coincident with the lowest drifting rates of the Indian plate.

plume, the subducting plate reaches a peak velocity of ~75 mm/Myr, and this time also marks the largest slab angle dipping (Figs. 6 and 7). After this time, the slab becomes stable with a marginally smaller plate velocity. Our modeling results further show that the effect of slab rollback represents a short-term driving force that decreases quickly over time (Figs. 5–7). Remarkably, the drifting rate of the Indian plate decreased by more than 3 cm/yr in the east at ~84 Ma (Fig. 5). Plume and normal slab pull contributed ~5 cm/yr to the acceleration of the Indian plate. The slab rollback contributed ~3.5 cm/yr but lasted for only ~5 Ma (Fig. 5).

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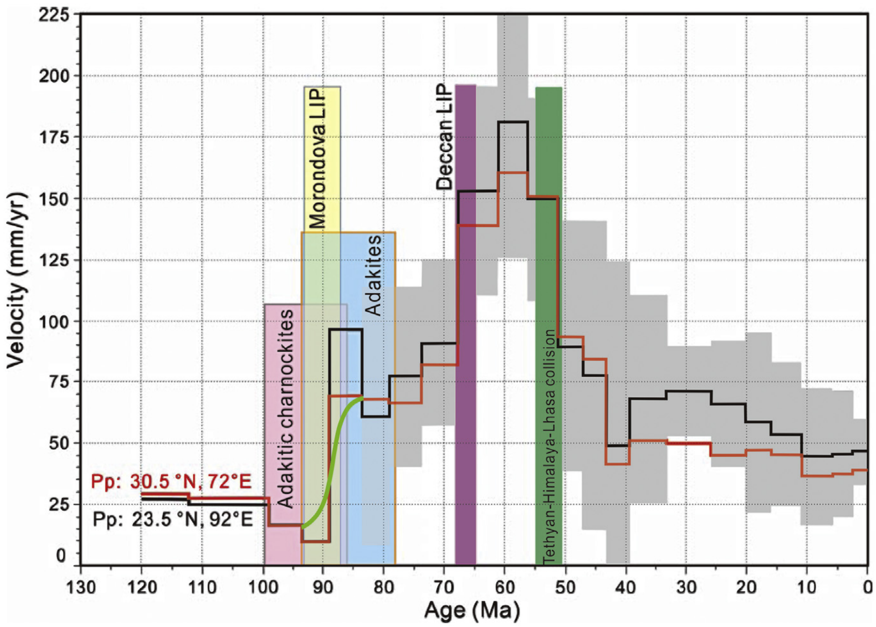

Fig. 5. The drifting history of the Indian plate, modified after ref (van Hinsbergen et al., 2011). The thick black and red lines represent the drifting history of two points in the eastern and western Himalayan syntaxis, respectively. The eastern and western drifting rates were similar to each other at the beginning, but were dramatically different during the abrupt acceleration at ~88 Ma. Also shown are the durations of adakites and adakitic charnockites emplacement (~100−86 Ma) (Ma et al., 2013; Wen et al., 2008; Zhang et al., 2010), initiation of Morondova (~93 Ma) (Bardintzeff et al., 2010; Torsvik et al., 2000) and Deccan (65 Ma) mantle plume activity (van Hinsbergen et al., 2011), and the collision between the Indian and Eurasian continent (van Hinsbergen et al., 2011). Note, the Morondova plume commenced at ~93 Ma (Bardintzeff et al., 2010), corresponding to the lowest drifting rate of the Indian plate. The thick green line during the adakite event represents the predicted Indian plate velocity from geodynamic modeling (Fig. 7).

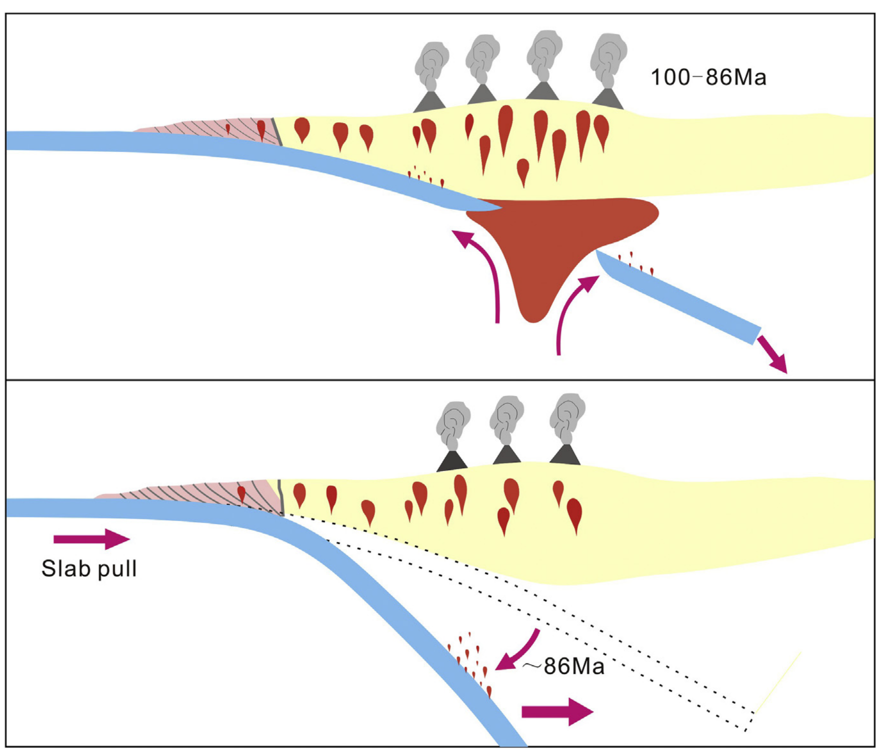

Fig. 6. Cartoons illustrating the effects of ridge subduction and slab rollback. (a) The Neotethys spreading ridge collided with the convergent margin at ~ 100 Ma, resulted in the deceleration of the Indian plate. Meanwhile, the subducted front (north) plate moved faster than the subducting south plate, leaving behind an opening slab window, which explains the formation of adakitic charnockites. (b) The initiation of slab rollback further disturbed the asthenospheric mantle, which accelerated the Indian plate and promoted the formation of adakitic charnockite. As slab rollback continued, the subducting slab became older, cooler and wetter, such that no adakitic charnockite formed.

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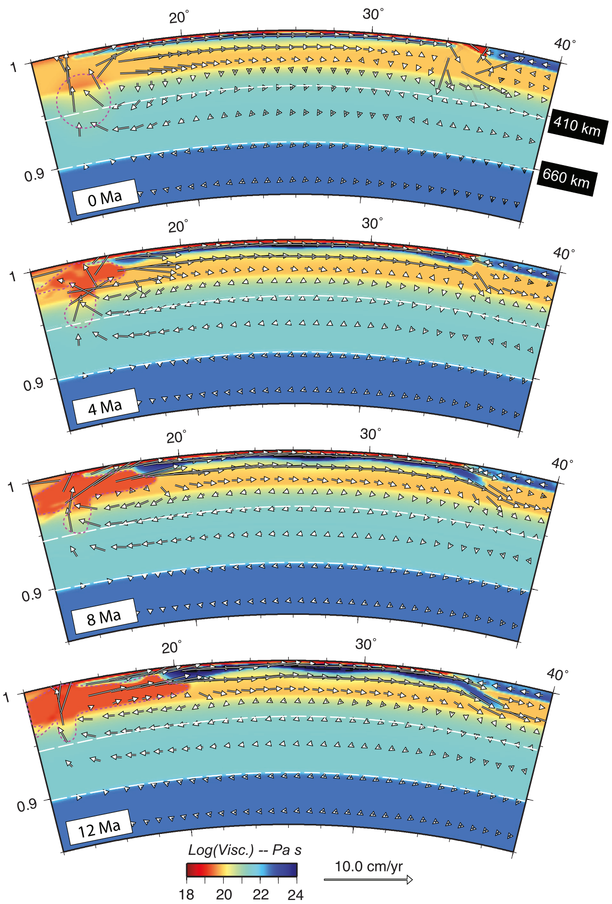

Fig. 7. Dynamic numerical model of northward Indian subduction during Late Cretaceous. Subduction is initiated by an ascending plume head on the southern side (0 Ma), and sustained by the spreading plume head within the asthenosphere until ~8 Ma. Slab pull starts to take over the driving force after 4 Ma when the northern end of the Indian lithosphere sinks to >100 km. The background color represents the effective viscosity structure, where the weak layer on top the subducting plate mimics a layer of 'sticky air'. Arrows indicate flow velocities. A four-layer ambient viscosity with strong temperature dependence and a visco-plastic rheology is adopted in calculating mantle flow.

4. Discussion

A considerable amount of Late Cretaceous adakites and adakitic charnockites are linearly distributed along the Gangdese belt, southern Tibet, roughly parallel to the subduction zone (Figs. 1–4, Supplementary Table 1) (Ma et al., 2013; Wen et al., 2008; Zhang et al., 2010). Adakites formed between 78 and 93 Ma, whereas adakitic charnockites formed between 86 and 99.5 Ma. This adakitic event has been attributed to the subduction of the Neotethys ridge (Zhang et al., 2010). Geochemical discrimination diagrams show that most of these adakitic rocks are similar to circum-Pacific adakites (Fig. 3), which were formed by dehydration partial melting of subducted young oceanic slabs at wet eclogite phases (Defant and Drummond, 1990; Ding et al., 2009; Sun et al., 2015, 2013, 2012; Xiong et al., 2011; Zhang et al., 2017). This is supported by positive whole rock ε_{Nd} and zircon ε_{Hf} values (Zhang et al., 2010).

Charnockites are orthopyroxene-bearing igneous rocks or granitic orthogneisses occurring in varies high temperature tectonic regimes, e.g., granulite terranes or deeply eroded arcs (Frost and Frost, 2008). Charnockites are characterized by ultra-high temperatures (up to 1000 °C) and very low water contents (Frost and Frost, 2008). Considering that an adakitic signature identifies an origin of slab melting, whereas a charnockite identifies high temperatures and low water activities, these Tibetan adakitic charnockites can best be explained by the opening of a slab window during ridge subduction.

As shown by the Farallon plate (Liu et al., 2008), for parallel ridge subduction, the subducting leading plate (e.g., the northern plate of the Neotethys ridge) should move faster than the rear plate (e.g., the southern plate) during the ridge subduction. Therefore, a slab window should have opened at the early stage of the ridge subduction, resulting in the exposure of the overriding plate to the high temperature asthenospheric mantle (Sun, 2016). As a consequence, the dry and/or dehydrated portions of the subducting slab might be partially melted, forming dry and hot adakitic charnockites. In principle, normal adakites would have already formed before adakitic charnockites. Nevertheless, early adakites may not have survived in a highly eroded arc as suggested by the association of granulite and adakitic charnockite (Zhang et al., 2010), i.e., exposure of the root of the arc.

This ridge subduction coordinates well with the drifting history of the Indian plate (van Hinsbergen et al., 2011). Ridge subduction is also known as ridge-arc interaction, during which the drifting of the subducting plate should be slowed down due to resisting forces from the collision of buoyant ridge and arc systems. The oldest Late Cretaceous adakitic rocks in the Gangdese formed at ~100 Ma, which is coincident with the first major deceleration of the Indian plate (Fig. 5). The lowest drifting rate of the Indian plate (Fig. 5) is coincident with the peak of the Late Cretaceous adakitic event (Fig. 4). These suggest that ridge subduction was the main reason that deceleration of the Indian plate occurred between 100 and 88 Ma.

Remarkably, the lowest drifting rate of the Indian plate was followed by an abrupt acceleration of the entire Indian plate at ~88 Ma (increasing by ~8.5 cm/year in the east and ~5.5 cm/year in the west) (Fig. 5), which commenced just before the end of the adakitic charnockite event (~86 Ma). For a parallel a ridge subduction, the opening of the slab window commences when the front limb of the ridge sinks, which disturb the asthenosphere and resulting in high temperature magmas. This is followed by rollback of the rear limb, which disturbs the asthenosphere again. Given that both a subducting young oceanic slab for producing slab melts and high temperatures for producing charnockite are required to form adakitic charnockite, the youngest adakitic charnockites should have formed shortly after the onset of slab rollback, during which the slab dip angle increases (Fig. 6). The coincidence of the abrupt acceleration of the Indian plate and the adakitic charnockite event implies that the acceleration was likely due to slab rollback.

The abrupt acceleration of the Indian plate was previously attributed to the eruption of the Morondova mantle plume (van Hinsbergen et al., 2011). This mantle plume, however, is located to the southwest of the Indian plate, which presumably should

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have accelerated the west part of the Indian plate more seriously than the east part. This is in direct contrast to the actual drifting rates, i.e., the acceleration in the east is ~50% higher than that in the west (Fig. 5) (van Hinsbergen et al., 2011). More importantly, the Morondova mantle plume commenced at ~93 Ma ago (Bardintzeff et al., 2010; Torsvik et al., 2000), which corresponds to a deceleration and the lowest drifting rate of the Indian plate, and predates the abrupt acceleration by ~5 Ma (Fig. 5) (van Hinsbergen et al., 2011). Note, the Deccan plume commenced at the same time as the onset of the second acceleration of the Indian plate (Fig. 5) (Eagles and Wibisono, 2013). The effects of the Morondova plume were likely counterbalanced by the subduction of the Neotethys ridge. It may have a major contribution to the initiation/subduction of the Neotethys ridge, but unlikely to be the main driving force responsible for the abrupt acceleration of the Indian plate at ~88 Ma.

Our geodynamic modeling show that, by overcoming the ridge buoyancy on the north, the plate starts to subduct at a very slow rate (<2.0 cm/yr) during the first few million years. As long as the crust sinks deeper than 100 km, it loses its positive buoyancy after completion of the basalt-eclogite phase transformation (Ahrens and Schubert, 1975), allowing the subduction rate to speed up. The push of the Morondova plume acts as a major driving force before 8 million years (Fig. 7), as can be seen from the increasing northward velocities within the plume head accompanying progressive thickening of the Indian lithospheric root due to lateral compression. On the other hand, the continuing acceleration of subduction after the plume is fully emplaced in the asthenosphere after 4 million years (Fig. 7) allows the down-going oceanic lithosphere to exert an increasing slab pull on the northward moving Indian plate. This can be seen from the steady increase of subduction speed on the northern side. As a result, the overall northward motion of the Indian plate demonstrates a rapid increase during the model period (Figs. 5 and 7).

The coincidence of the adakitic charnockite event with Indian plate's acceleration (Fig. 5) and the detailed geodynamic modeling (Fig. 7) suggest that the post-ridge-subduction slab rollback acted as a main driving force for plate motion. Slab rollback also marks the cessation of ridge-arc interaction, during which the resistance against the drifting of the Indian plate disappeared. Meanwhile, it also enhanced the slab pull force due to the negative buoyancy of the dense eclogitic crust (Ahrens and Schubert, 1975; Chatterjee et al., 2013), the direction of which is vertically downward. In contrast, the direction of slab pull is horizontal. This requires a mechanism to transform the vertical driving force into a horizontal pull. Slab rollback is the most efficient way to transform the vertical gravitational force into a horizontal force, which pushes mantle materials backward and thus drives the plate forward, analogous to an oar (Fig. 6).

The lack of decrease in plate velocity in the west after 84 Ma (Fig. 5) was likely due to different subduction regimes. There is a wide distribution of Late Cretaceous adakites and adakitic charnockites in the Gangdese belt, situated near the east syntaxis (Figs. 1—4), indicating subduction of the Tethys mid-ocean ridge. However, there are much fewer adakitic rocks but more Late Cretaceous ophiolites in the west part of the Neotethys convergent margin within the Zagros belt and Dazhuqu regions (Abrajevitch et al., 2005; Ali et al., 2012; Moghadam et al., 2013), implying that ridge obduction instead of ridge subduction happened in the west. The inferred transition between ridge subduction and obduction is likely located near the west syntaxis, which has strong influences to the drifting in the west.

5. Conclusions

In general, slab rollback may lead to two major consequences, backarc extension and acceleration of the subducting plate. In case of the Neotethys ridge subduction, there is no evidence for a backarc basin associated with the slab rollback. This is likely due to the strong northward push from the new Indian Ocean spreading ridge and the Morondova plume, which minimized arc extension along the Gangdese convergent margin.

Heat from the Earth's interior is the primary energy source of plate motion, whereas well focused heat loss, including spreading ridges, mantle plumes, and subducting slabs, is the main process that drives plate tectonics (Sun et al., 2007) by focusing the gravitational force along localized plate boundaries. Our study shows that slab rollback is an additional driving force that efficiently transforms vertical gravitational force into horizontal slab pull, through pushing mantle materials backward. We propose that slab rollback can be categorized as a type of slab pull, and this short-term force only acts on a 5—10 million-year-scale when the subduction angle deepens.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.sesci.2017.12.003.

References

Abrajevitch, A.V., et al., 2005. Neotethys and the India-Asia collision: insights from a palaeomagnetic study of the Dazhuqu ophiolite, southern Tibet. Earth Planet Sci. Lett. 233 (1—2), 87—102.

Ahrens, T.J., Schubert, G., 1975. Gabbro-eclogite reaction-rate and its geophysical significance. Rev. Geophys. 13 (2), 383—400.

Ali, S.A., et al., 2012. Recognition of late cretaceous hasanbag ophiolite-arc rocks in the kurdistan region of the iraqi Zagros suture zone: a missing link in the paleogeography of the closing Neotethys Ocean. Lithosphere 4 (5), 395—410.

Arculus, R.J., et al., 2015. A record of spontaneous subduction initiation in the Izu-Bonin-Mariana arc. Nat. Geosci. 8 (9), 728—733.

Bardintzeff, J.M., Liegeois, J.P., Bonin, B., Bellon, H., Rasamimanana, G., 2010. Madagascar volcanic provinces linked to the Gondwana break-up: geochemical and isotopic evidences for contrasting mantle sources. Gondwana Res. 18 (2—3), 295—314.

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Bokelmann, G.H.R., 2002. Which forces drive North America? Geology 30 (11), 1027−1030.

Capitanio, F.A., Morra, G., Goes, S., Weinberg, R.F., Moresi, L., 2010. India-Asia convergence driven by the subduction of the Greater Indian continent. Nat. Geosci. 3 (2), 136−139.

Chatterjee, S., Goswami, A., Scotese, C.R., 2013. The longest voyage: tectonic, magmatic, and paleoclimatic evolution of the Indian plate during its northward flight from Gondwana to Asia. Gondwana Res. 23 (1), 238−267.

Chung, S.L., et al., 2009. The nature and timing of crustal thickening in Southern Tibet: geochemical and zircon Hf isotopic constraints from postcollisional adakites. Tectonophysics 477 (1−2), 36−48.

Conrad, C.P., Lithgow-Bertelloni, C., 2002. How mantle slabs drive plate tectonics. Science 298 (5591), 207−209.

Defant, M.J., Drummond, M.S., 1990. Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature 347, 662−665.

Ding, X., et al., 2009. Natural and experimental constraints on formation of the continental crust based on niobium-tantalum fractionation. Int. Geol. Rev. 51 (6), 473−501.

Eagles, G., Wibisono, A.D., 2013. Ridge push, mantle plumes and the speed of the Indian plate. Geophys. J. Int. 194 (2), 670−677.

Eaton, D.W., Frederiksen, A., 2007. Seismic evidence for convection-driven motion of the North American plate. Nature 446 (7134), 428−431.

Elsasser, W.M., 1969. Convection and stress propagation in the upper mantle. In: Runcorn, S.K. (Ed.), The Application of Modern Physics to the Earth and Planetary Interiors. Wiley-Interscience, London, pp. 223−246.

Forsyth, D., Uyeda, S., 1975. Relative importance of driving forces of plate motion. Geophys. J. Roy. Astron. Soc. 43 (1), 163−200.

Frost, B.R., Frost, C.D., 2008. On charnockites. Gondwana Res. 13 (1), 30−44.

Gerya, T.V., Stern, R.J., Baes, M., Sobolev, S.V., Whattam, S.A., 2015. Plate tectonics on the Earth triggered by plume-induced subduction initiation. Nature 527 (7577), 221-+.

Griffiths, R.W., Campbell, I.H., 1991. Interaction of mantle plume heads with the earths surface and onset of small-scale convection. J. Geophys. Res. Solid Earth 96 (B11), 18295−18310.

Guan, Q., et al., 2010. Late cretaceous adakites in the eastern segment of the gangdese belt, southern Tibet: products of neo-tethyan ridge subduction? Acta Petrol. Sin. 26 (7), 2165−2179.

Holmes, A., 1933. The thermal history of the Earth. J. Wash. Acad. Sci. 23, 169−195.

Ji, W.Q., Wu, F.Y., Chung, S.L., Liu, C.Z., 2014. The Gangdese magmatic constraints on a latest Cretaceous lithospheric delamination of the Lhasa terrane, southern Tibet. Lithos 210, 168−180.

Jiang, Z.Q., et al., 2012. Late Cretaceous (ca. 90 Ma) adakitic intrusive rocks in the Kelu area, Gangdese Belt (southern Tibet): slab melting and implications for Cu-Au mineralization. J. Asian Earth Sci. 53, 67−81.

Jiang, Z.Q., et al., 2015. Zircon U-Pb geochronology and geochemistry of Late Cretaceous-early Eocene granodiorites in the southern Gangdese batholith of Tibet: petrogenesis and implications for geodynamics and Cu +/− Au +/− Mo mineralization. Int. Geol. Rev. 57 (3), 373−392.

Kang, Z.Q., Xu, F.J., Chen, J.L., Wang, B.D., Dong, Y.H., 2010. The geochronology of Sangri Group volcanic rocks in Tibet: constraints from later Mamen intrusions. Geochemica 39 (6), 520−530.

Li, C.Y., et al., 2012. The formation of the Dabaoshan porphyry molybdenum deposit induced by slab rollback. Lithos 150, 101−110.

Lin, J., Liu, Y., Yang, Y., Hu, Z., 2016. Calibration and correction of LA-ICP-MS and LA-MC-ICP-MS analyses for element contents and isotopic ratios. Solid Earth Sci. 1 (1), 5−27.

Ling, M.X., Liu, Y., Zhang, H., Sun, W.D., 2014. Sample preparation and x-ray fluorescence analysis of sulfide ores. Anal. Lett. 47 (9), 1598−1605.

Liu, Y., Liu, H.C., Li, X.H., 1996. Simultaneous and precise determination of 40 trace elements in rock samples using ICP-MS. Geochimica 25 (6), 552−558 (in Chinese with English abstract).

Liu, L.J., Spasojevic, S., Gurnis, M., 2008. Reconstructing Farallon plate subduction beneath North America back to the late cretaceous. Science 322 (5903), 934−938.

Liu, L.J., Stegman, D.R., 2011. Segmentation of the Farallon slab. Earth Planet Sci. Lett. 311 (1−2), 1−10.

Ma, L., et al., 2015. Late Cretaceous back-arc extension and arc system evolution in the Gangdese area, southern Tibet: geochronological, petrological, and Sr-Nd-Hf-O isotopic evidence from Dagze diabases. J. Geophys. Res. Solid Earth 120 (9), 6159−6181.

Ma, L., et al., 2013. Late Cretaceous (100−89 Ma) magnesian charnockites with adakitic affinities in the Milin area, eastern Gangdese: partial melting of subducted oceanic crust and implications for crustal growth in southern Tibet. Lithos 175, 315−332.

Moghadam, H.S., Corfu, F., Stern, R.J., 2013. U-Pb zircon ages of Late Cretaceous Nain-Dehshir ophiolites, central Iran. J. Geol. Soc. 170 (1), 175−184.

Niu, Y.L., 2016. Testing the geologically testable hypothesis on subduction initiation. Sci. Bull. 61 (16), 1231−1235.

Niu, Y.L., O'Hara, M.J., Pearce, J.A., 2003. Initiation of subduction zones as a consequence of lateral compositional buoyancy contrast within the lithosphere: a petrological perspective. J. Petrol. 44 (5), 851−866.

Stegman, D.R., Freeman, J., Schellart, W.P., Moresi, L., May, D., 2006. Influence of trench width on subduction hinge retreat rates in 3-D models of slab rollback. Geochem. Geophys. Geosys. 7.

Sun, W.D., 2016. Initiation and evolution of the South China Sea: an overview. Acta Geochimica 35 (3), 215−225.

Sun, W.D., Ding, X., Hu, Y.H., Li, X.H., 2007. The golden transformation of the Cretaceous plate subduction in the west Pacific. Earth Planet Sci. Lett. 262 (3−4), 533−542.

Sun, W.D., et al., 2015. Porphyry deposits and oxidized magmas. Ore Geol. Rev. 65, 97−131.

Sun, W.D., et al., 2013. The link between reduced porphyry copper deposits and oxidized magmas. Geochem. Cosmochim. Acta 103, 263−275.

Sun, W.D., et al., 2012. Geochemical constraints on adakites of different origins and copper mineralization. J. Geol. 120 (1), 105−120.

Tan, E., Choi, E., Thoutireddy, P., Gurnis, M., Aivazis, M., 2006. GeoFramework: coupling multiple models of mantle convection within a computational framework. Geochem. Geophys. Geosys. 7.

Torsvik, T.H., et al., 2000. Late Cretaceous India-Madagascar fit and timing of break-up related magmatism. Terra. Nova 12 (5), 220−224.

van Hinsbergen, D.J.J., Steinberger, B., Doubrovine, P.V., Gassmoller, R., 2011. Acceleration and deceleration of India-Asia convergence since the Cretaceous: roles of mantle plumes and continental collision. J. Geophys. Res. Solid Earth 116.

van Summeren, J., Conrad, C.P., Lithgow-Bertelloni, C., 2012. The importance of slab pull and a global asthenosphere to plate motions. Geochem. Geophys. Geosys. 13.

Wang, Q., McDermott, F., Xu, J.F., Bellon, H., Zhu, Y.T., 2005. Cenozoic K-rich adakitic volcanic rocks in the Hohxil area, northern Tibet: lower-crustal melting in an intracontinental setting. Geology 33 (6), 465−468.

Wen, D.R., et al., 2008. Zircon SHRIMP U-Pb ages of the gangdese batholith and implications for neotethyan subduction in southern Tibet. Chem. Geol. 252 (3−4), 191−201.

Wu, H., Li, C., Hu, P.Y., Li, X.K., 2015. Early cretaceous (100-105 Ma) Adakitic magmatism in the Dachagou area, northern Lhasa terrane, Tibet: implications for the Bangong-Nujiang ocean subduction and slab break-off. Int. Geol. Rev. 57 (9−10), 1172−1188.

Xiong, Q., et al., 2016. Southward trench migration at similar to 130−120 Ma caused accretion of the Neo-Tethyan forearc lithosphere in Tibetan ophiolites. Earth Planet Sci. Lett. 438, 57−65.

Xiong, X.L., et al., 2011. Partitioning of Nb and Ta between rutile and felsic melt and the fractionation of Nb/Ta during partial melting of hydrous metabasalt. Geochem. Cosmochim. Acta 75 (7), 1673−1692.

Xu, W.C., Zhang, H.F., Luo, B.J., Guo, L., Yang, H., 2015. Adakite-like geochemical signature produced by amphibole-dominated fractionation of arc magmas: an example from the Late Cretaceous magmatism in Gangdese belt, south Tibet. Lithos 232, 197−210.

Zhang, C.C., et al., 2017. Oxygen fugacity and porphyry mineralization: a zircon perspective of Dexing porphyry Cu deposit, China. Geochem. Cosmochim. Acta 206, 343−363.

Zhang, Z.M., et al., 2010. Late Cretaceous charnockite with adakitic affinities from the Gangdese batholith, southeastern Tibet: evidence for Neo-Tethyan mid-ocean ridge subduction? Gondwana Res. 17 (4), 615−631.

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