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Large igneous provinces linked to supercontinent assembly

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ABSTRACT

Models for the disruption of supercontinents have considered mantle plumes as potential triggers for continental extension and the formation of large igneous provinces (LIPs). An alternative hypothesis of top-down tectonics links large volcanic eruptions to lithospheric delamination. Here we argue that the formation of several LIPs in Tarim, Yangtze, Lhasa and other terranes on the Eurasian continent was coeval with the assembly of the Pangean supercontinent, in the absence of plumes rising up from the mantle transition zone or super-plumes from the core–mantle boundary. The formation of these LIPs was accompanied by subduction and convergence of continents and micro-continents, with no obvious relation to major continental rifting or mantle plume activity. Our model correlates LIPs with lithospheric extension caused by asthenospheric flow triggered by multiple convergent systems associated with supercontinent formation.

1. Introduction

The breakup of Phanerozoic and Proterozoic supercontinents such as Pangea, Rodinia and Columbia has commonly been linked to mantle plumes generated from the mantle transition zone, or super-plumes rising from the core–mantle boundary, with the process accompanied by the formation of large igneous provinces (LIPs) and the related deep-mantle source magmas (Morgan, 1971, 1972; Griffiths and Campbell, 1991; Ernesto et al., 2002; Ernst et al., 2005, 2013; Ernst, 2014; Maruyama et al., 2007; Arndt et al., 2008; Murphy et al., 2009; Santosh et al., 2009; Bryan and Ferrari, 2013; Nance et al., 2014; Kawai et al., 2013). It has also been suggested that plate subduction and oceanic ridge formation are the result of mantle plumes or convective mantle flow in the asthenosphere (Peltier, 1989; Anderson, 1998). Recent investigations from the Eurasian continent (Fig. 1; Deccan, Lhasa, Emeishan, Tarim, and Siberia; Chung and Jahn, 1995; Pirajno, 2000; Zhang et al., 2010, 2012, 2014; Zhu et al., 2010) show that the formation of 290–250 Ma LIPs in Emeishan and Tarim may not be related to the breakup of Pangea, but may instead be related to the assembly of this supercontinent.

In the case of the Emeishan and Tarim LIPs and Traps, many workers have invoked a mantle plume or even super-plume connection (Chung and Jahn, 1995; Pirajno, 2000; Xu et al., 2004; Zhang et al., 2010, 2013; and references therein), although the plume hypothesis and the alternative lithospheric delamination hypothesis are both inconsistent with new geological, geochemical, and paleomagnetic data, as evaluated in this study. Here we emphasize the possible link between the formation of LIPs and the assembly of supercontinents, and attempt to resolve the debate on the origin of the Emeishan and Tarim LIPs through a careful analysis of the geology, tectonics, paleomagnetism, and magma compositions in relation to plate convergence. Based on our analysis, we propose a new model of asthenospheric flow caused by multiple subduction systems as the dominant trigger for extensional tectonics and LIP formation.

2. Evidence for the 290–250 Ma events and related global tectonics

2.1. Regional characteristics of two LIPs and their time-scales

The Tarim LIP formed during the period ~290–275 Ma (e.g. Zhang et al., 2010, 2012) or slightly earlier at ~300 Ma (Zhang et al., 2013) and is located in the interior and northern margins of the Tarim Block. Its tectonic setting is post- or syn-orogenic (Figs. 2A and 3A), suggesting that the LIP formed during the closure of the Central Asian Ocean, after or during the Tianshan orogeny. A rift system formed in the center of the Tarim Block and along its northern margin. The LIP contains basalt as well as some felsic volcanics, and dykes of gabbro formed mainly parallel to the rift zones, rather than as giant radiating swarms. The magmas included kimberlite, rhyolite, alkaline-basalt, diabase, and gabbro, and their geochemical features suggest OIB and fore-arc material (Zhang et al., 2010, 2012).

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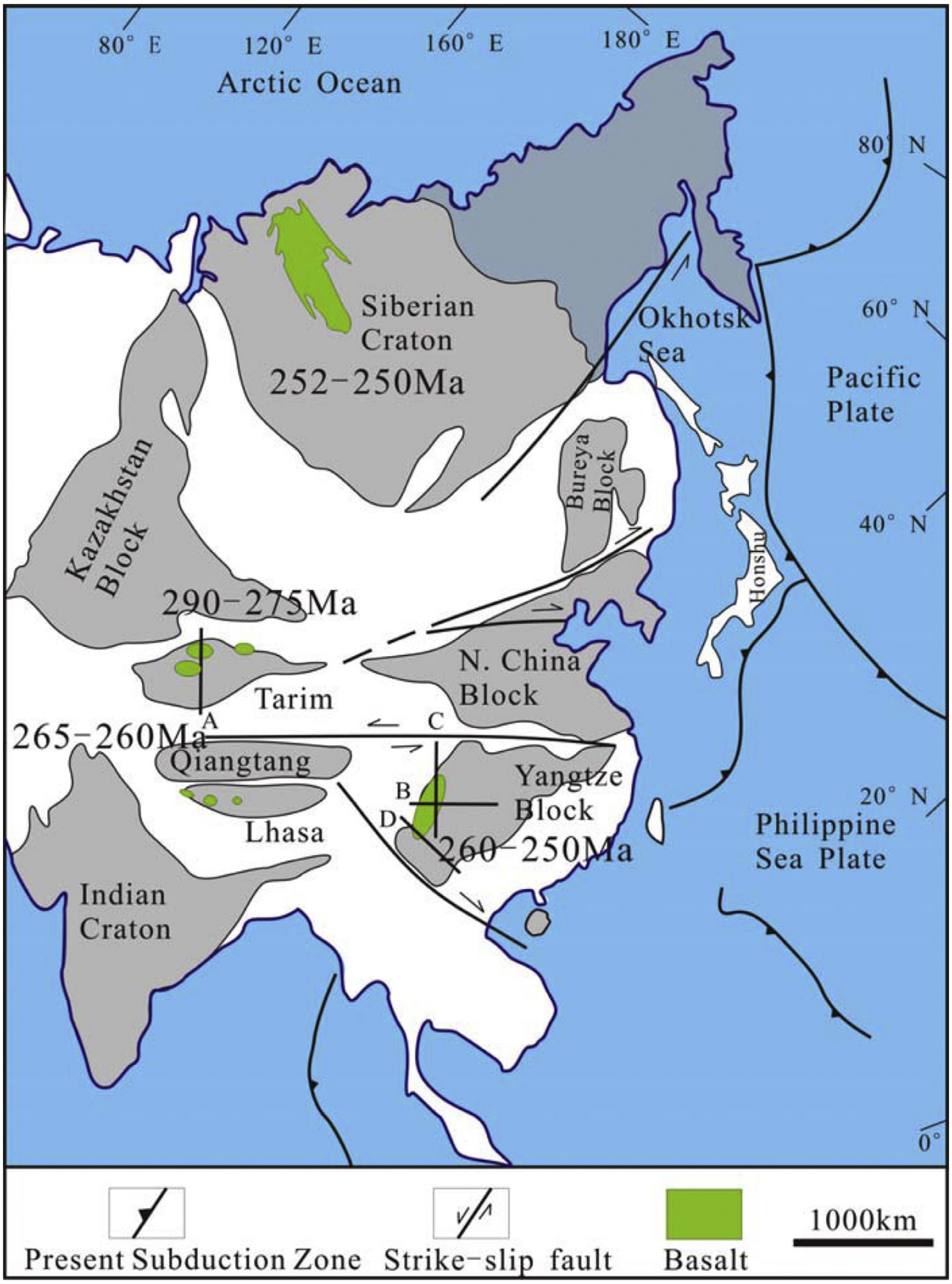

Fig. 1. Distribution of four major LIPs in the Eurasian continent and their regional tectonic settings (compiled from Sorkhabi and Heydari, 2008). Age data are from various studies (Deccan, Lhasa, Emeishan, Tarim, and Siberia; Pirajno, 2000; Zhang et al., 2010, 2012; Chung and Jahn, 1995; Zhu et al., 2010). Locations of geological cross sections of Fig. 3 are shown.

The Emeishan LIP occurs within the Yangtze Block, and Shellnutt et al. (2012) reported high precision zircon CA-TIMS U—Pb ages with a narrow range from 257 Ma to ~260 Ma (Figs. 2B and 3B–D) for the Panxi intrusive suite in the inner zone of the LIP. Prior to the LIP formation, this region witnessed coeval submarine sedimentation and subaerial basalt eruptions in time and space (Wang et al., 2014), but the sedimentation is not merely of shallow water setting (Ukstins Peate and Bryan, 2008). During the early stages of the LIP, rift systems formed along the western margin and in the interior of the Yangtze Block (Fig. 2B). Mafic–ultramafic dyke swarms and sheets formed along N–S trending rift zones, and V—Ti—Fe mineral deposits formed in association with the gabbros (Pang et al., 2013; Pecher et al., 2013).

The Emeishan basaltic rocks contain mega-phenocrysts of feldspar, and rhyolites occur in the bottom and upper layers. Overall, the rocks display OIB characteristics (Xiao et al., 2004) with the signature of recycled oceanic crust (Zhu et al., 2005). Some studies also reported the eruption of picrite, considered to be important evidence for a mantle plume (Zhang et al., 2006). However, more recently it has been argued that these picrites were actually sourced from the lithospheric mantle (Kamenetsky et al., 2012) or the asthenosphere (Hao et al., 2011), and that the subducted oceanic slab was remelted to form the picritic porphyries (Kou et al., 2012). These arguments suggest the rocks are not primary mantle material, contradicting the mantle plume hypothesis in earlier studies (e.g., Zhang et al., 2006; Xu et al., 2004). Moreover, the

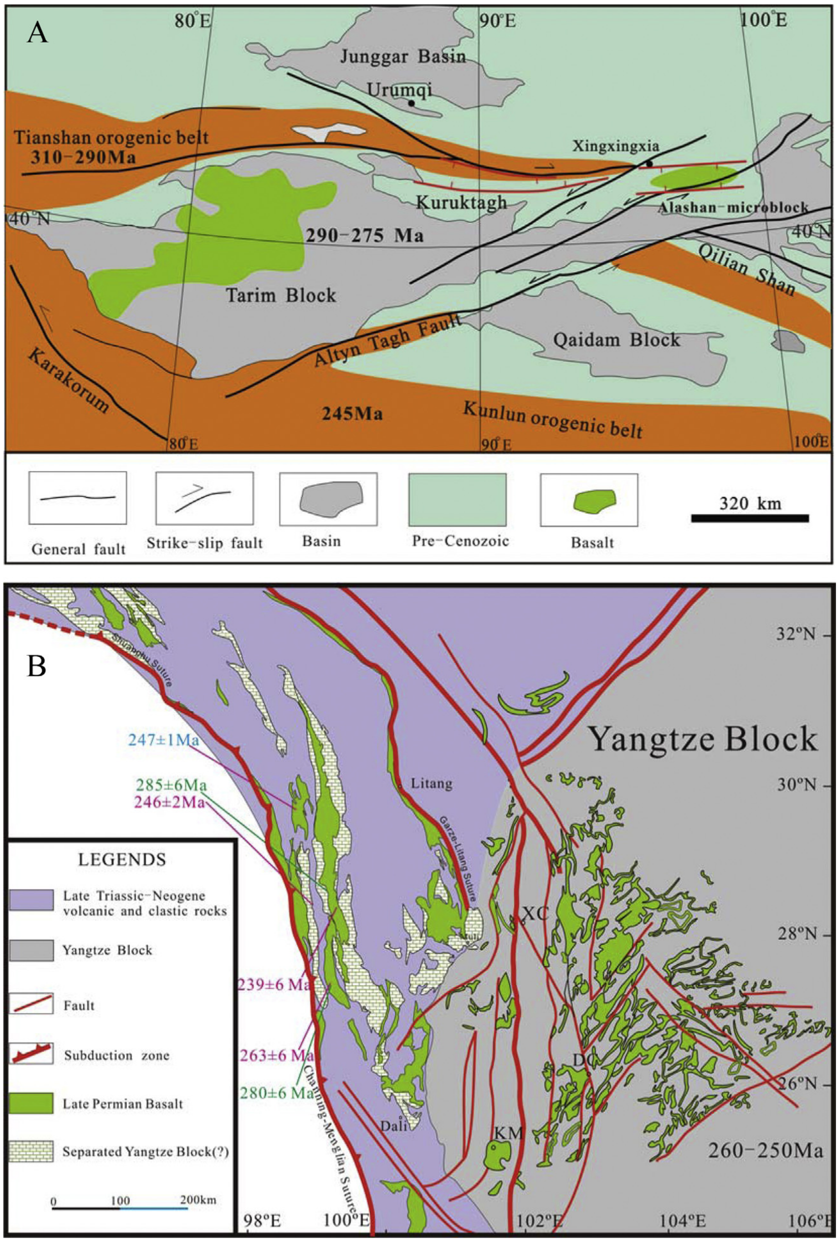

Fig. 2. Regional tectonic framework, location of LIPs and convergent boundaries, and distribution of LIP-related volcanic rocks. (A) Tarim LIP relative to its surrounding tectonics (compiled from Wang et al., 2010). (B) Emeishan LIP and related Yangtze tectonics (compiled from Yang et al., 2012; Xu et al., 2004).

geochemical data indicate the involvement of oceanic crust that was subducted under the Yangtze Plate (Zhu et al., 2005).

2.2. *Tectonic regimes and frameworks: local and regional characteristics*

In the Tarim Block and adjacent regions, there was local marginal extension, but the region mainly underwent contraction in association with the Kunlun and Tianshan orogenic belts along the southern and northern margins, respectively (Figs. 2A and 3A), followed by uplift and erosion. The northward subduction and collision in the Tianshan orogenic belt culminated in the late Carboniferous–Early Permian, and intracontinental deformation ensued (Fig. 3A). The southern margin of the Tarim Block experienced basaltic eruptions and late stage subduction and collision during 250–230 Ma (Wang et al., 2010) (Fig. 3A). It is clear, therefore, that from at least 290 Ma to later than 250 Ma, the Tarim Block and surrounding areas were in a tectonic regime dominated by N–S directed compression. Along the northern margin of the Tarim Block, subduction occurred from ~320 to 290 Ma (Wang et al., 2008). Along the southern margin of the Tarim Block, subduction and collision occurred around 250–230 Ma, forming the west Kunlun orogenic belt (Wang et al., 2010, and references therein).

In the case of the Emeishan LIP, most of the basaltic eruptions took place within a N–S rift system along the western side of the Yangtze Block (Fig. 2B). The western side of the block experienced subduction-related island arc magmatism during 280–240 Ma (Jian et al., 2009; Yang et al., 2012) related to E–W directed contraction and strike-slip motion (Fig. 3B). Island-arc rocks with ages of 270–250 Ma have been reported from the western part of the Yangtze Plate (Xiao et al., 2008; Jian et al., 2009; Yang et al., 2012), contemporaneous with or earlier than the Emeishan LIP. The volcanic arc and zone of subduction define a belt that extends from east Kunlun to the west of the Yangtze Block. At the time

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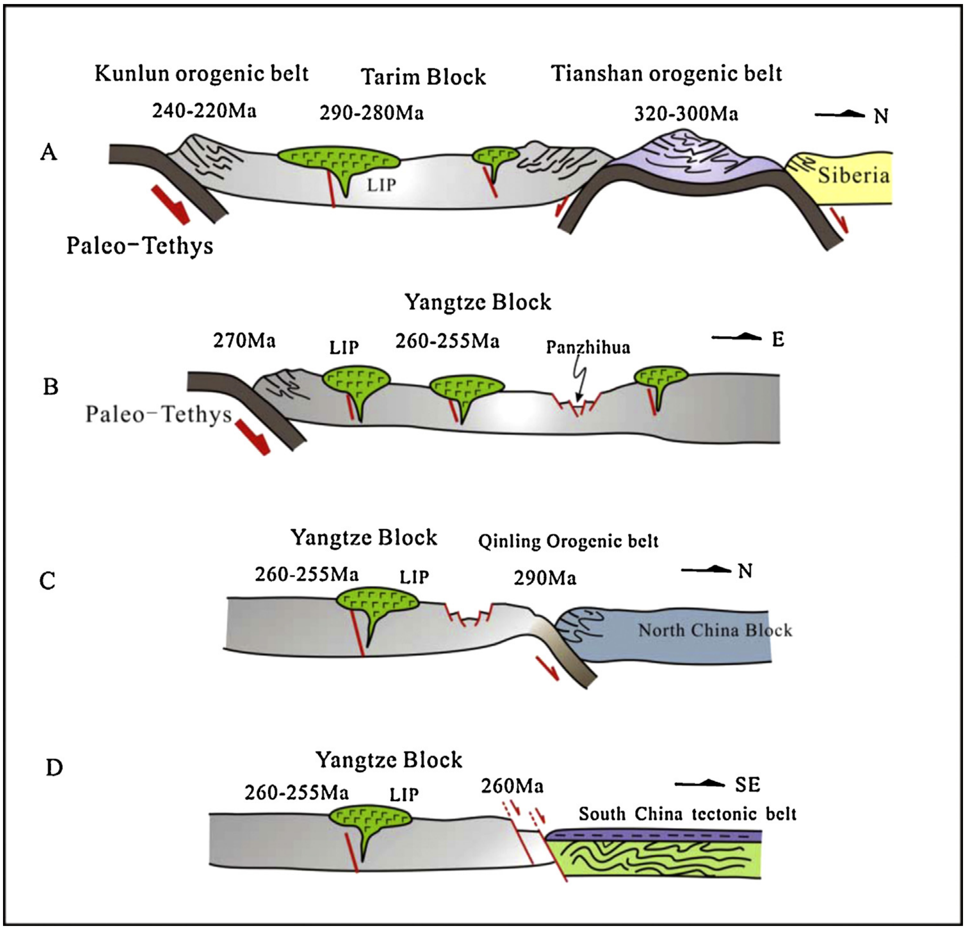

Fig. 3. Sketched sections of tectonics in the region with subduction, collision and volcanic eruptions (based on Jian et al., 2009; Wang et al., 2008, 2010; Zhang et al., 2010; Yang et al., 2012; and this study). (A) From the Kunlun orogenic belt, Tarim Block to the Tianshan orogenic belt, northwards. (B) From the Paleo-Tethys to the Yangtze Block, eastwards. (C) From the Yangtze Block, Qinling oeogenic belt to the north China Block, northwards. (D) From the Yangtze Block to the southeastern China tectonic belt, southeastwards.

of formation of the Emeishan LIP, the northern margin of the Yangtze Block witnessed subduction and collision of the Yangtze Block and North China Craton in a tectonic regime of N–S directed compression (Fig. 3C), but rifting occurred on the southeastern side (Fig. 3D) that is connected to the south China tectonic belt.

Thus, during the period 290–250 Ma, the marginal regions of the Yangtze and Tarim plates provide evidence of subduction and mountain building whereas the rest of the region experienced no obvious thrusting or folding (Wang et al., 2008, 2010; Jian et al., 2009; Yang et al., 2012). Convergence, subduction, and north-directed horizontal movements resulted in the closure of the east Paleo-Tethys ocean at this time (Sorkhabi and Heydari, 2008) (Figs. 2B, 3B, C and 4), accompanied or immediately followed by voluminous eruptions of basalt (Fig. 2). The eruptions were mainly along the western margin of the Yangtze Block, and the northern margin and north-central parts of the Tarim Block, where there were ancient tectonic or orogenic belts. There are no giant radiating dyke swarms in the Tarim Block, or Yangtze Block, but in both areas the volcanic rocks were erupted along zones that represent local extension.

2.3. Polar-wandering paths: convergent features

The Yangtze Block was separated from Gondwana at around 500 Ma, and subsequently moved northward (Huang et al., 2008). By 290 Ma, it was situated at 30–40° N, and at 260 Ma it was located at 24° N (Fig. 4B). The Tarim Block mainly moved northward. At 500 Ma it was in the region of the South Pole, but by 280 Ma it had moved to 40° N (Stampfli and Borel, 2002; Huang et al., 2008; Veevers, 2012), close to its present position, and collided and converged with the Kazakhstan Plate and Siberian Plate. The Siberian Plate was located at 30–50° N from 300 Ma to 250 Ma, and there is no clear evidence of any N–S longitudinal movements (Cocks and Torsvik, 2007). All the surrounding plates or micro-blocks such as Lhasa and Qiangtang (Fig. 1; belonging to south Tibet and north Tibet, respectively; Zhang et al., 2014) moved together from south to north during the period from 300 to 250 Ma (Stampfli and Borel, 2002). At around 230 Ma, the collage of these blocks reached its present position (Fig. 4B). The closure of the western Paleo-Tethys, and the associated convergence and collision of the continental blocks, took place at about 280 Ma (Stampfli and Borel, 2002; Veevers, 2004, 2012; Nance et al., 2012), and this coincides with the formation of the western part of Pangea. At the same time, the eastern part of Paleo-Tethys was still closing, and continents such as Tarim, Yangtze, Lhasa, Qiangtang, and others were converging, accompanied by basaltic eruptions at 290–250 Ma.

Therefore, during the period 290–250 Ma, the Tarim, Yangtze and Lhasa blocks were converging and moving from south to north, closing on the Siberian continent (Fig. 4), and the tectonic regime was dominated by continental convergence (Figs. 1, 3 and 4A), not divergence. This south-to-north convergence continued until 250–230 Ma. Global tectonic reconstructions show that the construction of Pangea included the following phases: closure of the Proto-Tethys from ~290 to 280 Ma (leading to the

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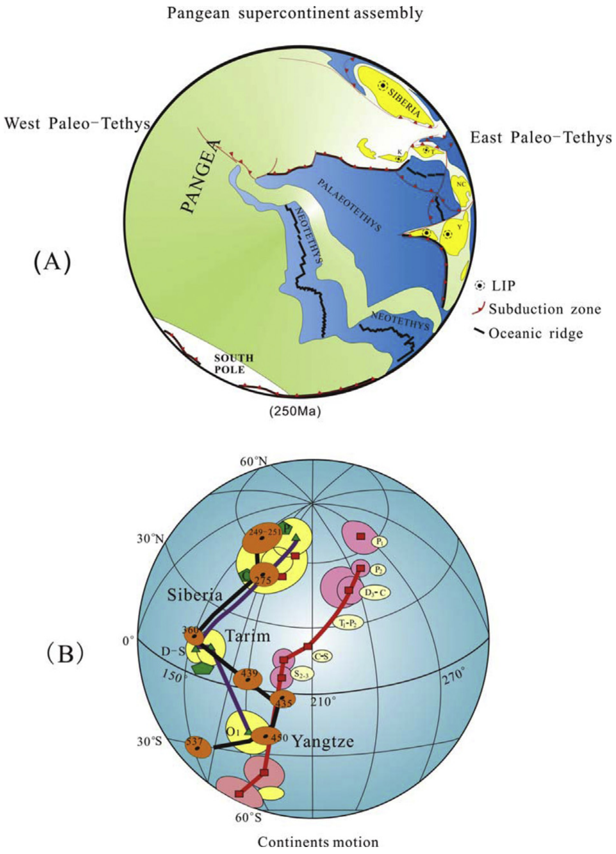

Fig. 4. Large igneous provinces linked to supercontinent assembly. (A) Global convergence of different plates during the 250 Ma time-interval, with specific reference to the formation of the supercontinent Pangea (compiled from Stampfli and Borel, 2002; Zhu et al., 2010; Xu et al., 2004; Saunders et al., 2005). In the figure, T – Tarim; Y – Yangtze; NC – North China. (B) Compilation of paleomagnetic data for the Siberia, Tarim, and Yangtze plates (data compiled from Cocks and Torsvik, 2007; Huang et al., 2008). Motion of the Siberia, Tarim, and Yangtze plates are from south to north, and their convergence formed Pangea.

construction of the Central Asian Orogenic belt); closure of the western Paleo-Tethys between Laurentia and Gondwana (concluding the formation of the Variscan orogen in western Pangea) at around 280 Ma (Veevers, 2004, 2012; Nance et al., 2012); and the onset of closure of the eastern part of the Paleo-Tethys from 290 to 250 Ma. By this time the western sector of the Paleo-Tethys was one continental mass, but the eastern part contained various continental fragments that were moving northward. After 250–230 Ma, the final phase of continental collision and closure of the Tethys and Neo-Tethys continued along the western side of the Yangtze Block.

3. Discussion

3.1. *Conflicting hypotheses for LIPs: geological and paleomagnetic evidence*

The mantle plume hypothesis of Morgan (1971, 1972) proposed that mantle hot-spots exist beneath moving plates. The hypothesis was extended to explain how a plume could interact with the overlying lithosphere and cause rifting and continental breakup (e.g., Storey, 1995; Courtillot et al., 1999; Hawkesworth et al., 1999; Pirajno, 2000). Other significant suggestions are: (1) that the material source for a plume is the core–mantle boundary (e.g. Maruyama et al., 2007), (2) that plume activity is accompanied by giant radiating dyke swarms (Ernst and Buchan, 1997), and (3) that the crust undergoes domal uplift on the kilometer-scale (Campbell, 2005). However, with regard to the LIPs formed between about 290 and 250 Ma, the geological and paleomagnetic evidence summarized above, conflicts with the plume hypothesis and suggests that LIPs coincided with the assembly of the supercontinent Pangea, and not with any major breakup event.

There are several reasons why the Tarim and Emeishan LIPs are probably not related to the postulated two mantle plumes. First, there are no radiating dyke swarms, and no features typical of mantle head and tail magmatism in the LIP that Zhang et al. (2006) advocated. Second, previous reports of a 1-km domal uplift before the formation of the Emeishan LIP (He et al., 2003, 2011) are based on fold interference patterns associated with at least three phases of deformation in sedimentary layers. Third, the basal conglomerate described by He et al. (2003, 2011) is in fact a fault breccia, as also observed in the upper part of the Emeishan basaltic system (Wang et al., 2014). Fourth, the kimberlites in the LIPs, which are interpreted to constitute evidence for a mantle plume (Wei et al., 2014), coexist with rhyolite and other felsic rocks, suggesting that they are related instead to a rift system. These rock types were emplaced over a long interval, from ~290 to 275 Ma. Fifth, so-called "primary magma" in the Emeishan LIP (Zhang et al., 2006) was actually sourced from the lithosphere or the subcontinental lithospheric mantle, rather than the convective asthenosphere or a deep mantle plume (Kamenetsky et al., 2012). In the Tarim and Emeishan LIPs, only some characteristics are compatible with the mantle plume hypothesis such as the sudden large-scale basaltic eruptions over a short time span.

The earlier models (Morgan, 1971, 1972; Griffiths and Campbell, 1991) do not explain several features of the 290–250 Ma LIPs: their tectonic setting, the input of oceanic crust materials, plate convergence, the construction of a supercontinent, the lack of evidence for any core–mantle boundary materials, and the absence of giant radiating dyke swarms. Another major problem is that during the formation of the Emeishan and Tarim LIPs there was no regional extension, either before or during the basaltic eruption. The nature of the magmatism, geological evidence, paleomagnetic data and plate motion reconstructions for the period 290–250 Ma, all show that from the Late Proterozoic to the Early Triassic, the main continents, including the Siberian continent, were converging, and in the Triassic the Chinese continent, especially the Yangtze and Tarim blocks, and the Siberian continent united to form a single Eurasian continent with Laurentia, which then combined with Gondwana to form the Pangean supercontinent.

Anderson's model (2001) of lithospheric delamination has also been used to explain the 290–250 Ma LIPs. This would require delamination on a wide scale, but the problem is lack of clear evidence for major crustal-lithospheric shortening–thickening during or prior to LIP formation, and the tectonic setting is therefore incompatible with a major delamination event. Even if all of the delaminated lithospheric material had been remelted, with all the magma erupted at the surface, it is still not possible to explain the observed large-scale basaltic eruptions. It is unrealistic to explain the formation of the Tarim and Emeishan LIPs with the lithospheric delamination model.

Local rift zones did form during LIP formation, but they occur in narrow regions and over short time intervals, as for example in the Yangtze and Tarim blocks (Fig. 2). These local extensional/rift zones are clearly unrelated to any widespread breakup of the Pangea supercontinent. The breakup of Pangea started after the Late Triassic, and took place mainly after the Middle-Jurassic at the same time as the formation of the Atlantic Ocean and the rapid formation of the Pacific Plate from 180 to 165 Ma (Bartolini and Larson, 2001; Veevers, 2004, 2012). The formation of Pangea was accompanied by several LIPs in different continents when the Lhasa Block and other regions in Eurasia (Fig. 1) experienced volcanic eruptions between 290 and 250 Ma. These global features suggest that the overall regional tectonic stresses were

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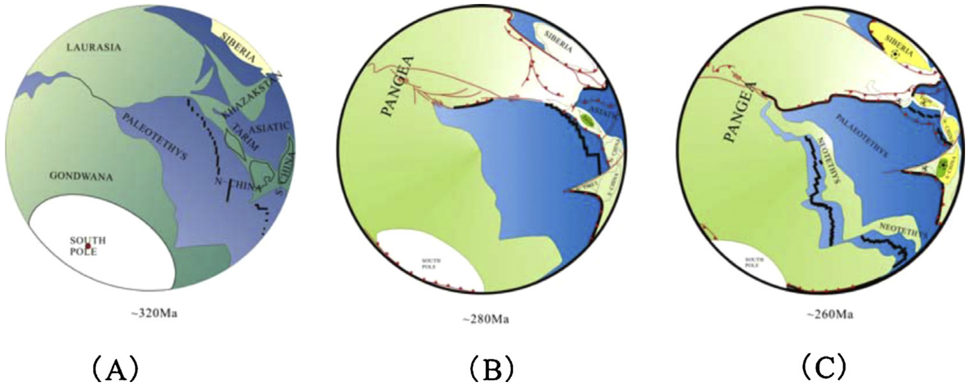

Fig. 5. Evolution of the Paleo-Tethys Ocean from ~320 Ma to 260 Ma (simplified from Stampfli and Borel, 2002). (A) At ~320 Ma, the Laurasia and Gondwana continents converged, resulting in the closure of the west Paleo-Tethys Ocean and the formation of the western part of the Pangea supercontinent. Meanwhile, west-to-east sub-horizontal mantle flow was initiated, influenced by movement in the asthenosphere. (B) At 280 Ma, large-scale strike-slip motion formed along the margins of continents or blocks, parallel to the direction of mantle flow, and this resulted in the formation of LIPs in the Tarim Block and adjacent regions, rifting, and local extension. (C) At 260 Ma, the Emeishan LIP formed, while western and northern parts of the Yangtze Plate were the sites of subduction and continent–continent convergence.

compressive, not extensional, except for local extension during the basaltic eruptions in the Yangtze and Tarim plates.

3.2. Proposed asthenospheric flow and its process

Traditionally, plate tectonics and the mantle convention hypothesis suggest that during plate subduction, the coupled mantle sinks into the lower mantle or even to the D″ layer of the mantle–core boundary, which is interpreted to be the source of mantle plumes (Morgan, 1971, 1972). However, subduction-induced mantle flow has recently been suggested and modeled by Schellart (2008, 2010). A number of recent papers presenting geodynamic subduction models have shown that upper mantle subduction with strong slab rollback motion generates strong sub-horizontal toroidal return flow in the sub-lithospheric upper mantle (Schellart, 2008). In a more recent work it was shown that such sub-horizontal toroidal flow drives the motion of tectonic plates (in particular the overriding plate) and also drives backarc extension (Schellart and Moresi, 2013). In addition it has been shown that subduction and slab rollback are associated not only with strong horizontal flows, but also with strong upwelling flows in a number of locations (in particular within the region surrounding lateral slab edges and in the distant part of the mantle wedge region) that could be responsible for intraplate magmatism (Schellart, 2010; Strak and Schellart, 2014). The horizontal motion and deformation of the frontal part of a slab located at the 660 km discontinuity can generate motion and deformation in the surrounding mantle (Strak and Schellart, 2014). Mantle flow can also drive motion in the surrounding lithosphere, as well a marginal strike-slip motion (e.g., Allen et al., 2006). When asthenospheric flow runs counter to that of the lithosphere, rift systems may form on the margins or interior of the plate, resulting in decompression melting of the mantle (Strak and Schellart, 2014). These new findings strongly suggest that the initial formation of mantle flow, such as during the 320–260 Ma time interval, was related to convergence at the western part of Pangea supercontinent, which would have produced asthenospheric flow from west to east (Fig. 5A). Lateral asthenospheric flow would produce lithospheric-scale marginal strike-slip motion and rift systems, and may explain the following features: the transcurrent motion of Siberia along the Laurussian margin (Sears, 2012) in the north Paleo-Tethys Ocean (Fig. 5B); extension and strike-slip motion in the western and southern Siberian Craton (Allen et al., 2006), as well as in the Tianshan orogenic belt during the early Permian (Natal'in and Şengör, 2005; Wang et al., 2008) along the trans-Eurasian structure (Natal'in and Şengör, 2005); and extension and strike-slip motion on the margin of the Yangtze Plate (Fig. 5C). Relative motion between the lithosphere and upper asthenosphere results in decoupling of the mantle and upper asthenospheric flow, and global westward drift of the lithosphere (Doglioni et al., 2014).

Lebedev et al. (2006) reported that sub-horizontal asthenospheric flow occurs in continental rift zones. Mantle flow can result in the movement of continents, in addition to rift formation such as the Baikal rift (Lebedev et al., 2006). Local extension and rift features within the Tarim, Yangtze, and Siberia continental blocks may also be related to asthenospheric flow and subsequent tear of the continent prior to LIP formation. Moreover, the asthenosphere itself cannot be assumed to be stationary or disturbed only by the drag from the lithosphere above (Lebedev et al., 2006). Not only are lithospheric-scale strike-slip zones and rift systems formed, but mafic–ultramafic intrusions are associated with major crustal structures (Lightfoot and Evans-Lamswood, 2015). These structures are linked to mantle-penetrating fractures associated with magmatism in the roots of large igneous provinces (Lightfoot and Evans-Lamswood, 2013, 2014). Typically, mantle plumes are a major control on rift structures (e.g., Allen et al., 2006); however, there are many rift systems that are related to asthenospheric or mantle flow rather than mantle plumes, such as the Baikal rift (Lebedev et al., 2006).

Thus, a four-stage evolution of asthenospheric flow can be proposed (Fig. 6) as follows. The initial formation of asthenospheric flow (Fig. 6A); flow resulting in lithospheric-scale strike-slip motion (Fig. 6B); local extension and continent or plate tearing and rifting (Fig. 6C and D); and finally, convergence of asthenospheric flows moving in different directions, resulting in the formation of huge LIPs (Fig. 6E).

3.3. Global asthenospheric perturbations and the convergence of continents during LIP formation

There is no robust evidence for picrite as an important primary source, but various reports point to its presence as inclusions of asthenospheric material, or as olivine rich cumulate. The materials might have also come from the lithosphere–asthenosphere transitional zone (Peate and Hawkesworth, 1996; Bryan and Ernst, 2008). The presence of picritic basalts and various other geochemical features indicate that the magmas associated with some LIPs, but not all, were derived in part from the lithospheric or asthenospheric mantle (Peate and Hawkesworth, 1996; Yaxley, 2000; Sobolev et al., 2007; Kamenetsky et al., 2012; Zhang et al., 2012). Some inferred mantle plumes elsewhere contain similar materials, as in the cases of Hawaii (from convected asthenosphere; Sobolev et al., 2005) and

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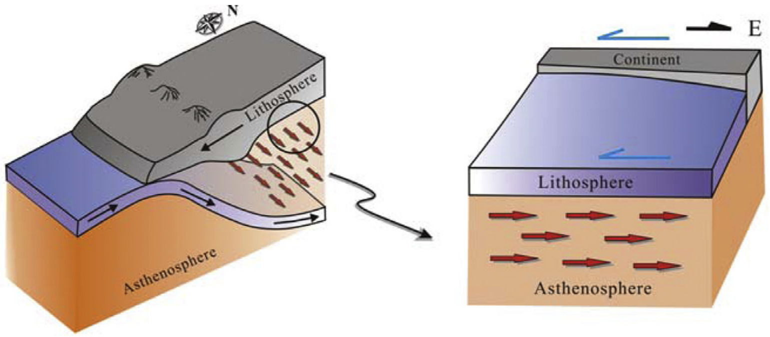
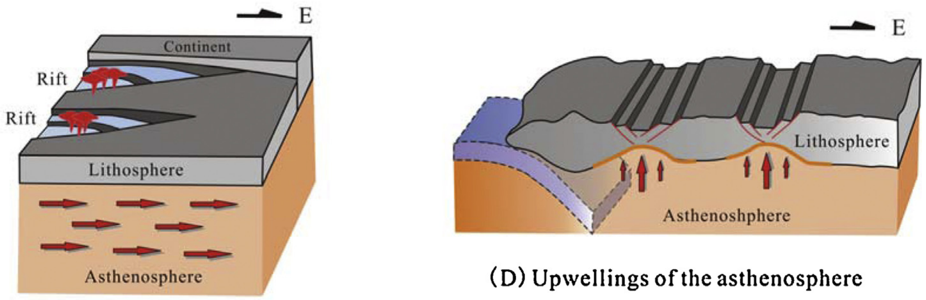
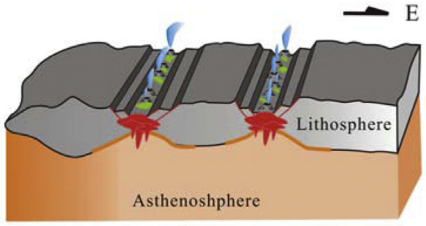


(A) Formation of asthenospheric flow (B) During asthenospheric flow



(D) Upwellings of the asthenosphere

(C) Interaction between asthenospheric flow and moved plate. as well upwellings of magma



(E) Confluence of asthenospheric flow and formation of LIPs

Fig. 6. Schematic model of the evolution of asthenospheric flow. (A) Initial development of asthenospheric flow. Subduction of an oceanic plate results in lateral mantle flow, parallel to the trench. (B) In response to asthenospheric flow, lithospheric-scale strike-slip faults develop in the marginal lithosphere. (C) In the case that the direction of mantle flow is parallel to the movement direction of a plate or continent, the margin of the continent is torn, forming a rift system that opens parallel to the mantle flow direction, as well as local intraplate extension. These structures then channel upwelling asthenospheric magma, resulting in basaltic eruptions. (D) In the case that mantle flow is in the opposite direction to that of the plate motion, a subduction system forms along with back-arc extension. (E) The convergence of mantle flows moving in two different directions results in a huge LIP (such as the Tarim and Emeishan LIPs) along the rifted or torn continent or plate.

the Deccan Traps (Melluso et al., 2006). There is adequate evidence to show that oceanic crust was recycled into the erupted magma in the Emeishan (Zhu et al., 2005; Song et al., 2008; Xiao et al., 2008), Tarim (Zhang et al., 2012), and Siberia (Sharma, 1997; Sobolev et al., 2007) LIPs. Thus, the Emeishan and Tarim LIP magmas are generally derived from sub-lithospheric sources and from recycled oceanic crustal materials in the asthenosphere, and were associated with the closure of Paleo-Tethys and its subduction under the continental margins.

Although the overall movement of Gondwana and its northern fragments was to the north, the scissor-like closure of the western part of Paleo-Tethys supposedly caused an eastward asthenospheric flow that interacted with the northward flow. During the period 290–250 Ma, the western sector of Paleo-Tethys experienced extensive horizontal flow of asthenospheric materials in a wide zone of ~80 to 410 km (Fig. 7) in two major directions: from west to east and from south to north. The downwelling mantle materials did not reach down to the core–mantle boundary, but were instead caught up in the extremely vigorous subhorizontal flow and the resultant mantle upwelling locally causing extensional tectonics. This asthenospheric horizontal or subhorizontal flow originated from a rather narrow and constricted domain (west Paleo-Tethys), and extruded toward a broad region (east Paleo-Tethys) (Fig. 5), thereby generating an intense and rapid flow. The confluence of the E–W and N–S directed flows generated asthenospheric upwelling (Fig. 7, the bottom panel) instead of normal sinking down of subducted material into the mantle transition zone (mantle convection) and from where, according to Maruyama et al. (2007), it would avalanche into the core–mantle boundary to be recycled as superplumes.

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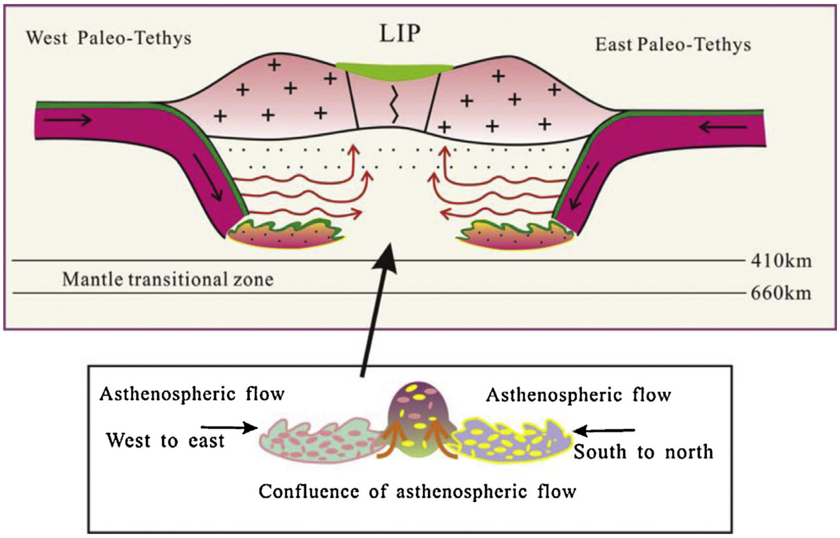

Fig. 7. Schematic model proposed in this study involving the confluence of asthenospheric flows and upwelling leading to the formation of LIPs. The three stages of evolution shown are: (1) asthenospheric flow and confluence, (2) lines of extensional zones formed by the rapid upwelling of the mantle and interaction with the lithosphere, and (3) the rapid or slow eruption of voluminous volcanic material. The bottom panel shows convergence, the resultant horizontal flow in the asthenosphere and the confluence of the flows.

During the convergent regime outlined above, multiple subduction zones operated at various continental margins, and LIPs formed with the recycling of oceanic slabs, together with the formation of oceanic ridges. All of these processes occurred at about the same time but in different tectonic domains, with a constraining force of asthenospheric flow, as discussed below. Horizontal flow in the asthenosphere can drive plates, cause continents to converge, and potentially lead, therefore, to the building of a supercontinent, such as Pangea. This convergence was the result of various continental motions, and was accompanied by the formation of huge LIPs during the period 290–250 Ma in a setting of contraction close to the Siberian continent. These features provide robust evidence for plate convergence accompanied by the formation of giant LIPs.

3.4. Formation of the LIPs: a new geodynamic hypothesis

The asthenosphere flow and resulting multiple convergent zones as proposed in this study, caused the build-up of Pangea. The 290–250 Ma LIPs discussed in this study were not associated with the breakup of a supercontinent, and are incompatible with the conventional mantle plume concept. The multiple convergent zones and the resulting asthenospheric flow in two major directions (from west to east and from south to north), as proposed in this study, were associated with supercontinent building, and not breakup. The mechanism that controlled the movements of the converging plates is linked to horizontal or sub-horizontal mantle flow in the asthenospheric layer at a depth of 80–410 km. The E–W flow of the asthenosphere was linked to the assembly of continents on the western side of Europe, associated with subduction and collision during the earlier stages of the formation of Pangea. The northward flow drove the Siberia, Tarim, and Yangtze plates. Horizontally or subhorizontally layered flow of the upper mantle changed to vertical upwelling when the two major flows from different directions intersected, and the mantle upwelling had a significant impact on the lithosphere and its extension. At the same time, or slightly earlier, rifts or normal faults formed along the continental margin or in the plate interiors where LIPs were forming. These local rifts or fractures represent minor and incipient rifting, a process that is quite different from the major breakup of a supercontinent.

At the time that the rapid basaltic eruptions were taking place along the continental margins, subduction and local horizontal-flow occurred in the asthenospheric mantle. Meanwhile, the western Paleo-Tethys had closed, and according to paleomagnetic data and paleogeographic reconstructions, the western regions of the globe had been brought together (Veevers, 2004, 2012; Nance et al., 2012). However, on the eastern side of the Paleo-Tethys, the different continental blocks remained unconnected within a vast domain. We speculate that at this time, the closure of the Paleo-Tethys in the west drove the asthenospheric mantle to flow horizontally from west to east at a depth of 80–410 km, along the center of the relict Paleo-Tethys. When this flow met the northward flow of the asthenosphere further east, the plates near the Tarim Block were moved around, and basaltic eruptions occurred along the northern side of the block. Further toward the east, LIPs formed in Emeishan and parts of south Lhasa and Tibet, on the southern side of the relict Paleo-Tethys (Fig. 6A). Finally the Siberian Trap formed when all the plates in the region moved northwards, and the convergence of the Tarim, Kazakhstan, North China, and other plates completed the amalgamation of Pangea.

Our model does not require top-down tectonics (lithospheric delamination; Anderson, 2001) and D″ mantle tectonics (mantle plume; Morgan, 1971, 1972) to explain the LIPs. In particular, these hypotheses appear incompatible with the formation of the Pangea supercontinent, which took place simultaneously with the formation of the LIPs. The horizontal-flow of the asthenospheric mantle in the regions of far-field subduction and near-margin subduction is regarded as the main mechanism that controlled the convective upwelling of the mantle and local extension leading to the formation of the LIPs.

The mantle plume and lithospheric delamination hypotheses have been used in attempts to explain how huge basaltic volcanic eruptions (LIPs) can take place over very short time intervals, in the order of some one million years, while ignoring the prolonged formation of for instance the Tarim LIP between ~290 and 270 Ma. However, our new hypothesis provides a straightforward explanation for either rapid or slow eruptive activity in different LIPs. In this model of continental convergence driven by asthenospheric flow, different cratons or continental blocks behave differently. The Siberian craton, for example, has a thick lithospheric keel that would have been difficult to break, but once it did fracture or rift,

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eruptions of sublithospheric and asthenospheric magma would have taken place quickly over a very short time. In contrast, the Tarim Block would have been relatively easily rifted, and this means that volcanic rocks would have been erupted over a longer period of time. For example, the Siberian Trap was erupted over little more than 1 Myr, whereas the Tarim LIP lasted for more than 15 Myr.

4. Concluding remarks

The formation of the Tarim and Emeishan LIPs on the Eurasian continent during 290–250 Ma, broadly coincided with the timing of assembly of the supercontinent Pangea. The mantle plume and delamination hypotheses cannot explain the features associated with the formation and evolution of these LIPs. We propose a new model involving the convergence of asthenospheric flow from different directions, and the gathering together of continental fragments. On a global scale, the oblique, relatively local closure of the western Paleo-Tethys domain caused a subhorizontal eastward asthenosphere flow which interacted with the overall northward flow that had earlier also translated the western Gondwana fragments to the north. These two major flows driving the continental blocks, generated a major upwelling of the mantle, which created weak zones in the overlying lithosphere and caused the formation of LIPs at different times and in different sectors of the continental margins and interior of Eurasia. This asthenospheric flow model can explain the formation of LIPs in a compressive regime, in the course of the construction of a supercontinent.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jog.2014.12.001.

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