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A tectonic model for Cenozoic igneous activities in the eastern Indo–Asian collision zone

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Abstract

Geochronologic dating and compilation of existing age data suggest that Cenozoic activities in the eastern Indo–Asian collision zone of southeast China and Indochina occurred in two episodes, each with distinctive geochemical signatures, at 42–24 Myr and 16–0 Myr. The older rocks are localized along major strike–slip faults such as the Red River fault system and erupted synchronously with transpression. The younger rocks are widely distributed in rift basins and are coeval with east–west extension of Tibet and eastern Asia. Geochemical data suggest that the early igneous phase was generated by continental subduction while the late episode was caused by decompression melting of a metasomatically altered, depleted mantle. The magmatic gap between the two magmatic sequences represents an important geodynamic transition in the evolution of the eastern Indo–Asian collision zone, from processes controlled mainly by crustal deformation to that largely dominated by mantle tectonics. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Indian Plate; plate collision; continental subduction; transpression; extension; Xizang China

1. Introduction

Cenozoic activities in northern Tibet have been variably attributed to continental subduction [1], convective removal of the mantle lithosphere [2], extension along strike–slip faults [3], and slab break-off [4]. In part, this lack of consensus reflects the fact that only small regions of northern Tibet have been investigated in detail, and thus the relationship between deformational processes and igneous activities remains poorly constrained [5–8]. In contrast, the deformation history of southeastern Asia has been much better studied due to the existence of 1:200 000–1:500 000 geologic maps and several systematic studies in the recent years [9–12].

The eastern Indo–Asian collision zone in southeast China lies east of the main part of the high-altitude and low-relief Tibetan plateau (Fig. 1).

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This region is characterized by high topographic relief and is bound by a series of north- and northwest-striking Cenozoic faults: to the west by the Gaoligong and Batang–Lijiang strike–slip systems, to the east by the Longmen Shan thrust belt and the Xiaojiang fault, and to the south by the Red River fault [11] (Fig. 1). South of the Red River fault, the Indochina block is highly deformed in the north but behaves approximately like a rigid block in the south. Both Cenozoic igneous rocks and a series of early–middle Cenozoic basins are localized in eastern Tibet [13] along a narrow belt following the Nangqian thrust belt, the Batang–Lijiang fault system, and the Red River Shear Zone (RRSZ) (Fig. 1). In contrast, Cenozoic igneous rocks are widespread in Indochina (Fig. 1).

The Cenozoic deformational history of the eastern Indo–Asian collision zone may be divided into three stages: (1) Eocene–Oligocene (~40–24 Myr) transpression in eastern Tibet, (2) early–middle Miocene (24–17 Myr) transtension in eastern Tibet, and (3) late Neogene–Quaternary east–west extension widespread in eastern Tibet and Indochina. The currently right-slip Red River fault previously accommodated left-slip shear between ~30 and 17 Myr [10,14,15]. While several authors [16,17] suggest that the southeastern RRSZ experienced regional extension between 34 and 25 Myr, the early mid-Tertiary development of the Lanping–Simao fold belt directly south of the RRSZ (Fig. 1) and associated development of late Eocene–late Oligocene compressional basins indicate that the region was undergoing contraction [13]. The proposed kinematic link between the development of the Lanping–Simao fold belt and left-slip ductile shearing along the RRSZ [18] implies that transpressional tectonics in the Red River region may have started as early as ~42 Ma. Similarly, the northern extension of the RRSZ along the Batang–Lijiang fault system also underwent east–west contraction during the Paleogene [19]. The east–west contraction in the north and transpression in the south along north- and northwest-striking strike–slip fault systems along the eastern margin of Tibet gave way to transtension in the latest Oligocene. This transition is well documented along the RRSZ between 24 and 17 Myr [20] from thermochronology. Transtension was replaced by east–west and northwest–southeast extension in the late Neogene. The extension is manifested by north-striking active normal faults and associated extensional basins north and south of the active right-slip Red River fault in eastern Tibet [10,18,21] and Indochina [21,22]. Similar to the relationship in central Tibet, north-striking normal faults in the Red River area and Indochina are kinematically linked with right-slip faults (for example, the relationship between active normal faults near Dali and the right-slip Red River fault, Fig. 1).

2. Geochronology and geochemistry

While the tectonic history of eastern Tibet is relatively well established, the relationship between deformational processes and the widespread occurrence of Cenozoic igneous activities has not previously been studied. Most previously determined ages of Cenozoic igneous rocks in the eastern Indo–Asian collision zone were determined by the K–Ar method [13,23,24] and are of variable quality or difficult to interpret. ^{40}Ar/^{39}Ar ages are in general more reliable as they permit direct tests of the underlying assumptions in the K–Ar dating method [25]. New ^{40}Ar/^{39}Ar ages and isotopic analyses of Cenozoic igneous rocks provide clues as to a causal relationship (see appendices 1–7 in the **EPSL Online Background Dataset**[1] for analytical methods and complete geochronological and geochemical data). Coupled with previously published results [17,26–28], our geochronological data reveal two distinctive magmatic episodes in eastern Tibet and Indochina: one between 42 and 24 Myr, and another since 16 Myr (Fig. 1). The older volcanic rocks and minor intrusions are distributed along the entire length of the RRSZ and its northern extension, the Batang–Lijiang fault system and the Nangqian thrust belt (Fig. 1). In contrast, the younger age group is distributed along the

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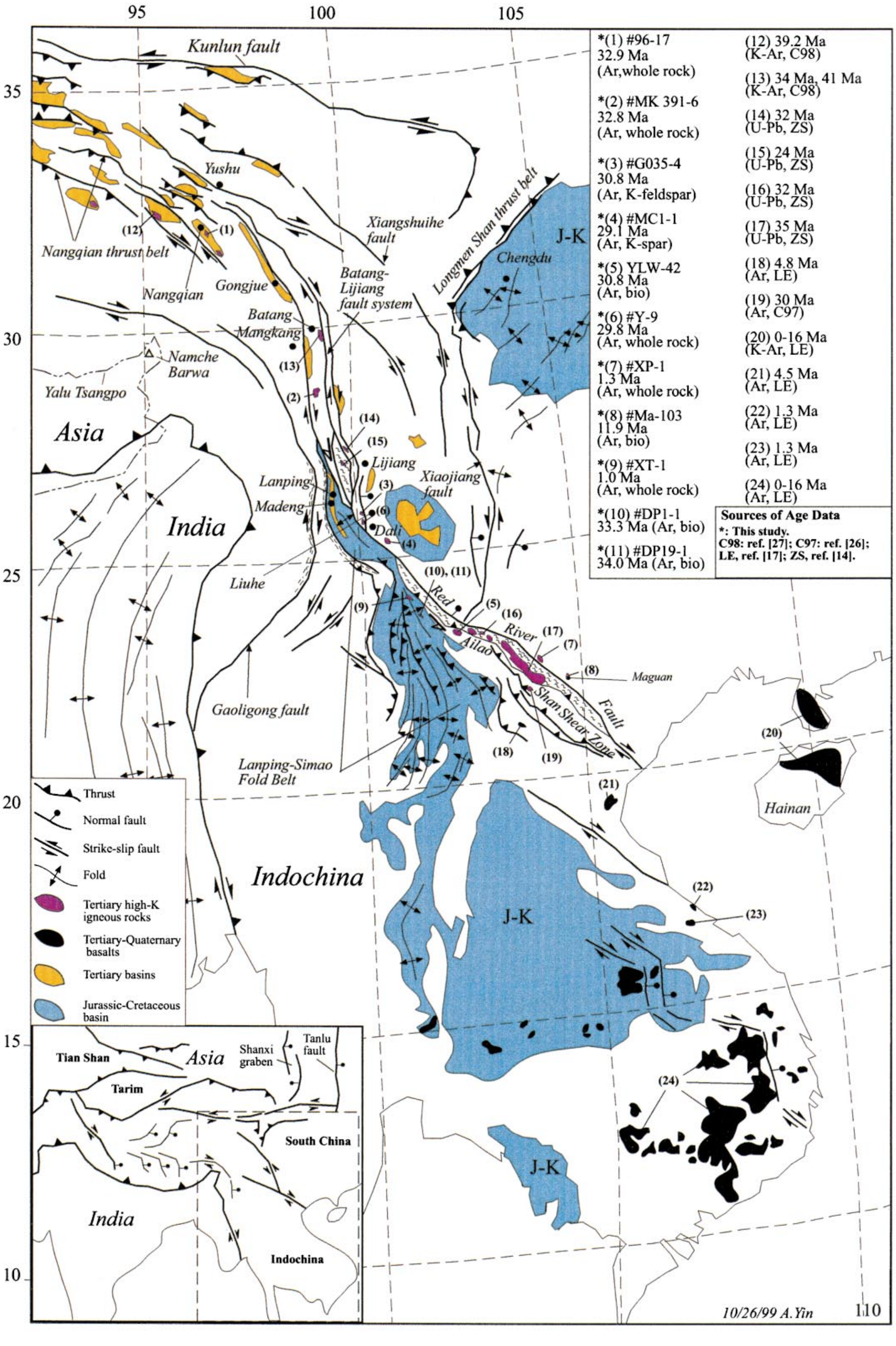

Fig. 1. Cenozoic tectonic map of eastern Tibet and Indochina [17,19,27,46,47].

southern segment of the active Red River fault and in the Indochina block to the south (Fig. 1). Systematic dating of Neogene–Quaternary intraplate activities in the Indochina block [17] reveals essentially continuous basaltic eruptions since ~16 Myr, coinciding with cessation of sea-floor spreading in the South China Sea [29] and termination of transtension along the RRSZ at ~17 Myr [20].

Rocks of the earlier igneous activity (42–24 Ma) in the eastern Indo–Asian collision zone include syenite, trachyte, shoshonitic lamprophyre and basaltic trachy andesite [23,24,30,31], which entrained the xenoliths of garnet- and clinopyroxene-bearing amphibolite, granulite and pyroxenite. A preliminary calculation of *P–T* conditions for the xenoliths at Liuhe and Madeng (Fig. 1) suggests that the equilibrated pressure and temperature of coexisting minerals range from 0.6 to 1.0 GPa and from 780 to 830°C, respectively. This result indicates that the xenoliths came from a depth of greater than 23–37 km and provides an upper bound for the depth of melt segregation. The full discussion of the composition data and

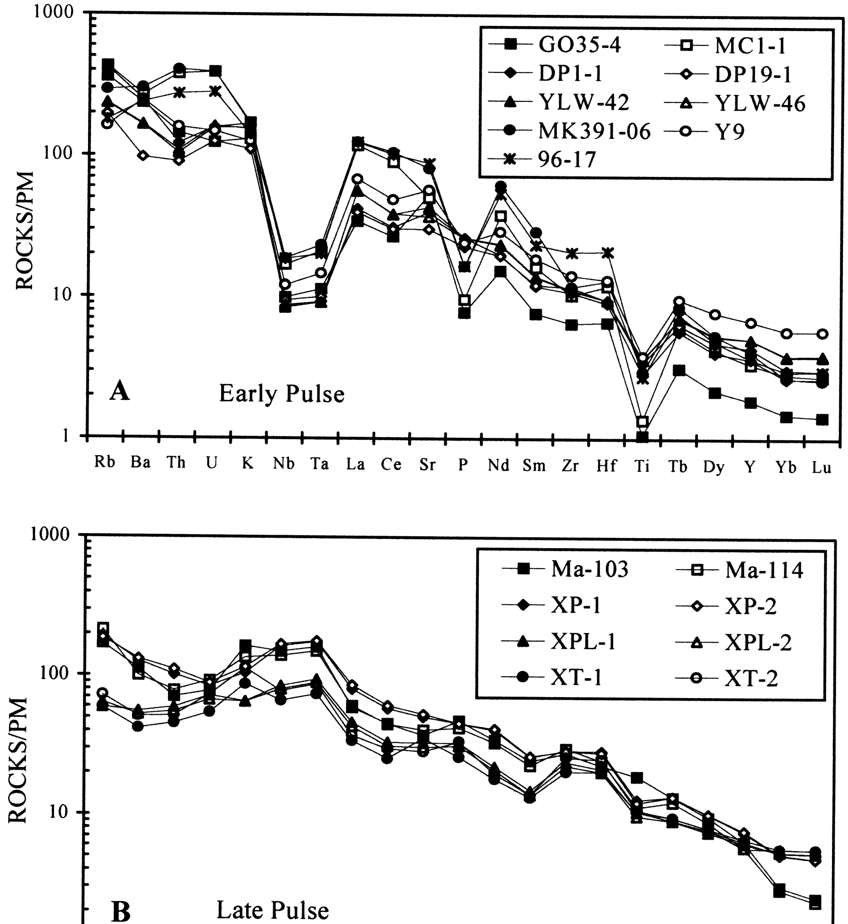

Fig. 2. Multi-element plots for Cenozoic igneous rocks in eastern Tibet. (A) Trace element data normalized to the primitive mantle for representative analyses of the earlier-phase high-potassic magmatic activities. (B) Trace element data normalized to the primitive mantle for representative analyses of the younger-phase high-potassic volcanic activities.

calculation procedures will be presented separately. We also calculated the *P–T* conditions for melt segregation by comparing the Mg-15 normalized compositions of the earlier-phase igneous rocks with high contents of MgO ($>7.5\%$) with parameterized hydrous experimental melt compositions [22]. The result shows that the conditions for melt segregation occurred at pressures of 1.0–1.2 GPa (~35–43 km deep) and 960–1050°C. Combining the *P–T* conditions from the xenoliths and chemical compositions of the earlier-phase magmatic rocks, we consider that the depth of melt segregation ranges from 23 to 43 km.

Compositionally, the earlier-phase high-potassic igneous rocks are characterized by relatively low TiO_2 ($<1.0\%$), P_2O_5 ($<0.6\%$) and FeO* ($<9\%$), and high Na_2O (1.3–5.1%) and K_2O (3.4–5.2%), coupled with high contents of incompatible trace elements. They are ultra-potassic or shoshonitic, and generally similar to Neogene high-potassic igneous rocks in northern Tibet [1,23]. The chondrite-normalized REE patterns of the early magmatic phase show negative Eu anomalies [2,4], suggesting that plagioclase is a major phase involved in fractional crystallization. This is consistent with the petrographical observation that plagioclase is one of the phenocrysts. The patterns of normalized trace elements exhibit pronounced negative anomalies in Nb, Ta, Ti and P (Fig. 2A), whereas the content of SiO_2 varies widely in the range of 52.8–69.2%. This indicates the involvement of a subduction-related component in the earlier magmatic phase [4]. The Sr and Nd isotopes of the earlier phase show a relatively broad range of $^{87}Sr/^{86}Sr$ with more restricted $^{143}Nd/^{144}Nd$ ratios (Fig. 3). In northern and eastern Tibet, high-potassic igneous rocks have high $^{87}Sr/^{86}Sr$ (0.705–0.710), $^{206}Pb/^{204}Pb$ (18.52–19.17), $^{207}Pb/^{204}Pb$ (15.78–15.60) and $^{208}Pb/^{204}Pb$ (38.56–39.98) ratios, but low $^{143}Nd/^{144}Nd$ (0.5120–0.5126) ratios [23–24]. Their Nd and Sr isotopic compositions lie in the enriched extension of the mantle array but fall far outside the fields of MORB and Hawaiian basalts (Fig. 3). The similarity in Nd and Sr isotopic compositions between the earlier igneous rocks and volcanic rocks in west Yunnan [30] indicates that they were derived from the same magmatic source. The Sr–Pb and Nd–Pb isotopic data also plot outside the field of oceanic basalts (Fig. 4A,B). The above signatures of Pb, Sr and Nd isotopes argue against exclusively asthenospheric or mantle plume sources. No correlation between $^{207}Pb/^{204}Pb$ and Ce/Pb or between $^{143}Nd/^{144}Nd$ and Ta/Nd or Ba/Nb ratios also argues against the mixing of asthenospheric and highly enriched lithospheric sources. In $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ vs. $^{206}Pb/^{204}Pb$ diagrams (Fig. 4A,B, cf. Fig. 3), the data mainly plot in or near the EM2 field. This indicates that the earlier magmatic phase may be derived from an EM2 mantle. However, some data deviate from the EM2 field, suggesting an input of continental materials with low $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ ratios and high $^{87}Sr/^{86}Sr$ ratios into mantle-derived melts (Fig. 4A,B). The high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ isotope signatures of the earlier phase (Fig. 3) require mantle sources with a time-integrated history of enrichment in LREE and Rb. The most plausible explanation is to as-

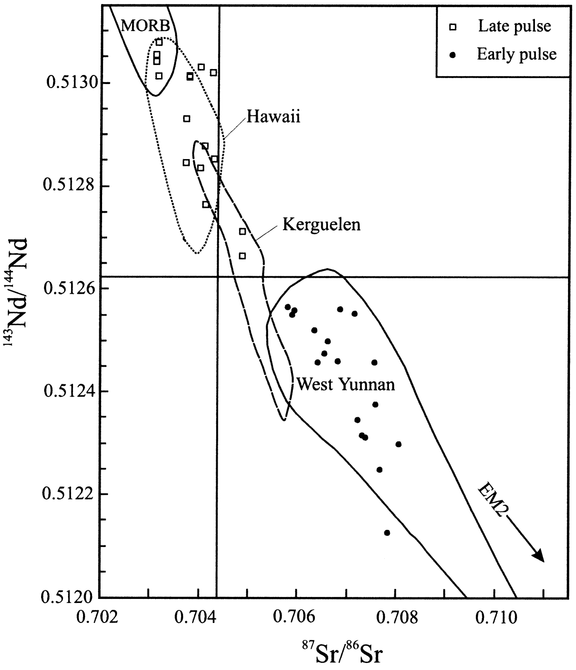

Fig. 3. Sr–Nd isotopic diagram for both phases of Cenozoic high-potassic igneous activities. Fields shown are for volcanic rocks of western Yunnan [30], MORB, Hawaiian, and Kerguelen basalts [48].

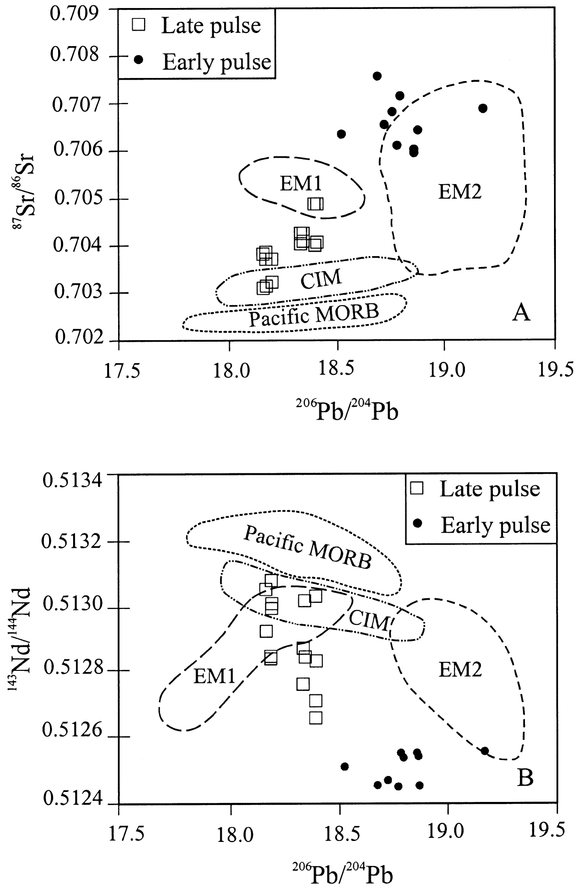

Fig. 4. $^{206}Pb/^{204}Pb$ vs. $^{87}Sr/^{86}Sr$ (A) and $^{206}Pb/^{204}Pb$ vs. $^{143}Nd/^{144}Nd$ (B) diagrams for both phases of Cenozoic high-potassic igneous activities. Fields shown are the EM1 and EM2 mantle end-members [48], Central Indian MORB (CIM) [49], and Pacific MORB [50].

cribe these combined trace-elemental and isotopic observations to a metasomatized subcontinental lithospheric mantle source before the onset of partial melting that led to the formation of early high-potassic igneous rocks [2,31]. The elemental enrichment results in an increase in U/Pb, Rb/Sr and Th/U ratios and a decrease in Sm/Nd ratios relative to the depleted mantle. The enrichment process also led to the stabilization of phlogopite-bearing mineral assemblage [2].

The younger-phase activity (16–0 Ma) in the eastern Indo–Asian collisional zone produced alkali basalt, basanite, trachy basalt and basaltic trachy andesite. Xenoliths of spinel lherzolite, garnet lherzolite and harzburgite were found in the volcanic rocks near Maguan (shown in locality (8) of Fig. 1). The occurrence of mantle xenoliths suggests that the mantle-derived high-potassic melts ascended rapidly avoiding significant interaction with crust and large-scale fractional crystallization. The estimated pressures and temperatures for the spinel-facies lherzolite at Maguan are 1.7–2.0 GPa ($\sim$59–66 km deep) and 980–1000°C, respectively [32]. In the above calculation, we assumed that the crustal thickness is 40 km, which is the average value for the current crust in the Yunnan region [33]. The *P–T* conditions for melt segregation were also estimated by comparing the Mg-15 normalized compositions of the younger-phase volcanic rocks with parameterized hydrous experimental melt compositions [22]. The result suggests that the conditions for melt segregation occurred at pressures of 1.6–2.3 GPa ($\sim$55–76 km deep) and 1250–1400°C. When combining the estimates from the xenoliths and melt chemistry, we conclude that the younger-phase high-potassic melts segregated at depths of 55–76 km.

The geochemistry of the younger-phase igneous activity is characterized by high-potassic calc-alkalic or shoshonitic compositions. They are high in TiO_2 ($>2\%$), P_2O_5 ($>0.6\%$), FeO^* ($>9\%$), Na_2O (2.4–4.0%), K_2O (2–5%) and incompatible trace elements. The positive anomalies in Nb and Ta (Fig. 2B, cf. Fig. 2A), high Ce/Pb (10.44–23.88) and Nb/U (36.07–65.82), and low La/Nb (0.38–0.53) indicate a similarity to oceanic island basalts [2]. They have low $^{87}Sr/^{86}Sr$ (0.703–0.705), $^{206}Pb/^{204}Pb$ (18.17–18.39), $^{207}Pb/^{204}Pb$ (15.51–15.57) and $^{208}Pb/^{204}Pb$ (38.03–38.69), but high $^{143}Nd/^{144}Nd$ (0.5127–0.5131). Nd and Sr isotopic compositions of these rocks plot in or near the MORB quadrant (Fig. 3). The striking resemblance in Nd and Sr isotopic compositions between the younger-phase volcanic rocks in the eastern Indo–Asian collision zone and Hawaiian basalts strongly argues against significant crustal contamination (Fig. 3). Thus, we consider that the geochemistry of the younger phase nearly reflects its original source compositions without significant continental contamination or fractional crystallization during magma ascent. If the magmatic melts were derived from an enriched Precambrian mantle, these volcanic rocks would have been characterized not only by high contents of K_2O and incompatible elements, but also by relatively high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratios. However, the apparent decoupling between isotopic and elemental compositions indicates that the younger magmatic activity was derived from a depleted mantle source enriched by recent mantle metasomatism. The Sr–Pb and Nd–Pb isotopic compositions of the younger-phase igneous activity (Fig. 4A,B) clearly reflect a hybrid of $^{206}Pb/^{204}Pb$-poor EM1 and MORB mantle sources. The Neogene–Quaternary basalts in Vietnam are a noticeable exception. These rocks erupted during the younger-phase igneous activity in the eastern Indo–Asian collision zone. However, this phase of volcanism in Vietnam may be further divided into two episodes by their individual geochemical signatures. In the early episode, the rocks are high-Si, low-Fe quartz and olivine tholeiites trapping a relatively refractory, lithospheric mantle-type source [22,34,35]. In the later episode, the rocks are low-Si, high-Fe olivine tholeiites, alkali basalts and basanites, trapping a fertile, asthenosperic source [22,34,35]. We interpret both episodes of volcanism in Vietnam as a result of a continuous lithospheric extension driven by the asthenospheric flow.

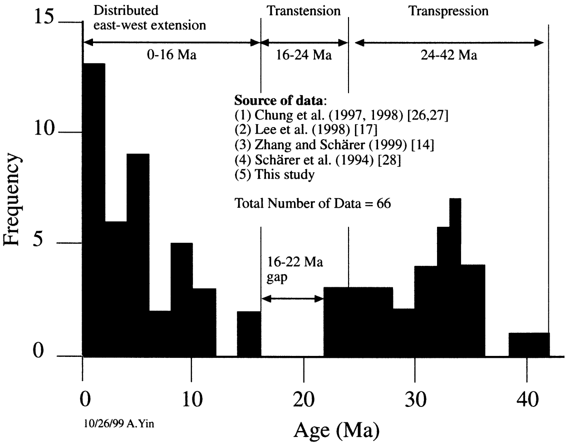

Fig. 5. Histogram of ages of Cenozoic igneous rocks in eastern Tibet and Indochina.

3. Tectonic model

To explain the episodic activities (Fig. 5), its geochemical characteristics (Figs. 2–4), and its spatial and temporal relationships to the major structures (Fig. 1) in the eastern Indo–Asian collision zone, we propose a new tectonic model. First, contraction along the Batang–Lijiang fault system and development of the Lanping–Simao fold belt in the early Tertiary caused local continental subduction along the RRSZ [18] leading to fluid infiltration into the overlying mantle wedge and subsequent melting (Fig. 6a). We interpret the narrow belt of late Paleocene to early Miocene basins in eastern Tibet, from the Nangqian thrust belt to the Lanping–Simao fold belt (Fig. 1), as representing foreland basins formed by transpression (Fig. 1). This proposal is similar to Meyer et al.'s [36] model for northern Tibet. The interpretation of Cenozoic strata in eastern Tibet as contraction-related deposits appears plausible for the Nangqian thrust belt to the north and the Lanping–Simao fold belt to the south where Cenozoic strata are clearly associated with thrusting and folding [13,18] (Fig. 1). While it has recently been suggested [27] that the Paleogene igneous activity in eastern Tibet is due to convective removal of the lower lithosphere beginning at ~40 Myr, this mechanism has been shown to be not only physically implausible [37] but also inconsistent with the geologic observation that the igneous activities were spatially and temporally associated with Paleogene contractional or transpressional deformation as discussed in this paper.

The 24–16 Myr magmatic gap coincides with an interval of transtension along the RRSZ [26] between 24 and 17 Myr. In addition to halting the flux of volatiles into the underlying mantle wedge, the transition to transtension may have also thinned or removed the crustal root created during the earlier phase of transpression (Fig. 6b), substantially restricting the conditions appropriate for generating partial melting.

The younger-phase igneous activity is temporally associated with widely distributed east–west extension in eastern Tibet and Indochina since the

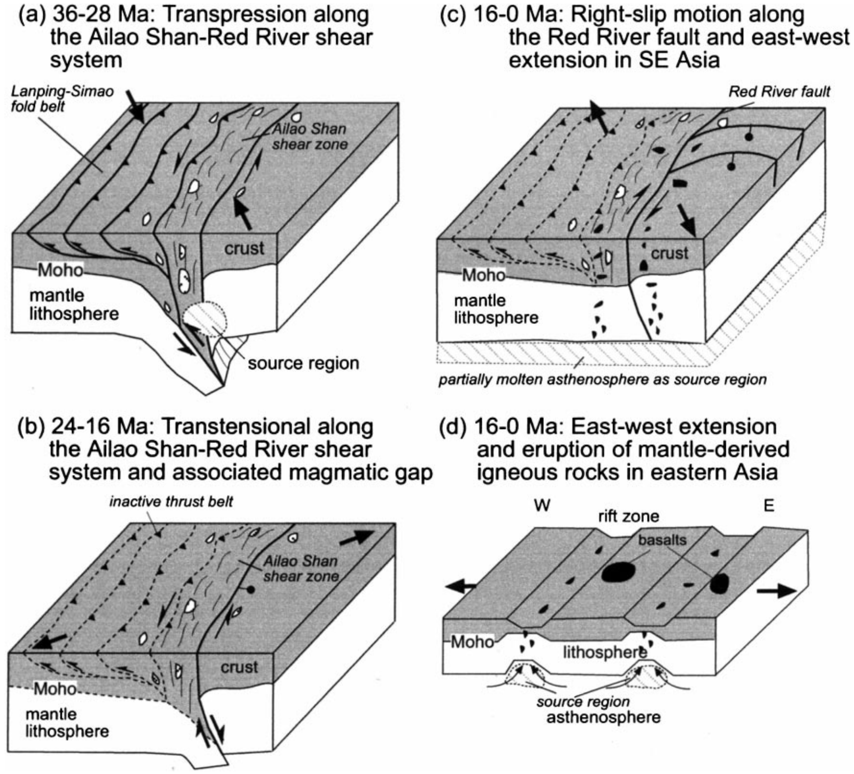

Fig. 6. Tectonic model for the occurrence of the three tectono-magmatic phases in eastern Tibet and southeastern Asia. (a) Subduction magmatism during transpression along the Ailao Shan–RRSZ, (b) a magmatic hiatus during transtension along the Ailao Shan–RRSZ, (c) partial melting in the asthenosphere in the Red River region and southeast Asia which caused the younger phase of volcanism, and (d) the younger-phase volcanism in eastern Indo–Asian collision zone may be a result of decompression-induced melting during distributed east–west extension in eastern Asia including the Tibetan plateau.

late Miocene [21] (Fig. 6c). Along the Red River fault, this is manifested by the development of several north-striking normal faults that merge with the coeval right-slip Red River fault (Fig. 1) [11]. This relationship between north–south-striking normal faults and west–northwest-striking right-slip faults is similar to that observed in southern Tibet (Fig. 1) [38]. This newly established tectonic regime is not restricted to the eastern Indo–Asian collision zone, but is widespread throughout eastern Asia, including the main part of the Tibetan plateau directly north of the indenting Indian continent (Fig. 6d). In Tibet, significant east–west extension began at about 8–4 Myr [39], although localized extension may have occurred earlier [40]. Although morphology of rift shoulders in Tibet implies that active east–west extension is restricted to the upper crust [41], normal-faulting earthquakes at mantle depths [42] and wide spacing of major Tibetan rifts [43] all indicate that Tibetan extension involves the mantle lithosphere. In North China, the north-south trending Shanxi graben began to develop at about 6 Myr [44]. In southeastern Siberia, the Baikal rift initiated since 10 Myr and was most active between 8–4 Myr [45]. Most of these eastern Asian rifts are associated with basaltic eruptions and mantle earthquakes, implying that extension is related to asthenospheric flow [22,34,42]. Thus, the new tectonic setting for the occurrence of the late Neogene–present igneous activity in eastern Tibet and Indochina may represent a fundamental change in geodynamic setting of the eastern Indo–Asian collision zone.

4. Conclusions

Cenozoic activities in the eastern Indo–Asian collision zone of southeast China and Indochina occurred in two episodes, each with distinctive geochemical signatures, at 42–24 Myr and 16–0 Myr. The older rocks are localized along major strike–slip faults such as the Red River fault system and erupted synchronously with transpression. The younger rocks are widely distributed in rift basins and are coeval with east–west extension in Tibet and entire eastern Asia. Geochemical data suggest that the earlier igneous phase was generated by continental subduction, while the younger episode was caused by decompression-induced melting of a metasomatically altered, depleted mantle. The magmatic gap between the two magmatic sequences represents an important geodynamic transition in the evolution of the eastern Indo–Asian collision zone, from deformation controlled by crustal processes to that largely dominated by mantle processes.

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References

[1] W.M. Deng, A preliminary study on the petrology and petrochemistry of the Quaternary volcanic rocks of northern Tibet autonomous region, Acta Geol. Sin. 52 (1978) 148–162.

[2] S. Turner, N. Arnaud, J.Q. Liu, N. Rogers, C.J. Hawkesworth, N. Harris, S. Kelley, P. van Calsteren, W.M. Deng, Post-collision, shoshonitic volcanism on the Tibetan Plateau: Implications for convective thinning of the lithosphere and the source of ocean island basalts, J. Petrol. 37 (1996) 45–71.

[3] A. Yin, T.M. Harrison, F.J. Ryerson, Transtension along the left-slip Altyn Tagh and Kunlun faults as a mechanism for the occurrence of late Cenozoic volcanism in the northern Tibetan plateau, EOS 76 (1995) 567.

[4] C. Miller, R. Schuster, U. Klözli, W. Frank, F. Purtscheller, Post-collisional potassic and ultrapotassic activities in SW Tibet Geochemical and Sr–Nd–Pb–O isotopic constraints for mantle source characteristics and petrogenesis, J. Petrol. 40 (1999) 1399–1424.

[5] A. Yin, P.A. Kapp, M.A. Murphy, C. Manning, T.M. Harrison, M. Grove, L. Ding, X.G. Deng, C.M. Wu, Evidence for significant late Cenozoic E–W extension in North Tibet, Geology 27 (1999) 819–822.

[6] P. Kapp, A. Yin, C. Manning, M.A. Murphy, T.M. Harrison, L. Ding, X.G. Deng, C.M. Wu, Blueschist-bearing metamorphic core complexes in the Qiangtang block reveal deep crustal structure of northern Tibet, Geology 28 (2000) 19–22.

[7] A. Yin, T.M. Harrison, Geologic evolution of the Himalayan–Tibetan orogen, Annu. Rev. Earth Planet. Sci. 28 (2000) 211–280.

[8] B.R. Hacker, E. Gnos, L. Ratschbacher, L. Webb, M. Grove, M. McWilliams, S.V. Sobolev, W. Jiang, Z.H. Wu, Hot and dry xenoliths from the lower crust of Tibet, Science 287 (2000) 2463–2465.

[9] B.C. Burchfiel, Z.L. Chen, Y.P. Liu, L.H. Royden, Tectonics of the Longmen Shan and adjacent regions, central China, Int. Geol. Rev. 37 (1995) 661–735.

[10] P.H. Leloup, R. Laccassin, P. Tapponnier, U. Schärer, D.L. Zhong, X. Liu, L.S. Zhang, S. Ji, T.T. Phan, The Ailao Shan–Red River shear zone (Yunnan, China), Tertiary transform boundary of Indochina, Tectonophysics 251 (1995) 3–84.

[11] E. Wang, B.C. Burchfiel, Interpretation of Cenozoic tectonics in the right-lateral accommodation zone between the Ailao Shan shear zone and the eastern Himalayan syntaxis, Int. Geol. Rev. 39 (1997) 191–219.

[12] D.L. Zhong, Paleotethyan orogenic belts in Yunnan and western Sichuan, Science Press, Beijing, 1998, 230 pp.

[13] G.T. Pan, P.S. Wang, Y.R. Xu, S.P. Jiao, T.X. Xiang, Cenozoic tectonic evolution of Qinghai–Xizang Plateau, Geological Publishing House, Beijing, 1990, 190 pp.

[14] L.S. Zhang, U. Schärer, Age and origin of magmatism along the Cenozoic Red River shear belt, China, Contrib. Mineral. Petrol. 134 (1999) 67–85.

[15] L. Gilley, T.M. Harrison, F.J. Ryerson, P.H. Leloup, J.H. Wang, Direct dating of left-lateral slip along the Red River shear zone, Earth Sci. Front. China Univ. Geosci. Beijing 7 (2000) 275.

[16] P.L. Wang, C.H. Lo, T.Y. Lee, S.L. Chung, C.Y. Lan, N.T. Yem, Thermochronological evidence for the movement of the Ailao Shan–Red River shear zone: A perspective from Vietnam, Geology 26 (1998) 887–890.

[17] T.Y. Lee, C.H. Lo, S.L. Chung, C.Y. Chen, P.L. Wang, W.P. Lin, N. Hoang, C.T. Chi, N.T. Yem, ^{40}Ar/^{39}Ar dating result of Neogene basalts in Vietnam and its tectonic implication, in: M.F.J. Flower, S.L. Chung, C.H. Lo (Eds.), Mantle Dynamics and Plate Interactions in East Asia, Geodyn. 27, AGU, Washington, DC, 1998, pp. 317–330.

[18] E. Wang, B.C. Burchfiel, Interpretation of Cenozoic tectonics in the right-lateral accommodation zone between the Ailao Shan shear zone and the eastern Himalayan syntaxis, Int. Geol. Rev. 39 (1997) 191–219.

[19] L. Ratschbacher, W. Frisch, C. Chen, G. Pan, Cenozoic deformation, rotation, and stress patterns in eastern Tibet and western Sichuan, China, in: A. Yin, T.M. Harrison (Eds.), The Tectonic Evolution of Asia, Cambridge University Press, New York, 1996, pp. 227–249.

[20] T.M. Harrison, P.H. Leloup, F.J. Ryerson, P. Tapponnier, R. Lacassin, W.J. Chen, Diachronous initiation of transtension along the Ailao Shan–Red River shear zone, Yunnan and Vietnam, in: A. Yin, T.M., Harrison (Eds.), The Tectonic Evolution of Asia, Cambridge University Press, New York, 1996, pp. 208–226.

[21] C. Rangin, P. Huchon, X. Le Pichon, H. Bellon, C. Lepvrier, D. Roques, N.D. Hoe, P.V. Quynh, Cenozoic deformation of central and south Vietnam, Tectonophysics 251 (1995) 179–196.

[22] N. Hoang, M. Flower, Petrogenesis of Cenozoic basalts from Vietnam: Implications for origin of a 'diffuse igneous province', J. Petrol. 39 (1998) 369–395.

[23] W.M. Deng, Cenozoic intraplate volcanic rocks in the northern Qinghai–Xizang Plateau, Geological Publishing House, Beijing, 1998, 180 pp.

[24] Y.Q. Zhang, Y.W. Xie, G.C. Tu, Preliminary studies of the alkali-rich intrusive rocks in the Ailaoshan–Jinshajiang belt and its bearing on rift tectonics, Acta Petrol. Sin. 3 (1987) 17–25.

[25] I. McDougall, T.M. Harrison, Geochronology and thermochronology by the ^{40}Ar/^{39}Ar method, Oxford University Press, New York, 1999, 269 pp.

[26] S.L. Chung, T.Y. Lee, C.H. Lo, P.L. Wang, C.Y. Chen, N.T. Yem, T.T. Hoa, G.Y. Wu, Intraplate extension prior to continental extrusion along the Ailao Shan–Red River shear zone, Geology 25 (1997) 311–314.

[27] S.L. Chung, C.H. Lo, T.Y. Lee, Y.Q. Zhang, Y.W. Xie, X.H. Li, K.L. Wang, P.L. Wang, Diachronous uplift of the Tibetan plateau starting 40 Myr ago, Nature 394 (1998) 769–773.

[28] U. Schärer, L.S. Zhang, P. Tapponnier, Duration of strike–slip movements in the large shear zones: The Red River belt, China, Earth Planet. Sci. Lett. 126 (1994) 379–397.

[29] A. Briais, P. Patriat, P. Tapponnier, Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: Implications for the Tertiary tectonics of SE Asia, J. Geophys. Res. 98 (1993) 6299–6328.

[30] B.Q. Zhu, X.H. Li, D.M. Dai, Y.W. Chen, S.K. Fan, X.T. Gui, H.F. Wang, The theory of isotope systems in earth sciences and its application, Science Press, Beijing, 1998, pp. 61–87.

[31] G.H. Xie, C.Q. Liu, A. Masuda, S.Y. Qing, The geochemical characteristics of Cenozoic volcanic rocks in the area of Qinghai–Tibet plateau: Evidence for existing of an ancient enriched mantle, in: R.X. Liu (Ed.), The age and geochemistry of Cenozoic volcanic rocks in China, Seismological Press, Beijing, 1992, pp. 400–427.

[32] X.X. Shu, The genesis of Cpx-peridotite xenoliths in basanite of Maguan, Yunnan province, Acta Petrol. Mineral. 14 (1995) 47–51.

[33] F.T. Liu, J.H. Liu, J.K. He, Q.Y. You, The subducted slab of the Yangtze continetal block beneath the Tethyan orogen in western Yunnan, Chin. Sci. Bull. 45 (2000) 466–469.

[34] M. Flower, K. Tamaki, H. Hoang, Mantle extrusion: A model for dispersed volcanism and DUPAL-like asthenosphere in east Asia and the western Pacific, in: M.F.J. Flower, S.L. Chung, C.H. Lo (Eds.), Mantle Dynamics and Plate Interactions in east Asia, Geodyn. Ser. 27, AGU, Washington, DC, 1998, pp. 67–88.

[35] N. Hoang, M.F.J. Flower, R.W. Carlson, Major, trace element, and isotopic compositions of Vietnamese basalts: Interaction of hydrous EM1-rich asthenosphere with thinned Eurasian lithosphere, Geochim. Cosmochim. Acta 60 (1996) 4329–4351.

[36] B. Meyer, P. Tapponnier, L. Bourjot, F. Metivier, Y. Gaudemer, G. Peltzer, S.M. Guo, Z.T. Chen, Crustal thickening in Gansu–Qinghai, Lithospheric mantle subduction, and oblique, strike–slip controlled growth of the Tibet Plateau, Geophys. J. Int. 135 (1998) 1–47.

[37] A. Lenardic, W.M. Kaula, More thoughts on convergent crustal plateau formation and mantle dynamics with regard to Tibet, J. Geophys. Res. 100 (1995) 15193–15203.

[38] R. Armijo, P. Tapponnier, T. Han, Late Cenozoic right-lateral strike–slip faulting across southern Tibet, J. Geophys. Res. 94 (1989) 2787–2838.

[39] T.M. Harrison, P. Copeland, W.S.F. Kidd, O.M. Lovera, Activation of the Nyainqentanghla shear zone: Implications for uplift of the southern Tibetan plateau, Tectonics 14 (1995) 658–676.

[40] A. Yin, T.M. Harrison, F.J. Ryerson, W.J. Chen, W.S.F. Kidd, P. Copeland, Tertiary structural evolution of the Gangdese thrust system, southeastern Tibet, J. Geophys. Res. 99 (1994) 18175–18201.

[41] J.G. Masek, B.L. Isacks, E.J. Fielding, J. Browaeys, Rift flank uplift in Tibet: Evidence for a viscous lower crust, Tectonics 13 (1994) 659–667.

[42] W.P. Chen, H. Kao, Seismotectonics of Asia: Some recent progress, in: A. Yin, T.M. Harrison (Eds.), The Tectonic Evolution of Asia, Cambridge University Press, New York, 1996, pp. 37–52.

[43] A. Yin, Mode of Cenozoic east–west extension in Tibet suggesting a common origin of rifts in Asia during the Indo–Asian collision, J. Geophys. Res. 105 (2000) 21745–21759.

[44] N. Wang, J. Yang, Z. Xia, D. Me, Y. Li, M. Pan, Cenozoic Sedimentation and Tectonic Geomorphology of the Shanxi Graben, Science Press, Beijing, 1996, 400 pp.

[45] D. Delvaux, R. Moeys, G. Stapel, C. Petit, K. Levi, A. Miroshnichenko, V. Ruzhich, V. San'kov, Paleostress reconstructions and geodynamics of the Baikal region, Central Asia, Part 2. Cenozoic rifting, Tectonophysics 282 (1997) 1–38.

[46] CAGS (Chinese Academy of Geologic Sciences), Geologic map of Asia, Cartographic Publishing House, Beijing, 1978.

[47] P. Tapponnier, R. Lacassin, P.H. Leloup, U. Schärer, D.L. Zhong, H.W. Wu, X.H. Liu, S.C. Ji, L.S. Zhang, J.Y. Zhong, The Ailao Shan/Red River metamorphic belt Tertiary left-lateral shear between Indochina and South China, Nature 343 (1990) 431–437.

[48] A. Zindler, S.R. Hart, Chemical geodynamics, Annu. Rev. Earth Planet. Sci. 14 (1986) 493–571.

[49] J.J. Mahoney, J.H. Natland, W.M. White, R. Poreda, S.H. Bloomer, R.L. Fisher, A.N. Baxter, Isotopic and geochemical provinces of the western Indian Ocean spreading, J. Geophys. Res. 94 (1989) 4033–4052.

[50] W.M. White, A.W. Hofmann, H. Puchelt, Isotope geochemistry of Pacific mid-ocean ridge basalt, J. Geophys. Res. 92 (1987) 4881–4893.