GEOLOGICAL NOTES

Jurassic Dextral Movement along the Dien Bien Phu Fault, NW Vietnam: Constraints from $^{40}Ar/^{39}Ar$ Geochronology

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ABSTRACT

The NNE-SSW-trending Dien Bien Phu fault, which dextrally displaces the NW-SE-trending Song Ma suture, in northwestern Vietnam, is widely considered one of the most seismically active faults in Indochina. In order to better understand the fault's activity, this study reports new $^{40}Ar/^{39}Ar$ geochronological data for mica schists and mylonites from several areas along the Dien Bien Phu fault, showing $^{40}Ar/^{39}Ar$ ages of 194–212 Ma for mica schists and 158–198 Ma for mylonites. These ages suggest that after the collision of the South China and Indochina blocks, dextral shearing deformation initiated along the Dien Bien Phu fault in the Jurassic, significantly earlier than previously thought. In light of the relevant tectonic events in Indochina, the successive suturing/collision of the Indochina, Simao, and Sibumasu blocks may have been responsible for the initiation of dextral shearing along the Dien Bien Phu fault, which in turn resulted in offset of the Song Ma suture.

Online enhancement: color version of figure 2.

Introduction

The collision between India and Eurasia, which led to the activation of major faults and plate reorganization in East Asia, represents the most significant tectonic event of the Cenozoic Earth (for a recent review, see Burchfiel 2004). In this context, many workers have investigated the NW-SE-trending transverse fault systems in Southeast Asia (fig. 1) since the collision-extrusion tectonic model was proposed by Tapponnier et al. (1982). Recent GPS data suggest that the Tibetan extrusion involved clockwise rotation (e.g., Zhang et al. 2004), meaning that crustal flow is now bounded to the east by a sinistral strike-slip system consisting of the Xianshuihe, Xiaojiang, and Dien Bien Phu faults (fig. 1). However, geological correlations indicate that the Dien Bien Phu fault has dextrally offset the Song Ma belt (Fontaine and Workman 1997; Lepvrier et al. 2004; fig. 1), implying a complicated movement for the fault. This complexity has apparently been magnified by the multiple collision events involved in the amalgamation of the South China, Indochina, Sibumasu, and Simao blocks during the Indosinian Orogeny (Carter et al. 2001; Carter and Clift 2008).

In order to better understand the fault activities, we undertook a detailed $^{40}Ar/^{39}Ar$ geochronological study of the Dien Bien Phu fault. Mesozoic ages obtained for mica fish in mylonites from two areas along the Dien Bien Phu fault suggest that the fault is long-lived and that it may have dextrally offset the Song Ma suture during the Jurassic. Using both our own and previously published age and structural data, we suggest that the successive suturing/collision of the Indochina, Simao, and Sibumasu blocks probably played an important role in controlling dextral movement along the Dien Bien Phu fault.

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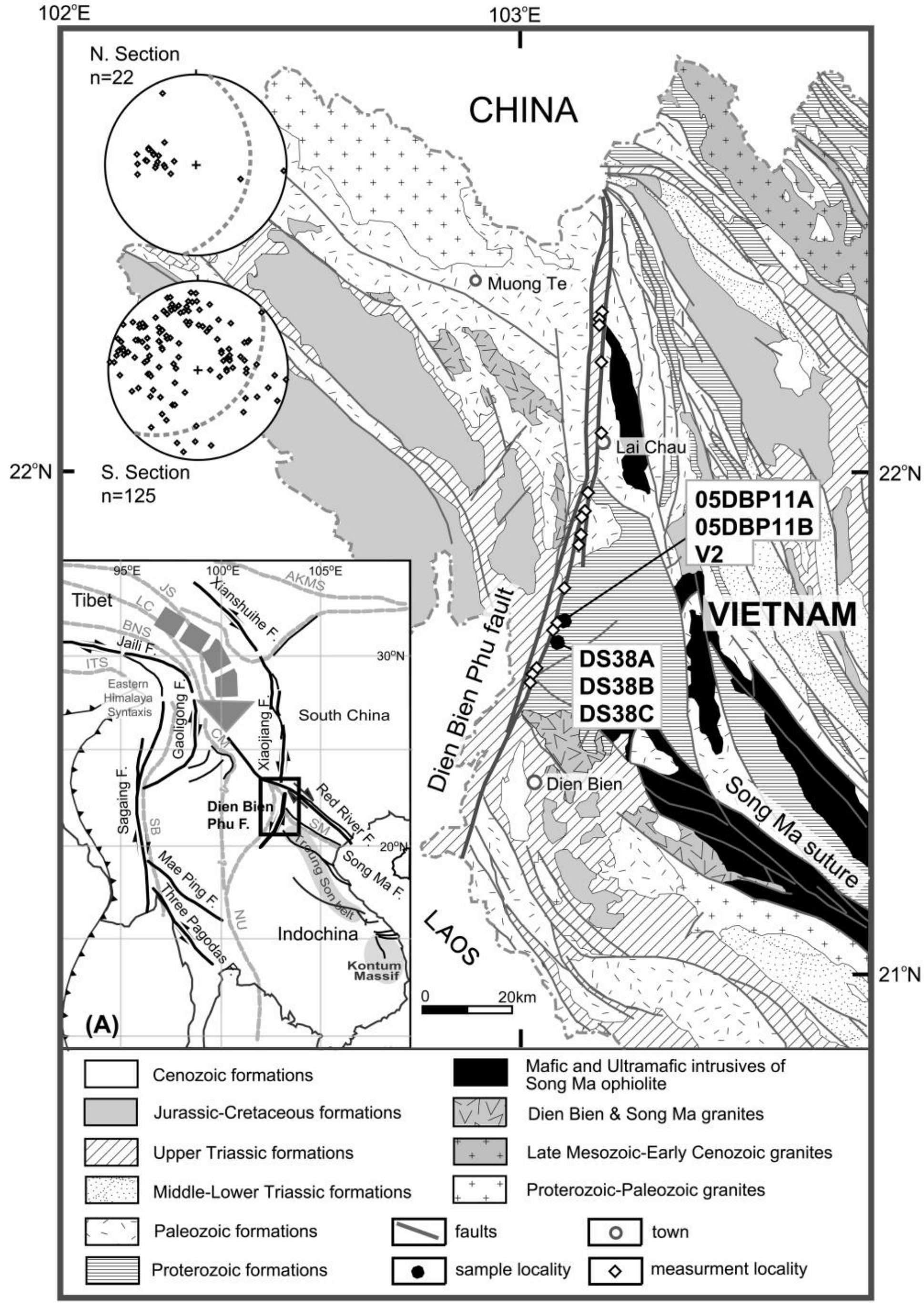

Figure 1. *Inset*, tectonic framework of southeastern Asia, showing the distribution of major faults. The thick gray arrow indicates the movement direction of crustal fragments around the Eastern Himalaya Syntaxis. *AKMS* = Ayimaqin-Kunlun-Muztagh Suture; *BNS* = Bangong-Nujiang Suture; *CM* = Changning-Menglian Suture; *ITS* = Indus-Tsangpo Suture; *JS* = Jinsha Suture; *LC* = Lancangjiang Suture; *NU* = Nan-Uttaradit Suture; *SB* = Shan Boundary Suture; *SM* = Song Ma Suture. Area in box is enlarged for main image: a simplified geological map of northern Vietnam, showing sample localities (*filled circles*). Equal-area stereonets show poles to foliation in areas north and south of the Dien Bien Phu fault.

Geological Background

The NNE-SSW- to N-S-trending Dien Bien Phu fault, 160 km long and 6–10 km wide, is one of the most active fault zones in Indochina. The fault extends southward into Laos and Thailand, probably continuing as far as the Gulf of Thailand (Wang et al. 1998). It cuts late Paleozoic–Triassic sediments and granitoids (fig. 1; Tuyet et al. 1978; Lan et al. 2000; Zuchiewicz et al. 2004), dextrally offsetting the Song Ma suture zone in northwestern Vietnam. This suture zone, separating the Indochina and South China blocks (fig. 1), is a relic of the Laos-Vietnam branch of the Paleotethys and is characterized by metamorphosed mafic and ultramafic masses thought to be ophiolitic fragments (Hutchison 1975, 1989; Lepvrier et al. 2004; Trung et al. 2006). Although fossil fish records favor a close geographic association between the South China and Indochina blocks during the Devonian (Thanh et al. 1996), $^{40}Ar/^{39}Ar$ age data from the Song Ma belt (Lepvrier et al. 1997) suggest that the final amalgamation of the two blocks took place in the Early Triassic (ca. 245 Ma).

The Dien Bien Phu fault crosscuts a late Paleozoic to Early Triassic granitic complex (the Dien Bien Complex) that is unconformably overlain by upper Triassic clastics of the Lai Chau and Suoi Bang formations (fig. 1). The main fault zone and associated subsidiary faults record strike-slip and oblique-slip displacement, with the principal fault plane dipping 60°–70° to the west and steepening to 70°–80° (and even vertical) in the south (Hung and Vinh 2001). The Permo-Triassic granitoid batholith emplaced along the southern part of the Song Ma suture (fig. 1) has been dextrally offset by ca. 50 km along the Dien Bien Phu fault (Fontaine and Workman 1997; Lepvrier et al. 1997). This suggests that the Dien Bien Phu fault may have been active after the Late Triassic.

Although seismic and geomorphic data from the Dien Bien Phu fault suggest a sinistral slip accompanied by a component of normal faulting (Tapponnier et al. 1986; Zhang et al. 2004; Zuchiewicz et al. 2004), no sinistral ductile deformation is observed in the field except sinistral brittle deformation and a series of small, narrow pull-apart basins filled with Quaternary sediments. Estimated slip rates (0.4–3.8 mm/yr) of sinistral movement along the Dien Bien Phu fault are broadly comparable with those of present-day dextral movement along the Red River fault, indicating a conjugate relationship between the two faults since the Holocene (Zuchiewicz et al. 2004).

Samples

Matrix foliations within late Paleozoic to Triassic metamorphic rocks along the Dien Bien Phu fault are consistent with the strike of the fault and the dextral sense of shearing (figs. 1, 2). Unfortunately, rocks along the Dien Bien Phu fault are poorly exposed and highly weathered. Three samples of mica schist (DS38A, DS38B, and DS38C) and three samples of mylonite (DBP11A, DBP11B, and V2) were collected from two outcrops that contain meso- and microscale structures indicative of dextral shearing, including asymmetric boudins, sigmoidal lenses, and well-developed shear bands (fig. 2).

All the samples are foliated and contain similar mineral assemblages dominated by biotite, muscovite, K-feldspar, and quartz. Their quartz, feldspar, and mica grains possess a lattice-preferred orientation parallel to the strike of the Dien Bien Phu fault. In mylonite samples DBP11A and DBP11B (fig. 2),

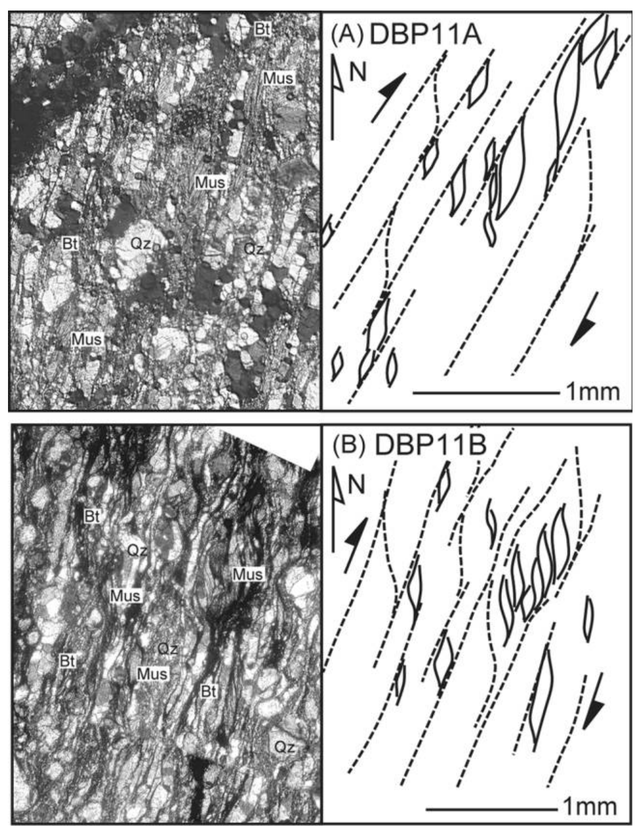

Figure 2. Microphotographs and accompanying line diagrams showing muscovite fish and interpretation of dextral shear sense. *Bt* = biotite; *Mus* = muscovite; *Qz* = quartz. A color version of this figure is available in the online edition.

linear ribbons of quartz and feldspar define the foliation. The ribbons show evidence of undulose extinction and recrystallization, indicating medium-grade metamorphism at temperatures above 400°C (Passchier and Trouw 1998). Syntectonic muscovite porphyroblasts occur as mica fish (fig. 2), showing monoclinic shape symmetry indicative of intensive ductile deformation. Tiny muscovite grains occur at the sides and tips of the mica fish, a feature related to grain-size reduction via recrystallization that leads to the formation of trails that define the mylonitic foliation (fig. 2). Even in mylonite samples in which the matrix has undergone static recrystallization, mica fish retain an asymmetric geometry, indicating a sense of shear. The monoclinic shape of the fish and the stair-step geometry of the trails indicate dextral shear, which we interpret as reflecting the earlier event that dextrally offset the Song Ma belt. The sinistral shear along the fault indicated by geodetic data is not apparent in the observed microstructures, implying that recent shearing may have had little effect on the analyzed samples.

Laser $^{40}Ar/^{39}Ar$ single-grain fusion experiments were performed on muscovite and biotite separated from the six analyzed samples. All the mineral separates were obtained by handpicking under a microscope and were irradiated, along with LP-6 biotite standards with an $^{40}Ar/^{39}Ar$ age of 128.4 ± 0.4 Ma (Renne et al. 1998), at the Tsing-Hua Open-Pool Reactor (THOR), Taiwan, for 30 hours. Calculations of J values were based on the laser fusion data of the standard. Isotope compositions were corrected for mass discrimination, system blanks, isotope interference, and radiometric decay. Details of the analytical method are outlined in Lo et al. (2002). Results of $^{40}Ar/^{39}Ar$ analyses are available on request from the corresponding author.

Results

The analytical data are presented as age distributions and $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isotope correlation diagrams (fig. 3) and are summarized in table 1. As shown in figure 3, the age data for each sample define a single mode with a small standard deviation; none of the samples shows large grain-by-grain variation. The isotope correlation diagrams show excellent linear arrays, with reasonable MSWD values, and acceptable $^{40}Ar/^{36}Ar$ initial ratios that are in general agreement with the present-day atmospheric ratio (295.5). All the intercept ages appear to agree with their respective mean ages (fig. 3; table 1). These results suggest that since passing through the closure temperature, the argon isotopic systematics in the samples have not been significantly disturbed by excess argon or overprinting thermal events.

As shown in figure 3, three biotite grains from the schist samples show ages in the range 194–211 Ma, younger than the coexisting muscovite (212 ± 0.4 Ma) in sample DS38A. Two biotite grains from the mylonite samples, DBP11A and DBP11B, yield young ages of 158.4 ± 3.9 and 196.5 ± 3.3 Ma, respectively, both younger than the coexisting muscovite (173.6 ± 0.7 and 183.1 ± 1.2 Ma, respectively). The oldest age obtained from a mylonite sample is 196.5 ± 3.3 Ma, for the V2 muscovite (table 1).

Discussion

The mica $^{40}Ar/^{39}Ar$ ages obtained for mica schists (194–212 Ma) and mylonites (158–197 Ma) are younger than those reported by previous authors for tectonothermal and subsequent cooling events related to the amalgamation of the South China and Indochina blocks during the Indosinian Orogeny (~250–233 Ma; Lepvrier et al. 1997; Carter and Clift

Table 1. Summary of $^{40}Ar/^{39}Ar$ Dating Results

Lithology, locality, sample	Phase	Mean age (Ma)	SD of mean age (Ma)	Intercept age (Ma)	$(^{40}Ar/^{39}Ar)_i$	MSWD
Mylonite, 21.6968°N, 103.0867°E:						
DBP11A	Biotite	157.5	4.6	158.4 ± 3.9	290 ± 9	3.599
DBP11A	Muscovite	173.3	.8	173.6 ± .9	287 ± 12	1.608
DBP11B	Biotite	161.4	2.3	161.9 ± 1.6	280 ± 14	2.505
DBP11B	Muscovite	184.3	3.4	183.1 ± 1.2	321 ± 11	3.752
V2	Muscovite	195.8	2.1	196.5 ± 3.3	288 ± 11	2.907
Mica schist, 21.6498°N, 103.0636°E:						
DS38A	Biotite	209.8	4.7	207.8 ± .6	304 ± 2	1.546
DS38A	Muscovite	212.6	1.2	212.2 ± .4	302 ± 6	0.966
DS38B	Biotite	210.5	1.6	210.5 ± .8	326 ± 20	1.937
DS38C	Biotite	193.4	.8	193.7 ± .2	296 ± 69	0.202

Note. Errors quoted are ±1σ.

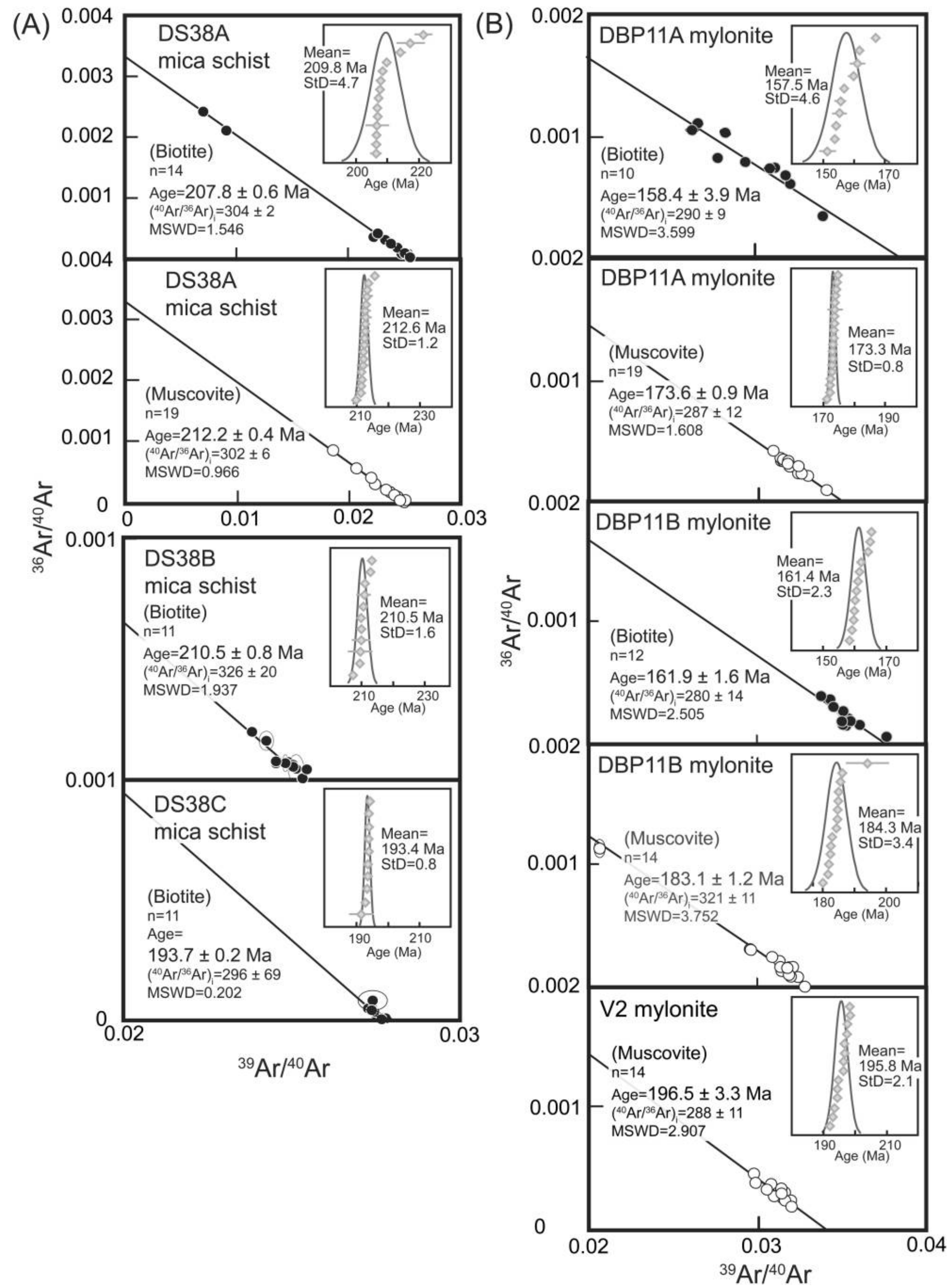

Figure 3. $^{40}Ar/^{39}Ar$ age distribution and isotope correlation diagrams for schist (*A*) and mylonite (*B*) samples. MSWD = mean square weighted deviation; StD = standard deviation.

2008; Nakano et al. 2008). Despite a lack of suitable index minerals for precise *P-T* estimates, medium- to high-grade metamorphism (temperatures $\gtrsim$ 400°C) are indicated by deformation patterns in the mylonites (see Passchier and Trouw 1998). In terms of $^{40}Ar/^{39}Ar$ geochronology, these estimated temperatures broadly correspond to the closure temperature for muscovite (i.e., ~400°C) but are higher than that for biotite (~350°C). Given that mica fish are important products of shearing deformation (Lister and Snoke 1984), muscovite $^{40}Ar/^{39}Ar$ dates from shear zones have proved to be a useful tool in providing age constraints on synkinematic recrystallization (Mulch et al. 2005). Since the muscovite fish observed in mylonite samples indicate a dextral shear sense, we suggest that they were formed during the dextral shearing along the Dien Bien Phu fault that offset the Song

Ma suture. Thus, the $^{40}Ar/^{39}Ar$ dates obtained for muscovite fish and biotite from mylonites along the Dien Bien Phu fault can be used to constrain the timing of a syntectonic thermal event and/or long-lasting cooling events during the Early Jurassic (158–197 Ma).

Alternatively, the large range in mica ages of mylonite samples (158–197 Ma) might reflect the partial resetting of isotopic systematics and probably records an early Mesozoic tectonothermal event and subsequent overprinting by younger thermal events. Indeed, thermal events associated with Tertiary extrusion tectonism are widely distributed throughout Indochina, mainly along NW-SE-trending shear zones. For example, Lepvrier et al. (1997, 2004) reported that the K-Ar isotopic systems of the early Mesozoic Troung Son belt were partially overprinted by a Tertiary tectonothermal event, resulting in a lowering of Mesozoic mica $^{40}Ar/^{39}Ar$ ages in the belt. However, this does not appear to be the case for the samples in this study. Although the Tertiary extrusion could have induced brittle deformation and pull-apart basins in the region along the Dien Bien Phu fault, it is unlikely to have strongly influenced our samples. Furthermore, thermal overprinting of isotopic systems usually results in significant age variation between mineral grains, because argon loss via diffusion during thermal overprinting is dependent on grain size (Lo and Onstott 1995). From our samples, however (see fig. 3), we obtained relatively minor intergrain age variation.

However, it remains possible that dextral shearing occurred along the Dien Bien Phu fault in the Late Jurassic (around 158 Ma) and that the associated thermal event partially reset the isotopic systems in the mylonites. This partial resetting would be expected to yield isotopic ages intermediate between the two thermal events, with a wide range of ages, similar to that expected for a long-lasting cooling and deformation event. It is not possible to rule out a Late Jurassic thermal overprint on the Late Triassic isotopic systematics. In any case, the mica ages of mylonite samples (158–197 Ma) suggest a dextral shearing along the Dien Bien Phu fault during the middle Mesozoic.

It is of interest to further examine the mechanism for the initiation of dextral shearing along the Dien Bien Phu fault. Indochina was formed by amalgamation, including fragments of the South China, Indochina, Simao, and Sibumasu blocks during the Indosinian Orogeny. The timing of the collision between Indochina and South China, generally believed to be the key event that initiated the Indosinian Orogeny (Hutchison 1989), is probably best constrained by $^{40}Ar/^{39}Ar$ ages of ca. 245 Ma and a U-Pb age of ca. 233 Ma reported for high-grade metamorphic rocks from the Song Ma suture (Lepvrier et al. 1997; Nakano et al. 2008).

The Early Jurassic dextral movement along the Dien Bien Phu fault, as inferred from this study, appears to postdate the collision between the Indochina and South China blocks. Although the timing of the suturing of the Indochina and Sibumasu blocks remains poorly constrained, it is generally believed to have occurred in the Late Triassic to earliest Jurassic, as argued from sedimentary and magmatic records in Thailand and Malaysia (Liew and Page 1985; Charusiri et al. 1993; Dunning et al. 1995; Wu et al. 1995; Singharajwarapan and Berry 2000). If this was the case, the collision of the Indochina, Sibumasu, and Simao blocks (Metcalfe 2000, 2002) may have played an important role in the initiation of the dextral shearing of the Dien

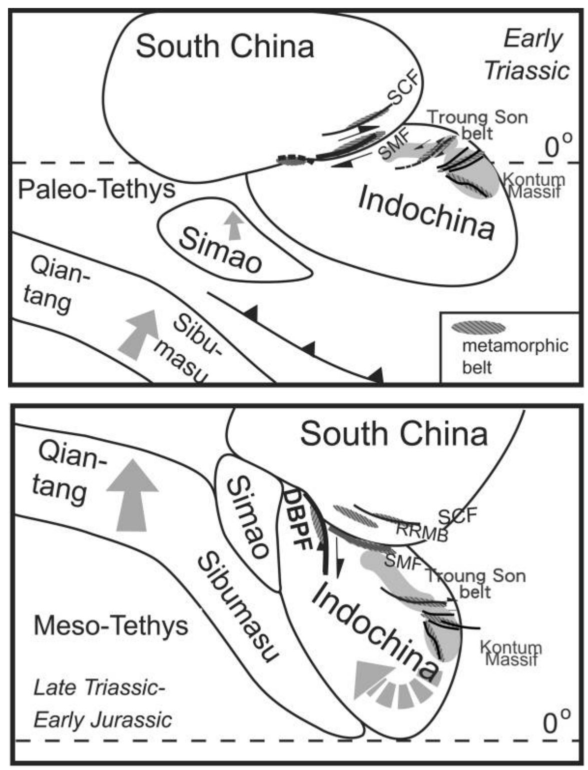

Figure 4. Schematic paleogeographic reconstruction of continental blocks in Indochina from the Early Triassic (modified after Carter et al. 2001; Metcalfe 2002) to Early Jurassic. Gray arrows denote the strike-slip movements during the Indochina Orogeny. Gray areas display the locations of the Troung Son belt and the Kontum Massif. Black lines represent the major faults. Large gray arrows show the movement direction of the blocks. *DBPF* = Dien Bien Phu Fault; *RRMB* = Red River Metamorphic Belt; *SCF* = Song Chay Fault; *SMF* = Song Ma Fault.

Bien Phu fault. Moreover, according to Carter et al. (2001) and Metcalfe et al. (2002), the successive suturing/collision of these blocks could potentially generate a clockwise rotation in the Indochina block. This rotational stress may have eventually induced the initiation of dextral shearing along the NNE-SSW-trending Dien Bien Phu fault (fig. 4).

Conclusion

We obtained unexpectedly old $^{40}Ar/^{39}Ar$ ages (Late Triassic to Early Jurassic) for schists and mylonites collected from the Dien Bien Phu fault. The Triassic dates obtained from schist samples may indicate partial resetting of an Indosinian metamorphic age by a Jurassic tectonothermal event along the Dien Bien Phu fault; however, mica $^{40}Ar/^{39}Ar$ ages from mylonite samples indicate that dextral shearing along the Dien Bien Phu fault began in the earliest Jurassic, meaning that the fault is not a young structure related to Tertiary extrusion tectonism in Indochina. Collision between the Indochina, Sibumasu, and Simao blocks, known to be the most important tectonic activity in the region during the Mesozoic, may have been responsible for the initiation of Mesozoic dextral shearing along the Dien Bien Phu fault.

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