Paleotethyan evolution of the Indochina Block as deduced from granites in northern Laos

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Abstract: Increasing level of details about the Paleotethyan evolution of the SE Asia have been defined in recent years. Questions remain, however, over the role of the Dien Bien Phu Suture Zone in the evolution of the Indochina block and whether the Song Ma Suture represents the boundary between the Indochina block and the South China Block; such debate extends to their plate convergence geometry prior to collision. Granitoid geochronological and geochemical data obtained in northern Laos provide new information *vis-à-*vis these arguments. Zircon U-Pb ages together with whole rock, trace and rare earth element data from 27 granitic rocks from five complexes allow us to conclude that these granites are typical of I-type Indosinian volcanic arc granites. However, the 234-256Ma I-type granites mismatch the initiation age obtained from the ductile shear zone of the Dien Bien Phu Fault, thus repudiating the existence of the Dien Bien Phu Suture Zone. This then implies that the Qamdo-Simao and Indochina blocks were united. Zircon inheritance ages and zircon crustal two-stage model ages suggest that the main crust in the Indochina Block formed in the Late Paleoproterozoic to Early Mesoproterozoic, much later than the Archean crustal formation age identified east of the Song Ma Suture. Moreover, the 440–404Ma and 234–256Ma I-type granites suggest that the boundary between Indochina and South China should be the Jinsha River Suture-Song Ma Suture-Kontum Massif, instead of the Jinsha River Suture-Song Chay Suture. Finally, the Emeishan basalt and granite complexes both form part of the South China tectonic units subducting westward (or southward in a palaeogeographic sense) under the Qamdo-Simao and Indochina blocks**.**

Keywords: granite; Laos; zircon U-Pb age; Lu-Hf; whole-rock major, trace and rare earth elements

1. Introduction

Mainland SE Asia is formed of several micro-continents (*e.g.* the Sibumasu, Indochina, Qamdo-Simao and South China blocks) which amalgamated during the closure of the Paleotethyan Ocean from the Late Permian to the Early Triassic (*e.g.* Sengor, 1979; Metcalfe 1996, 1999, 2002, 2013; Lepvrier *et al*., 2004, 2008; Carter *et al*., 2001; Ueno, 2003; Ferrari *et al*., 2008; Liu *et al*., 2012; Faure *et al*., 2014). A long S-N trending line of ophiolitic mélange suites, forming part of the Paleotethys Suture Zone, can be followed from the Malaysian Peninsula in the south to southwestern China in the north (Fig. 1). These are the Bentong-Raub Suture in the Malaysian

Peninsula, the parallel Inthanon Suture and Nan-Uttaradit Sutures in north-central Thailand, the so-called Dien Bien Phu Suture in Laos and Vietnam (where the Dien Bien Phu fault is developed) and the Changning-Menglian Suture in China (*e.g.* Hutchison, 1975; Barr and MacDonald, 1987; Barr *et al*., 2000; Wu *et al*., 1995; Singharajwarapan and Berry., 2000; Sone and Metcalfe, 2008). A granitoid belt is distributed parallel to the Paleotethys Suture. The age of the granitoids in the granitoid belt ranges from 265 to 230Ma (*e.g.* Beckinsale *et al*., 1979; Liew and McCulloch, 1985; Barr *et al*., 2000; Searle *et al*., 2012; Gardiner et al., 2015), the same age as the blueschist facies metamorphic rocks that are in association with the Paleotethys Suture (e.g. Barr and MacDonald, 1987; Singharajwarapan and Berry., 2000). Conversely, radiometric dating of syn-tectonic high-pressure metamorphic rocks (*e.g*. Lepvrier *et al*., 1997, 2004; Lan *et al*., 2003; Osanai *et al*., 2001, 2004; Nakano *et al*., 2007) and Indosinian granitoid (*e.g*. Nagy *et al*., 2001; Lan *et al*., 2000; Owada *et al*., 2007; Sanematsu *et al*., 2011) in Vietnam, including in the Truong Son Belt and the Kontum Massif of central-southwestern Vietnam, has recorded Indosinian orogeny within a restricted time interval between 258±6.6Ma and 243±6.5Ma. The Late Permian to Early Triassic coeval events in Southeast Asia are broadly accepted as indicating the initial subduction between the Sibumasu-Indochina and South China blocks.

Despite some progress, arguments remain about the welding of the blocks in Southeast Asia. For example, new progress confirm that the Changning–Menglian and Inthanon suture zones are regarded as the Palaeo-Tethys Suture Zone, the

Jinghong-Luang Prabang-Nan-Sra Kaeo suture is regarded as a closed back-arc basin (e.g. Sone and Metcalfe, 2008; Metcalfe, 2011, 2013; Qian et al., 2015). Uncertainty exists about the role of the Dien Bien Phu suture in the Paleotethys evolution of the SE Asia (Fig. 1). Establishing this would help determine whether the Qamdo-Simao Block is part of the Indochina Block, or if the Indochina and the Qamdo-Simao blocks are two separate blocks. This question has perplexed geologists for a long time **(***e.g*. Metcalfe, 1996, 2002, 2006; Wang *et al*., 2000; Carter *et al*., 2001**).** One view insists that the Sukhothai Arc and the Inthanon Suture correlate with the Lincang-Jinghong Volcanic Belt and the Changning-Menglian Suture in Yunnan, China (*e.g*. Sone and Metcalfe, 2008; Metcalfe, 2011, 2013). Taking this view, the Qiangtang-Baoshan Block west of the suture would form the northern part of the Sibumasu Continent, and the Qamdo-Simao Block east of the suture would represent the northern continuity of the Indochina Continent (*e.g*. Wang *et al*., 2000; Carter *et al*., 2001; Carter and Clift, 2008; Ferrari *et al*., 2008; Liu et al., 2012; Faure et al., 2014); But others argue that the Nan-Uttaradit Suture bends northeastward at the Dien Bien Phu Segment and joins the Song Ma Suture, separating the Nan-Uttaradit Suture from the Changning-Menglian Suture by hundreds of kilometers (Sengor, 1979; Leloup *et al*., 1995; Singharajwarapan and Berry., 2000; Lepvrier *et al*., 2004, 2008). Another question concerns the time and geometry of plate convergence prior to collision between the Indochina and the South China blocks. Paleogeographic evidence suggests a connection between Indochina and South China up to the Carboniferous (*e.g*. Hutchison, 1989; Janvier *et al*., 1997; Racheboeuf *et al*., 2005, 2006; Metcalfe, 1996, 2002, 2013), but syn-tectonic magmatic and metamorphic data show a tectono-thermal event that occurred between 260Ma and 240Ma (*e.g.* Lepvrier *et al*., 1997, 2004, 2008, 2011; Nagy *et al*., 2001; Lan *et al*., 2000, 2003; Owada *et al*., 2007; Nakano *et al*., 2007; Sanematsu *et al*., 2011; Lai *et al*., 2014). Additionally, varying opinions about the geometry of block convergence prior to collision exist, and include: 1) the eastward subduction of the Indochina Block beneath the South China Block (Lepvrier *et al*., 1997, 2004; Lan *et al*., 2000); 2) the westward (or southward in a palaeogeographic sense, the same below) subduction of the South China Block beneath the Indochina Block (Liu *et al*., 2012; Faure *et al*., 2014); and 3) the existence of a pair of subduction zones dipping in opposite directions (Lepvrier *et al*., 2008).

Most areas of Laos are covered by virgin forest, which makes tracking the outcrops of the Dien Bien Phu ophiolitic suture difficult. Fortunately, granitoids are distributed broadly along the road from Phonsavan to Sam Neua in northern Laos, south of the junction between the Dien Bien Phu Suture and the Song Ma Suture (Fig. 2). It is widely accepted that the geochronological and geochemical data of granitic rocks can provide important information regarding the crustal evolution of tectonic plates. The geochronology and geochemistry of granitic rocks in northern Laos, however, is poorly known, due to their inaccessibility. In recent years we have collected more than 100 samples from different granitoid complexes in northern Laos in order to reconstruct the convergence process of Southeast Asian blocks during the closure of the Paleotethyan Ocean.

2. **Geological setting**

2.1 The rocks in northern Laos

Proterozoic to Quaternary strata outcrop in central-northern Laos (Department of Geology and Mine, Lao P. D. R. (DGM), 1991; Fig. 2), and can be divided into three main units: Late Palaeozoic, Early Mesozoic and Late Mesozoic. Late Palaeozoic strata are mainly shallow sea shelf sequences interbedded with volcano-sedimentary sequences, mostly of sandstone, siltstone and shale. There are a few outcrops of Early Palaeozoic rocks, which are mainly deep-water, marine volcano-sedimentary, metamorphosed to low or low-medium grades (DGM, 1991). Early Mesozoic strata are mostly of continental rock, with local shallow-water marine facies. Rocks in this unit are red argillaceous sandstone, with occasional thin coal seams and conglomerates. These two stratigraphic units are distributed in a N-S direction. Late Mesozoic strata are mainly confined to the Vientiane Basin; rocks are mainly red continental sandstones and clays, with lagoonal mud rocks in the upper levels bearing evaporate rocks of halite and gypsum. Granitoid complexes have developed on the Xieng Khoang Plateau of northern Laos (Fig.2), which is located at the junction of the N-S trending granitoid belt at the Dien Bien Phu Segment of the Nan and Dien Bien Phu suture zones and the NW-striking Truong Son Belt. The granitoid belt along the Nan Suture has been interpreted being composed of syn-tectonic granitoids from the subduction of the Sibumasu Continent eastward into Indochina (*e.g*. Beckinsale *et al*., 1979; Charusiri *et al*., 1993; Barr *et al*., 2000). Conversely, the granitoids located along the northwestern extension of the Truong Son Belt have been attributed to the syn-tectonic or within-plate granitoids of the Indochina Block during its subduction eastward under the South China Block (*e.g.* Lepvrier *et al.*, 1997, 2004; Sanematsu *et al.*, 2011).

2.2 The tectonic setting around northern Laos

2.2.1 The Nan and Dien Bien Phu Suture Zones

The magmatic and sedimentary rocks in northern Laos are confined by two tectonic boundaries: the Nan-Dien Bien Phu Suture Zone in the west and northwest, and the Truong Son Belt in the east. The S-N striking Nan Suture Zone west of Laos consists of a belt of ophiolitic mafic and ultramafic rocks formed in a back-arc or inter-arc setting (Barr and MacDonald, 1987; Barr *et al.*, 2000; Singharajwarapan, 2000), accompanied by metasedimentary rocks of the Sukhothai Fold Belt and syn-tectonic granite defined as a granite belt (Sone and Metcalfe, 2008). Northward, the suture bends eastward and joins with the Song Ma Suture, thus separating the Indochina Block from the Qamdo-Simao Block (Sengor, 1979; Leloup *et al.*, 1995; Singharajwarapan and Berry, 2000). Alternatively, the Nan Suture could connect northward with the Jinghong Suture in Yunnan, China (*e.g.* Bar *et al.*, 1987, 2000; Wu *et al.*, 1995; Sone and Metcalfe, 2008).

2.2.2 Tectonic units from Inner Indochina to the Red River Fault

The Song Ma Suture defines the boundary between the Indochina and South China blocks, although the Song Da or Song Chay sutures have also been considered the boundary (*e.g.* Lepvrier *et al.*, 2004; Liu *et al.*, 2012; Faure *et al.*, 2014). Eastward, the tectonic units from inner Indochina to South China can be subdivided into: the Indochina Basement; the Song Ma Suture Zone; the Nam Co Complex; the Song Da

Rift Zone; the Tu Le Basin and the Song Chay Suture Zone (dissected by the Red River Fault (RRF) during the Cenozoic). The features of these tectonic units are described below; the relations between the units are shown as a simplified section in Figure 3.

1) The Indochina Basement. Some high-grade metamorphic rocks and granite complexes in northern Laos and northwestern Vietnam are attributed to the Archean to Proterozoic eons (DGM, 1991; Department of Geological and Minerals of Vietnam (DGMV), 2005), similar to the basement of the Kontum Massif in the southernmost part of Vietnam (*e.g*. Osanai *et al*., 2001, 2004; Owada *et al*., 2007; Nakano *et al*., 2007; Sanematsu *et al*., 2011);

2) The Song Ma Suture Zone, which is composed of Song Ca volcanic arc, the Truong Son Belt (Truong Son arc granitoids) and the Song Ma tectonic mélange from W-E. The Song Ca volcanic arc is comprised mainly of a sequence of calcalkaline volcanic associations of ages 270–248Ma, using $^{40}Ar/^{39}Ar$ dating (Lan *et al*., 2003). The Truong Son Belt consists of widespread Late Paleozoic to Early Mesozoic intrusions. Truong Son Belt strata exhibit: Neoproterozoic high-grade metamorphic rocks; Silurian to Lower Devonian and Upper Permian marine sedimentary rocks; Upper Permian basalt, amygdaloidal basalt and tuffs; and Triassic marine and terrigenous sedimentary rocks. The Song Ma mélange is defined as the boundary between the Indochina and South China blocks that occurred during the westward subduction of the South China Sea under the Indochina Block in the Later Permian to Early Triassic (*e.g*. Lepvrier *et al*., 2004, 2008; Liu *et al*., 2012; Faure *et al*., 2014). It

consists of sheets of rocks with ages from Neoproterozoic to Early Triassic. These rocks are highly sheared, juxtaposed by shear zones and intruded by gabbro, plagiogranite, granodiorite and granite (DGMV, 2005).

3) The Nam Co complex, a high-grade metamorphic massif. Proterozoic greenschist to amphibolite facies metamorphic rocks, including gneisses, schists, amphibolites, quartzite and marbles constitute the majority of the massif. The metamorphic rocks are highly foliated and lineated, and formed ca. 245Ma (Lepvrier, *et al*., 2004).

4) The Song Da Rift Zone. The lowermost sequence is composed of Lower Permian carbonates overlain by a sequence of mafic to ultramafic volcanic rocks of the Lower Permian Cam Thuy Formation. The middle sequence is Upper Permian to Early Triassic, and is composed of an association of komatiite-basalt, trachytic basalt，trachytic andesite and trachytic dacite . Upward, the sequence exhibits calcareous sediments interlayered with felsic volcanics in its Mid to Late Triassic sediments. The top sequence is Cretaceous sedimentary rocks unconformably overlying old sequences. East of the Song Da Rift Zone is the Tu Le Basin, which is filled with Mesozoic continental sediments. East of the Tu Le Basin is the Song Chay Suture Zone, which includes the Song Chay ophiolitic mélange and the Day Nui Con Voi (DNCV) gneiss belt, where the Red River Fault dissected the mélange during the Cenozoic.

The Indochina block has been thoroughly overprinted and cut by Neogene strike-slip faults such as the Ailaoshan-Red River Fault, the Wangchao Fault and the

Dien Bien Phu Fault. The NE-trending Dien Bien Phu Fault in the study area was the southernmost segment of the Xianshuihe fault system during the Late Cenozoic; the fault has been an active left-lateral strike slip fault since ca. 5.5Ma, and reactivated after 228Ma or 198-158Ma with totally 30-40km right-lateral offset accumulated (*e.g.* Wang *et al*., 1998; Zuchiewicz *et al*., 2004; Koszowska *et al*., 2007; Lin *et al*., 2009; Roger *et al*., 2014).

3. Analytical method

About 24 granite samples were prepared for zircon U-Pb LA-ICP-MS dating. Zircons were separated using conventional heavy-liquid and magnetic techniques. Pure zircon grains were selected using a binocular microscope. Representative grains were placed into an epoxy resin, along with several standard transmission electron microscopy (TEM) samples, and ground down by about half to expose the zircon interior, before performing U-Pb dating. Before and after the dating, the transmitted and reflected light were analyzed using a microscope and backscattering images, together with cathode luminescence images, in order to determine crystalline shape, inner structure and dating position.

U–Pb dating of zircons was conducted using a New Wave UP193FX Excimer laser, coupled with an Agilent 7500a ICPMS, at the Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences (CAS), Beijing. The diameter of the laser beam was 36mm, and the duration of ablation was 45s. Zircon standard 91500 was used as an external standard to correct isotopic ratios. TEM characterization of zircon was used to monitor results.

Concentrations of the elements were calculated using NIST612 glass as the external standard and ^{29}Si as the internal standard. Age data were processed using Glitter 4.4 software (details can be found in Jackson *et al*., 2004). Diagrams were produced using the Isoplot 3.0 Toolkit (Ludwig, 2003).

In-situ Hf isotope analysis was performed on zircon grains using LAICPMS with a beam size of 60μm and a laser pulse frequency of 8Hz. Details of instrument conditions and data acquisition are given in Wu *et al*. (2006) and Xie *et al*. (2008). During the analysis, 176Hf/177Hf ratios of the zircon standard (91500) were 0.282286±12 (2σ, n=21). The εHf(t) values (parts in 104 deviations in initial Hf isotope ratios between the zircon sample and the chondritic reservoir) and T_{DM2} (zircon Hf isotope crustal model ages based on a depleted-mantle source and an assumption that the protolith of the zircon's host magma has a mean continental crustal $^{176}Lu/^{177}Hf$ ratio of 0.015) were calculated following Griffin *et al*. (2002), using the ^{176}Lu decay constant given in Blichert-Toft and Albarède (1997).

About six granite samples were chosen for whole-rock major, rare earth and trace element analysis. Samples for elemental analysis were powdered to <20μm using an agate mill. Major element analyses were conducted at the Institute of Geology and Geophysics, CAS. Major element abundances (wt.%) of whole-rock samples were determined using a Phillips PW X-ray fluorescence spectrometer (XFR-2400) and yielded an analytical uncertainty of <5% (±1σ). Rare earth and other trace elements were analyzed using ICP-MS techniques at the Institute of Tibetan Plateau Research, CAS. The detailed operating conditions for the laser ablation system, the ICP-MS instrument and data reduction were the same as those described by Liu *et al*. (2008), with the uncertainties for all elements <5%.

4 Results

4.1 U-Pb dating

More than 40 samples from six granite complexes along the road from Phonsavan to Sam Neua in northern Laos were selected for zircon analysis, and ca. 20 representative samples are presented in this paper to show the geochronology of the complexes. The samples collected are termed LC-1, LC-6 and LC-8 (from the Lat Boua Complex), LC-12, LC-16 and LC-17 (from the Kham Complex), LH-1, LH-4 and LH-5 (from the Phon Thong Complex), LH-11, LH-13 and LH-16 (from the Luu Complex), LT-1, LT-3, LT-4 and LT-6 (from the Na The Complex), and LB-3, LB-5, LB-6 and LB-7 (from the Laosang Complex) (Fig. 2). The sites of the complexes are located between 19^{o}41.396'N to 20^{o}49.650'N, and 103^{o}28.176'E to 104^{o}19.781'E. Of the six complexes, the Lat Boua, Kham, Phon Thong, Luu and Na The complexes exhibit ages ca. 234–256Ma; the Laosang Complex gives a mean age of 420Ma (Fig. 4, Table 1 in Appendix A). Only a few zircons from some samples show the existence of inherited cores as described in Section 4.2 and Table 2 in Appendix B.

Zircons from the 16 samples from the Lat Boua, Kham, Phon Thong, Luu and Na The complexes are mainly light yellow to transparent, euhedral prismatic grains. Cathode luminescence images (CL) show that these zircons generally have luminescent (low U) cores with euhedral fine-scale oscillatory igneous zoning. They generally range from 120–200μm in length and 50–80μm in width. As a rule, we selected 25-35 representative zircons from these 16 samples for U-Pb dating (Table 1 in Appendix A). Th/U ratios range from 0.18 to 1.58, indicating a typical magmatic origin. Analytical results generally group together and yield weighted mean $^{206}Pb/^{238}U$ ages ranging from 234.3±1.5Ma to 256.4±3.1Ma (95% confidence; MSWD values range from 0.9 to 1.5) (Fig. 4), which we interpret as the crystallization ages of the Lat Boua, Kham, Phon Thong, Luu and Na The complexes.

The Laosang granite complex, where samples LB-3, LB-5, LB-6 and LB-7 were collected, is located at approximately 19°13.872'N, 103°40.482'E. Zircons from samples LB-3, LB-5, LB-6 and LB-7 consist of light yellow to transparent, euhedral prismatic grains. CL images show that these zircons generally have luminescent (low U) cores with euhedral fine-scale oscillatory igneous zoning. They generally range from 120–180μm in length and 50–80μm in width. Zircon characteristics are similar to those of zircon from the other five complexes. We selected 30, 22, 25 and 26 representative zircons respectively from the four samples for U-Pb dating (Table 1 in Appendix A). The Th/U ratios range from 0.18 to 1.58, 0.20 to 2.06, 0.16 to 1.30 and 0.18 to 0.76, respectively, indicating typical magmatic origins. Analytical results gained generally group together and yield a weighted mean $^{206}Pb/^{238}U$ age of 431.4±2.6Ma (95% confidence, MSWD=1.5) from LB-3, 425.4±2.4Ma from LB-5 (95% confidence, MSWD=0.5), 435.1±3.8Ma from LB-6 (95% confidence, MSWD=1.0) and 402.5±1.9Ma (95% confidence, MSWD=1.8) from LB-7 (Figs. 4q, 4r, 4s, 4t), which we interpret as the crystallization ages of the Laosang granite complex.

4.2 Zircon Lu-Hf isotopic data

We selected a total of 12 samples, *i.e.* LC-1, LC-8, LC-12, LC-17, LH-4, LH-5, LH-11, LH-16, LT4, LT6, LB-5 and LB-7, for *in-situ* Lu-Hf isotopic analyses based on zircon U-Pb dated samples of the six complexes described in section 4.1. Approximately 15-20 spots in each sample (totally 201 spots) were selected for analysis. The results are listed in Table 2 in Appendix B and shown in Figure 5.

The 31 analyses of protogenetic magmatic zircon from the Lat Boua Complex display initial $^{176}Hf/^{177}Hf$ ratios ranging from 0.282075 to 0.282644, and εHf(t) values from -19.1 to 0.9, with only spot LC-8-6 having a positive εHf(t) value. Corresponding Hf crustal two stage model ages (T_{DM2}) range from 1218Ma to 1701Ma, with a mean of 1526 Ma. The 29 analyses of young U-Pb ages from the Kham Complex display initial 176Hf/177Hf ratios ranging from 0.282336 to 0.282604 and εHf(t) values from -9.5 to -0.5; corresponding Hf crustal T_{DM2} ages range from 1218Ma to 1701Ma, with a mean of 16984Ma. The 37 analyses from the Phon Thong Complex display initial 176Hf/177Hf ratios ranging from 0.282369 to 0.282632, εHf(t) values from -8.9 to 0.4, and Hf crustal T_{DM2} ages from 1245Ma to 1835Ma, with a mean of 1606Ma. 21 spots from the Luu Complex show initial 176Hf/177Hf ratios ranging from 0.281943 to 0.282687 and εHf(t) values from -24.0 to 2.5, with only spot LH-4-13 having a positive εHf(t) value; Hf crustal T_{DM2} ages range from 1120Ma to 2789Ma, with a mean of 1679 Ma. The 33 isotopic analyses of the Na The Complex display initial 176Hf/177Hf ratios ranging from 0.282333 to 0.282636 and εHf(t) values from -9.9 to 0.5 (only spot LT-4-18 has a positive value), with a mean value of -4.6; Hf crustal T_{DM2} ages range from 1240Ma to 1909Ma, with a mean of 1574Ma. The 38 analyses from the Laosang Complex display initial 176Hf/177Hf ratios ranging from 0.282283 to 0.282540, εHf(t) values from -8.1 to 1.2 (only spot LB-5-17 has a positive value), and Hf crustal T_{DM2} ages from 1220Ma to 2751Ma, with a mean of 1678Ma. These Lu-Hf isotopic features obtained from protogenetic magmatic zircons indicate that the rock formations of the complexes were principally resourced from the Late Paleoproterozoic to Early Mesoproterozoic continental crust, with a minute quantity from the depleted mantle.

Besides the analyses of protogenetic magmatic zircons, Hf crustal T_{DM2} ages were recorded using inherited zircons in four complexes, *i.e.* the Lat Boua, Kham, Luu and Laosang complexes. The U-Pb ages of two inherited zircons from spots LC-8-2 and LC-8-15 in the Lat Boua Complex are 667Ma and 892Ma, respectively; their 176Hf/177Hf ratios are 0.282844 and 0.282944, their εHf(t) values are 4.9 and 6.8, and they exhibit corresponding T_{DM2} values of 1336 and 1288Ma, respectively. In the LC-12 sample from the Kham Complex, the U-Pb ages of two inherited zircons from spots LC-12-6 and LC-12-12 are 530Ma and 580Ma, respectively; their 176Hf/177Hf ratios are 0.282366 and 0.282049, their εHf(t) values are -9.2 and -11.0, and they give corresponding T_{DM2} values of 2070 and 2222Ma, respectively. In the LC-17 sample, the U-Pb ages of the five inherited zircons are 440Ma, 750Ma, 618Ma, 822Ma and 915Ma, respectively; their 176Hf/177Hf ratios range from 0.282140 to

0.282573, their mean εHf(t) value is -6.0, and corresponding T_{DM2} values lie between 1710Ma and 2446Ma. In the LB-5 sample from the Laosang Complex, the U-Pb ages of three inherited zircons from spots LB-5-6, LB-5-16 and LB-5-19 are 645Ma, 1367Ma and 515Ma respectively; their 176Hf/177Hf ratios are 0.282103, 0.282453 and 0.282345, their εHf(t) values are -13.1, -1.7 and -6.0, and their corresponding T_{DM2} values are 1860, 2233 and 2408Ma, respectively. In the LB-7 sample, the U-Pb age of the inherited zircon is 636Ma, its 176Hf/177Hf ratio is 0.282411, its mean εHf(t) value is -7.7, and its corresponding T_{DM2} value is 2054Ma. All the Lu-Hf isotopic features obtained from inherited zircons indicate that the complexes are sourced partly by Late Paleoproterozoic to Early Mesoproterozoic continental crust and depleted mantle, with a minute quantity coming from the Archeozoic lower crust.

4.3 Whole-rock major, trace and rare earth element data

33 granitic samples were collected from the six complexes for major, trace and rare earth element (REE) analysis (Table 3 in Appendix C). As seen in the QAP diagram (Fig. 6) (Steckeisen, 1976), granitic rocks from the Lat Boua, Kham and Laosang complexes fall into the monzogranite field. Granites from the Phon Thong and Na The complexes, as well as four samples from the Luu Complex, fall into the granodiorite field. Two samples from the Luu Complex fall into the tonalite field. All the samples have similar SiO_2, Na_2O+K_2O and Al_2O_3 contents, but their K_2O/Na_2O ratios and aluminium indices (A/CNK) vary in different complexes (Table 4). Thus, in the K_2O *vs*. SiO_2 and A/NK *vs*. A/CNK diagrams (Fig.7) (Peccerillo and Taylor, 1976;

Middlemost, 1985; Maniar and Piccoli, 1989), samples from the Lat Boua, Kham, Na The and Laosang complexes all fall into the peraluminous high-K calcalkaline field, but samples from the Phon Thong and Luu complexes fall into the meta-aluminous calcalkaline or meta-aluminous low-K fields.

Granite samples from the six complexes display similar patterns in the chondrite (Boynton, 1984) and primitive mantle (Sun and McDonough, 1989) normalized rare earth and trace element plots. All rocks show enriched Light Rare Earth Element (LREE) and flat Heavy Rare Earth Element (HREE) chondrite-normalized REE patterns (Fig. 8a), with the LREE/HREE ratio between 6.38 and 8.06 in the Lat Boua Complex, between 6.87 and 7.83 in the Kham Complex, between 6.25 and 10.37 in the Phon Thong Complex, between 5.30 and 9.48 in the Luu Complex, between 3.05 and 4.76 in the Na The Complex, and between 7.89 and 9.97 in the Laosang Complex. The La_N/Yb_N ratio ranges from 7.19 to 10.03 in the Lat Boua Complex, from 7.23 to 8.80 in the Kham Complex, from 5.94 to 11.87 in the Phon Thong Complex, from 5.09 to 10.67 in the Luu Complex, from 2.78 to 4.70 in the Na The Complex, and from 7.73 to 15.07 in the Laosang Complex. Eu negative anomalies are observed, with mean σ Eu ranging from 0.49 to 0.56. The rocks have similar patterns in the chondrite (Boynton, 1984) and primitive mantle (Sun and McDonough, 1989) normalized rare earth and trace element plots, marked by variable enrichments in Rb, Ba, Th and Ce and depletions in Ta, Nb, Sr and Ti (Fig. 8b). Furthermore, the Sr values from all the samples are ca. 100–330ppm, other than for LH-14, which is 89ppm, and LT-7 and LB-4, which are as low as 58.7ppm. Yb values are <2ppm. The granite shows low content in Sr and Yb, indicating that the magmatic source of the granite contained relics of plagioclase and garnet. The original rocks are plagioclase and garnet high-pressure metamorphic rocks. Additionally, in the Th/Yb *vs*. Ta/Yb and Hf-Rb-Ta tectonic classification diagrams (Fig. 9) (Pearce, 1984; Harris *et al*., 1986), all the granitic rocks fall into the volcanic arc granite field, and are classified as I-type granites in the (Na2O+K2O) *vs*. (Zr+Nb+Ce+Y) and the Th *vs*. Rb diagrams (Fig. 10) (Whalen *et al*., 1987; Chappell and White, 1992). Overall, the whole-rock major, trace and rare earth element characteristics of the 33 granites from the six complexes are typical of I-type volcanic arc granites.

5. Discussion

5.1 Crustal characteristics of the Indochina Block

According to zircon U-Pb ages from northern Laos (Section 4.1), the Indochina Block experienced two periods of magmatic activity from the Early Paleozoic to the Early Mesozoic. One lasted from 402.5Ma to 435.1Ma, and the second from 234.3Ma to 256.4Ma. Additionally, some inherited zircon cores disclose the occurrence of magmatic from the Early Paleozoic to the Late Paleoproterozoic. Inherited zircon grains from the same Indochina block in Malaysia and the Kontum Massif also exhibit Proterozoic ages (800Ma, 1200Ma, 1350Ma, 1403Ma, 1600Ma, 1800Ma and 2600Ma) (Liew and McCulloch, 1985; Carter *et al*., 2001; Nagy *et al*., 2001). Furthermore, detrital zircon ages from the Indochina Block also suggest that basement metasedimentary rock protoliths were formed during the Meoproterozoic-Early

Paleozoic (Burrett *et al*., 2014), which differs from the Archean basement age (3.5–2.7Ga) obtained from central Vietnam, east of the Song Ma Suture (Lan *et al*., 2001; Lan *et al*., 2003).

Moreover, T_{MD2} ages of Late Permian to Early Triassic granites mainly range from 1511 to 1621Ma in the Lat Boua Complex, 1670 to 1718Ma in the Kham Complex, 1598Ma to 1613Ma in the Phon Thong Complex, 1735 to 1782Ma in the Luu Complex and 1565 to 1584Ma in the Na The Complex. The T_{MD2} ages of some spots fall within the 2500-2000Ma period, and only a few spots render modelled ages older than 2500Ma. T_{MD2} ages of Early Paleozoic granite (Laosang Complex) are ca. 1702-1760Ma. The εHf(t) values of the 12 samples are almost all negative, with mean εHf(t) values ranging from -3.4 to -8.2, indicating that these samples were sourced principally by re-melted crust. Only a few spots have positive εHf(t) values, indicating a depleted mantle source.

Zircon inheritance ages and T_{MD2} ages suggest that the main crust of the Indochina Block was formed in the Late Paleoproterozoic to Early Mesoproterozoic, and that the role of Archean rocks in the crustal evolution of the Indochina Block was limited. This conclusion is similar to observations from the Kontum Massif (Carter *et al*., 2001; Nagy *et al*., 2001) and in the East Coast Province batholiths of the Malaysian Peninsula (Liew and McCulloch, 1985), located in the southwestern part of the Indochina Block (Metcalfe, 2000). The ages are much younger than those obtained in the Cavinh Complex of northern Vietnam, which is Archean (Lan *et al*., 2001). The differences in crustal evolution between the Indochina Block and the block east of the Song Ma Suture further confirm that the boundary between Indochina and South China is the Song Ma Suture (Lepvrier *et al*., 2004; Liu *et al*., 2012; Faure *et al*., 2014), not the Song Da or Song Chay sutures, as once assumed.

5.2 A single Qamdo-Simao-Indochina block

Overall, the characteristic patterns exhibited by whole-rock major, trace and rare earth element data from the six plutons are typical of I-type volcanic arc granites (Section 4.3; Figs. 6-10). This result is similar to data from the Dien Bien granite massif west of the Song Ma Suture (Lan *et al*., 2001; Liu *et al*., 2012; Roger *et al*., 2014). The granites located at the junction of the Dien Bien Phu and Song Ma sutures, and once attributed to the Sibumasu-Simao Block, clearly subducted eastward under the Indochina Block along the Dien Bien Phu Suture. Sengor and Hsu (1984) named the Dien Bien Phu Suture the "Dien Bien Phu arm of the Paleo-Tethys". Leloup *et al*. (1995) correlated the Dien Bien Suture with the Jinsha River Suture as fault markers of the Ailaoshan-Red River Fault, calculating that Indochina extruded ca. 500-700km along the Ailaoshan left-lateral strike slip fault during 35-22Ma. However, recent geochronological studies have disclosed that the initiation time of the Dien Bien Phu Fault was after 228Ma (Lin *et al*., 2009; Roger *et al.*, 2014); the fault thus mismatches the volcanic arc I-type granites described in this paper. Furthermore, structural studies (DGM, 1991; Lepvrier *et al*., 1997; Lin *et al*., 2009; Faure *et al*., 2014; Roger *et al*., 2014) show that the Song Ma Suture is right-laterally offset ca. 30-40km by the Dien Bien Phu Fault; the strata and fold axes have also bent eastward, but the primary structure of the Truong Son Belt has not been significantly altered. So, the Dien Bien Phu Fault does not present a suture branch separating Qamdo-Simao from the Indochina Block. Thus, the Nan Suture should connect northward with the Jinghong Suture (Sone and Metcalfe, 2008; Faure *et al*., 2014), and the Qamdo-Simao-Indochina Block should be a united block (Fig. 11).

The similarity of the characteristics of the Qamdo-Simao and Indochina blocks when treated as a united block can be proven using other evidence. First, although Lepvrier *et al*. (1997, 2004) suggested that the Indochina Block subducted eastward under South China during the Late Permian-Early Triassic, increasing quantities of structural, geochronological and geochemical data confirm that the geometry of the block convergence between Indochina and South China was a westward subduction of South China under Indochina (Liu *et al*., 2012; Faure *et al*., 2014; this paper). The same is true for South China subducting westward under the Qamdo-Simao Block. The precise timing of the two block convergences has been corrected from 220Ma (Rb-Sr age, Wang *et al*., 2000) to 270–240Ma (Jian *et al*., 2008, 2009; Lai *et al*., 2014), almost the same age as we obtained in this paper. Secondly, the 440-400Ma granite complexes that were found along the Jinsha River Suture in China (*e.g.* Jian *et al*., 2009), have also been found along the Song Ma Suture (this paper) and along the Kontum Massif in Vietnam (*e.g.* Carter *et al*., 2001; Nagy *et al*., 2001; Sanematsu *et al*., 2011). There is no magmatic event either in the Qamdo-Simao Block or in the Indochina Block from 400Ma to 280Ma. Thus the Qamdo-Simao Block and the Indochina Block experienced similar magmatic events from the Early Paleozoic to the

Early Mesozoic. Instead, the early Paleozoic magmatic event before the Indosinian magmatic event in Sibumasu-Bao Shan-South Qiangtang block occurred around 500-470Ma (*e.g.* Lin et al., 2013; Dong et al., 2013; Hu et al., 2015), about 100-60Ma earlier than that in the Qamdo-Simao-Indochina block. Further, evidence of the existence of the same Gigantopteris flora and warm-water fauna in the Indochina and Qamdo-Simao blocks proves that they were once rifted and drifted northward from Gondwana in the Early Devonian (Metcalfe, 1996, 1999). Lastly, as deduced from εNd and T_{MD2} ages, the principal period of crust formation in the Qamdo Block was ca. 1.4-1.7Ga (*e.g.* Zhai *et al*., 2012; Zhang *et al*., 2014), similar to that of the Indochina Block.

5.3 The Jinsha River Suture-Song Ma Suture-Kontum Massif as the boundary between the Qamdo-Simao-Indochina and South China blocks

The Late Permian-Early Triassic I-type granites detailed in this paper belong to the Truong Son Belt, thus corroborating the tectonic model of the South China Block subducting westward under the Indochina Block (Liu *et al*., 2012; Faure *et al*., 2014). In interpreting the relation between the Song Ma and Song Chay sutures in northern Vietnam, Faure *et al*. (2014) suggested that these two northern Vietnam belts are parts of a single orogen dismembered by Cenozoic wrenching along the Red River Fault. There are several reasons for disagreeing with this hypothesis.

First, structural studies (Lepvrier *et al*., 1997, 2004, 2008; Tran *et al*., 2014) show an E-W striking shifting to a N-S striking along the Tam Ky-Phuoc Son Suture in the southern part of the Truong Son Belt, and north of the Kontum Massif. Southward, the Tam Ky-Phuoc Son suture connects with the Poko Suture west of the Kontum Massif. Geochronological magmatism (*e.g*. Carter *et al*., 2001; Nagy *et al*., 2001; Lan *et al*., 2000; Owada *et al*., 2007; Sanematsu *et al*., 2011) and metamorphism (*e.g*. Lan *et al*., 2003; Osanai *et al*., 2001, 2004; Nakano *et al*., 2007) relating to the Poko suture also give ages between 260Ma and 240Ma. Lepvrier *et al*. (2008) even suggest that the Kontum Massif subducted westward under the Indochina Block, with the time and manner the same as for the two blocks along the Song Ma Suture (this paper; Liu *et al*., 2012; Faure *et al*., 2014). Thus, if the Song Ma Suture is offset from the Jinsha -Song Chay Suture, the role of the Kontum Massif in the convergence of Indochina and South China *vis-à-vis* the Poko Suture is difficult to interpret.

Second, if the Song Ma Suture Zone is taken as forming the northern segment of the Song Chay Suture, there would be no system of tectonic units related to the Indochina orogenic zone around the Song Chay Suture. For example, no volcanic arc belt exists on either side of the Song Chay Suture; granites southwest of the Song Chay Suture are A-type granite with positive Nd(t) values (Pham *et al*., 2013), and are thus related to the Song Da Rift.

Third, in the Indochina Block, there is no other continental-scale ductile shear zone that, coupled with the Ailaoshan-Red River Fault, could produce the documented Early Miocene Truong Son Belt extrusion. For example, within the Indochina Block, the Dien Bien Phu Fault forms the western boundary of the Truong Son Belt, but geochronological and structural studies show that it was a right-lateral strike slip fault after 228Ma, with 30-40km offset ; the fault, as the southernmost part of the Xianshuihe fault system, was reactive from ca. 5Ma to the present, with a left-lateral offset <10km (*e.g*. Wang *et al*., 1998; Zuchiewicz *et al*., 2004; Koszowska *et al*., 2007; Lin *et al*., 2009; Roger *et al*., 2014).

We therefore propose that the Jinsha River Suture, the Song Ma Suture and the Kontum Massif form the boundary between the Indochina and South China blocks.

5.4 The Emeishan Plume: the dynamics of a Permo-Triassic block convergence

Southeast Asia is a composite landmass of Gondwana-derived continental blocks. Having been detached from the northeastern margin of Gondwana, they progressively assembled with each other and accreted to form a proto-Asia. A major part of this evolution took place from the Mid Paleozoic to the Early Mesozoic. Several episodes of rifting and northward drifting occurred, followed by subduction and subsequent narrowing and closure of different branches of the Paleotethyan Ocean (*e.g*. Hutchison, 1989; Sengor, 1979; Sengor and Hsu, 1984; Metcalfe, 1986, 1999, 2002; Lepvrier *et al*., 1997, 2004, 2008). Without doubt, the closure of the Paleotethyan Ocean and the opening of the Mesotethyan Ocean provided the main dynamics for the convergence of the Sibumasu, Qamdo-Simao-Indochina and South China blocks. Against this background, we would also suggest that the Emeishan Plume contributed to the convergence of the Qamdo-Simao-Indochina and South China blocks.

The Emeishan basalts, also known as the Emeishan large igneous province (ELIP), outcrop principally in the Chinese provinces of Sichuan, Yunnan and

Guizhou and the Song Da region of northern Vietnam. The ELIP is composed mainly of flood basalts and mafic-ultramafic intrusions. The volcanic sequence ranges in thickness from several hundred meters in the east to nearly 5km in the west (Chung and Jahn, 1995; Song *et al.*, 2001; Xu *et al.*, 2001; Xiao *et al.*, 2004). The lavas include picrites, tholeiites and basaltic andesites, all of which are believed to have formed from an upwelling mantle plume (Chung and Jahn, 1995; Xu *et al.*, 2001; Zhou *et al.*, 2006). Recent research has found that Late Permian A-type granite is related to the Emeishan Plume in the Panzhihua and Dali rifts in the Sichuan-Yunnan area (Shellnutt *et al.*, 2007, 2009), similar to a study of the Song Da rift (Pham *et al.*, 2013). Permian flood basalts and associated mafic-ultramafic intrusions form a narrow (≤20km), NW-trending belt >350km long in the Jinping-Song Da Rift. The belt is bounded by the Ailaoshan-Red River Fault Zone to the northeast and the Jinsha-Song Ma Suture to the southwest (Wang *et al.*, 2007). South of this, there is no report of Emeishan basalts outcropping in the Kontum Massif, but a NW-SE striking normal shear zone has developed in the Ngoc Linh and Kannack complexes, which is composed of HT to UHT metamorphic rocks (Osanai *et al.*, 2004; Lepvrier *et al.*, 2008). Both the Ngoc Linh and the Kannak complexes are locally intruded by granitic rocks, with fine-grained gabbro enclaves; the igneous activity and HT to UHT metamorphism coincide with each other at 250Ma to 260Ma. An upwelling mantle plume would explain the formation of the syn-tectonic magmatism with the HT-UHT metamorphism (Osanai *et al.*, 2001, 2004; Owada *et al.*, 2007). The plume related to the Emeishan Plume thus appears to represent a particular tectonic feature at the western boundary of the South China Block.

I-type volcanic arc granites in the Late Permian-Early Triassic can be treated as an index of the subduction between the Sibumasu, Indochina and South China blocks during the Paleotethyan Ocean closure (Carter *et al*., 2001; Lepvrier *et al*., 2004, 2008; Liu *et al*., 2012). Subsequently, S-type granites with 220Ma to 200Ma ages, as well as I-type granites of Late Mesozoic age, developed at the western boundary of the Sibumasu Block (*e.g.* Charusiri, 1993; Searle *et al*., 2012), indicating compressional conditions during the Mesozoic. In contrast, A-type granites developed after 200Ma in the South China Block. It has been suggested that these magmas were generated as a consequence of intraplate extension in the western part of the South China Block (*e.g*. Chung *et al*., 1997; Lan *et al*., 2000; Maluski *et al*., 2001). The different stresses prevalent in the South China Block *vis-à-vis* the Sibumasu Block could be attributed to the dynamic conditions produced by the Emeishan Plume in the mantle after 260Ma. We therefore propose that the Emeishan Plume formed part of the dynamic driving Permo-Triassic block convergence and subsequent extension into the South China Block (Fig. 12).

6. **Conclusions**

33 samples from six granite complexes along the road from Phonsavan to Sam Neua in northern Laos were selected for zircon U-Pb age, Lu-Hf ratio and whole-rock major, trace and rare earth element analysis. Geochronological and geochemical data from these samples can be summarized as follows:

1) The zircon U-Pb ages of 600 spots from 16 samples taken from five granite complexes range from 234Ma to 256Ma. 234-256Ma magmatic arc granites mismatch the initiation time of the Dien Bien Phu fault. The existence of the Dien Bien Phu Suture can therefore be repudiated. This evidence further suggests the existence of a united Qamdo-Simao-Indochina Block.

2) The εHf(t) values of zircon Lu-Hf data from a total of 201 spots from 20 samples are generally negative, with corresponding T_{DM2} ages dated to the Late Paleoproterozoic. Zircon inheritance ages and T_{MD2} ages suggest that the formation of the main crust of the Indochina Block was during the Late Paleoproterozoic; these ages are much younger than the Archean ages obtained in the Cavinh Complex of northern Vietnam east of the Song Ma Suture. Thus, the different crustal evolutions of the Indochina Block and the block east of the Song Ma Suture further confirm that the boundary between Indochina and South China is the Song Ma Suture rather than the Song Da or Song Chay sutures.

3) Major, trace and rare earth element data from the granitic rocks of six complexes indicate mainly peraluminous high-K calcalkaline granite. The Indochina granite samples have similar patterns in their chondrite and primitive mantle normalized rare earth and trace element plots, marked by variable enrichments in Rb, Ba, Th and Ce and depletions in Ta, Nb, Sr and Ti, typical of I-type volcanic arc granites. These granites, together with other tectonic units of the Song Ma Suture, suggest a westward subduction of the South China Block beneath the Qamdo-Simao-Indochina Block.

4) 440-404Ma and 234-256Ma I-type granites suggest that the boundary between Indochina and South China should be the Jinsha River Suture–Song Ma Suture–Kontum Massif, rather than the Jinsha-Song Chay Suture.

5) Both the Emeishan basalt and granite complexes form part of the tectonic units of the South China Block subducting westward under the Qamdo-Simao-Indochina Block. The plume beneath the Emeishan basalt also contributes to the convergence of the two blocks following the opening of the Mesotethyan Ocean.

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Captions:

Figure 1 Distribution of principal continental terranes and sutures of Mainland SE Asia (After Sone and Metcalfe, 2008). C. M. S. Z= Changning-Menglian Suture zone, the locations of Figures 2 & 3 are also shown.

Figure 2 Distribution of strata and granite complexes in northern Laos. Locations of granite samples are also shown (after DGM, 1991).

Figure 3 Cross-section of the Song Ma Suture Zone shows the simplified geological relation between different tectonic units eastward from the Indochina Block to the South China Block.

Figure 4 Cathodoluminescence (CL) images of representative zircon grains and zircon age concordia diagrams of granites from northern Laos.

Figure 5 Plot of $\varepsilon Hf(t)$ *vs*. U–Pb ages for granites from northern Laos.

Figure 6 Modal classification of granitoids (after Streckeisen, 1967). Granites from the Lat Boua, Laosang and Kham complexes mainly in the monzogranite field; granites from the Phon Thong, Na The, and Luu complexes in the granodiorite field; two samples from the Luu complex in the tonalite field. 1-alkali feldspar syenite; 2-syenite; 3-monzonite; 4-monzodiorite; 5- diorite; 6-quartz alkali feldspar syenite;

7-quartz syenite; 8-adamellite; 9- quartz monzobiorite; 10- quartz diorite; 11- alkalic feldspar granite; 12- syengranite; 13-monzogranite; 14-granodiorite; 15-tonalite; 16-quartz granite; 17- quartzite

Figure 7 Plots of (a) K_2O *vs.* SiO_2 (solid line after Peccerillo and Taylor, 1976; dash line after Middlemost, 1985) and (b) A/NK *vs*. A/CNK (after Maniar and Piccoli, 1989) for granites from northern Laos. A = Al_2O_3, N = Na_2O, K = K_2O, C = CaO (all in molar proportion).

Figure 8 Chondrite-normalized REE patterns (Boynton, 1984) and primitive-mantle normalized trace element patterns for I-type granites in northern Laos (Sun and McDonough, 1989).

Figure 9 Th/Yb *vs.* Ta/Yb diagram (Pearce, 1983) and Hf -Rb-Ta discrimination diagram (Harris *et al*., 1986) identifying tectonic setting.

Figure10 (Na_2O+K_2O) *vs*. (Zr+Nb+Ce+Y) diagram (Whalen *et al*., 1987) and Th *vs*. Rb diagram (Chappell *et al*., 1992) identifying I-S type granites.

Figure 11 Paleogeographic reconstructions of the Tethyan region in the Late Permian to Early Triassic showing relative positions of the east and Southeast Asian blocks and distribution of land and sea (after Metcalfe, 2006). Abbreviations: SC=South

China; NC=North China; I=Indochina; QS=Qamdo-Simao; EM=East Malaya; S=Sibumasu; WB=West Burma; QI=Qiangtang; L=Lhasa; WC=Western Cimmerian Continent.

Figure 12 Geodynamic model of the convergence of the Southeast Asian blocks during closure of the Paleotethyan Ocean (after Jian *et al*., 2009, Liu *et al*., 2012; Faure *et al*., 2014).

Table 4 The whole-rock major element components in the 33 samples from six complexes in northern Laos.

Appendix A: Supplementary data

Table 1 LA-ICPMS U–Pb zircon age data for granites from northern Laos.

Appendix B: Supplementary data

Table 2 Hf isotopic data for zircons from the granite complex.

Appendix C: Supplementary data

Table 3 Major (wt.%), trace (ppm) and rare earth (ppm) elements of granites from the northern Laotian complexes.

e-component

Click here to download e-component: Table 2 Lu-Hf.doc

Figure

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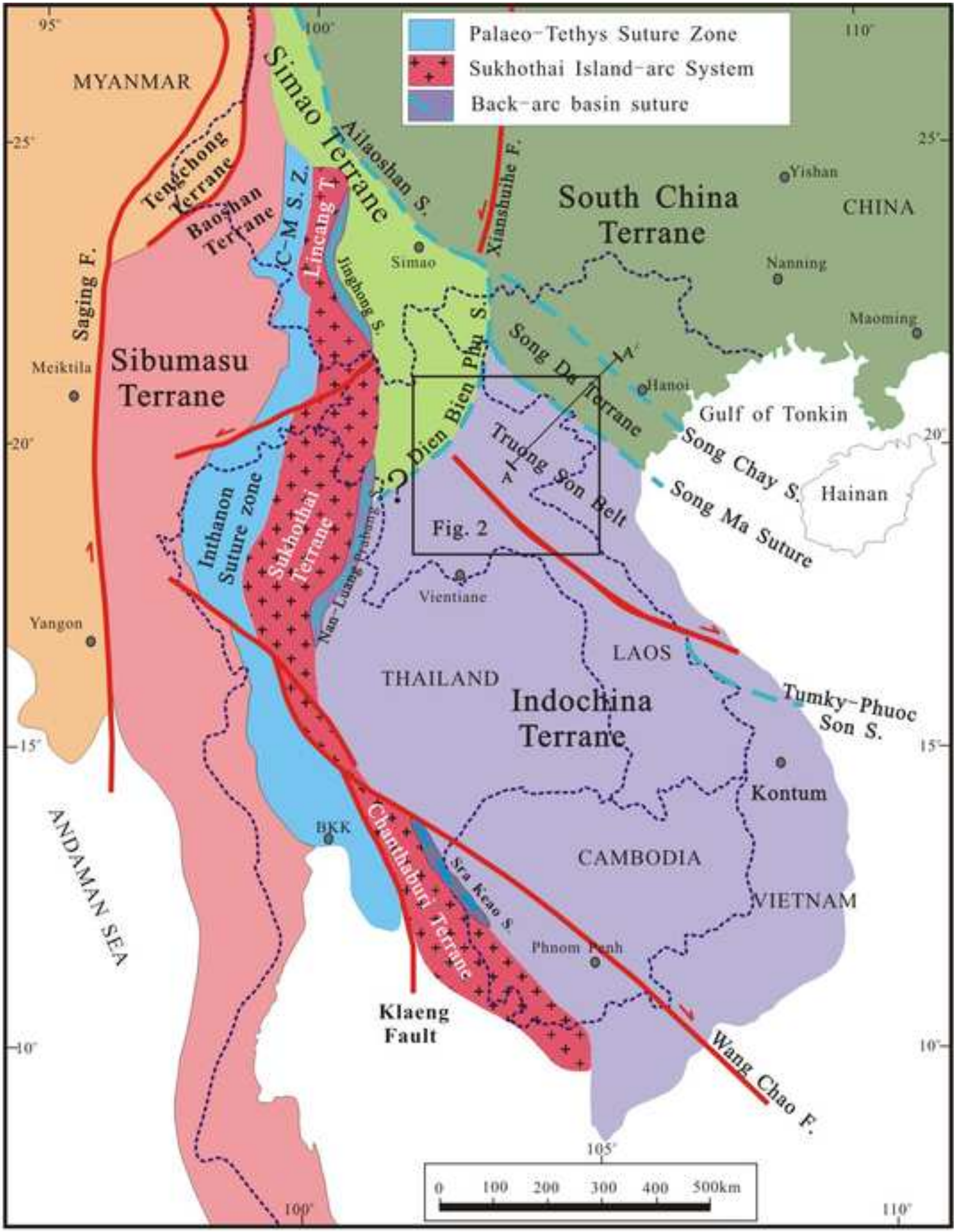

Fig. 1

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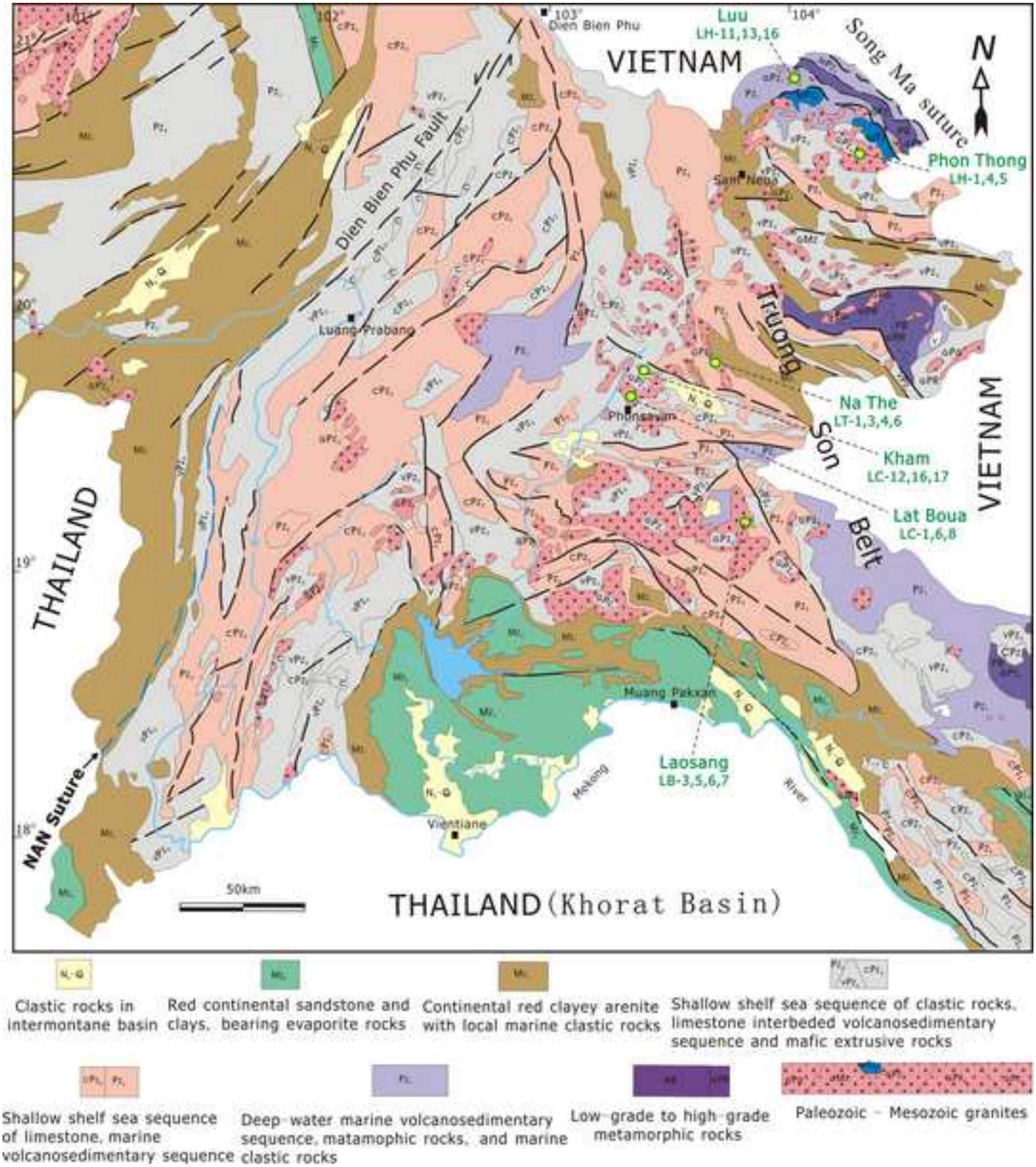

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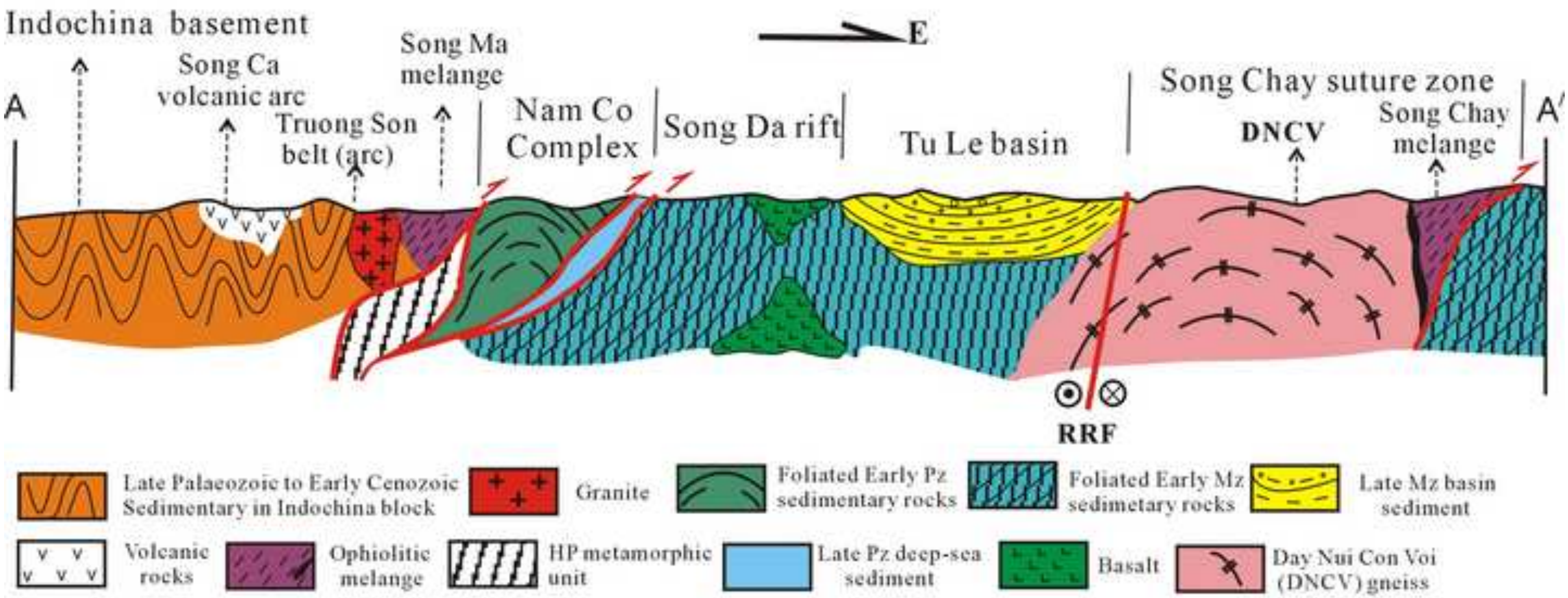

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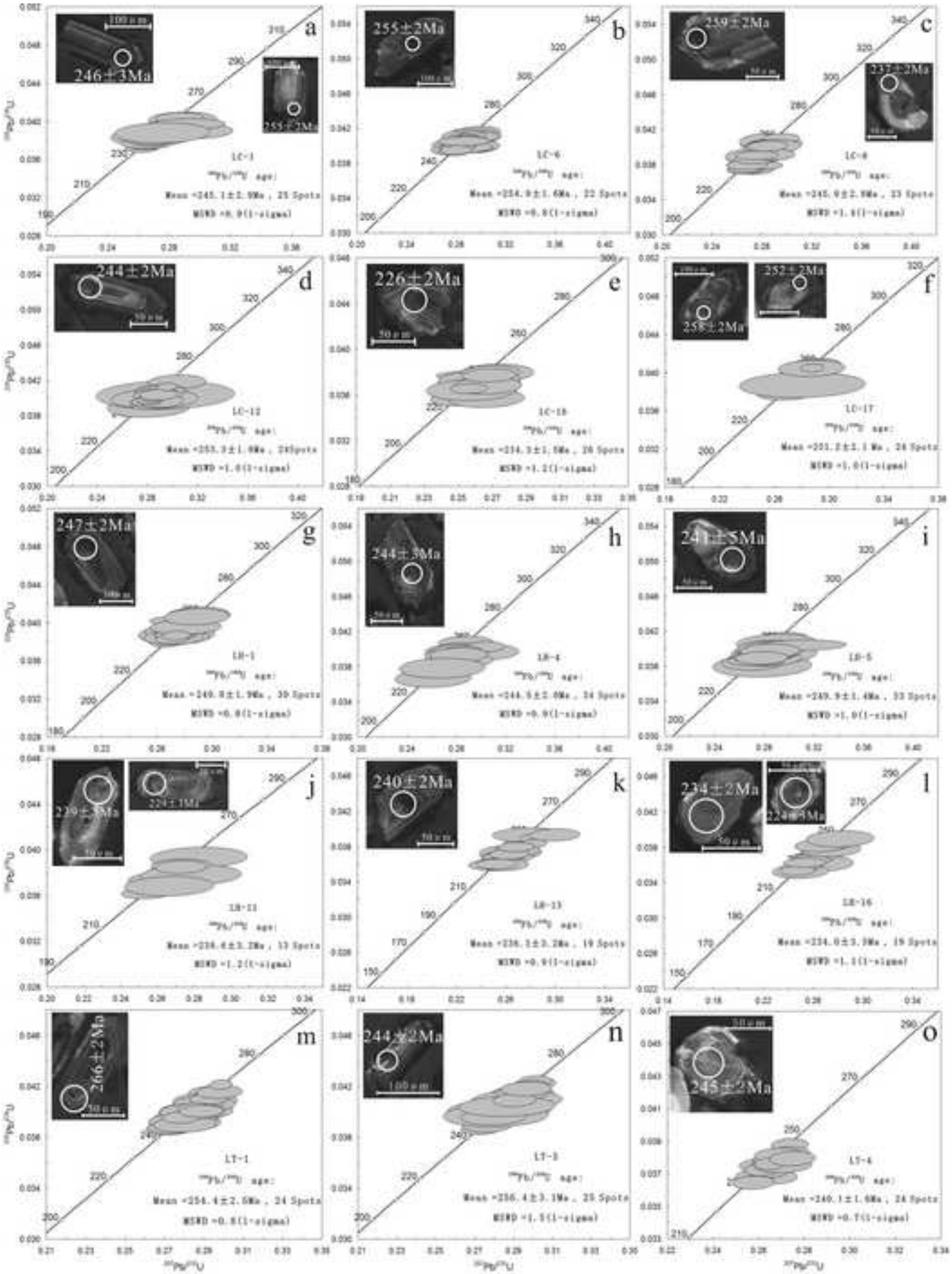

Fig. 4

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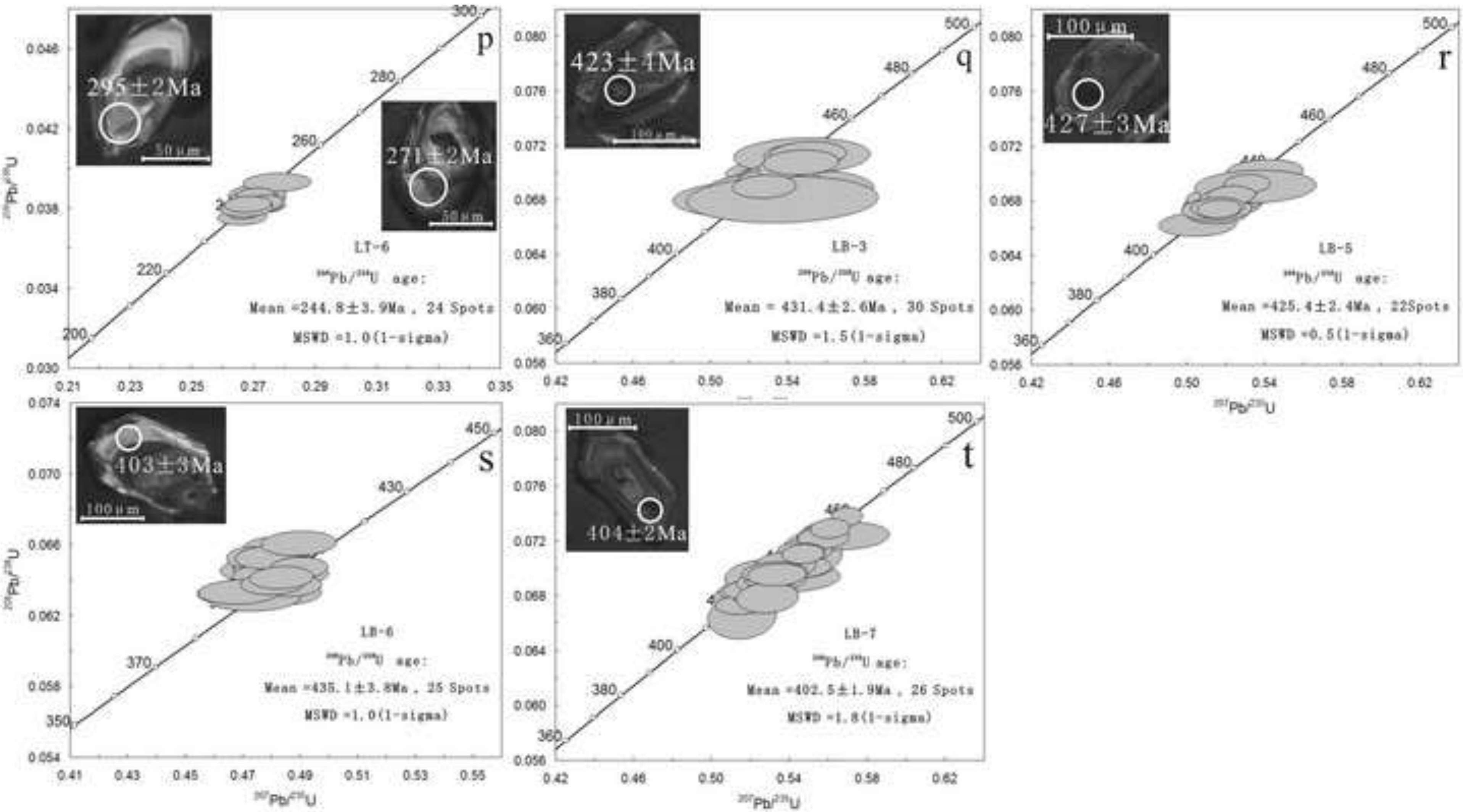

Fig. 4. *(continued)*

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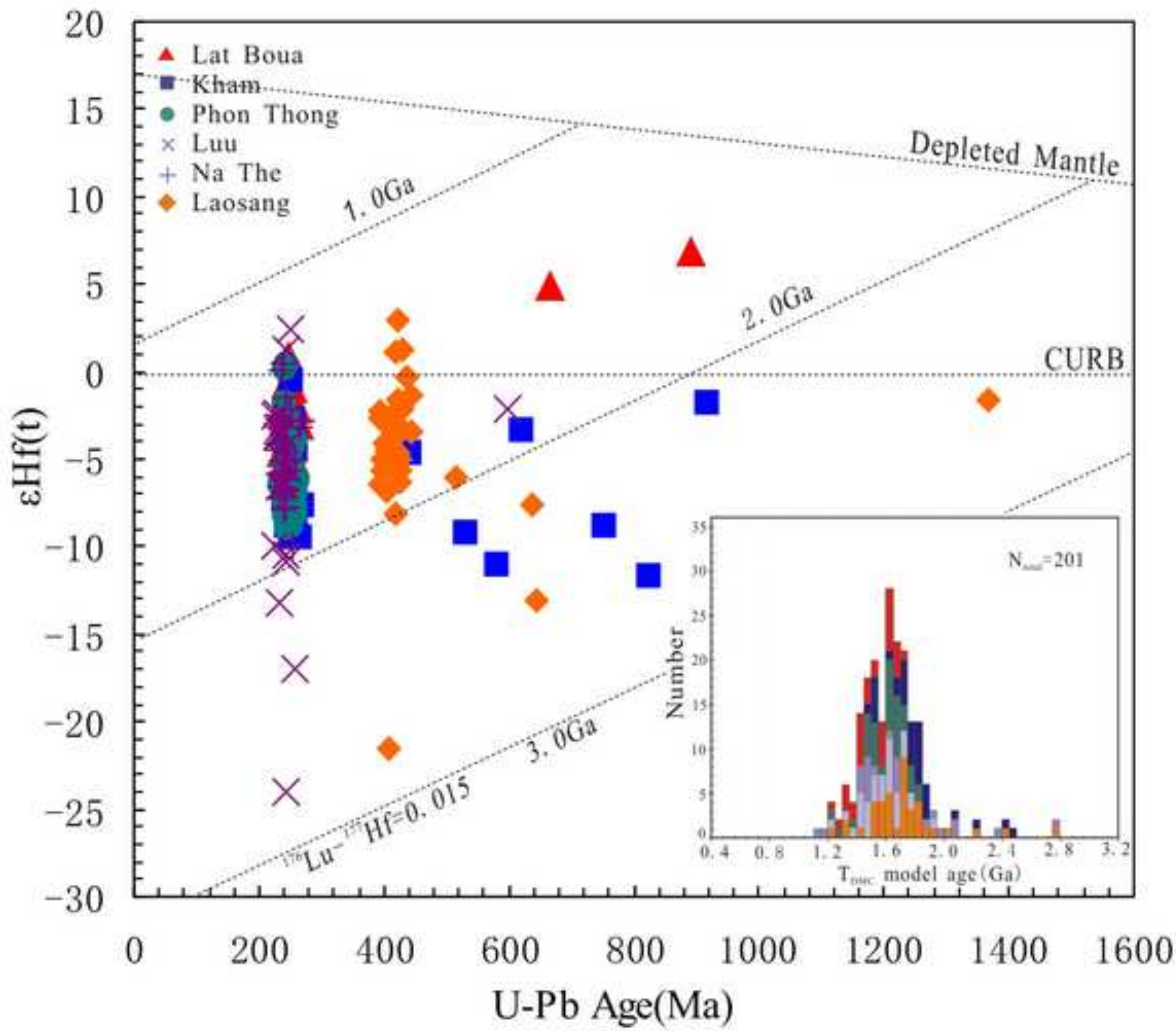

Fig. 5

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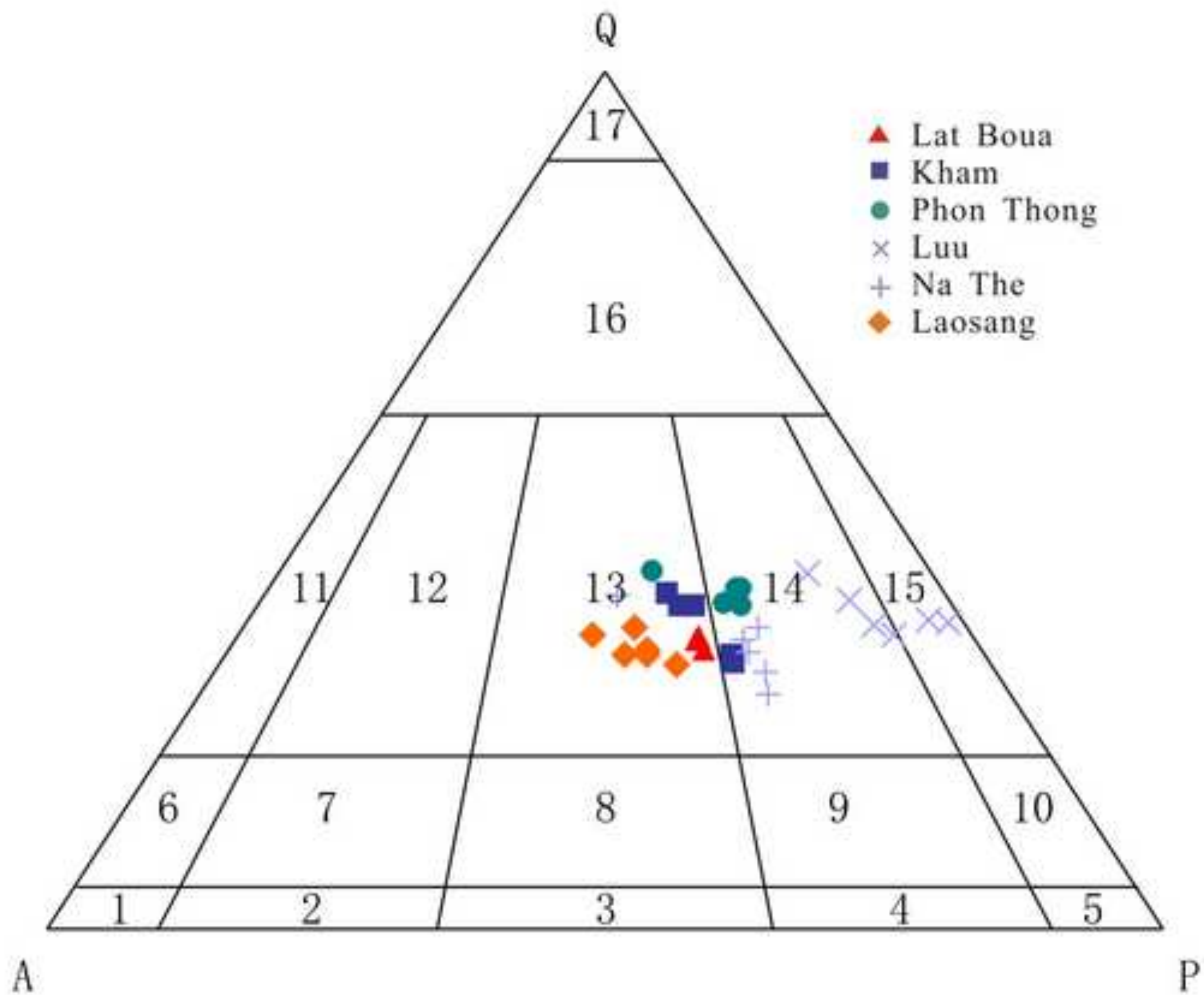

Fig. 6

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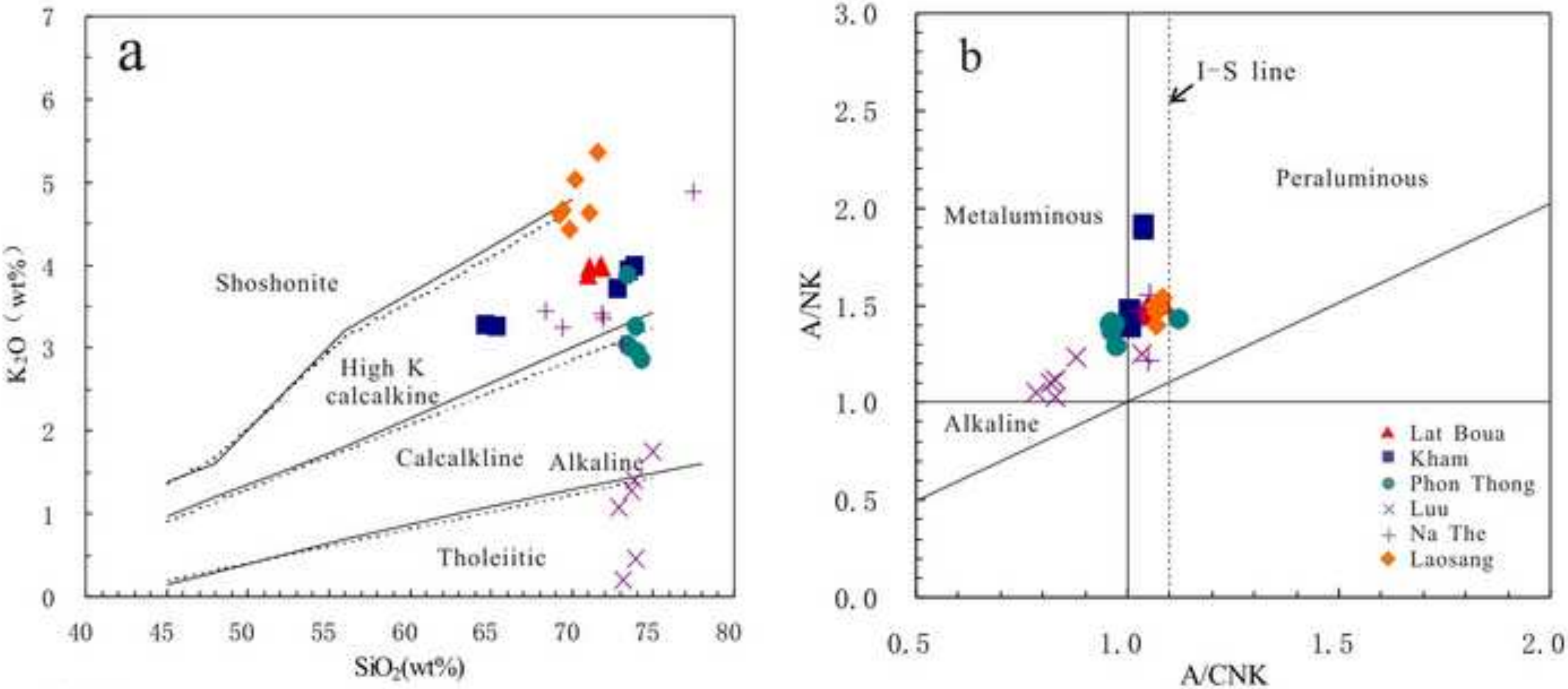

Fig. 7

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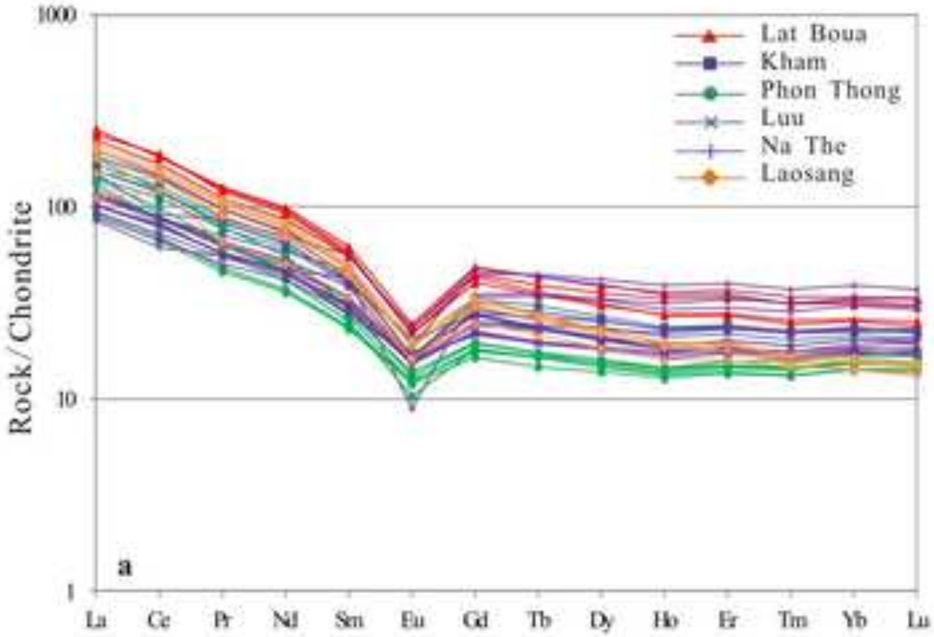

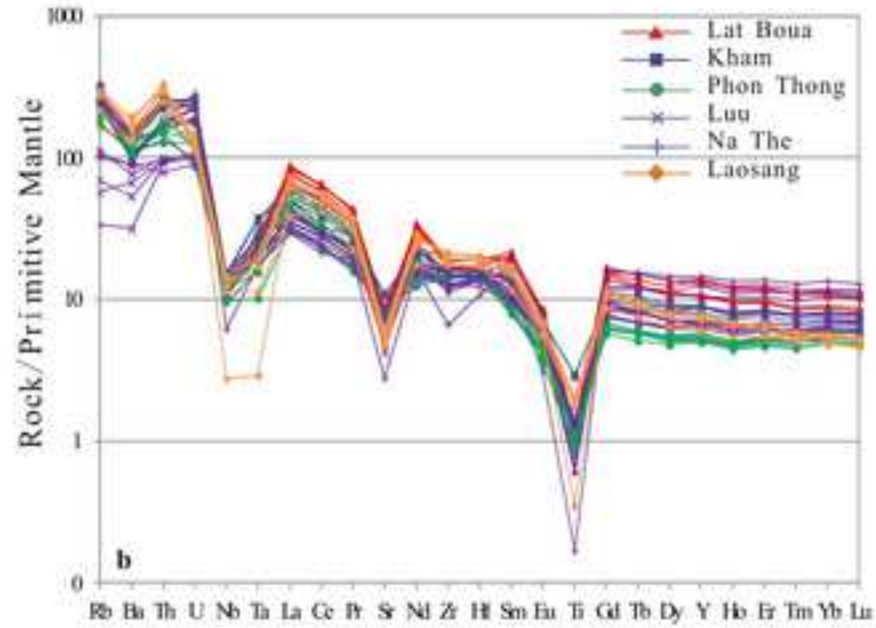

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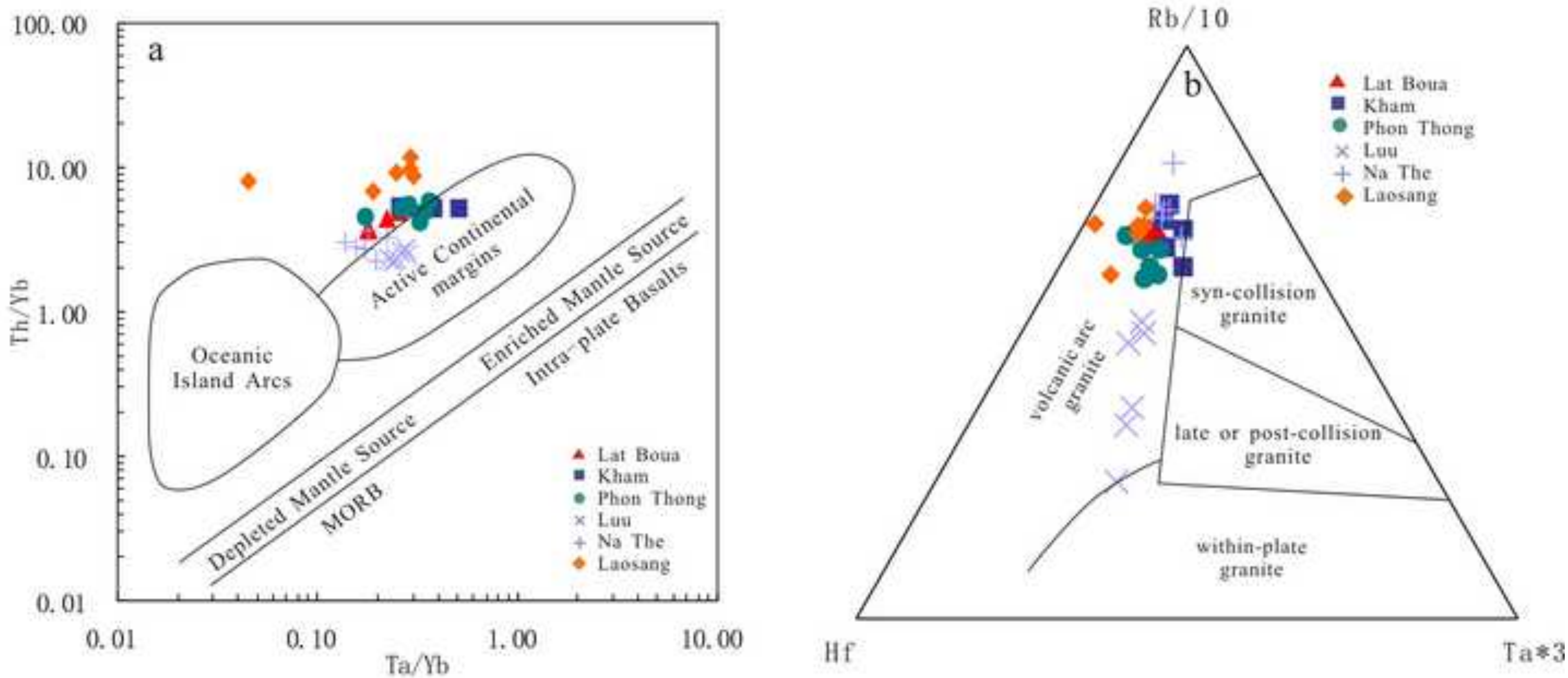

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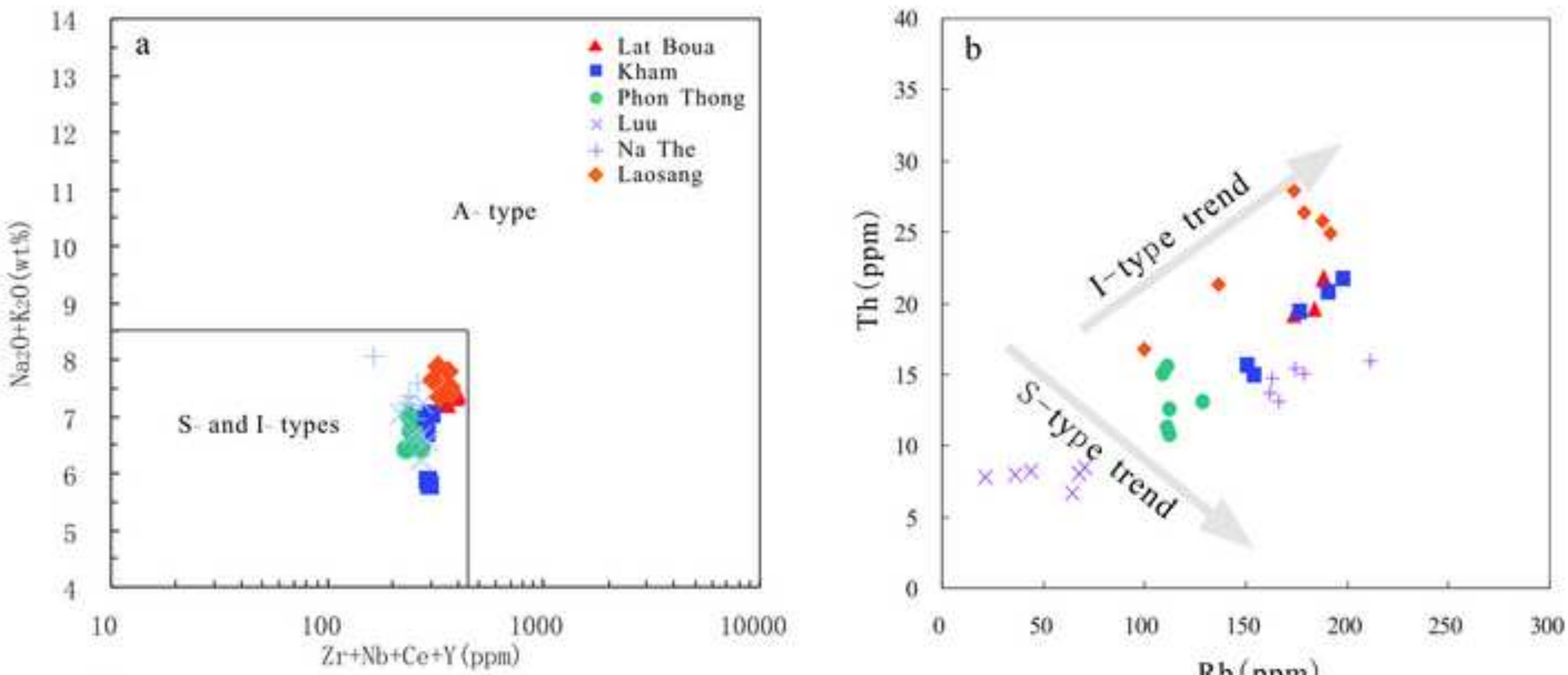

Fig. 10

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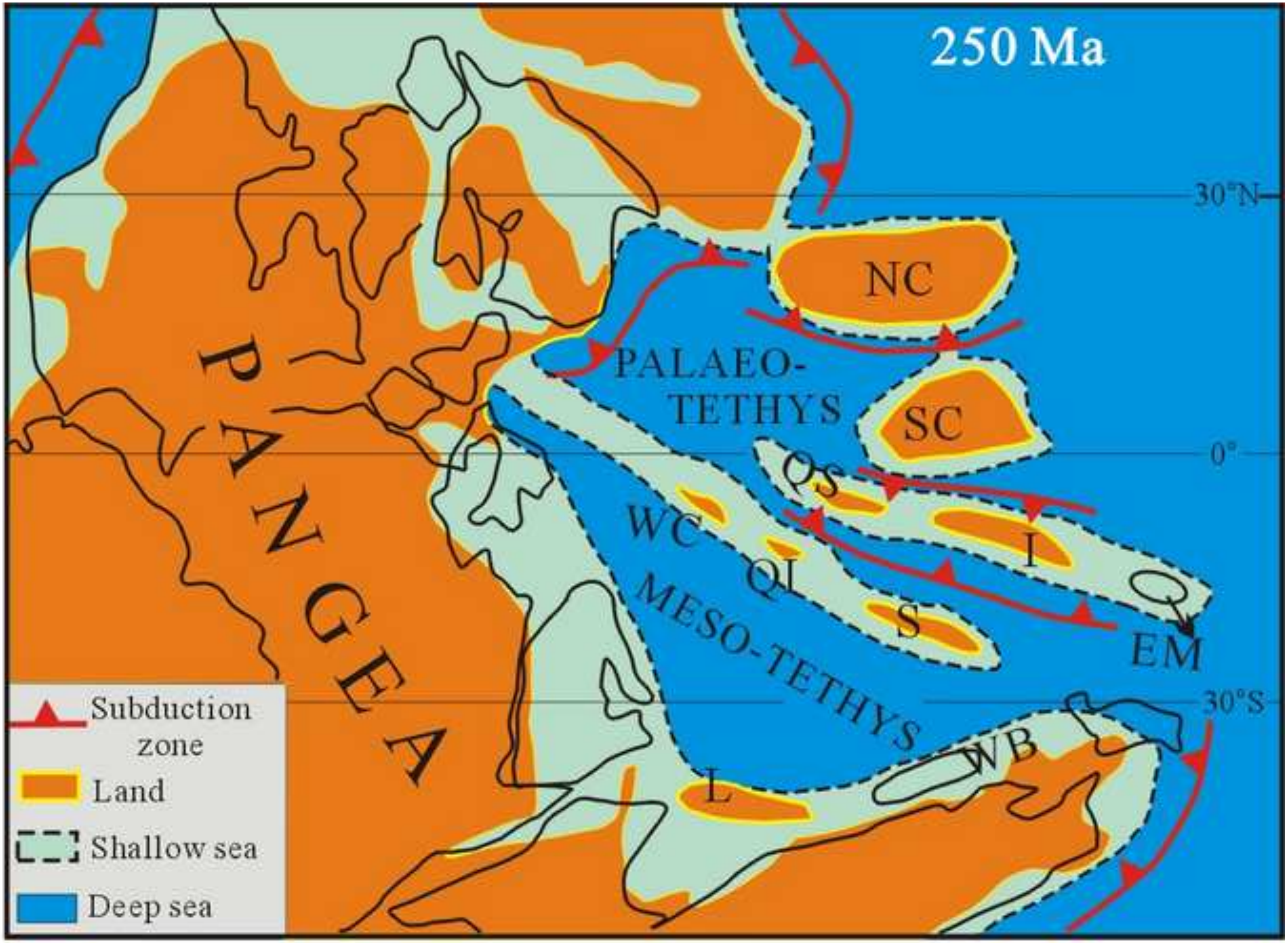

Fig. 11

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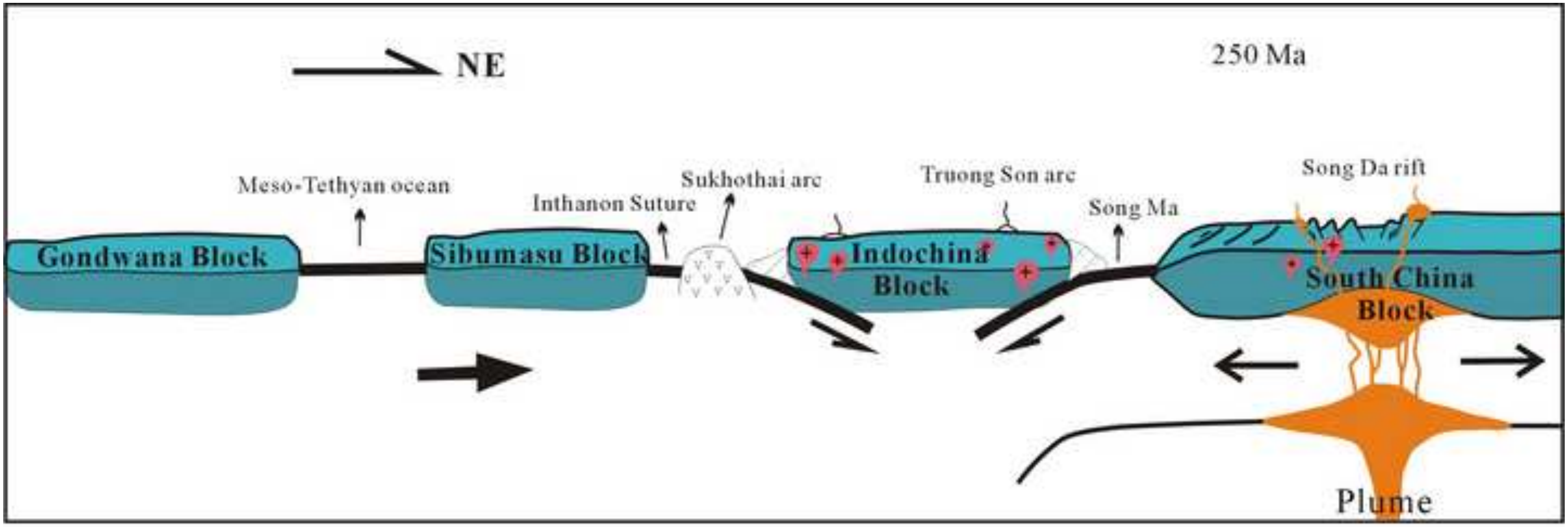

Fig. 12

Table

Table 4

	Lat Boua	Kham	Na The	Phon Thong	Luu	Laosang
SiO2 (%)	71-71.8	64.6-73.9	68.4-77.5	73.4-74.3	72.9-75.0	69.2-71.6
Na_2O+K_2O(%)	7.24-7.41	7.1-7.8	7.0-8.1	6.4-7.1	6.3-7.2	7.4-7.9
K_2O/Na_2O	1.15-1.19	1.23-1.35	0.78-1.53	0.8-1.36	0.03-0.39	1.39-2.11
Al_2O_3 (%)	14.5-14.8	12.8-14.8	12.8-15.9	12.6-13.0	11.4-12.5	14.0-15.5
Aluminium index	1.04-1.08	1.0-1.04	1.03-1.05	0.96-1.12	0.78-1.03	1.06-1.08
Litman index	1.87-1.96	1.50-1.63	1.61-2.28	1.32-1.59	1.22-1.75	1.92-2.24
Granites	monzogranite	monzogranite	granodiorite	granodiorite	tonalite	monzogranite
Alkalinity	high-K calc-alkaline	high-K calc-alkaline	high-K calc-alkaline	calc-alkaline	low-K	high-K calc-alkaline
Aluminium	peraluminous	peraluminous	peraluminous	meta-aluminous	meta-aluminous	peraluminous