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Geochemistry of Mesozoic intracontinental basalts from Yunnan, southern China: implications for geochemical evolution of the subcontinental lithosphere

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With 8 Figures

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Summary

Southwestern Yunnan, comprising the Yangtze and Shan-Thai microcontinents and the Simao block, has successively undergone subduction of an oceanic plate, followed by a collision of the microcontinents and intracontinental rifting associated with basaltic volcanism during Late Paleozoic to Mesozoic.

The Triassic Nanjian basalts, erupted on the Yangtze microcontinent, have more enriched isotopic ratios and higher LREE/HFSE and LREE/HREE ratios. This suggests the existence of an enriched subcontinental lithosphere under the Yangtze microcontinent which stabilized over long periods of the earth's history (> 2Ga).

The Middle Jurassic Simao basalts have more depleted geochemical features and also have element enrichments characteristic of a subduction zone environment, although the basalts were erupted in an intracontinental graben. It may be inferred that the lithospheric mantle of the Simao block was modified by subduction processes during Latest Carboniferous to Late Triassic prior to the onset of the Middle Jurassic continental rifting. The lack of correlation between depletion of HFSE, Y and HREE,

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and relative enriched Nd isotopic ratios suggests that the source depletion of the Simao basalts is not an old feature and has been contemporaneous with the subduction-related enrichment through mantle metasomatism shortly before the basalts were produced.

The Middle Jurassic Baoshan basalts which erupted during the continental rifting on the Shan-Thai microcontinent have an Sr-Nd isotopic composition similar to the bulk earth and higher concentrations of incompatible trace elements. These features suggest that the subcontinental lithosphere under the Shan-Thai microcontinent underwent mantle metasomatism just prior to eruption of the Baoshan basalt.

Zusammenfassung

Geochemie mesozoischer interkontinentaler Basalte aus Jünnan, Südchina: Hinweise auf die geochemische Entwicklung der subkontinentalen Lithosphäre

Südwestjünnan umfaßt den Jangtse und den Shan-Thai Mikrokontinent und den Simao-Block. Das Gebiet wurde von aufeinander folgenden Subduktionsphasen einer ozeanischen Platte betroffen, auf die Kollision der Mikrokontinente und interkontinentales Rifting folgte. Dieses war mit basaltischem Vulkanismus während des späten Paläozoikums bis ins Mesozoikum assoziiert.

Die triassischen Nanjian-Basalte, die auf dem Jangtse Mikrokontinent eruptierten, haben mehr angereicherte Isotopenverhältnisse und höhere LREE/HFSE und LREE/HREE Verhältnisse. Dieses weist auf eine angereicherte subkontinentale Lithosphäre unter dem Jangtse Mikrokontinent hin, die sich während langer Perioden der Erdgeschichte stabilisierte (>2Ga).

Die mittel-jurassischen Simao-Basalte haben eine mehr verarmte geochemische Signatur aber auch Elementanreicherungen, die für ein Subduktionszonen-Milieu charakteristisch sind, obwohl die Basalte in einem interkontinentalen Graben ausgetreten sind. Man kann daraus schließen, daß der lithosphärische Mantel des Simao-Blockes durch Subduktionsprozesse während des jüngsten Karbons bis in die späte Trias vor dem Beginn des mittel-jurassischen kontinentalen Riftings modifiziert worden war. Das Fehlen einer Korrelation zwischen der Anreicherung von HFSE, Y und HREE und relativ angereicherter Nd-Isotopenverhältnisse weist darauf hin, daß die Verarmung der Quelle der Simaobasalte nicht weit zurückreicht. Sie dürfte viel eher gleichaltrig mit der subduktions-bedingten Anreicherung durch Mantel-Metasomatose kurz vor der Entstehung der Basalte sein.

Die mittel-jurassischen Baoshan-Basalte, die während des kontinentalen Riftings auf den Shan-Thai Mikrokontintent eruptierten, haben eine Sr-Nd-Isotopensignatur, die ähnlich der Gesamterde ist, jedoch höhere Konzentrationen inkompatibler Spurenelemente zeigt. All dies legt nahe, daß die subkontinentale Lithosphäre unter dem Shan-Thai-Mikrokontinent kurz vor der Eruption der Baoshan-Basalte von Mantel-Metasomatose betroffen worden ist.

Introduction

West Yunnan comprises the Yangtze microcontinent, the Simao block and the Shan-Thai microcontinent (Fig. 1) which are interpreted to have been assembled by continent(arc)-continent(arc) collision in late Middle Triassic to Middle Jurassic. An expected consequence of a rifting event and of major thinning of the lithosphere in the descending plate of the continental collision system is regional heating of the lower plate. This would occur as a consequence of lithosphere

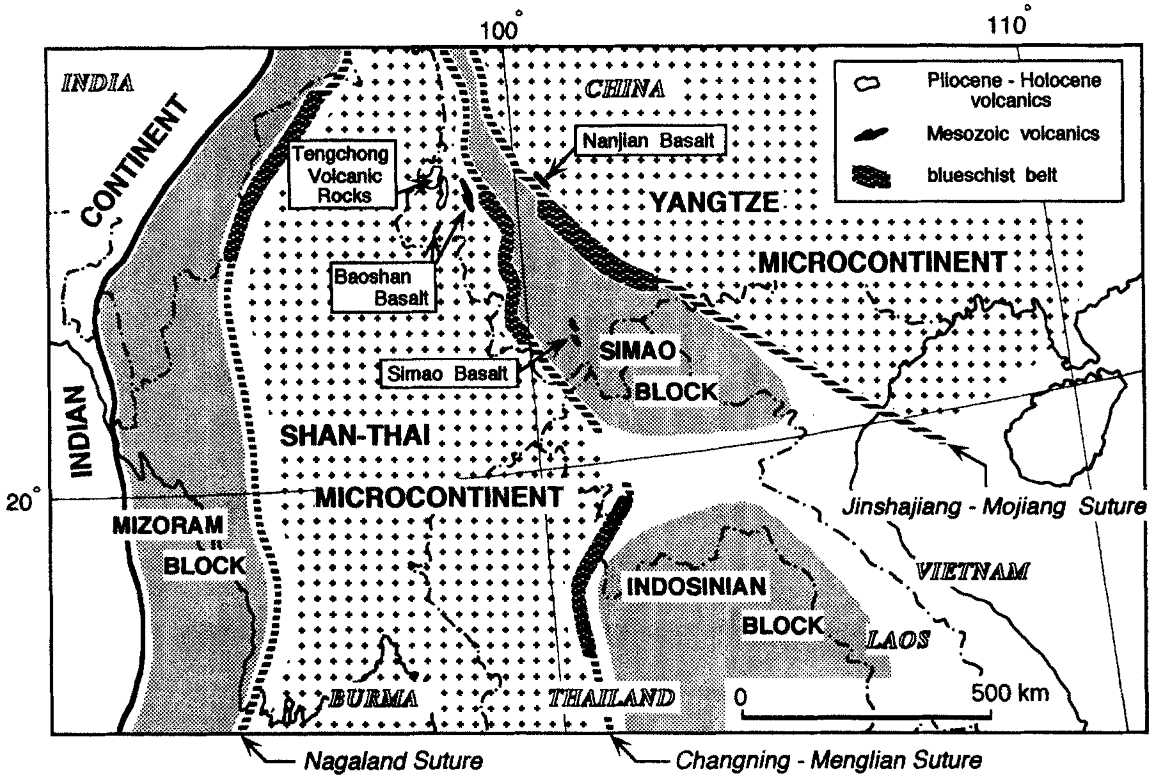


Fig. 1. Tectonic map of the Yunnan-Indosina region and distribution of Mesozoic volcanic rocks (compiled from various sources including *Barr* and *Macdonald*, 1987 and *Zhang* et al., 1993)

delamination (*Sacks* and *Secor*, 1990; *Nelson*, 1992) in the initial stages of continental collision. As the heat is conducted upward, this would result in early high-temperature metamorphism, crustal melting producing granites, and intrusion of basaltic magma produced by decompression melting of underlying asthenosphere. Near the suture of the structural units from west Yunnan are sporadic intracontinental basalts associated with the continental rifting (*Wu* and *Yano*, 1993, 1994). There has been little petrological study of these basalts, even though it is important to elucidate the nature and timing of heating events for synorogenic magmatism during continental collision.

This paper focuses on three locations from west Yunnan. Triassic basalts occur within the Central Yunnan Intracontinental Rift, at the western margin of the Yangtze microcontinent (Fig. 2). Jurassic basalt occurrences are within the half-graben in the Simao block, and in the shallow marine basin on the Shan-Thai microcontinent. These basalts show distinct geochemical characteristics: for example, the Simao Basalt shows typical subduction-related geochemical features, in spite of its tectonic association with continental rift volcanism, not subduction. These data may reflect the geochemical evolution of the subcontinental lithospheric mantle sources of each volcanic province.

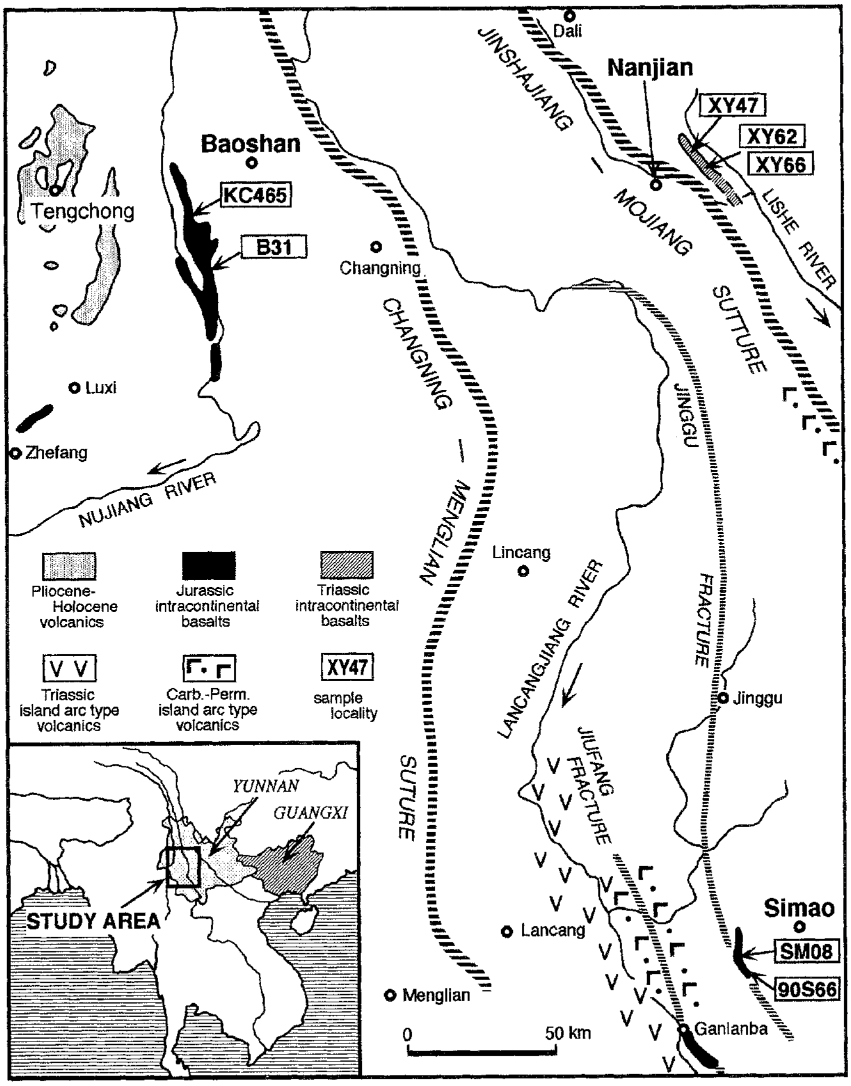


Fig. 2. Distribution of Mesozoic volcanic rocks in southwest Yunnan

Geological setting

In southwestern Yunnan, subduction of oceanic plates and collision of continental blocks occurred repeatedly during the Late Paleozoic to Mesozoic (Fig. 3). The late Paleozoic Changning -Menglian oceanic basin originally separated the Shan-Thai microcontinent from the Simao block, representing the major Paleotethyan oceanic basin in the Yunnan–Burma region. This was partly subducted in the Late Carboniferous and the Early Permian, with the products of island arc volcanism, now exposed along the Jiufang fracture to the west of Simao. The volcanic products, more than 1,000 m thick, are composed of basaltic andesite, rhyolite, trachyandesite and quartz porphyry.

One of the branches of the Paleotethyan ocean, the Mojiang ocean between the Simao block and the Yangtze microcontinent, was subducted along the eastern margin of the Simao block, with the products of island arc volcanism, now exposed to the west of the Jinshajiang-Mojiang suture. The early Late Permian volcanic products are composed mainly of volcaniclastic rocks and contain some intercalated lava (basalt, andesite, dacite and rhyolitic porphyries). The geochemical features of the volcanic rocks are reported by *Zhou* et al. (1992).

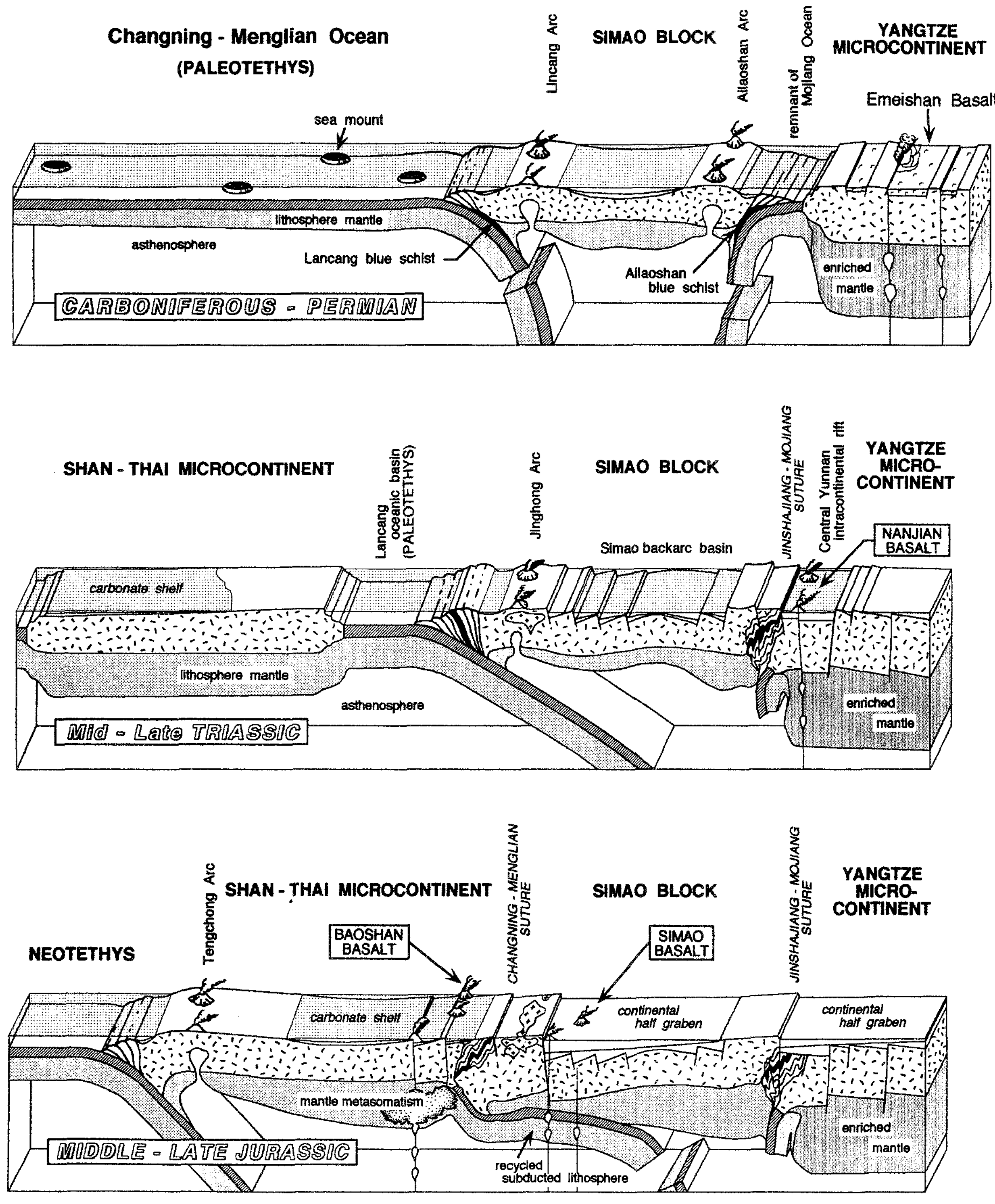
During the Triassic, the Yangtze microcontinent amalgamated with the Simao block. The remnant of this collision is the Jinshajiang-Mojiang suture. In the Lancang oceanic basin (*Wu*, 1993), the relic basin of the Changning-Menglian oceanic basin, began to subduct around Ladinian time (233–230Ma). In the Simao area, in the southwestern part of Yunnan, three tectonic units of Carnian to Early Norian age (230–215Ma) are distributed from west to east as follows (*Wu* and *Yano*, 1992): (1) The Lancang oceanic basin; (2) The Jinghong volcanic arc composed of basic and acidic volcanic rocks; and (3) The Simao back arc basin filled by bathyal and abyssal deposits. They formed a typical island arc-trench system with a back arc basin, and west-directed subduction. Further landward, the Central Yunnan Intracontinental Rift was simultaneously formed on the western margin of the attached Yangtze continent. This rift basin filled with terrigenous turbidites with intercalations of basaltic lavas (Nanjian basalt) and volcaniclastic rocks (*Wu* and *Yano*, 1993).

During the Late Norian (215–210 Ma), the Shan-Thai microcontinent collided with the Yangtze block to close the Lancang oceanic basin. This represents one of the collisional events that assembled the Cimmerian continent (*Sengör* et al., 1988) from a number of microcontinents, and is called the Indosinian Movement. The collision between the Shan-Thai microcontinent and the Yangtze-Simao microcontinent was accompanied by uplift and erosion which continued until earliest Middle Jurassic. K-Ar dating of hornblende from the Lancang paired metamorphic belt gives an age of 188 Ma (*Zhang* et al., 1993), and the granites from Lancang 230–210 Ma (*Cong* et al., 1994). These may designate thermal events related to the Indosinian movement.

The Neotethyan oceanic basin was situated oceanwards of the Shan-Thai microcontinent towards Eurasia, and was formed after the separation of the Shan-Thai microcontinent from Gondwana. After collision of the microcontinent, the Neotethyan oceanic plate was subducted beneath the consolidated Eurasian continent along the Nagaland belt in Burma (Myanmar). The Yangtze area became continental and was affected by intracontinental rifting. A block-depression in the Simao area which resulted from rifting during Middle Jurassic formed a half-graben filled mostly by fluvio-lacustrine deposits (*Wu* and *Yano*, 1994) and minor marine deposits during the maximum marine-flooding stage in the Bathonian (Middle Jurassic) (*Haq* et al., 1987). Along the Jinggu fracture, a main western boundary fault of the half-graben in the Simao area, basaltic lavas (Simao basalt) up to 20 m thick were erupted.

In the Shan-Thai area, terrigenous clastics and platform carbonates were deposited after a sealevel rise during the Middle Jurassic. In a shallow marine basin on the northeastern margin of the Shan-Thai area, called the Zhefang Basin, basaltic lava flows (Baoshan basalt), up to 335 m thick, were erupted.

Thus, Mesozoic collisions of continental blocks enlarged the Eurasian continent toward the Tethys. As a result follows the Tethys-ward shift of subduction


Changning - Menglian Ocean
(PALEOTETHYS)
Lincang Arc
SIMAO BLOCK
Ailaoshan Arc
remnant of Mojiang Ocean
YANGTZE MICROCONTINENT
Emeishan Basalt
sea mount
lithosphere mantle
asthenosphere
Lancang blue schist
Ailaoshan blue schist
enriched mantle
CARBONIFEROUS - PERMIAN
SHAN - THAI MICROCONTINENT
Lancang oceanic basin (PALEOTETHYS)
Jinghong Arc
SIMAO BLOCK
JINSHAJIANG - MOJIANG SUTURE
Central Yunnan intracontinental rift
YANGTZE MICRO-CONTINENT
NANJIAN BASALT
Simao backarc basin
carbonate shelf
lithosphere mantle
asthenosphere
enriched mantle
Mid - Late TRIASSIC
Tengchong Arc
SHAN - THAI MICROCONTINENT
CHANGNING - MENGLIAN SUTURE
SIMAO BLOCK
JINSHAJIANG - MOJIANG SUTURE
YANGTZE MICRO-CONTINENT
NEOTETHYS
BAOSHAN BASALT
SIMAO BASALT
carbonate shelf
continental half graben
continental half graben
mantle metasomatism
enriched mantle
recycled subducted lithosphere
MIDDLE - LATE JURASSIC

zones, the eruption of sporadic intracontinental basalts shifted in the same direction (Fig. 3). The Late Triassic Nanjian basalt erupted on the western margin of the Yangze microcontinent, and then the Middle Jurassic Simao and Baoshan basalts erupted on the western margin of the Simao block and within the Shan-Thai microcontinent respectively.

Samples and petrography

Nanjian Basalt (XY47,XY62,XY66)

The Nanjian basalt is composed mainly of tuff breccias of aphyric basalts (XY47,XY62) and olivine basalt(XY62). Olivine as phenocryst and micropheno-cryst of XY62 is completely replaced by chlorite and calcite. Plagioclase is partly to completely replaced by albite, sericite and calcite. The groundmass of basalt, consisting of clinopyroxene, plagioclase, Fe-Ti oxides and interstitial glass, shows intersertal to intergranular texture and is partly altered. This alteration involves partial to complete conversion of pyroxene and glass to quartz, chlorite, calcite and pyrite, rarely to epidote(XY47), and partial conversion of plagioclase to albite and calcite. The groundmass of XY47 and XY66 contains cavities filled with quartz, calcite, chlorite and epidote.

Simao Basalt(SMO8,90S66)

The Simao basalt, composed of olivine-clinopyroxene basalt lava flows, is fresher than the Nanjian and Baoshan basalts. The phenocrysts consist of olivine, clino-

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Fig. 3. Late Paleozoic to Mesozoic tectono-magmatic development of Yunnan-Burma region (not to scale, modified from *Zhang* et al., 1993; *Wu*, 1993 and *Cong* et al., 1994). *Carboniferous to Permian:* Both eastward subduction of the Paleotethys plate and westward subduction of the Simao plate caused high-P/T metamorphism, and subsequently, the Lancang and Ailaoshan blue schists uplifted possibly by cutting off of subducted slabs. These events have poor geochronological controls, but occurred certainly after the Devonian and before the Triassic. *Mid-Triassic:* The Simao block amalgamated with the Yangtze microcontinent along the Jinshajiang-Mojiang suture. The Paleotethys became narrow to be named the Lancang oceanic basin. On the back arc side, continental volcanism took place in the Central Yunnan Intracontinental Rift on the Yantze microcontinent. The remaining Nanjian basalt with enriched isotopic ratios and higher LREE/HFSE and LREE/HREE ratios suggest the existence of enriched lithosphere mantle under the microcontinent. *Middle Jurassic:* The Shan-Thai microcontinent, a rifted continental fragment of the Cimmerian continent, collided with the Simao block along the Changning-Menglian suture, and subsequently the Neotethys oceanic plate subducted under the amalgamated Eurasian continent. Regional continental rifting on the back arc side was associated with continental volcanism. The Simao basalt on the Simao block has a geochemical feature of depleted and subduction-related enrichment, indicating the presence of an underplated recycled subducted lithosphere under the Simao block. The Baoshan basalt with a geochemical feature of highly incompatible trace element-enrichment and Nd isotopic compositions similar to those of the bulk earth suggests mantle metasomatism of the subcontinental lithosphere under the Shan-Thai microcontinent

pyroxene and plagioclase. Olivine and clinopyroxene phenocrysts constitute glomeroporphyritic aggregates. Olivine as phenocrysts and microphenocrysts, is completely replaced by chlorite. Zoned clinopyroxene phenocrysts are partly replaced by chlorite. Plagioclase phenocrysts are partly replaced by albite, and rarely sericite and chlorite. The groundmass shows intersertal texture with flowing structure, consisting of lath-shaped plagioclase partly replaced by albite and sericite, intergranular clinopyroxene and Fe-Ti oxides, and interstitial glass which is completely replaced by albite and sericite, and rarely quartz and calcite.

Baoshan Basalt(B31,KC465)

The Baoshan basalt occurring as lava flows, is composed of plagioclase, olivine, pyroxene, Fe-Ti oxides and interstitial glass. The texture is intersertal to intergranular. Intergranular olivine and pyroxene are completely replaced by smectite and partly by sericite. Euhedral plagioclase laths as phenocrysts and groundmass, are often turbid in the interior, owing to alteration to albite and sericite. Interstitial glass is mostly replaced by sericite, smectite and pyrite. Small vesicles filled with smectite and sericite are present in the groundmass.

Geochemistry

Volcanic rocks from the Nanjian, Simao and Baoshan basalts were analysed for major element by XRF techniques (*Tsuchiya* et al., 1989) at Hokkaido University (Japan), REE by ICP at the Institute of Geology, Chinese Academy of Sciences, and trace element without REE by instrumental photon activation (IP) (*Yoshida* et al., 1981) at Tohoku University (Japan). Sr and Nd isotope measurements were performed at Okayama University (Japan). Mass spectrometric analyses were made following the procedure of *Kagami* et al. (1987, 1989). Analytical results are given in Table 1.

Trace and minor elements relative immobile during hydrothermal alteration have been used successfully as petrogenetic indicators and are used here to determine the magmatic affinities of Yunnan basalts.

Of the elements listed in Table 1, the most useful are HFSE, such as Ti, Zr, Nb and Y, and the REE. Two distinct geochemical groups can be identified within the Yunnan basalts as shown on Primordial mantle-normalized diagrams (Fig. 4). The Nanjian and Baoshan basalts have fairly smooth mantle-normalized patterns that are convex upwards. Compared with Hawaiian tholeiites and alkali basalts (*BVSP*, 1981), both Nanjian and baoshan basalts show oceanic island basalt (OIB)-like abundances of HFSE, but variable LILE. In the Yunnan basalts, Rb, Ba and K have all been affected to some degree by alteration, which is difficult to quantify. If this is taken into account, both Nanjian and Baoshan basalts may be geochemically similar to OIB.

On the contrary, the Simao basalt displays an irregular mantle-normalized pattern. The most striking geochemical feature is the relatively low abundance of the HFSE with respect to the LILE and the LREE. Nb has the greatest depletion on a mantle-normalized diagrams, a geochemical feature commonly found in island-arc volcanics (*Gill*, 1981). High La/Nb (> 2) is a common and widespreaded

Table 1. *Major and trace elements, and isotopic data of Mesozoic basalts from southwest Yunnan*

Sample	Triassic Nanjian XY47	Triassic Nanjian XY62	Triassic Nanjian XY66	Jurassic Simao SM08	Jurassic Simao 90S66	Jurassic Baoshan B31	Jurassic Baoshan KC465
SiO_2(%)(XRF)	52.39	53.71	49.37	47.67	46.70	50.43	50.48
TiO_2	1.47	1.97	2.15	1.20	1.12	2.39	2.15
Al_2O_3	13.82	14.59	16.24	16.74	16.65	17.27	15.38
Fe_2O_3	12.83	12.95	13.84	11.74	11.17	18.48	19.66
MnO	0.10	0.13	0.11	0.12	0.14	0.01	0.03
MgO	7.72	7.99	8.19	7.10	7.09	2.05	6.04
CaO	6.19	6.39	5.42	8.68	9.80	2.46	2.57
Na_2O	3.48	2.04	2.56	4.40	4.22	6.30	5.83
K_2O	2.21	1.14	2.43	0.72	0.53	1.78	0.81
P_2O_5	0.17	0.17	0.31	0.49	0.48	0.23	0.18
Total	100.37	101.10	100.62	98.86	97.90	101.40	103.14
La(ppm)(ICP)	13.4	13.8	24.6	11.2	nd	17.2	13.6
Ce	26.4	30	46	24.4	33.3	35	27.6
Pr	4.4	4	6.4	3.8	nd	5.4	2.8
Nd	14	13.6	20.4	13	14.4	18.8	15
Sm	3.6	2.9	4.4	2.7	2.6	4.4	4.0
Eu	1.0	1.04	0.88	0.8	nd	1.35	1.25
Gd	3.3	2.6	3.6	2	nd	4	4.4
Tb	0.57	0.46	0.6	0.28	nd	0.60	0.62
Dy	3.2	2.5	3.4	1.5	nd	3.4	3.1
Ho	0.68	0.53	0.71	0.35	nd	0.75	0.60
Er	1.8	1.4	2	0.82	nd	1.9	1.88
Tm	0.25	0.23	0.3	0.12	nd	0.29	0.24
Yb	1.4	1.2	1.6	0.62	nd	1.3	1.18
Lu	0.22	0.18	0.22	0.11	nd	0.2	0.17
Sr(IP)	252	461	217	1021	877	373	233
Rb	70.4	37.5	70.1	11.3	7.6	31.5	7.2
Ba	566	579	759	183	156	100	328
Nb	10.9	12.8	15.5	3.0	3.2	15.5	8.9
Zr	128	138	167	53.2	53.9	127	91.2
Y	26.7	23.1	35.1	11.4	10.4	33.4	22.6
Co	49.3	46.0	48.0	33.9	35.1	25.4	51.2
Cr	677	396	211	105	95.3	195	254
Cs	0.61	9.89	9.34	0.26	0.13	0.01	nd
Ni	116	90.1	30.0	70.3	35.1	47.9	282
Sc	35.0	33.4	32.1	27.1	17.7	36.0	23.1
Zn	72	86	176	75	104	57	66
$^{87}Sr/^{86}Sr$	0.710415	0.708118	0.710205	0.705570	0.705345	0.707307	0.706589
2σ	0.000013	0.000013	0.000012	0.000014	0.000014	0.000012	0.000017
SrI	0.708004	0.707416	0.707417	0.705488	0.705281	0.706682	0.706360
$^{143}Nd/^{144}Nd$	0.512272	0.512328	0.512125	0.512794	0.512791	0.512528	0.512628
2σ	0.000016	0.000016	0.000014	0.000014	0.000011	0.000013	0.000015
NdI	0.512058	0.512151	0.511946	0.512646	0.512662	0.512361	0.512438
Age	210Ma	210Ma	210Ma	180Ma	180Ma	180Ma	180Ma

Fe_2O_3 total iron as Fe_2O_3, *nd* not determined, *SrI* initial $^{87}Sr/^{86}Sr$ ratio, *NdI* initial $^{143}Nd/^{144}Nd$ ratio, *XRF*, X-ray fluorescence, *ICP* inductively coupled plasma, *IP* instrumental photon activation. Initial ε_{Nd} and ε_{Sr} values were calculated at 210Ma for Triassic basalts and at 180Ma for Jurassic basalts by using the following CHUR parameters. $^{87}Sr/^{86}Sr(present) = 0.7045$, $^{87}Rb/^{86}Sr(present) = 0.0827$, λ^{87} Rb $= 1.42 \times 10^{-11}y^{-1}$, $^{143}Nd/^{144}Nd(present) = 0.512638$, $^{147}Sm/^{144}Nd(present) = 0.1966$, $\lambda^{147}Sm = 6.54 \times 10^{-12}y^{-1}$. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are normalized to $^{87}Sr/^{86}Sr = 8.375209$ and $^{143}Nd/^{144}Nd = 0.7219$, respectively. The measured $^{87}Sr/^{86}Sr$ ratio for NBS987 during this study is 0.710248 ± 0.000008 (N = 3). The $^{143}Nd/^{144}Nd$ ratios are reported relative to $^{143}Nd/^{144}Nd = 0.512640$ for BCR-1 (*Wasserburg* et al., 1981)

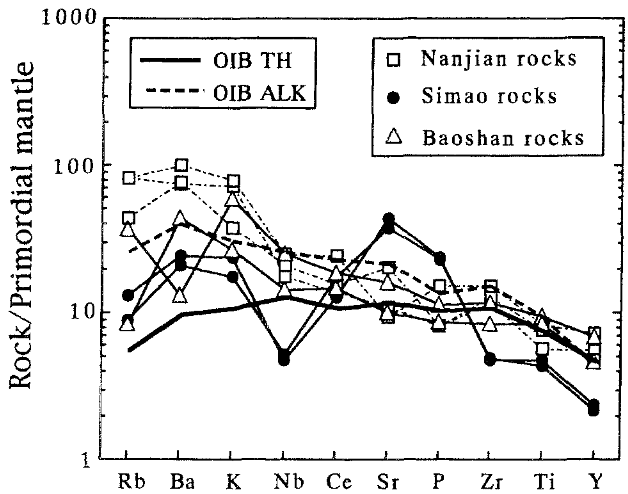

Fig. 4. Primordial mantle-normalized incompatible element patterns of Mesozoic basalts from southwest Yunnan. Hawaiian tholeiite (OIB TH) and alkali basalt (OIB ALK)(*BVSP*, 1981) are also shown. Normalizing values are from *Wood* et al. (1979)

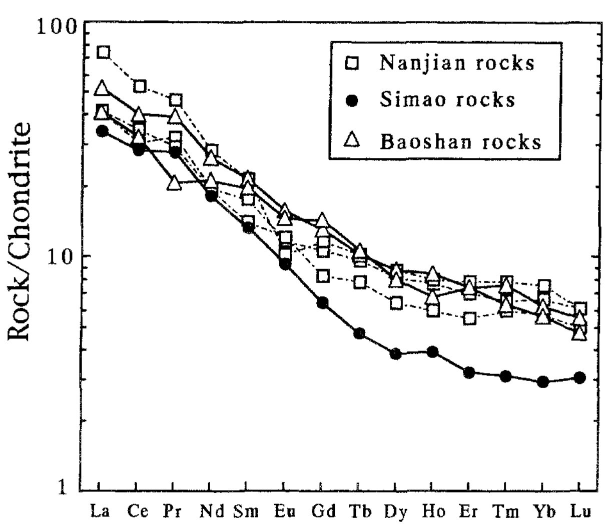

Fig. 5. Chondrite-normalized REE patterns of Mesozoic basalts from southwest Yunnan

feature in island-arc volcanics (*Salters* and *Hart*, 1991). The Simao basalt has high La/Nb $= 3.7$, thus it seems that Nb depletion is a firm signature. In the REE patterns (Fig. 5), The very high chondrite-normalized La/Yb value (11.6) suggests a more alkaline affinity of Simao basalt. The LREE enrichment of Simao basalt is similar to and parallel to those of Nanjian and Baoshan basalts, but the HREE concentrations of the Simao basalt are lower. Thus, we note that depletion in Simao basalt is not restricted to the HFSE but includes at least Y and the HREE.

Elements that are equally incompatible during fractional crystallization and partial melting should behave coherently and preserve the element/element ratios of their source regions. The Yunnan basalts plots in the La-Zr diagram (Fig. 6) are along with model melting curves (solid line) and constant La/Zr ratios in source (dashed line). All of the Yunnan basalts studied here have chondrite-normalized La/Zr ratios between 1.7 and 3.5 times that of chondrite, confirming an enriched source region for all of the basalts. Because mineral/liquid partition coefficients for

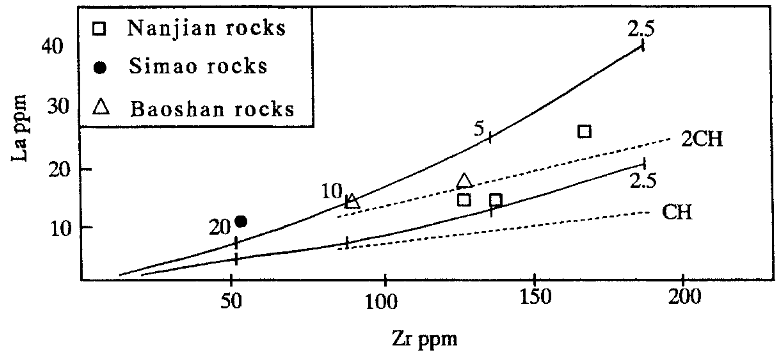

Fig. 6. La versus Zr diagram of Mesozoic basalts from southwest Yunnan. Also shown are model curves for partial melting (solid line) and constant La/Zr ratios in source (dashed line). Lower solid curve for melting source with La/Zr=chondritic, upper solid curve for melting source with La/Zr=two times chondritic. Numbers on curves refer to percentage of melting. The melting model is based on the non-modal melting equation of *Shaw* (1970). This is equivalent to the batch melting equation. The source material is assumed to be spinel lherzolite. The initial modal mineralogy, the melting proportions, and mineral/liquid partition coefficients for La and Zr are used following the procedure of *Shervais* and *Kimbrough* (1987)

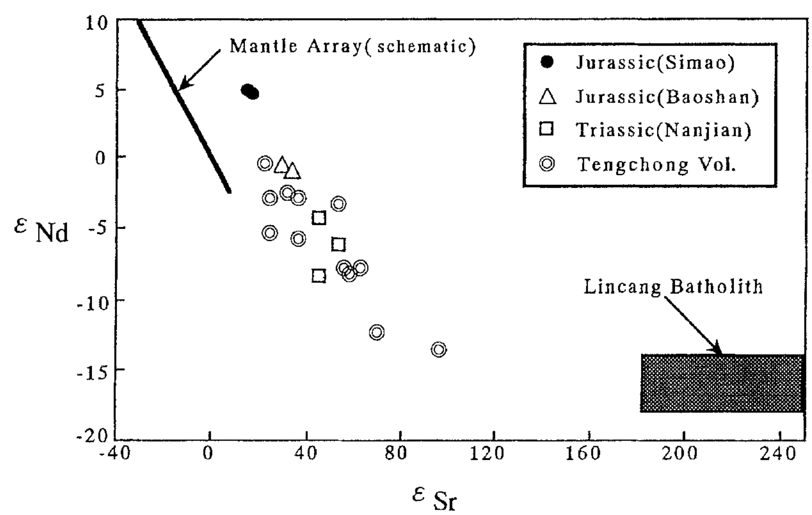

Fig. 7. Initial ε_{Nd} versus ε_{Sr} diagram of Mesozoic basalts from southwest Yunnan. Compositions of Tengchong Volcanics (*Zhu* et al., 1983) and Lincang Batholith (*Zhang* et al., 1993) are also shown

La are smaller than those for Zr, partial melting will increase La/Zr to some degree, whereas fractional crystallization will have little or no effect. Data for the Nanjian, Baoshan and Simao basalts lie above the melting curve for a chondrite source, and near the curve for a source with La/Zr = 2 times chondritic. These data are consistent with the conclusion that the Nanjian, Baoshan and Simao basalts are enriched magmatic affinities. The Simao basalt is characterized by higher LREE/HREE

((La/Yb)n = 11.6) relative to MORB, but low absolute concentrations of Nb, Zr, and Y, suggesting a petrogenetic model that requires enrichment (metasomatism) of depleted mantle to create alkalic sources.

Initial Sr isotopic ratios for the Yunnan basalts range from 0.7052 (initial $\varepsilon_{Sr} = 14.0$) to 0.7080 (53.2), and initial Nd isotopic ratios range from 0.51194 (initial $\varepsilon_{Nd} = -8.3$) to 0.51266 (+4.9) (Fig. 7). Phenocrysts and groundmass of the Yunnan basalts are more or less altered to secondary minerals such as chlorites and calcites, so higher Sr isotopic ratios of basaltic rocks from Yunnan may be due to alteration. ε_{Nd} data indicate that the Nanjian and Baoshan basalts were derived from a more or less enriched source compared to the bulk earth, whereas the Simao basalt had a more depleted source.

Discussion

1. Enriched subcontinental lithosphere of the Yangtze microcontinent

The volcanism forming the Nanjian basalt occurred in the Central Yunnan Intracontinental Rift along the western margin of the Yangtze microcontinent (*Wu* and *Yano*, 1993), which might stretch to western Guangxi where the rifting occurred since Early Triassic, associated with thick bimodal volcanics and mafic-ultramafic intrusions (*BGMRGZAR*, 1985). The Nanjian basalt indicates not only higher LREE/HFSE and LREE/HREE relative to chondrite, but also more enriched isotopic ratios. This could be explained by an enriched source compared to CHUR, or the interaction of sialic components (continental crust) with mantle-derived basic magmas (MORB-like depleted materials). High MgO, Cr, and Ni contents indicate the relatively primitive nature of the Nanjian basalt (Table 1). Using partition coefficients for Fe/Mg, Ni/Mg and Mn/Mg between olivine and silicate melts and composition of most primitive Nanjian basalt (XY47), an estimated parent melt was calculated. The olivine fractionation model (*Takahashi*, 1986) suggested for the Nanjian basalt 8 wt% olivine fractionation and a mantle source containing olivine Fo_{86}. This residual olivine composition is similar to those estimated from Kilauea basalts (*Takahashi*, 1986) and is consistent with the conclusion that the Nanjian basalts have an enriched OIB affinity. The calculation considered here suggests that the most primitive Nanjian basalt represents mantle-derived liquids that have undergone only limited differentiation, and only modest contamination by sialic crust. The enriched isotopic compositions of the Nanjian basalt must closely approximate those of the subcontinental mantle.

Wide ranges in Sr and Nd isotopic ratios are observed in continental flood basalts from Columbia River and Deccan Provinces. High Sr and low Nd isotope ratios of the Nanjian basalt are similar to relatively primitive basalts from the Snake River Plain and Columbia River Plateau (*Menzies* et al., 1983; Hess, 1989). *Hess* (1989) argues that the isotope compositions of those basalts are those of the subcontinental lithospheric mantle. They indicate element ratios for Rb/Sr and Nd/Sm greater than chondritic values over long periods of the Earth's history (> 2 Ga). Higher Nd/Sm ratios combined with lower Nd isotopic ratios of the Nanjian basalt clearly reflect the enriched characteristics of its subcontinental mantle source over a long time period. This indicates that the Yangtze microcontinent has a lithosphere which has remained convectively isolated for > 2 Ga, similar to the subcontinental lithospheric mantle in other regions (e.g. the Snake River plain and Columbia River Plateau).

2. Recycled subducted lithosphere of the Simao block

The Simao basalt shows typical subduction-related geochemical features with more alkaline affinity in spite of the fact that tectonically the Simao basalt was associated with continental rift volcanism. There were, however, two episodes of arc volcanism in the Simao area; in Latest Carboniferous- Early Permian, and in late Middle Triassic-early Late Triassic (Fig. 3; *Wu* and *Yano*, 1992; *Wu*, 1993). At the former time, subduction is suggested by Late Permian andesitic rocks exposed along Lancang Jiang River, which imply that the Lancang oceanic basin was being subducted to the east to produce the Jinghong volcanic arc.

If the mantle had inherited subduction-related enrichment prior to the onset of the Middle Jurassic tectonic regime, a geochemical signature of subduction may be inherited. Late Cenozoic continental flood basalts from the Basin and Range province, generated in a period of extensional tectonics, demonstrate two distinct geochemical features. The first component is within-plate type basalts attributed to asthenospheric source region, whereas the second component is characterized by much lower concentrations of HFSE relative to LILE and LREE of similar incompatibility and is inferred to be derived from the subcontinental mantle lithosphere modified by previous subduction episodes (*Davis* et al., 1988; *Ormerod* et al., 1988; *Bradshaw* et al., 1993). The Simao basalt produces a Nb trough on mantle-normalized diagrams, such as that observed in the second group of basalts from the Basin and Range province. This geochemical feature is characteristic of 'island-arc volcanics' (*Gill*, 1981). Several basaltic rocks from the oceanic basins such as Kod Ali, Red Sea (*Menzies* and *Hawkesworth*, 1987), Malaita, Solomon Islands (*Bielski-Zyskind* et al., 1984) and extensional volcanics from the western USA (*Atwater* and *Molnar*, 1973) include mantle xenoliths showing an isotopic signature related to subduction. *Menzies* and *Hawkesworth* (1987) suggested that these xenoliths must have been derived from recycled lithospheric mantle associated with influx of a high Rb/Sr melt or fluid related to subduction. The Simao basalt may also have retained a geochemical signature of subduction prior to the Middle Jurassic continental rifting.

The Sr and Nd isotopic ratios of the Simao basalt are the most depleted among the Mesozoic basalts from southwest Yunnan region. This means that the source mantle for the Simao basalt must have had Rb/Sr and Nd/Sm ratios lower than those of the bulk earth for a long time of Earth's history. These basalts are, however, characterized by higher Nd/Sm, corresponding to the alkali basalt series (Fig. 8), but low absolute concentrations of Nb, Zr, and Y (Fig. 4). The most likely petrogenetic model for the Simao basalt is that the source mantle was enriched in Rb/Sr and Nd/Sm through mantle metasomatism related to previous subduction shortly before the basalts were produced.

The island arc basalts are characterized by low abundances of incompatible HFSE and also Y (HREE), and high La/Nb (> 2) relative to average N-MORB (La/Nb $= 1.1$), providing evidence for depletion of the mantle wedge relative to N-

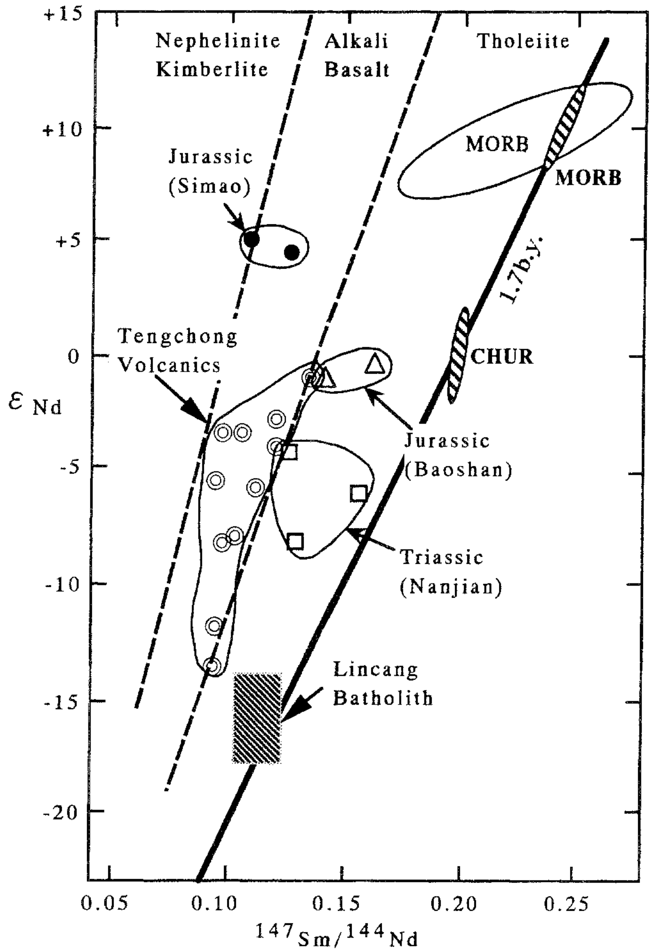

Fig. 8. ε_{Nd} versus $^{147}Sm/^{144}Nd$ diagram (*DePaolo*, 1988) of Mesozoic basalts from southwest Yunnan. Symbols and data sources as in Fig. 7

MORB sources (*Salters* and *Hart*, 1991; *Woodhead* et al., 1993). *Pearce* and *Parkinson* (1993) and *Woodhead* et al. (1993) argue that island arc basalts can be produced by melting of depleted residual source after prior back-arc basin basalts melt extraction. *Salters* and *Hart* (1991) show, from the lack of correlation between $^{176}Hf/^{177}Hf$ ratios and Hf depletion in island arc basalts, that the time scale between source HFSE depletion and subsequent melting will be less than 250 Ma. The Simao basalt shows depletion of HFSE, Y and HREE, and high La/Nb ratio (3.7) similar to the island arc basalts, but more enriched Nd isotopic ratios relative to N-MORB. This means that the incompatible HFSE, Y and HREE depletions of the Simao basalt are not old feature. Thus, the depletion of HFSE, Y and HREE of the Simao basalt seems to have been contemporaneous with the enrichment in Rb/Sr and Nd/Sm through mantle metasomatism shortly before the basalts were produced. The Simao basalt may have retained a geochemical signature of subduction associated with back-arc basin volcanism prior to the Middle Jurassic continental rifting.

3. Metasomatized mantle under the Shan-Thai microcontinent

The Zhefang Basin was a shallow marine basin joining the Neo-Tethyan ocean to the west of the Shan-Thai microcontinent, and existed contemporaneously with the intracontinental rifting accompanied with the Simao basalt eruption. The Baoshan basalt resulted from continental rifting on the margin of the Shan-Thai microcontinent. They have distinct geochemical features from those of the Simao basalt indicating subduction-related trace element abundances, that is, higher contents of more incompatible elements similar to an enriched OIB magmas (Fig. 4). These data suggest that the source mantle of the Baoshan basalt was free from the recycled subduction component.

The Tengchong area in the Shan-Thai microcontinent is a region of Pliocene-Holocene volcanism and geothermal activity (Figs. 1 and 2; *Zhu* et al., 1983; *Zhou* et al., 1988; *Nakai* et al., 1993). This volcanism began after the collision event between the Indian and Eurasian plates, in response to the extensional stress which created a series of grabens (*Zhou* et al., 1983). The Tengchong volcanic rocks range in compositions from tholeiitic basalt to calc-alkali andesite-dacite, with most lavas being K-rick. These volcanic rocks are geochemically similar to typical island arc volcanic rocks despite their apparent relation to the collision tectonics between the Indian and Eurasian plates (*Zhou* et al., 1988; *Zhao* and *Chen*, 1992; *Cong* et al., 1994). Chemical compositions, including Sr and Nd isotopic data, indicate crustal assimilation and crystal fractionation were involved in andesite-dacite formation of the Tengchong volcanic rocks. Most depleted isotopic compositions ($\varepsilon_{Nd} = 0.7$, $^{87}Sr/^{86}Sr = 0.705950$) among the Tengchong volcanic rocks suggest that end-member basalts were derived from uncontaminated sub-Tengchong mantle (*Zhu* et al., 1983). The Baoshan basalt shows Nd isotopic compositions similar to those of the most depleted basalts from the Tengchong volcanic rocks, which resemble those of the bulk earth (Fig. 8). This means that subcontinental mantle with CHUR-like compositions contributed to volcanism in the Shan-Thai microcontinent since early Middle Jurassic.

The Baoshan basalt shows geochemical features similar to those of an enriched OIB. High concentrations of incompatible trace elements such as LREE, Ti and Zr, and relatively depleted character of the Nd isotopic ratios of the Baoshan basalt suggest that the parent mantle may have been enriched in trace elements by mantle metasomatism just prior to eruption. It may be inferred that the invasion of trace element-rich fluids into the lithospheric mantle of the Shan-Thai microcontinent with bulk earth-like isotopic composition resulted in partial melting and thereby allowing magma to form.

Concluding remarks

The tectono-magmatic evolution of Yunnan-Burma region during the Late Paleozoic to Mesozoic is summarized below:

1. Geochemical features of within-plate type basalt for the Nanjian and Baoshan basalts are consistent with development of an extensional regime associated with continental rifting in the Yunnan province in Triassic and Jurassic. The Simao basalt shows subduction-related geochemical features, although intracontinental

grabens formed in Simao area during Middle Jurassic. The geochemistry suggests that the Simao basalt may have derived from a lithospheric mantle modified by subduction during Latest Carboniferous to Late Triassic, prior to the onset of the Middle Jurassic continental rifting.

2. Southwestern Yunnan, comprising the Yangtze and Shan-Thai microcontinents and Simao block, has successively undergone subduction of oceanic plates, collision of the microcontinents, and intracontinental rifting during the Late Paleozoic to Mesozoic (Fig. 3). These microcontinents and blocks indicate a distinct geochemical evolution of subcontinental lithosphere, reflecting their tectonic history.

The Nanjian basalts erupted on the Yangtze microcontinent have more enriched isotopic ratios and higher LREE/HFSE and LREE/HREE ratios, which indicate the existence of the enriched subcontinental lithosphere under the Yangtze microcontinent stabilized over long periods of the Earth's history (> 2 Ga). The lithospheric mantle of the Simao block, which yielded the Simao basalt, indicates geochemical features of more depleted mantle, and possible subduction-related enrichment. The Shan-Thai microcontinent, where the Baoshan basalt was erupted in Mid-Jurassic, has a subcontinental lithosphere with an isotopic composition similar to the bulk earth, but which underwent mantle metasomatism just prior to eruption of the Baoshan basalt.

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