Research Article

Geochemical and Sm–Nd isotopic characteristics of metabasites from central Hainan Island, South China and their tectonic significance

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Abstract Major and trace elements and Sm–Nd isotopic data are presented for metabasites that are present as lenses within Paleozoic metasediments in the Chenxing and Bangxi regions, central Hainan Island, Southeast (SE) China. Most metabasites are metamorphosed cumulated gabbroic rocks tholeiitic in nature, and characterized by varying degrees of depletion in Th, Nb, Ta and light rare earth elements (LREE). Moreover, they show high positive $\epsilon_{\text{Nd}}(T)$ values of approximately +7, similar to those of mid-ocean ridge basalts (MORB). A Sm–Nd isochron age of 333 ± 12 Ma obtained for the metabasites is interpreted as their crystallization age. The combined geochemical and Sm–Nd isotopic data suggest that the metabasites were generated by dynamic partial melting from a MORB-like mantle source in an oceanic regime. These rocks probably represent remnants of fragmented oceanic crust of the eastern part of Paleo-Tethys. They were obducted onto the continental crust as part of the ‘Shilu Mélange’ in earliest Mesozoic time when southern Hainan (part of the Indochina block) collided with northern Hainan (part of South China). Alternatively, they could be formed in a volcanic rifted passive margin at the sea-floor spreading stage as part of MORB-like seaward-dipping reflector break-up packages.

Key words: Eastern Paleo-Tethys, geochemistry, Hainan Island, metabasites, Sm–Nd isotope, South China.

INTRODUCTION

South-east Asia constitutes one of the most complicated tectonic regions of the Earth, being a convergent triple junction at the global scale between the Pacific, Indo-Australian and Eurasian plates. It consists of a complex assembly of allochthonous continental blocks. These blocks rifted from the northern margin of Gondwanaland, drifted northwards, and eventually amalgamated to form the South-east Asian land mass during Paleozoic and Mesozoic time (Metcalf 1996). These processes involved the opening and closing of successive

eastern Tethys oceans. Study of the suture zones and ophiolites between these blocks is particularly important for understanding the amalgamation and evolution of South-east Asia and eastern Tethys. So far, much attention has been paid to the ophiolites occurring along a few of major suture zones in South-east Asia, such as the Jinsha Suture (Chen & Xie 1994; Jian *et al.* 1999), Shuanggou Suture (Zhang *et al.* 1994; Jian *et al.* 1998), Song Ma Suture (Hutchison 1989; Lepvrier *et al.* 1997), and Changning–Menglian Suture (Zhang *et al.* 1985; Liu *et al.* 1991; Wu *et al.* 1995; Fang *et al.* 1998).

Among these accreted blocks, Hainan Island is the least well understood as regards its nature and tectonic evolution. It is situated at the eastern flank of the South-east Asian continent (Fig. 1),

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Fig. 1 Distributions of principal continental terranes and sutures of SE Asia (modified after Metcalfe 1996). QT, Qiangtang Terrane; QS, Qamdo-Simao Terrane; SG, Songpan Ganzi accretionary complex; L, Lhasa Terrane; WB, West Burma; SI, Simao Terrane; HT, Hainan Island terranes.

linking the South China and Indochina blocks (Metcalfe 1996). Although the island was generally considered to be the south-western end of the Cathaysia block in many Chinese studies (Shui 1987; Guangdong 1988; Zhang *et al.* 1990), other researchers considered Hainan Island to consist of two tectonostratigraphic terranes, with the boundaries of these still controversial. Yang *et al.* (1989) divided Hainan Island into a northern Qiongzhou terrane and a southern Yaxian terrane, bounded by the east-west-trending Jiushuo-Lingshui Fault (Fig. 2a). Hsü *et al.* (1990) and Chen *et al.* (1992) interpreted the island as part of a Mesozoic orogenic belt formed by collision of the Gondwanaland-derived Dongnanya block (comprising the major part of Hainan Island) and the (South China) Huanan block. The 'Shilu Group' consists of tectonic mélange (Fig. 2b). Metcalfe *et al.* (1994) suggested that Hainan Island consists of two terranes, northwest Hainan and southeast Hainan, bounded by the southwest-northeast-oriented Baisha Fault (Fig. 2c). Finally, Xia *et al.* (1991) and Fang *et al.* (1992) proposed the east-west-trending Changjiang-Qionghai Fault in central Hainan as a Paleozoic rift (Fig. 2d). In the present paper we report major and trace element and Sm-Nd isotopic data for metabasites from central Hainan Island. Our data demonstrate that these metabasites have typical normal (N)-type mid-ocean ridge basalt (MORB) geochemical features, providing important constraints on the tectonic evolution of the island and the evolution of eastern Paleo-Tethys.

Fig. 2 Comparison of different tectonic models for Hainan Island. Two tectono-stratigraphic terranes, with different subdivisions, for the island were suggested by (a) Yang *et al.* (1989); (b) Hsü *et al.* (1990) and Chen *et al.* (1992); and (c) Metcalfe *et al.* (1994). Alternative Paleozoic rift model (d) was proposed by Xia *et al.* (1991) and Fang *et al.* (1992).

GEOLOGICAL BACKGROUND

Hainan Island, the second largest island in China, is a continental-type island, separated from the mainland by the Qiongzhou Strait (Fig. 3). Proterozoic basement (the Baoban Group; Guangdong 1988) is exposed in the southwest of the island, and the Paleozoic strata crop out in the central band. Most of these Proterozoic and Paleozoic rocks, however, were re-interpreted as the 'Shilu Mélange' of late Paleozoic to early Mesozoic age by Hsü *et al.* (1990) and Chen *et al.* (1992; Fig. 2b). Mesozoic basins in the middle of the island trend northeast-southwest. Late Paleozoic-Mesozoic granites constitute more than 60% of the island's area. Cenozoic volcanic rocks are present in the north of the island. Three large east-west-trending faults, called, from north to south, the Wangwu-Wenjiao Fault, Changjiang-Qionghai Fault, and Jiushuo-Lingshui Fault, were inferred to be present in the island based on aeromagnetic data (Guangdong 1988).

Our recent field investigations identified a number of metabasites present as lenses within the Paleozoic metasediments exposed in two regions; that is, the Chenxing Farm in the Tunchang County and the Bangxi Farm in the Changjiang-Qionghai County at the northern side of the Changjiang-Qionghai Fault (Fig. 3). They are structurally enclosed by the Paleozoic metasediments. Clear fault contact was observed between the

Fig. 3 Simplified geologic map of Hainan Island (modified after Guangdong 1988) illustrating the sample localities (triangles). WWF, Wangwu–Wenjiao Fault; CQF, Changjiang–Qionghai Fault; JLF, Jiusuo–Lingshui Fault.

metabasites and the host phyllites, all of which are cut by granites of Late Paleozoic to early Mesozoic age (Hainan 1995). All Chenxing samples underwent metamorphism of amphibolite facies with a mineral assemblage of hornblende + plagioclase + diopside + biotite, and their original textures cannot be deciphered. Most Bangxi samples experienced metamorphism of greenschist facies, consisting of actinolite, chlorite, epidote and albite as well as a minor amount of apatite and Ti-Fe oxides. They generally have a hypidiomorphic-granular texture. Twinned plagioclase crystals can be observed in thin sections. Thus, plutonic protoliths are inferred for the Bangxi metabasites in terms of their petrographic features. The analyzed samples were altered to varying degrees with replacement of hornblende by tremolite.

ANALYTICAL METHODS

Major element oxides were determined using a Rigaku RIX 2000 X-ray fluorescence spectrometer (XRF) at the Department of Geology, National Taiwan University. Analytical precision as determined on duplicate analyses is generally approximately 1–5%. The detailed analytical procedures for major element analysis by XRF were described by Lee *et al.* (1997).

Trace elements were analyzed using a Perkin–Elmer Sciex ELAN 6000 inductively coupled plasma mass spectrometer (ICP-MS) at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Approximately 50 mg sample powders were dissolved in Teflon bombs using a HF+HNO₃ mixture for 2 days at 200°C. An internal standard solution containing a single-element Rh was used to monitor signal drift during counting. The US Geological Survey (USGS) standard BCR-1 was chosen to calibrate element concentrations of measured samples. In-run analytical precision for most elements is better than 2%. Detailed analytical procedures of inductively coupled plasma mass spectrometer (ICP-MS) were reported by Liu *et al.* (1996) and Li (1997).

The Nd isotopic compositions (unspiked aliquots) were determined using a multicollector Finnigan MAT-261 mass spectrometer operated in static multicollector mode at the Isotope laboratory of the China University of Geosciences (Wuhan). The measured ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. The ¹⁴³Nd/¹⁴⁴Nd ratio of the La Jolla standard measured on this MAT-261 mass spectrometer during the present study was 0.511870 ± 8 (2σ) on 20 runs. Sm–Nd concentrations, spiked with mixed ¹⁴⁶Nd–¹⁴⁹Sm tracers, were determined using a multicollector VG-354 mass spectrometer at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. Analytical precision for Sm and Nd concentrations and ¹⁴⁷Sm/¹⁴⁴Nd ratios is generally better than 0.5%.

RESULTS

Ten least-altered metabasite samples were analyzed for major and trace elements. Eight of these were analyzed for Sm–Nd isotopes. The elemental and Sm–Nd isotopic results are listed in Table 1 and Table 2, respectively.

MAJOR AND TRACE ELEMENT GEOCHEMISTRY

Because all metabasite samples were subject to greenschist- to amphibolite-facies metamorphism during which K, Na and other low-field-strength elements are most likely changed, only immobile elements such as the high-field-strength elements, Th and rare earth elements (REE) are used to explore the magmatic affinity and petrogenesis. The metabasite samples have low Zr/TiO₂ (0.0045–

Table 1 Major and trace element results for the metabasites from Hainan Island

Sample Location	cx-1 CX	cx-2 CX	cx-3 CX	cx-4 CX	cx-5 CX	cx-6 CX	hn-7 BX	b-1 BX	h-1 BX	s-3 BX
Major elements (wt%)										
SiO ₂	49.97	47.96	47.40	50.92	44.78	45.84	43.79	49.29	46.28	47.76
TiO ₂	0.56	0.62	0.41	0.39	0.50	0.47	0.94	0.63	0.95	2.02
Al ₂ O ₃	12.24	14.62	13.43	12.63	15.41	15.21	11.12	13.59	15.79	16.52
ΣFe ₂ O ₃	9.80	10.06	9.79	7.97	11.00	10.59	14.44	11.01	12.22	11.78
MnO	0.15	0.16	0.17	0.15	0.15	0.14	0.20	0.18	0.17	0.18
MgO	13.18	12.32	11.64	10.71	13.78	11.94	21.04	13.72	13.24	8.63
CaO	12.31	12.26	15.31	14.77	12.62	14.00	7.94	10.28	9.66	9.60
Na ₂ O	1.74	1.31	1.39	2.12	0.98	1.17	0.58	1.34	1.78	3.00
K ₂ O	0.19	0.82	0.63	0.50	0.93	0.79	0.01	0.06	0.01	0.45
P ₂ O ₅	0.05	0.05	0.02	0.02	0.03	0.03	0.12	0.07	0.09	0.24
Total	100.18	100.01	99.47	99.72	99.82	100.09	100.08	99.31	100.21	99.87
LOI	1.52	2.16	3.02	2.52	3.29	2.54	3.50	2.29	2.80	1.22
Mg#	0.76	0.75	0.74	0.76	0.75	0.73	0.78	0.75	0.72	0.64
Trace elements (p.p.m.)										
Sc	32.9	34.7	31.8	31.5	38.7	38.2	22.4	35.1	43.6	37.8
V	197	216	181	180	261	198	146	215	259	258
Cr	887	881	1006	769	1192	1091	1091	859	825	290
Co	59.9	59.0	58.0	46.5	60.5	55.5	81.9	64.8	64.7	49.0
Ni	382	337	280	211	275	322	719	418	354	133
Cu	48.9	29.3	56.8	14.6	80.0	94.8	81.4	97.9	86.5	72.0
Zn	99.4	109	91.9	102	130	107	121	69.1	72.3	86.0
Ga	9.91	12.0	9.42	8.09	13.0	11.9	13.0	13.1	17.8	19.2
Rb	5.55	24.1	17.5	13.7	27.7	22.0	0.35	5.07	3.12	24.3
Sr	141	136	172	189	89.9	154	9.76	143	149	315
Y	17.2	18.9	14.0	12.7	16.9	14.9	16.5	16.4	23.6	33.9
Zr	34.0	36.5	24.3	20.1	22.6	22.9	71.1	48.0	56.8	143
Nb	0.48	0.50	0.42	0.35	0.32	0.42	4.40	1.70	2.63	9.00
Cs	2.61	7.24	4.56	2.98	6.63	5.56	0.26	0.82	0.26	1.69
Ba	18.9	138	51.7	45.1	80.8	28.7	1.34	15.5	56.0	198
La	0.72	0.66	0.59	0.47	0.34	0.45	4.27	1.66	2.89	8.96
Ce	2.37	2.15	1.39	1.30	0.95	1.29	9.67	4.58	7.45	23.6
Pr	0.45	0.41	0.24	0.23	0.20	0.24	1.86	0.87	1.32	3.64
Nd	3.09	2.94	1.87	1.71	1.67	1.86	8.67	4.67	6.74	17.0
Sm	1.30	1.35	0.89	0.76	0.91	0.89	2.38	1.80	2.29	4.75
Eu	0.56	0.32	0.38	0.41	0.41	0.42	1.00	0.64	1.08	2.08
Gd	1.99	2.19	1.55	1.37	1.64	1.58	2.84	2.22	3.04	5.38
Tb	0.39	0.44	0.32	0.29	0.35	0.33	0.46	0.40	0.58	0.92
Dy	2.78	3.15	2.24	2.04	2.61	2.45	2.94	2.78	4.15	6.07
Ho	0.63	0.71	0.48	0.47	0.61	0.56	0.60	0.58	0.87	1.21
Er	1.88	2.07	1.49	1.41	1.80	1.68	1.78	1.69	2.53	3.39
Tm	0.27	0.30	0.23	0.21	0.26	0.25	0.26	0.26	0.38	0.48
Yb	1.85	2.03	1.57	1.49	1.76	1.74	1.67	1.69	2.48	3.08
Lu	0.30	0.32	0.25	0.25	0.28	0.27	0.24	0.23	0.37	0.44
Hf	0.91	0.99	0.62	0.54	0.59	0.64	1.94	1.35	1.53	3.89
Ta	0.028	0.030	0.024	0.021	0.018	0.025	0.24	0.10	0.16	0.58
Th	0.020	0.027	0.031	0.019	0.029	0.026	0.26	0.15	0.21	0.75
U	0.06	0.07	0.11	0.06	0.34	0.26	0.09	0.14	0.07	0.19

Note: Major elements are in dry system. Mg# = $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$, assuming $\text{Fe}_2\text{O}_3/(\text{FeO} + \text{Fe}_2\text{O}_3) = 0.20$. Total iron as Fe_2O_3 . CX = Chenxing; BX = Bangxi.

0.0076) and Nb/Y (0.03–0.3) ratios, similar to those of tholeiitic basalts (Winchester & Floyd 1976). In the Zr/TiO₂ versus SiO₂ diagram of Winchester and Floyd (1976), all but one of the samples (HN-7) plot within the subalkaline field (Fig. 4).

These metabasites can be subdivided into two groups in terms of major and trace element

geochemistry, as shown in the Harker-type MgO variation diagrams (Fig. 5). Group 1, including all six Chenxing samples and two Bangxi samples (H-1 and B-1), display coherent variations for most major and trace elements. The remaining two Bangxi samples, HN-7 and S-3, referred to here as group 2, plot as outliers in composition from the

Table 2 Sm–Nd isotopic data for the metabasites from Hainan Island

Sample	Sm (p.p.m.)	Nd (p.p.m.)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma_m$	$\epsilon_{\text{Nd}}(\text{T})$
CX-1	1.27	3.15	0.2445	0.513083 ± 0.000011	6.66
CX-2	1.40	2.86	0.2953	0.513194 ± 0.000011	6.66
CX-3	0.870	1.89	0.2777	0.513158 ± 0.000018	6.71
CX-5	0.943	1.80	0.3167	0.513243 ± 0.000016	6.57
CX-6	0.881	1.88	0.2834	0.513171 ± 0.000012	6.72
B-1	1.80	4.97	0.2188	0.513038 ± 0.000013	6.87
S-3	4.88	17.2	0.1720	0.512929 ± 0.000006	6.74
HN-7	2.43	8.81	0.1670	0.512913 ± 0.000009	6.64
JYVR*	2.29	5.85	0.2365	0.513074 ± 0.000011	7.06

$^{143}\text{Nd}/^{144}\text{Nd}$ ratios are further adjusted relative to La Jolla standard = 0.511860; T = Sm–Nd whole-rock isochron age of 333 ± 12 Ma, representing the crystallization age of the metabasites.

*Data after Fang *et al.* (1992).

Fig. 4 SiO_2 versus Zr/TiO_2 diagram (Winchester & Floyd 1976) for classification of the Bangxi–Chenxing metabasites. Bas–Trach–Neph, basanite–trachybasanite–nephelinite; TrAn, trachyandesite; Com/Pan, comendite/pantellerite.

coherent trends of group 1 samples. In the chondrite-normalized REE distribution diagram (Fig. 6), the metabasite samples have a relatively small range of heavy REE (HREE) abundances, but significantly variable light REE (LREE) depletion. Group 1 samples display LREE-depleted patterns, with the Chenxing samples having the lowest LREE abundance and a chondrite-normalized $(\text{La}/\text{Yb})_N$ ratio = 0.13–0.26. In contrast, group 2 samples have higher LREE abundance and nearly flat REE patterns. Such LREE depletion to varying degrees indicates that these metabasites could have been generated by relatively large degrees of partial melting of depleted mantle source, similar to the basaltic rocks in MORB and intra-arc/back-arc basin. Group 2 sample HN-7 has the highest MgO (21.04%) and Ni (719 p.p.m) but medium high Cr

(1091 p.p.m), indicating significant amounts of olivine accumulation. In contrast, the other group 2 sample S-3 has relatively lower MgO (8.63%), Ni (133 p.p.m) and Cr (290 p.p.m).

It is noted that the group 1 samples generally have a high MgO content (10.71–13.78%), which is significantly more magnesian than the vast bulk of the MORB, which rarely have MgO > 10% (Fig. 5). There are significant differences in trends and major element compositions between group 1 samples and MORB (Fig. 5). These major element features suggest that group 1 metabasites were not typical MORB lavas. Group 1 samples show a deviation from the MORB spread in the direction of the clinopyroxene-dominated clinopyroxene–olivine mixture line, indicating that they were likely to be orthocumulate gabbroic rocks. Increase of Cr, V and Sc with increasing MgO also suggests the clinopyroxene-dominated accumulation for group 1 samples (Fig. 5). Such clinopyroxene- and olivine-enriched cumulate gabbros are similar in major elements to the abundant gabbros in arc crust, particularly in intraoceanic arc such as the Mariana arc, but significantly different from the gabbro in mid-ocean ridge oceanic crust (Fig. 5).

Figure 7 shows the primitive mantle-normalized trace element variation patterns for the studied metabasites. Group 1 samples show varying degrees of depletion of Th, Nb, Ta and LREE, with the Chenxing samples having abundances of these elements that are even lower than those of primitive mantle. In contrast, group 2 metabasites have a relatively higher abundance of trace elements and less depletion of these highly incompatible trace elements, resembling those of enriched (E)-type MORB (Sun & McDonough 1989). Sample HN-7 has a relatively lower abundance of most

Fig. 5 Major and trace elements versus MgO variation diagram for the Bangxi–Chenxing metabasites, comparing with the major elements for mid-ocean ridge basalt (MORB) glass and gabbros (with MgO > 10%) in the Pacific MORB-type and in the Mariana arc (arc-type). Data source: (1) MORB glasses are after Miyashiro *et al.* (1969), Hekinian (1971), Shido *et al.* (1974), Hermes & Schilling (1976); Dickey *et al.* (1977), Batiza *et al.* (1988), Humler and Whitechurch (1988), Sinton *et al.* (1993), and Bach *et al.* (1996); (2) MORB-type gabbros are after Engel & Fisher (1969, 1975), Wood *et al.* (1978), Tarney *et al.* (1979), Saunders *et al.* (1982), Hebert *et al.* (1983), and Weaver *et al.* (1985); (3) arc-type gabbros are after Dietrich *et al.* (1978), Meijer and Reagan (1981), Woodhead (1988), and Newman *et al.* (2000).

Fig. 6 Chondrite-normalized rare earth element (REE) diagrams for the Bangxi-Chenxing metabasites. Normalization values after Sun and McDonough (1989).

Fig. 7 Primitive mantle-normalized trace element spidergram for the Bangxi-Chenxing metabasites, comparing with the mid-ocean ridge basalt (MORB)- (shaded) and arc-type (bold line) gabbros. Normalization values after Sun and McDonough (1989). Data sources: (1) MORB-type gabbro are after Saunders *et al.* (1982) and Spadea *et al.* (1991); (2) arc-type gabbro is a representative sample (90AMM3001) from the Aleutian arc after Nye *et al.* (1994).

trace elements possibly due to olivine accumulation. It is noted that all the metabasite samples have trace element patterns significantly different from the arc gabbros (elevated Th and LREE and significant Nb-Ta negative anomaly), with group 1 samples B-1 and H-1 resembling the MORB-type gabbros (Fig. 7).

In summary, the Bangxi-Chenxing metabasites appear to be metamorphosed cumulated gabbroic rocks with major element variations similar to arc gabbros but trace element features resembling N-MORB. They can be subdivided into two groups in terms of major and trace element characteristics, with group 1 metabasites showing more depleted geochemical features than those of group 2.

Fig. 8 Sm-Nd isochron diagram for the Bangxi-Chenxing metabasites. Sm-Nd isochron age and $\epsilon\text{Nd}(T)$ values were calculated using Isoplot/Ex after Ludwig (1998), where 0.5% was chosen as the error of $^{147}\text{Sm}/^{144}\text{Nd}$ ratios. Errors are quoted at the 2σ level. (---) Group 1 samples (7 data): age = 320 ± 24 Ma, $\epsilon\text{Nd}(T) = 6.9 \pm 0.8$, MSWD = 0.30. (—) All samples (9 data): age = 333 ± 12 Ma, $\epsilon\text{Nd}(T) = 6.7 \pm 0.4$, MSWD = 0.48.

SM-ND ISOTOPES

Group 1 metabasites, including one sample (JYRV) from Junying in western Bangxi reported by Fang *et al.* (1992), have high and variable $^{147}\text{Sm}/^{144}\text{Nd}$ ratios (0.2188–0.3199), which are higher than the chondritic value of 0.1967. In contrast, group 2 samples have relatively low and uniform $^{147}\text{Sm}/^{144}\text{Nd}$ ratios (0.1670–0.1720). In the conventional Sm-Nd isochron diagram (Fig. 8), seven group 1 samples yield a Sm-Nd isochron age of 320 ± 24 Ma and an initial $\epsilon\text{Nd}(T)$ value of $+6.9 \pm 0.8$. Two group 2 samples, which cannot be regressed for an isochron owing to limited $^{147}\text{Sm}/^{144}\text{Nd}$ variation, plot along the lower extension of the isochron of group 1 samples. All nine samples yield a Sm-Nd isochron age of 333 ± 12 Ma and an $\epsilon\text{Nd}(T)$ value of $+6.7 \pm 0.4$, which are indistinguishable within error from those of the seven-point isochron of group 1 samples. It should be noted that the Sm-Nd isotopic system can behave as an open system during metamorphism (Vervoort *et al.* 1996), although REE are generally immobile in most crustal processes. In order to properly interpret the geologic meaning of the aforementioned Sm-Nd isochron age, it is necessary to verify if the Sm-Nd system of the metabasites has been modified during subsequent greenschist to amphibolite metamorphism.

As mentioned earlier, group 1 samples have very low LREE contents and display LREE-depleted patterns, resembling those of N-MORB.

If the Sm–Nd system of these samples has been modified through interaction with the crustal fluids during metamorphism, a small amount of crustal contamination (with a typical average crustal value of 25 p.p.m. Nd) would significantly increase their LREE contents and consequently change their REE patterns and Nd isotopic compositions. However, such elevated LREE patterns were not seen in these samples. In addition, MORB and oceanic island tholeiite (OIT) commonly have Nb/Th of 14–20 (Sun & McDonough 1989), whereas the crustal rocks have much lower Nb/Th values, with the average crust having an Nb/Th of approximately 3 (Taylor & McLennan 1985). The Hainan metabasites have Nb/Th values of 11–24, with most samples being between 13 and 19, comparable with those of MORB and OIT. The slightly wider range of Nb/Th is possibly due to analytical uncertainties associated with the very low Nb and Th contents.

The immobility of REE for the metabasites indicates that the Sm–Nd whole-rock isochron age of 333 ± 12 Ma can be interpreted as the crystallization age, rather than the metamorphic age, of these samples. High $\epsilon_{\text{Nd}}(\text{T})$ values of approximately +7 indicate that these metabasites were derived from a highly depleted mantle source without continental crust contamination. The MORB-type mantle is estimated to have had an $\epsilon_{\text{Nd}}(\text{T})$ value of $+9 \pm 2$ at $T = 330$ Ma, assuming its present average $\epsilon_{\text{Nd}}(0)$ value of $+10 \pm 2$ evolved linearly from a chondritic source since the Early Archean (4.0 Ga). Thus, the initial $\epsilon_{\text{Nd}}(\text{T})$ value of approximately +7 for the Bangxi–Chenxing metabasites is marginally within the range of the expected value for Carboniferous MORB. Although the two groups of Bangxi–Chenxing metabasites have different trace element features, they were probably generated contemporaneously from MORB-like mantle sources with similar Nd isotopic compositions, or possibly from the same MORB-like mantle source.

DISCUSSION

PETROGENESIS

The aforementioned geochemical and Nd isotopic data indicate that all metabasite samples analyzed in the present study show MORB affinity, most likely originating from MORB-like mantle sources. Such MORB-like mafic rocks are commonly formed in the oceanic settings, for example

along mid-ocean ridges and in mature intra-arc or back-arc basins, rather than in continental or island arc regimes. But given the unique high positive $\epsilon_{\text{Nd}}(\text{T})$ value of approximately +7, these metabasites, however, display apparent differences in their major and trace elements, with group 1 and group 2 samples having trace element features similar to N-type and E-type MORB, respectively. Geochemical variations of these metabasites point to a role of (i) source heterogeneity; (ii) variable degrees of partial melting; and (iii) fractional crystallization in their petrogenesis and genetic relations.

Sun *et al.* (1979) demonstrated that $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 in relatively primitive MORB vary with the degree of partial melting and the nature of the source region. In the $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 versus TiO_2 diagrams (Fig. 9), all samples

Fig. 9 $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 versus TiO_2 diagrams for the Bangxi–Chenxing metabasites. The shaded area indicates mid-ocean ridge basalt (MORB) field confined by the MORB glasses (Data sources are the same as in Fig. 5).

have a curved negative correlation. Two group 1 samples (B-1 and H-1) plot within the MORB field with relatively primitive compositions of major and trace elements. They were likely generated by relatively large (approx. 20%) degrees of partial melting from a depleted source (Jaques & Green 1980). Most Chenxing samples have high $\text{Al}_2\text{O}_3/\text{TiO}_2$ (>25) and CaO/TiO_2 (>20) exceeding values of the MORB field, probably due to larger degrees of partial melting from a relatively more depleted mantle source (Sun *et al.* 1979). Sample S-3 has high abundances of Al_2O_3 , TiO_2 , P_2O_5 and most incompatible trace elements, and the lowest $\text{Al}_2\text{O}_3/\text{TiO}_2$ and CaO/TiO_2 ratios, indicating derivation from smaller degrees of partial melting accompanied by some subsequent crystal fractionation of pyroxene and/or olivine. Sample HN-7 probably contains accumulated olivine from an incompatible element-enriched magma, probably similar to the parent magma of sample S-3, because of its relatively high contents of TiO_2 , P_2O_5 and most incompatible trace elements.

In the La/Sm versus La diagram (Fig. 10), which has proven useful in distinguishing the effects of partial melting from fractional crystallization (Allègre & Minster 1978), all but one of the samples (S-3) follow a partial melting trend. With decreasing chondrite normalized $(\text{La}/\text{Sm})_n$ ratios from >1 for samples HN-7 and S-3, through 0.6–0.8 for samples B-1 and H-1 down to 0.24–0.43 for the Chenxing samples, parent magmas of these metabasites were likely generated by a

dynamic melting process similar to that described in Langmuir *et al.* (1977).

TECTONIC IMPLICATIONS

Remnants of fragmented oceanic crust in Hainan

Our geochemical and Sm–Nd isotopic data demonstrate that the Bangxi–Chenxing metabasites with MORB affinity were formed in an oceanic environment. They were cumulated gabbroic rocks that might have been crystallized from MORB-like magmas in an intraoceanic arc basin. Thus, these metabasites are most likely remnants of fragmented oceanic crust. These oceanic crust fragments, possibly as part of a mafic member of an unidentified ophiolite suite, were obducted onto the continental crust during closure of the ocean basin, which has significant implications for the tectonic evolution of Hainan Island and surrounding areas.

Identification of the Bangxi–Chenxing metabasites with MORB affinity indicates that Hainan Island was separated by an oceanic basin in late Paleozoic time; that is, the southern and northern Hainan blocks (Hsü *et al.* 1990; Chen *et al.* 1992). The Bangxi–Chenxing metabasites crop out within the 'Shilu mélange', which Hsü *et al.* (1990) and Chen *et al.* (1992) proposed as representing a Mesozoic orogenic belt formed by collision of the Indochina and South China blocks (Fig. 2B). The presence of metabasites with MORB affinity lends support to this tectonic model. The Sm–Nd isochron age of 333 ± 12 Ma for these metabasites has placed a maximum age limit on the timing of the collision between the southern and northern Hainan blocks.

In contrast, it is worthwhile to note that the Bangxi–Chenxing metabasites are coeval with the Carboniferous tholeiites along the southern side of the Changjiang–Qionghai Fault; the latter, associated with rhyolites and having intraplate geochemical characteristics, LREE enrichment and $\epsilon\text{Nd}(\text{T})$ values of +6.9 to +7.7, have been interpreted as a rift-related bimodal volcanic suite (Fang *et al.* 1992). Thus, it is possible that the MORB-like metabasites and the intraplate tholeiites could be generated by the same magmatic event during the middle Carboniferous (i.e. the central Hainan started as a rift and then developed into an ocean). Such a tectono-magmatic scenario seems analogous to the volcanic rifted passive margin off northwestern Australia (Colwell *et al.* 1994; Crawford & von Rad 1994).

Fig. 10 Chondrite-normalized La/Sm versus La diagram for the Bangxi–Chenxing metabasites.

The Chenxing metabasites are similar to the strongly depleted basalts drilled at Ocean Drilling Program (ODP) Sites 765 and 766, both having more extreme compositional characteristics (lower $(\text{La}/\text{Sm})_{\text{N}}$ and Ti/Zr values (averaging 110) than the typical N-MORB. In this volcanic rifted passive margin regime, the intraplate tholeiites were generated at the earlier rift stage, while the Bangxi–Chenxing MORB-like metabasites formed at the later sea-floor spreading stage as part of the MORB-like seaward-dipping reflector break-up packages (Crawford & von Rad 1994). The juxtaposition of the MORB-like metabasites with the intraplate tholeiites in central Hainan might be caused by incorporation of both into a fold belt during later arc–continent or continent–continent collision.

Comparison with the eastern Paleo-Tethys ophiolites

It is widely accepted that the Song Ma ophiolite in northern Vietnam and the Shuanggou ophiolites in western Yunnan are correlative and together represent the main plate boundary between the Indochina and South China blocks (Zhang *et al.* 1994; Chung *et al.* 1999; Lan *et al.* 2000). The age of ophiolites exposed in the suture zones and the collision time of the two blocks have not yet been well-constrained. Recently, Lepvrier *et al.* (1997) showed through ^{40}Ar – ^{39}Ar dating that all members of the Song Ma Ophiolite share the same metamorphic age of *ca* 245 Ma, implying suturing between Indochina and South China in the earliest Triassic. Jian *et al.* (1998) reported U–Pb zircon dates of 362 ± 41 Ma for gabbro and 328 ± 16 Ma for plagiogranite from the Shuanggou Ophiolite, which may indicate the formation ages of the ophiolite. Moreover, Jian *et al.* (1999) also obtained U–Pb zircon ages of 340 ± 3 Ma for anorthosite from the Jinsha Ophiolite, and interpreted that the Jinsha Ophiolite can be correlated with the Shuanggou Ophiolite. The Jinsha Ophiolite is thus regarded as the northwestern extension of the Shuanggou Ophiolite (Jian *et al.* 1999). These data indicate the presence of an oceanic plate (i.e. the eastern Paleo-Tethys) between Indochina and South China during the Carboniferous. Before the suturing of the two blocks that occurred in the earliest Triassic (Lepvrier *et al.* 1997), the Paleo-Tethyan plate may have subducted beneath the Indochina block, which resulted in a magmatic arc along the Indochina margin (Chung *et al.* 1999; Lan *et al.* 2000). It is interesting to note that the Bangxi–Chenxing MORB-like metabasites in

central Hainan are broadly synchronous with the ophiolites in the Jinsha–Shuanggou–Song Ma sutures (Hutchison 1989; Zhang *et al.* 1994; Lepvrier *et al.* 1997; Jian *et al.* 1998, 1999), and the proposed Shilu mélange (Hsü *et al.* 1990; Chen *et al.* 1992) seems coeval with the early phase of the Indosinian orogeny. Furthermore, basaltic rocks from the Shuanggou and Song Ma ophiolites also have MORB-type geochemical affinities (Zhang *et al.* 1994; Chung *et al.* 1999). Such similarities in age may imply a common petrogenetic process and tectonic background. Therefore, the Bangxi–Chenxing MORB-like metabasites in central Hainan Island may represent the remnant oceanic crust of the easternmost part of Paleo-Tethys. Consequently, Hainan Island is most likely composed of two blocks, similar to the interpretation of Hsü *et al.* (1990) and Chen *et al.* (1992). The southern and northern Hainan blocks are correlated with the Indochina and South China blocks, respectively. In this interpretation, Hainan Island is thus neither an independent terrane (Metcalf 1996), nor the southwestern end of Cathaysia (Shui 1987; Guangdong 1988; Zhang *et al.* 1990). It should be pointed out, however, that a complete ophiolitic suite (including ultramafic mantle peridotite and deep-sea sediments and cherts) has not yet been identified in central Hainan. Such a tectonic model can be further tested by the following work: (i) detailed field investigations to identify whether a late Paleozoic ophiolitic suite exists in the Shilu mélange; (ii) a more comprehensive comparison of the geology of the northern and southern Hainan blocks with that of the Huanan and Indochina blocks in nearby regions; and (iii) geochronological and geochemical study of late Paleozoic to Mesozoic intrusives and extrusives on Hainan (Guangdong 1988).

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