Geochemical, Sr and Nd isotopic characteristics and tectonic implications for three stages of igneous rock in the Late Yanshanian (Cretaceous) orogeny, SE China

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ABSTRACT: Late Yanshanian magmatism in SE China includes three stages of thermal event induced by the interaction between the continental margin of Eurasia and the paleo-Pacific plate during the Cretaceous period. Products of syn-orogenic magmatism (130–110 Ma) include high-Al gabbros (HAG), and gneissic tonalite, trondhjemite and granodiorite (TTG), which intruded into the deep basement (18–24 km). Rocks of the post- and an-orogenic magmatism are shallow-level (6–8 km) I-type granitoids (110–99 Ma), and miarolitic A-type granites plus rhyolite-dominated bimodal volcanics (94–81 Ma), respectively. Geochemically, HAG and TTG belong to the medium-K calc-alkaline affinity with high Sr/Y, whereas other granitoids are mainly high-K calc-alkaline to shoshonitic rocks with low Sr/Y. Sr and Nd isotope compositions suggest different sources of HAG and TTG from other rocks. Progressive depletions of Ba, Sr, Eu and P from I- to A-type granites reflect partial melting of felsic granulites from hydrous to dry conditions, whereas high Sr/Y in HAG and TTG are compatible with dehydration melting of amphibolites. Tectonic models which accommodate HAG and TTG may involve thickening of the lithosphere to convert the pre-existing lower-crust basic rocks into amphibolites. It was followed by basaltic underplating which is attributed to delamination of the thickened lithosphere and led to triggering of crust melting under extension.

KEY WORDS: Amphibolite, basaltic underplating, dehydration melting, HAG and TTG.

Granitoids in S China are distributed across a vast area (~250,000 km²), and thus, play an important role in our understanding of the late Mesozoic geohistory of crustal accretion in the Cathaysia Block – one of the major granitic provinces in the world. It is generally believed that the Yanshanian orogeny outlined the present-day geological configuration that has developed since the Jurassic (Li 2000), by which the Early Yanshanian (EY, late Jurassic) dominated the Cathaysia interior, whereas the Late Yanshanian (LY, early Cretaceous) dominated the southeast coastal area.

Influenced by subduction of the paleo-Pacific plate, LY magmatism has been attributed to the change of plate convergence rate (Northrup *et al.* 1995). Basically, products of the LY magmatism are more restricted in a NE–SW trending zone – the Southeast Coast Magmatic Belt (SCMB) – that is separated from the Cathaysia interior to the west and the Changle-Nanao Metamorphic Belt (CNMB) to the east by two deep faults (Fig. 1). Previous investigations have revealed that rock assemblages are mainly shallow-level, calc-alkaline, I-type granitoids ranging from granodiorite to alkali feldspar granite, and succeeding A-type granites and basalt-rhyolite bimodal volcanics (Chen *et al.* 2000). The CNMB, although intruded by undeformed granitoids as well, is a shear zone characterised by ductile deformation and greenschist to amphibolite facies metamorphism, leading to the development of strong schistosity and gneissosity in the pre-existing and simultaneous igneous rocks (Tong & Tobisch 1996). For the presence of such tectonic uplift towards the subduction zone, the CNMB has been proposed to represent the metamorphic core complex of the SCMB, or the LY syn-orogenic products (Chen *et al.* 2000). With a number of ⁴⁰Ar/³⁹Ar mineral ages reported for

these metamorphic rocks (Yang *et al.* 1997; Wang & Lu 2000), the regional exhumation rates of this metamorphic core complex, as calculated from cooling rates, were estimated to vary from 1.3 to 0.8 Km/Myr in different terranes during 130–110 Ma (Chen *et al.* 2002).

In the CNMB, mafic intrusive rocks are distributed sporadically from Matsu southward to Dongshan, including Lienhuashan, Daiqianshan, Qinglanshan, Taohuashan and Dongyue (Fig. 1). The associated rocks of these mafic intrusives are mostly granitic gneiss (e.g. tonalite, trondhjemite and granodiorite) and migmatite. Their contact relationships are rather complicated. The outcrop at Qinglanshan is reflected by a mylonitic ductile shear zone, indicating a tectonic contact. Mafic rocks in Daiqianshan show an obvious cumulate layering structure, characterised by a chilled gabbro base that grades into medium grained gabbro, or diorite. Those in Lienhuashan occur mainly as stocks and dykes, or as enclaves within the granodiorite host (Wang 2002). In the SCMB, gabbros (e.g. Kuanshan and Shanfang) are precursors of the large I-type granitic complexes (Pitcher 1997).

Although the structure features and dynamics of this ductile shear zone have been extensively studied (Tong & Tobisch 1996; Wang & Lu 1997, 2000), the association of mafic and gneissic rocks has seldom been discussed on the basis of magmatic processes contemporaneous with the ductile deformation and mylonisation. Here, in addition to two ⁴⁰Ar/³⁹Ar hornblende ages of mafic rocks to supplement previous dating works in the CNMB, the present authors describe new major and trace element contents, and Sr and Nd isotope ratios for both the mafic and associated gneissic rocks. These geochemical and isotopic characteristics can reveal the genesis of

Figure 1 Localities of gabbros (shaded rectangles) and gneissic rocks (numbered circles), and distribution of igneous complex (open rectangles) and volcanic rocks in the Southeast Coast Magmatic Belt (SCMB) and the Changle-Nanuo Metamorphic Belt (CNMB), which are two tectonic units in the Cathaysia block (inset). Other localities in boxes represent A-type granites.

such deep-seated rocks in a collisional tectonic setting, which can further be used to differentiate the post-orogenic, I-type granitoids and an-orogenic, A-type granites (Chen *et al.* 2000), as well as the pre-existing late Jurassic granitoids in S China (Chen & Jahn 1998). On this basis, the tectonic evolution in the SE China continental margin may be deciphered.

1. Analytical methods

Mineral compositions were analysed with electron probe X-ray microanalysers including a JEOL JXA-8900R (Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan) and a Shimadzu-ARL EMX-SM7 (Department of Geosciences, National Taiwan University, Taipei, Taiwan). Data reductions for the atomic number effect, absorption and fluorescence were calculated with the ZAF correction computer program (Chen & Tung 1984). Amphibole analysis is particularly useful for $^{40}\text{Ar}/^{39}\text{Ar}$ age dating and the application of the Al in the hornblende geobarometer (Table 1).

Fresh amphiboles were dated using the step-heating $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum technique described by Lo & Lee (1994).

Here, the present authors only describe $^{40}\text{Ar}/^{39}\text{Ar}$ age plateau, and Cl/K and Ca/K spectra for two mafic rocks which had not been firmly dated before (i.e. Daiqianshan and Shanfang). Because the inverse slope correlation ages are similar to the plateau ages, they are not shown. Those of the gneissic rocks are based on previous works (Yang *et al.* 1997; Chen *et al.* 2002).

In the present study, 56 mafic and gneissic rocks were measured for their major and trace element abundances, and 16 samples among them were measured for Sr and Nd isotope compositions using the same methods as described in Chen *et al.* (2000). The analytical uncertainties are generally better than 5% for all elements. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were corrected for mass fractionation by normalising to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$, respectively. The standards used were SRM987 for Sr ($^{87}\text{Sr}/^{86}\text{Sr}=0.710226$), with a long-term reproducibility of 0.000038 (95% confidence level), and the La Jolla (UCSD) standard for Nd ($^{143}\text{Nd}/^{144}\text{Nd}=0.511845$), with a long-term reproducibility of 0.000020. Whole-rock chemical analyses, and Sr and Nd isotope ratios for representative samples are presented in Table 2.

Table 1 Representative amphibole compositions of various rock types in SE China: (1) Xiaojiang; (2) Liangnong; (3) Fuzhou; (4) Zhangzhou; (5) Putien; (6) Huian; (7 & 8) Pingtan; (9) Gaoshan; (10) Ginjiang. (Mgr) monzogranite; (Gdr) granodiorite; (Mig) migmatite; (Gab) gabbro; (Gn) gneiss; (tFeO) total Fe as FeO; and (n.d.) not determined.

Lithology	1 (Mgr)	2 (Mgr)	3 (Gdr)	4 (Mgr)	5 (Mig)	6 (Mig)	7 (Gab)	8 (Gn)	9 (Gn)	10 (Gn)
<i>wt. %</i>										
SiO _{2reset}	50.06	52.27	46.66	50.23	45.42	45.75	43.71	42.75	41.90	43.91
TiO ₂	1.06	0.57	1.04	0.55	1.64	1.52	1.01	0.87	0.87	0.84
Al ₂ O ₃	4.38	3.54	6.08	5.65	7.57	7.54	12.01	10.82	10.83	11.68
tFeO	12.92	10.87	14.19	12.71	16.93	16.97	11.56	19.92	20.73	19.20
MnO	0.64	0.53	0.93	1.44	0.81	0.81	0.28	0.62	0.75	0.35
MgO	15.73	16.92	14.09	14.87	11.65	11.82	14.45	8.82	8.35	7.78
CaO	11.11	12.34	12.12	11.82	11.65	11.60	11.67	11.35	11.78	11.86
Na ₂ O	1.32	0.75	1.34	1.30	1.49	1.46	1.75	1.35	1.28	1.25
K ₂ O	0.48	0.30	0.67	0.45	0.88	0.88	0.62	1.41	1.38	1.40
Cr ₂ O ₃	0.28	0.24	0.04	0.03	n.d.	n.d.	0.07	n.d.	n.d.	n.d.
Total	97.98	98.33	97.48	99.04	98.04	98.35	97.13	97.91	97.87	98.27
<i>Molecular proportion based on 23 oxygen</i>										
Si	7.280	7.475	6.951	7.241	6.807	6.832	6.429	6.506	6.454	6.537
Al	0.752	0.597	1.069	0.962	1.338	1.328	2.082	1.941	1.959	2.149
Na	0.371	0.209	0.492	0.358	0.432	0.422	0.499	0.397	0.376	0.371
K	0.089	0.055	0.128	0.082	0.167	0.168	0.117	0.293	0.275	0.279
P* (Kb)	0.6	<0.6	2.1	1.6	3.4	3.3		6.2	6.3	7.2

*P (± 0.6 Kb) = $-3.01 + 4.76$ Al (Schmidt 1992).

2. Results

2.1. Mineral composition and geobarometric data

Mafic rocks generally consist of the plagioclase, amphibole, pyroxene and spinel groups of minerals, with minor amounts of olivine, biotite and quartz in a few samples. Highly calcic plagioclases are present in the cumulated rocks; for example, some Lienhuashan (An₉₇₋₈₅), Daiqianshan (An₉₃₋₈₆) and Taohuashan (An₈₈₋₇₄) samples. On the other hand, less calcic plagioclases are found in other Lienhuashan (An₄₈₋₃₄) gabbros, indicating a large degree of crystal fractionation. The precursory gabbros of Kuanshan (An₉₃₋₈₃) show cumulate textures, but those of Shanfang (An₈₂₋₆₇) are less obvious.

Olivine is only found in the mafic rocks of Kuanshan (Fo₇₉₋₇₇) and Lienhuashan (Fo₆₈). Both orthopyroxene and clinopyroxene are present in the mafic rocks, except those from Dongyue, where only clinopyroxene is found. Orthopyroxenes are mainly enstatite (En₈₁₋₈₀ in Kuanshan and En₇₂₋₆₅ in other areas), while clinopyroxenes are mainly diopside (Wo₄₂En₄₃Fs₁₅–Wo₄₈En₄₀Fs₁₂) and minor augite (Wo₃₀En₅₃Fs₁₇ in Kuanshan). The amphiboles are the calcic varieties; those with high Al_{IV} content (1.4–1.9) have (Na+K)_A ≥ 0.5 , while others with low Al_{IV} content (0.8–1.3) have (Na+K)_A < 0.5 , corresponding to pargasitic and edenitic hornblendes, respectively (Fig. 2a). Brown micas are found in a few mafic rocks in Lienhuashan, Taohuashan and Shanfang, ranging from phlogopite [Fe⁺²/(Mg+Fe⁺²), or Fe' = 17.4] in Lienhuashan to biotite (Fe' = 31.8 to 38.7) in other two areas. Magnetites contain some amounts of Cr₂O₃ (2.8–13.6 wt.%) and Al₂O₃ (2.8–4.3 wt.%) which replace ferric iron. Following the method of Powell & Powell (1977), coexisting magnetite and exsolved ilmenite in Shanfang gabbro give rise to equilibration temperatures of 465–430°C, which is indicative of subsolidus oxidation.

Gneissic rocks are generally grey in colour and consist mainly of quartz, sphene, K-feldspar, plagioclase, biotite and hornblende. In a few localities (e.g. Chinmen), K-feldspars are pinkish and associated with white micas. Quartz may be

myrmekitically included in plagioclase and/or graphically intergrown with K-feldspar. Plagioclase and K-feldspar compositions vary with rock types: An₃₆₋₃₃ and Or₉₁₋₉₀ for tonalite, An₂₀ and Or₉₂₋₈₉ for trondhjemite, and An₄₀₋₂₈ and Or₉₆₋₉₀ for granodiorite (Lan *et al.* 1997). Biotites are separated into two groups: Fe' = 51–57 in tonalite and trondhjemite, and Fe' = 69–76 in granodiorite. Calcic amphiboles are commonly present in the gneissic rocks and construct a similar trend with the mafic rocks, which is clearly distinguished from the other obtained from the granulites of the major igneous complexes in the SCMB (Fig. 2a).

The alumina contents of amphibole in the granitic rocks can be used as pressure indicators, but are restricted to those in presence of quartz, plagioclase, K-feldspar, biotite, sphene and Fe-Ti oxides (Hammerstrom & Zen 1986). Using the geobarometer of Schmidt (1992), a few examples show that the pressure condition differs in rock types and in tectonic units (Fig. 2b). The CNMB hornblendes are characterised by higher total Al contents, by which the host granitic gneisses are estimated to have formed under a pressure of 6.2–7.2 kb in Pingtan, Gaoshan and Ginjiang, while migmatites were formed at a lower pressure of ~ 3.3 kb in Huian and Putien. On the other hand, those estimated for the plutons of major igneous complexes in the SCMB are much lower (Table 1).

2.2. Time of mafic emplacement and metamorphism

To constrain the time of thermal event, available U-Pb zircon and ⁴⁰Ar/³⁹Ar hornblende and biotite ages are adopted (Table 3). Because the closing temperatures of hornblende and biotite have been suggested to be 550 $\pm$ 20°C and 300 $\pm$ 30°C (Rollinson 1993), the similarity of these two mineral ages in one intrusive body would indicate a rapid cooling, and thus, can be used to represent the time close to the event. However, mafic rocks are based on the hornblende age alone for the lack of biotite in the dated samples. The ⁴⁰Ar/³⁹Ar age spectra of amphiboles separated from mafic rocks of Daiqianshan (125.1 $\pm$ 2.3 Ma) and Shanfang (105.2 $\pm$ 1.9 Ma) are shown in Figure 3. Such results are in accord with those available for

Table 2 Chemical compositions of representative gabbros and gneissic rocks in SE China (sample numbers in brackets): (1) Daiqianshan; (2 & 7) Pingtan; (3) Taohuashan; (4) Shanfang; (5, 9 & 10) Chinmen; (6) Dongshan; (8) Huian. (Gab) gabbro; (Tonal) tonalite; (Trond) trondhjemite; (Gdr) granodiorite; (c) cumulate; (n) gneiss; and (tFe₂O₃) total Fe as Fe₂O₃

Lithology	1 (FJ920826) [Gab (c)]	2 (FJ9405) [Gab]	3 (FJ9416) [Gab (c)]	4 (TSFO1) [Gab]	5 (20HSHO3) [Gab (n)]	6 (FJ9337) [Gab (n)]	7 (FJ9501) [Tonal (n)]	8 (FJ9413) [Tonal (n)]	9 (KMB-2) [Tonal (n)]	10 (SKM7-1) [Gdr (n)]
<i>wt. %</i>										
SiO ₂	37.41	51.67	41.88	47.29	53.74	49.20	60.73	66.48	70.98	70.60
TiO ₂	2.19	1.15	1.47	0.78	1.22	1.09	0.73	0.52	0.33	0.29
Al ₂ O ₃	17.95	18.82	16.38	19.28	19.77	16.71	18.73	16.09	14.74	15.35
tFe ₂ O ₃	16.50	10.26	17.65	10.61	9.30	10.53	6.30	4.36	3.49	2.79
MnO	0.13	0.18	0.17	0.18	0.09	0.45	0.10	0.10	0.07	0.09
MgO	7.30	3.79	7.39	7.42	2.58	7.10	1.29	1.10	0.56	0.54
CaO	13.94	8.85	12.14	11.22	7.04	8.54	4.67	3.85	2.46	2.39
Na ₂ O	1.34	2.82	0.77	1.96	4.26	3.44	3.72	3.56	4.03	3.60
K ₂ O	0.21	0.71	0.29	0.22	1.70	1.81	1.48	2.36	2.00	3.58
P ₂ O ₅	1.09	0.36	0.05	0.22	0.32	0.35	0.26	0.14	0.10	0.08
LOI	0.68	0.65	0.32			0.39	1.35	0.39	1.35	0.72
Total	98.73	99.26	98.52	99.18	100.02	99.59	99.36	98.95	100.60	100.03
<i>ppm</i>										
Sc	58	26.5	42.5			36	11	12.5		6
V	407	177	745	246	210	214	19	53		10
Cr	0.7	4.1	8.0	173	4.5	190	5	3	28	18
Co	37.9	20.9	60.9	38.0	13.6	31.7	8.1	7.4	3.31	1
Ni	3.4	5.4	10.4	70		62.3	2.7	4.8	12.8	6
Ga	21	20	21	22	24	19	22.5	17	17	15
Rb	2	19	13	6	160	99	63	61	139	104
Sr	829	677	630	797	728	410	419	425	281	369
Y	20.2	15.4	9.7	11.3	25.9	29.0	17.3	21.9	21.6	24
Zr	114	114	57	12	171	219	366	181	211	160
Nb	1.5	4.1	1.5	0.5	7.8	8.3	6.3	7.5	11.6	9.2
Cs	0.1	0.9	1.2	1.2	4.7	2.5	1.3	1.2	2.5	
Ba	74	297	73	91	238	156	621	1081	874	967
La	4.16	12.01	5.94	7.58	24.78	27.32	32.59	21.94	49.6	42.7
Ce	12.79	26.14	12.55	14.80	53.00	54.84	66.50	45.48	89.5	76.1
Pr	2.47	3.66	1.76	1.89	7.17	7.50	7.77	5.50	8.86	
Nd	14.25	15.78	7.63	8.91	27.93	30.48	27.81	19.92	31.20	33.95
Sm	4.18	3.25	1.76	2.15	5.85	6.08	5.02	3.78	5.23	5.76
Eu	1.45	1.16	0.59	0.99	1.53	1.83	1.20	1.06	1.07	0.98
Gd	4.65	3.01	1.73	2.23	5.45	5.33	4.06	3.90	4.72	
Tb	0.72	0.47	0.29	0.35	0.81	0.86	0.63	0.64	0.63	1.15
Dy	4.03	2.63	1.67	1.90	4.78	4.79	3.34	3.70	3.38	
Ho	0.76	0.53	0.34	0.37	0.94	0.94	0.64	0.77	0.66	
Er	1.85	1.41	0.92	1.02	2.67	2.63	1.76	2.16	1.86	
Tm	0.25	0.21	0.14	0.14	0.38	0.42	0.26	0.33	0.28	
Yb	1.41	1.32	0.91	0.90	2.53	2.67	1.69	2.27	1.81	2.87
Lu	0.21	0.22	0.15	0.14	0.38	0.44	0.27	0.36	0.29	0.47
Hf	3.02	2.71	1.40	0.44	4.63	5.14	8.92	5.07	5.01	5.37
Ta	0.08	0.25	0.15	0.03	0.52	0.48	0.75	0.55	0.44	0.95
Th	0.18	1.60	2.01	0.77	5.92	2.24	11.7	5.9	17.3	15.2
U	0.04	0.27	0.58	0.26	1.53	1.61	1.41	1.29	2.34	3.7
I _{Sr} *	0.7059	0.7056	0.7056	0.7057	0.7061	0.7056			0.7065	0.7051
εNd _(T) *	-3.1	-2.4	-4.4	-3.1	-3.0	-2.3			-2.4	-2.9

*In deriving I_{Sr} and εNd_(T), the age of 105 Ma is adopted for the gneissic rocks which have no dating data.

gabbroic rocks in the CNMB (Table 3), and support the present authors' previous proposition that basic magmas were generally emplaced between 130 and 110 Ma (Chen *et al.* 2000). It is also noted that the U-Pb zircon age of gabbro (115.2 ± 1.2 Ma) in Pingtan is similar to the ⁴⁰Ar/³⁹Ar hornblende (114.8 ± 1.3 Ma) and biotite (115.0 ± 1.4 Ma) ages of the associated gneiss (Table 3), which is indicative of

nearly simultaneous syn-orogenic magmatic activities and metamorphism.

A number of paired ⁴⁰Ar/³⁹Ar hornblende and biotite ages for some gneissic rocks and migmatites in the CNMB show insignificant or only slight differences (Table 3). Accordingly, gneissic rocks of Pingtan and Gaoshan were postulated to have formed at 115 and 110 Ma, respectively. Combined with two

Figure 2 (a) Amphibole distribution trends for gabbroic and gneissic rocks in the Changle-Nanao Metamorphic Belt (CNMB), and I-type granitoids in the Southeast Coast Magmatic Belt (SCMB). (b) The pressure of rock suites estimated from the Al-in-amphibole geobarometer (Table 1). The bars denote the range of hornblende compositions in the sample.

U/Pb zircon age data on gneissic granodiorites near Huian (~130 Ma; Li *et al.* 2003) and one datum from Dongshan (121 Ma; Tong & Tobisch 1996), it can be concluded that gneissic rocks were formed at the same time as the mafic intrusions. The $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende age of migmatites in Putien (108.6 ± 2.7 Ma; Chen *et al.* 2002) is similar to that of mylonites in Huian (109.2 ± 2.2 Ma; Wang & Lu 2000). Other migmatites show younger $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende and biotite ages of ~102 Ma (Huian) and ~92 Ma (Longhai). Therefore, migmatitisation and mylonitisation could be related to the contact aureoles of shallower intrusions (Fig. 2b) in later stages (e.g. Lin *et al.* 1997).

2.3. Major and trace elements, and Sr and Nd isotopes

There is a wide range of silica contents for mafic rocks ($\text{SiO}_2 = 37.4\text{--}53.7$ wt.%) and associated gneisses ($\text{SiO}_2 = 60.7\text{--}71.0$ wt.%). In contrast with other late Mesozoic igneous rocks in this area, they generally belong to the medium-K calc-alkaline affinity (Fig. 4). A few other felsic gneisses which fall within the high-K affinity may represent pre-existing granitoids affected by thermal metamorphism (see below). The high alumina and low magnesium contents of the mafic rocks ($\text{Al}_2\text{O}_3 = 15\text{--}26$ wt.% and $\text{MgO} = 6\text{--}8$ wt.%) reveal them to be the more differentiated high-Al gabbros (HAGs) and cumulates. The CIPW normative compositions were calculated in order to reveal the relationship between HAGs and associated gneisses in the An-Ab-Or diagram (Fig. 5), and hence, these

gneisses belong to the assembly of peraluminous tonalite-trondhjemite-granodiorite (TTG) that can be extended from the high-Al basalts of Wolf & Wyllie (1994).

The chondrite-normalised, multi-element distribution patterns for the TTG display different patterns from the granitoids which appeared during other stages of the LY orogeny, and even the EY orogeny (Fig. 6). A systematic decrease in Ta and Nb depletion, and an increase in Ba, Sr, P, Eu and Ti depletion from the syn- to an-orogenic stages (Fig. 6b–d) is a sign of less involvement by subduction-related calc-alkaline magmatism, or in other words, more involvement by the crustal component. The pre-orogenic rocks with moderate depletion in Ba, Nb, Sr, P and Ti (Fig. 6a) are comparable with the LY post-orogenic rocks. Similarly, the decrease in Sr/Y ratios with time is also significant in differentiating the rock associations in the temporal distribution of the LY orogeny, with the pre-orogenic rocks mostly corresponding to those which appeared during the post-orogenic stage (Fig. 7).

The age-corrected Sr and Nd isotopic ratios for gabbroic rocks and associated gneissic rocks are presented in Figure 8. The $\epsilon\text{Nd}_{(T)}$ falls in the -1.3 to -4.4 range, the I_{Sr} constant is 0.706 for gabbros, and the associated gneissic rocks share similar values [$\epsilon\text{Nd}_{(T)} = -2.3$ to -4.9 ; $I_{\text{Sr}} = 0.705\text{--}0.707$]. As a whole, they are distributed in a small field, overlapping with mafic dykes which are more depleted than the younger shallow intrusives and volcanics in the SCMB, as well as the late Jurassic felsic granites in the Cathaysia interior (Fig. 8). Therefore, the Sr and Nd isotope data imply that gabbro and gneissic rocks are most probably derived from a common source distinguished from the products of both the earlier and later thermal events.

3. Discussion

3.1. Magma differentiation between gabbroic and gneissic rocks

Based on the chondrite-normalised rare-earth element (REE) patterns (Fig. 9a), mafic rocks can be grouped into two types, the gabbro and the cumulate. The latter is particularly characterised with an Eu(+) anomaly including the precursory gabbro of Kuanshan (KUS01). With various degrees of crystal fractionation, some gabbros become more fractionated and so possess higher total REE abundances. Despite the great majority of mafic rocks displaying light REE (LREE)-enriched patterns, the Daiqianshan samples (e.g. FJ920826) are depleted in LREE. Their whole-rock compositions are high in Ti and P, but low in Si, Ni and Cr content (Table 2), reflecting the highly fractionated type of cumulates with a minor role for feldspar. As for gneissic rocks, they show similar REE patterns to the gabbroic rocks (Fig. 9b). Crystal fractionation must involve significant amounts of feldspar to account for samples which present Eu(–) and Eu(+) anomalies.

Figure 9c shows the REE patterns for gabbroic and associated gneissic rocks in the Pingtan Island. These rocks, which exhibit parallel slopes slightly enriched with LREE, have $\text{SiO}_2 = 51.7\text{--}60.7$ wt.% clustering in the centre. More basic rocks (e.g. FJ9406, $\text{SiO}_2 = 46.5$ wt.%) contain lower REE abundances with an Eu(+) anomaly whereas more fractionated rocks (e.g. FJ9401, $\text{SiO}_2 = 68.5$ wt.%) display higher REE abundances with Eu(–) anomaly. This can be explained by magmas derived with different degrees of partial melting from a common source and followed by a large degree of crystal fractionation, in which FJ9401 represents the fractionate and FJ9406 the cumulate. Therefore, the present case clearly

Table 3 $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende and biotite ages for gabbroic and associated gneissic rocks in SE China compared with available U-Pb zircon ages: (Hb) hornblende; (Qz) quartz; (Zr) zircon; (Bi) biotite and (Mn) monazite

Sample number	Locality	Lithology	Size (km ²)	Age (Ma)	Method	Reference
<i>Pre-orogenic</i>						
KM8-3	Chinmen	Gneiss	20	139.4 ± 0.4	U-Pb (Zr)	Yui <i>et al.</i> (1996)
<i>Syn-orogenic</i>						
FJ920826	Daiqianshan	Hb gabbro	3.5	125.1 ± 2.3	Ar/Ar (Hb)	Present study
TSF01	Shanfang	Gabbro	1	105.2 ± 1.9	Ar/Ar (Hb)	Present study
FJ9407	Lienhuashan	Hb gabbro		131.2 ± 0.6	Ar/Ar (Hb)	Yang <i>et al.</i> (1997)
ZK302-60	Taohuashan	Qz gabbro	4	106.5 ± 0.2	U-Pb (Zr)	Xu <i>et al.</i> (1999a)
Pin4-5	Pingtang	Hb gabbro	<10	115.2 ± 0.2	U-Pb (Zr)	Dong <i>et al.</i> (1997)
FJ9501	Pingtang	Gneiss		114.8 ± 1.3	Ar/Ar (Hb)	Yang <i>et al.</i> (1997)
				115.0 ± 1.4	Ar/Ar (Bi)	
Pu1-4	Huian	Gneiss	~1.5	131.0 ± 0.5	U-Pb (Zr)	Li <i>et al.</i> (2003)
Pu2-1	Huian	Gneiss		129.9 ± 0.8	U-Pb (Zr)	Li <i>et al.</i> (2003)
DS-25	Dongshan	Gneiss		121.5 ± 2.8	U-Pb (Zr)	Tong & Tobisch (1996)
FJ05	Gaoshan	Gneiss		109.6 ± 2.6	Ar/Ar (Hb)	Chen <i>et al.</i> (2002)
				105.3 ± 2.1	Ar/Ar (Bi)	
FJ07	Putien	Migmatite		108.6 ± 2.7	Ar/Ar (Hb)	Chen <i>et al.</i> (2002)
				106.7 ± 2.6	Ar/Ar (Bi)	
D58-7	Huian	Mylonite		109.2 ± 2.2	Ar/Ar (Hb)	Wang & Lu (2000)
<i>Post-orogenic</i>						
KM10-3	Chinmen	Granite	1	100.9 ± 0.5	U-Pb (Mn)	Yui <i>et al.</i> (1996)
KM3	Chinmen	Gneiss	20	100.2 ± 0.9	Ar/Ar (Hb)	Lo <i>et al.</i> (1993)
				97.4 ± 0.9	Ar/Ar (Bi)	
FJ08	Huian	Migmatite		102.4 ± 2.5	Ar/Ar (Hb)	Chen <i>et al.</i> (2002)
				101.4 ± 2.5	Ar/Ar (Bi)	
FJ17	Longhai	Migmatite		91.6 ± 1.9	Ar/Ar (Hb)	Chen <i>et al.</i> (2002)
				86.9 ± 1.8	Ar/Ar (Bi)

Figure 3 Cl/K and Ca/K spectra, and $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende plateau ages for two gabbroic rocks in SE China, including (a) the Daiqianshan cumulate and (b) the Shanfang gabbro.

demonstrates that intrusions of basic magma in a single location could lead to the formation of a wide range of rock association. Large-scale mixing between gabbroic and granitic magmas in Pingtan is not consistent with geochronological

constraints (Xu *et al.* 1999a). Those more felsic rocks which display intermediate compositions could be derived from gabbros, by small amounts of assimilation (Griffin *et al.* 2002) during magma differentiation.

Figure 4 K_2O versus SiO_2 plots for (a) pre- and syn-orogenic, (b) post-orogenic, and (c) an-orogenic igneous rocks in SE China. Some data points in (a) are suggested to be derivatives of Early Yanshanian (late Jurassic) magmatism. The subdivision of calc-alkaline rocks follows the scheme of Le Maitre (1989). Symbols in (a): (solid squares) granite gneisses >130 Ma (pre-orogenic); and (open circles) gabbros and associated gneissic rocks (syn-orogenic). Symbols in (c): (solid circles) bimodal basalts; (open triangles) mafic dykes; (solid squares) A-type granites; and (open circles) bimodal rhyolites. In addition to the present study, data sources also include unpublished data by the author and co-workers.

3.2. Geochemical and isotopic characteristics of igneous rocks

Geochemical and isotopic characterisations are apparently distinguishable in rocks which occurred at three different stages in the LY orogeny. As a whole, the early-stage gabbros and the associated gneissic rocks are characterised by possessing lower K, higher Al and Sr/Y, and more depleted Sr and Nd

isotope compositions. They can be separated into HAGs and TTG, respectively. Rocks from the later stages become more potassic and even shoshonitic, contain less Ba, Sr, P, Eu, Ti and Sr/Y, and show more enriched Sr and Nd isotopic compositions. Furthermore, the HAGs and TTG are geochemically and isotopically distinguished from the EY granitoids (i.e. the pre-orogenic rocks) which are widely distributed in S China (Figs 4, 6, 7 & 8).

In order to assess the influence of subduction on the source of basic rocks, late Jurassic mafic dykes (140 Ma) in the Cathaysia interior and late Cretaceous basic rocks (94–76 Ma) in the SE China were compared with the HAGs by using petrogenetic indicators such as Th/Nb and Zr/Nb ratios (Fig. 10). Since the late Jurassic and late Cretaceous samples are indistinguishable, and both originate in the subcontinental lithospheric mantle (Li & McCulloch 1998; Chen *et al.* 2000), whereas the HAGs are apparently lower in Th and Zr contents than these rocks, but relatively unaffected by Nb (the subduction-related indicator), the HAGs are suggested to have formed in a source region other than the metasomatised mantle wedge or the subcontinental lithospheric mantle. Using the partition coefficients for Th and Zr in amphibole and plagioclase (Rollinson 1993), they would be compatible elements in an amphibolite source. Hence, simple batch melting of amphibolitic basic rocks with chemical compositions similar to the 140-Ma mafic dykes would be expected to produce lower values of Th and Zr (Fig. 10).

Although TTG in the CNMB show weak signatures of arc magmas (e.g. Ta-Nb-Ti depletions in Fig. 6b), the high Sr/Y ratios are characteristic of TTG formed under thickened crust (e.g. in the Andes; Atherton & Petford 1993). In fact, the late Jurassic lithosphere has already been influenced by ancient subduction, as shown by the presence of an arc signature of the 140-Ma mafic dykes in SE China (Li & McCulloch 1998). The unique geochemical characters in HAGs and TTG relative to the earlier and later igneous rocks in the continental margin of SE China indicate that the onset of the LY magmatism, or the syn-orogenic magmatism, could have been accompanied by an increase in lithosphere thickness during transpression (Brown & Solar 1999).

3.3. Magma generation in various orogenic stages

Magmas generated in the syn-orogenic stage are complicated: their possible genesis may have included the intrusion of mantle-derived melts, partial melting of mafic residues, migmatization between mafic magmas and the country rocks, metasomatism caused by ductile deformation in the shear zone, and anatexis of the deep crust (Pitcher 1997). Recent studies have revealed that heat transferred from basaltic underplating in the lower crust plays an important role to the generation of granitic magmas (Bonin *et al.* 1998; Petford *et al.* 2000). As basic intrusions in the CNMB emplaced at a depth of 18–24 km, with a temperature >900°C (Huppert & Sparks 1988), they would cause partial melting of adjacent crust materials, forming felsic granites, or lead to the thermal metamorphism or in-site melting of wall rocks, forming migmatites. Basically, they are rather small in dimension.

The appearance of HAG and TTG in the CNMB is significant. In terms of time sequence, they predate the major felsic magmatism in the LY orogeny and occur mainly along the strike-slip fault. Geochemically, they are distinguishable from common arc magmas in having a higher Sr/Y ratio, but not one that is high enough for adakites (Martin 1999). Syn-orogenic HAG and tonalite-trondhjemite-granodiorite have been found in the Cordillera Blanca of the Peruvian Andes and the Klamath of North America (Atherton & Petford 1993; Barnes *et al.* 1996). They all indicate the

Figure 5 Normative An-Ab-Or triangular plots for gabbros and the associated gneissic rocks as compared with the granites which include both deform (pre-orogenic) and undeform (post-orogenic) samples. The gneissic rocks constitute a peraluminous tonalite-trondhjemite-granodiorite assembly when taking the alumina saturation index (ASI) versus SiO_2 plots (upper right) into consideration.

Figure 6 Primitive mantle-normalised, multi-element distribution patterns for pre-, syn-, post- and an-orogenic igneous rocks in SE China. Two typical late Jurassic granites in S China (97GD-57 and -63) are incorporated in (a) for comparison with the pre-orogenic gneisses in the Changle Nanao Metamorphic Belt. Normalising values are from McDonough & Sun (1995).

Figure 7 Sr/Y versus Y plots for pre-, syn-, post- and an-orogenic igneous rocks in SE China. Fields for adakite (AD) and classical arc (CA) are taken from Martin (1999).

Figure 8 $\epsilon\text{Nd}_{(T)}$ versus I_{Sr} plots for gabbros and tonalite-trondhjemite-granodiorite (TTG), as compared with the late Cretaceous shallow-level I-type granitoids, A-type granites and bimodal volcanics in the Southeast Coast Magmatic Belt (Chen *et al.* 2000). The fields of the 140-Ma and 94–76-Ma mafic dykes (Li & McCulloch 1998; Chen *et al.* 2000) and the late Jurassic granitoids in S China (Chen & Jahn 1998) are used to constrain the mantle and crust sources.

evolution of arc magmas towards a more sodic trend in the early stage of orogeny – typical of the Cordillera orogenesis away from the subduction zone.

Two different processes for the generation of high-Al and Na-trending arc magmas have been suggested: high-pressure partial melting of basic rocks with garnet in the residue (Johnson *et al.* 1997); and partial melting of subducted slab under garnet amphibolite to eclogite conditions (Drummond *et al.* 1996). The present authors believe that the syn-orogenic HAG and TTG in the CNMB represent partial melts of amphibolite under pressure, and that TTG was formed at P/T conditions of 3–5 kb and 650–800°C because of dehydration of amphibole, whereas HAG are large degree partial melts from the same materials formed at 5–10 kb and 900°C, based on the experimental works of Wolf & Wyllie (1994). When garnet is involved in the amphibolite residues, melts have a

higher Sr/Y ratio because of the retention of Y and HREE in the garnet. On the other hand, slab-melting needs to be under conditions of high shear stresses, incipient subduction and/or near volcanic front to account for the more adakite-like rocks.

This model requires the pre-existence of basic residues in the lower crust to serve as the source for melting. It is suggested that generation of the widely distributed late Jurassic high-K, calc-alkaline granitoids in S China was under the continental rifting environment in conjunction with the formation of extensional basins (Li 2000). Such a tectonic environment could facilitate decompressional melting of the upwelled mantle, and result in a large amount of basic magma emplacing at the base of the lower crust to trigger crustal melting for the generation of the extensional type of the granitic magmas (Bonin *et al.* 1998). Therefore, voluminous basic magmas are postulated to have emplaced in the Cathaysia crust prior to the

Figure 9 Chondrite-normalised rare earth element distribution patterns for (a) gabbroic rocks and (b) gneissic rocks in the Southeast Coast Magmatic Belt, and (c) both gabbroic and gneissic rocks in Pingtan. Normalising values are from McDonough & Sun (1995).

onset of the LY orogeny. Parts of these basic layers were then metamorphosed into amphibolites in a thickened crust during syn-orogenic collision. The direct evidence to support the existence of a thickened crust is the finding of gabbroic granulite xenoliths captured by the Neogene basaltic pipes in Qilin (Fig. 1). Such xenoliths, dated as 112 ± 18 Ma on a Sm-Nd isochron (Xu *et al.* 1999b), were estimated to more probably equilibrate under an extraordinarily high pressure of 15–17 kb (Y. Xu *et al.* 1999).

In the post-orogenic stage, rocks are dominantly high-K calc-alkaline I-type shallow intrusives which constitute the major igneous complexes in the SCMB. Magmatism occurred at this stage, lasting for ~ 12 Mys; it was intensive, and is thought to relate to a combined lithospheric extension and basaltic underplating (Chen *et al.* 2000). The succeeding emplacement of near-surface A-type granite and eruptions of

Figure 10 Distinction of high-Al gabbros from pre- and post-orogenic basic rocks in SE China using (a) Th/Nb versus Th and (b) Zr/Nb versus Zr plots. Note that a few cumulates which have high Zr/Nb ratios may reflect discordant Zr concentrations in the sample.

A- and I-type rhyolite intercalating basalts reflect further extension. In sum, I- and A-type magma generation was not only related to the extent of dryness in the source region, but was also controlled by the degree of lithospheric extension in different areas (Chen *et al.* 2000).

3.4. Tectonic evolution

To account for the geochemical and isotopic characters of the staged igneous rocks, the following tectonic evolution in SE China is suggested. In the late Jurassic period, the Cathaysia block was dominated with high-K, calc-alkaline granitoids. The extensional environment (Li 2000) caused the emplacement of underplated basalts. Thickening and downwarping of the lithosphere because of plate convergence converted the preceded underplating basalts into amphibolites. The sizes of gabbro and TTG plutons are small (Table 3), which is typical of those formed under a compression environment (Vigneresse 1995). Dehydration melting of hydrous minerals in the lower-crust amphibolites initiated the LY high-Al magmatism, and partial melting of amphibolites in deep shear zones was responsible for those with a high Sr/Y ratio. The HAG and TTG formed at this stage were metamorphosed into gneisses along the major shear zone caused by the plate subduction.

As a consequence of the thickened lithosphere, detachment or delamination of the lithosphere root could have taken place

(Gvirtzman & Nur 1999). Moreover, this could have resulted in a lithospheric extension and new-phase underplating of basaltic magmas (Turner *et al.* 1992). Therefore, heat transferred from these magmas could have triggered the partial melting of the lower and middle crust necessary for producing I-type magmas. The isotopic analogy between I- and A-type granites is the evidence needed to indicate a common source. On this basis, dry melting of the residue after extraction of I-type magmas heated by further basaltic underplating was the main mechanism by which A-type magmas were formed.

The final phase of LY magmatic evolution can be explained by the increasing degree of lithospheric extension, which led to regional emplacements and eruptions of A-type magmas and associated basaltic melts to form miarolitic granites, mafic dykes and bimodal volcanism. I-type magmas could also be simultaneously formed where a lesser degree of lithospheric stretching had happened. The entire LY magmatism terminated when the basaltic magmas were no longer underplated.

4. Conclusions

The LY magmatism in SE China provides a good model for unravelling cyclic magmatic evolution in a subduction-initiated orogenesis. The amphibole geobarometer and age dating revealed that the LY magmatism can be separated into deep and shallow intrusions in the early and late stages, reflecting compressive and extensional tectonism in the LY orogeny. Magmatism of compressive tectonism (130–110 Ma) produced HAG and TTG suites. These magmas intruded into the deep basement along the ductile shear zone and thermally metamorphosed pre-existing igneous rocks into migmatites. Geochemically, these high-Al rocks are also marked by a high Sr/Y ratio but a low K₂O content, resembling of materials derived from dehydration melting of amphibolites at depth. The more depleted Sr and Nd isotope compositions in the later felsic rocks support their derivation from pre-existing basic layers in the lower crust.

At the beginning of extensional tectonism (110–99 Ma), rocks became dominated by high-K, calc-alkaline I-type granitoids. Following a short non-magmatic period, miarolitic A-type granites (94–91 Ma) and bimodal volcanics (91–81 Ma) were the essence of magmatism. Based on the general similarity of the Sr and Nd isotope compositions among these rocks, the progressive melting of felsic granulites from wet to dry conditions is responsible for the generation of I- and A-type magmas as a result of constant basaltic underplating. The common existence of simultaneous mafic dykes (94–76 Ma), which differ from HAG in geochemical and isotopic composition, and represent derivatives from the lithospheric mantle, is evidence of basaltic underplating.

To account for the geochemical and isotopic variations of LY magmatism and the heat budget under the lithospheric extension, lithosphere detachment or delamination is suggested. Basically, subduction of paleo-Pacific plate during the early Cretaceous resulted in thickened-crust, pre-existing basic layers in the lower crust which most probably emplaced during Jurassic EY extensional magmatism and were metamorphosed into amphibolites. As a consequence of crustal thickening, lithospheric delamination or detachment took place. The upwelled mantle brought up extra heat, causing an immense melting of the crustal material through basaltic underplating. Magmas thus generated were emplaced at a higher level than

extensional environments. Until lithospheric extension became less effective, orogenic magmatism terminated.

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