Vol. 79 No. 2 pp. 201-210 ACTA GEOLOGICA SINICA April 2005

Geological and Geochemical Characteristics of Early Cretaceous Mafic Dikes in Northern Jiangxi Province, SE China and Their Geodynamic Implications

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Abstract The development of Early Cretaceous mafic dikes in northern and southern Jiangxi allows an understanding of the geodynamic setting and characteristics of the mantle in southeast China in the Cretaceous. Geological and geochemical characteristics for the mafic dikes from the Wushan copper deposit and No. 640 uranium deposit are given in order to constrain the nature of source mantle, genesis and tectonic implications. According to the mineral composition, the mafic dikes in northern Jiangxi can be divided into spessartite and olive odinite types, which belong to slightly potassium-rich calc-alkaline lamprophyre characterized by enrichment in large ion lithophile elements (LILE) and light rare earth elements (LREE), large depletion in high strength field elements (HSFE) and with negative Nb, Ta and Ti anomalies, as well as $^{87}Sr/^{86}Sr$ ratios varying from 0.7055 to 0.7095 and $^{143}Nd/^{144}Nd$ ratios varying from 0.5119 to 0.5122. All features indicate that the magma responsible for the mafic dikes was derived mainly from metasomatic lithosphere mantle related to dehydration and/or upper crust melting during subduction. Differences in geochemical characteristics between the mafic dikes in northern Jiangxi and the Dajishan area, southern Jiangxi were also studied and they are attributed to differences in regional lithospheric mantle components and/or magma emplacement depth. Combining geological and geochemical characteristics with regional geological history, we argue that southeast China was dominated by an extensional tectonic setting in the Early Cretaceous, and the nature of the mantle source area was related to enrichment induced by asthenosphere upwelling and infiltration of upper crust-derived fluids responding to Pacific Plate subduction.

1 Introduction

Southeast China lies at the plate junction between the Pacific and the Eurasian plates, where granitoids and volcanic rocks are widely exposed and large-scale mineralization was developed in the Late Mesozoic. Therefore, many geologists have paid much attention to the geodynamics in this region (Jahn et al., 1990; Lampierre et al., 1997; Zhou and Li, 2000; Li, 2000; Chen et al., 2002; Li et al., 2003). Many achievements in scientific research on the Late Mesozoic granitoids and volcanic rocks in Zhejiang, Fujian and Guangdong indicate that the geodynamic setting was in close relationship with subduction of the Pacific Plate and that lithospheric extension began in the Late Cretaceous (Jahn et al., 1990; Lampierre et al., 1997). Recent research into the geochemistry of the Middle Jurassic shoshonitic intrusive, bimodal volcanic rocks and A-type granite in the Nanling Mountains indicates that lithospheric extension in southeast China probably began in the Middle Jurassic (Li et al., 1999; Chen et al., 2002; Li et al., 2003). Geologists from China and elsewhere have studied geological and geochemical characteristics of the Cenozoic basalts and the hosted mantle xenoliths in southeast China (Qi et al., 1994; Zhou and Li, 2000; Xu et al., 2002; Xu et al., 2003). However, little scientific research has been carried out on the Mesozoic mantle. The few geochemical and isotopic data on basalts in the coastal areas of Zhejiang and Fujiang Provinces give rise to much controversy relating to either a depleted or enriched mantle in southeast China in the Late Mesozoic (Xing et al., 1999). The tectonic setting and nature of the mantle in the Early Cretaceous are of key importance to understanding the geodynamic evolution of southeast China in the Mesozoic. Mafic dikes are the product of mantle-derived magma that is associated with extensional tectonics, which provide important scientific information for understanding mantle characteristics beneath the crust as well as tectonic evolution (Hall, 1982;

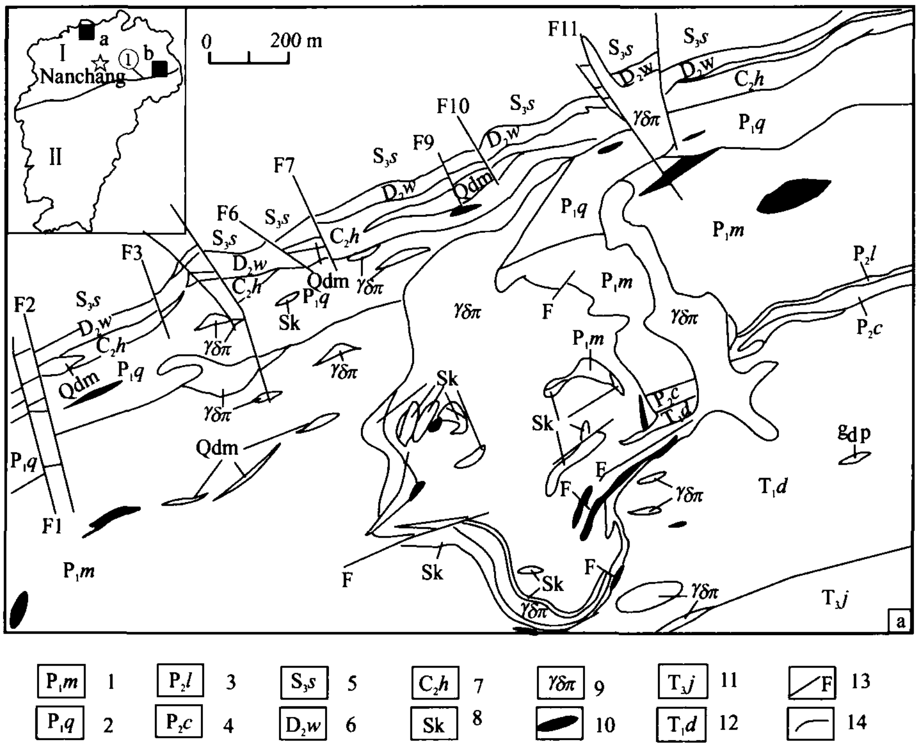

Fig. 1. Distribution sketch map of the Early Cretaceous mafic dikes in northern Jiangxi, SE China.

a - Location (on small insert map) and geological sketch map of the mafic dikes in the Wushan copper deposit (RGMB-JX, 1984); b - Location of No. 640 uranium deposit.

1. Permian Maokou Formation; 2. Permian Qixian Formation; 3. Permian Longtan Formation; 4. Permian Changxing Formation; 5. Silurian Shamao Member; 6. Devonian Wutong Member; 7. Carboniferous Huangling Formation; 8. Skarn; 9. Granodiorite porphyry; 10. Mafic dike; 11. Triassic Jialijiang Member; 12. Triassic Daiye Member; 13. faults; 14. Geological boundary; I - Yangtze Block; II – Cathaysia Block; ① - Pingxiang-Gangfeng faults.

Lan et al., 1995; Li et al., 1998; Sun et al., 2001; Ge et al., 2003).

The widespread Early Cretaceous mafic dikes exposed in northern Jiangxi and intruded into all kinds of strata as well as the Yanshanian granite masses can provide clues for the solution of this tectonic problem. However, as yet, little research on the mafic dikes has been made. For example, only simple petrographical descriptions occur in the 1:50000 regional geological surveying reports. Mafic dikes in northern Jiangxi are generally small in size and easy to weather. However, the mafic dikes from the Wushan copper and No. 640 uranium ore district, which are available from drill cores, not only are equivalent to the mafic dike swarms in northern Jiangxi, but also are fresh and not weathered. In this paper, we report new results of K-Ar ages, major and trace elements, and Nd-Sr isotopic compositions for the northern Jiangxi mafic dikes. We also document their geochemical and isotopic characteristics, and discuss the nature of mantle sources and petrogenesis. In addition, we compare differences between the mafic dikes from this region and those from the Dajishan area in southern Jiangxi, and from all this discuss the geodynamic evolution in southeast China.

2 Geological Setting

The research area is located to the eastern margin of the Yangtze Block. The mafic dikes are exposed in the Wanshan copper ore district to the north of Ruichang and in the No. 640 uranium mining area to the south of Yanshan, northern Jiangxi (Fig. 1). The mafic dike swarms, which are extensively exposed in the north and south ore zones of the Wushan copper deposit, were emplaced in granodiorite porphyry, the Permian Maokou Formation and the Triassic Daye Formation and are mostly in endocontact and exocontact of the granite pluton and interlayered fractured zone. A single dike can be 5-6 m wide and about 270 m long. Most of the mafic dikes occur as swarms with little variation in occurrence ranging from 125°-165° to 50°-65°, and are characterized by inflation and filiations. The mafic dikes in the No. 640 uranium deposit occur along a narrow belt with an occurrence of 75° to 70°-80° in sandstone and tuff of the Upper Jurassic Daguding and Ehuling formations, and contain tuff of the Upper Jurassic sequences. Generally, they have not been subjected to deformation and metamorphism.

The mafic dikes are composed mainly of spessartite and olive odinite. The spessartite consists mainly of plagioclase (50%), hornblende (40%), minor quartz (5%) and biotite (5%), with sometimes, pyroxene and olivine (5%). Phenocrysts consist of hornblende and minor plagioclase, while the matrix is composed of plagioclase and minor hornblende with a grain size of 0.05-0.03 mm; the matrix was subjected to weak carbonate alteration. The olive odinite is composed of olivine (10%), pyroxene (40%) and plagioclase (45%), with phenocrysts consisting predominantly of olivine, pyroxene and plagioclase. Olivine grains with cracks are 1.0-1.5 mm in grain size and slightly replaced by secondary calcite; plagioclases with a

Table 1 Contents of major elements (%), trace elements and REE (in ppm) for the Early Cretaceous mafic dikes from the Wushan copper and No. 640 uranium deposits in northern Jiangxi, SE China

Sample	6402	6403	XWS1	XWS2	XWS3	XWS4	XWS5	DDX1	DDX4	DDX8	DDX10	DDX13	DDX14	DDX12
SiO_2	50.68	51.19	48.94	47.64	47.49	49.44	48.31	48.54	49.57	45.79	52.91	52.89	50.43	49.35
TiO_2	1.00	1.07	0.87	0.97	1.00	0.87	0.85	1.05	0.67	0.97	0.77	0.85	0.90	0.10
Al_2O.,	19.42	19.63	17.95	16.06	16.29	17.01	15.58	15.25	14.68	14.55	13.84	14.51	15.25	13.63
Fe_2O_3	3.35	3.89	4.75	4.58	3.20	5.56	4.50	5.48	5.66	5.85	5.99	4.87	6.19	3.10
FeO	4.90	4.10	3.15	3.22	5.10	3.74	3.50	7.49	7.70	8.80	7.10	6.95	7.00	8.98
MnO	0.24	0.36	0.10	0.16	0.15	0.05	0.15	0.28	0.25	0.32	0.27	0.24	0.24	0.28
MgO	2.52	1.03	6.90	5.80	5.90	5.70	5.50	5.60	5.92	7.88	4.56	4.65	5.10	6.25
CaO	7.86	8.40	7.50	13.60	11.70	4.50	12.20	9.64	8.93	8.60	8.63	8.93	9.51	9.59
Na_2O	2.00	2.08	2.14	2.49	2.31	1.18	2.42	2.21	2.39	1.52	1.95	2.37	2.36	1.90
K_2O	2.14	2.17	1.41	1.73	1.74	1.53	1.52	1.11	0.87	2.72	1.72	1.28	0.91	2.72
P2O5	0.40	0.40	0.40	0.50	0.60	0.43	0.50	0.13	0.13	0.12	0.22	0.13	0.12	0.23
LOI	2.09	1.54	5.21	2.67	3.92	9.34	4.81	2.15	2.20	2.30	1.75	1.72	1.40	2.70
CO_2	3.05	3.97	-	-	-	-	-	0.65	0.50	-	-	-	-	0.95
Total	99.65	99.83	99.32	99.42	99.40	99.35	99.84	99.58	99.47	99.42	99.71	99.39	99.41	99.78
Sc	20.3	19.5	24.2	26.7	26.1	24.3	23.5	33.4	31.3	44.4	37.3	35.2	34.0	34.5
Cr	227	223	278	514	584	283	519	53.0	53.7	49.7	47.6	41.0	42.5	169
V	73	64	193	228	223	201	203	463	452	386	376	383	440	377
Co	63.3	54.9	38.1	37.2	35.0	42.8	42.4	88.0	104	88.3	102.5	132	94.2	50.5
Ni	15.1	13.6	99.4	163	159	125	179	29.5	32.3	35.9	28.5	27.5	29.9	55.5
Pb	14.1	12.6	9.09	8.07	6.25	7.93	8.41	8.10	8.10	5.80	8.95	8.26	7.50	12.0
U	2.05	1.38	1.43	1.27	1.23	1.36	1.19	0.782	0.784	0.947	1.05	0.807	0.717	0.761
Sr	641	561	488	660	662	134	732	364	401	264	344	348	381	270
Rb	42.1	36.0	41.5	50.7	51.2	45.0	40.4	392	229	783	598	302	225	1081
Ba	690	574	360	491	454	364	404	119	97.0	187	184	149	89.1	243
Th	6.40	6.46	6.43	7.05	6.95	6.49	7.05	2.69	2.77	3.22	3.26	2.50	2.53	3.11
Ta	0.63	0.57	0.52	0.49	0.46	0.49	0.50	0.977	1.20	1.45	1.24	1.28	1.10	1.76
Nb	12.4	12.2	8.37	9.06	9.08	8.11	8.60	15.2	16.8	19.4	18.4	16.7	15.9	16.4
Zr	155	150	120	148	152	116	145	160	174	200	198	158	160	151
Hf	4.84	4.59	3.86	4.27	4.54	3.49	4.26	5.09	5.48	6.24	6.89	6.21	4.91	4.9
Y	30.7	30.1	18.0	21.5	22.8	15.6	20.5	36.5	40.2	48.4	46.2	38.4	38.4	29.7
La	34.5	32.4	28.1	39.7	39.8	25.9	38.1	17.4	19.2	22.7	25.5	17.5	17.8	37.2
Ce	57.6	53.4	59.4	84.9	85.9	56.2	81.3	42.1	46.4	54.7	58.6	41.3	42.7	62.9
Pr	7.82	7.36	6.70	9.74	10.02	6.34	9.33	5.49	5.98	7.06	7.31	5.39	5.33	7.07
Nd	31.2	29.0	27.6	41.2	41.7	25.8	38.3	25.9	27.2	32.1	33.5	24.7	25.6	27.1
Sm	6.13	5.76	5.69	8.12	8.21	5.35	7.71	6.39	7.38	8.54	7.87	6.24	6.94	6.22
Eu	1.68	1.46	1.53	2.08	2.10	1.31	1.97	2.06	2.19	2.48	2.49	2.01	1.94	1.59
Gd	6.06	5.52	4.83	6.43	6.63	4.11	6.38	6.67	7.00	8.86	8.24	6.86	6.74	5.88
Tb	0.914	0.933	0.643	0.826	0.836	0.573	0.751	1.13	1.29	1.56	1.39	1.19	1.12	0.916
Dy	5.58	5.35	3.78	4.20	4.57	3.11	4.27	7.30	7.57	9.45	9.09	7.34	7.71	5.45
Ho	1.04	0.986	0.733	0.822	0.847	0.559	0.817	1.39	1.52	1.78	1.74	1.33	1.42	1.09
Er	3.10	3.02	1.96	2.18	2.24	1.64	2.11	3.79	4.22	4.91	4.65	3.86	3.77	2.90
Tm	0.451	0.400	0.264	0.28	0.297	0.224	0.287	0.511	0.528	0.652	0.592	0.546	0.534	0.373
Yb	3.25	2.92	1.69	1.86	2.01	1.49	1.99	3.38	3.67	4.35	4.23	3.44	3.48	2.69
Lu	0.448	0.440	0.216	0.266	0.25	0.191	0.26	0.457	0.536	0.583	0.592	0.486	0.509	0.371
REE	160	149	143	203	205	133	194	124	135	160	166	122	126	162
δ8Eu	0.84	0.79	0.89	0.88	0.87	0.85	0.86	1.0	1.0	1.0	1.0	1.0	1.1	0.93
δCe	0.84	0.83	1.0	1.0	1.0	1.1	1.0	0.96	0.93	0.87	0.95	0.94	0.87	0.80

Note:-: not analyzed; LOI: loss of ignition; DDX: sample for the mafic dikes from the Dajishan area, southern Jiangxi, SE China.

Table 2 Sr and Nd isotope data of the Early Cretaceous mafic dikes from the Wushan copper deposit and No. 640 uranium deposit in northern Jiangxi, SE China

Sample	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2SIGMASE	$(^{143}Nd/^{144}Nd)_i$	$\varepsilon_{Nd}(t)$	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2SIGMASE	$(^{87}Sr/^{86}Sr)$,	$\varepsilon_{Sr}(t)$
XWS1	5.22	33.2	0.0952	0.512274	0.000005	0.5122	-5.3	91.2	619	0.426	0.706322	0.000005	0.7055	16
XWS2	7.93	40.2	0.1192	0.512133	0.000004	0.5120	-8.5	119	1114	0.3103	0.706855	0.000007	0.7062	27
XWS5	7.46	38.3	0.1178	0.512032	0.000006	0.5119	-10.4	87.7	1038	0.2446	0.706926	0.000006	0.7064	29
6403	5.76	29.0	0.1201	0.51219	0.000013	0.5121	-7.4	36.0	561	0.1857	0.709870	0.000011	0.7095	73

Note: initial $(^{141}Nd/^{144}Nd)$, and $(^{87}Sr/^{86}Sr)_i$ were calculated using a mean K-Ar age of 140 Ma. $(^{87}Sr/^{87}Sr)^0_{UR}=0.7045$, $(^{87}Rb/^{86}Sr)^0_{UR}=0.0827$, $(^{143}Sm/^{144}Nd)^0_{UR}=0.51238$, $(^{143}Nd/^{144}Nd)^0_{UR}=0.1967$; $\lambda_{Rb}=1.42\times10^{-11}$, $\lambda_{Sm}=6.54\times10^{-12}$(Rollinson, 1993).

Table 3 K-Ar dating of the Early Cretaceous mafic dikes from the Wushan copper deposit and No. **640** uranium deposit **in** northern Jiangxi, SE China

Sample	Weight (g)	K(%)	$^{40}Ar^*(10^{-10}$ mol/g)	$^{40}Ar^*$ (%)	$^{40}Ar^*/^{40}K$ (10^{-3})	*t* (Ma)
XWS2	0.03312	1.46	3.6782	88.54	8.4408	**139.7±2.1**
XWS5	0.02998	1.49	3.8589	82.07	8.6773	**143.5±2.7**
6403	0.03358	2.35	5.9222	83.22	8.4434	**139.8±2.8**

grain size of about 0.45 mm are characterized by polysynthetic twinning with biaxial crystals of positive optical character, usually weakly sericitized in the center showing the edulcoration rim phenomena; pyroxene grains with a size of 0.45-1.5 mm exhibit bi-orthogonal cleavage and are often partially replaced by calcite and chlorite. The matrix consists of plagioclase, a small amount of pyroxene as well as minor accessory minerals (ca. 5%), such as magnetite.

Samples of the studied mafic dikes were collected from drill cores in the Wushan copper ore district and the No. 640 uranium ore district, with the sampling sites as far away as possible from the lodes which subjected to hydrothermal alteration. The samples XW1S to 5 in the Wushan copper ore district are collected from sites CK91 and CK272 and CK261 and CK102 and CK251, respectively, while such samples as 6403 and 6402 are collected from ore zone I in the No. 640 uranium deposit.

3 Analytical Methods

Following petrographic examination to insure freshness, rock samples were crushed to mm scale and then under magnification, weathered rims were removed. Fresh chips were selected and then powered in an agate mill to a grain size of 200 meshes. Seven samples were analyzed for major and trace elements and four samples were analyzed for Sr-Nd isotope composition. Three least altered samples crushed to 40-60 mesh were used for K-Ar dating.

Major element analysis was carried out using conventional wet chemical methods at the Chemical Analytical Center, Institute of Geochemistry, Chinese Academy of Sciences (CAS); the analytical errors for major oxides are less than 2%. Trace element and rare earth element content were determined by solution ICP-MS analysis, which was performed at the ICP-MS Laboratory, Institute of Geochemistry, Chinese Academy of Sciences (CAS). Precision for most elements was typically better than 5% RSD, and for Zr, Hf, Nb and Ta elements, the measured values were less than 10% in error when compared to certified values. The detailed preparations, instrument operating conditions and calibration procedures of the analyses follow Qi and Gregoire (2001). Sr and Nd isotopic ratios for the mafic dike samples from the No. 640 uranium deposits were measured using a Micro-mass Isoprobe multi-collector mass spectrometer (MC-ICPMS) that operated in static mode at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (CAS); measured $^{87}Sr/^{86}Sr$ and $^{43}Nd/^{144}Nd$ ratios were normalized to $^{87}Sr/^{86}Sr=0.1194$ and $^{146}Nd/^{144}Nd=0.7219$, respectively. The analytical procedures are similar to those described by Wei et al. (2002) and Liang et al. (2003). Nd-Sr isotopic analyses for the mafic dike samples from the Wushan copper deposits were carried out at the Tianjing Institute of Geology and Resources, Chinese Academy of Geological Sciences (CAGS), on a VG-354 multi-collector mass spectrometer, as described by Peng et al. (2003). K-Ar dating was performed at the K-Ar and ^{40}Ar-^{39}Ar isotopic laboratories, Institute of Geology, CAGS. Major and trace element compositions, Nd-Sr isotopic data and K-Ar dating results for the samples studied are listed in Tables 1-3, respectively.

4 Results

4.1 Major elements

As shown in Table 1, contents of major elements of the studied lamprophyre are similar to those from elsewhere

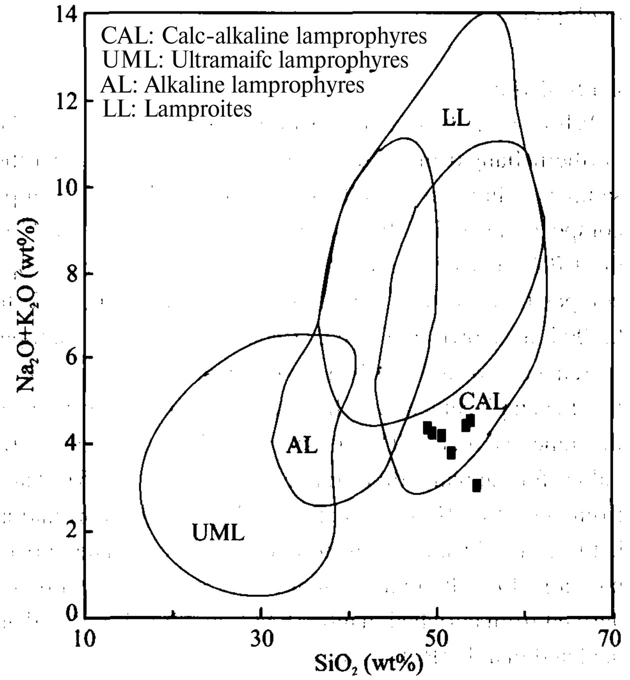

Fig. 2. (K_2O+Na_2O)-SiO_2 classification diagram for the Early Cretaceous mafic dikes in northern Jiangxi, SE China (Rock, 1987).

(Rock et al., 1990), Comparing with the (K_2O + Na_2O)-SiO_2 diagram of Rock (1987), most of the studied samples are calc-alkaline lamprophyre (Fig. 2). The K/(K+Na) ratios for the northern Jiangxi mafic dikes range from 0.41 to 0.59 with an average value of 0.49, and the K/Al ratios vary from 0.12 to 0.17, averaging 0.16. Therefore, they are slightly rich in potassium (Lu et al., 1991).

Table 1 shows that losses on ignition (LOI) of the samples from the northern Jiangxi mafic dikes are relatively high, ranging from 2.67% to 9.34% with an average of 5.23%, suggesting that the presence of high volatile components (from 3.05% to 3.97%) such as CO_2. The SiO_2 contents of the studied lamprophyre range from 47.64% to 51.19% with an average of 49.10%, being similar to those for basic rocks. In addition, all samples are characterized by high alkalinity with K_2O contents ranging from 1.41% to 2.17% and (K_2O+Na_2O) contents ranging from 2.71% to 4.25% with an average of 3.84% as well as K_2O/Na_2O ratios of 0.63-1.30, which indicates that the dikes are potassium-rich. The samples contain 0.85 to 1.07% TiO_2 with an average of 0.95% and 15.48-19.63% Al_2O_3 with an average of 17.42%. All the samples contain 1.03% to 6.90% MgO, which suggests that the lamprophyre magma underwent fractional crystallization. The Harker diagram for the major elements indicates that SiO_2 in the samples is in positive correlation with Al_2O_3 and ΣFeO and in slight negative correlation with MgO. CaO and P_2O_5 also increase with a decrease in SiO_2, which suggests that fractional crystallization of apatite and clinopyroxene took place during magmatic evolution (Wilson, 1989). In addition, CaO/Al_2O_3 increases with CaO, as shown in Table 1, indicating fractional crystallization of Clinopyroxene (Qi et al., 1994).

4.2 Trace elements

The mafic dikes contain 223-584 ppm Cr, 13.6-179 ppm Ni and 63.9-228 ppm V. The Cr and Ni contents are lower than those in basaltic magma resulting from partial melt of 20-30% lherzolite, suggesting that the northern Jiangxi mafic dikes resulted from secondary magma other than primary magma undergoing fractional crystallization

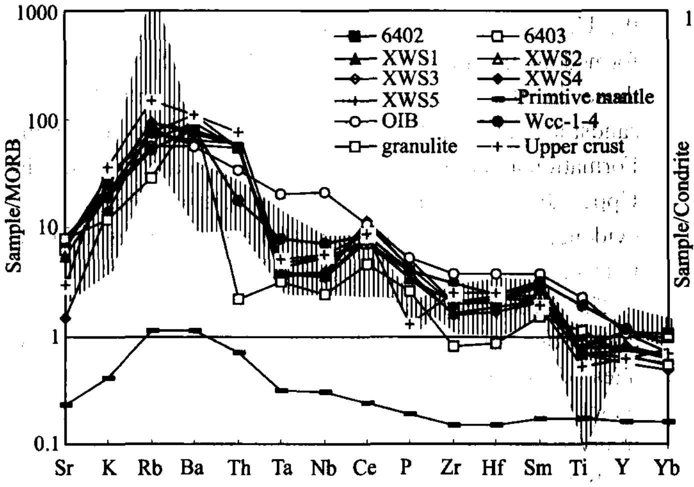

Fig. 3. MORB-normalized spidergrams for the Early Cretaceous mafic dikes in northern Jiangxi, southeast China.

PM, MORB and OIB - from Sun and McDonough (1989); upper crust - from Gao et al. (1998); average value of magmatic granulite in the Cathaysian block - from Yu et al. (2003); shade area - mafic dikes from the Dajishan area, southern Jiangxi; Wcc-1-4 - Early Cretaceous diabase dikes from the Weicheng area in the coastal area of Zhejiang province (Chen and Zhou, 1999).

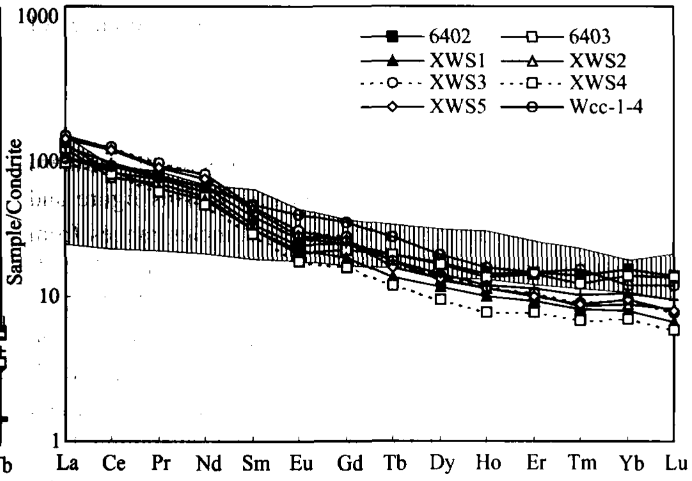

Fig. 4. Chondrite-normalized REE patterns for the Early Cretaceous mafic dikes in northern Jiangxi, southeast China.

chondrite (Boynton, 1984, from Rollinson, 1993); shade area - mafic dikes from the Dajishan area, southern Jiangxi; Wcc-1-4 - Early Cretaceous diabase dikes from the Weicheng area in the coastal area of Zhejiang province (Chen and Zhou, 1999).

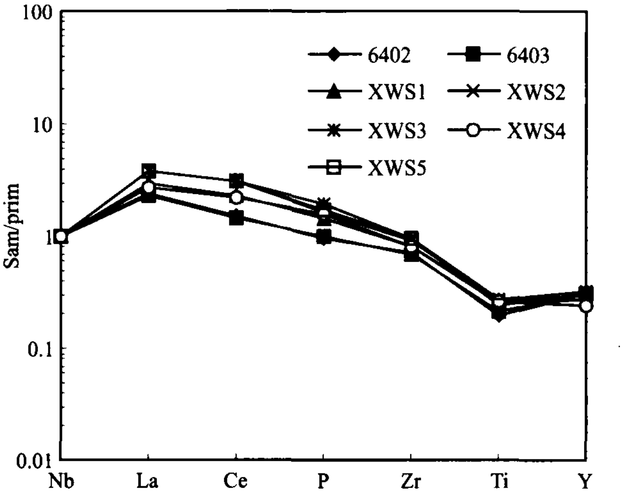

Fig. 5. Nb-normalized spidergrams for the Early Cretaceous mafic dikes in northern Jiangxi, southeast China.
Primitive mantle from Sun and McDonough (1989).

(Wilson, 1989).

MORB-normalized spidergrams for incompatible elements in the mafic dikes are shown in Fig. 3. This figure and Table 1 show that the trace element contents in the mafic dikes are higher than those in middle oceanic ridge basalts (MORB) and primitive mantle (Sun and McDonough, 1989). MORB-normalized spidergrams for incompatible elements in the mafic dikes have "hunch" patterns that are similar to those of continental basalts from subduction zones (McCulloch and Gamble, 1991); distinguished from Ocean Island Basalts (OIB); characterized by significant enrichment in large ion lithophile elements (LILE) and light rare earth elements (LREE); and highly deplete in high strength field elements (HSFE) with negative anomalies of Nb, Ta and Ti and Nb/Ta ratios of 0.23-0.38, suggesting the presence of components from a subducted plate.

4.3 Rare earth elements

The chondrite-normalized REE patterns for the northern Jiangxi mafic dikes are shown in Fig. 4. This figure and Table 1 show that ΣREE for all the samples ranges from 133 to 205 ppm with an average of 169 ppm and ΣLREE and ΣHREE are 121-188 ppm and 11.9-20.8 ppm, averaging 153 ppm and 16.8 ppm, respectively. All the samples have similar REE patterns with LREE/HREE ratios ranging from 6.6 to 11.0 with an average of 9.2 and La_N/Yb_N ratios varying from 7.1 to 14.4, averaging 11.2, indicating enrichment in LREE. The chondrite-normalized REE patterns are characterized by slightly negative Eu anomalies and positive Ce anomalies with δEu value of 0.79-0.89 (average value of 0.86) and δCe value of 0.83-1.1 (average value of 0.98), showing no fractional crystallization of plagioclase phases during magmatic evolution.

4.4 Sr-Nd isotope data

Whole-rock Nd- and Sr-isotope compositions for the northern Jiangxi mafic dikes are given in Table 2. All the samples show a small variation in Rb-Sr isotope compositions with ^{87}Rb/^{86}Sr of 0.1857-0.426 and ^{87}Sr/^{86}Sr of 0.7066-0.7099, and relatively high initial Sr isotope compositions with $(^{87}Sr/^{86}Sr)_i$ ranging from 0.7055 to 0.7095, as shown in Table 2. Because the Sm-Nd isotopic system can avoid the influence of secondary alteration after magma emplacement, it is helpful to diagnose the origins of the igneous rock. The $(^{143}Nd/^{144}Nd)_i$ ratios and $\varepsilon_{Nd}(t)$ values for the mafic dikes range from 0.5119 to 0.5122 and from -5.3 to -10.4, respectively. There is no correlation between the Sr and Nd isotope compositions. The above-mentioned results indicate that these rocks were probably derived from enriched mantle (EM II and EM I) rather than depleted mantle (Rollinson, 1993).

5 Discussion

5.1 Tectonic implications

As mentioned above, the tectonic regime in southeast China in the Early Cretaceous is of key importance to the geodynamic setting in southeast China in the Late Mesozoic. In addition, mafic dikes are a common expression of mantle-derived magma generation that is associated with extensional tectonics. In this circumstance, precise dating of mafic dikes can provide important information to help understand the tectonic evolution in continental settings (Hall, 1982; Li and McCulloch, 1998). The mafic dikes in the Wushan copper deposit intruded into the Upper Triassic and granodiorite porphyry which was formed in the Late Jurassic (BGMR-JX, 1984) whereas those in the No. 640 uranium deposit intruded into sandstone and tuff of the Upper Jurassic Daguding Formation and into the Ehuling Formation that contains the Upper Jurassic tuff mass. These relationships provide evidence for the emplacement of the mafic dikes after the Late Jurassic.

The three fresh mafic dike samples from the Wushan copper deposit and No. 640 uranium deposit yielded K-Ar ages of 140-144 Ma and 140 Ma, respectively (Table 3), which are consistent with field observations. These results indicate that the mafic dike swarms were emplaced in the Early Cretaceous, while mafic dikes in the Dajishan area, southern Jiangxi were formed at 147 to 141 Ma (Li and McCulloch, 1998; Xie, 2003).

It is accepted that the South China blocks had amalgamated and gone into an orogenic stage since the Triassi. Emplacement of the mafic dikes in northern and southern Jiangxi in the Early Cretaceous suggests that the tectonic regime in southeast China in the Late Mesozoic was extensional rather than compressional. This is supported by evidence from the other areas in southeast China, as for instance, in southern Anhui, Hong Kong and Qianlishan in Hunan, where late-orogenic and anorogenic granitoids were emplaced in the Early Cretaceous (Li, 2000). Recent studies indicate that mantle hotspot agpaitic lamprophyres with an age of 136.6 Ma and A-type granites with an age of 140±Ma occurred in northeastern Hunan (Jia et al., 2002; 2003), which suggests that asthenosphere upwelling and lithospheric extension had already begun in southeast China in the Early Cretaceous. In addition, diabase dikes with a single-zircon U-Pb age of 133 Ma had developed at Weicheng in the coastal area of Zhejiang Province in the Early Cretaceous, which also supports the case for an extensional regime in southeast China at that time (Chen and Zhou, 1999). Recent studies indicates that transformation from an E-W-trending Indosinian tectonic regime into a NE-trending Pacific tectonic regime in eastern China took place during the Late Jurassic to Early Cretaceous (Mao et al., 2003). Consequently, the geodynamic setting in southeast China at the beginning of the Early Cretaceous might be related to the same tectonic regime transformation as that in east China.

5.2 Nature of the mantle source

Some geochemical and isotopic data on basalts from the coastal areas of Zhejiang and Fujiang provinces have given rise to controversies over claims for an enriched versus depleted mantle beneath southeast China in the Late Mesozoic (Xing et al., 1999). The Early Cretaceous mafic dikes are widespread throughout northern Jiangxi, which makes it possible to discuss the nature of the mantle source areas in southeast China in the Cretaceous. It is necessary for the sake of understanding the nature of the source areas for the mafic dikes to discuss whether basaltic magma was affected by strong crustal contamination en route to the surface. The following several lines of evidences suggest that most of the basaltic magmatisms studied were not significantly affected by crustal contamination: (1) the northern Jiangxi mafic dikes were emplaced along faults in an extensional tectonic regime. Consequently, the basaltic magma resided for only a short time in the crust and ascended very quickly through the lithosphere; (2) the Nb/Ta ratios of these dikes range from 16.5 to 21.5 with an average of 18.5, which is slightly higher than those of primitive mantle (17.5±2.0) and significantly higher than those of continental crust (11.0) (Taylor and McLennan, 1995); (3) the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ for the mafic dikes range from 0.7055 to 0.7095 and 0.5119 to 0.5122, respectively, which are similar to those of the Late Mesozoic basalts in the coastal area of southeast China with $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ranging from 0.70667 to 0.71061 and 0.5120 to 0.5124, respectively, and to those of lamprophyres in Laowangzhai gold deposits from Yunnan Province and Xikuangshan tungsten deposits from Hunan Province, which were not affected by contamination from crust during ascension of the magma from the mantle to the surface (Xie et al., 2001; Xie and Hu, 2002; Huang et al., 2002). Hence, crust contamination had a negligible effect upon the magma responsible for these dikes.

Recent studies indicate that the basaltic underplating occurred in southeast China in the Late Mesozoic (Zhou and Li, 2000; Yu et al., 2003). The contents of large ion lithophile elements (LILLE), high strength field elements (HSFE) and light rare earth elements (LREE) for the mafic dikes are higher than those of the magmatic granulite derived from the lower crust (Yu et al., 2003; Fig. 3). Additionally, as noted above, the magma responsible for the mafic dikes rose very quickly and resided for only a short time in the lower crust. Hence, by contrast to MORB, such features for the mafic dikes as enrichment in LILE and LREE with $\varepsilon_{Sr}(t)>0$ and $\varepsilon_{Nd}(t)<0$ are attributed to an enriched lithospheric mantle other than by mantle mixed with lower crust. Primitive mantle Nb (0.62 ppm)-normalized trace element spidergrams for the mafic dikes indicate characteristics of the mantle sources. Moreover, the Nb content of the enriched mantle is higher than that of the depleted mantle. The Nb contents of all the mafic dikes are higher than those of the primitive mantle, and the primitive mantle-normalized spidergrams show left-inclined and slightly dispersed patterns (Fig. 5), suggesting that the magma source was probably heterogeneous enriched mantle (Myers and Breitkopf, 1989), which is supported by a large variation in incompatible elements. The Nb/U and Ce/Pb ratios for the mafic dikes are 6.9±0.8 and 8.0±2.9, respectively, which are significantly lower than those (40±5, 25±5, respectively) for MORB and OIB (Hoffman et al., 1986), meanwhile the Nb/La ratio for the mafic dikes is as low as 0.29±0.05. All the features indicate that the mafic dikes cannot be attributed to partial melt of asthenospheric mantle (Miller et al., 1999), and the source of the mafic dikes is similar to that of other continental basalts that resulted from a mixture of such end members as DMM and HIMU and EM I and EM II mantle (Zinlder and Hart, 1986).

The above-mentioned geological and geochemical features indicate that the magma responsible for the mafic dikes was little contaminated with a crustal component en route. The geochemical features of the dikes are probably, in addition to asthenospheric mantle, attributable to enriched continental lithospheric mantle induced by dehydration and/or melting of subducted slabs, which is supported by the negative Nb, Ta, Ti anomalies (Xu, 1999). Rock et al. (1990) have demonstrated that the geodynamic setting of juvenile lamprophyres with negative Nb, Ta, Ti anomalies is not beyond the subduction setting. Southeast China during the Cretaceous time lay in the NNE-trending Pacific plate tectonic domain. Although northern Jiangxi was far away from the Pacific subduction zones (Li, 2000), it seems that it was affected by long-distance and lagged subduction. Therefore, there is evidence that the source area of the relatively young lamprophyres were related to enriched lithosphere mantle resulting from infiltration of upper crust-derived fluids into the mantle responding to early subduction. The REE geochemical features for the mafic dikes suggest the presence of residual garnet in the source area and rocks derived from the significantly deep garnet lherzolite. In addition, the thickened crust and basaltic underplating took place in southeast China from the Indosinian epoch to Late Cretaceous time (Wang et al., 2002; Yu et al., 2003; Zhou and Li, 2000), and the underplating had reached as far as the Xiangshan area in central Jiangxi in the Cretaceous (Fan et al., 2001), while large-scale lithospheric thinning occurred in southeast China in the Late Mesozoic (Wu et al., 2003). All the features indicate that extension in southeast China in the Early Cretaceous was closely related to lithospheric thinning and basaltic underplating.

Only preliminary study of the spatial and temporal evolution of the mantle source area in southeast China in the Early Cretaceous has been made (Li and McCulloch, 1998). The development of the Early Cretaceous mafic dikes in northern and southern Jiangxi has created a favorable opportunity to do research on the nature of the lithosphere mantle in different areas of southeast China. This is because the mafic dikes in northern and southern Jiangxi are significantly different from each other in geochemical characteristics, as follows: (1) the mafic dikes in northern Jiangxi are calc-alkaline, while those in southern Jiangxi are tholeiitic; (2) the mafic dikes in northern Jiangxi are characterized by strong negative Nb, Ta,Ti anomalies with Nb/La ratios ranging from 0.23 to 0.38, with most of the samples showing negative Zr, Hf anomalies, while those in southern Jiangxi are characterized by weak negative Nb, Ta, Ti anomalies with Nb/La ratios of 0.44-0.95 with an average of 0.80 (Fig. 3); (3) the northern Jiangxi mafic dikes exhibit uniform LREE patterns and dispersing HREE patterns with little variation in La/Sm (4.9-5.6) and broad variation in Sm/Yb (1.9-4.4), while those in southern Jiangxi show dispersing LREE patterns and uniform HREE patterns with a broad variation in La/Sm (2.0-6.0) and little variation in Sm/Yb (1.6-2.3) (Fig. 4), and fractional degrees of LREE and HREE for the rocks from southern Jiangxi are significantly smaller than those from northern Jiangxi, which suggests that the rocks in southern Jiangxi were derived from the shallow spinel mantle, while the rocks in northern Jiangxi were derived from the deep garnet mantle; (4) Solid-liquid partition coefficients for Th-U and Rb-Sr element-couples during the evolutionary process of the basic magma (SiO_2<55%) are the same (Williams and Gill, 1989), and consequently, the Th/U and Rb/Sr ratios are representative of the mantle source. The Th/U and Rb/Sr ratios for the mafic dikes in northern Jiangxi are 4.9±0.7and 0.11±0.07, respectively, similar to those (4.8 and 0.12) for the Late Cretaceous mafic dikes in southern Hainan (Ge et al., 2003), while those for the mafic dikes in south Jiangxi are 3.6±0.4 and 1.5±1.1, respectively; (5) The $\varepsilon_{Nd}(t)$, $(^{143}Nd/^{144}Nd)_i$ and $(^{87}Sr/^{86}Sr)_i$ values for the mafic dikes in northern Jiangxi are -7.9, 0.5121 and 0.7069 on the average, respectively, whereas $\varepsilon_{Nd}(t)$, $(^{143}Nd/^{144}Nd)_i$ and $(^{87}Sr/^{86}Sr)_i$ for the mafic dikes in southern Jiangxi are +4.3, 0.5127 and 0.7045 (Li and McCulloch, 1998) on the average, respectively. All these features indicate that the source areas of the mafic dikes in northern and southern Jiangxi are significantly different in character, although the whole of southeast China in the Early Cretaceous had the same lithospheric extensional regime. The mafic dikes in northern Jiangxi were derived from metasomatic mantle with enrichment in large ion lithopile element (LILE) and isotopic fluids induced by early subduction, which is similar to the Early Cretaceous diabase dikes in the coastal area of Zhejiartg (Chen and Zhou, 1999). Whereas the mafic dikes in southern Jiangxi were derived from long-term depleted mantle which were more recently influenced by CO_2 and H_2O fluids rich in incompatible elements and bulk silicate earth isotopes that might be related to lithospheric mantle replacement by asthenosphere for thermal diffusion (Li and McCulloch, 1998; Xu et al., 2002; Xu et al., 2003) and/or metasomatic fluids induced by subduction in the Cretaceous (Li and McCulloch, 1998). The above-mentioned differences in geochemical characteristics between the source areas of the mafic dikes in southern and northern Jiangxi can be attributed to differences in composition of the lithospheric mantle and/or in the depth of the magma chamber. Recent study of agpaitic lamprophyre from northeast Hunan indicates that metasomatic primitive mantle related to fluid/melting from the asthenosphere occurred at the bottom of the lithospheric mantle (Jia et al., 2002). Therefore, the present data suggest two possible reasons and it is necessary to do further research. Regional differences in composition of the lithosphere are also responsible for differences in character of the source areas for the Late Mesozoic mafic dikes in southern Hainan, in the coastal area of Fujian and in northern Guangdong (Ge et al., 2003).

6 Conclusions

The mafic dikes in northern Jiangxi and in the Dajishan area, southern Jiangxi were emplaced synchronously with an isotopic age of 140±Ma. Taking this in combination with the data on contemporary hotspot agpaitic lamprophyre and granitoids, we can conclude that lithospheric extension did occur in southeast China in the Early Cretaceous. The magma responsible for the northern Jiangxi mafic dikes in this region was derived from enriched lithospheric mantle resulting from asthenosphere upwelling and infiltration of upper crust-derived fluids induced by the subduetion of the paleo-Pacific slab beneath the East China. This magma is distinguished from that responsible for the contemporary mafic dikes in the Dajiashan area, southern Jiangxi. The mafic dikes in southern and northern Jiangxi were derived from lithospheric mantle different in composition and/or from basaltic magma from different depths.

Acknowledgements

This research was supported jointly by the National Natural Science Foundation of China (Grant No. 40402011 and No. 40434011), the Ministry of Science and Technology of China (G1999043200) and the Chinese Academy of Sciences (KZCX3-SW-125) and China Postdoctoral Science Foundation. We are grateful to the geological department of the Wushan copper deposit, to the No. 270 Institute, Nanchang, and to Liu Chongqi from the No. 265 geological team for field trips. We thank Prof. Zhang Lishen for correcting the English of an earlier draft of the manuscript.

Manuscript received June 11, 2004
accepted Nov. 4, 2004
edited by Xie Guanglian and Susan Turner

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