Petrogenesis of post-orogenic syenites in the Sulu Orogenic Belt, East China: geochronological, geochemical and Nd–Sr isotopic evidence

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Abstract

The Jiazishan alkaline complex in the eastern Sulu ultrahigh pressure (UHP) metamorphic orogenic belt of eastern China is composed of potassic to ultrapotassic pyroxene syenite, quartz syenite and associated mafic dikes. A SHRIMP zircon $^{206}\text{Pb}/^{238}\text{U}$ age of 215 ± 5 Ma was obtained for the quartz syenite and mineral $^{40}\text{Ar}/^{39}\text{Ar}$ dating gave emplacement ages of 214.4 ± 0.3 and 214.6 ± 0.6 Ma for the pyroxene syenite and 200.6 ± 0.2 Ma for the mafic dike. These dates establish that the Jiazishan Complex was emplaced shortly after the UHP metamorphic event at 240 to 220 Ma due to the continental collision between the North China and Yangtze cratons. The ultrapotassic mafic dikes, with $\text{K}_2\text{O} \approx 4.4\text{--}6.4$ wt.% and $\text{K}_2\text{O}/\text{Na}_2\text{O} \approx 3.5$, have high MgO (8.06–12.44 wt.%), Ni (119–319 ppm) and Cr (477–873 ppm) and moderately low $\text{CaO}/\text{Al}_2\text{O}_3$ (~ 0.76) and TiO_2 (~ 1.12 wt.%). They also have high Sr ($^{87}\text{Sr}/^{86}\text{Sr} \sim 0.7073$), low Nd ($\epsilon_{\text{Nd}} = -16.5$) isotopic ratios, enriched LILE ($\text{Ba}/\text{La} = 66\text{--}74$), LREE [$(\text{La}/\text{Yb})_N = 28\text{--}33$] and depleted HFSE ($\text{La}/\text{Nb} = 4\text{--}6$). It appears that the mafic dikes were derived from a refractory, re-enriched lithospheric mantle source. The syenites have Sr and Nd isotopic compositions similar to the mafic dikes, implying a common origin. Geochemical and isotopic modeling suggests that the pyroxene syenites may have been generated by early fractionation of clinopyroxene and olivine, coupled with minor amounts of crustal contamination, of a mafic magma that had a similar composition to the mafic dikes. Subsequent fractionation of feldspar-dominated assemblages, with minor or no contamination, would result in the quartz syenites. This post-orogenic magmatism, resulting most likely in an extensional setting, provides time constraints on the major geodynamic transition from convergence to extension at the eastern margin of the North China craton. The Jiazishan potassic magmatism and geodynamic transition from convergence to extension can be explained by convective removal of the lower lithospheric mantle. © 2004 Elsevier B.V. All rights reserved.

Keywords: Post-orogenic magmatism; Potassic to ultrapotassic magmatism; Sulu UHP belt; North China craton

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1. Introduction

Syenites and alkaline felsic rocks are commonly intimately associated with alkaline mafic rocks, especially alkali to transitional basalts. The origin of the more evolved rocks, however, remains controversial. Models proposed for the generation of syenites may be divided into three groups. First, syenite magmas may originate by partial melting of crustal rocks resulting from an influx of volatiles (e.g., Lubala et al., 1994) or in a closed system at pressures typical of the base of over-thickened crust (Huang and Wyllie, 1981). Second, syenite magmas may be products of partial melting of metasomatized mantle (Sutcliffe et al., 1990; Lynch et al., 1993) or the residual melts formed by differentiation of alkali basalt magma (Parker, 1983; Brown and Becker, 1986; Thorpe and Tindle, 1992). Third, syenites may result by magma mixing processes, particularly mixing of basic and silicic melts with subsequent differentiation of the hybrid liquids (Barker et al., 1975; Sheppard, 1995; Zhao et al., 1995; Litvinovsky et al., 2002), or by mixing of mantle-derived, silica-undersaturated alkaline magmas with lower crustally derived granitic magmas (e.g., Dorais, 1990). This range of petrogenetic models also reflects the diversity of geological settings in which syenite magmas are generated. For example, it is generally assumed that these rocks characterize non-orogenic, within-plate environments. However, several alkaline associations, although not strictly non-orogenic, post-date orogenic episodes by a short interval of time, such as the Permian–Triassic Western Mediterranean province (Bonin et al., 1987), the Pan-African Arabian Shield (Harris, 1985), in Tibet (Turner et al., 1996; Miller et al., 1999; Williams et al., 2004) and other examples (Sylvester, 1989). In this context, it is important to undertake detailed studies on plutonic complexes where one particular mechanism of syenite magma production can be established with confidence.

The Jiazishan Complex, exposed in the Sulu ultrahigh pressure (UHP) orogenic belt of NE China and comprised of an intrusive association of basanite–pyroxene syenite–quartz syenite, is one such example. In this paper, we present petrographic, geochronological, geochemical and Sr–Nd isotopic data for these rocks and demonstrate that the syenite

magmas were mainly formed as a result of crystal fractionation from enriched lithospheric mantle-derived magmas, with little or no assimilation of crustal material. Interpretation of the data leads to an integrated model of syenite genesis in a post-orogenic extensional setting.

2. Geological setting and petrography

2.1. Regional context

The Dabie–Sulu orogenic belt in east-central China (Fig. 1a) contains the largest distribution of UHP metamorphic rocks in the world, marking the collision zone between North China and Yangtze cratons (Huang, 1978; Wang et al., 1995; Cong, 1996). The Sulu terrane was offset to the north by sinistral movement on the Tanlu Fault of about 500 km (Xu and Zhu, 1994). Metamorphic rocks of the Sulu UHP belt are mainly amphibolite facies granitic gneisses, with subordinate amounts of coesite-bearing eclogites (e.g., Yang and Smith, 1989; Hirajima et al., 1990, 1992; Enami and Zang, 1993) and other UHP metamorphic rocks such as ultramafics (Yang et al., 1993; Zhang et al., 1994), marbles (Kato et al., 1997), pelitic schists (Zhang et al., 1995) and meta-granitoids (Hirajima et al., 1992). These UHP metamorphic rocks occur as sporadic lenticular bodies in the regional granitic gneisses. The margins of most eclogite lenses are transformed to amphibolite and reveal a significant amphibolite facies overprint after UHP metamorphism (Yao et al., 2000). While deep subduction of the Yangtze continental crust to over 120 km is evident from the occurrence of micro-diamond in eclogites (Xu et al., 1992), exhumation of more deeper rocks from over 200 km was deduced from exsolution minerals in eclogitic garnet (Ye et al., 2000). Abundant Sm–Nd mineral isochron and U–Pb zircon ages have documented that the continental collision and UHP metamorphism took place in the Early–Middle Triassic at 240–220 Ma (e.g., Ames et al., 1993; Li et al., 1993a,b; Chavagnac and Jahn, 1996; Hacker et al., 1998; Zheng et al., 2002; Liu et al., 2004).

High-K calc-alkaline granitic rocks are widely distributed in the Sulu orogenic belt, but most of them formed in the Late Jurassic (160–150 Ma) and

Fig. 1. Location maps showing position of the Jiazishan Complex in eastern China. (a) Relation to the Dabie–Sulu ultrahigh pressure metamorphic belt; (b) position within the Jiaodong Peninsula and (c) distribution of components in the Jiazishan Complex.

Early Cretaceous (130–125 Ma) (Wang et al., 1998; Zhang et al., 2003). Only one syenitic complex—the Jiazishan Complex—has been reported to be of Late Triassic age (Lin et al., 1992; Chen et al., 2003).

2.2. Jiazishan syenites

The Jiazishan Complex, located in the Jiaodong Peninsula (East China) and intruded into the Sulu UHP metamorphic belt, is one of the easternmost outcrops in the Sulu UHP metamorphic belt (Fig. 1b). It covers an area of ~140 km² and comprises at

least two magmatic sequences (Lin et al., 1992). Field mapping and detailed description of the Jiazishan rocks reveal the following sequence of magmatic events: (1) intrusion of pyroxene syenite and quartz syenite; (2) intrusion of biotite granite into the syenite and (3) intrusion of mafic dikes into the syenite.

Five alkaline phases (Fig. 1c) are distinguished in the complex according to field and petrographic data.

Phase 1 is a trachtyoid biotite–pyroxene syenite. Samples (JZS-11 and JZS-12) from phase 1 are composed of 54–68% subhedral alkali feldspar, 16–26% plagioclase (with composition An_{51–55}), 2–11%

biotite, 5–12% amphibole and 2–8% pyroxene, with minor olivine, titanite and magnetite. The rocks are porphyritic and characterized by phenocrysts of pyroxene and perthitic alkali feldspar. Alkali feldspar laths define a subparallel flow direction. Perthitic textures are abundant including mesoperthite intergrowth of alkali and plagioclase feldspar and micropertthite exsolution intergrowth of sodium- and potassium-rich feldspars. Plagioclase is weakly sericitized.

Phase 2 is a porphyritic biotite–pyroxene syenite. Samples (JZS-7 to JZS-10 in Table 3) are from this phase. The rocks are medium- to coarse-grained and porphyritic, consisting of up to 35% phenocrysts of perthitic alkali feldspar in a microcrystalline groundmass of 4–6% pyroxene, 3–9% biotite, 8–25% plagioclase and 40–50% alkali feldspar. Minor olivine (<1%) is found as inclusions in the pyroxene. Some pyroxenes are also altered to hornblende. Alkali-feldspar phenocrysts range from 2 to 7 cm long and some grains are concentrically zoned. Mafic enclaves (samples JZS-7-1 and JZS-8-1) are also common in this phase and have similar mineral assemblages to the syenites, but with more abundant mafic minerals including biotite, hornblende, olivine and pyroxene. Plagioclase is weakly sericitized.

Phase 3 is a coarse-grained biotite–pyroxene syenite. Samples (JZS-13 to 17 in Table 3) from this phase have similar mineralogy to the trachytoid biotite–pyroxene syenite.

Phase 4 is a quartz syenite. Samples (JZS-1 to JZS-6 in Table 3) from this phase have 70% alkali feldspar, 10% plagioclase (with composition An_{20-22}) and 10% quartz, with accessory amphibole, clinopyroxene, apatite, titanite and magnetite. Perthitic alkali feldspars are observed as inclusions in non-perthitic varieties. Quartz occurs as inclusions in the alkali feldspar or as anhedral grains interstitial to other minerals.

Phase 5 is a mafic dike that intruded into the syenites. Samples JZS-D-2 to JZS-D-5 are from this phase and are characterized by local phenocrysts of pyroxene and minor biotite in a groundmass of 35% pyroxene, 35% alkali feldspar, 10% olivine, 5% plagioclase, 5% hornblende and 10% biotite. The rocks have a massive texture. Plagioclase is weakly sericitized and olivine is locally replaced by iddingsite.

Lin et al. (1992) determined the age of the pyroxene syenite and intrusive biotite granite as 220–217 Ma, using whole rock and biotite Rb–Sr geochronology, but they did not relate the origin of the complex to the overall development of the UHP belt. Guo et al., (2001b) and Chen et al. (2003) reported zircon U–Pb ages of 225–205 Ma for the pyroxene syenite, but no detailed geochemical data were presented.

3. Analytical methods

3.1. Zircon SHRIMP U–Pb dating

SHRIMP U–Pb zircon analyses were performed at Curtin University of Technology. Sample preparation and basic operating procedures are described by Nelson (1997). An average mass resolution of 4800 was obtained during measurement of the Pb/Pb and Pb/U isotopic ratios and Pb/U ratios were normalized to those measured on the standard zircon [CZ3- ($^{206}\text{Pb}/^{238}\text{U}=0.0914$)], with the calibration error on the standards being 1.54%. The $^{206}\text{Pb}/^{238}\text{U}$ ages are considered the most reliable, since the zircons are concordant and the low count rates on ^{207}Pb result in large statistical uncertainties, making the $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{235}\text{U}$ ratios less sensitive measures of age for younger zircons (Compston et al., 1992). The measured ^{204}Pb on the zircons was similar to the standard, and therefore common lead corrections were made assuming an isotopic composition of Broken Hill lead, since common lead is considered to be mainly related to surface contamination (Nelson, 1997). Data reduction was performed using the Krill 007 program of P.D. Kinny applying the ^{208}Pb correction, since there is no evidence of post-crystallization disturbance to the U–Pb–Th system. Errors on individual analyses are at the 1σ level (Table 1) and errors on pooled analyses are quoted at 2σ or 95% confidence.

3.2. $^{40}\text{Ar}/^{39}\text{Ar}$ dating

Hornblende, K-feldspar and whole rock samples from the Jiazishan Complex were dated by $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating and single-grain fusion methods using furnace and laser heating techniques.

Table 1

SHRIMP zircon U/Pb isotopic data for quartz syenite (JZS-3) from Jiazishan Complex

Spot	U	Th	Th/ U	Pb	$^{204}\text{Pb}/$ ^{206}Pb	f206%	$^{207}\text{Pb}^a/$ $^{206}\text{Pb}^a$	$\pm 1\sigma$	$^{208}\text{Pb}^a/$ $^{206}\text{Pb}^a$	$\pm 1\sigma$	$^{206}\text{Pb}^a/$ ^{238}U	$\pm 1\sigma$	$^{207}\text{Pb}^a/$ ^{235}U	$\pm 1\sigma$	$^{208}\text{Pb}^a/$ ^{232}Th	$\pm 1\sigma$	Age $\pm 1\sigma$ (Ma)			
	(ppm)	(ppm)		(ppm)													$^{206}\text{Pb}^a/$ ^{238}U	$^{207}\text{Pb}^a/$ ^{235}U	$^{207}\text{Pb}^a/$ $^{206}\text{Pb}^a$	$^{208}\text{Pb}^a/$ ^{232}Th
JZS-3-1	475	435	0.92	20	0.00118	1.893	0.04223	0.00412	0.2692	0.0100	0.0343	0.0007	0.20	0.02	0.0101	0.0004	217 $\pm$ 4	185 $\pm$ 17	0 $\pm$ 43	203 $\pm$ 8
JZS-3-2	662	633	0.96	26	0.00016	0.249	0.05056	0.00198	0.2992	0.0053	0.0335	0.0006	0.23	0.01	0.0105	0.0003	213 $\pm$ 4	213 $\pm$ 9	221 $\pm$ 91	211 $\pm$ 5
JZS-3-3	720	1404	1.95	35	0.00015	0.235	0.04842	0.00159	0.6082	0.0060	0.0341	0.0006	0.23	0.01	0.0106	0.0002	216 $\pm$ 4	208 $\pm$ 7	120 $\pm$ 74	214 $\pm$ 4
JZS-3-4	83	61	0.73	4	0.00392	6.269	0.06075	0.02282	0.3084	0.0534	0.0300	0.0010	0.25	0.10	0.0126	0.0022	190 $\pm$ 6	227 $\pm$ 78	630 $\pm$ 652	253 $\pm$ 44
JZS-3-5	429	605	1.41	16	0.00085	1.357	0.06113	0.00544	0.4803	0.0140	0.0264	0.0005	0.22	0.02	0.0090	0.0003	168 $\pm$ 3	204 $\pm$ 17	644 $\pm$ 192	181 $\pm$ 6
JZS-3-6	38	78	2.08	2	0.00474	7.579	0.02887	0.04208	0.6184	0.1033	0.0311	0.0017	0.12	0.18	0.0092	0.0016	198 $\pm$ 10	119 $\pm$ 152	0 $\pm$ 107	186 $\pm$ 33
JZS-3-7	186	623	3.35	11	0.00001	0.012	0.05443	0.00499	1.0196	0.0189	0.0333	0.0007	0.25	0.02	0.0101	0.0003	211 $\pm$ 4	226 $\pm$ 20	389 $\pm$ 207	203 $\pm$ 6
JZS-3-8	260	675	2.59	14	0.00120	1.914	0.04053	0.00514	0.7849	0.0162	0.0324	0.0007	0.18	0.02	0.0098	0.0003	205 $\pm$ 4	169 $\pm$ 20	0 $\pm$ 61	197 $\pm$ 6
JZS-3-9	274	656	2.40	15	0.00038	0.611	0.04963	0.00486	0.7399	0.0148	0.0343	0.0007	0.23	0.02	0.0106	0.0003	217 $\pm$ 4	214 $\pm$ 20	178 $\pm$ 213	213 $\pm$ 6
JZS-3-10	773	1693	2.19	39	0.00010	0.155	0.05145	0.00175	0.6587	0.0064	0.0339	0.0006	0.24	0.01	0.0102	0.0002	215 $\pm$ 4	219 $\pm$ 8	261 $\pm$ 78	205 $\pm$ 4
JZS-3-11	56	92	1.65	3	0.00188	3.015	0.04462	0.01722	0.4668	0.0429	0.0331	0.0011	0.20	0.08	0.0094	0.0009	210 $\pm$ 7	188 $\pm$ 67	0 $\pm$ 107	188 $\pm$ 18
JZS-3-12	1074	2763	2.57	62	0.00016	0.260	0.04816	0.00141	0.8097	0.0061	0.0357	0.0006	0.24	0.01	0.0112	0.0002	226 $\pm$ 4	216 $\pm$ 7	108 $\pm$ 65	226 $\pm$ 4
JZS-3-13	470	815	1.73	22	0.00000	0.000	0.05447	0.00112	0.5614	0.0060	0.0344	0.0006	0.26	0.01	0.0111	0.0002	218 $\pm$ 4	233 $\pm$ 6	391 $\pm$ 46	224 $\pm$ 5
JZS-3-14	118	233	1.98	6	0.00057	0.912	0.05243	0.00899	0.6095	0.0243	0.0344	0.0008	0.25	0.04	0.0106	0.0005	218 $\pm$ 5	226 $\pm$ 36	304 $\pm$ 350	214 $\pm$ 10

f206% denotes (common ^{206}Pb)/(total measured ^{206}Pb).^a Radiogenic lead.

Table 2

 $^{40}\text{Ar}/^{39}\text{Ar}$ data for K-feldspar, hornblende and whole rocks for the pyroxene syenites and mafic dike from the Jiazishan Complex

JZS-13 amphibole									
<i>T</i> (°C)	Cum. 39	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	Ca/K	Date (Ma)	1 σ
650	0.019	8.59e-01	4.87e-01	5.02e-01	3.20e+02	3.72e+02	1.62	317.3	3.7
725	0.079	1.62e-01	6.12e-01	1.40e-01	8.88e+01	5.50e+02	2.04	204.2	4.5
800	0.103	4.42e-02	1.43e-04	1.43e-04	5.66e+01	1.28e+03	0.00	215.5	2.7
850	0.128	2.57e-02	7.80e-02	1.31e-04	5.09e+01	1.98e+03	0.26	214.6	5.4
900	0.154	2.07e-02	4.39e-01	1.29e-04	4.99e+01	2.42e+03	1.46	217.1	3.0
925	0.176	2.28e-02	8.85e-01	1.54e-04	5.03e+01	2.21e+03	2.95	215.9	4.2
950	0.214	3.63e-02	1.69e+00	1.97e-02	5.00e+01	1.38e+03	5.63	196.1	3.0
975	0.240	1.91e-02	4.46e+00	4.30e-02	5.08e+01	2.66e+03	14.88	225.1	2.8
1000	0.287	2.60e-02	6.66e+00	1.71e-01	5.13e+01	1.98e+03	22.28	219.4	2.1
1025	0.364	2.01e-02	7.16e+00	2.24e-01	4.94e+01	2.46e+03	23.94	218.8	1.0
1050	0.451	1.51e-02	6.85e+00	2.22e-01	4.70e+01	3.11e+03	22.90	214.1	1.2
1075	0.569	8.05e-03	6.83e+00	2.49e-01	4.54e+01	5.64e+03	22.82	216.2	1.1
1100	0.695	6.77e-03	6.41e+00	2.42e-01	4.46e+01	6.58e+03	21.44	214.1	1.4
1150	0.792	7.06e-03	6.05e+00	2.13e-01	4.43e+01	6.27e+03	20.20	212.3	0.7
1200	0.899	1.07e-02	6.83e+00	2.26e-01	4.50e+01	4.19e+03	22.83	210.8	1.1
1400	1.000	3.14e-02	1.16e+01	2.60e-01	5.15e+01	1.64e+03	38.84	215.0	1.2

Sample mass=402.3 mg; *J*-value=0.002917±0.000003; Integrated date=215.7±0.5 Ma (^{39}Ar volume=0.1559e-11 ccSTP/g; $^{40}\text{Ar}^*$ volume=0.6787e-10 ccSTP/g); Plateau age=214.6±0.6 Ma (1000–1400 °C; 71.3% ^{39}Ar).

JZS-11 K-feldspar

<i>T</i> (°C)	Cum. 39	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	Date (Ma)	1 σ
600	0.008	8.09e-05	8.09e-05	8.09e-05	5.73e+01	7.08e+05	278.7	3.3
700	0.115	5.97e-06	6.30e-02	1.18e-02	4.05e+01	6.78e+06	201.2	0.3
800	0.230	5.59e-06	5.70e-02	3.66e-03	4.10e+01	7.34e+06	203.7	0.5
850	0.247	3.70e-05	3.70e-05	3.70e-05	3.90e+01	1.06e+06	194.3	1.0
900	0.299	1.23e-05	4.55e-02	1.23e-05	4.06e+01	3.31e+06	201.9	0.7
950	0.330	2.08e-05	3.42e-03	2.08e-05	4.03e+01	1.94e+06	200.3	0.7
1000	0.352	2.88e-05	2.88e-05	2.88e-05	4.07e+01	1.42e+06	202.4	0.9
1025	0.415	1.02e-05	1.69e-02	2.35e-03	4.22e+01	4.15e+06	209.2	0.5
1075	0.484	9.29e-06	1.84e-02	7.36e-03	4.31e+01	4.64e+06	213.5	0.4
1100	0.546	1.03e-05	1.69e-02	6.29e-03	4.31e+01	4.18e+06	213.5	0.4
1125	0.647	6.33e-06	2.16e-02	1.38e-02	4.35e+01	6.87e+06	215.3	0.4
1175	0.791	4.69e-06	1.39e-02	1.13e-02	4.33e+01	9.23e+06	214.4	0.6
1200	0.861	9.17e-06	3.22e-03	1.72e-03	4.34e+01	4.73e+06	214.7	0.3
1220	0.923	1.04e-05	3.41e-05	9.32e-04	4.35e+01	4.20e+06	215.3	0.3
1270	0.933	6.28e-05	6.28e-05	6.28e-05	4.21e+01	6.71e+05	208.9	1.0
1350	0.964	2.05e-05	2.05e-05	2.05e-05	4.41e+01	2.15e+06	218.1	0.6
1400	0.978	4.62e-05	4.62e-05	4.62e-05	4.47e+01	9.69e+05	221.0	1.3
1600	1.000	2.91e-05	2.91e-05	2.91e-05	4.90e+01	1.68e+06	240.9	1.3

Sample mass=305.6 mg; *J*-value=0.002917±0.000003; Integrated date=211.0±0.2 Ma (^{39}Ar volume=0.1074e-10 ccSTP/g; $^{40}\text{Ar}^*$ volume=0.4568e-09 ccSTP/g); Plateau age=214.4±0.3 Ma (1075–1220 °C; 50.8% ^{39}Ar).

JZS-D-01 whole rock

<i>T</i> (°C)	Cum. 39	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	Ca/K	Date (Ma)	1 σ
400	0.003	2.22e-04	2.22e-04	2.22e-04	2.99e+01	1.35e+05	0.00	150.6	2.4
450	0.005	3.33e-04	3.33e-04	3.33e-04	3.65e+01	1.10e+05	0.00	182.1	6.1
500	0.009	1.52e-04	1.52e-04	1.52e-04	3.41e+01	2.25e+05	0.00	170.7	7.2
600	0.029	7.32e-04	8.97e-02	3.29e-05	3.24e+01	4.42e+04	0.30	161.7	0.4
650	0.076	2.56e-04	1.63e-01	1.66e-02	3.60e+01	1.41e+05	0.54	179.7	0.3

Table 2 (continued)

JZS-D-01 whole rock									
<i>T</i> (°C)	Cum. 39	$^{36}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{40}\text{Ar}/^{36}\text{Ar}$	Ca/K	Date (Ma)	1 σ
700	0.168	1.84e−03	1.16e−01	4.60e−02	3.97e+01	2.16e+04	0.38	195.1	0.4
760	0.234	9.84e−06	5.18e−02	4.52e−02	3.97e+01	4.03e+06	0.17	197.3	0.9
840	0.340	6.10e−06	1.20e−01	4.65e−02	3.93e+01	6.45e+06	0.40	195.6	0.5
900	0.376	1.82e−05	1.11e−01	6.97e−03	3.99e+01	2.20e+06	0.37	198.4	0.3
950	0.432	5.23e−04	2.25e−01	4.45e−02	4.08e+01	7.80e+04	0.75	202.1	0.3
1000	0.508	8.55e−06	3.29e−01	6.69e−02	4.07e+01	4.76e+06	1.09	202.3	0.4
1050	0.609	6.43e−06	2.77e−01	7.50e−02	4.05e+01	6.30e+06	0.92	201.3	0.5
1100	0.717	6.01e−06	2.63e−01	6.33e−02	4.01e+01	6.67e+06	0.88	199.5	0.3
1150	0.831	5.90e−04	4.65e−01	4.71e−02	4.03e+01	6.82e+04	1.55	199.6	0.3
1200	0.928	3.26e−04	1.48e+00	4.14e−02	4.02e+01	1.24e+05	1.94	200.2	0.3
1250	0.964	1.83e−05	4.35e+00	2.92e−02	4.11e+01	2.24e+06	14.5	204.5	0.6
1300	0.976	5.09e−05	1.20e+01	5.09e−05	4.20e+01	8.26e+05	40.2	210.0	2.7
1600	1.000	2.71e−05	1.19e+01	4.18e−02	4.36e+01	1.61e+06	40.0	217.2	0.8

Sample mass=563.2 mg; *J*-value=0.002917±0.000003; Integrated date=197.9±0.2 Ma (^{39}Ar volume=0.5745e−11 ccSTP/g; $^{40}\text{Ar}^*$ volume=0.2283e−09 ccSTP/g); Plateau age=200.6±0.2 Ma (950–1200 °C; 55.2% ^{39}Ar).

Mineral separates (>99% pure) were prepared using conventional heavy liquid and magnetic separation techniques. After sieving, mineral grains in the range of 250–140 μm were ultrasonically cleaned in 0.5 N HCl, washed with distilled water and then dried and handpicked to remove any visible contamination.

The samples were irradiated in the VT-C position at the THOR Reactor in Taiwan for 30 h. In order to monitor the neutron flux in the reactor, two aliquots of the LP-6 Biotite standard were stacked along with the samples in each irradiation. Standards and samples were either incrementally heated or totally fused using a double-vacuum resistance furnace and/or a US LASER Nd-YAG laser operated in continuous mode, and the gas was measured by a VG-3600 mass spectrometer at the National Taiwan University. The *J*-values were calculated using argon compositions of the LP-6 biotite standard with an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 128.4±0.2 Ma (Renne et al., 1998). Ages were calculated from Ar isotope ratios measured after corrections made for mass discrimination, interfering nuclear reactions, decay of radiometric isotopes, procedural blanks and atmospheric Ar contamination. Total gas ages were calculated from the sum total of the argon compositions of all the temperature steps. Plateau dates were calculated by the same approach, but utilizing only the adjacent temperature steps

yielding dates which are concordant with each other within 2 σ . The $^{39}\text{Ar}_\text{K}$, $^{38}\text{Ar}_\text{Cl}$ and $^{37}\text{Ar}_\text{Ca}$ release data potentially reflect the chemical compositions (K, Cl and Ca, respectively) of the samples. Ca/K and Cl/K ratios were calculated according to the relationships $\text{Ca/K}=3.319(\pm 0.17)\times^{37}\text{Ar}_\text{Ca}/^{39}\text{Ar}_\text{K}$ and $\text{Cl/K}=0.22(\pm 0.04)\times^{38}\text{Ar}_\text{Cl}/^{39}\text{Ar}_\text{K}$, obtained from the analyses of irradiated salts. The analytical results are given in Table 2 and the data are plotted graphically as age spectra in Fig. 3. All errors given in the tables and figures are at 1 σ .

3.3. Major and trace elements

After petrographic examination, 24 fresh rock samples were selected, crushed and powdered in an agate mill. Major elements were determined by X-ray fluorescence techniques on fused glass beads using Rigaku® RIX-2000 spectrometers at the National Taiwan University. The analytical procedures were the same as those described by Lee et al. (1997) and Wang et al. (2004), yielding analytical uncertainties better than ±5% (2 σ) for all major elements. The fused glass beads were powdered and dissolved using an HF/HNO₃ (1:1) mixture in screw-top Teflon beakers for >2h at ~100 °C, followed by evaporation to dryness, then refluxing in 7N HNO₃ for >12h at ~100 °C and, finally, diluting the sample

solution by 2% HNO_3 . An internal standard solution of 5 ppb Rh and Bi was added and the spiked solution was diluted with 2% HNO_3 to a sample/solution weight ratio of 1:2000. An internal standard was used for monitoring the signal shift during inductively coupled plasma-mass spectrometry (ICP-MS) measurements using an Agilent 7500s spectrometer at the National Taiwan University; it shows a good stability range with $\sim 10\%$ variation. The precision was generally better than $\pm 5\%$ (2σ) for most trace elements, as shown by the statistics of duplicate analyses on five rock standards AGV-1, AGV-2, GSP-1, JB-1 and JG-1 (see Appendix Table A).

3.4. Sr and Nd isotopes

Samples for isotopic analysis were dissolved in Teflon bombs after being spiked with ^{84}Sr , ^{87}Rb , ^{150}Nd and ^{147}Sm tracers prior to $\text{HF}+\text{HNO}_3$ (with a ratio of 2:1) dissolution. Rubidium, Sr, Sm and Nd were separated using conventional ion exchange procedures and measured using a Finnigan MAT 262 multi-collector mass spectrometer at the Institute of Geology and Geophysics, Chinese Academy of Sciences, China. Procedural blanks were <100 pg for Sm and Nd and <500 pg for Rb and Sr. $^{143}\text{Nd}/^{144}\text{Nd}$ were corrected for mass fractionation by normalization to $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios normalized to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$. Typical within-run precision (2σ) for Sr and Nd was estimated to be ± 0.000015 . The measured values for the La Jolla and BCR-1 Nd standards and the NBS-607 Sr standard were $^{143}\text{Nd}/^{144}\text{Nd}=0.511853\pm 7$ ($2\sigma_n$, $n=3$) and 0.512604 ± 7 ($2\sigma_n$, $n=3$) and $^{87}\text{Sr}/^{86}\text{Sr}=1.20042\pm 2$ ($2\sigma_n$, $n=12$) during the period of data acquisition.

4. Results

4.1. Geochronology

SHRIMP U–Pb dating of zircon from the quartz syenite (JZS-3) defines a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 215 ± 5 Ma (Fig. 2). A K-feldspar sample from the trachytoid pyroxene syenite (sample JZS-11) was dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method and yields a plateau age of 214.4 ± 0.3 Ma at high temperature

Fig. 2. SHRIMP U–Pb zircon concordia diagram for quartz syenite (JZS-3) from the Jiazishan Complex.

(Fig. 3a). A hornblende sample from porphyritic pyroxene syenite sample JZS-13 gives a plateau age of 214.6 ± 0.6 Ma, composed of the steps with indistinguishable Ca/K ratio (22.56 ± 0.44 , Fig. 3b). These ages are consistent with the earlier Rb–Sr results of 220 ± 13 Ma (Lin et al., 1992) and zircon U–Pb TIMS ages of 225 ± 2 Ma and 211 ± 3 Ma for pyroxene and quartz syenite, respectively (Chen et al., 2003), and 211.9 ± 1.5 Ma and 205.4 ± 3.9 Ma for pyroxene syenites (Guo et al., 2001b). Our new data indicate that the emplacement age of the syenites ranges from 215 to 209 Ma. The whole rock sample of ultrapotassic mafic dike defines an $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 200.6 ± 0.2 Ma (Fig. 3c), constraining the emplacement age of the mafic dike. All these ages post-date the orogenic and UHP metamorphic ages of coesite-bearing eclogites in the Dabie–Sulu orogeny (240–220 Ma; Ames et al., 1993; Li et al., 1993a,b; Chavagnac and Jahn, 1996; Hacker et al., 1998; Webb et al., 1999; Zheng et al., 2002; Liu et al., 2004).

4.2. Geochemical characteristics

The geochemical and isotopic data for the syenites and mafic dike from the Jiazishan Complex are listed in Tables 3 and 4.

The Jiazishan syenites show a range in SiO_2 values from 54.44 to 64.20 wt.%. Nepheline-normative pyroxene syenites, mafic enclaves and the mafic dike represent a silica-undersaturated suite of rocks,

Fig. 3. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of (a) K-feldspar from pyroxene syenite sample JZS-11, (b) hornblende from pyroxene syenite sample JZS-13 and (c) whole rock mafic dike (JZS-D-01).

whereas the quartz syenites have normative quartz and are silica-saturated.

All samples plot in the alkaline field on the total alkali-silica (TAS) diagram (Fig. 4a). Three samples of mafic dike plot in the potassic trachybasalt field with $>10\%$ normative olivine (Table 3), whereas the other sample plots in the shoshonite field with $\text{Na}_2\text{O}-2<\text{K}_2\text{O}$ (Table 3). Pyroxene syenite samples plot in the latite and trachyte fields and quartz syenite plots in the trachyte field. One mafic enclave sample plots in the phonotephrite field and the other sample plots in the latite field (Fig. 4a). In the Na_2O vs. K_2O plot (Fig. 4b), pyroxene and quartz syenites belong to the shoshonitic series, whereas the mafic dike samples, having $\text{K}_2\text{O}>3$ wt.%, $\text{K}_2\text{O}/\text{Na}_2\text{O}>2$, $\text{MgO}>3$ wt.% and high Cr (477–873 ppm), are ultrapotassic rocks as defined by Foley et al. (1987).

Fig. 4c shows the composition of the syenites and mafic dikes in terms of their molar ratios of $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ (A/CNK) and $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ (A/NK). Based on these ratios, the pyroxene syenite and mafic dikes are metaluminous, whereas the quartz syenites straddle the metaluminous–peraluminous boundary. All rocks of the Jiazishan Complex display regular trends of increasing Al_2O_3 , SiO_2 , Na_2O , K_2O and decreasing CaO , Fe_2O_3 , TiO_2 , P_2O_5 , V, Cr and Ni with decreasing MgO (Figs. 5 and 6). Pyroxene syenites and mafic enclaves have high Sr, Ba and Rb, whereas quartz syenites have low Sr and Ba contents (Fig. 6d–f). The mafic dikes always have a separate trend (Figs. 5 and 6), indicating that they are not comagmatic with the syenites.

The more siliceous rocks of the Jiazishan Complex (quartz syenite, $\text{SiO}_2>60$ wt.%) display characteristics of A-type magmas as defined by Eby (1990), exhibiting anhydrous, hypersolvus mineralogy and an alkaline chemical affinity with low CaO (1.15–1.43 wt.%) and Sr and Ba concentrations (Table 3) and high Ga concentrations (>20 ppm). High concentrations of Zr, Nb, Ce and Y distinguish the Jiazishan quartz syenites from I- and S-type granites and classify them as an A-type granite on the 10000 Ga/Al vs. Zr and $\text{Na}_2\text{O}+\text{K}_2\text{O}$ discrimination diagrams (Fig. 7a and b) of Whalen et al. (1987).

The chondrite-normalized REE patterns of the pyroxene syenites (Fig. 8a) show LREE enrichment,

Table 3
Chemical compositions of rocks from the Jiazishan Complex

No.	JZS-01	JZS0-02	JZS-03	JZS-04	JZS-05	JZS-06	JZS-07-1	JZS-07-2	JZS-08-1	JZS-08-2	JZS-09	JZS-10	JZS-11	JZS-12	JZS-13	JZS-14	JZS-15	JZS-16	JZS-17	JZS-D-2	JZS-D-3	JZS-D-4	JZS-D-5	
Rock	Quartz syenite						Enclave	Py syenite	Enclave	Pyroxene syenite				Pyroxene syenite		Pyroxene syenite				Mafic dike				
Longitude and latitude	E122°24'10.7", N36°54'22.6"						E122°21'33.3", N37°00'33.1"						E122°26'16.9", N37°01'13.7"		E122°27'06.4", N36°58'05.5"				E122°27'06.4", N36°58'05.5"					
Major element (in wt.%)																								
SiO ₂	63.57	63.70	64.03	64.01	64.20	63.13	53.45	60.10	48.09	60.06	59.72	60.11	59.31	58.47	54.44	56.59	56.29	55.86	56.67	48.05	48.27	46.60	50.81	
TiO ₂	0.32	0.34	0.33	0.33	0.30	0.39	0.84	0.52	1.20	0.52	0.52	0.52	0.53	0.70	1.00	0.64	0.69	0.80	0.80	1.16	1.16	1.12	1.32	
Al ₂ O ₃	18.45	18.49	18.53	18.56	18.72	18.23	17.00	18.29	16.82	17.80	18.13	18.13	18.09	17.79	15.22	16.98	17.15	16.36	17.67	12.44	11.51	11.10	12.43	
Fe ₂ O ₃	2.37	2.34	2.28	2.37	2.03	2.87	7.54	3.84	10.20	3.88	3.97	3.82	4.09	4.49	7.27	5.56	5.62	5.87	5.15	8.84	8.90	8.60	7.33	
MnO	0.11	0.10	0.10	0.11	0.08	0.13	0.16	0.10	0.16	0.10	0.11	0.10	0.10	0.10	0.15	0.11	0.13	0.14	0.10	0.13	0.14	0.13	0.11	
MgO	0.35	0.24	0.28	0.32	0.20	0.41	3.07	1.36	4.80	1.44	1.40	1.33	1.49	1.17	3.56	2.36	2.52	3.22	2.36	10.04	12.44	11.97	8.06	
CaO	1.37	1.27	1.31	1.34	1.15	1.43	5.90	3.06	6.74	3.14	3.13	3.03	3.38	2.74	5.44	4.21	4.20	4.93	3.91	8.24	8.78	8.47	6.88	
Na ₂ O	5.23	5.23	5.23	5.31	5.33	5.14	4.02	4.27	3.19	3.65	4.22	4.30	4.29	3.84	3.49	3.93	3.96	3.69	3.83	1.56	1.37	1.42	1.85	
K ₂ O	6.82	6.94	6.94	6.75	7.05	6.97	4.59	7.04	4.23	7.57	6.89	6.99	6.76	7.88	6.04	6.53	6.64	6.40	6.83	5.39	4.41	4.98	6.40	
P ₂ O ₅	0.09	0.07	0.07	0.08	0.06	0.10	0.81	0.33	1.26	0.35	0.33	0.32	0.35	0.24	0.73	0.54	0.52	0.59	0.51	0.99	0.96	0.93	0.97	
TOTAL	98.68	98.71	99.10	99.17	99.11	98.78	97.38	98.90	96.69	98.50	98.42	98.65	98.39	97.41	97.33	97.46	97.72	97.86	97.82	96.84	97.94	95.32	96.14	
Mg#	22.40	16.83	19.33	21.08	16.16	21.90	44.68	41.21	48.23	42.35	41.14	40.84	41.86	34.14	49.24	45.70	47.08	52.07	47.64	69.22	73.46	73.40	68.53	
A/CNK	1.00	1.00	1.00	1.01	1.01	0.98	0.76	0.91	0.76	0.89	0.90	0.90	0.88	0.90	0.69	0.80	0.80	0.74	0.85	0.53	0.50	0.48	0.55	
A/NK	1.15	1.15	1.15	1.16	1.14	1.14	1.47	1.25	1.71	1.25	1.26	1.24	1.26	1.20	1.24	1.25	1.25	1.26	1.29	1.48	1.64	1.44	1.25	
CIPW normative minerals (%)																								
Q	3.84	3.83	4.02	4.16	3.62	3.24		1.03		2.38	1.22	1.22	0.47											
Ne							0.50		2.82						0.84	0.42	1.63	0.99	0.31	3.45	0.85	4.34	1.06	
Trace elements (in ppm)																								
V	32.6	30.5	29.6	31.4	26.7	29.1	162	76.3	185	72.4	76.2	70.0	79.1	76.8	126	103	104	98.7	104	172	166	154	133	
Cr	2.80	4.47	3.16	2.96	2.42	2.05	6.09	10.3	36.9	7.74	9.56	15.2	12.3	11.6	63.1	18.8	19.5	51.2	14.9	630	873	834	477	
Co	1.41	1.28	1.31	1.48	1.16	1.40	22.9	8.17	28.8	7.31	8.75	8.32	9.25	8.60	20.4	14.0	15.9	19.1	14.8	39.7	45.1	42.2	30.5	

Ni	1.81	2.77	1.79	1.73	1.63	1.65	13.6	6.38	18.4	6.78	8.13	9.14	7.76	8.55	18.2	12.6	15.0	15.2	12.9	224	319	300	119
Cu	5.30	3.92	4.56	4.23	3.91	3.95	47.0	6.41	27.3	21.4	7.47	10.2	9.98	14.8	15.3	10.5	12.4	39.6	18.3	45.9	58.8	57.4	133
Zn	57.5	47.5	50.0	53.9	44.5	58.0	132	65.0	141	68.6	64.7	67.8	80.0	69.9	84.8	64.4	67.3	81.0	68.4	81.2	77.1	72.0	108
Ga	21.9	21.5	21.8	21.8	21.6	22.0	21.4	20.0	20.4	19.5	20.3	20.0	20.3	22.2	23.3	21.3	21.3	22.1	20.2	16.0	14.9	14.3	16.4
Rb	145	146	150	138	147	145	126	162	113	159	155	155	153	179	184	179	196	193	179	113	86.4	102	161
Sr	221	205	192	191	217	213	2352	1323	3832	1409	1319	1213	1411	1053	1411	1790	2002	1511	2064	1649	1484	1413	1644
Y	44.0	50.4	47.0	47.0	43.4	53.7	37.1	25.9	30.5	28.2	25.4	23.7	24.7	49.0	45.5	29.1	27.4	35.7	32.2	24.2	23.3	22.2	20.8
Zr	699	635	675	680	557	848	514	651	276	588	685	621	631	1422	973	654	613	543	123	458	526	498	622
Nb	28.5	31.9	30.5	30.5	27.2	34.7	32.2	9.62	9.75	17.6	10.7	10.2	9.6	50.4	64.4	30.0	24.6	43.9	37.5	12.8	14.6	13.9	16.6
Cs	1.35	1.43	1.43	0.96	1.16	1.14	2.55	2.12	3.85	2.88	1.94	1.93	2.23	1.85	9.34	4.73	5.70	6.37	4.86	2.55	2.29	3.19	2.42
Ba	469	597	462	425	437	508	103700	4142	102000	4287	3914	3814	3939	2769	3448	5031	5689	3863	56230	5167	4763	4628	4254
La	168.4	135.5	133.8	147.9	135.1	164.4	150.4	97.20	129.1	100.6	89.95	79.66	84.27	194.7	147.1	118.0	115.8	132.9	137.6	78.75	65.68	62.94	62.02
Ce	322.9	280.9	266.4	282.0	256.9	320.1	282.5	174.3	248.7	188.1	167.4	148.7	157.2	389.6	306.0	220.0	210.6	258.1	272.5	157.9	136.7	130.8	125.0
Pr	33.60	31.56	29.03	29.52	27.09	33.86	30.17	18.95	28.43	20.27	18.05	16.08	17.12	41.67	33.41	22.85	21.92	27.27	29.16	19.35	16.96	16.12	15.21
Nd	121.1	120.2	108.0	106.6	97.17	124.3	113.3	72.51	116.8	77.23	69.24	62.50	66.68	152.7	126.1	84.32	81.68	101.5	109.6	75.83	66.46	63.43	58.82
Sm	17.77	20.29	17.42	16.28	14.88	18.96	16.49	10.67	17.46	11.45	10.42	9.53	10.13	21.80	18.86	12.27	11.87	14.98	16.45	12.82	11.69	11.00	10.03
Eu	2.31	2.25	2.01	1.94	1.69	2.19	4.45	2.96	5.36	2.93	2.82	2.69	2.83	3.50	3.61	3.05	3.17	3.05	3.99	4.06	3.54	3.31	3.15
Gd	13.86	15.32	13.25	12.83	11.72	14.44	12.65	8.24	13.13	8.76	7.94	7.15	7.71	16.09	14.09	9.42	9.11	11.22	11.78	9.82	8.85	8.22	7.56
Tb	1.85	2.24	1.86	1.74	1.63	1.98	1.52	1.03	1.50	1.10	1.00	0.92	0.98	2.04	1.78	1.14	1.11	1.41	1.45	1.08	1.00	0.94	0.86
Dy	8.60	10.89	8.98	8.28	7.71	9.37	6.50	4.64	6.15	4.88	4.46	4.12	4.37	8.87	7.95	5.04	4.76	6.21	6.21	4.62	4.44	4.19	3.85
Ho	1.55	1.99	1.64	1.52	1.42	1.72	1.17	0.82	1.03	0.89	0.81	0.74	0.79	1.57	1.41	0.89	0.85	1.09	1.05	0.87	0.83	0.78	0.73
Er	4.59	5.71	4.69	4.48	4.09	5.05	3.38	2.43	2.75	2.57	2.35	2.17	2.28	4.67	4.10	2.63	2.45	3.17	2.98	2.24	2.15	2.02	1.92
Tm	0.69	0.84	0.71	0.66	0.61	0.74	0.50	0.35	0.36	0.39	0.34	0.32	0.33	0.70	0.63	0.40	0.36	0.49	0.43	0.27	0.26	0.25	0.24
Yb	4.31	5.07	4.41	4.07	3.58	4.72	3.21	2.22	2.18	2.47	2.22	2.04	2.12	4.47	4.05	2.63	2.33	3.12	2.64	1.70	1.71	1.58	1.54
Lu	0.63	0.72	0.62	0.58	0.51	0.68	0.49	0.34	0.32	0.38	0.34	0.32	0.33	0.69	0.62	0.41	0.35	0.47	0.37	0.25	0.24	0.23	0.22
Hf	18.4	19.8	18.1	16.8	14.5	20.0	12.6	14.8	6.3	13.1	14.9	13.5	13.6	31.4	23.0	15.1	13.7	13.2	4.03	10.1	11.5	10.9	14.8
Ta	2.42	3.05	2.58	2.42	2.17	2.66	2.14	0.62	0.61	1.44	0.64	0.62	0.56	5.54	5.33	1.64	1.58	3.13	2.71	0.61	0.70	0.66	0.74
Pb	54.4	54.6	164	59.3	81.6	64.5	113	81.1	78.2	80.9	71.0	298	99.1	219	79.2	68.1	58.0	73.6	74.1	28.8	30.4	31.1	26.4
Th	24.2	21.8	21.4	22.0	22.2	26.2	46.5	10.5	5.72	17.6	10.5	9.00	8.42	47.6	49.7	28.4	28.4	59.8	26.4	8.82	9.24	8.99	5.81
U	2.58	2.76	2.99	2.91	1.98	2.73	7.33	1.98	1.44	5.36	1.94	1.97	2.07	5.06	15.2	6.02	7.27	9.02	5.09	1.68	1.80	1.73	1.21

Table 4
Sr and Nd isotopic compositions of rocks from the Jiazishan Complex

Sample no.	Rock type	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	$^{87}\text{Sr}/^{86}\text{Sr}_i$	$\varepsilon_{\text{Nd}}(t)^a$	$T_{\text{DM}}(\text{Ma})^b$	$f_{\text{Sm/Nd}}$
JZS-01	Qz syenite	138	221	1.805	0.712435	11	17.7	122	0.0882	0.511688	11	0.70692	−15.6	1771	−0.55
JZS-02	Qz syenite	138	205	1.947	0.713034	8	18.6	112	0.1000	0.511702	5	0.70708	−15.6	1934	−0.49
JZS-03	Qz syenite	141	195	2.090	0.713454	11	17.8	113	0.0952	0.511665	12	0.70706	−16.2	1904	−0.52
JZS-04	Qz syenite	132	195	1.966	0.712971	16	17.9	120	0.0907	0.511680	9	0.70696	−15.8	1817	−0.54
JZS-07-1	Mafic enclave	120	2352	0.1480	0.706891	11	18.0	126	0.0862	0.511733	7	0.70644	−14.6	1690	−0.56
JZS-08-1	Mafic enclave	112	3814	0.0853	0.706844	7	20.2	137	0.0890	0.511730	7	0.70658	−14.8	1732	−0.55
JZS-09	Py syenite	153	1215	0.3634	0.707840	14	11.7	80.3	0.0882	0.511687	6	0.70673	−15.6	1773	−0.55
JZS-10	Py syenite	153	1213	0.3638	0.707799	11	11.0	73.6	0.0900	0.511684	10	0.70669	−15.7	1801	−0.54
JZS-11	Py syenite	145	1294	0.3245	0.707695	8	11.4	77.0	0.0898	0.511709	7	0.70670	−15.2	1769	−0.54
JZS-12	Py syenite	173	1053	0.4745	0.708044	12	25.1	179	0.0852	0.511689	8	0.70659	−15.5	1728	−0.57
JZS-13	Py syenite	184	1339	0.3981	0.708026	10	22.3	151	0.0892	0.511710	6	0.70681	−15.2	1759	−0.55
JZS-14	Py syenite	182	1705	0.3091	0.707743	9	14.2	99.5	0.0862	0.511703	5	0.70680	−15.2	1726	−0.56
JZS-15	Py syenite	186	1837	0.2930	0.707711	8	13.6	94.7	0.0867	0.511673	12	0.70682	−15.8	1769	−0.56
JZS-16	Py syenite	187	1409	0.3840	0.708038	7	17.5	121	0.0876	0.511692	10	0.70686	−15.5	1758	−0.55
JZS-D-2	Mafic dike	110	1668	0.1908	0.707801	13	13.2	81.3	0.0981	0.511656	9	0.70722	−16.5	1963	−0.50
JZS-D-3	Mafic dike	102	1529	0.1923	0.707872	8	12.0	72.3	0.1007	0.511660	4	0.70728	−16.4	2003	−0.49
JZS-D-4	Mafic dike						5.97	36.2	0.0999	0.511655	6		−16.5	1996	−0.49

a and b: The $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ of chondrite and depleted mantle at present day are 0.512638 and 0.1967, 0.51315 and 0.222, respectively.

$^{87}\text{Sr}/^{86}\text{Sr}_i$ and $\varepsilon_{\text{Nd}}(t)$ were calculated at 215 Ma.

Fig. 4. Classification of the Jiazishan Complex on the basis of (a) the TAS diagram. All the major element data have been recalculated to 100% on a H_2O - and CO_2 -free basis (after Middlemost, 1994; Le Maitre, 2002); (b) K_2O vs. Na_2O diagram, showing the Jiazishan Complex to be shoshonitic and ultrapotassic (after Middlemost, 1972); (c) A/NK vs. A/CNK plot. All samples except for quartz syenites fall in the metaluminous field.

with steep slopes ($\text{La}_N/\text{Yb}_N=28\text{--}37$) and small or no negative Eu anomalies. The quartz syenites (Fig. 8b) are also enriched in LREE, with La_N/Yb_N values of 19–28. The distinctive negative Eu anomalies (Fig. 8b) and low Ti, Ba and Sr contents suggest that quartz syenites are highly differentiated rocks, in contrast to the pyroxene syenites. The chondrite-normalized REE patterns of the mafic dikes (Fig. 8c) are also steeply inclined and show relative enrichment of LREE over HREE ($\text{La}_N/\text{Yb}_N=29\text{--}43$) without Eu anomalies. They have lower total REE contents than either the pyroxene or quartz syenites.

In the primitive mantle-normalized trace element diagrams, pyroxene syenites (Fig. 9a) have highly variable trace element contents, particularly for Ba, Th, U, Nb, Ta, Zr and REE. They are characterized by enrichment in LILEs (i.e., Rb, Ba, Sr, Th and U) relative to LREEs (i.e., La, Ce, Pr, Nd and Sm) and HFSEs (i.e., Nb, Ta, P and Ti) with Ba/La and La/Nb ratios of 14–79 and 2.3–13. Quartz syenites have different patterns from the pyroxene syenites (Fig. 9b), with negative Ba and Sr anomalies and strong depletion in P and Ti. Mafic dikes have similar trace element patterns to the pyroxene syenites, but with weak Ti and P anomalies (Fig. 9c).

4.3. Nd and Sr isotopes

Table 4 gives the results of 17 new Nd and Sr isotopic analyses which cover the major rock types of the Jiazishan Complex. The data are shown in a plot (Fig. 10) of $\varepsilon_{\text{Nd}}(t)$ vs. initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and are compared on that diagram with published compositional fields for Late Mesozoic volcanic rocks from the Jiaodong Peninsula (Fan et al., 2001; Guo et al., 2001a), granites and lamprophyres (Yang, 2000; Yang et al., 2004). Also shown are compositional trends from available data for components of the lower and upper crust in the Jiaodong Peninsula (Jahn et al., 1999). Data for the Early Cretaceous samples were recalculated to a common age of 125 Ma.

The pyroxene syenites and quartz syenites from the Jiazishan Complex have very similar Nd and Sr isotopic ratios despite their geochemical differences. They have strongly negative $\varepsilon_{\text{Nd}}(t)$ values of -15.2 to -16.2 and low radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of

Fig. 5. Major element oxides vs. MgO plots for the Jiazishan Complex. (a) Al_2O_3 ; (b) SiO_2 ; (c) Fe_2O_3 ; (d) TiO_2 ; (e) Na_2O ; (f) CaO ; (g) K_2O and (h) P_2O_5 .

0.70659–0.70708. The mafic dikes have similar $\varepsilon_{\text{Nd}}(t)$ values (~ -16.5) to the syenites but have more radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70722–0.70728)

than the syenites. The mafic enclaves have slightly higher $\varepsilon_{\text{Nd}}(t)$ values (-14.6 to -14.8) and less radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70644–0.70658)

Fig. 6. Selected trace element and elemental ratios vs MgO plots for the Jiazishan Complex. (a) V; (b) Cr; (c) Ni; (d) Rb; (e) Sr; (f) Ba; (g) Ce/Pb and (h) Nd/P₂O₅.

than either the syenites or the mafic dikes (Fig. 10). All these rocks plot near the field of Early Cretaceous mafic volcanic rocks but far from those of

Late Jurassic to Early Cretaceous granites and mafic dikes, lower crust and upper crust (Fig. 10). The model age (T_{DM} , depleted mantle age, Sm–Nd) of

Fig. 7. (a) $\text{Na}_2\text{O}+\text{K}_2\text{O}$ and (b) Zr vs. $10000\text{Ga}/\text{Al}$ discrimination diagrams showing that the syenites are A-type granites. After Whalen et al. (1987), I=I-type, S=S-type and M=M-type granitoids.

the Jiazishan samples is mainly in the range of 2.0–1.7 Ga (Table 4).

5. Petrogenesis of the mafic dikes

5.1. Mantle source

The low silica contents (46.6–50.8 wt.%) and relatively high concentrations of MgO (8.1–12.4 wt.%), Cr (477–872 ppm) and Ni (119–318 ppm) suggest that the mafic dikes were derived from an ultramafic source. Crustal rocks can be ruled out as possible sources because experimental evidence shows that partial melting of any of the older, exposed crustal rocks (e.g., Hirajima et al., 1990; Yang et al., 1993; Zhang et al., 1994, 1995; Kato et al., 1997) and lower crustal intermediate granulites (Gao et al.,

1998a,b) in the deep crust would produce high-Si, low-Mg liquids (i.e., granitoid liquids; Rapp et al., 2003), not the highly magnesian magmas present in the Jiazishan Complex.

The parental magmas to the Jiazishan ultra-potassic mafic dikes have undergone variable amounts of clinopyroxene and olivine fractionation inferred from the correlation between Cr, Ni and MgO (Fig. 6b and c). Plagioclase was not an important fractionated phase, given the absence of negative Eu anomalies (Fig. 8c) and the occurrence of plagioclase phenocrysts in these lavas. Clinopyroxene and olivine were the main fractionated phases (see below). However, mafic lavas (such as JZS-D-3

Fig. 8. Chondrite-normalized REE patterns for (a) pyroxene syenite, (b) quartz syenite and (c) mafic dike from Jiazishan Complex. Note that all the quartz syenites have negative Eu anomalies. The chondrite values are from Sun and McDonough (1989).

Fig. 9. Primitive mantle (PM) normalized diagrams for (a) pyroxene syenite and enclave, (b) quartz syenite and (c) mafic dike. Elements are arranged in the order of decreasing incompatibility from left to right. The PM values are from Sun and McDonough (1989).

and 4) with high MgO contents and $Mg\# \approx 73$ are near-primary melts.

The parental magmas, represented by samples JZS-D-3 and 4, have 46.6–48.3 wt.% SiO_2 and 12.0–12.4 wt.% MgO, as well as elevated $Mg\#$ (~ 73.5), Cr (834–873 ppm) and Ni (300–319 ppm), moderately low CaO/Al_2O_3 (~ 0.76) and low TiO_2 (~ 1.12 wt.%). The composition of these mafic dikes is similar to that of experimental melts from depleted

peridotite (Falloon et al., 1988), indicating a dominantly refractory lithospheric mantle contribution to the magma. The mafic dikes also share high La/Sm (~ 6) and depleted heavy REE and HFSE signatures, along with low Ti/V and Ti/Zr ratios and enrichment in Zr relative to Sm (Table 3 and Fig. 9c). The trace element systematics of the mafic dikes signify derivation from a refractory peridotite more depleted than the residua from MORB generation (Hickey and Frey, 1982), which has been overprinted by an enriched component.

The high K_2O content (>4 wt.%) of the mafic dikes requires a potassic phase in the source region. Melts in equilibrium with phlogopite are expected to have significantly higher Rb/Sr and lower Ba/Rb values than those formed from amphibole-bearing sources (Furman and Graham, 1999). High Ba/Rb (>45) and relatively low Rb/Sr (<0.1) ratios strongly suggest that the parental magmas to the mafic dikes formed through partial melting of an amphibole-bearing source. Therefore, the mafic dikes were derived from partial melting of an amphibole-bearing, refractory lithospheric mantle source.

5.2. Lithospheric mantle beneath the Sulu region

The incompatible element contents and negative $\varepsilon_{Nd}(t)$ values (~ -16.5) of these mafic dikes are more typical of crust-derived melts. The possibility remains that these chemical signatures resulted from crustal contamination during transport through the continental crust. However, the low silica and high MgO and the lack of correlation of isotopic compositions with MgO (Fig. 11) preclude significant crustal assimilation during magma ascent.

The Nb/U (7.6–13.7) and Ce/Pb (7.6–9.9) ratios for the Jiazishan mafic dike are significantly lower than in mid-ocean ridge basalt or ocean island basalt (47 and 27, Hofmann et al., 1986), indicating the involvement of crustal components in their source region. The depletion of HFSEs relative to LILEs and LREEs (Fig. 9c) is usually considered to be indicative of arc magmas or magmas derived from ancient crust. However, O and H isotopic evidence indicates that the process of continental subduction is characterized by the relative lack of fluids (Zheng et al., 2003). Therefore, no significant amount of slab-released fluids or melts metasomatized the overlying

Fig. 10. Sr and Nd isotopic data from the Jiazishan Complex compared with those of various Late Mesozoic igneous rocks from the Jiaodong Peninsula (Yang, 2000; Fan et al., 2001; Guo et al., 2001a; Yang et al., 2004). Also plotted are trends to Lower and Upper Crust (after Jahn et al., 1999). Inset is enlargement of Jiazishan Complex data set. Initial Sr and Nd isotopic ratios were calculated at 215 Ma, whereas those of Late Mesozoic rocks were calculated at 125 Ma.

lithospheric mantle during the Triassic subduction. Instead, the Yangtze lithospheric mantle can be considered the candidate that is consistent with the enrichment in incompatible and mobile elements, such as K, Rb, Pb and the LREEs, and depletion in the HFSEs. Nevertheless, the enrichment of mobile elements like K and Rb may be caused by the introduction of metamorphic fluids that were derived from decompression exsolution from amphibole, phengite and clinopyroxene and thus their arrival triggered partial melting (Zheng et al., 2003). The slight enrichment of the mafic dike samples in Rb/Sr and Nd/Sm, combined with their high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and negative $\varepsilon_{\text{Nd}}(t)$ values, is consistent with derivation from such an enriched part of the lithosphere.

In summary, the ultrapotassic mafic dike originated from mafic magma that was derived from partial melting of an enriched lithospheric mantle source that was metasomatized by a subducted crustal component prior to magma generation and experienced fractionation of clinopyroxene and olivine. Unlike the subduction of oceanic crust that

accompanied a significant release of aqueous fluid to result in arc magmatism, a continental subduction did not produce a sufficient amount of aqueous fluid to metasomatize the overlying lithospheric mantle (Zheng et al., 2003). Therefore, we prefer the subducted Yangtze lithospheric mantle as the source of mafic dike.

6. Petrogenesis of the syenites

Assimilation, crystal fractionation (AFC) or magma mixing are usually postulated to explain the occurrence of comagmatic mafic and felsic rocks (e.g., DePaolo, 1981; Devey and Cox, 1987; Marsh, 1989; Mingram et al., 2000). Crustal assimilation, coupled with fractional crystallization, would result in progressive decreases in Cr, Ni, Co and MgO (or Mg#s), with concomitant increase in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and decrease in $\varepsilon_{\text{Nd}}(t)$ values. Magma mixing should generate mixing curves in the isotopic correlation diagrams and in plots between isotopic ratios and certain elements (e.g., MgO or SiO_2). These

Fig. 11. Plot of (a) initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and (b) $\epsilon_{\text{Nd}}(t)$ value vs. MgO, indicating crystal fractionation. See text for detailed discussion.

features are not observed in the Jiazishan Complex (Figs. 6a–c and 11). The variation in composition within the Jiazishan Complex is not associated with a significant shift in isotopic composition (Fig 11); thus, neither magma mixing nor crustal assimilation are feasible mechanisms.

A major obstacle in identifying petrogenetic lineage among the syenites is that most rocks probably do not represent liquid compositions. The close similarities in Sr and Nd isotopic composition between syenites (containing mafic enclaves) and mafic dikes suggest a common source region. The most obvious candidates for the parental magmas of the syenites are similar to those of the mafic dikes, which have low silica (46–48 wt.%) and relatively high MgO content (~12 wt.%; Mg#~73.5). Although the dikes have been intruded after the syenites, it is possible that they crystallized from liquids equivalent in composition to those from which the syenites evolved.

On various major and trace element plots (Figs. 5 and 6), the relationship between mafic dike and syenite samples are in agreement with closed-system crystal fractionation of mafic magma. The CaO content decreases with decreasing MgO contents (Fig. 5a). The Fe_2O_3 vs. MgO is similar to that of CaO vs. MgO in that it steepens with declining MgO content (Fig. 5c and f). Cr, on the other hand, shows a continual decline as MgO decreases down to MgO~3 wt.%, when the Cr content becomes zero (Fig. 6b). As extensive clinopyroxene and feldspar fractionation would strongly alter the Ca/Al ratio of the melt, these two observations are consistent with continuous fractionation of pyroxene and feldspar and the onset of magnetite fractionation from MgO<3 wt.%. This is supported on the Ni and V vs. Cr diagrams (Fig. 12a and b) in which the variations in the mafic dikes and pyroxene syenites are consistent

Fig. 12. (a) Ni and (b) V vs. Cr diagrams showing olivine- and clinopyroxene-dominated fractionation in the evolution of parental magmas to the Jiazishan Complex. Partition coefficients are from Rollinson (1993).

with fractionation of clinopyroxene and olivine. The quartz syenites have lower Cr, Ni, Co and MgO, perhaps the result of these magmas having passed the peritectic where clinopyroxene and olivine disappear and feldspar fractionates.

The plots of Al_2O_3 and Sr vs. MgO are similar (Figs. 5a and 6e). The Al_2O_3 content increases as MgO decreases from 13 to ~2 wt.% and shows a sudden decline for MgO less than ~2 wt.%. Sr shows a general increase as MgO decreases to about MgO=5 wt.%, then shows a steep decline as MgO decreases further. These plots are consistent with feldspar fractionation below MgO~5 wt.%, which may explain the lack of Eu anomalies in the pyroxene syenites and mafic dikes with MgO>5 wt.% (Fig. 9a and c). Feldspar fractionation is also supported by significant depletions in Sr, Ba and Eu shown in the mantle-normalized trace element patterns (Figs. 8b and 9b). Negative Eu anomalies, combined with decreases in Ba and Sr (Fig. 13a and b), indicate that alkali feldspar and plagioclase have been

removed during magma evolution. In the Rb/Sr and Ba vs. Sr diagrams (Fig. 13c and d), decrease in Ba contents and increase in Rb/Sr ratios with decreasing Sr concentrations are the result of fractionation of alkali feldspar and plagioclase with biotite.

In addition to major phases, accessory minerals would have controlled much of the REE variation. The decrease in REE with increasing SiO_2 contents (Table 3) suggests a separation of minerals with high partition coefficients (K_d), such as apatite, titanite, zircon, allanite and monazite, all of which are important accessory minerals in these rocks. The sharp P_2O_5 decrease and Nd/ P_2O_5 increase through pyroxene syenites to quartz syenites (Figs. 5h and 6h) are consistent with progressive removal of apatite. Accessory allanite (increasing Ce/Sr, Fig. 6g) is probably involved. Limited Zr variation restricts the involvement of zircon.

On the basis of the geochemical and isotopic data, we can conclude that the Jiazishan syenites

Fig. 13. Eu/Eu^* vs. (a) Sr and (b) Ba. (c) Rb/Sr and (d) Ba vs. Sr diagrams showing plagioclase-, K-feldspar- and biotite-dominated fractionation in the evolution of the syenitic magma. Partition coefficients are from Rollinson (1993).

were derived from an enriched mantle source, similar to that of the mafic dikes. Major and trace element trends can be explained by the switch from clinopyroxene- and olivine-dominated crystallization, controlling evolution of the mafic magmas to metaluminous pyroxene syenite, to biotite- and plagioclase-dominated crystallization, with minor hornblende and accessory mineral contribution, controlling the pyroxene syenite to quartz syenite trend, i.e., A-type granites.

7. Tectonic implications

Field relationships, petrological, geochronological and geochemical data emphasize that the syenites and mafic dike from the Jiazishan Complex in the Sulu Orogenic belt were derived by partial melting of a metasomatized, refractory lithospheric mantle source, displaying features similar to other alkaline rocks referred to in the literature as post-collisional (Sylvester, 1989) or post-orogenic/anorogenic syenites (Bonin, 1990). Bonin (1990) proposed that alkaline granitoids post-dating a major orogenic episode can be divided into two groups, i.e., post-orogenic (PO) and early anorogenic (EA) granitoids. Post-orogenic magmas are characterized by Mg/Mn-rich mafic minerals, high Ba and Sr abundances and crustal Sr isotopic signatures, whereas the early anorogenic granitoids are characterized by Fe-rich mafic mineral assemblages, low Ba and Sr abundances and low initial Sr isotopic ratios. The transition from PO to EA types takes place within a rather short time period (10 Ma long) and has been ascribed to a new mantle source replacing an old complex system of mixed oceanic–continental crust–mantle sources and producing alkaline melts (Bonin et al., 1998).

The Jiazishan intrusive suite belongs to the PO group of alkaline rocks. Ages of emplacement (215–200 Ma) indicate the magmatism post-dates the UHP metamorphic event at 240 to 220 Ma and thus the continental collision between North China and Yangtze cratons. Furthermore, the ultrapotassic basic magmas of the Jiazishan Complex were derived from an enriched lithospheric mantle source without addition of new mantle material (e.g., asthenospheric mantle). They are also distinguished geochemically

and by tectonic setting from the anorogenic Na-rich granitoid suites of alkaline ring complexes derived from OIB-type mantle sources (e.g., Bonin, 1990; Bonin et al., 1998).

Chen et al. (2003) suggested that these syenites were syn-orogenic granitoids, resulting from oceanic slab breakoff of the buoyant continental lithosphere during subduction (Davies and von Blanckenburg, 1995; Chen et al., 2003). However, zircon SHRIMP U–Pb data and inferred P – T paths of metamorphic rocks show that the ultrahigh pressure metamorphic event occurred at 240 to 230 Ma, with a late amphibolite facies retrogressive overprint at 220 to 200 Ma (Hacker et al., 1998; Webb et al., 1999; Zheng et al., 2002; Liu et al., 2004), indicating the protoliths of UHP metamorphic rocks were subducted to mantle depths in the Early–Middle Triassic and exhumated to mid-crustal levels in the Late Triassic. Furthermore, the syenites and mafic dikes of the Jiazishan Complex have significant arc signatures such as enrichment in LILE and LREE and depletion in HFSE (Fig. 9). Geochemical and Sr and Nd isotopic data indicate that they were derived from an enriched lithospheric mantle and formed by closed-system fractionation of their parental magmas. Because small fractions of K-rich melt can be produced by fluid-absent phengite dehydration-melting of metabasalts (flush melting) (Schmidt and Poli, 2003), Zheng et al. (2003) advocated that this mechanism is responsible for the generation of the Late Triassic potassic–ultrapotassic rocks in the Dabie–Sulu orogenic belt and thus classified them as the product of syn-exhumation magmatism rather than syn-collisional magmatism. In this regard, partial melting of the subducted Yangtze lithospheric mantle and its overlying lower crust after the breakoff is principally capable of generating the observed geochemical and isotopic features for both mafic dike and syenites. They are distinguished geochemically and tectonically from those syn-collisional granites which are generally peraluminous granitoids (granodiorites and leucogranite) and K-rich calc-alkaline granitoids (monzogranites) (Barbarin, 1990). In addition, slab breakoff should induce a linear heat pulse along the subduction zone that produces a long linear belt of high-K calc-alkaline bodies associated with high- or low-grade regional metamorphism (Davies and

von Blanckenburg, 1995; Atherton and Ghani, 2002). These have not been found in the Dabie–Sulu UHP belt. In contrast, there is a large Triassic granitoid belt in southern Qinling (Sun et al., 2002), but no UHP metamorphic rocks were ever reported there.

An alternative possibility is lithospheric thinning and crustal extension induced by convective instability of a thickened mantle boundary layer (Houseman et al., 1981). The change in potential energy in the remaining lithosphere would then lead to a sudden uplift of the Sulu orogen (e.g., England and Houseman, 1989; Houseman and England, 1993). This is evidenced by the Sm–Nd and Rb–Sr isotopic chronology of UHP metamorphic rocks and their country rocks, which distinguish two stages of rapid cooling of the deep-subducted slab corresponding to two stages of fast uplift (Li et al., 2003): initial rapid uplifting and cooling subsequent to the peak UHP metamorphic event may be caused by slab breakoff, and later rapid cooling may be caused by partial delamination due to the convective removal of lithospheric mantle and related extension. Davies and von Blanckenburg (1995) suggested that slab breakoff in the Dabie–Sulu orogenic belt occurred at great depth to allow the subduction of crustal rocks to pressures of 4 GPa (>130 km). Linear magmatism would occur with breakoff at such great depths, which is not observed in the Dabie–Sulu orogenic belt. Consequently, the Jiazishan syenites and ultrapotassic dike would result from the convective removal of the lower continental lithospheric mantle, which triggers crustal extension and decompressional melting of subducted lithospheric mantle. These rocks were emplaced where there is transition from continental plate convergence to continental plate divergence and may be good indicators of major change in the geodynamic environment.

8. Concluding remarks

The zircon U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the Jiazishan syenites and mafic dikes in the Sulu UHP belt indicate that they evolved between 215 and 201 Ma, post-dating the UHP metamorphism due to continental collision of the North China and

Yangtze cratons. The suite has the characteristics of post-orogenic alkaline sequences as defined by Bonin, (1990, 1998), i.e., alkaline pyroxene syenite–quartz syenite–ultrapotassic mafic dike association, representing the last magmatic event of the Sulu orogenesis due to partial melting of the subducted Yangtze lithospheric mantle during exhumation. The Jiazishan syenites and mafic dike belong to the potassic to ultrapotassic series and are of alkaline affinity. Field relations, petrography, geochemistry and isotopic composition define an evolution of lithospheric mantle-derived magmas that have experienced extensive fractionation and minor contamination by crustal material. The silica-saturated A-type magmatism was not an intracrustal differentiation process but involved redistribution of mass vertically within the lithosphere. Partial melting occurred in a post-orogenic setting related to lithospheric removal and crustal extension induced by convective instability of a thickened mantle boundary layer and was not directly related to subduction. Interpretation of the data leads to an integrated model of syenite genesis in a post-orogenic extensional setting.

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Appendix A

Table A

Measured and recommended trace element data (ppm) for rock standards

	AGV-1	AGV-1	AGV-1	AGV-1 ^a	BCR-2	BCR-2 ^a	BHVO-2	BHVO-2	BHVO-2 ^a	BIR-1	BIR-1	BIR-1 ^a	JB-1	JB-1	JB-1 ^a	JG-1	JG-1 ^a
V	109	118	115	120±11	408	416±14	283	320	317±3	315	316	310±11	195	195	211±20	26	25.2±3.7
RSD%	3.7	6.3	0.9		0.9		1.9	1.3		3.9	1.8		0.2	0.2		1.2	
Cr	8.16	7.59	8.33	10±3	17.22	18±2	267	278	280±7	375	375	370±8	492	425	425±63	54.2	53±6.9
RSD%	3.4	5.2	0.7		4.4		1.6	0.8		3.9	0.8		1.5	0.3		1.2	
Co	13.9	14.4	15.9	15±1.2	37.11	37±3	41.8	46.6	45±7	50.6	50.7	52±2	43.2	37.4	38.2±5.2	4.16	4.1±0.8
RSD%	1.2	4.7	0.4		2.5		2.8	2.5		1.4	1.1		0.8	0.2		1.4	
Ni	14.0	14.6	16.2	16	12.71		113	123	119±6	164	164	170±6	155	132	133±17	7.6	7±2.6
RSD%	2.7	4.3	0.3		3.0		3.4	2.3		2.44	0.97		0.5	0.5		1.4	
Cu	56.9	60.0	62.5	60±6	21.59	19±2	129	130	127±6	123	121	125±4	59.8	51.3	55±5.5	2.64	2.5±1.2
RSD%	3.1	3.9	0.5		2.6		3.4	0.5		1.2	0.7		0.4	0.4		1.4	
Zn	82.2	85.3	84.6	88±9	131.38	127±9	104	110	103±6	68.0	67.3	70±9	92.9	82.9	85.2±9.9	45.4	41.1±5.6
RSD%	2.3	4.8	0.7		1.0		3.1	1.7		2.2	1.4		1.2	1.0		0.8	
Ga	19.7	20.5	21.2	20±3	23.3	23±2	20.8	21.6	21.7±4.0	14.6	14.6	16	18.1	17.3	17.9±2.9	17.4	17.8±3.1
RSD%	0.2	5.0	1.1		0.6		1.8	0.1		2.2	0.4		0.7	0.8		0.8	
Rb	68.1	69.6	67.7	67±1	50.18	48±2	9.73	9.63	9.8±1.0	0.21	0.14	1.0±0.9	41.4	41.0	41.3±5.1	182	182±9.1
RSD%	1.4	4.3	0.9		0.6		1.9	1.9		36.1	18.5		1.4	0.4		0.7	
Sr	644	656	642	660±9	350.88	346±12	413	397	389±6	108	108	110±2	444	454	444±29	186.0	184±17
RSD%	1.5	6.4	1.3		2.7		2.2	0.8		3.9	2.3		1.5	0.4		0.6	
Y	19.4	20.0	20.0	20±3	38.47	37±2	28.3	27.6	26±2	15.6	15.6	16±1	24.3	24.0	24.3±3.6	31.4	30.6±2.5
RSD%	1.4	5.5	0.6		0.5		1.2	1.4		4.9	1.4		1.1	0.4		0.6	
Zr	220	226	227	227±18	190.57	188±16	177	176	172±6	13.6	13.5	18±1	138	133	141±22	118	111±27
RSD%	3.8	3.9	0.7		3.4		0.9	1.1		4.9	1.2		1.3	0.7		0.6	
Nb	12.7	13.0	14.9	15	11.88		17.8	17.4	18±2	0.47	0.46	0.6	35.2	33.6	33.3±6.5	11.4	12.4±1.3
RSD%	1.7	4.8	0.5		2.3		2.6	1.3		4.1	1.9		0.9	0.8		0.5	
Cs	1.23	1.26	1.15	1.3±0.1	1.22	1.1±0.1	0.10	0.10				0.45±0.1	1.17	1.41	1.23±0.2	9.00	10.1±1.1
RSD%	2.3	2.7	1.0		2.3		4.3	1.3		91	13		0.8	1.2		0.4	
Ba	1172	1209	1188	1230±16	707.68	683±28	142	130	130±13	7.37	6.38	7	477	594	493±46	468	466±27
RSD%	0.8	2.6	0.7		1.7		3.2	2.2		17.8	2.5		0.5	0.5		0.4	
La	38.32	39.46	38.79	38±2	26.72	25±1	15.97	15.68	15±1	0.65	0.56	0.63±0.1	42.89	35.01	38.6±4.3	22.82	22.4±2.7
RSD%	1.0	3.5	0.7		0.8		2.2	1.0		6.9	1.5		0.4	0.9		0.5	
Ce	67.97	69.90	69.44	67±6	51.57	53±2	39.21	40.49	38±2	1.92	1.72	1.90±0.4	74.82	61.40	67.8±6.8	45.71	45.8±4.7
RSD%	2.2	3.3	1.0		1.3		1.9	0.6		3.8	2.5		0.3	0.7		0.8	
Pr	7.85	8.07	8.33	7.6	6.89	6.8±0.3	5.30	5.41		0.35	0.34	0.5±0.4	7.44	6.29	7.01±0.8	4.87	4.83±1.0
RSD%	1.2	4.1	0.6		1.7		0.6	1.4		2.6	1.4		0.3	0.4		1.4	
Nd	30.88	31.31	32.04	33±3	30.40	28±2	25.48	25.97	25.0±1.8	2.32	2.24	2.5±0.7	28.29	24.64	26.8±2.3	19.76	19.3±2.5

(continued on next page)

Appendix A (continued)

	AGV-1	AGV-1	AGV-1	AGV-1 ^a	BCR-2	BCR-2 ^a	BHVO-2	BHVO-2	BHVO-2 ^a	BIR-1	BIR-1	BIR-1 ^a	JB-1	JB-1	JB-1 ^a	JG-1	JG-1 ^a
RSD%	1.5	4.7	0.5		1.5		1.7	1.7		3.2	0.8		0.5	1.2		0.7	
Sm	5.62	5.70	5.83	5.9±0.4	6.74	6.7±0.3	6.33	6.38	6.2±0.4	1.06	1.02	1.1	5.45	4.83	5.13±0.5	4.68	4.62±0.56
RSD%	1.9	4.9	0.9		0.9		2.4	1.1		2.8	0.9		1.8	1.0		2.1	
Eu	1.58	1.61	1.84	1.6±0.1	1.96	2.0±0.1	2.01	2.03		0.46	0.44	0.55±0.05	1.50	1.31	1.49±0.15	0.78	0.73±0.95
RSD%	1.8	3.3	0.8		0.9		4.3	0.9		0.7	2.4		0.8	1.1		0.8	
Gd	4.83	4.92	5.35	5±0.6	6.60	6.8±0.3	6.11	6.04	6.3±0.2	1.53	1.48	1.8±0.4	5.14	4.48	4.90±0.47	4.23	4.28±0.69
RSD%	2.5	3.2	1.0		3.2		2.3	1.4		1.3	2.0		0.7	1.3		1.7	
Tb	0.66	0.68	0.73	0.7±0.1	1.11	1.07±0.04	1.00	1.02	0.9	0.35	0.33	0.41±0.10	0.84	0.76	0.82±0.2	0.81	0.78±0.31
RSD%	3.0	5.4	0.8		0.9		1.3	0.4		1.8	1.8		0.7	1.5		0.7	
Dy	3.48	3.55	3.59	3.6±0.4	6.56		5.57	5.37		2.42	2.38	2.4±0.3	4.46	4.15	4.14±0.38	4.35	4.14±1.22
RSD%	0.6	4.9	0.8		1.1		2.8	2.2		0.9	1.4		1.0	1.8		0.7	
Ho	0.65	0.67	0.70		1.32	1.33±0.06	1.05	0.99	1.04±0.04	0.54	0.53	0.5±0.1	0.84	0.79	0.79±0.098	0.87	0.81±0.23
RSD%	0.7	4.0	1.1		1.2		1.9	2.3		1.5	2.1		0.8	2.4		0.6	
Er	1.78	1.82	1.92	1.7	3.74		2.73	2.54		1.57	1.57	1.8±0.3	2.36	2.24	2.27±0.19	2.32	2.16±0.65
RSD%	1.9	1.6	0.9		1.7		2.3	2.0		1.93	0.86		0.5	1.2		0.2	
Tm	0.26	0.26	0.27	0.34	0.54	0.54	0.36	0.34		0.25	0.24	0.27±0.10	0.36	0.34	0.35±0.056	0.45	0.41±0.14
RSD%	1.5	3.1	1.6		2.2		3.5	0.7		2.4	0.8		2.5	1.3		1.9	
Yb	1.63	1.64	1.67	1.72±0.2	3.46	3.5±0.2	2.17	2.09	2.0±0.2	1.56	1.53	1.7±0.2	2.20	2.11	2.13±0.26	2.46	2.47±0.73
RSD%	1.3	5.9	1.1		2.0		1.9	2.7		0.8	3.0		1.8	0.4		1.3	
Lu	0.25	0.26	0.26	0.27±0.03	0.52	0.51±0.02	0.31	0.30	0.28±0.01	0.24	0.24	0.26	0.33	0.31	0.31±0.029	0.40	0.39±0.12
RSD%	1.4	4.4	1.2		4.8		3.4	4.5		2.8	0.9		0.6	1.4		1.0	
Hf	4.97	4.97	5.09	5.1±0.4	4.82	4.8±0.2	4.77	4.38	4.1±0.3	0.54	0.53	0.6±0.08	3.51	3.40	3.31±0.56	3.53	3.56±1.03
RSD%	1.5	3.9	0.8		1.4		1.1	0.6		4.3	2.7		0.9	0.9		1.1	
Ta	0.83	0.85	1.04	0.9±0.1	0.73		1.29	1.18	1.4	0.04	0.04	0.06±0.05	3.25	2.88	2.93±0.79	1.79	1.79±0.51
RSD%	1.6	4.8	5.7		3.0		1.8	1.2		7.7	1.6		1.1	0.8		1.1	
Pb	37.0	37.3	38.1	36±5	11.10	11±2	1.70	1.58		3.19	3.06	3	10.1	10.1	10±4.1	25.1	25.4±3.1
RSD%	1.0	3.3	0.5		0.3		1.7	2.3		3.6	1.5		1.6	0.6		1.6	
Th	6.43	6.56	6.49	6.5±0.5	6.27	6.2±0.7	1.39	1.28	1.2±0.3	0.24	0.13	0.89±0.7	8.85	9.52	9.3±0.7	13.46	13.2±1.6
RSD%	2.5	3.2	0.8		1.4		0.9	0.8		28.4	8.2		0.4	0.5		1.0	
U	1.85	1.91	1.93	1.92±0.2	1.56	1.69±0.19	0.46	0.43		0.01	0.01	0.05	1.59	1.72	1.67±0.28	3.59	3.47±0.71
RSD%	2.0	3.7	0.5		0.5		3.8	1.1		29.9	4.3		1.3	1.5		0.6	

Recommended data are from:

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