by Xian-hua Li

Timing of the Cathaysia Block formation: Constraints from SHRIMP U-Pb zircon geochronology

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Geochemical data and SHRIMP U-Pb zircon isotopic age of 1766 ± 19 Ma are reported for the amphibolites exposed in NW Fujian-SW Zhejiang and generally accepted as the oldest rocks in the Cathaysia Block. These data, combined with previous U-Pb zircon and Nd isotopic studies for the gneissic granites in the region, provide new constraints on the crustal evolution of the Cathaysia Block. It is therefore concluded that the Cathaysia Block was most likely formed at 1.77 Ga through cratonization by granite formation as the result of recrystallization of crustal materials derived from an Archean provenance, which was probably triggered by the intraplate basaltic magmatism.

Introduction

The southeastern part of China is tectonically divided into two major blocks: Yangtze Block to the northwest and Cathaysia Block to the southeast (Figure 1). The crustal evolution of the Cathaysia Block has been an issue of long-term debate. Grabau (1923) first proposed a Precambrian "Cathaysia old land" which refers to the metamorphic basement rocks unconformably underlying the Devonian sandstone in Fujian and Zhejiang Provinces, SE China. The existence of the Precambrian Cathaysia old land was further supported by Chan (1956) and Zhang (1959). Alternatively, southeastern China was described as Caledonian geosyncline rather than Precambrian Cathaysia Block by Xie (1961), Huang (1977), and Ren et al. (1987). A model of multiple-stage island-arc accretions for the crustal evolution of SE China was proposed by Guo et al. (1980), which also precludes the existence of the Precambrian Cathaysia Block. In the past few years, however, the existence of the Paleoproterozoic-mid-Mesoproterozoic Cathaysia Block has gained increasing acceptance largely due to the enormous amount of radiometric work in the region (e.g., Shui, 1987; Jahn et al., 1990; Hu et al., 1991; Li et al., 1992; Gan et al., 1993, 1995). Furthermore, a few workers deduced the Cathaysia Block as old as Archean in terms of Sm-Nd isochron and inherited zircon U-Pb ages (Fu et al., 1991; Zhou, 1997). The debate on the timing of the Cathaysia Block formation and its evolution, is largely attributed to the complex of geology of the region. On the other hand, the lack of precise radiometric age data for the key rock units has confused the debate.

In this paper, new SHRIMP U-Pb zircon age data for the amphibolites with a depth of about seven meters from Tianjinping, NW Fujian, which, together with the previously published isotopic data, enable new constraints to be placed on the timing of the Cathaysia Block formation.

Geologic background

Precambrian basement of the Cathaysia Block comprises two metamorphic sequences that are mainly exposed in an area between Jiangshan-Shaoxing and Lishui-Haifeng Faults, SW Zhejiang-NW Fujian Provinces (Figure 1). The lower sequence with a total thickness of ~3600 m, which termed as the Badu Group in Zhejiang and the Mayuan Group in Fujian, consists mainly of leptynites, schists, gneissic granites and metamorphosed volcanics. Amphibolites are mainly associated with biotite leptynites and gneissic granites. The latter crops out mostly in the Tangyuan Formation (the lowest part of the Badu Group), and displays transitional relationship with the surrounding leptynites, with a few of gneissic granite plutons showing intrusive contacts with the country rocks (Hu et al., 1991). These

Figure 1 Simplified geologic map of the Cathaysia Block showing Precambrian basement distribution (modified after Hu et al., 1992 & Gan et al., 1993). Sample localities 1, 2 and 3 are Tianjinping of Jianning County, Xinan of Pucheng County and Zhulu of Longquan County, respectively, where amphibolite samples were collected for zircon U-Pb and major and trace element analyses reported in this study.

rocks underwent relatively higher grade regional metamorphism of amphibolite facies. The upper sequence with a thickness of more than 2000 m, named as the Longquan Group in Zhejiang and the Mamianshan Group in Fujian, dominantly comprises volcanic sediments including schists, meta-volcanics, Fe-bearing quartzites and marbles. These rocks were metamorphosed to relatively lower grade of greenschist facies (Hu et al., 1991; Jin et al., 1992).

Previous radiometric age data

In the past few years, a number of U-Pb zircon ages clustering around 1.74–1.98 Ga for gneissic granites within the Badu Group have been reported, including granites at Xiaji (1975±80 Ma),

Lizhuang (1870±36 Ma), Tianhou (1832±80 Ma), Sanzhishu (1863±44 Ma), Danzhu (1837±36 Ma), Tianben (1889±95 Ma), Quankeng ($^{207}\text{Pb}/^{206}\text{Pb}$ age = 1755±3 Ma), and Zhukou Pegmatite ($^{207}\text{Pb}/^{206}\text{Pb}$ = 1743±8 Ma) (Hu et al., 1992; Gan et al., 1993, 1995). As these gneissic granites were either transitional to the surrounding leptynites, or intruded into leptynites and schists, the age of 1.74–1.98 Ga have been interpreted as the upper limit of the formation age of the Badu Group. However, all these U-Pb data are highly discordant and display significant Pb loss subsequent to the granite formation. All the above zircon U-Pb ages, except two $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ~1.75 Ga, are upper-intercept ages rather than concordant ages.

A Sm-Nd isochron age of 2682±148 Ma for the amphibolites from Tianjinping, NW Fujian was reported and therefore considered as the convincing evidence for the existence of late Archean crust in the Cathaysia Block (Fu et al., 1991). The reported Sm-Nd regression line, however, is most likely an errorchron rather than an isochron, because all the analyzed samples have a very limited $^{147}\text{Sm}/^{144}\text{Nd}$ variation ranging from 0.1432 to 0.1557 and an unreasonably high initial ϵNd value of +8.7 at 2.7 Ga. Thus, the date of 2.7 Ga for the amphibolite has been questioned and considered to be geologically meaningless (Li, 1996).

Geochemical characters of amphibolites

The Tianjinping amphibolite is almost the same in lithology and geochemistry as the amphibolites within the Badu and Mayuan Groups (Table 1). They are mainly composed of 55–60% amphibole and 45–40% plagioclase (An_{43-78}) with minor amount of magnetite, ilmenite, zircon and monazite. The amphibolites have basaltic compositions. Because the samples are metamorphosed and the mobile elements (such as K, Na, Rb, Sr, Ba, etc.) are susceptible to change during metamorphism, they are not classified further on an alkali-SiO₂ diagram. However, on a Zr/TiO₂-Nb/Y diagram (Winchester and Floyd, 1976) in which all elements are not as susceptible as the above mobile elements, the amphibolite samples mostly plot within alkali basalt field (figure is not shown). They are enriched in incompatible elements, including the light rare-earth elements with (La/Yb)_n ratios up to 10. On a MORB-normalized trace element distribution spiderdiagram of Pearce (1982), all the amphibolite samples have similar “humped” patterns, which are characterized by variable enrichment in all the trace elements except Y and Yb relative to average MORB (Figure 2). This resembles many alkali basalts formed in oceanic islands and continental rift area. The geochemical similarity indicates that amphibolites from different localities of NW Fujian-SW Zhejiang might have been derived from a similar mantle source. Obviously, there is no compelling evidence to subdivide the Tianjinping amphibolite into an Archean rock unit proposed by Fu et al. (1991), contrasting to those Paleoproterozoic amphibolites within the Mayuan and Badu Groups (Hu et al., 1992; Gan et al., 1993, 1995).

SHRIMP U-Pb zircon geochronology

The amphibolite sample used in this study was collected from Tianjinping, Jianning County of NW Fujian Province. The whole-rock sample was crushed and pulverized down to <250 µm in an alloy mill, carefully washed, and separated through standard mineral separation procedures including gravitational and magnetic techniques. Zircon grains were then handpicked from the final concentrate. Most zircons from the Tianjinping amphibolite are light brown, euhedral to subhedral, and stubby with length/width ratios of about 2:1. Some grains, however, show a central brown core surrounded by a turbid or thin, clear overgrowth. Occasionally, dark-brown anhedral zircon grains were observed. Representative zircon grains were loaded onto an epoxy mount, which was then polished to section the zircon grains in half. U-Pb isotopic determination was undertaken on the

Table 1 Selected chemical analyses of amphibolites from NW Fujian and SW Zhejiang, the Cathaysia Block

	LG24 Tianjinping	LB117B Xi nan Mayuan	LB261 Zhulu Badu
SiO ₂	48.31	49.46	48.17
TiO ₂	2.56	2.02	1.82
Al ₂ O ₃	17.00	15.70	17.02
Fe ₂ O ₃	2.59	2.14	5.58
FeO	10.38	9.75	6.50
MnO	0.19	0.18	0.17
MgO	4.48	5.00	5.25
CaO	7.33	7.65	9.47
Na ₂ O	4.08	3.09	3.31
K ₂ O	1.11	1.47	0.96
P ₂ O ₅	0.32	0.38	0.24
Loss	1.52	2.84	1.47
Sum	99.87	99.68	99.96
Sc	19.0	28.6	34.5
V	184	325	249
Cr	78.7	55.8	689
Co	41.9	37.9	50.1
Ni	38.0	50.5	245
Cu	57.7	66.5	3.03
Zn	119	118	77.3
Ga	22.7	22.6	22.2
Ge	1.69	2.05	1.99
Rb	32.5	62.5	40.4
Sr	448	348	315
Y	26.7	27.3	28.6
Zr	191	153	159
Nb	17.1	35.5	17.4
Cs	3.66	5.12	2.85
Ba	469	333	155
La	17.6	25.5	20.1
Ce	42.7	55.8	42.0
Pr	5.81	6.93	5.28
Nd	25.0	27.9	20.9
Sm	6.21	5.64	4.97
Eu	2.40	1.73	1.91
Gd	6.73	5.43	5.11
Tb	1.02	0.88	0.89
Dy	5.95	4.97	4.77
Ho	1.16	0.99	1.05
Er	3.13	2.66	2.94
Tm	0.43	0.38	0.42
Yb	2.65	2.26	2.64
Lu	0.39	0.33	0.41
Hf	4.54	3.52	3.88
Ta	0.99	2.02	1.05
Pb	7.39	8.46	8.11
Th	2.00	2.96	3.14
U	0.67	1.19	0.95

Major elements (wt.%) of the samples were measured by wet chemistry. Trace element concentrations (µg/g) were determined using PE Elan 6000 ICP-MS at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The ICP-MS analytical procedures used were similar to those reported by Liu et al. (1996).

Table 2 SHRIMP U-Pb zircon geochronological data for amphibolite from Tianjinping, the Cathaysia Block

Site	U ($\mu\text{g/g}$)	Th ($\mu\text{g/g}$)	Th/U	^{204}Pb (ng/g)	Comm. $^{206}\text{Pb}(\%)$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$	Age ^a (Ma)	Disc.
1-1	26	48	1.81	2	0.24	0.481 ± 16	12.82 ± 0.51	0.1933 ± 32	2770 ± 27	91
1-2	27	52	1.95	<1	0.11	0.509 ± 18	13.40 ± 0.60	0.1847 ± 45	2696 ± 41	101
2-1	51	37	0.74	3	0.37	0.312 ± 10	4.59 ± 0.19	0.1067 ± 23	1745 ± 40	100
2-2	59	45	0.76	8	0.82	0.307 ± 10	4.61 ± 0.19	0.1088 ± 24	1780 ± 40	97
3-1	177	72	0.41	5	0.13	0.358 ± 12	6.16 ± 0.21	0.1248 ± 10	2026 ± 14	97
4-1	71	33	0.16	3	0.22	0.291 ± 09	4.41 ± 0.17	0.1097 ± 17	1795 ± 29	92
5-1	158	239	1.52	145	3.71	0.434 ± 14	9.44 ± 0.35	0.1577 ± 24	2432 ± 26	96
6-1	160	86	0.54	9	0.18	0.535 ± 17	14.67 ± 0.49	0.1990 ± 10	2818 ± 08	98
7-1	137	113	0.82	2	0.08	0.292 ± 09	4.36 ± 0.15	0.1084 ± 11	1773 ± 19	93
8-1	93	89	0.95	4	0.27	0.300 ± 10	4.50 ± 0.16	0.1086 ± 15	1776 ± 25	95
9-1	80	62	0.78	1	0.09	0.304 ± 10	4.73 ± 0.17	0.1128 ± 16	1845 ± 26	93
10-1	188	217	1.15	7	0.23	0.287 ± 09	4.21 ± 0.15	0.1063 ± 11	1737 ± 18	94
11-1	90	91	1.02	5	0.35	0.317 ± 10	4.77 ± 0.18	0.1091 ± 16	1784 ± 28	100
12-1	39	52	1.34	3	0.44	0.321 ± 11	4.75 ± 0.21	0.1075 ± 28	1757 ± 26	102

U-Pb ages are corrected for common lead. Uncertainties are given at the 1 σ level. Comm. ^{206}Pb = amount of ^{206}Pb that is common; Disc. = discordancy $\{(^{206}\text{Pb}/^{238}\text{Pb} \text{ age})/(^{207}\text{Pb}/^{206}\text{Pb} \text{ age})\} \times 100$. Age^a = $^{207}\text{Pb}/^{206}\text{Pb}$ age

exposed zircons using the SHRIMP-II ion microprobe at the Research School of Earth Sciences, Australian National University. The detailed procedures of the SHRIMP analysis have been given in Williams and Claesson (1987).

Fourteen analyses have been obtained for the amphibolite samples (Table 2), and most of which have low U concentrations, with nine being <100 ppm, significantly lower than those in normal granites. Consequently, the radiogenic Pb concentrations are low, which result in comparatively large analytical errors in the measured isotopic ratios. Eight out of fourteen analyses give indistinguishable $^{207}\text{Pb}/^{206}\text{Pb}$ ratios within analytical errors and correspond to a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1766 ± 19 Ma (2 σ) (Figure 3). This zircon U-Pb age of 1766 ± 19 Ma is interpreted as the crystal-

lization age of the amphibolite for the following reasons: (1) The analyzed zircon grains are euhedral and prismatic, and contain low U and Th, which are typical of magmatic origin from a mantle-derived low U and Th melt. (2) The best domains within a single zircon grain were chosen for analysis using ion microprobe, with cracks and inclusions which are most susceptible to Pb loss being eliminated. (3) The main group of analyses are concordant within analytical errors, displaying a simple age population.

Five analyses (1-1, 1-2, 3-1, 5-1 and 6-1) were performed on either rounded cores or dark-brown anhedral zircon grains. These analyses yield a significantly older $^{207}\text{Pb}/^{206}\text{Pb}$ age ranging from 2026 ± 14 Ma to 2818 ± 8 Ma, thus being interpreted as the ages of inherited zircons which were likely assimilated during crystallization of the basaltic magma.

Figure 2 MORB-normalized incompatible element spiderdiagram of Pearce (1982) and chondrite-normalized REE patterns (inset) for amphibolites in NW Fujian-SW Zhejiang.

Discussion

SHRIMP U-Pb zircon results indicate that the Tianjinping amphibolite was crystallized at 1766 ± 19 Ma, precluding the existence of Archean volcanic rocks in the region. Furthermore, this SHRIMP U-Pb zircon age is roughly similar to, but slightly younger than, the previously published U-Pb zircon ages of 1.74–1.98 Ga for gneissic granites within the Badu Group (Hu et al., 1992; Gan et al., 1993, 1995). This small age difference indicates that the Tianjinping amphibolites are probably slightly younger than those within the Badu Group. Alternatively, all the amphibolite is likely coeval in terms of their field relationship and geochemical characteristics mentioned above.

It is worth to note that the U-Pb zircon isotopic system in crust-derived granites is usually complicated and characterized by inherited radiogenic Pb and secondary Pb loss during subsequent geological events (e.g. Paterson et al., 1992; Williams, 1992; Li et al., 1996). In such complicated zircons, highly discordant U-Pb age data obtained by the

Figure 3 SHRIMP U-Pb zircon concordia diagram for the Tianjinping amphibolite.

means of conventional multi-grain zircon U-Pb analysis usually result in an upper-intercept age which may differ from the real crystallization age to varying degrees. In other words, in order to precisely determine the crystallization age, it is crucial to obtain concordant U-Pb zircon age by ion microprobe and single-grain zircon U-Pb dating techniques. As mentioned in earlier section, all the U-Pb data for the gneissic granites within the Badu Group are highly discordant, and only the upper-intercept ages with large errors, rather than concordant ages, have been obtained. These upper intercept ages are usually older than those measured $^{207}\text{Pb}/^{206}\text{Pb}$ ages. It is tentatively suggested based on the field relations and the published age data that these granitic gneisses were likely formed at late Paleoproterozoic, either coeval with, or slightly younger than the amphibolites of 1.77 Ga. Further zircon U-Pb analysis, especially the SHRIMP zircon U-Pb analysis, is very much needed in order to obtain the precise crystallization age of these gneissic granites.

SHRIMP zircon U-Pb analysis in this study gives some inherited zircons of early Paleoproterozoic to late Archean ages in the Tianjinping amphibolite, indicating the existence of late Archean crustal components in the Cathaysia Block. Inherited zircons in ages of 2.5–2.7 Ga have also been recognized in some Phanerozoic granites (Li et al., 1989; Gan et al., 1996). Previously published Nd isotope data for these gneissic granites yield consistent late Archean Nd model ages ranging from 2.5 to 2.8 Ga (Hu et al., 1991; Wang et al., 1992), suggesting a source with late Archean crust residence ages for these gneissic granites. These isotopic data imply that the early crustal components in the Cathaysia Block were derived from an Archean provenance. However, there has been no compelling geological and radiometric evidence so far for any outcrops of the late Archean crystalline basement rocks. The amphibolites of 1766 ± 19 Ma and the nearly contemporaneous gneissic granites are known as the oldest crystalline basement rocks in the Cathaysia Block.

Concluding Remarks

SHRIMP zircon U-Pb analysis yields a precise crystallization age of 1766 ± 19 Ma for the Tianjinping amphibolite in NW Fujian. Field relationship and geochemical characters suggest that the amphibolites, the oldest crystalline basement rocks exposed in NW Fujian-SW Zhejiang of the Cathaysia Block, are most likely coeval. Although a few of zircon U-Pb upper-intercept ages of 1.8–1.98 Ga have been previously reported for the gneissic granites within the Badu Group, it is argued that these gneissic granites are either contemporaneous with or slightly younger than the amphibolites in terms of their field relations and the uncertainties of the highly discordant U-Pb ages for the crust-derived granites. Existence of the Archean crustal components is suggested in the Cathaysia Block based on both inherited zircon U-Pb ages for the Tianjinping amphibolite and Nd model ages for the granitic gneisses within the Badu Group. However, there has been no compelling evidence for existence of the late Archean crystalline basement rocks.

The SHRIMP zircon U-Pb analysis in this study provides important radiometric constraints on the crustal evolution of the Cathaysia Block. The Cathaysia Block was most likely formed at 1.77 Ga through cratonization by granite formation as the result of recrystallization of crustal materials derived from an Archean provenance, which was probably triggered by the intraplate basaltic magmatism.

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