ALKALI AMPHIBOLES FROM LATE ARCHEAN GNEISS OF THE WUHE GROUP, ANHUI, CENTRAL CHINA——NOT AN INDICATION OF HIGH *P/T* METAMORPHISM

Liou J. G. Wang Xiaomin
(*Dept. of Geology, Stanford University, Stanford CA* 94305)
Choi Seon-gyu
(*Dept. of Earth Sciences, Korea National University of Education, Korea*)
Liang Wantong
(*Changchun University of Earth Sciences, Changchun, China*)
Jing Yanren Pan Guoqiang Xia Mulin
(*Regional Geological Survey, Anhui, China*)

Abstract

In some alkali gneisses of the Late Archean Wuhe Group in central China, occurrence of blue amphibole and jadeite has been reported and used as indicators for high P/T metamorphism concurrently with that of the Zhangbaling Group. Petrochemical studies indicate that foliated gneisses contain characteristic amphibolite facies assemblage, alkali amphiboles + acmite + microcline + biotite + quartz ± albite ± hematite. Alkali amphiboles are zoned with cores of igneous Mg-Arfvedsonite and rims of amphibolite facies magnesioriebeckite; these alkali amphiboles contain extremely low Al_2O_3 and high in both Fe^{2+} and Fe^{3+}; they are distinctly different from crossitic amphiboles of the Zhangbaling Group. Sodic pyroxenes lack jadeitic component and have pure acmite composition. The observed mineral assemblage including abundant microcline, the compositions of blue amphiboles, the low jadeitic component of analyzed acmitic pyroxenes, and P-T estimates all suggest that the investigated gneisses of the Wuhe Group were products of the amphibolite facies but not high P/T blueschist facies metamorphism. Previous reports of the jadeite occurrence in the Wuhe Group and in high P/T metamorphic rocks of central China were not supported by the published microprobe data, nor our petrological results.

1 Introduction

Investigation of blueschist facies metamorphism has attracted a great deal of attention in China because of its significance in interpretation of regional tectonics by subductions and because of the abundance of such high P/T metamorphic rocks in China(e. g. , Dong et al., 1986; Liou et al., 1988; Dong, 1990). However, we have encountered some problems in several recent Chinese publications on the subject related to the study of blueschist facies minerals and rocks. These are: (1) the concept of blueschist facies metamorphism has been misused for rock classification; (2) microprobe analyses of jadeitic pyroxenes reported in Chinese literature are albite but not jadeite; (3) occurrence of blue amphibole ± sodic pyroxene does not necessarily imply high P/T metamorphism. The problem with regard to rock name"blueschist"("glaucophane-schist") with the facies name"the blueschist facies"("glaucophane-schist facies") and thier subdivision (glaucophane-lawsonite facies and glaucophane-greenschist facies) will not be described in this short note. The other two problems are illustrated below using our reconnaissance study of the Wuhe Group of the Late Archean age. Our petrological study including microprobe analyses of alkali amphibole and pyroxene concluded that the Wuhe Group has not been subjected to high P/T metamorphism; this conclusion is not consistent with the previous suggestion. Review of reported mineral assemblages and compositions from Chinese literature leads us to emphasize that the reported occurrence of some index minerals (e. g., jadeite and lawsonite) in central China should be cited with care for tectonic interpretation.

2 Regional Geology and Occurrence of Jadeite

As shown in Fig. 1, the Wuhe Group lies to the west of the Tanlu Fault and southeast of the Sino-Korean craton in northern Anhui; it forms part of the Precambrian metamorphic basement of the Sino-Korean craton. The Group consists of a variety of gneisses, granulites, migmatites, quartzites and marbles. It is unconformably overlain by Early Proterozoic greenschist facies rocks and unmetamorphosed non-marine Jurassic to Cretaceous strata. To the east, this group was terminated by several N-S trending branches of the Tanlu fault zones. Immediately the east of the Tanlu fault, a coherent blueschist facies terrane of the Zhangbaling Group occurs.

During the geological survey of the Bonpu area at the scale of 1:200, 000 in 1978, the Regional Geological Survey of the Anhui Bureau of Geology and Mineral Resources first discovered blue amphibole in k-feldspar-bearing gneisses of the Wuhe Group. Metamorphic blue amphibole in gneiss has been

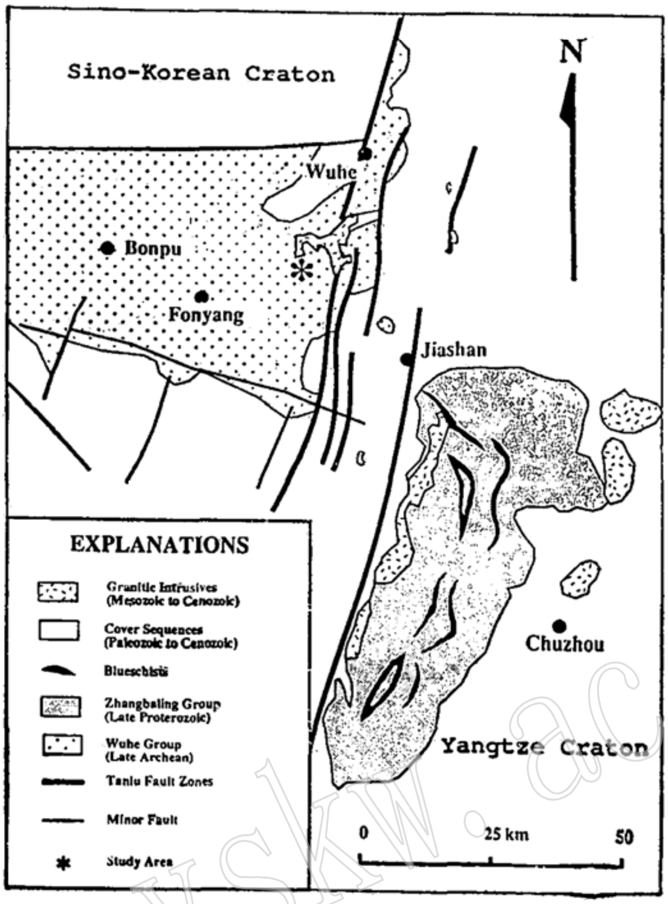

Fig. 1 Location and regional tectonics of the Wuhe Group in northern Anhui. Major geologic units include the Late Archean Wuhe Group, Proterozoic Zhangbaling Group with blueschist lenses, unmetamorphosed cover sequences of Paleozoic to Cenozoic age, and granitic intrusives of mainly Mesozoic age Sample locality for the present study is shown

later optically studied by Fu et al. (1984); crossite and magnesioriebeckite have been identified by using optical properties, and high P/T metamorphism of the Wuhe Group has been suggested. Subsequent study by Jing et al. (1989) substantiated their conclusion by discovery of "minor jadeite" + stilpnomelane in association with blue amphibole. According to the metamorphic facies map of Jing et al. (1989), most of the Wuhe Group are underlain by medium-pressure low amphibolite facies rocks with several small patches mapped as high-pressure metamorphic areas. In one such high-pressure area, blue amphiboles and jadeite have been found; hence on the map, Gl-Jd is labelled in the area. This is the region where we collected samples for our microprobe study (see Fig. 1 for locality). Two stages of metamorphism have been suggested (Jing et al., 1989): Late Archean amphibolite facies and Late Proterozoic blueschist facies metamorphism. The latter event has been considered to be coeval with the blueschist/greenschist facies metamorphism of the Zhangbaling Group which occurs on the eastern side of the Tanlu fault. Microprobe analyses by Jing et al. (p. 138, Table 3) indicate that the blue amphiboles contain 2 to 3 wt% K_2O and 5 to 7 wt% Na_2O whereas the "jadeitic pyroxenes" have 14 to 17 wt% K_2O and less than 1 wt% Na_2O.

Before we present our analytical data and interpretation for the collected samples from the Wuhe Group, it is appropriate to make some general comments with regard to the reported occurrence of jadeitic pyroxenes in high *P/T* metamorphic belts of China. Based on literature review (e. g., Dong, 1990; Liou et al., 1988) and our field-petrological study during the last 5 years in China, jadeitic pyroxenes with a Jd content greater than 60 mol % have not been confirmed, although omphacitic pyroxenes are common in eclogitic rocks in Qilin, Dabie, Shandong, Jingsu, and the Yarlung Zangbo belt. However, jadeite has been reported in several recent Chinese literatures (e. g., Jiang et al., 1987), particularly in rocks of a long discontinuous blueschist belt in central China. A few examples are described below in order to be specific.

Table 1 Examples of Probe data of Jadeite in Chinese Literature

	SiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total
1	67.67	17.64	0.05		0.05	0.17	7.49		93.07
2	68.07	17.80	0.03	0.24		0.98	11.70		99.80
3 a	67.03	19.65	0.11		0.09	0.07	10.62		97.65
3 b	60.95	18.42	0.86	0.03			0.33	17.05	97.64
4	67.71	17.80	0.34	1.03	0.44	0.65	10.41		99.00
5 a	59.38	25.82	0.45		0.12	0.13	13.40		99.30
5 b	67.84	19.65	0.03	0.04	0.02	0.00	11.07	0.29	99.80
5 c	64.46	18.55	0.14			0.17	0.49	16.07	99.88

1. Precambrian Blueschist, SE flank of the Jiangnan Island Arc, (Shu & Zhou, 1988, p. 425)
2. Precambrian Blueschist, Zhangbaling, Anhui, (Jing et al., 1989, P. 138)
3a. Archean High P/T Rocks from the Wuhe Group, Anhui
3b. K-Jadeite from Archean High P/T Rocks from the Wuhe Group, (Jing et al., 1989, P. 138)
4. Precambrian Blueschist, Central China, (Zhang et al., 1990)
5. Compositions of Jadeite (a), albite(b), and microcline(c)(Deer, Howie & Zussman, 1966)

Table 1 lists several chemical analyses of jadeites from a few papers in Chinese literature together with end-member compositions of jadeite, albite and microcline (after Deer, Howie and Zussman, 1966). The first analysis from recently discovered alleged Precambrian (?) blueschist belt, SE flank of the Jaingnan Island Arc is from Shu and Zhou (1988). The low total of

93.07 wt% and low Na_2O of 7.49 wt % and Al_2O_3 of 17.64 wt % compared to those of the end-member jadeite rule out its occurrence in the blueschist. Except for low Na_2O, the other oxide contents are similar to those of albite. Moreover, they also reported lawsonite occurrence with probe analysis which is not compatible with lawsonite composition. The finding of lawsonite and jadeite (+quartz) in Precambrian blueschist terrane is significant, as these phases required extremely low P/T gradient for their formation; and are mainly restricted to Phanerozoic blueschist terranes (e. g., Ernst, 1971, Liou et al., 1990). The second "jadeite analysis" of Table 1 is from another alleged Precambrian blueschist terrane in Zhangbaling, Anhui reported by Jing et al (1989) (see Fig. 1 for locality). As shown in Table 1, the amounts of SiO_2, Al_2O_3 and Na_2O are almost identical to those of the endmember albite. We have investigated some samples from the Zhangbaling high P/T terrane together with Jing and Liang; no jadeitic pyroxene was found in investigated samples at Stanford. The 3a and 3b analyses of Table 1 are respectively for jadeite and "K-jadeite" from the Archean Wuhe Group by Jing et al. (1989). Again, these data are very compatible with albite and microcline compositions; albite and microcline, as described below are common in Wuhe gneisses of this area. The fifth jadeite analysis (4) by Zhang et al. (1990) is also from Central China; its high SiO_2 and low Al_2O_3 is not compatible with jadeite composition; the analysis is almost identical to that of albite.

In short, the previous analyses of jadeites from so-called Precambrian blueschist terranes in central China are all albites. Conclusive identification of jadeite occurrence in the high P/T metamorphic belt of central China has not been established. Hence, readers should be extremely cautious to use the index minerals described in a Chinese literature for interpretation of tectonic setting; occurrence of jadeite in quartz-bearing rocks requires extremely high-pressure and/or low geothermal gradient. From our investigation during the period of 1988—1990, there is no lawsonite and jadeite occurrence in any high P/T metamorphic rock from central China, except for those in the Qilian Mountains (Wu et al., in press).

3 Present Study

Field and Petrographic Features

During our field study of the Zhangbaling blueschist terrane we visited three closely spaced outcrops of the Wuhe Group. The Wuhe gneisses are very poorly exposed as they were covered mainly by rice fields; only some small low rounded hills provide limited outcrops. Many small ditches and trenches have been made by local farmers to collect veined quartz samples for highway pavement and house construction. It was in these ditches, that exposures of amphibole-bearmg gneisses were observed, and samples were collected. Compositional bands occur and foliation of rocks are defined by abundant mafic minerals including sodic amphibole and biotite. The foliation crosscuts the compositional band and was measured to be similar to the orientation of foliation in the Zhangbaling Group across the Tanlu fault. This structural feature has provided additional evidence for our Chinese colleagues to support their interpretation-gneisses of blue amphiboles was contempor aneous with those of the Zhangbaling Group. Because of the poor exposures and strong alteration of gneissic rock, we did not spend a long time conducting field investigation. We collected five gneissic samples in order to examine compositional characteristics of blue amphiboles and sodic pyroxene and to evaluate the proposed high P/T metamorphism for the Wuhe Group.

These rocks exhibit gneissose structure, are medium- to coarse-grained, and contain abundant microcline, albitic plagioclase, quartz, biotite, and about 10%—15% blue amphibole together with minor acmite (less than 2%), hematite, and stilpnomelane (?). Mineral assemblages of microcline + blue amphibole + minor acmite + biotite + quartz + albitic plagioclase have been reported in alkalic granite or syenite in the Fujushin-zan District, Korea by Miyashiro and Miyashiro (1956). This district, presumably, is the north-eastern extension of the Sino-Korean Craton. They occur also as primary phases in some alkaline volcanics and granitic rocks elsewhere (e. g., Czmanske & Dillet, 1988). However, these assemblages in the Wuhe Group appear to have been recrystallized and deformed in amphibolite facies conditions. This suggestion is supported by the rock associations in this region, the gneissic structure, and the distinctly zoned feature of alkali amphiboles described below.

Blue amphibles are fine- to medium-grained; some are prismatic, others are highly irregular lozenge-like shapes; they tend to cluster with iron oxides and acmite. Rare, better-formed prismatic amphiboles of medium-grained size also occur as isolated grains, and display distinct pleochroism from violet ($=N_\gamma$), through light yellow ($=N_\beta$) to dark blue ($=N_\alpha$) in color. They show negative elongation with the maximum extinction angle of 13°. Refractive indices were determined to be $N_\gamma=1.668$, $N_\beta=1.664$, $N_\alpha=1.657$; they are optically negative with $2V=74°$. It should be noted that many of these amphibole crystals are distinctly zoned, with darker blue-violet prismatic cores surrounded by pale bluish green rims. Compositional characteristics of alkali amphibole will be discussed in the next section.

Table 2 Microprobe Analyses of Sodic Pyroxenes from the Wuhe Group

	2-B-7	2-B-7	2-B-9	2-B-10	1-A-6	2-B-1	2-B-2	2-B-3
SiO_2	53.34	53.10	53.27	52.86	53.07	52.9	52.83	51.86
TiO_2	0.48	0.34	0.65	0.15	0.4	0.48	0.54	0.07
Al_2O_3	0.18	0.29	0.15	0.5	0.01	0.2	0.68	0.33
Fe_2O_3*	31.27	30.71	29.97	32.55	31.76	30.96	30.89	31.3
MnO	0.04	0.05	0.05	0.03	0.09	0.03	0.03	0.01
MgO	0.63	0.87	0.54	0.01	0.63	0.57	0.5	0.27
CaO	0.78	1.28	0.69	0.06	1.28	0.76	0.69	0.61
K_2O	0.01	0	0.02	0	0	0	0	0
Na_2O	13.48	12.95	13.19	13.92	12.78	13.66	13.80	13.89
Cr_2O_3	0.05	0	0	0.03	0	0.01	0	0
Total	100.25	99.59	98.51	99.11	100.02	99.58	99.96	98.34
Si	2.013	2.014	2.027	2.004	2.010	2.011	2.001	2.013
Al^{IV}								
Al^{VI}	0.008	0.013	0.007	0.05	0.001	0.009	0.031	0.015
Ti	0.014	0.01	0.019	0.004	0.011	0.014	0.015	0.002
Fe^{3+}	0.894	0.882	0.868	0.935	0.911	0.892	0.886	0.916
Mn	0.001	0.002	0.002	0.001	0.003	0.001	0.001	0
Mg	0.036	0.05	0.031	0.001	0.036	0.033	0.028	0.016
Ca	0.032	0.052	0.028	0.002	0.052	0.031	0.028	0.025
Na	0.993	0.959	0.984	1.033	0.945	1.014	1.02	1.037
K	0.001	0	0.002	0	0	0	0	0
Cr	0.002	0	0	0.001	0	0	0	0

* Total Fe as Fe_2O_3 (Analyzed by choi).

Sodic pyroxenes are medium-grained, occur in clusters, with quartz, alkali feldspar, micas, hematite, and alkali amphiboles or as discrete aggregates, and have both prismatic euhedral and granular anhedral forms. Where they are intimately intergrown with alkali amphiboles, sodic pyroxenes appear to have crystallized later than amphibole. They show distinct pleochroism from pale yellowish green to deep greenish brown; however, zoning was not detected. Seven probe analyses were completed for three samples and representative data are listed in Table 2. These data indicate that all analyzed sodic pyroxenes are acmite with very low jadeite (< 2 mol%) and diopside components (< 5 mol %) and contain low TiO_2, Cr_2O_3 and MnO. These pyroxene analyses do not contain any detectable K_2O; this conclusion is just opposite to the K_2O content of 14%—17 wt% for K-jadeite reported by Jing et al. (1989). The Si values of 2.02 to 2.05 are higher than normal for pyoxene; similar Si excess has been reported(e.g., Czamanski & Dillet, 1988).

Table 3 Representative analyses of biotite and microcline from the Wuhe Group

	Biotite			Microcline		
SiO_2	42.22	42.51	42.41	63.86	64.17	64.1
Al_2O_3	9.64	9.37	8.93	18.41	18.26	17.9
TiO_2	2.03	2.01	1.97	0.01	0.01	0.05
FeO*	15.04	14.41	14.27	0.1	0.05	0.11
MgO	14.56	14.35	14.34	0	0	0
MnO	0.08	0.13	0.13	0	0	0.05
Cr_2O_3	0	0.12	0.01	0.09	0	0.01
CaO	0.28	0	0.45	0.08	0.07	0.05
Na_2O	0.07	0.06	0.1	0	0.34	0.38
K_2O	8.39	9.21	9.31	16.21	16.25	16.38
Subtotal	92.32	92.17	92.01	99.14	99.16	99.15

* Total Fe as FeO (Analyzed by Choi).

Biotite in these samples is fine-grained and tends to be partly altered to chlorite. When it is unaltered, it shows distinct pleochroism. Reconnasance analyses of biotite are shown in Table 3; they are characteristically low in total, and in K_2O content; this may be due in part to alteration and in part to fine-grained nature. Nevertheless. the biotite analyses show high Al_2O_3 of 9%—10 wt%, and K_2O of 7 to 8.3 wt%, moderate amount of TiO_2 of about 2 wt% and low Na_2O and CaO. They are very different in composition from stilpnomelane. Microcline is abundant and occurs as medium to coarse clear, equidimensional, xenomorphic grains, and exhibits good cross-hatched twinning. No perthite was found. Analyses of microcline shown in Table 3 has almost end-member composition with a Na_2O content less than 0.4 wt% and CaO 0.05 wt%. In microcline-rich samples, albitic plagioclase was not fond; however, other samples contain microcline and abundant sodic plagioclase.

Characteristic Features of Alkali Amphiboles

Compositions of alkali amphiboles have been analyzed by Changchun College of Geology by both wet chemical method and microprobe analyzer. The wet chemical analysis listed in Table 4 represents an averaged composition for zoned amphiboles with a K_2O content characteristically greater than 2 wt%. They plotted their analyses into the field of magnesioriebeckite which is supported by their X-ray diffraction data. The distinctly high K_2O content can be used to differentiate the alkali amphiboles of the Wuhe

Group from those in the high P/T belts of central China, in the Franciscan Complex or in the Sanbagawa belt.

Table 4 Chemical compositions of Mg-Arlvedsonite from the Wuhe Group

SiO_2	54.49	54.98	55.31	54.59	54.69	55.30	55.95	56.32	55.93	56.21	55.70
Al_2O_3	0.20	0.42	0.15	0.54	0.55	0.37	0.50	0.28	0.50	0.12	0.19
FeO	9.38	9.31	8.04	9.77	9.12	8.68	7.14	8.63	8.74	7.03	8.51
Fe_2O_3	7.42	7.96	8.85	9.27	9.90	10.44	11.54	9.78	8.86	9.97	7.71
Mgo	12.90	12.31	12.67	11.49	11.71	11.91	12.53	12.29	12.50	13.32	13.10
MnO	0.25	0.32	0.35	0.07	0.06	0.13	0.23	0.08	0.26	0.27	0.24
TiO_2	0.35	0.42	0.40	0.16	0.20	0.14	0.04	0.38	0.19	0.08	0.32
Cr_2O_3	0.14	0.04	0.00	0.00	0.00	0.00	0.03	0.08	0.03	0.00	0.03
CaO	0.85	0.87	0.17	1.12	1.99	2.08	0.58	1.05	0.82	0.81	0.64
Na_2O	6.91	6.92	6.56	6.15	5.91	5.69	6.22	5.84	6.16	6.49	6.17
K_2O	4.28	3.80	4.14	3.19	2.40	1.98	2.12	2.35	3.43	3.78	4.26
Total	97.16	97.35	97.24	96.35	96.53	96.73	96.88	97.08	97.42	98.08	96.86
						O = 23					
Si	7.97	7.95	7.98	7.97	7.95	7.97	7.99	8.02	8.01	7.98	8.02
Al	0.03	0.07	0.03	0.09	0.10	0.06	0.09	0.05	0.09	0.02	0.03
Fe^{2+}	1.16	1.14	0.98	1.21	1.12	1.06	0.87	1.05	1.06	0.85	1.04
Fe^{3+}	0.82	0.88	0.97	1.03	1.10	1.15	1.26	1.07	0.97	1.08	0.85
Mg	2.83	2.69	2.76	2.53	2.57	2.59	2.71	2.65	2.71	2.86	2.86
Mn	0.03	0.04	0.04	0.01	0.01	0.02	0.03	0.01	0.03	0.03	0.03
Ti	0.04	0.05	0.04	0.02	0.02	0.02	0.00	0.04	0.02	0.01	0.04
Cr	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Ca	0.13	0.10	0.12	0.18	0.31	0.33	0.09	0.16	0.13	0.13	0.10
Na	1.98	1.97	1.86	1.77	1.69	1.61	1.75	1.64	1.74	1.81	1.75
K	0.81	0.71	0.77	0.60	0.45	0.37	0.39	0.43	0.64	0.70	0.80
Sum	15.77	15.64	15.57	15.41	15.31	15.18	15.17	15.13	15.49	15.47	15.51

FeO and Fe_2O_3 were calculated by using Papike's program with intermediate Fe^{3+}/Fe^{3+} ratio (Analyzed by Choi).

More than 20 amphibole analyses were completed at Stanford. Representative analyses together with the calculated structural formula are listed in Table 4 and graphically shown in Figs.2—5. The analyzed amphiboles are characteristically low in Al_2O_3 (<0.9 wt%), CaO, and TiO_2, but high in SiO_2, total alkali and total Fe as FeO*, and show distinct differences in compositions between cores and rims. The cored amphiboles contain high K_2O ranging from about 3 to 4.5 wt% and have A site occupancy greater than 0.5; they are magnesio-arfvedsonite according to Leake's classification (1978) as shown in Fig.2.(top). On the other hand, the amphibole rims are rich in FeO* and Na_2O and low in K_2O; the A site occupancy is less than 0.5; they are magnesio-riebeckite as shown in Fig. 2(bottom). Both cores and rims show rather restricted $Fe^{3+}/(Fe^{3+}+Al)$ ratios of 0.89—0.99 and a wide range in $Mg/(Mg+Fe^{2+})$

Table 5 Chemical compositilons of Mg-Riebeckite from the Wuhe Group

SiO_2	54.35	54.16	54.58	53.98	55.36	55.08	54.54	54.69	54.59	54.77	54.60
Al_2O_3	0.60	0.55	0.55	0.42	0.77	0.95	0.80	0.70	0.67	0.77	0.84
FeO	8.83	10.22	10.99	12.62	10.82	12.67	13.28	12.72	8.73	9.68	9.92
Fe_2O_3	13.09	14.78	15.70	15.25	14.31	14.24	14.46	14.74	15.49	16.25	15.70
MgO	10.23	8.47	7.28	6.57	8.22	7.75	6.85	6.87	8.99	7.81	8.40
MnO	0.31	0.20	0.07	0.14	0.10	0.13	0.06	0.00	0.08	0.00	0.12
TiO_2	0.08	0.05	0.00	0.10	0.06	0.10	0.04	0.00	0.04	0.06	0.11
Cr_2O_3	0.04	0.00	0.00	0.00	0.05	0.04	0.00	0.04	0.04	0.04	0.11
CaO	0.57	0.37	0.00	0.16	0.37	0.39	0.19	0.17	0.33	0.17	0.20
Na_2O	7.32	7.30	7.48	7.37	7.49	7.52	7.64	7.62	6.92	6.97	6.97
K_2O	0.76	0.12	0.02	0.00	0.22	0.05	0.00	0.00	0.37	0.00	0.20
Total	96.18	96.22	96.67	96.61	97.77	98.92	97.86	97.55	96.24	96.52	97.17
Si	7.96	7.98	8.01	7.99	8.02	7.95	7.98	7.99	7.96	8.00	7.94
Al	0.10	0.10	0.10	0.07	0.13	0.16	0.14	0.12	0.12	0.13	0.15
Fe^{2+}	1.09	1.27	1.36	1.58	1.32	1.54	1.64	1.57	1.08	1.19	1.22
Fe^{3+}	1.45	1.65	1.75	1.72	1.57	1.56	1.61	1.64	1.72	1.80	1.73
Mg	2.25	1.87	1.61	1.46	1.79	1.68	1.51	1.51	1.98	1.72	1.84
Mn	0.04	0.03	0.01	0.02	0.01	0.02	0.01	0.00	0.01	0.00	0.01
Ti	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01
Cr	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Ca	0.09	0.06	0.00	0.03	0.06	0.06	0.03	0.03	0.05	0.03	0.03
Na	2.10	2.10	2.15	2.14	2.12	2.12	2.19	2.18	1.98	1.99	1.98
K	0.14	0.02	0.00	0.00	0.04	0.01	0.00	0.00	0.07	0.00	0.04
Sum	15.24	15.08	14.99	15.01	15.08	15.12	15.10	15.04	14.96	14.89	14.97

SiO_2	54.68	55.52	54.67	55.87	55.70	55.70	55.37	54.83	55.95	53.90
Al_2O_3	0.82	0.95	0.47	0.63	0.58	0.55	0.51	0.51	0.50	1.02
FeO	10.41	10.21	11.55	6.69	7.00	6.48	10.35	7.38	7.14	6.77
Fe_2O_3	9.15	16.35	16.74	16.19	14.86	12.92	17.06	12.70	11.54	12.88
MgO	11.61	8.48	6.90	10.19	10.59	11.83	7.33	11.47	12.53	12.28
MnO	0.07	0.07	0.05	0.18	0.19	0.24	0.10	0.07	0.23	0.72
TiO_2	0.10	0.00	0.15	0.14	0.00	0.17	0.02	0.26	0.04	0.65
Cr_2O_3	0.00	0.02	0.10	0.08	0.00	0.04	0.03	0.00	0.03	
Ca_2O	3.19	0.25	0.07	0.35	0.46	0.57	0.02	1.14	0.58	2.53
Na_2O	5.51	7.02	6.94	7.10	7.11	7.05	6.96	6.42	6.22	4.75
K_2O	1.40	0.13	0.00	0.04	0.78	1.65	0.00	1.46	2.12	2.37
Total	96.94	99.00	97.64	97.45	97.27	97.19	97.75	96.23	96.88	97.87
Si	7.95	7.94	7.98	7.98	7.99	7.99	8.01	7.96	8.03	7.98
Al	0.14	0.16	0.08	0.11	0.10	0.09	0.09	0.09	0.09	0.18
Fe^{2+}	1.28	1.23	1.42	0.81	0.85	0.78	1.26	0.90	0.87	0.84
Fe^{3+}	1.01	1.77	1.86	1.75	1.62	1.41	1.88	1.40	1.26	1.44
Mg	2.53	1.82	1.51	2.19	2.28	2.55	1.60	2.50	2.71	2.76
Mn	0.01	0.01	0.01	0.02	0.02	0.03	0.01	0.01	0.03	0.09
Ti	0.01	0.00	0.02	0.02	0.00	0.02	0.00	0.03	0.00	0.07
Cr	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	
Ca	0.00	0.04	0.01	0.05	0.07	0.09	0.00	0.18	0.09	0.40
Na	1.57	1.96	1.98	1.98	2.00	1.98	1.97	1.82	1.75	1.37
K	0.26	0.02	0.00	0.01	0.14	0.30	0.00	0.27	0.39	0.45
Sum	15.26	14.96	14.88	15.93	15.08	15.14	14.83	15.17	15.21	15.22

1. FeO and Fe_2O_3 of most analyses were calculated by using Papkie's program with intermediate Fe^{2+}/Fe^{3+} ratio (Analyzed choi).
2. The last one is chemical analysis by Changchung University, China.

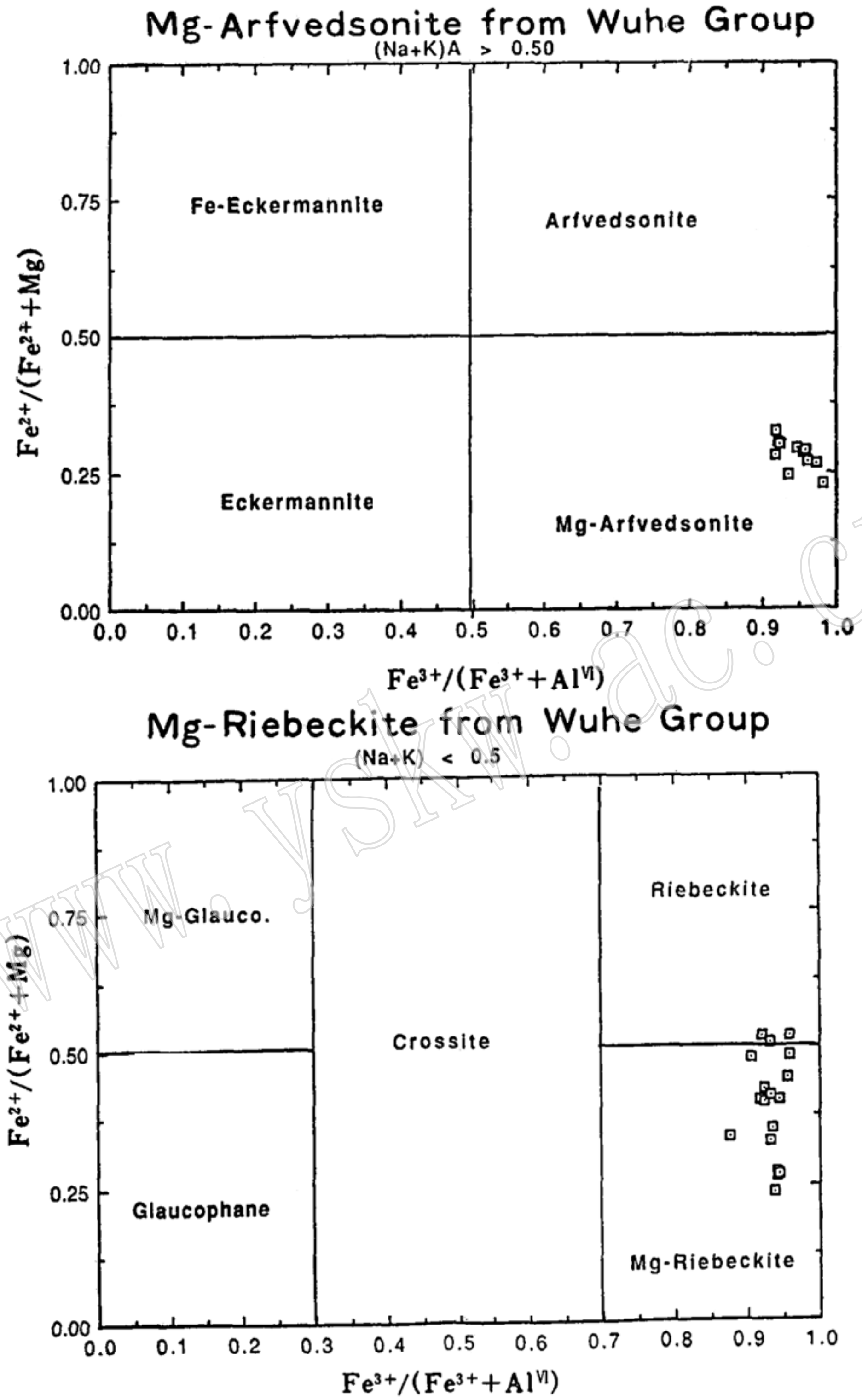

Fig. 2 Top: Compositional plot of cored alkali amphiboles from the Wuhe Group. The analyses listed in Table 4 have total A site occupancy of Na + K greater than 0.5; and are plotted into Mg-Arfvedsonite field (after Leake's classification, 1978)

Bottom: Compositional plot of rimmed alkali amphiboles from the Wuhe Group. The analyses listed in Table 5 have low K_2O and total A site occupancy of Na + K less than 0.5; they are Mg-Riebeckite after Miyashiro (1957) ratios of 0.49 to 0.78. In terms of $Ca+Al^{IV}$ vs $Si+Na+K$ plot of Fig. 3, core and rim amphiboles are respectively plotted in arfvedsonite and riebeckite fields; they are distinguished from winchite and richterite by very low $Ca+Al^{IV}$. Similar riebeckitic amphiboles together with richterite and acmite in alkali rocks in the Fukushin-zan District, Korea have been described by Miyashiro and Miyashiro (1956).

Compositions of both core and rim amphiboles are plotted in the Miyashiro diagram of Fig. 4 together with selected analyses of sodic amphiboles from the Zhangbaling high P/T metamorphic belt across the Tanlu Fault. Several distinct features are apparent from this diagram. First, compositions of the cores, and rims of the Wuhe amphiboles and those of the Zhangbaling are distinictly different; each has rather uniform composition. Second, the Zhangbaling sodic amphiboles contain very low K_2O and do not overlap in composition with those of the Wuhe Group; they are crossite and exhibit wider variations in $Fe^{3+}/(Fe^{3+}+Al^{VI})$. Third, the Wuhe amphiboles are Mg-riebeckites (or Mg-Arfvedsonites), have much higher and narrow ranges in $Fe^{3+}/(Fe^{3+}+Al^{VI})$, and larger variation in $Fe^{2+}/(Fe^{2+}+Mg)$ ratios. The high Fe_2O_3 content of the Wuhe amphiboles is consistent vith their coexistence with acmitic pyroxene and hematite. Such compositional characteristics of alkali amphiboles mentioned above suggest that the amphiboles from the Zhangbaling and Wuhe Groups may have formed from very different protoliths at very different P-T conditions.

Miyashiro (1957) differentiated alkali amphiboles of igneous and metamorphic origin based on available chemical data as shown in Fig. 5. Those alkali amphiboles of the metamorphic origin tend to have higher octahedral Al and ferric iron compared to those of igneous arfvedsonite and kartophorite groups. Hence, most amphiboles of the riebeckite-magnesioriebeckite series may be of metamorphic origin and most arfvedsonite group amphiboles of igneous origin. The analyses of cored and rimmed amphiboles of the Wuhe Group were plotted respectively in igneous and metamorphic fields of Miyashiro (1957) as shown in Fig. 5. In other words, the Mg-arfvedsonite amphiboles may have formed as primary phases in water saturated granitic melt at temperatures above the solidus. This and other rocks of the Wuhe Group were subsequently deformed and recrystallized during amphibolite facies metamorphism and the Mg-arfvedsonite was rimmed by magnesioriebeckites.

Conditions of Formations

P-T conditions for formation of the observed assemblages in the Wuhe

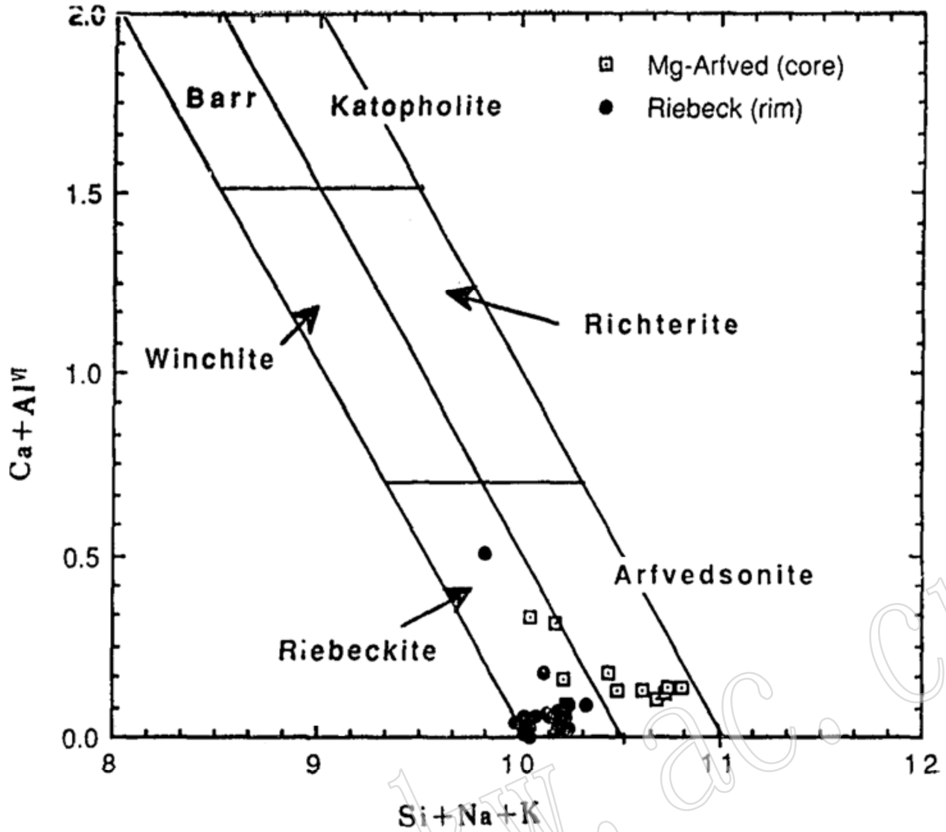

Fig. 3 The analyzed compositions of cores and rims for Wuhe alkali amphiboles are plotted in Ca + tetrahedral Al versus Si+Na+K. Again, these amphiboles are low in Ca and tetrahedral Al; both cores and rims are respectively plotted mainly in arfvedsonite and riebeckite fields

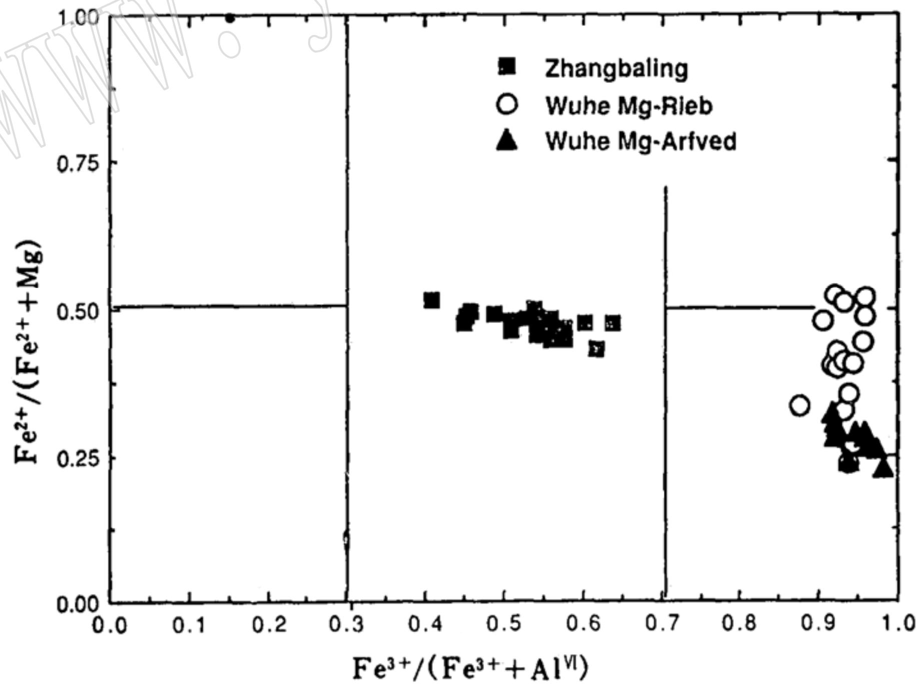

Fig. 4 Comparison of analyses of zoned alkali amphiboles from the Wuhe Group with crossitic amphiboles from the Zhangbaling Group in a Miyashro's diagram (1957). (Compositions of crossitic amphiboles are from our unpublished data). No compositional overlap between the amphiboles from the Wuhe and Zhangbaling Group is apparent

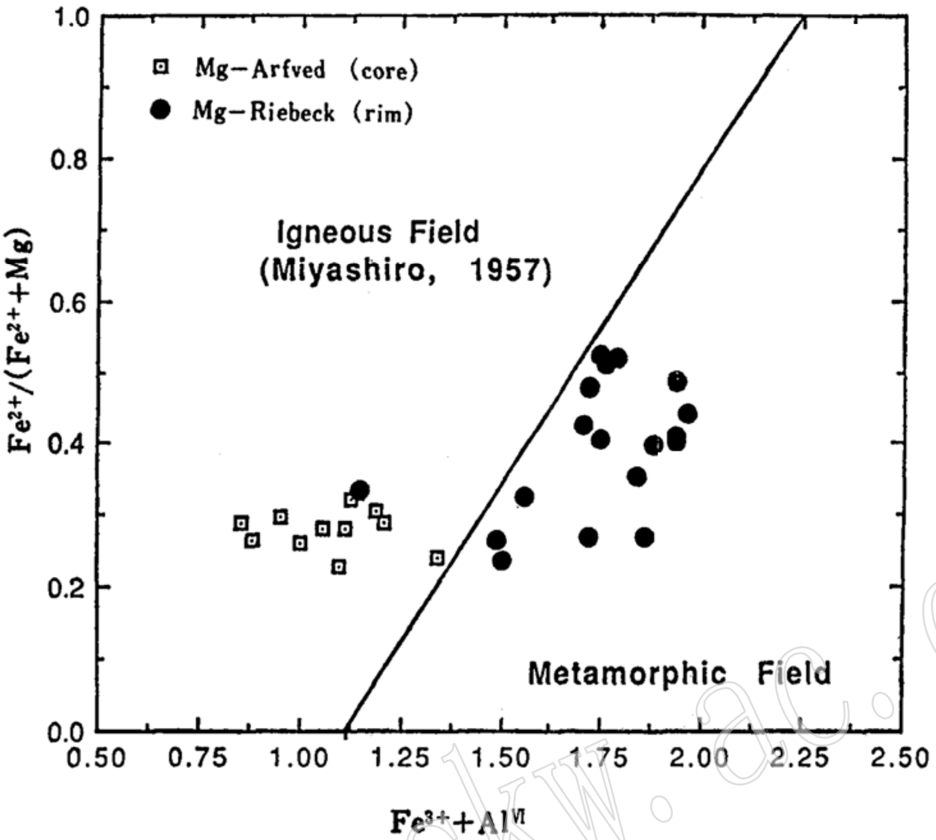

Fig. 5 The analyzed compositions of alkali amphiboles are plotted in $Fe^{2+}/(Fe^{2+}+Mg)$ against $Fe^{3+}+Al^{VI}$ after Miyashiro(1957). Core and rim compositions are respectively plotted in igneous and metamorphic fields suggesting the cores are relict igneous amphiboles and rims are the product of subsequent amphibolite facies metamorphism

Group have not been quantitatively estimated. The low-Al_2O_3 content of alkali amphiboles both in core and rim is most characteristic and bulk rock composition could be significant in controlling the low Al_2O_3 in amphiboles. Unfortunately, bulk compositions of these 5 samples were not analyzed. However, based on the reported whole rock data by Fuh et al. (1984), the alkali amphibole-bearing Wuhe gneisses range in SiO_2 from 54 to 70 wt%, Al_2O_3 from 13 to 14 wt%, Fe_2O_3 from 12 to 4 wt%, FeO from 1 to 2.4 wt%, MgO from 1 to 12 wt%, CaO from 0 to 1.85 wt%, Na_2O from 0.7 to 2 wt% and K_2O from 10 to 6 wt%. The analyzed gneisses are variable in SiO_2 and MgO, very high in Al_2O_3, Fe_2O_3 and K_2O and low in FeO and CaO contents. Because of low CaO, characteristic hornblende did not occur in the Wuhe gneisses. Otherwise, the observed mineral assemblages are similar to some buffered assemblages such as Hb + Bi + K-spar + Pl + Qz + magnetite ± melt for granitic composition. The Al-in-hornblende of such buffered assemblages has been suggested to be sensitive to pressure of its formation based on both experimental calibration (e. g., Johnson & Rutherford, 1989) and empirical observation (e. g., Hammarstron & Zen, 1986; Hollister et al., 1987). The low Al_2O_3 content (or tsermakite component) of alkali amphiboles from the Wuhe gneiss rules out the high-pressure origin for its formation. This suggestion is supported by the low jadeitic component in acmitic pyroxene together with quartz and albite.

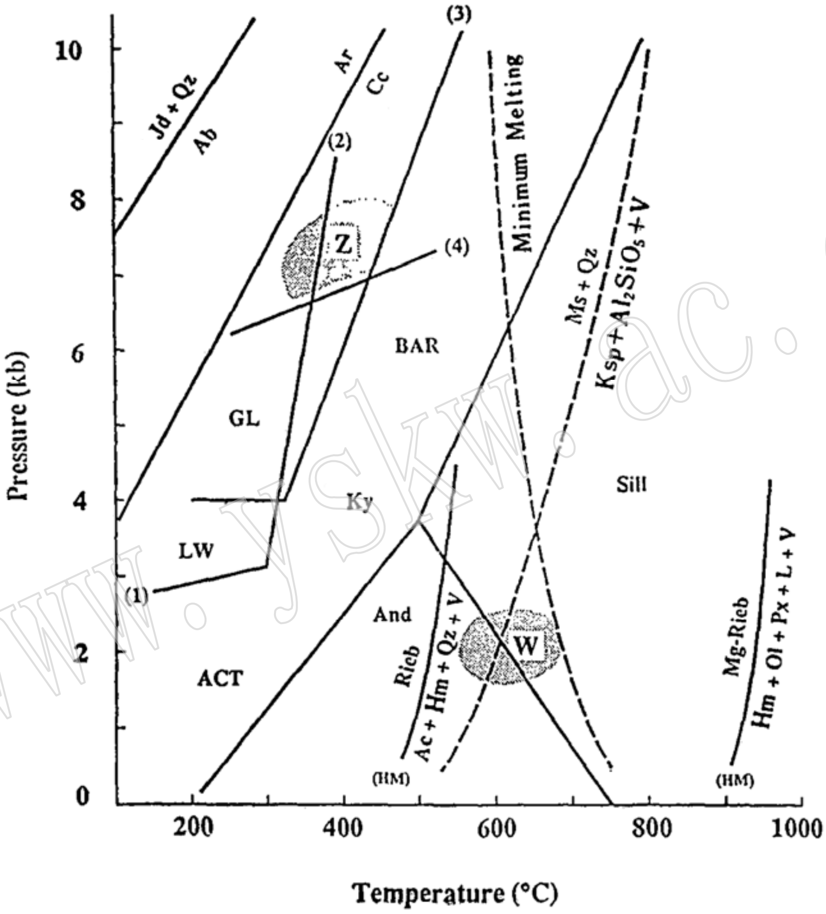

Fig. 6 *P-T* diagram shows thermal stability limits of jadeite + quartz (Newton & Smith, 1967), aragonite (Carlson, 1981), lawsonite (1, 2) (Liou, 1971; Nitsch, 1974), glaucophane (3) (Maresch, 1977), glaucophane + epidote (Ps 30) (4) (Maruyama et al., 1986), Al_2SiO_5 (5) (Holdaway, 1971), muscovite + quartz (Kerrick, 1974), riebeckite and magnesioriebeckite (Ernst, 1960, 1962), the solidus of granitic magma (Luth et al., 1964), and *P-T* estimates for metamorphism of the Zhangbaling Group (Z) and Wuhe Group (W). Note the stability of jadeite in the presence of quartz requires extremely high P and low T for its occurrence

In terms of temperature of metamorphism, two independent estimates could be applied. First, phase equilibria of alkali amphiboles have been investigated by Ernst (1960, 1962) and his results are shown in Fig. 6. In the presence of quartz + hematite, riebeckite-arfvedsonite amphibole is stable up to about 510℃ (HM buffer) at 2 kb, whereas the assemblage acmite + Hm + Qz is stable at higher temperatures. With lowering the fo_2 (IW buffer), the arfvedsonite component of amphibole increases and its maximum thermal stability reaches to about 700℃ at 1000 bars. The acmite + magnesioarfvedsonitic amphibole solid solution (+ magnetite + Qz or fayalite) assemblage occurs over broader *P-T* conditions (e. g., 700℃) under progressively more reducing conditions. Moreover, magnesioriebeckite, as shown in Fig. 6, is stable at temperatures about 400℃ higher than the high-T stability limit of riebeckite at the fo_2 of the HM buffer (Ernst, 1960). In the presence of excess quartz, the maximum thermal stability limit of magnesioriebeckite will be significantly lower. Nevertheless, the assemblage of acmite + arfvedsonite together with alkali feldspar, quartz and sodic plagioclase has been reported as magmatic products in peralkaline granite (e. g., Czamanske & Dillet, 1988). Arfvedsonite is a characteristic ferromagnesian phase of alkaline plutonic rocks and their associated pegmatites. It occurs in quartz-bearing syenites as a late crystallization product and is commonly associated with acmitic pyroxenes. Fig. 6 shows the thermal stability limits of riebeckite and magensioriebeckite of their end-member compositions together with solidus of peralkaline granitic rock. Although the effect of K_2O on the stability of magnesioarfvedsonite has not been experimentally determined, comparison with other occurrences (Fig. 5) suggests that the magnesioarfvedsonite cores of the Wuhe gneisses may be relicts of a primary plase crystallized from the melt of an alkaline granitic composition. On the other hand, the assemblages magnesio-riebeckite + acmite + biotite + feldspar + qhartz + hematite were formed in subsequent amphibolite facies metamorphism.

Two alkali feldspars of some Wuhe gneisses are almost pure end-member compositions, hence, they are stable at temperatures above 550℃ at 1 kb relative to muscovite-paragonite + quartz (Thompson, 1974). Muscovite is not common and is absent in some samples. The absence of muscovite and the coexistence of two alkali feldspars in quartz-rich Wuhe gneisses suggests that *P-T* conditions may be above the second sillimanite isograd. Considering the effect of variability in fluid and rock compositions, *P-T* estimates for amphibolite facies metamorphism of the Wuhe Group is shown in Fig. 6. Because of the very limited samples investigated in the present study, this estimate should be considered to be very preliminary. It should be noted that k-feldspar is not common in blueschist facies terrane of the world and it is replaced by phengitic mica or chessborad-twinning albite

(e. g., Moore and Liou, 1976). Thus far, no K-feldspar has been reported in high *P/T* metamorphic rocks from central China although some host rock compositions contain high K_2O, Al_2O_3 and SiO_2 necessary for cıystallization of microcline. Based on the compositions of crossitic amphibole in a buffered assemblage crossite + actinolite + albite + chlorte + quartz + sphene (e. g., Maruyama et al., 1986), *P-T* condition for blueschist facies metamorphism of the Zhangbaling Group was estimated. The result shown in Fig. 6 is very different from the *P-T* estimate for the Wuhe Group. In short, the observed mineral assemblage, the occurrence of two feldspars, the compositions of blue amphiboles, the low jadeitic component of analyzed acmitic pyroxenes, and the amphibolite facies *P-T* conditions all suggest that the investigated gneisses of the Wuhe Group were products of the amphibolite facies but not high *P/T* blueschist facies metamorphism.

4 Conclusions

The Archean alkali granitic rocks of the Wuhe Group probably have been deformed and recrystallized in amphibolite facies conditions during the consolidation of the Sino-Korean craton. The effect of such metamorphic recrystallization is best exhibited on the growth of magnesioriebeckite around Mg-Arfvedsonite together with acmite + microcline + biotite + hematite + quartz. This assemblage was formed at temperatures slightly less than 600℃ but greater than 500℃ and pressures less than 5 kb under high fo_2 conditions; this *P-T* condition may not be significantly lower than that for crystallization of the protolith of alkali granite. The primary phases of the granitic rocks may contain Mg-Arfvedsonite + acmite + k-feldspar + quartz ± biotite ± plagioclase; these phases have been commonly reported in alkali granites, alkali syenites and nepheline syenite and their volcanic equivalents (e. g. Czamanske & Dillet, 1988). Thus, the occurrence of blue amphibole in the Wuhe gneisses does not support the previous suggestions that the Wuhe Group has been subjected to high *P/T* metamorphism concurrently with that of the Zhangbaling group.

Moreover, metamorphic age of the Zhangbaling terrane, which is an eastern extension of a long discontinuous blueschist belt in central China, may not be in the Precambrian as suggested by many Chinese geologists (e. g., Dong et al., 1986; Dong, 1990; Zhang et al., 1990). Instead, timing of such high *P/T* metamorphism could be as young as Indosinian (about 230 Ma) immediately before the collision between the Sino-Korean and Yangtze cratons (e. g., Mattauer et al., 1986; Pan et al, in preparation). Hence, new geochronological dates of the blueschist belt and its adjacent Dabie eclogite terrane together with present petrological data indicate that the formation of the Wuhe Precambrian gneiss was not related to the Indosinian high P/T metamorphic event. Previous reports of the jadeite occurrence in the Wuhe Group and in high P/T metamorphic rocks of central China were not supported by the published microprobe data, nor our petrological results. As shown in Fig. 6, in the presence of quartz, jadeite stability is restricted to extremely high pressures and low temperatures; its occurrence requires very low geothermal gradient.

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中国中部安徽晚太古代五河群碱性角闪石——并非高压变质的指示矿物

刘忠光　王小民　　崔善奎

（美国斯坦福大学地质学系，斯坦福 94305）　（南朝鲜国立教育大学地球科学系）

梁万通　　荆延仁　潘国强　夏木林

（长春地质学院地质系）　（安徽省区域地质大队）

摘　要

在中国中部晚太古代五河群的碱性片麻岩中，曾报导有蓝色角闪石和硬玉的存在，并且认为它们是与安徽张八岭群同期的高压变质矿物。本文作者经过对岩石和矿物成分的详细研究，证实五河群中的碱性角闪石＋锥辉石＋斜长石＋黑云母＋石英±钠长石±赤铁矿等矿物组合是典型的角闪岩相变质矿物组合，这些碱性角闪石的核部是岩浆岩成因的镁钠铁闪石，其边部是角闪岩相变质成因的镁钠闪石，这些碱性闪石的 Al_2O_3 含量特别低，而 FeO 和 Fe_2O_3 含量很高，它们与张八岭群的青铝闪石在化学成分上差别很大。五河群片麻岩中的钠质辉石是很纯的锥辉石而没有硬玉组分。从含大量微斜长石的矿物组合、蓝色角闪石的矿物成分、低硬玉质的钠辉石和估算的温度和压力条件来看，我们认为五河群的片麻岩并不是高压蓝闪片岩相的变质产物。此外，以前关于五河群和中国中部其他变质岩中（如张八岭群）有关硬玉的报导中所发表的电子探针和化学分析资料与辉石的化学分子式不符，我们的岩石学研究也没有证实硬玉的存在。