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The ilmenite-series and magnetite-series classification of the Yanshanian granitoids of South China

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Abstract: Yanshanian (Jurassic-Cretaceous) granitoids of South China were evaluated in terms of the ilmenite/magnetite-series classification defined by their bulk Fe_2O_3/FeO ratios. Early Yanshanian granitoids are composed of 59 percent ilmenite series and 41 percent magnetite series, while Late Yanshanian granitoids consist of 43 vs. 57 percent, respectively, indicating an oxidized nature toward the younger generation. Yanshanian granitoids tend to have higher Fe_2O_3/FeO ratios in the Lower Yangtze region and the Southeast Maritime volcanic belt; however, no asymmetrical zoning of the ilmenite/magnetite-series distribution is observed in the main, Cathaysian folded zone of the Nanling Range, unlike Late Mesozoic granitoids occurring in the island-arc setting (e.g., Japanese Islands and Sierra Nevada-Peninsular Range batholiths). Genetic relationships of ilmenite-series granitoids with W, Sn, REE and Nb–Ta ore deposits, and magnetite-series granitoids with magnetite-hematite and Cu–Pb–Zn deposits observed in the Yanshanian granitoids of South China are consistent with the results of the Japanese Islands.

Introduction

Granitoids are widely distributed in South China, rich in associated metallic ore deposits, and thus studied in detail. They are classified into Middle Proterozoic, latest Proterozoic-Early Paleozoic, Caledonian, Hercynian, Indosinian and Yanshanian cycles, and are distributed mainly in the Nanling Range, which extends 550,000 km^2, among which the granitoids occupy 190,000 km^2 (Chen *et al.*, 1989; 1995; GRGNP, 1989). A majority of the granitoids belong to Early and Late Yanshanian cycles of Jurassic (partly Triassic) to Cretaceous age, which have been further subdivided into two to four substages, depending upon researchers.

The Yanshanian granitoids have been classified into two types, as (1) transformation type and syntexis type by Xu *et al.* (1982), or (2) Series I (Nanling Series) and Series II (Yangtze Series) by Wang *et al.* (1982). These two types have been considered equivalent to S- and I-types (Chappell and White, 1974, 1982) of the Lachlan folded belt, and even to the ilmenite-series and the magnetite-series granitoids of Ishihara (1977) of the Japanese Islands by many Chinese authors (e.g., Zhu, 1998). No precise correlations have been made so far, however, only Yuan and Yang (1982) pointed out some disagreement of the two classifications in South China.

Later Xu *et al.* (1987) modified the original proposal, and added alkaline type and mantle-derived types, although the additional two types are minor in amount in China. GRGNP (1989) classified the Nanling Range granitoids by accessory mineral assemblages, as (1) Magnetite-allanite-apatite type (correlative to I type), (2) Ilmenite-magnetite-monazite-xenotime type (correlative to S type), and (3) Magnetite-ilmenite(-allanite)-zircon type (correlative to A type), implying that all the granitoids belong to magnetite series.

In this paper, we try to identify the redox state of the Yanshanian granitoids in terms of the ilmenite-series and magnetite-series classifications, by compiling recently increased amounts of the bulk chemical data of the granitoids. The original data were mainly taken from regional geological reports of each province published as Geological Memoirs, Series 1, by the Ministry of Geology and Mineral Resources. Eight provinces, Hubei (BGMRHP, 1990), Jiangsu (BGMRJP, 1984), Anhui (BGMRAP, 1987), Jiangxi (BGMRJP, 1984) and Hunan (BGMRHP,1987), and coastal region of Zhejiang (BGMRZP, 1989), Fujian (BGMRFP, 1985) and Guangdong (BGMRGP, 1988), were selected. Very limited data of Guangxi Province were taken from Chen *et al.* (1989, 1993). Localities of the studied plutons and samples are shown in Figure 1.

In these reports, most chemical data are given as averages for intrusive bodies; some may be single analysis. The ilmenite-series/ magnetite-series granitoids are empirically divided by the Fe_2O_3/FeO of 0.5 (Ishihara *et al.*, 1979). This is strictly so at SiO_2 70 percent. An average composition of all the Japanese granitoids (Ishihara, unpublished data) has this ratio of 0.5 at SiO_2 70 percent. It is, therefore, the average composition that

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Keywords: South China, granitoids, Yanshanian, Series I, Series II, ilmenite series, magnetite series, redox state

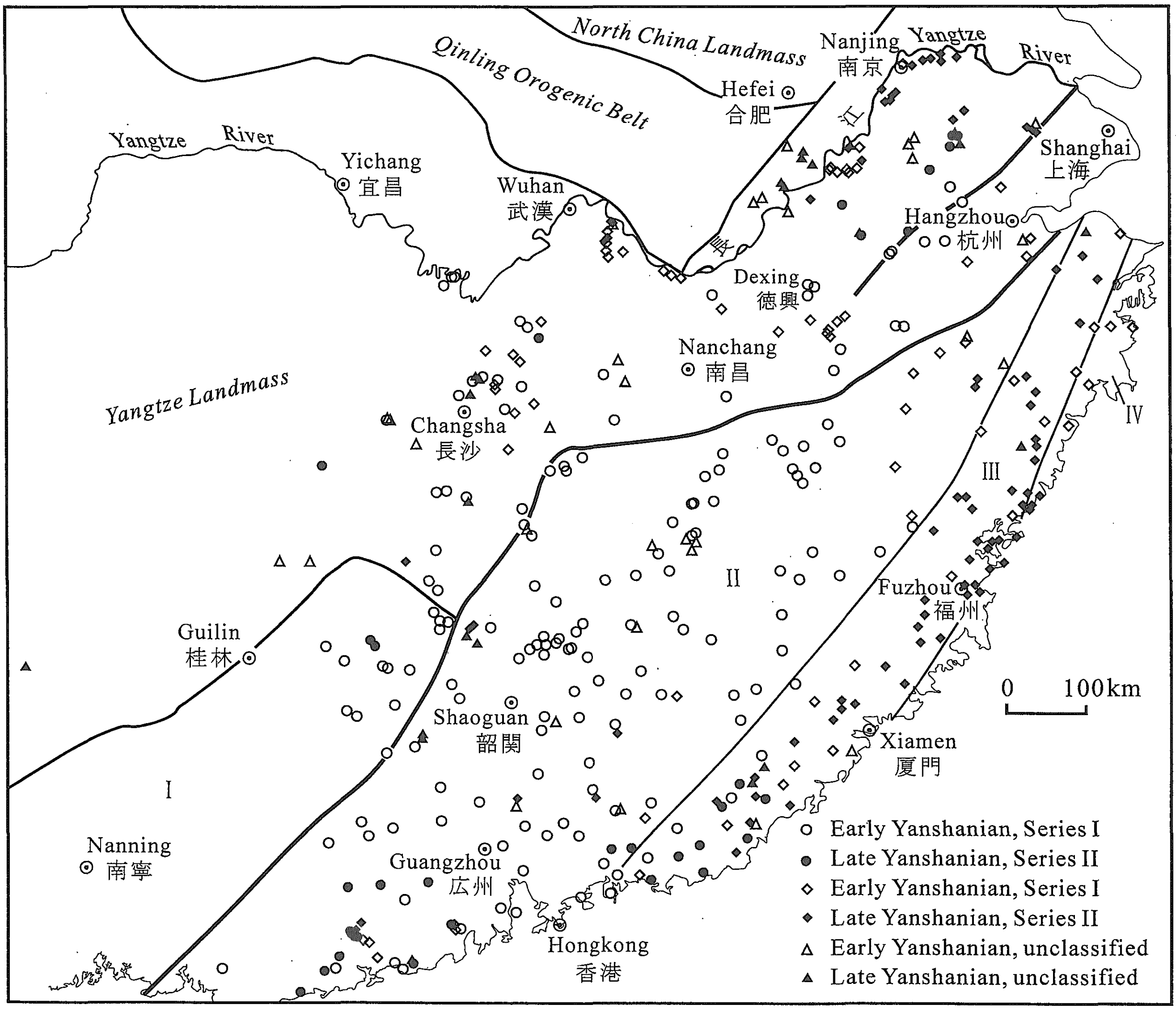

Fig. 1 Distribution of Yanshanian granitoids in South China. The classification of Series I and Series II is taken from Wang *et al.* (1985). Solid triangle, unclassified. The tectonic division after Cheng ed. (1994). I, Hunan-Guangxi folded zone; II, Cathaysian folded zone; III Southeast Maritime volcanic & fault-depression zone; IV, Southeast Maritime folded zone. Thick line implies crustal matching line.

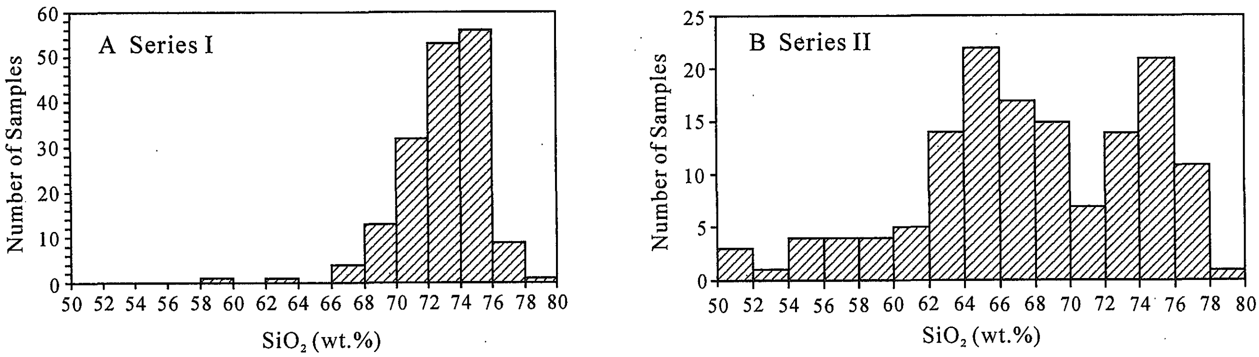

Fig. 2 Histograms of SiO_2 content of the Yanshanian granitoids in South China.

was used to separate the two series.

Ilmenite/magnetite-series granitoids thus defined were identified into either Series I or Series II, in referring to the 1/2,000,000 scale geological map of the two genetic series granitoids in South China (Wang *et al.*, 1985). Distribution of the two-series granitoids is examined spatially and temporally, based on the sample points shown in Figure 1.

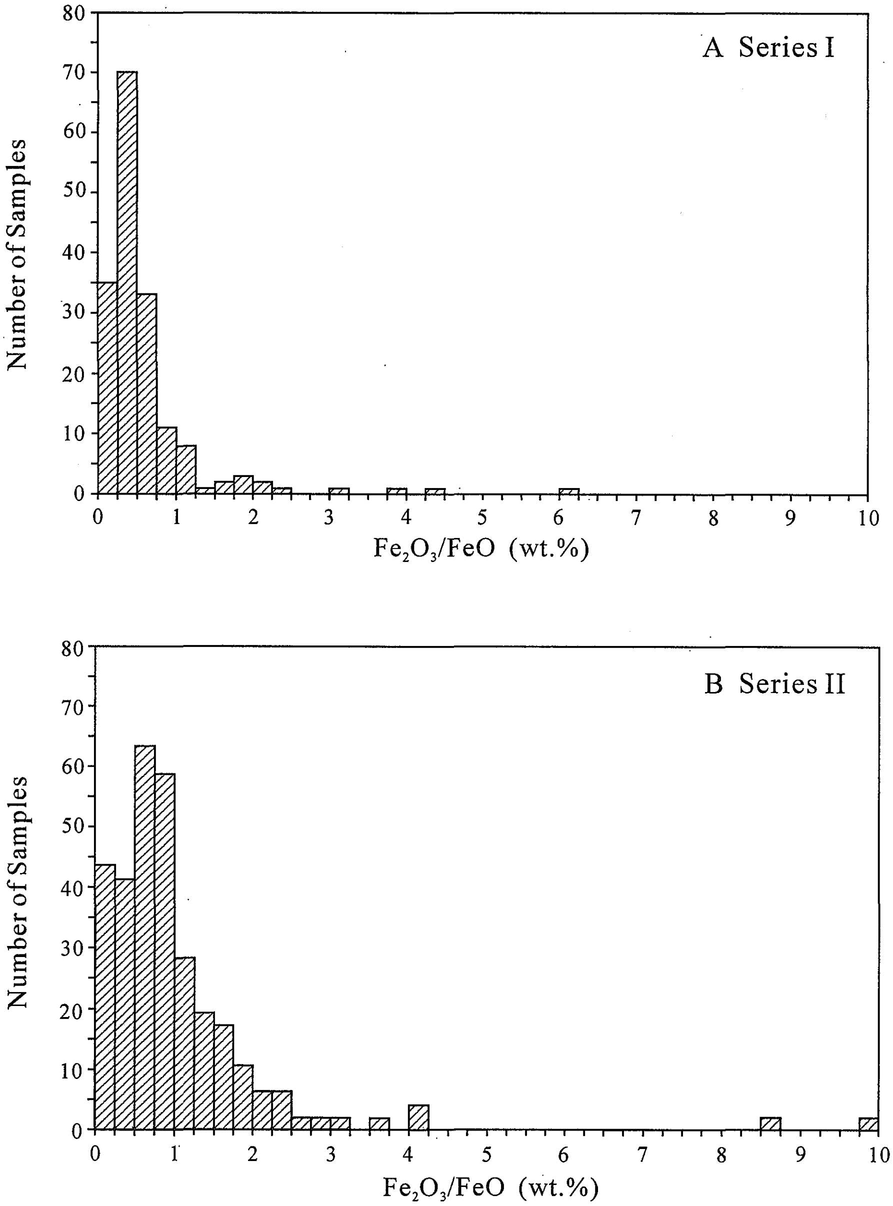

Fig. 3 Histograms of Fe_2O_3/FeO ratio of the Yanshanian granitoids in South China.

General Statements

Wang *et al.* (1982) described that Series I granitoids have a sequence of granodiorite or monzonitic granite, biotite granite, leucocratic granite and related porphyries, while Series II granitoids are composed of pyroxene diorite, diorite or quartz diorite, granodiorite or monzonitic granite, granite, K-feldspar granite and related porphyries. About accessory mineral assemblage, they noted magnetite-ilmenite-zircon or monazite-xenotime-zircon for the Series I, and magnetite-sphene-apatite or magnetite-ilmenite-REE-rich zircon for Series II. In other words, Series I granitoids seem to belong to both ilmenite and magnetite series, while all Series II granitoids belong to the magnetite series.

Xu *et al.* (1987) reported the following average chemical compositions for their four series of granitoids:

	Types	Fe_2O_3/FeO	SiO_2(%)
(1)	Continental crust transformation (n=300)	0.39	72.8
(2)	Transitional crust syntexis (n=182)	0.56	64.9
(3)	Alkaline (n=68)	2.37	71.6
(4)	Mantle-derived (n=24)	0.55	66.6

The alkaline type has a very high Fe_2O_3/FeO ratio of 2.37, which agrees to an oxidized nature of alkaline rocks in the world and Ningwu basin (Ishihara *et al.*, 1986). The syntexis type of 0.56 is very close to the boundary value of 0.5, implying that this type may be composed of both ilmenite and magnetite series. On the other hand, the transformation type has the lowest

Fe_2O_3/FeO ratio, indicating that the majority of this type belongs to the ilmenite series. Thus, Series I granitoids are not correlated exactly with the transformation type and Series II granitoids are somewhat different from the syntexis type in terms of the ferric/ferrous classification.

Silica contents of our examined granitoids are shown in histogram of Figure 2. It is obvious that Series I granitoids have SiO_2 range of granite composition mostly, while Series II granitoids have a much lower silica range. The results agree with the description of Wang *et al.* (1982), indicating the validity of our identification of Series I and II.

Histograms of the Fe_2O_3/FeO ratio are shown in Figure 3. This ratio of Series I granitoids are low in general. The ratios lower than 0.5, i.e., ilmenite series, represent 61.8 percent of the total number (n=170). It is concluded that Series I granitoids are composed of both ilmenite series and magnetite series, as mentioned by Wang *et al.* (1982), with an approximate ratio of ilmenite series 62 percent vs. magnetite series 38 percent.

On the other hand, Series II granitoids are not solely the magnetite series, contrary to the finding of Wang *et al.* (1982). They are composed of 73 percent magnetite series and 27 percent ilmenite series (n=144).

Spatial Distribution

Asymmetrical zoning of the ilmenite-series and magnetite-series distributions has been observed in the Phanerozoic granitic terranes in the Circum-Pacific region, such as Japanese Islands (Ishihara, 1979) and Sierra Nevada batholith (Bateman *et al.*, 1991). In these examples, magnetite contents increase towards the continent. In the Peninsular Range batholith (Gastil *et al.*, 1990), magnetic susceptibility is high in the western belt but low in the eastern belt, then increases again further in the interior. Here, our compiled data are plotted geographically, and contoured for SiO_2 and Fe_2O_3/FeO ratio in Figures 4 and 5, respectively.

Series I granitoids are widespread in the whole Nanling Range region of the Cathaysian folded zone and its

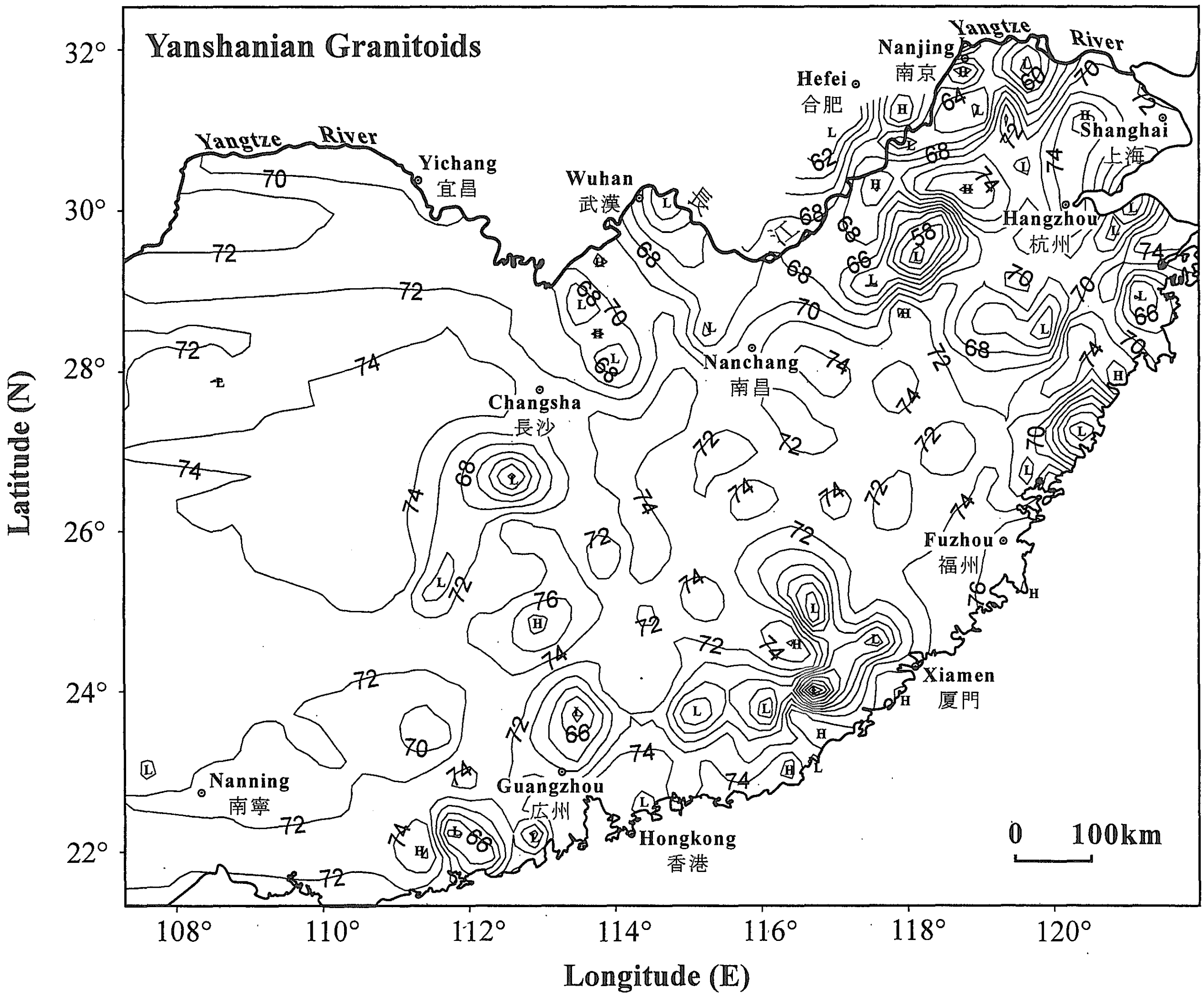

Fig. 4 Spatial distribution of SiO_2 content (wt.%) of the Yanshanian granitoids in South China.

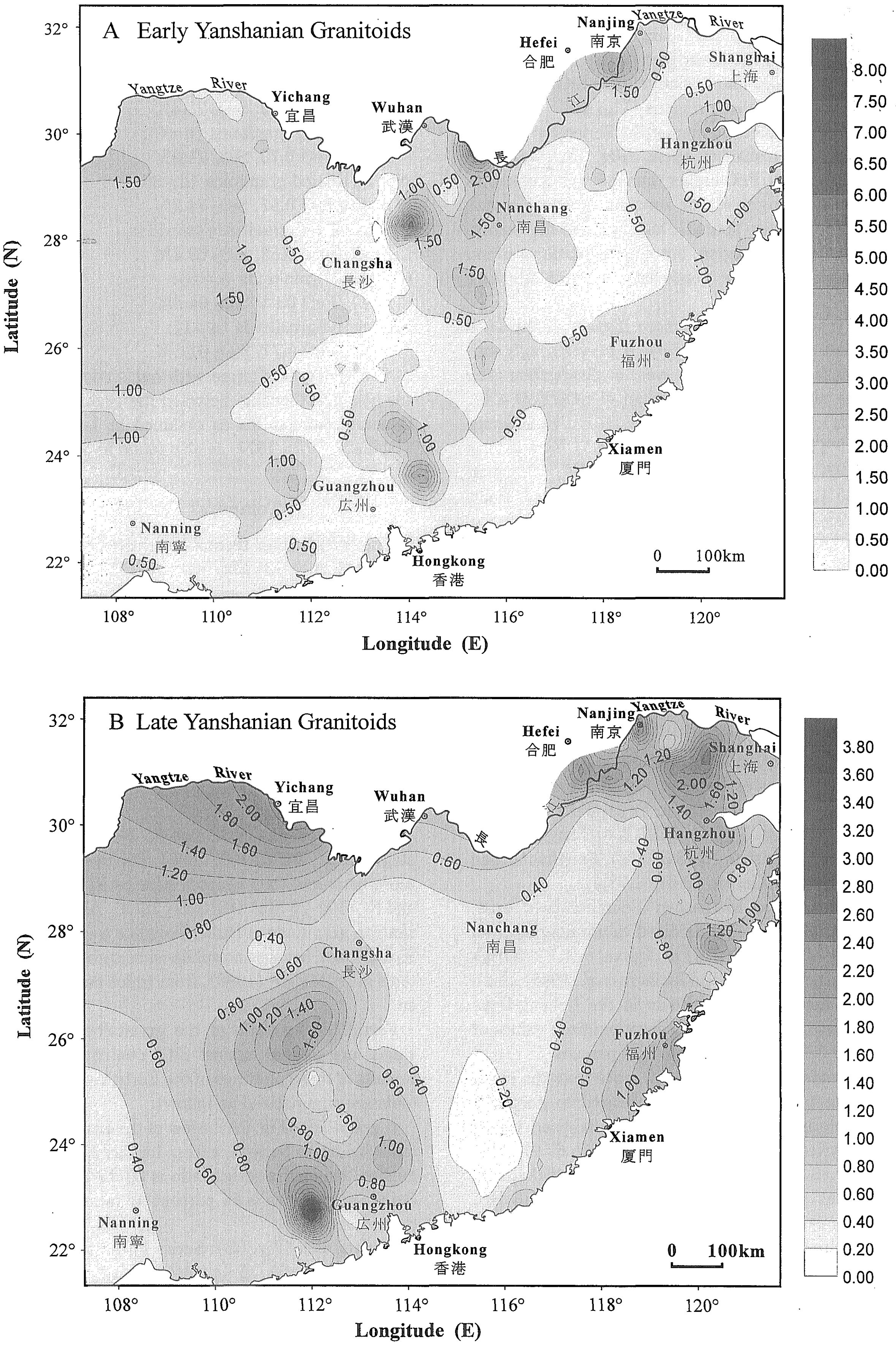

Fig. 5 Spatial distribution of Fe_2O_3/FeO ratio (wt.%) of the Yanshanian granitoids in South China.

northern fringe area (Fig. 1), but Series II granitoids are mostly confined to the Guangdong-Fujian-Zhejiang maritime zone and the lower part of the Yangtze River (Wang *et al.*, 1985). Thus, relatively low SiO_2 granitoids are concentrated in these regions (Fig. 4).

In the Fe_2O_3/FeO ratio map of the Series I granitoids of the Early Yanshanian cycle (Fig. 5A), oxidized values, e.g., Fe_2O_3/FeO higher than 0.5, are confined to the Fujian-Zhejiang maritime zone and Lower Yangtze areas. There are also sporadic high spots in the Guangdong-Hunan-Jiangxi region, but no systematic variation is observed across the northeast-southwest trending zones.

These tendencies become more distinct in the Late Yanshanian granitoids (Fig. 5B). A very strongly oxidized spot is also seen to the west of Guangzhou area where the plutons of Dayunwushan (Fe_2O_3/FeO 4.42: $SiO_2$74.8%), Ziluoshan (1.15:75.1%), Heishigang (0.99:60.9%), Balianshan (0.91:74.4%), Xianjiadong (0.61:75.9%), Huangnitian 0.61:64.7%), Shayuan (0.59:70.6%), Daniangshan (0.53:74.9%) and Shilu (0.52:64.9%) are responsible for the anomaly. No linear zoning in any direction is observed again in the whole region.

About mineralized plutons, W–Sn–Nb–Ta–REE related granitoids give mostly low Fe_2O_3/FeO ratios as follows: Yangchuling (Fe_2O_3/FeO 0.10: SiO_2 67.6%), Dachang (0.29:72.7%), Xihuashan (0.32:75.9%), Limu (0.48:74.1%), and Qianlishan at Shizhuyuan (0.44:74.5%). Chen *et al.* (1989) reported 0.46:71.9% for Dajishan.

On the contrary, related granitoids to Cu–Fe ore deposits of the Lower Yangtze region are highly oxidized as follows: Chengmenshan Fe_2O_3/FeO 1.55: SiO_2 64.4%), Wushan (1.41:64.1%), Tongguanshan (1.10:63.6%), Shizishan (0.93:55.8%), Fenghuangshan (0.86:62.9%) and Xinqiao (0.84:61.7%).

Granitoids in the Ma'anshan Fe-mineralized area, southwest of Nanjing, give oxidized values ranging from Fe_2O_3/FeO 4.2 (SiO_2 64.2%) at Xipixia to 1.1 (73.0%) at Niuluoshan (this study and Ishihara *et al.*, 1986). Similar Fe–Cu mineralized granitoids in the Echeng-Daye area, southeast of Wuhan, also show oxidized values of Fe_2O_3/FeO 3.69–0.72: $SiO_2$75.5–52.0 percent.

In the Dexing Cu–Mo ore field, more than ten small granodiorite porphyry stocks are related to porphyry copper mineralizations. They are the oxidized types. The porphyries have Fe_2O_3/FeO 0.43 (SiO_2 62.9%, this study) or 0.85 (Yang and Hu, 1980) at Tongchang, 1.28 (64.4%, this study) or 0.75 (65.6%, Yang and Hu, 1980) at Fujiawu and 0.62 (62.0%) at Zhushahong.

Pb–Zn mineralized stocks are also the oxidized type as follows: Cunqian (Fe_2O_3/FeO 2.32: SiO_2 64.5%), Shuikoushan (1.36: 59.1%), Huangshaping (0.65: 73.6%) and Baoshan (0.65: 73.6%).

GRGNP (1989) gave the following average values for various ore-forming granitoids in the Nanling region, most of which were formed in the Yanshanian cycle:

W–Sn-related granitoids (n=8):
Fe_2O_3/FeO 0.34, SiO_2 73.8%
HREE-related granitoids (n=7):
Fe_2O_3/FeO 0.39, SiO_2 73.4%
LREE-related granitoids (n=6):
Fe_2O_3/FeO 0.70, SiO_2 71.9%
Nb–Ta-related granitoids (n=35):
Fe_2O_3/FeO 0.57, SiO_2 74.2%
Pb–Zn-related granitoids (n=11):
Fe_2O_3/FeO 0.52, SiO_2 69.4%
Cu-related granitoids (n=8):
Fe_2O_3/FeO 0.94, SiO_2 64.8%
Mo-related granitoids (n=1):
Fe_2O_3/FeO 0.77, SiO_2 61.1%

The above data agree with our study results. Thus, the same relationship between the granitoid series and mineral commodities as obtained in Japanese Islands (Ishihara, 1975, 1977) is also found in South China.

Temporal Variation

The Yanshanian tectono-magmatic cycle is divided into Early (190–135 Ma) and Late (135–70 Ma) Yanshanian cycles in China, and the Early Yanshanian cycle is further subdivided into 3 or 4 sub-cycles by different authors (Ishihara and Sato, 1982). Here, we adopt the classification of GRGNP (1989), who subdivided the Early Yanshanian one into three stages, as J_1 (195–175 Ma), J_2 (175–155 Ma) and J_3 (155–137 Ma). Granitoids of the J_1 substage have Late Triassic to Early Jurassic age in the Zhejiang, Jiangxi and Guangxi Provinces, while those of the other provinces are Early Jurassic (190–170 Ma) in age.

Late Yanshanian cycle may be divided into four substages (e.g., BGMRHP, 1990), but two subdivision is more common, thus adopted here as K_1 (137–100 Ma) and K_2 (100–70 Ma) (GRGNP, 1989). All the Late Yanshanian granitoids of Hubei Province were grouped into K_1 substage, because no subdivision is given to the granitoids in BGMRHP (1990), from which our data originated.

Ferric/ferrous ratio of the granitoids of these substages are plotted against SiO_2 contents in Figure 6. Results of these plottings of the Early Yanshanian granitoids are summarized as follows:

J_1 granitoids (Fig. 6A): Most of the granitoids (36 plutons) belong to Series I, except for three plutons. The ilmenite-/magnetite-series ratio is 23/13 (n=36). Thus, the ilmenite series is 64 percent by number of the plutons.

J_2 granitoids (Fig. 6B): Series I granitoids are mostly ilmenite series, 31/15 (n=46); ilmenite series 67 percent, while Series II granitoids have an equal amount of ilmenite-/magnetite series (10/9, n=19).

J_3 granitoids (Fig. 6C): Series I granitoids are predominantly ilmenite series 48/13 (n=61); i.e., il-

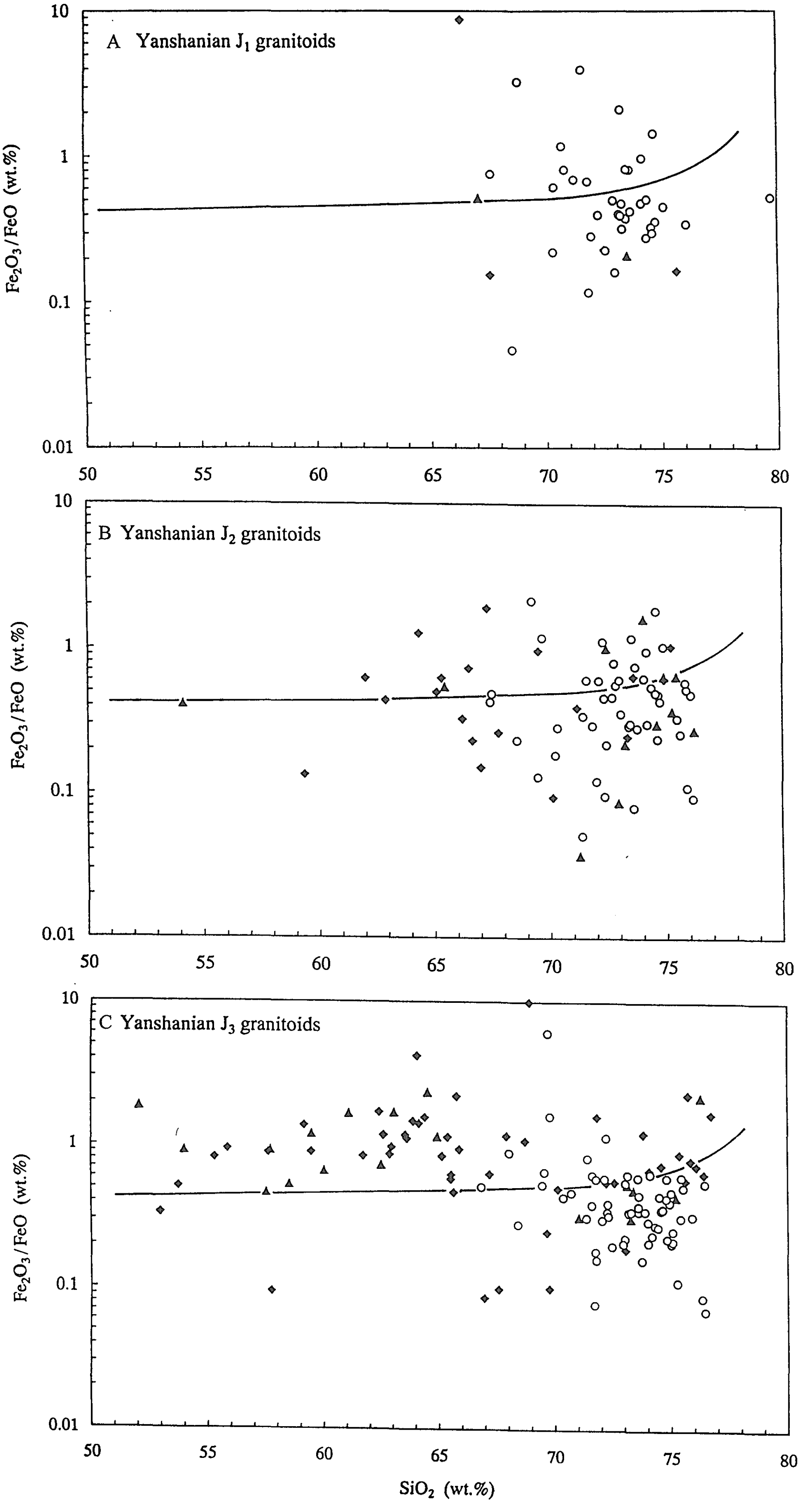

Fig. 6 Fe_2O_3/FeO (wt% ratio) plotted against SiO_2 of the Early Yanshanian granitoids in South China. Solid line is the separation line of the ilmenite-series and magnetite-series granitoids in Japan.

menite series 79 percent. On the contrary, Series II granitoids are mostly magnetite series (ilmenite/magnetite series=14/35, n=49), magnetite series 71 percent.

All the Series I granitoids of Early Yanshanian cycle are composed of 59 percent ilmenite series and 41 percent magnetite series, while the Series II granitoids have a reverse ratio of 40 percent ilmenite series and 60 percent magnetite series.

Among Late Yanshanian granitoids of K_1 cycle (Fig. 7A), Series I granitoids are dominantly ilmenite series (71%); but Series II granitoids are mostly magnetite series (69%).

K_2 granitoids (Fig. 7B) are small in number of the analytical data, but appear to be composed of an equal amount of ilmenite and magnetite series.

All the Series I granitoids of the Late Yanshanian cycle consist of 67 percent ilmenite series and 33 percent magnetite series, while the Series II granitoids have 31 percent ilmenite vs. 69 percent magnetite series.

All Series I and II, and unclassified granitoids data indicate that Early Yanshanian granitoids are composed of 59 percent ilmenite series and 41 percent magnetite series, but Late Yanshanian granitoids consist of 43 percent ilmenite and 57 percent magnetite series. Thus, the magnetite-series rocks increase in amount with younger age, which is observed in the Cretaceous-Tertiary granitoids of the Japanese Islands (Ishihara, 1981).

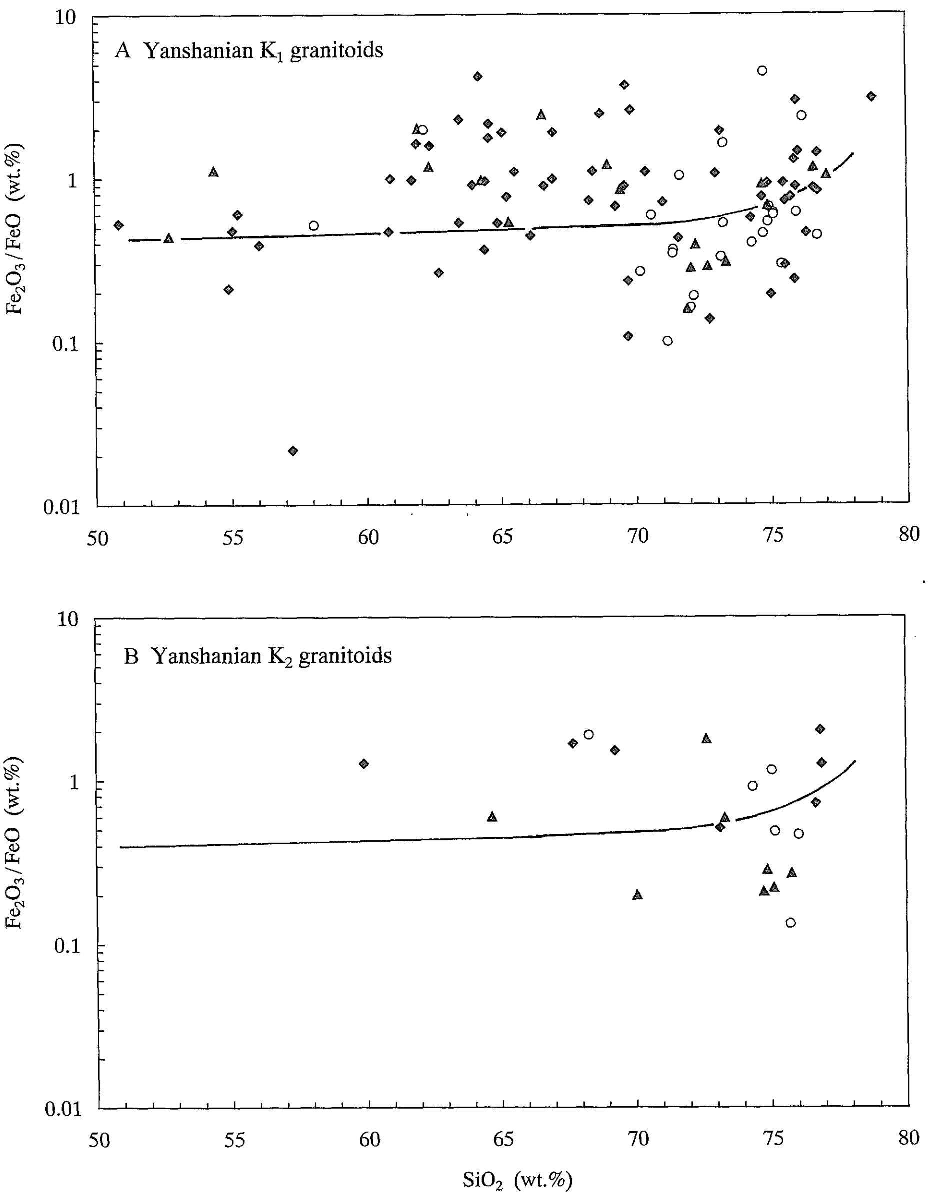

Fig. 7 Fe_2O_3/FeO (wt% ratio) plotted against SiO_2 of the Late Yanshanian granitoids in South China. For solid line, see Fig. 6.

Concluding Remarks

Yanshanian granitoids of South China were classified into ilmenite and magnetite series using average Fe_2O_3/FeO ratios of individual plutons. They are dominantly ilmenite series (59%) in the Early Yanshanian granitoids, and magnetite series (57%) in the Late Yanshanian granitoids. Thus, the younger granitoids are more oxidized.

Our results are consistent with the summary of GRGNP (1989) who pointed out that the granitoids become oxidized from Triassic Period onward as follows:

Indosinian (Triassic) granitoids: Fe_2O_3/FeO 0.21, SiO_2 70.8% (number of plutons, nP=67, number of analyses, nA=560, and total calculated area, Ta=23,019 km^2).

Early Yanshanian granitoids: Fe_2O_3/FeO 0.37, SiO_2 73.1% (nP=261, nA=859, Ta=59,389 km^2).

Late Yanshanian granitoids:

Calc-alkaline rocks: Fe_2O_3/FeO 0.48, SiO_2 71.4% (nP=111, nA=291, Ta=9,700 km^2).

Alkaline series: Fe_2O_3/FeO 1.21, SiO_2 76.4% (nP=27, nA=60, Ta=1,691 km^2).

Geographically the two series of granitoids show no asymmetric linear distribution, which is typically seen in the Japanese Islands and western North America, indicating that they were not products of the island-arc magmatism but generated in a unique continental margin environment.

This study needs to be cross-checked in the future by measurement of magnetic susceptibility and microscopic study of opaque minerals.

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華南の燕山期花崗岩類のチタン鉄鉱系列と磁鉄鉱系列

石原舜三・王　平安

要　旨

華南の燕山期（ジュラ紀―白亜紀）花崗岩類を最近発行された広域報告書に公表された化学分析値の Fe_2O_3/FeO 比 0.5 を基準に，チタン鉄鉱系と磁鉄鉱系に分類し，それぞれの時間・空間変化を追求した．燕山早期花崗岩類はチタン鉄鉱系 59% と磁鉄鉱系 41% であり，燕山晩期花崗岩類はチタン鉄鉱系 43%，磁鉄鉱系 57% であって，時代的に若いものが酸化的である．これら花崗岩類は地域的には揚子江下流域と福建―せつ江沿岸火山帯では酸化的な傾向を示すが，南嶺山地の主部であるカタシア褶曲帯では非対称分布のような特徴的なパターンを示さず，島弧環境下の産物である日本やシエラ・ネバダ―ペニンスラー・レンジの花崗岩類とは明らかに異なっている．チタン鉄鉱系花崗岩類が W, Sn, REE, Nb–Ta 鉱床と，また磁鉄鉱系花崗岩類が Fe, Cu, Pb–Zn 鉱床と密接である点は日本の場合と同じである．