# Early Yanshanian post-orogenic granitoids in the Nanling region

——Petrological constraints and geodynamic settings

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**Abstract** Early Yanshanian magmatic suites predominate absolutely in the Nanling granite belt. They consist mainly of monzogranite and K-feldspar granite. There occur associations of early Yanshanian A-type granitoids (176 Ma—178 Ma) and bimodal volcanic rocks (158 Ma—179 Ma) in southern Jiangxi and southwestern Fujian in the eastern sector of the granite belt and early Yanshanian basalts (177 Ma—178 Ma) in southern Hunan in the central sector of the belt. Both the acid end-member rhyolite in the bimodal volcanic rock association and A-type granitoids in southern Jiangxi have the geochemical characteristics of intraplate granitic rocks and the basic end-member basalt of the association is intraplate tholeiite, while the basaltic rocks in southern Hunan include not only intraplate tholeiite but also intraplate alkali basalt. Therefore the early Yanshanian magmatic suites in the Nanling region are undoubtedly typical post-orogenic rock associations. Post-orogenic suites mark the end of a post-collision or late orogenic event and the initiation of Pangaea break-up, indicating that a new orogenic Wilson cycle is about to start. Therefore it may be considered that the early Yanshanian geodynamic settings in the Nanling region should be related to post-orogenic continental break-up after the Indosinian orogeny and the break-up did not begin in the Cretaceous.

**Keywords: granite, post-orogenic, early Yanshanian, Nanling.**

It was generally considered that pre-Late Cretaceous geodynamic settings in southeastern China during the Late Mesozoic were related to the subduction of the Kula plate or Izanagi plate[1—7], belonging to Andean-type continental margins[8,9] and after the end of the subduction in the Late Cretaceous, the lithosphere began to extend, inducing eruption of bimodal volcanic rocks[10] and emplacement of A-type granitoids[11,12] along the coastal areas of Zhejiang and Fujian. Therefore geologists proposed that the earliest break-up of the continent of southeastern China during the Mesozoic took place in the late Yanshanian, ~120 Ma—140 Ma ago[13—15]. In this paper we suggest that the early Yanshanian granitoids in the Nanling region have the typical characteristics of post-orogenic granite associations; especially the occurrence of early Yanshanian A-type volcanic-intrusive complexes and bimodal volcanic rock associations in southern Jiangxi and occurrence of contemporaneous basaltic magmatism in southwestern Fujian, northeastern Guangdong and southern Hunan suggest that extensional break-up of the lithosphere took place in South

China in the early Yanshanian, i.e. Jurassic.

## 1 Geological settings

Geographically, Nanling refers to a general E-W-trending mountain system composed of the Yuechengling, Dupangling, Mengzhuling, Qitianling and Dayuling on the Hunan-Guangxi, Hunan-Guangdong and Jiangxi-Guangdong borders (fig. 1) and is a divide between the Yangtze drainage system and the Zhujiang drainage system.

Since the Early Palaeozoic this region has undergone strong influences of the Caledonian orogeny, Indosinian orogeny and Yanshanian tectono-magmatism, forming granitoids of different ages and rich mineral resources. The Indosinian orogeny occurring in the Middle Triassic brought about the final complete amalgamation of the Yangtze plate and Cathaysian plate[16,17], thus giving rise to the unifying South China continent. Afterwards the region entered the stage of intraplate continental dynamic evolution.

In this region granitic rocks predominate absolutely, with small amount of basaltic rocks exposed. Three granite belts traverse the region from east to west[18] and affect Hunan, Guangxi, Jiangxi, Guangdong and Fujian. The Nanling region is also an important production base of W, Sn, Bi, REE, U, Cu, Pb and Zn minerals, where large numbers of large and superlarge rare metal and nonferrous metal deposits have been controlled[19].

## 2 Distribution characteristics of granitoids of different ages in the Nanling region

The Nanling granitoids and mineral resources have long been studied and many important achievements have been scored[18—23]. On the basis of previous studies, combining with our recent study of A-type granitoids and bimodal volcanic rocks in the eastern sector of the Nanling region, i.e. southern Jiangxi, and 99 isotopic age data of granitoids published in the last ten-odd years (table 1)[23—52], we have further determined the ages and distribution characteristics of granitoids in the Nanling region (which is largely confined to latitudes 26°—23°20′N and longitudes 110°—118°E, covering an area of ~210000 km$^2$, where granite bodies extend obviously in an E-W direction) (fig. 1) and got the following understanding.

(1) Caledonian granitoids mainly distribute in the Hunan-Jiangxi, Fujian-Jiangxi and Guangxi-Guangdong border areas in the Wuyi and Yunkai Caledonian uplifts[16] and in the Hunan-Guangxi border area near the suture zone between the Yangtze plate and Cathaysian plate. They do not show the pattern of E-W-trending belt-like distribution. Hercynian-Indosinian granitoids generally occur in areas adjoining the Caledonian uplifts and their peripheral Hercynian depressions[16], e.g. the border areas of Fujian, Jiangxi, Guangdong and Hunan on the peripheries of the Wuyi Caledonian uplift and southern Guangxi and the Guangxi-Guangdong border area on the peripheries of the Yunkai Caledonian uplift. They do not show the pattern of E-W-trending belt-like distribution either.

(2) Granitoids at the first stage (180 Ma—155 Ma) of the early Yanshanian mainly distribute

Table 1 Isotopic ages of Nanling granites

| Serial number | Locality | Rock name | Age/Ma | Method | Data sources |
|---|---|---|---|---|---|
| Guangxi Province | | | | | |
| 1 | Miaoershan | biotite monzogranite | 368 | Rb-Sr | Xu Weichang, et al., 1993[24] |
| 2 | Dengjiawan | biotite granite | 260 | Rb-Sr | Xu Weichang, et al., 1993[24] |
| 3 | Douzhashan | two-mica granite | 214 | Rb-Sr | Xu Weichang, et al., 1993[24] |
| 4 | Yuechengling | biotite monzogranite | 411 | U-Th-Pb | Granite Subject Group, 1989[23] |
| 5 | Haiyangshan | biotite monzogranite | 403 | U-Th-Pb | Granite Subject Group, 1989[23] |
| 6 | W-Dupangling | biotite monzogranite | 403 | U-Th-Pb | Granite Subject Group, 1989[23] |
| 7 | Daning | granodiorite | 398 | K-Ar | Mo Zhusun et al., 1987[25] |
| 8 | Darongshan | cordierite biotite granite | 265 | Rb-Sr | Fang Qinghao et al., 1987[26] |
| 9 | Niumiao-Tongan | hornblende monzogranite | 211 | Rb-Sr | Zhu Jinchu et al., 1988[27] |
| 10 | Huashan | hornblende biotite monzogranite | 165 | Rb-Sr | Zhu Jinchu et al., 1988[27] |
| 11 | Huashan | granite | 129 | Rb-Sr | Zhu Jinchu et al., 1988[27] |
| 12 | Guposhan | biotite granite | 148 | Rb-Sr | Zhang Dequan et al., 1985[28] |
| 13 | Lisong | hornblende biotite monzogranite | 160 | Rb-Sr | Zhang Dequan et al., 1985[28] |
| 14 | Guangping | biotite monzogranite | 179 | U-Th-Pb | Granite Subject Group, 1989[23] |
| Hunan Province | | | | | |
| 15 | Xuehuading | biotite monzogranite | 490 | Rb-Sr | Li Yaosong et al., 1986[29] |
| 16 | Baiyunwei | biotite monzogranite | 208 | Rb-Sr | Granite Subject Group, 1989[23] |
| 17 | E-Dupangling | biotite monzogranite | 173 | U-Th-Pb | Granite Subject Group, 1989[23] |
| 18 | Tianezhai | biotite granite | 150 | Rb-Sr | Li Yaosong et al., 1986[29] |
| 19 | Jinjiling | two-mica granite | 154 | Rb-Sr | Li Yaosong et al., 1986[29] |
| 20 | Shaziling | biotite monzogranite | 170 | Rb-Sr | Li Yaosong et al., 1986[29] |
| 21 | Qitianling | hornblende biotite monzogranite | 157—161 | Rb-Sr | Huang Gefei et al., 1992[30] |
| 22 | Huangshaping | granite-porphyry | 148 | Rb-Sr | Yie Bodan et al., 1986[31] |
| 23 | Qianlishan | monzogranite | 162 | Rb-Sr | Yie Bodan et al., 1986[31] |
| 24 | Qianlishan | K-feldspar granite | 163 | Ar-Ar | Liu Yimao et al., 1997[32] |
| 25 | Baoshan | granodiorite | 173 | U-Pb | Wang Yuejun et al., 2001[33] |
| 26 | Shuikoushan | granodiorite | 172 | U-Pb | Wang Yuejun et al., 2001[33] |
| 27 | Jianghua | granodiorite | 177 | U-Pb | Wang Yuejun et al., 2001[33] |
| 28 | Jiangyong | granodiorite | 181 | U-Pb | Wang Yuejun et al., 2001[33] |
| Guangdong Province | | | | | |
| 29 | Taibao | granodiorite | 390 | U-Th-Pb | Granite Subject Group, 1989[23] |
| 30 | Fengchun | biotite monzogranite | 446 | Rb-Sr | Wu Guangyu et al., 1986[34] |
| 31 | Shidong | biotite monzogranite | 443 | Rb-Sr | Wu Guangyu et al., 1986[34] |
| 32 | Guangning-Hengshan | biotite monzogranite | 277 | Rb-Sr | Wu Guangyu et al., 1986[34] |
| 33 | Wuchun | biotite monzogranite | 210 | Rb-Sr | Wu Guangyu et al., 1986[34] |
| 34 | Lujing | biotite granite | 215 | Rb-Sr | Shen Jie et al., 1991[35] |
| 35 | Guidong | granodiorite | 358 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 36 | Shangbao | granodiorite | 388 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 37 | Fuxi | granodiorite | 558 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 38 | Heping | granodiorite | 421 | U-Th-Pb | Granite Subject Group, 1989[23] |
| 39 | Huangdong | two-mica monzogranite | 155 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 40 | Zhongpeng | two-mica monzogranite | 149 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 41 | Qiling | two-mica K-feldspar granite | 166 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 42 | Jiufeng | biotite monzogranite | 162 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 43 | Zhaiqian | biotite monzogranite | 176 | Rb-Sr | Mo Zhusun et al., 1987[25] |
| 44 | Dadongshan | biotite monzogranite | 173 | K-Ar | Granite Subject Group, 1989[23] |
| 45 | Dadongshan | biotite monzogranite | 159 | K-Ar | Granite Subject Group, 1989[23] |
| 46 | Reshui | biotite monzogranite | 177 | Rb-Sr | Granite Subject Group, 1989[23] |
| 47 | Hongling | biotite granite | 148 | Rb-Sr | Yie Bodan et al., 1986[31] |
| 48 | Guidong | biotite monzogranite | 157 | Rb-Sr | Wang Xuecheng et al., 1986[a)] |
| 49 | Siqian | granite | 151 | Rb-Sr | Deng Ping et al., 2000[b)] |
| 50 | Baishigang | biotite monzogranite | 142 | K-Ar | Granite Subject Group, 1989[23] |
| 51 | Fogang | biotite monzogranite | 154 | Rb-Sr | Granite Subject Group, 1989[23] |
| 52 | Ejinao | nepheline syenite | 127 | Ar-Ar | Zhou Lingdi et al., 1996[36] |
| 53 | Nankunshan | alkaline feldspar granite | 126 | K-Ar | Granite Subject Group, 1989[23] |
| 54 | Wudouzhu | biotite monzogranite | 123 | K-Ar | Granite Subject Group, 1989[23] |
| 55 | Qingxi | biotite granite | 147 | U-Th-Pb | Yie Bodan et al., 1986[31] |
| 56 | Jingwei | biotite granite | 145 | U-Th-Pb | Yie Bodan et al., 1986[31] |

(*To be continued on the next page*)

(*Continued*)

| Serial number | Locality | Rock name | Age/Ma | Method | Data sources |
|---|---|---|---|---|---|
| 57 | Baipu | biotite granite | 139 | U-Th-Pb | Yie Bodan et al., 1986[31] |
| 58 | Longwo | granodiorite | 165 | Rb-Sr | Zhao Zijie et al., 1987[37] |
| 59 | Luogang | biotite monzogranite | 126 | U-Th-Pb | Yie Bodan et al., 1986[31] |
| 60 | Shangdianzi | biotite granite | 128 | Rb-Sr | Yie Bodan et al., 1986[31] |
| 61 | Lianhuashan | granite | 137 | Rb-Sr | Yie Bodan et al., 1986[31] |
| Jiangxi Province | | | | | |
| 62 | Shangyou | biotite granite | 377 | K-Ar | Granite Subject Group, 1989[23] |
| 63 | Anxi | granodiorite | 412 | Rb-Sr | Chen Peirong, 1998c) |
| 64 | Aigao | biotite granite | 256 | Rb-Sr | Chen Peirong et al., 1989[38]] |
| 65 | Baimianshi | two-mica granite | 250 | Rb-Sr | Chen Peirong et al., 2000[39] |
| 66 | Dafuzhu | biotite K-feldspar granite | 230 | Rb-Sr | Regional Geological Research Party of Jiangxi, 1990d) |
| 67 | Dafuzhu | biotite monzogranite | 216 | Rb-Sr | Regional Geological Research Party of Jiangxi, 1990d) |
| 68 | Zhaibei | biotite K-feldspar granite | 178 | Rb-Sr | Chen Peirong et al., 1998[40] |
| 69 | Pitou | biotite K-feldspar granite | 176 | Rb-Sr | Fan Chunfang et al., 2000[41] |
| 70 | Guanxi | biotite alkaline-feldspar granite | 176 | Rb-Sr | Huang Dianhao et al., 1989[42] |
| 71 | Zhudong | two-mica alkaline-feldspar granite | 148 | Rb-Sr | Huang Dianhao et al., 1989[42] |
| 72 | Keshubei | biotite granite | 158 | Rb-Sr | Chen Peirong, this paper |
| 73 | Dajishan | muscovite alkaline-feldspar granite | 159 | Rb-Sr | Sun Gongan et al., 1989[43] |
| 74 | Dajishan | two-mica K-feldspar granite | 161 | Rb-Sr | Sun Gongan et al., 1989[43] |
| 75 | Dajishan | biotite monzogranite | 167 | Rb-Sr | Sun Gongan et al., 1989[43] |
| 76 | Xihuashan | biotite K-feldspar granite | 151 | Rb-Sr | Chen Zhixiong et al., 1989[44] |
| 77 | Xihuashan | biotite K-feldspar granite | 148 | Rb-Sr | Chen Zhixiong et al., 1989[44] |
| 78 | Xihuashan | biotite K-feldspar granite | 139 | Rb-Sr | Chen Zhixiong et al., 1989[44] |
| 79 | Piaotang | biotite granite | 156 | K-Ar | Li Huaqin et al., 1993[45] |
| 80 | Sanbiao | biotite granite | 153 | K-Ar | Mei Yongwen et al., 1994[46] |
| 81 | Lanshan | quartz syenite | 175 | U-Th-Pb | Regional Geological Research Party of Jiangxi, 1990d) |
| 82 | Shangchun | monzogranite | 146 | Rb-Sr | Regional Geological Research Party of Jiangxi, 1990d) |
| 83 | Zhongchun | two-mica monzogranite | 133 | Rb-Sr | Regional Geological Research Party of Jiangxi, 1990d) |
| 84 | Yuanling | biotite granite | 169 | U-Th-Pb | Jiangxi Bureau of Geology and Mineral Resources, 1984e) |
| 85 | Jiuqu | two-mica granite | 136 | U-Th-Pb | Jiangxi Bureau of Geology and Mineral Resources, 1984e) |
| 86 | Danguanzhang | biotite monzogranite | 144 | Rb-Sr | Jiangxi Bureau of Geology and Mineral Resources, 1995f) |
| 87 | Maoziding | biotite granite | 123 | Rb-Sr | He Bochu et al., 1990[47] |
| 88 | Tongkengzhang | granite | 125 | Rb-Sr | He Bochu et al., 1990[47] |
| 89 | Yanbei | granite | 123 | Rb-Sr | Mei Yongwen et al., 1994[46] |
| Fujian Province | | | | | |
| 90 | Zhenfengding | biotite monzogranite | 265 | K-Ar | Granite Subject Group, 1989[23] |
| 91 | Weipu | biotite monzogranite | 248 | U-Th-Pb | Chen Riming et al., 1999[48] |
| 92 | Wuping | granite | 166 | Rb-Sr | Ling Hongfei et al., 1999[49] |
| 93 | Xiaotao | granite | 180 | Rb-Sr | Zhao Zifu et al., 2000[50] |
| 94 | Yongding | granite | 145 | Rb-Sr | Ling Hongfei et al., 1999[49] |
| 95 | Hetian | biotite monzogranite | 146 | Rb-Sr | Granite Subject Group, 1989[23] |
| 96 | Juzhou | K-feldspar granite | 162 | Rb-Sr | Granite Subject Group, 1989[23] |
| 97 | Dayang | granite | 158 | Rb-Sr | Mao Jianren et al., 1998[51] |
| 98 | Xinchun | geode granite | 97 | Rb-Sr | Zhou Xunruo et al., 1988[52] |
| 99 | Changtai | granodiorite | 123 | Rb-Sr | Zhou Xunruo et al., 1988[52] |

a) Wang Xuecheng, Geological and geochemical characteristics of Guidong rock body and genesis study of No. 339 deposit, Doctoral Thesis of Nanjing University, unpublished, 1986. b) Deng Ping et al., Tectonic-magma activity of granite and uranium mineralization series, northern Guangdong Province, Uranium Geology of South China, 2000, 17(1-2): 32—43. c) Chen Peirong, Geodynamic settings, petrogenesis and evolution of Early Yanshanian bimodal volcanic-intrusive complexes in south Jiangxi Province, Doctoral Thesis of Nanjing University, unpublished, 1998. d) Regional Geological Research Party of Jiangxi, Granitic magmatism and its relationship with mineralization in Huichang region, Jiangxi Province, unpublished, 1990. e) Jiangxi Bureau of Geology and Mineral Resources, Explanatory notes on the geological map of Zhushanwei (1:50000) (in Chinese), unpublished, 1984. f) Jiangxi Bureau of Geology and Mineral Resources, Explanatory notes on the geological map of Kongtian (1:50000) (in Chinese), unpublished, 1995.

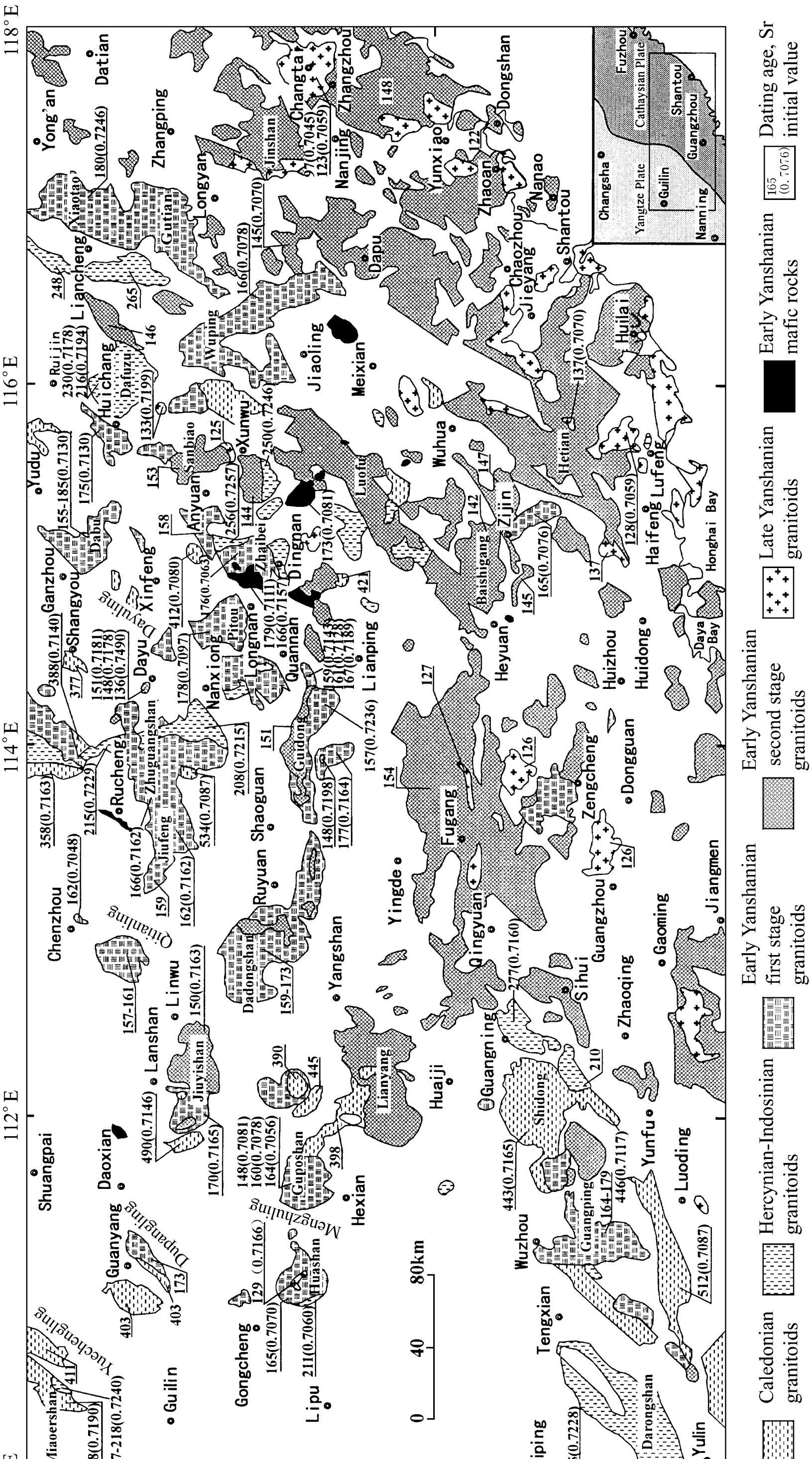


Fig. 1. Distribution of granitoids in the Nanling region.

in the northern Nanling Mountains (e.g. the Dupangling-Jiuyishan-Qitianling-Zhuguangshan-Dabu-Gutian rock belt and the Huashan-Guposhan-Guidong-Zhaibei-Wuping rock belt) and also outcrop sporadically in southern Nanling Mountains. Granitoids of this stage extend markedly in an E-W direction. Granitoids at the second stage (155 Ma—140 Ma) of the early Yanshanian mainly distribute in the southern Nanling Mountains (e.g. the Lianyang-Fogang-Baishigang-Hetian-Dapu rock belt), while in the northern part magmatism weakened. They also notably distribute in an E-W direction. The centre of early Yanshanian magmatism migrated from north to south.

(3) Late Yanshanian granitoids (140 Ma—70 Ma) principally distribute along the coastal areas of Fujian and Guangdong provinces, parallel to the coastline, and generally extend in an NE direction.

(4) The bulk part of the Nanling granite belt consists of early Yanshanian granitoids, which distribute in an E-W-trending belt, parallel to the general strike of the Nanling Mountains. It is evident that early Yanshanian granitoids are the main factor for determining the Nanling granite belt and the Nanling mountain system.

## 3 Petrological constraints on early Yanshanian post-orogenic magmatism in the Nanling region

### 3.1 Characteristics of rock associations of early Yanshanian granitoids in the Nanling region

Statistics of the exposed area of granitoids in Hunan, Guangxi, Guangdong and Jiangxi and their adjacent areas by Shi Mingkui et al. (1993)[16] indicates that early Yanshanian granitoids consist dominantly of granodiorite, monzogranite, K-feldspar granite and syenite with a small amount of alkali feldspar granite, of which monzogranite and K-feldspar granite predominate (table 2). This type of rock association is entirely comparable to typical post-orogenic granite suites, e.g. the Taourirt suite of Hoggar, Algeria related to the Pan-African orogeny and the Mont-Blanc-Aar-Gotthard suite related to Variscan orogeny in western-central Europe[54]. The Taourirt post-orogenic suite of Hoggar is dominantly granitic, with scarce basic to intermediate rocks, and there appears a Daly gap. Granitoids may fall into four rock associations (table 3), G1 monzogranite, G2a monzogranite and syenogranite, G2b alaskite (alkali feldspar granite) and G3 alkali feldspar syenite and granite, with G2a predominating. Granodiorite is widespread in the Mont-Blanc-Aar-Gotthard suite[54]. Apparently, early Yanshanian granitoids in the Nanling region are strikingly similar not only in rock type but also in rock-forming and accessory mineral assemblages and isotopic composition to granitic rocks of the Taourirt post-orogenic suite (table 3). In addition, early Yanshanian basaltic magmatism also occurred in the Nanling region, for example, the basalt exposed in southern Jiangxi and southern Hunan has been determined to have isotope ages in the range of 158 Ma—179 Ma (table 4), and intermediate rocks are rare and there appears a Daly gap. Therefore early Yanshanian granitoids in the Nanling region have the typical characteristics of post-orogenic suites.

Table 2 Early Yanshanian granitoids and their exposed areas[a)]/km$^2$ in Hunan, Guangxi, Guangdong and Jiangxi and adjacent areas

| Age | Alkali feldspar granite | K-feldspar granite | Monzo-granite | Grano-diorite | Granite porphyry | Grano-diorite porphyry | Syenite | Total area | Proportion (%) in total area of Nanling granitoids[b)] |
|---|---|---|---|---|---|---|---|---|---|
| $J_3$ | | 543 | 19406 | 352 | 401 | 7 | 94 | 20803 | 28.16 |
| $J_2$ | 1 | 1520 | 8030 | 80 | | 4 | | 9635 | 13.04 |
| $J_1$ | 10 | 226 | 5216 | | | | | 5452 | 7.38 |
| Rock proportion (%) in J granitoids | 0.03 | 6.38 | 90.98 | 1.20 | 1.12 | 0.03 | 0.26 | | |

a) Data from Shi Mingkui et al. (1993) [16]. Hunan, Guangxi, Guangdong and Jiangxi and adjacent areas refer to the region between latitudes 23°20′—26°40′ and longitudes 107°—117°. The nomenclature of K-feldspar granite in the table is given by the Institute of Geochemistry, Chinese Academy of Sciences (1979), being equivalent to syenogranite[53], plotted in Field 3a in the QAP triangle diagram. b) The total area proportions of these rocks were recalculated by us excluding Precambrian granitoids far from the study region.

Table 3 Mineralogy and petrology of early Yanshanian granitoids in the Nanling region

| | Early Yanshanian granitoids in the Nanling region | Post-orogenic granitoids related to the late Proterozoic Pan-African orogeny (Taourirt suite of Hoggar, Algeria) |
|---|---|---|
| Rock types | Basalt, diabase (dykes) and gabbro (stocks) | Gabbro and diorite (stocks and enclaves) |
| | Granodiorite | G1: monzogranite |
| | Monzogranite and K-feldspar granite (predominant) | G2a: monzogranite and syenogranite (predominant) |
| | Alkali feldspar granite | G2b: alaskite (alkali feldspar granite) |
| | Syenite | G3: alkali feldspar syenite and granite |
| Rock-forming mineralogy | Granodiorite: qartz + plagioclase + K-feldspar + Biotite + hornblende | G1: qartz + K-feldspar + plagioclase + Hornblende + biotite |
| | Monzogranite: quartz + K-feldspar + plagioclase + biotite ± hornblende | G2a: quartz + K-feldspar + plagioclase + biotite ± hornblende |
| | K-feldspar granite: quartz + K-feldspar + plagioclase + biotite ± protolithionite ± hornblende | G2b: quartz + K-feldspar + albite + protolithionite-zinnwaldite |
| | Alkali feldspar granite: K-feldspar±albite± plagioclase + quartz±arfvedsonite±biotite | G3: alkali feldspar±quartz±plagioclase + hedenbergite + hastingsite-hornblende + biotite± grunerite±riebeckite |
| Accessory mineralogy[a)] | Granodiorite: zircon + allanite + sphene + ilmenite + magnetite + apatite + monazite + tourmaline + garnet | G1: zircon + allanite + sphene + ilmenite + magnetite + apatite |
| | Monzogranite: zircon + allanite + sphene + ilmenite + magnetite + apatite + thorite + fergusonite + columbite-tantalite + monazite + tourmaline + fluorite + garnet | G2a: zircon + allanite + sphene + ilmenite + magnetite + apatite + thorite + fergusonite + monazite + xenotime |
| | K-feldspar granite: zircon + allanite + sphene +ilmenite+magnetite + apatite + thorite + columbite-tantalite + monazite + tourmaline + fluorite | G2b: zircon + allanite + sphene + fluorite + topaz ± tourmaline ± garnet |
| | Alkali feldspar granite: zircon + apatite + columbite-tantalite + garnet | G3: zircon + thorite + allanite + chevkinite + ilmenite + magnetite + apatite + fluorite |
| Isotopic ratios | Sri = 0.7048—0.7240 | Sri = 0.706—0.723 |
| Emplacement age | 180 Ma—140 Ma | 570 Ma—520 Ma |

a) Accessory minerals with a content <1 g/t are excluded. The statistics of the rock-forming and accessory mineral assemblages is based on 5 granodiorite bodies, 27 monzogranite bodies, 20 K-feldspar granite (equivalent to syenogranite commonly used internationally) bodies and 7 alkali feldspar granite bodies (after Granite Subject Group of the Nanling Project, 1989[23]; Chen Peirong, 1998, Doctoral Thesis of Nanjing University, unpublished). The Sri values correspond with the rock bodies with Rb-Sr ages in fig. 1.

Table 4 Isotopic ages of early Yanshanian basalts in the Nanling region

| Locality | Rock name | Method | No. of samples | MSWD | Age/Ma | Data sources |
|---|---|---|---|---|---|---|
| Xunwu, S Jiangxi | Tholeiite | Whole-rock Rb-Sr isochron | 5 | 0.7 | 173±5.5 | This paper |
| Xunwu, S Jiangxi | Tholeiite | Whole-rock Rb-Sr isochron | | | 179 | Lai, 1996[55] |
| Longnan, S Jiangxi | Tholeiite | Whole-rock Rb-Sr isochron | 5 | 2.84 | 179±8.4 | This paper |
| Longnan, S Jiangxi | Tholeiite | Whole-rock Rb-Sr isochron | 6 | 1.90 | 173.7±2.5 | This paper |
| Longnan, S Jiangxi | Tholeiite | Whole-rock Rb-Sr isochron | | | 175.5 | Lai, 1996[55] |
| Longnan, S Jiangxi | Tholeiite | Whole-rock K-Ar dilution | | | 162.8±4.8 | Wu et al., 1998[56] |
| Longnan, S Jiangxi | Tholeiite | Whole-rock K-Ar dilution | | | 157.8±5.7 | Wu et al., 1998[56] |
| Yizhang, S Hunan | Tholeiite | $^{40}Ar$-$^{39}Ar$ | | | 178.0±3.6 | Zhao et al. 1998[57] |
| Ningyuan, S Hunan | Alkali basalt | Whole-rock K-Ar dilution | | | 177 | Zhao et al. 1998[57] |
| Ningyuan, S Hunan | Alkali basalt | Whole-rock K-Ar dilution | | | 177 | Zhao et al. 1998[57] |

## 3.2 Occurrence of early Yanshanian A-type granitoids in the Nanling region

Now it has been ascertained that there occur early Yanshanian A-type granitoids in southern Jiangxi in the eastern sector of the Nanling Mountains, e.g. the Zhaibei rock body in Dingnan County and the Pitou rock body in Longnan County[40,58]. The latter contains the alkaline dark-colored minerals aegirine and arfvedsonite, and their Rb-Sr isochron age is 176 Ma and 178 Ma respectively. The two rock bodies are mainly composed of K-feldspar granite, which are metaluminous (ANKC = 0.94—1.08, with an average of 0.98), rich in silica ($SiO_2$ = 71.06%—76.74%) and alkalis ($Na_2O+K_2O$ = 7.93%—9.80%), and have higher $FeO^T/MgO$(%) value (9.60—145.00), lower CaO and MgO contents (0.10%—1.16% and 0.01%—0.25% respectively), higher REE (∑REE = 271.35—724.97 mg/g) and high-field-strength element (HFSE) (e.g. Y, Zr, Nb etc.) abundances. Their geochemical characteristics are the same as those of A-type granitoids, but notably different from those of I- and S-type granitoids in the region (fig. 2).

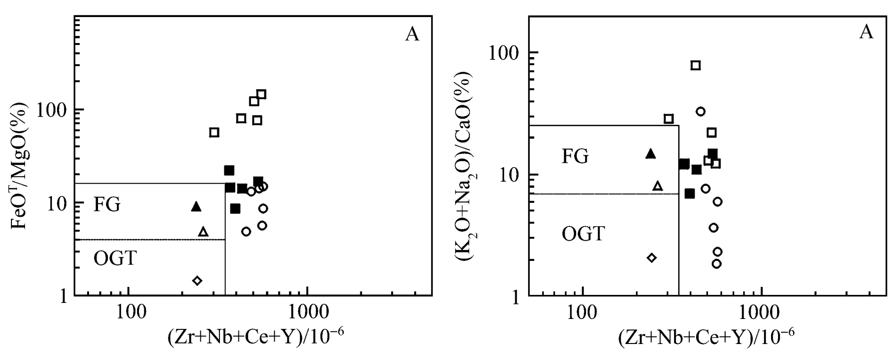


Fig. 2. Zr+Nb+Ce+Y versus $FeO^T/MgO$ and $(Na_2O+K_2O)/CaO$ discriminant diagram for granitoids (after Whalen et al., 1987)[59]. A = field for A-type granitoids; FG = field for fractionated felsic granitoids; OGT = field for unfractionated M-, I- and S-type granitoids. □, Zhaibei rock body; ■, Pitou rock body; ○, rhyolite in bimodal volcanic rock associations; ◇, I-type granitoids in the region; △, S-type granitoids in the region; ▲, fractionated S-type granitoids in the region.

3.3 Occurrence of early Yanshanian bimodal volcanic-intrusive complexes in the Nanling region

In the eastern sector of the Nanling Mountains there occur early Yanshanian bimodal volcanic associations in the Changpu basin and Baimianshi basin in Xunwu County and the Dongkeng basin and Linjiang basin in Longnan County, southern Jiangxi, and the Pankeng basin in Yongding County, southwestern Fujian[60,61]. The basic end-member basalt has isotopic ages ranging from 158 Ma to 179 Ma (table 4) and the acid end-member rhyolite has Rb-Sr isochron ages of 165 Ma—178 Ma (based on three isochrons) (Chen Peirong, 1998, Doctoral Thesis of Nanjing University, unpublished; Kong Xinggong, 2001, Doctoral Thesis of Nanjing University, unpublished). In the Zhaibei A-type granite body (176 Ma) there are many small gabbro bodies, e.g. the Chebu rock body, whose geochemical characteristics are the same as those of the basic end-member basalt in bimodal volcanic suites. They, being products of the same source but different facies, form bimodal intrusive rocks together with the Zhaibei A-type granitoids.

In the bimodal volcanic rock associations in southern Jiangxi and southwestern Fujian, basalt is enriched in incompatible elements, especially HFSE such as Nb, Ta, Ce, Zr, Hf, Sm and Ti, so it is intraplate tholeiite (fig. 3). Rhyolite is metaluminous (average ANKC = 0.99) and enriched in HFSE such as Zr, Hf, Ti and Y and REE such as La, Ce, Nd, Sm, Tb and Yb, exhibiting the geochemical characteristics of A-type granitoids[64] (fig. 2).

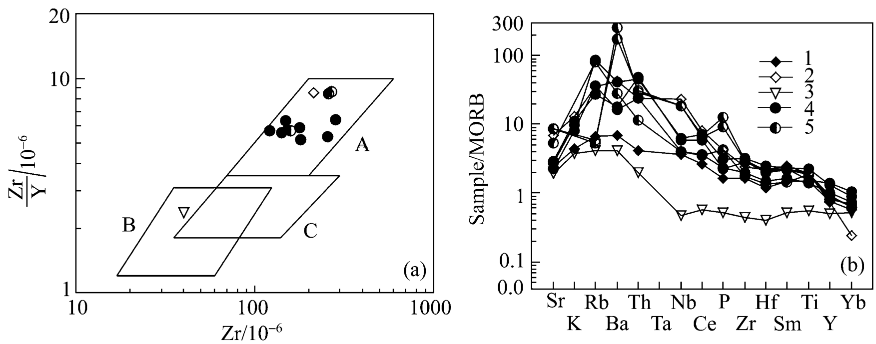


Fig. 3. Zr-Zr/Y and incompatible element MORB normalized patterns (after Pearce, 1973, 1982)[62,63]. A, Intraplate basalt; B, island arc basalt; C, middle oceanic roof basalt; 1, Intraplate tholeiite; 2, intraplate alkali basalt; 3, volcanic arc tholeiite; 4, basalt of southern Jiangxi[60]; 5, basalt of southern Hunan[57].

Moreover, there occur early Yanshanian basalts in Rucheng, Daoxian, Ningyuan and Yizhang counties, southern Hunan. Their $^{40}Ar$-$^{39}Ar$ ages are 175 Ma—178 Ma[65,57] and geochemical characteristics are the same as those of intraplate tholeiite and intraplate alkali basalts (fig. 3).

## 4 Discussion and conclusions

4.1 Geodynamic settings of the Nanling region during the early Yanshanian

"Post-orogenic" stands for the subsequent tectono-magmatic episode occurring after the end of an orogenic Wilson cycle, when the geodynamic context becomes entirely intraplate[54]. It is characterized by motion of the welded terranes according to the same pole of rotation and emplacement of magmatic suites along shear zones in reactivated transcurrent tectonic regimes.

Post-orogenic suites mark the end of a post-collision or late orogenic event, i.e. the late stage of an orogenic Wilson cycle, and the initiation of Pangaea break-up, and indicate that a new Wilson cycle is about to start.

Early Yanshanian magmatic suites predominate absolutely in the Nanling granite belt. They consist mainly of monzogranite and K-feldspar granite (syenogranite). There occur associations of early Yanshanian A-type granitoids (176 Ma—178 Ma) (the Pitou rock body contains alkaline dark-colored minerals) and bimodal volcanic rocks (158 Ma—179 Ma) in the eastern sector of the granite belt. Both the acid end-member rhyolite in the bimodal volcanic rock association and A-type granitoids have the geochemical characteristics of intraplate granitic rocks (fig. 4) and the basic end-member basalt of the association is intraplate tholeiite, while early Yanshanian basaltic rocks in southern Hunan include not only intraplate tholeiite but also intraplate alkali basalt (fig. 3). The Fogang rock body (~154 Ma)——the south belt of the Nanling granite belt——is also considered by some people as A-type granitoids[68]. Therefore the early Yanshanian magmatic suites in the Nanling region are undoubtedly typical post-orogenic rock associations. Bimodal volcanic-intrusive complexes and A-type granitoids and their related alkaline complexes are the most direct evidence for the ascent of the asthenosphere, thinning of the lithosphere and initiation of extensional rifting of the continental crust[69—76]. Thus it may be considered that the early Yanshanian geodynamic setting in the Nanling region should be related to post-orogenic continental break-up.

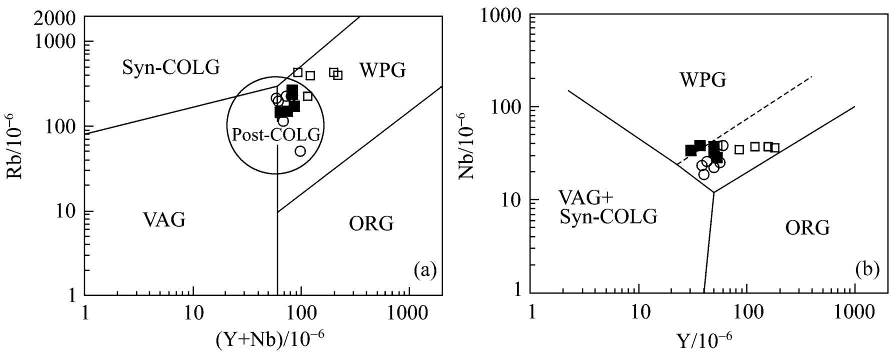


Fig. 4. Y-Nb and Y+Nb-Rb tectonic discriminant diagrams (after Pearce et al., 1984, 1996)[66,67] (symbols as in fig. 2).

## 4.2 Conclusions

The bulk granite bodies of the Nanling granite belt originated in the early Yanshanian, and extends in an E-W direction and constitute the main constraint on the formation of the Nanling mountain system.

Early Yanshanian granitoids in the Nanling region have the mineralogical and petrological characteristics of post-orogenic granitoids and there occur A-type granitoids, bimodal volcanic rocks and basaltic magmatism, which suggests that extensional break-up of the lithosphere took place in the region during the early Yanshanian.

Geologists have to reconsider the timing of the action of the subduction of Palaeo-Pacific plate on the continent margin of South China and how deep it may have influenced the interior of the continent, i.e. the geodynamic settings of the widespread Late Mesozoic granitoids and rich mineral resources in the Nanling region. Therefore, it is necessary now to study the geology and origin of mineral deposits in the Nanling region, particularly such important scientific subjects as the origin of granitoids and crust-mantle interaction, as well as the geodynamic setting of the E-W-trending Nanling tectono-magmato-metallogenic belt and its tectonic framework (whether it belongs to the Pacific or Tethys tectonic domains) and evolution.

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