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Paleoproterozoic lower crust beneath Nushan in Anhui Province: Evidence from zircon SHRIMP U-Pb dating on granulite xenoliths in Cenozoic alkali basalt

HUANG Xiaolong[1], XU Yigang[1], LIU Dunyi[2] & JIAN Ping[2]

1. Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China;
2. Laboratory of SHRIMP Beijing, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China

Correspondence should be addressed to Huang Xiaolong (e-mail: xlhuang@gig.ac.cn)

Abstract **Zircon SHRIMP U-Pb dating was carried out for an intermediate granulite xenolith in Cenozoic alkali basalt from Nushan. The results suggest that the lower crust beneath Nushan may have formed at about 2400—2200 Ma, and have been subjected to granulite-facies metamorphism at 1915±27 Ma. The old age of the Nushan lower crust is consistent with the geochemical similarities between Nushan granulite xenoliths and Archean-Paleoproterozoic granulite terrains in the North China craton, but it is not distinguishable from high-grade metamorphic rocks in the Yangtze craton where such old ages were also reported. Significant Pb-loss occurs in the Nushan zircons, implying important influence of widespread Mesozoic to Cenozoic underplating in East China on the lower crust beneath Nushan.**

Keywords: zircon U-Pb dating, granulite xenoliths, Paleoproterozoic, Nushan.

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Nushan (Anhui Province) and Hannuoba (Hebei Province) are the two representative granulite xenolith localities in the North China craton (Fig. 1). The granulite xenoliths from these two localities are distinctly different in mineral chemistry, whole rock major and trace element compositions[1,2]. The Hannuoba granulites are compositionally similar to the world-wide granulite xenoliths carried by alkali basalts. They represent granulite-facies metamorphosed products of mantle-derived magmas that underplated in the crust-mantle boundary[3−6]. Zircon U-Pb dating reveals that the magmatic underplating occurred mainly in late Mesozoic[3,6]. In contrast, the composition of the Nushan granulite xenoliths is very similar to that of Archean granulite terrains in the North China craton. The model calculation shows that assimilation-fractional crystallization (AFC) played an important role in the formation of the Nushan granulite xenoliths, and the Archaean mafic volcanic rocks and the Archaean intermediate granulite of the North China craton are the most possible initial magma and mixing source, respectively[2]. This suggests that the lower crust beneath Nushan, as represented by granulite xenoliths, is likely old in age. So far, the age of the Nushan lower crust is poorly constrained due to the small size of xenolith samples and the unavailability of analyzing techniques. This report presents zircon SHRIMP U-Pb dating results of the Nushan granulite xenolith and aims to discuss the formation age of the lower crust beneath Nushan.

1 Geological background

Nushan is located at southwestern Subei Basin and to the east of the Tan-Lu Fault Zone (Fig. 1). The Nushan lower crust is considered to belong to the North China craton in precedent studies[4,9]. However, the debates about the location of the suture between the South and North China blocks to the east of the Tan-Lu fault zone[7,8,10 − 12] indicate the controversy of the tectonic affinity of the Nushan lower crust. Yin and Nie[10] proposed that the suture lies close to the northern margin of the Su-Lu ultra-high-pressure metamorphic belt at southern Jiaodong, which is shown as a northeast-trending line (S1, Fig. 1). Faure et al.[11] interpreted the suture to the north of Jiaodong Peninsula. According to these models, the Nushan lower crust should belong to the Yangtze craton. However, a crustal-detachment model proposed by Li[7] and Chung[8] suggested an east-trending subsurface suture near Nanjing (S2, Fig. 1), and the lower crust beneath the Subei basin should be a part of the North China craton.

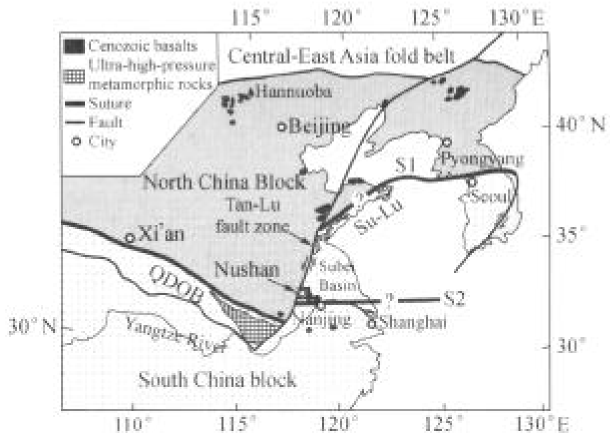

Fig. 1. Distribution of Cenozoic basalts and tectonic sketch map of East China. Modified according to Li[7] and Chung[8]. QDOB, Qinling-Dabieshan orogenic belt.

2 Dating techniques and results

Sample NS214 is an intermediate granulite xenolith collected from Cenozoic alkali basalts at Nushan. The mineral assemblage of the sample is $Opx_{11}Cpx_{12}Pl_{66}Qz_{6}$-

Mt_5, and whole rock SiO_2 content is 55.3% (weight percent)[1,2]. Zircons were separated using conventional heavy liquid and magnetic techniques. Zircons were then hand- picked under binocular and mounted. Execution of sample target was similar to Song et al.[13]. Examination of internal structures was performed using back scatter electron (BSE) and cathodoluminescence (CL) images prior to analyses. U, Th, and Pb isotopic compositions of zircons were analyzed by using Sensitive High-Resolution Ion Microprobe (SHRIMP Ⅱ) in Institute of Geology, Chinese Academy of Geological Sciences, and detailed analytical procedures are similar to those described by Compston et al.[14] and Williams[15]. The standard TEM zircons (age 417 Ma) of RSES were used in interelement fractionation, and U, Th and Pb concentrations were determined based on the standard Sri Lankan gem zircon SL13, which has a U concentration of 238 μg/g corresponding to an age of 572 Ma. Data processing procedures were after PRAWN[16], and the ^{204}Pb-based method of common Pb correction was applied. Uncertainties of data points reported in Table 1 are given at $\pm 1\sigma$. The ages quoted in the text are $^{206}Pb/^{207}Pb$ ages, which are the weighted mean at the 95% confidence level.

CL images are important and effective in distinguishing magmatic zircons from metamorphic zircons[17−19]. Zircons of magmatic origin are characterized by oscillatory zoning, whereas metamorphic zircons are characterized by radial sector overgrowth zoning, planar overgrowth banding or the patches without zoning[17−20]. Zircons of NS214 are dominantly sub-euhedral columnar crystals, and a few fine grains are sub-rounded. CL images clearly show that most of the zircons are composed of the micro-scale oscillatory cores and the planar overgrowth bandings. The zoning cores could be of magmatic origin, and the overgrowth rim could be metamorphic zircons. Some original magmatic zircon with oscillatory zoning is partly recrystallized or metamorphically recrystallized[17,18], in which the oscillatory zoning is weak, and the original growth banding is partly or completely extinguished, in which the CL intensity is distinctly higher (Fig. 2(h)). In addition, a thin brightly luminescent rim frequently developed in all zircon crystals, which was probably resulted from resorption[17].

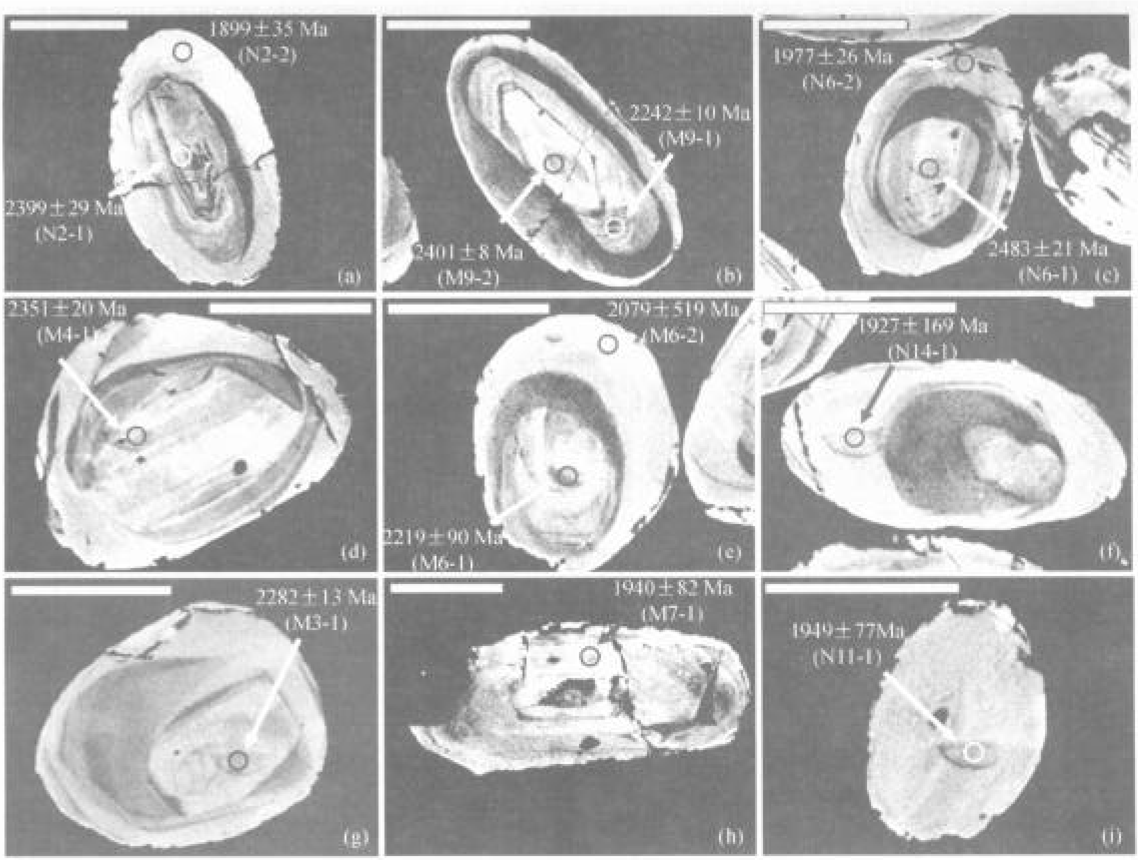

Fig. 2. Selected CL images of zircons in NS214. The numbers refer to the $^{207}Pb/^{206}Pb$ ages of the analytical spots, and the length of scale bar is 100 μm.

The Th/U ratio of magmatic zircon is generally high and varies in a range of 0.1—1.0[21], whereas that of metamorphic zircon is generally less than 0.1[17−20]. Nevertheless, metamorphically recrystallized zircons or those with planar overgrowth contain low Th and U relative to the magmatic cores. The Th/U ratio in these zircons is fairly constant, or even higher than that of the magmatic core[17,18]. Thirty spot analyses on 23 grains of zircons from Nushan show relatively high Th/U ratios, which vary in the range of 0.35—1.15 except for the spot N6-2 (Table 1). Some of the results are magmatic zircons and others are metamorphic or zircons with planar overgrowth. N2-2, N6-2, N8-2, N14-1, M2-1 and M6-2 are spots on the planar overgrowths parts of rounded cores (Fig. 2(a), (c), (e) and (f)), and M7-1 is the spot on the metamporphic recrystallized region of magmatic zircons with oscillatory zoning (Fig. 2(h)). The U and Th contents of these analyses are relatively low, or distinctively lower than those of magmatic cores (Table 1). In addition, N4-1, N11-1 and N13-1 are all the spots of sub-rounded zircon without any oscillatory zoning (Fig. 2(i)). Given the high Th/U ratios (Table 1), they are probably the results of strong metamorphic recrystallization.

Most of the results of Nushan zircons are discordant except for a few spots such as N11-1 and M3-1 (Table 1, Fig. 3). $^{207}Pb/^{206}Pb$ ages of majority zoning cores cluster within the range of 2.0—2.3 Ga (Table 1, Fig. 2). Spot M3-1 yields a concordant $^{207}Pb/^{206}Pb$ age of 2282±13 Ma (Fig. 3), which suggests that the protolith of Nushan granulite xenoliths may have been formed at 2.2 Ga ago. In addition, $^{207}Pb/^{206}Pb$ ages of a small proportion of zoning cores (such as N2-1, N6-1, N9-1, N12-1, M4-1 and M9-2, Table 2) are close to 2.4 Ga, and regression of these analyses gives an upper intercept age of 2409±77 Ma (Fig. 3). The analyses of most of metamorphic recrystallized or planar overgrowth zircons (see above) are also

Table 1 Zircon SHRIMP U-Pb data for NS214

Grain spot	Type	U /μg・g⁻¹	Th /μg・g⁻¹	Th/U	Pb /μg・g⁻¹	f_{206} (%)	$^{207}Pb/^{206}Pb$ ±1s	$^{206}Pb/^{238}U$ ±1s	$^{207}Pb/^{235}U$ ±1s	Ages/Ma $^{206}Pb/^{238}U$	Ages/Ma $^{207}Pb/^{206}Pb$
N1-1	c	107	66	0.62	19	0.21	0.1301±14	0.1581±73	2.84±14	946±41	2100±19
N1-2	r	282	186	0.66	58	0.04	0.1295±11	0.1803±73	3.22±14	1069±40	2092±14
N2-1	c	679	782	1.15	340	0.01	0.1548±27	0.3890±138	8.30±34	2118±64	2399±29
N2-2	r	44	35	0.80	19	0.10	0.1162±22	0.3757±157	6.02±29	2056±74	1899±35
N3-1	c	903	717	0.79	354	0.08	0.1376±7	0.3321±110	6.30±21	1848±53	2197±8
N3-2	r	30	16	0.53	15	0.09	0.1376±14	0.4400±190	8.35±38	2351±85	2198±18
N4-1	m	319	177	0.55	47	0.10	0.1154±22	0.1336±48	2.13±9	808±27	1886±34
N5-1	c	642	409	0.64	225	0.02	0.1340±7	0.3075±106	5.68±20	1729±53	2151±8
N6-1	c	200	178	0.89	91	0.06	0.1626±20	0.3689±131	8.27±32	2024±62	2483±21
N6-2	r	13	3	0.19	1	0.67	0.1214±165	0.0747±63	1.25±21	464±38	1977±264
N7-1	c	130	70	0.54	44	0.10	0.1260±14	0.3080±103	5.35±19	1731±51	2043±19
N8-1	c	77	55	0.72	5	0.14	0.1159±59	0.0587±28	0.94±7	368±17	1894±94
N8-2	r	33	20	0.61	1	1.41	0.1113±70	0.0358±18	0.55±5	227±11	1821±119
N9-1	c	160	110	0.69	26	0.08	0.1515±55	0.1391±93	2.90±23	840±53	2362±64
N10-1	c	66	36	0.55	24	0.22	0.1474±23	0.3285±113	6.67±26	1831±55	2316±27
N11-1	m	96	83	0.86	40	0.06	0.1195±50	0.3574±218	5.89±46	1970±105	1949±77
N12-1	c	114	72	0.63	25	0.13	0.1491±40	0.1883±89	3.87±22	1112±49	2335±47
N13-1	m	51	27	0.54	1	0.40	0.1131±65	0.0245±10	0.38±3	156±6	1850±108
N14-1	r	25	14	0.56	2	1.58	0.1180±105	0.0690±36	1.12±12	430±22	1927±169
M1-1	c	174	62	0.35	25	0.03	0.1404±25	0.1343±51	2.60±11	813±29	2232±31
M2-1	r	25	18	0.70	4	1.10	0.1239±66	0.1474±55	2.52±17	886±31	2013±98
M3-1	c	131	108	0.82	65	0.06	0.1445±11	0.4258±167	8.49±35	2287±76	2282±13
M4-1	c	153	153	1.00	70	0.07	0.1505±18	0.3731±125	7.74±28	2044±59	2351±20
M5-1	c	451	306	0.68	163	0.03	0.1432±6	0.3131±144	6.18±29	1756±71	2266±8
M6-1	c	222	89	0.40	52	0.04	0.1393±70	0.2177±80	4.18±27	1269±42	2219±90
M6-2	r	24	16	0.66	3	10.32	0.1286±320	0.1165±75	2.07±55	710±44	2079±519
M7-1	r	328	166	0.51	64	0.58	0.1189±53	0.1757±69	2.88±18	1043±38	1940±82
M8-1	c	101	41	0.41	34	0.03	0.1387±15	0.3127±113	5.98±23	1754±56	2211±19
M9-1	c1	145	101	0.70	59	0.00	0.1412±8	0.3553±177	6.92±35	1960±85	2242±10
M9-2	c2	285	229	0.80	125	0.01	0.1549±7	0.3671±171	7.84±37	2016±81	2401±8

c, Core; r, rim; m, metamorphically recrystallized zircon. Spots N1-2 and N3-2 are the rims of magmatic zircon with oscillatory zoning, and other spots in rim are all the metamorphically recrystallized or planar overgrowth zircons. f_{206}(%) is percent of total ^{206}Pb which is non-radiogenic.

discordant. The exception is spots N11-1 and N2-2 which yield concordant or near concordant $^{207}Pb/^{206}Pb$ ages of 1949±77 Ma and 1899±35 Ma, respectively. However, regression of all the analyses of metamorphic zircons yields an upper intercept age of 1915±27 Ma (MSWD = 1.01) (Fig. 3).

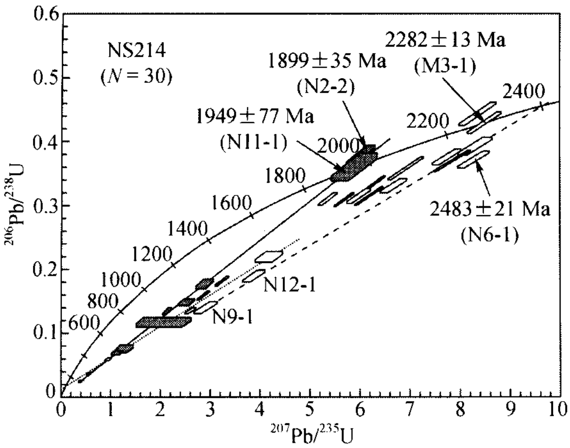

Fig. 3. U-Pb zircon concordia diagram for an intermediate granulite xenolith (NS214). The metamorphic zircons (filled symbols) define a linear array (solid line) that gives an upper intercept age of 1915±27 Ma (MSWD = 1.01); the lower intercept age of discordia curve (dotted line) is 115±100 Ma (MSWD = 25); The upper intercept age of discordia curve (dashed line) is 2409±77 Ma (MSWD = 15). The numbers denote the $^{207}Pb/^{206}Pb$ ages.

3 Age of the Nushan lower crust

Mineral chemistry and trace element compositions of granulite xenoliths suggest a relatively old age for the lower crust beneath Nushan[1,2]. This is confirmed by the present study. SHRIMP U-Pb dating of metamorphic zircons defines a discordia curve with an upper intercept at 1915±27 Ma, which is interpreted as the age of granulite facies metamorphism on the basis of CL images and relatively low MSWD. Data on igneous cores do not define any linear array. Nevertheless, the protolith of the Nushan granulite xenoliths may have been formed at least 2.2 Ga ago because most of the $^{207}Pb/^{206}Pb$ ages are older than 2.2 Ga. Furthermore, $^{207}Pb/^{206}Pb$ age of 2483±21 Ma for spot N6-1 on an igneous core (Fig. 2(c), Table 1) suggests that the protolith of the Nushan granulites could have been formed during the late Archean. In addition, most of SHRIMP U-Pb dating results are discordant suggesting an extensive Pb-loss. Accordingly, the Nushan lower crust may have been affected by a strong thermo-tectonic event of young ages. The discordia curve (dotted line, Fig. 3) defined by the plots near the lower part of concordant curve gives a lower intercept at 115±110 Ma. This age is consistent with the extensive Mesozoic magmatic underplating in East China (including North China craton)[3,5,22−24].

The debates prevail as to the location of suture zone between the North China and South China blocks to the east of the Tan-Lu Fault Zone. An assessment of tectonic affinity of the lower crust beneath Nushan is therefore critical in regarding this issue. Recently, some basic or ultrabasic metamorphic rocks of late Archean age are discovered in the North China craton. For examples, the Manjinggou high-pressure basic granulite was formed at 2647±115 Ma and experienced medium-pressure retrogression metamorphism at 1.83 Ga[25]. The Taishan complex was formed at 2.4—2.75 Ga[26]. Similar ages have been found for the Wutai complex (2.5 Ga), the Hutou Group metabasalt (2.4 Ga)[27] and the Fuping complex (2.52 Ga)[20]. As a whole, the majority of the basement of the Central Zone of the North China craton was established during the period from 2.5 to 1.9 Ga[28]. In addition, the granulite-facies metamorphism in the Sanggan area occurred at about 1.87 Ga[29,30]. Zircon U-Pb age of 1960±67 Ma for the Mazhengkou granitic gneiss[31] suggests that the Precambrian crystalline basement in Eastern Shandong Province may also have experienced a very strong thermo-tectonic events during the late Paleoproterozoic. All these data suggest that the major crustal formation events in the North China craton took place during 2.65—1.9 Ga, and this late Archean to Paleoproterozoic crust has been thermally and tectonically affected during 1.95—1.82 Ga. The age of the Nushan granulites is broadly consistent with these crustal forming events in the North China craton. Unfortunately, the late Archean to Paleoproterozoic age is also ubiquitous in southern China including Yangtze block and Cathaysia block[32]. For instance, the zircon U-Pb dating of the Huangtuling granulite from Northern Dabieshan yields the protolith age of ca. 2.7 Ga and the granulite-facies metamorphic ages of 2052±100 Ma[33]. Chen et al.[34] suggested that the protolith of Shuanghe ultra-high pressure eclogite from Southern Dabieshan may have been formed at 2489 ± 25 Ma. As a consequence, zircon U-Pb age alone is not sufficient to assess the tectonic affinity of the Nushan lower crust to either the North China craton or the Yangtze craton. Nevertheless, available geochemical data suggest that the lower crust beneath Nushan more likely belongs to the North China craton[35]1), but it remains to resolve whether there exists the lower crust in the Yangtze craton similar to that in the North China craton.

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