Discovery of the Early Mesozoic granulite xenoliths in North China Craton

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Abstract The discovery of the Early Mesozoic basic granulite xenoliths in the Harqin area of the Inner Mongolia Autonomous Region (for short Inner Mongolia) is reported for the first time in this paper. According to the mineral assemblage the xenoliths include two-pyroxene granulite, clinopyroxene granulite, and hypersthene granulite. Their protolytes are mainly gabbroite rocks. The zircon U-Pb age of the granulite xenoliths is 251 Ma, and K-Ar age of the hypersthene is 229 Ma. They represent the times of metamorphism and cooling of the granulite facies respectively. The host rock of the xenoliths is Early Mesozoic biotite-quartz diorites, whose whole-rock K-Ar age is 219 Ma. This discovery confirms existence of an Early Mesozoic underplating in the North China Craton, which is of much importance in research on the Early Mesozoic mantle-crust interaction in the concerned area.

Keywords: North China Craton, Early Mesozoic, granulite xenolith and lower crust.

Granulite is produced by the high-temperature metamorphism of the lower crust. Most of the granulites occurring on the surface are Precambrian terrain granulites, which have undergone long-term complicated variation and thus recorded the history of metamorphism in various stages. On the contrary, the Phanerobiotic granulites appearing as xenoliths may directly reflect the heat events experienced by the lower crust since Phanerobiotic, and thus can be used as microprobes for studying the lower crust.

In recent years, the authors successively discovered mafic-ultramafic cumulate xenoliths in the Early Mesozoic diorites from the Harqin area in eastern Inner Mongolia. Their isotopic ages are in the range of 237—220 Ma[1]. Most recently, we for the first time discovered basic granulite xenoliths in diorites, whose mineral composition and temperature-pressure conditions of forming are quite different from those of the Precambrian terrain granulites occurring on the surface of the North China Craton[2]. Measurement of the elastic wave velocity at high pressure and high temperature reveals that those granulite xenoliths originate from the mantle-crast transition zone[3]. Thus they may be used as evidence for studying the composition features and lithosphere evolution of the Early Mesozoic lower crust in the concerned area. This paper will mainly report our research results on the petrologic features and isotopic dating of the granulite xenoliths.

1 Geological settings and petrographic features of the granulite xenoliths

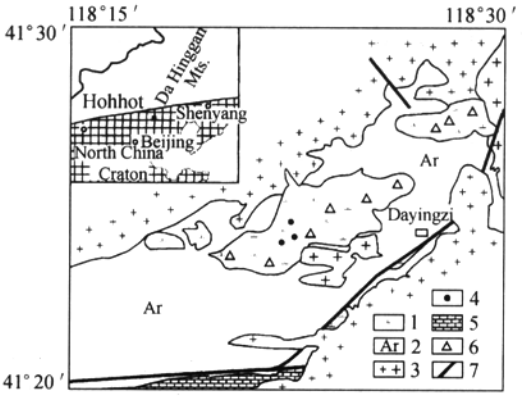

Fig. 1. Geological sketch of the Dayingzi area in Harqin Qi. 1, Early Mesozoic diorite; 2, Archaeozoic metamorphic rock; 3, Mesozoic granite (left), Palaeozoic granite; 4, sampling locations of granulite xenoliths; 5, Proterozoic Changcheng System; 6, outcropping points of Early Mesozoic mafic-ultramafic xenoliths; 7, faults.

The granulite concerned occurs in the Dayingzi area of Harqin on the border of Inner Mongolia and Hebei Province, which tectonically belongs to the North China Craton and is located at the intersection of two faults, one of which is the Longhua-heilihe-yebaishou deep fault at the southern edge of Inner Mongolia Earth's axis[4] and the other is the Balihan fault at the eastern edge of Harqin uplift (fig. 1). In the concerned area are mainly metamorphic rocks of the Archeozoic Jiwangyingzi Group, whose isotopic ages are 2.8—2.4 Ga[5], large amount of Mesozoic intrusive rocks and volcanic rocks also exist in this area.

All of several dozens collected granulite xenoliths samples are included in biotite-quartz diorite. The sampling localities are shown in fig. 1. The xenoliths appear fresh, in gray-black color, with large specific weight, and in compact lumps of irregular sizes and forms. Their sizes range from 50 cm×25 cm to 10 cm×8 cm, and their forms are mostly rounded with a few triangular and meniscus ones. No obvious alteration edges are seen on the xenoliths, showing that they are captured under the high-temprature condition in the lower crust. A few of them show weak banded structures, which are interphase arrays of light- and dark-colored minerals.

According to the mineral assemblage features the granulite xenoliths can be divided into three categories: two-pyroxene granulite, clinopyroxene granulite, and hypersthene granulite, with the first category as the main part. Two-pyroxenes are composed of Opx_{15-30} + Cpx_{20-30} + Pl_{40-50} + $Bi_{5\%\pm}$. Clinopyroxene is composed of Cpx_{30-40} + Pl_{40-50} + $Bi_{5-10.}$ Hypersthene is composed of Hy_{20} + Pl_{65} + Bi_5 + $Q_{10.}$ The microprobe analysis results of the hypersthene are shown in table 1. The granulitic accessory minerals of the granulite are mainly magnetite, zircon, and apatit with occasional rutile.

Table 1 Microprobe analysis data of hypersthenes

	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	FeO*	Cr_2O_3	Total
NH8-1	0	22.65	1.11	51.86	0.1	0.49	0.6	0.39	22.87	0.02	99.49
NH8-2	0.25	21.24	1.28	51.66	0.04	0.81	0.05	0.47	23.30	0	99.12
NH9	0	21.63	1.81	52.10	0.23	1.07	0	0.31	23.21	0.16	100.64
HN11-1	0.44	22.67	0.47	52.50	0.3	0.73	0.02	0.24	22.59	0.04	99.73
HN11-2	0	21.50	1.14	52.14	0	1.31	0.34	0.33	22.55	0	99.57
HN12**	0.29	18.66	0.83	51.40	0	1.25	0.23	0.35	27.2	0.04	100.25

FeO* means total iron; ** was measured by Han Xiuling of the Institute of Geology and Geophysics, the Chinese Academy of Sciences, and the rest by Shu Guiming of Department of Geology, Peking University.

The granulites show a crude gneissic structure for the minerals in them are lens-like and paralelly arranged. The grain size of the master minerals are 0.5—2 mm, with most around 1 mm.

A typical granuloblastic texture can be observed. Most of the granulites show a residual igneous texture, such as the interstitial texture or the intergranular texture. Their protolith is suggested as basaltic rocks. No multiple phases of metamorphic phenomenon are seen in the rocks. The recrystallized peroxenes are mainly subhedral-allotromorphic-granular with an occasional triple junction texture. The content of the biotites in the rocks varies largely, from 1% to 10%. None of the samples contains hornblende and garnet, and no mineral enclosure exists in the peroxene. Those features make them differing from the Precambrian granulite of the Huabei area. Meanwhile, the enstenite in them also shows higher CaO and lower Al_2O_3 and Na_2O compared with the enstenite of Precambrian granulite of the North China area. Those features reflect that they are formed at higher temperature and lower pressure. The concerned granulite xenoliths have a metamorphic temperature within 850—900℃, thus belonging to high temperature granulite[2].

2 Methodology of analysis

Fresh rock samples were selected for regular X-ray fluorescence analysis (XRF) in the Test Center of Beijing Design & Research Institute of Nonferrous Metallurgy to obtain the bulk petrochemical composition of the granulite xenoliths. The analysis errors of the GSR2 standard sample are all less than 5% except for Na_2O (less than 6%).

Determination of the U-Pb age of the zircons in the granulite xenoliths was carried out in Tianjin Institute of Geology and Mineral Resources. About 7 kg of hypersthene granulite samples were crushed into grains of smaller than 200 μm, from which 100 or so perfect zircon grains without fractures, alteration, or enclosures were selected under a binocular microscope. The selected zircon grains are in two forms. One is columnar or irregular sheet-like with lighter colors (Nos. 204601, 204602 and 204603 in fig. 2), which is determined by Wang Xiang's research as of metamorphic origin (personal communication of Li Huimin with Wang Xiang). The other is irregular sheet-like or rounded or granular with a darker yellow-brown color (Nos. 204604 and 204605 in fig. 2).

Procedures for dissolution of the zircon and U-Pb separation are as described in Li et al.[6]. The laboratory Pb blank is 0.03—0.05 ng, and U blank 0.002—0.004 ng. The ages were calculated with an ISOPLOT code (version 2.9) developed by Ludwig[7].

In addition, K-Ar dating for whole rock of the host rock-diorite and hypersthenes in the hypersthenes granulite xenoliths was carried out in the Institute of Geology and Geophysics, the Chinese Academy of Sciences. The detailed procedures can be seen in ref. [8]. The constants used in calculation are: $\lambda = 5.543\times10^{-10}$/a and $^{40}K/K = 1.167\times10^{-4}$ (weight ratio).

3 Results

3.1 Petrochemistry

The representative bulk petrochemical compositions of the granulite xenoliths are shown in

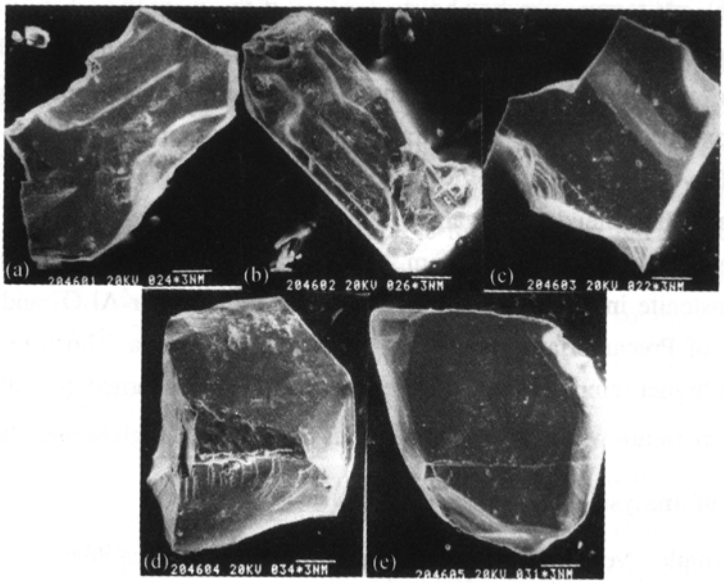

Fig. 2. Scanning electron microscope pictures of the zircon in the granulite xenoliths (the pictures, by order, are of the first 5 samples listed in table 3).

table 2. It can be seen that they are basically a suite of basalt, in which SiO_2 varies within 46%—52%, MgO within 0.6%—12.6%, (Na_2O + K_2O) within 2.7%—4.3%, and Mg′ (=Mg/(Mg+Fe^{2+})) within 0.65—0.80. Samples HN11 and HN20 contain the normative mineral quartz, appearing as silicon saturated rocks. And sample HN20 also contains the normative mineral corundum, showing the feature of an aluminium saturated rock. The normative mineral nopheline or acmite occurs in samples HN10 and HN11, showing that the rocks are alkali-rich. The normative mineral hypersthene also appears in all samples except for HN10. Therefore, the composition of the granulite xenoliths is quite complicated.

Table 2 Petrochemical compositions of granulites

	Two-pyroxene granulite				Clinopyroxene granulite	Hypersthene granulite
	HN7	HN12	HN1	HN11	HN10	HN20
SiO_2	50.74	51.68	48.55	52.34	45.90	50.85
TiO_2	0.37	0.86	0.39	0.38	1.69	1.46
Al_2O_3	16.38	17.38	14.42	3.72	13.02	16.98
Fe_2O_3	3.64	5.55	0.96	0.41	3.57	2.76
FeO	3.48	3.76	7.38	7.53	6.19	8.02
MnO	0.15	0.17	0.26	0.27	0.15	0.24
MgO	7.61	5.89	12.57	11.19	11.99	8.36
CaO	12.21	8.45	10.84	8.5	10.90	5.33
Na_2O	2.26	3.62	1.32	0.62	1.13	0.68
K_2O	1.01	0.67	1.33	2.55	2.92	2.96
P_2O_5	0.15	0.33	0.10	0.10	0.14	0.71
H_2O	0.39	0.53	0.40	0.63	0.93	0.75
Volatile	1.96	0.64	1.21	1.20	1.19	0.40
Total	100.35	99.53	99.73	99.48	99.72	99.50
Mg′	0.80	0.74	0.75	0.73	0.78	0.65

3.2 Isotopic Geochronology

3.2.1 U-Pb isotopic age of zircons in the granulite. As mentioned above, the zircons separated from the samples can be roughly divided into two populations. The measured representative U-Pb isotopic ages of different zircons are shown in table 3 and in fig. 3. In table 3, the zircons of Nos. 1－3 belong to the first population, and Nos. 4—6 to the second population. Two zircon U-Pb ages are determined for the two populations. The age of the first category is (251±5) Ma, and that of the second population is (1 839±15) Ma. The U-Pb apparent ages of the three samples of the first population are basically concordant within the experimental error, with the data points located on the concordia (fig. 3(a)). The $^{206}Pb/^{238}U$ apparent age data for such young zircons are relatively reliable, and thus can be used for their crystallization age. The weighted average $^{206}Pb/^{238}U$ apparent age of samples Nos. 1—3, (251±5) Ma, should represent the formation (crystallization) age of the category of zircons. Because those zircons are metamorphogenitic, such an age can be interpreted as the time when granulite facies metamorphism occurs. It is also reasonable that this age should be older than the ages of other cumulate xenoliths in the same area.

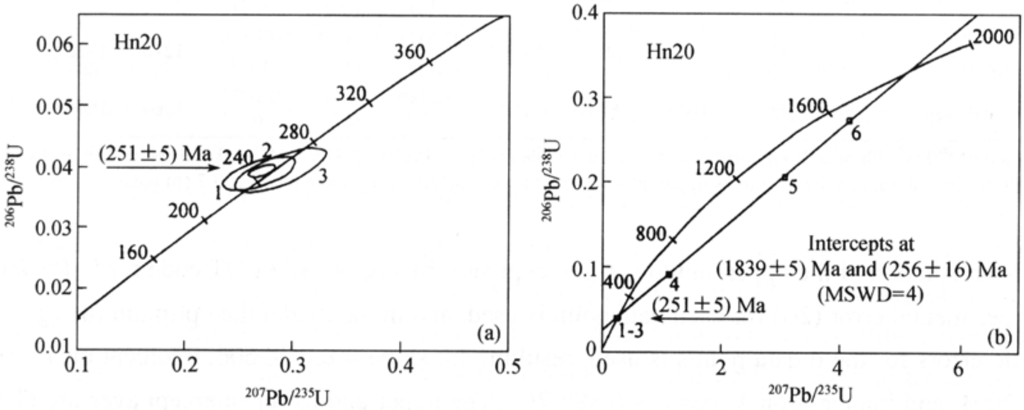

Fig. 3. Concordia diagram of U-Pb isotopic ages of the zircons in Harqin granulite xenoliths.

The U-Pb apparent ages of zircons Nos. 4—6 in the second population are obviously discordant within the experimentat errors. The data points depart from the concordia curve, showing different degrees of radiogenic lead loss from the zircons. A discordant line is drawn through the 6 points (fig. 3(b)). The upper intercept age is (1 839±15) Ma and the lower intersection age (256±16) Ma. The former can be interpreted as the formation (crystallization) age of zircons of Nos. 4—6. And the latter is the formation (crystallization) age of zircons of Nos. 1—3, which is also the age of the granulite facies metamorphic event. It is this granulite facies metamorphism that causes radiogenic lead loss from Nos. 4—6 zircons, which should be crystallized when the protolith of granulite-basalt is formed. The U-Pb age of 1 839 Ma implicates that the protolith of granulite is formed in the Proterozoic, while the North China Craton is characterized by an extensional tectonic framework, showing an orogenic magmatic activity accompanied with aulacogen in the end of the Proterozoic (1.8—1.9 Ga)[9]. Thus this age could be a record of such a thermal event. The lower intercept age of (256±16) Ma is consistent with the weighted average $^{206}Pb/^{238}U$ apparent age of (251±5) Ma of Nos. 1－3 zircons within the experimental errors. But the latter is more accurate and reliable so the time of the granulite facies metamorphism should be considered as (251±5) Ma.

Table 3 U-Pb isotopic age data of zircons in the granulites

Sample No.	Weight /μg	Concentration /μg • g^{-1}		Content of common lead/ng	Isotopic atom ratio							
		U	Pb		$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1	5	596	33	0.036	225	0.4623	0.0392 (22)	0.268 (27)	0.0496 (39)	248	241	177
2	15	454	21	0.009	1895	0.2393	0.0396 (9)	0.270 (10)	0.0495 (13)	251	243	172
3	5	435	25	0.030	198	0.2513	0.0397 (30)	0.287 (34)	0.0524 (43)	251	256	301
4	20	302	31	0.017	1888	0.1991	0.0912 (12)	1.128 (20)	0.08975 (88)	563	767	1420
5	45	144	33	0.011	6867	0.1578	0.2075 (11)	3.080 (19)	0.1076 (30)	1216	1428	1760
6	20	109	33	0.018	1939	0.1546	0.2746 (37)	4.152 (62)	0.1097 (6)	1564	1664	1794

Data of $^{206}Pb/^{204}Pb$ have been corrected for laboratory blanks (Pb = 0.050 ng, U = 0.002 ng) and spike. The lead isotopes in other ratios are all radiogenic. Numbers in parentheses are 2σ absolute errors, for example, 0.109 7 (6) means 0.109 7±0.000 6 (2σ).

In calculation of the upper and lower intercept ages by use of ISOPLOT code for U-Pb dating, the experimental error (2σ) for each data point is used, and in the model the optimum fitting of the analytic errors for the 6 data points is used, resulting in: slope = 0.0599606, intercept on *Y* axis = 0.0232804, and intercept on *X* axis = – 0.388 262. The upper and lower intercept ages are (1 839 ±15) Ma and (256±16) Ma (MSWD = 4) respectively. In the meantime, the weighted average $^{206}Pb/^{238}U$ apparent age of Nos. 1—3 zircon samples is (250.6±4.8) Ma (1.9% error, 95% confidence, MSWD = 0.0791, probability = 0.92). The reliability of the ages, therefore, is very high in terms of isotopic age determination.

3.2.2 K-Ar ages of individual mineral (hypersthene) and whole rock (host diorite). The K-Ar dating results of individual mineral-hypersthenes in the granulite xenoliths and the whole rock of the host rock-diorite are shown in table 4. The K-Ar age of the hypersthene is 229 Ma, which will indicate the time when the granulite facies metamorphic rock is cooled down for the closure temperature of the K-Ar isotopic system of hypersthene is about 600℃. The whole rock K-Ar age of the host rock-diorite is 219 Ma, which reflects the time when the diorite is cooled and coincides with the thermal events occurring in the concerned area for the same time[10].

Table 4 K-Ar ages of hypersthenes in granulite xenoliths and whole rock of host rock-diorite

Lithology	Sample No.	Sample	Weight/g	K (%)	$^{40}Ar^{*}\times10^{10}$ /mol • g^{-1}	$^{40}Ar_a$ (%)	$^{40}Ar^{*}/^{40}K$	Apparent age/Ma (±1σ)
Granulite	NH	hypersthene	0.1884	0.24	1.0159	5.00	0.014184	229.0± 6.8
Diorite	Xd	whole rock	0.1829	2.17	10.9170	9.04	0.013497	218.5±4.5

The test was made by Sang Haiqing with the Institute of Geology and Geophysics, the Chinese Academy of Sciences.

4 Discussions

Commonly used methods in researches on the isotopic geochronology of the granulite xenoliths of the lower crust include Rb-Sr, Sm-Nd, and Pb-Pb isochron dating of whole rock, Nd model dating, U-Pb dating of zircon, and K-Ar dating of individual minerals. Rudnick considered the last two methods as most reliable[11]. The U-Pb age of zircon and K-Ar age of the hypersthene in the granulite xenoliths concerned in this paper are determined as 251 Ma and 229 Ma, representing the metamorphic age and cooling age of the granulite xenoliths respectively. If the granulite forming age of 251 Ma represents occurring of the thermal metamorphism previous to the Early Mesozoic underplating and the aforementioned cumulate forming age of 237—221 Ma represents the main stage of the underplating, the time lag (about 20 Ma) will be in accordance with the general rule of underplating and describes the Early Mesozoic underplating process the North China Craton experiences. According to the current chronological table, the metamorphism of the granulite mentioned in this paper should be considered as a thermal event from the end of the Late Paleozoic to the beginning of the Early Mesozoic. However, recently the isotopic age of boundary line between Permian and Triassic is determined as (251.3±3.4) Ma (2σ) directly from the boundary strato-type between the Permian and the Triassic[12]. Hence the age of (250.6±4.8) Ma should be seen as in the Early Mesozoic. More importantly, in terms of the regional tectonic evolution[10,13], this age should indicate the beginning of the Mesozoic underplating event. This is why the granulite is considered in our work as a product of the Early Mesozoic metamorphism and the paper is titled as “Discovery of Early Mesozoic Granulite Xenoliths”. This underplating event is an important geological record of the transform process of the North China tectonic framework.

For the recent two decades, much intention has been drawn to the study of granulite as a window to look into the continental lower crust and especially the granulite xenoliths as direct evidence for the lower crust evolution. In 1992, Rudnick discovered through summary of the global space-time distribution of the granulite xenoliths that Archaeozoic granulite xenoliths occupy a share of 14%, Proterozoic ones 52%, and Phanerozoic ones 34%[11]. Then Chinese geologists successively made similar researches in the east, north, and south of China[14—16]. Age data of the Late Mesozoic granulite xenoliths (140—120 Ma) have been obtained from the Hannuoba area in the west North China Craton[17].

Furlong et al. discussed the underplating of the continental crust, which is considered as a process of addition of mantle material to the bottom of the continental crust[18]. Studying granulite xenoliths is an important approach to understanding the process. Underplating of the North China area in Late Mesozoic has been preliminarily understood through studying metamorphic core complex and granulite xenoliths, but little research has been done on the Early Mesozoic lower crust. The authors of this paper reported recently that the mafic cumulates discovered in the same area are added to the lower crust by the Early Mesozoic Underplating[1]. And the granulite xenoliths discovered in the same host rock further prove the existence of the Early Mesozoic underplating of the North China Craton. Combining the Early Mesozoic granulites in the east North China Craton (Harqin) with the Late Mesozoic granulites in the west North China Craton (Hannuoba) will provide important evidence for studying the composition and evolution of the Mesozoic North China lower crust.

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