# Sm-Nd age dating of high-pressure granulites and amphibolite from Sanggan area, North China craton

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**Abstract** **The high pressure (HP) metamorphic age has been dated to HP rocks from the Sanggan area, North China craton. We have got garnet+whole rock isochron ages of (1 842±38) Ma for HP granulite, and (1 856 ± 26) Ma for HP amphibolite. The Sm-Nd whole rock isochron of HP granulites give out an age of (1 870±150) Ma with Nd depleted mantle model age of (2402—2 482) Ma. Considering the Nd isotope homogenization during the peak metamorphism of the HP granulite, Sm-Nd closure temperature and the retention of Nd isotopic memory in garnets partially broken down during decompression, all these isochron ages are thought to be HP metamorphic age. Furthermore, we proposed that the HP metamorphism took place at the end of Paleoproterozoic during the large-scale collision and assembly of the North China craton.**

**Keywords:** **Sm-Nd dating, high pressure granulite, Paleoproterozoic collision, North China craton.**

In recent years, most high pressure (HP) metamorphic rocks have been recognized from the Hengshan Mt. to Chicheng in the Sanggan area, North China craton[1,2]. The major rock types are HP basic granulites, amphibolites and retrograde eclogites. The HP granulites subjected to HP metamorphism at about 1.3—1.6 GPa and 800—850℃. All the HP rocks have a clockwise PT path with rapid isothermal decompression[3—5]. They are most probably the products of collisional orogen. However, it has not yet been determined when the significant Precambrian collisional orogenic event occurred.

In general, Sm-Nd isochron of garnet+whole rock± other minerals is supposed to produce metamorphic age determination. These years, more understanding to Sm-Nd system in garnet has been achieved, especially about how the closure temperature is affected by garnet radius, initial temperature and cooling rate[6—10]. That made the garnet Sm-Nd method capable of dating metamorphic age. Particular advances are in age determination of multi-metamorphism[11—14].

In this note, we apply garnet+whole rock Sm-Nd isochron to determine the age of the HP metamorphism. A whole rock isochron of HP granulites is also measured. Then, the most possible age of HP metamorphism will be discussed, which will define the age of the collisional orogeny and assembly of the North China craton.

## 1 Geological background and petrology of the HP metamorphic rocks

The major HP metamorphic rocks in the North China craton are HP basic granulite, HP amphibolite and retrograde eclogite[4, 5, 15]. In the Sanggan area, plenty of HP rocks were distributed northeast from the Hengshan Mt. to Chicheng as lenticular blocks or enclaves in highly deformed TTG gneiss, granitic gneiss, migmatite and granite. Therefore, the occurrences of HP rocks define the Sanggan strucure zone (fig. 1). The samples of HP granulites and amphibolite of this note are from Xiwangshan and Womakeng respectively. These HP metamorphic rocks have been carefully investigated petrologically[3, 16, 17], which will make the samples typical and representative.

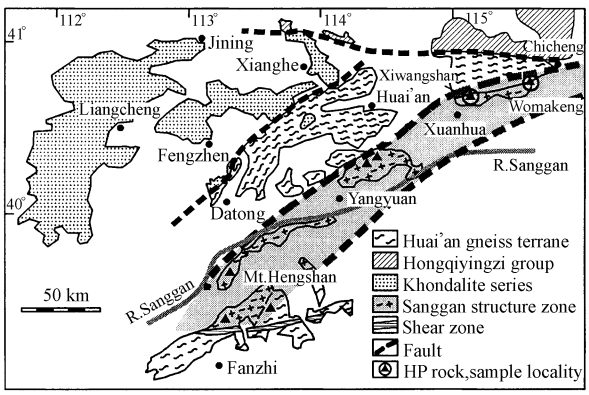


Fig. 1. Sketch map of Precambrian geology in the Sanggan area, North China craton.

The HP granulites contain abundant garnet porphyroblasts, in which mineral inclusions of clinopyroxene + plagioclase + quartz as well as the garnet core constitute the early metamorphic assemblage. Thermobarometric calculation gives the metamorphic condition of 800—850℃ and 1.3—1.5 GPa. Around garnet, there developed kelyphite, which is radial fine grain intergrowth of plagioclase + otherpyroxene ± amphibole ± clinopyroxene. The kelyphite is the typical garnet breakdown product during decompression, formed at about 700—800℃ and 0.8—1.0 GPa.

The garnet compositional profiles reveal that the garnet interior has been affected by the garnet breakdown reaction during decompression to very different extent. The effect varies depending on different localities and even different samples in the same localities. Some samples were strongly affected so that the major part of garnet has been broken down, and the relict part shows the strong diffusion zoning. Some other samples were slightly affected by the garnet broken down, the interior of the garnet has not been affected by the garnet breakdown reaction. Only the very rim of the garnet shows the resorption zoning. One sample (xw99-8) of this type of rock has been chosen for garnet+whole rock Sm-Nd age dating.

The major element compositional profile (fig. 2) of

garnet porphyroblast from the HP granulite sample xw99-8 shows that the major element compositions in garnet vary only slightly from core to near rim. That indicates that the nearly diffusion equilibrium was reached at the high-pressure high-temperature metamorphic episode. The sharp compositional change in very rim (<30 μm) is the resorption zone formed during the garnet breakdown. It can be considered that the rate of the garnet breakdown was relatively quick. Therefore, the relict garnet was not affected markedly by the diffusion corresponding to the garnet broken down.

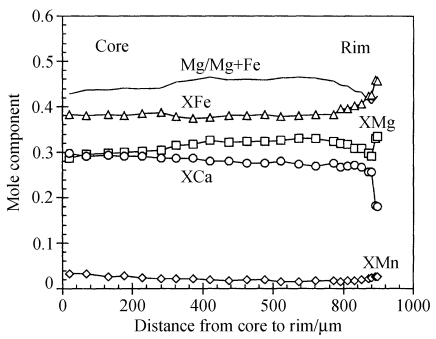


Fig. 2. Major element compositional profile of metamorphic garnet porphyroblast of HP basic granulite from Xiwangshan, Xuanhua, North China craton.

The HP amphibolite sample wm99-7 is from Womakeng, Xuanhua. The rock is mainly composed of garnet, clinopyroxene, plagioclase, as well as amphibole. It has an equigranular mosaic texture. The peak metamorphism took place at about 700℃ and 1.2—1.4 GPa. And some of amphiboles formed after the metamorphic peak.

## 2 Analytical technique and results

Seven whole rock samples and 2 garnet samples were analyzed for Sm and Nd isotopic composition. Briefly, the rock samples were crushed into blocks with size of 2—3 cm, then washed in diluted HCl. 3—5 representative blocks of each sample were ground into fine powder. Garnet separations were picked out grain by grain under a binocular microscope at 0.5 mm grain size. Whole rock samples weighing about 100 mg and garnet samples weighing about 150 mg were spiked by mixture of $^{149}$Sm and $^{146}$Nd for isotope dilution measurements. Samples were dissolved using a mixture of HF and $HClO_4$ acids in tightly closed teflon jars. Sm-Nd containing fractions were separated from major cations using AG50W×8($H^+$) cation-exchange resin. Separation of Sm from Nd was effected using P507 leaching resin.

Isotope measurements were carried out on the VG354 mass-spectrometer. Sm isotope ($^{149}$Sm/$^{147}$Sm) was measured in single-collection peak jumping mode. Nd isotopes were measured as $NdO^{1+}$ using single filament in static multi-collection peak jumping mode. Oxygen isotopes were calibrated by $^{18}$O/$^{16}$O=0.000387 and $^{17}$O/$^{16}$O=0.00211. Nd isotopes were normalized to $^{142}$Nd/$^{144}$d=1.141835 and $^{146}$Nd/$^{144}$Nd=0.7219. Procedral blank was about $5\times10^{-11}$g. The measurement of the international standard specimen La Jolla was $^{143}$Nd/$^{144}$Nd =0.511 862±0.000 004 (average measurement is 0.511 859). So, the data present here are quite reliable.

The Sm-Nd isotope analyses are listed in table 1. Three isochron ages are introduced below:

(i) For HP granulite sample xw99-8 from Xiwangshan, a two-point garnet+whole rock isochron (fig. 3) yielded an age of (1 842±38) Ma.

Table 1 Sm-Nd isotope analysis of whole rock and garnet samples of HP granulites and amphibolite from the North China craton

| Sample | Sm/μg • g$^{-1}$ | Nd/μg • g$^{-1}$ | $^{147}$Sm/$^{144}$Nd | $^{143}$Nd/$^{144}$Nd[a)] | $T_{DM}$[b)] / Ma | $\varepsilon_{Nd}(0)$ |
|---|---|---|---|---|---|---|
| HP granulites from Xiwangshan, Xuanhua | | | | | | |
| xw96-22 | 2.008 | 8.392 | 0.144 7 | 0.511 917± 0.000 009 | 2 482 | −14.03 |
| xw96-23 | 1.663 | 7.358 | 0.167 | 0.511 818± 0.000 008 | 2 417 | −15.96 |
| xw96-25 | 1.589 | 7.193 | 0.133 6 | 0.511 777± 0.000 007 | 2 410 | −16.76 |
| xw96-26 | 1.438 | 6.019 | 0.142 8 | 0.511 897± 0.000 014 | 2 458 | −14.42 |
| xw96-29 | 3.369 | 15.139 | 0.134 6 | 0.511 792± 0.000 008 | 2 402 | −16.46 |
| xw99-8 | 1.262 | 4.814 | 0.158 6 | 0.512 085± 0.000 010 | 2 657 | −10.75 |
| xw99-8-garnet | 0.601 | 0.781 | 0.460 3 | 0.515 742± 0.000 050 | 1 668 | 60.59 |
| HP amphibolite from Womakeng, Chicheng | | | | | | |
| wm99-7 | 6.483 | 28.37 | 0.138 2 | 0.511 842± 0.000 014 | 2 417 | −15.49 |
| wm99-7-garnet | 2.195 | 2.343 | 0.566 5 | 0.517 073± 0.000 018 | 1 739 | 86.55 |

a) Precisions on $^{143}$Nd/$^{144}$Nd ratios are 2$\sigma$. 1% error of $^{147}$Sm/$^{144}$Nd ratios is taken into account. b) Calculations were carried out using ISOPLOT programme (Ludwig, 1996, ver. 2.90). Depleted mantle model is $\varepsilon_{Nd}(t)=0.25T^2-3T+8.5$ ($T$ in Ga). The following parameters are used in calculations: CHUR $^{143}$Nd/$^{144}$Nd=0.512636, $^{147}$Sm/$^{144}$Nd=0.1967, $\lambda^{147}$Sm=6.54×10$^{-12}$/a.

(ii) Sm-Nd data of 6 whole rock samples from Xiwangshan formed an isochron yielding an age of (1 870±150) Ma (fig. 4). But the error is relatively high because of the small $^{147}Sm/^{144}Nd$ range probably. The $\varepsilon_{Nd}(t)$ of the isochron is –1.6, much lower than that of depleted mantle of that time. For 5 samples with $^{147}Sm/^{144}Nd$ ratios of 0.10—0.15, Nd depleted mantle model ages range from 2 402 to 2 482 Ma with the average of 2 431 Ma. These ages are much higher than the isochron age.

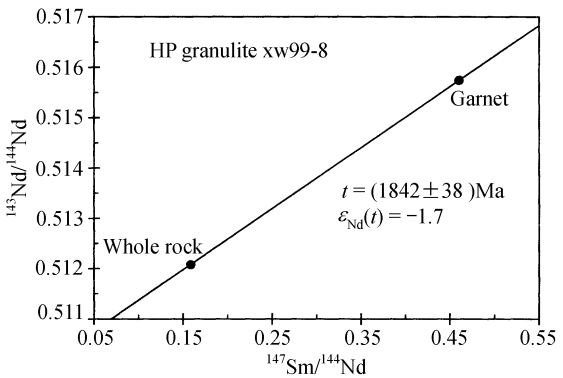


Fig. 3. Garnet+whole rock Sm-Nd isochron of HP granulite (xw99-8) from Xiwangshan, Xuanhua, North China craton.

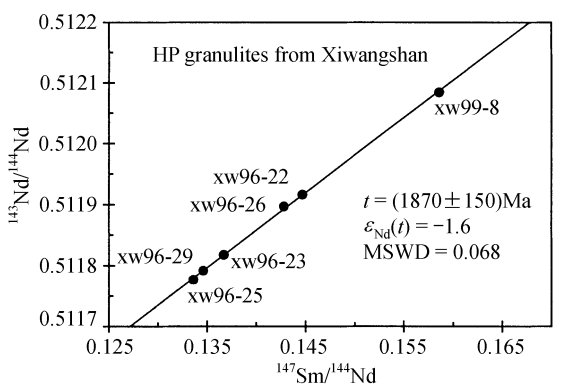


Fig. 4. Whole rock Sm-Nd isochron of HP granulites from Xiwangshan, Xuanhua, North China craton.

(iii) For HP amphibolite sample wm99-7 from Womakeng, a two-point garnet+whole rock isochron yielded an age of (1 856±26) Ma (fig. 5). The data of whole rock sample gave out a Nd depleted mantle model age of 2417 Ma, which is very similar to that of Xiwangshan.

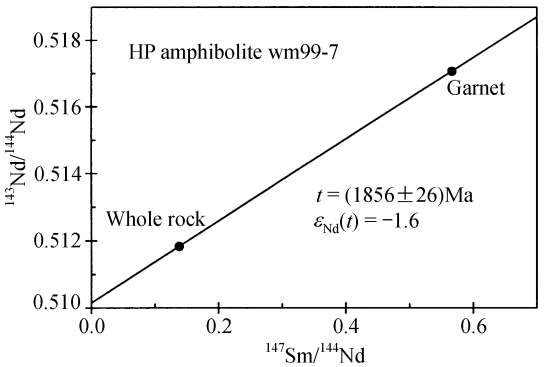


Fig. 5. Garnet+whole rock Sm-Nd isochron of HP amphibolite from Womakeng, Xuanhua, North China craton.

## 3 Discussions and conclusions

(i) Significance of the three Sm-Nd isochron ages. This note reports a garnet+whole rock Sm-Nd isochron age and a whole rock Sm-Nd isochron age for HP granulites, as well as a garnet+whole rock Sm-Nd isochron age for HP amphibolite. The ages are (1 842±38) Ma, (1 870±150) Ma and (1 856±26) Ma respectively. We consider these as the ages of HP metamorphism based on the following discussions.

(1) HP granulite garnet+whole rock two-point Sm-Nd isochron age (1 842 Ma). Whether this age indicates the HP metamorphic age or not depends upon closure temperature of the garnet Sm-Nd decay system, and the retention of isotopic memory in garnet partially broken down during decompression.

The closure temperatures of garnet Sm-Nd system are considered to be from 600℃ to more than 800℃ by different authors[6—9]. In essence, the closure temperature is controlled by cooling rate, initial temperature and garnet radius according to recent study of Ganguly et al.[10]. In a word, for big garnet, rapid cooling and higher initial temperature, the Sm-Nd system in garnet closes in high temperature and the garnet could record the early metamorphic age. On the contrary, the Sm-Nd system in garnet will open to low temperature, even below 650℃.

The HP granulite xw99-8 contains big garnet porphyroblasts with size of 2—10 mm. The compositional profile shows that the garnet has resorption zonning in very rim of <50 μm, and the nearly homogenous garnet interior was not affected markedly. Also, the garnet separation was obtained in about 500 μm grain size, which reduced the contribution of the narrow resorption rim of garnet to the Sm-Nd measurements. In addition, the metamorphic temperature of HP granulite episode is higher than 800℃[4,17], which is quite high as the initial temperature. And the decompression is relatively quick, we think, otherwise, more fraction of garnet porphyroblasts should be used out, or the diffusional compositional profile will develop as observed in samples from some other localities. In conclusion, the garnet we analyzed

here is capable of reserving the Sm-Nd isotopic memory of HP metamorphic episode.

For the rocks of multi-metamorphism, there are many successful examples of revealing the retention of Sm-Nd isotopic memory of early metamorphism in garnet[11—14]. The typical one is from Hensen and Zhou[14] on the Pan African granulite terrain in southeast Antarctic. In the condition of widespread granulite facies overprint during 500 Ma, the core part of garnet porphyroblast still preserved the age of early metamorphic episode of 941 Ma. The HP granulite in this note is very similar to the granulite in southeast Antarctic petrologically. Therefore, although outer part of garnet broke down, the relict inner part was capable of preserving the isotopic memory of early HP metamorphic episode to most extent.

From above, we consider that the garnet+whole rock Sm-Nd isochron age of 1 842 Ma indicates the HP metamorphic age.

(2) HP granulite whole rock Sm-Nd isochron age (1 870 Ma). The whole rock isochron age with identical corresponding Nd depleted mantle model ages indicates the formation age of the rocks in general[18]. But the whole rock Sm-Nd isochron age here is particular in that it has very low $\varepsilon_{Nd}(t)$, –1.6, and very high Nd depleted mantle model ages of 2 430 Ma on average, much higher than the isochron age. Theoretically, this isochron age could have two different meanings: i) the isochron gives out the formation age of the rocks, but the older crustal contamination created the low $\varepsilon_{Nd}(t)$ and the high Nd depleted mantle model ages; and ii) the isochron gives out the HP metamorphic age, because of the Nd-isotopic homogenization during the HP metamorphism.

The major part of the Sanggan area formed during 2 600—2 400 Ma[19], only minor rocks formed at about 2 800 Ma. All these rocks are not much older than the Nd depleted mantle ages of the HP rocks. The HP basic granulites have $SiO_2$ contents of 45.3%—46.2% and MgO contents of 9.6%—11.4%. We cannot find any evidence of significant older crustal contamination.

On the other side, the high-grade metamorphism and the growth of metamorphic minerals will impose intensively on the partition of REE between minerals, and result in Nd-isotopic homogenization to some extent as revealed from Lewis granulite terrane in Scotland[21].

The HP granulites here were collected within several meters in the same outcrop. The whole rock Sm-Nd system was very likely to be reset in so small scale due to the growth of the garnet porphyroblasts and the strong ion diffusion rate in HP metamorphic condition of 800—850℃ and 1.3—1.5 GPa. Presumably, the homogenization was not very complete, which causes the big error of the isochron.

Consequently, the whole rock Sm-Nd isochron age of 1 870 Ma indicates the HP metamorphic age.

(3) HP amphibolite garnet+whole rock two-point Sm-Nd isochron age (1 856 Ma). The HP amphibolite has an equigranular mosaic texture. Some amphiboles probably formed after peak metamorphism, but there is no coronitic texture arround garnet. The peak metamorphic temperature is about 700℃. So, the Sm-Nd system intended to close quickly after peak metamorphism. The garnet+whole rock two-point Sm-Nd isochron (fig. 5) age of 1 856 Ma has been certainly considered as HP metamorphic age.

(ii) HP metamorphism and the age of continental collision in North China craton

(1) The age of HP metamorphism. The precise age dating for the HP metamorphism is not so easy to be accomplished. i) Some HP basic rocks do contain very little zircon. But these zircons were easily affected during cooling because of their small size. In fact, the published zircon U-Pb ages by conventional or chemical single grain methods are both 1 833 Ma[15, 23], which are identical with the age of the large-scale crustal melting granites in this area. So, they could not present the HP metamorphic age obviously. ii) The whole rock Sm-Nd isochron ages of 2 400—2 600 Ma are certainly the formation age of the protoliths[15, 22, 23], not inevitably the metamorphic age because the corresponding Nd depleted mantle model ages are in the same range. iii) In general, the Sm-Nd isochron of garnet+whole rock ± other metamorphic minerals could give out the reliable metamorphic age. However, the published data (i.e. 1 824 Ma)[15] was still low. The possible reason is that the diffusion during garnet breakdown was not considered when choosing samples and separating garnet. Therefore, the result probably indicates the age of garnet broken down during decompression.

The results reported here are different from those mentioned above. First, the samples have been chosen on the basis of garnet compositional profile and other petrological research. Also, particular attention has been given to separating interior part of garnet porphyroblasts. In addition, the whole rock isochron age (1 870 Ma) is similar to the other two double point garnet+whole rock isochron ages (1 842 Ma and 1 856 Ma). From both theoretical and technical views, these age results are reliable measurements of the HP metamorphic age. The most possible age of the HP metamorphism in the North China craton is 1 870—1 840 Ma.

(2) Age of assembly of the North China craton.
The HP granulites, amphibolites and retrograde eclogites have clockwise PT paths[4, 5, 24]. Associated with the HP rocks are highly deformed TTG gneiss, granitic gneiss, migmatite, granite and many small shears. These and some other features are reasonably believed to be products of collisional orogeny. So, the collisional tectonic model has been proposed by many authors these years[24—27].

However, there are also other views on the area. i) Zhao et al.[28] considered the structure zone mentioned

above as a central arc zone. But it is well known that the North China craton subjected to the island arc accressional stage during late Archaean[19, 30, 33], rather than Paleoproterozoic. And consequentially, there was not a collisional stage in the end of Archaean just following the island arc accressional stage. ii) Li et al.[29] insist on the extensional tectonic process in the end of Paleoproterozoic. We all know that the North China craton subjected to extensional tectonics during Paleoproterozoic, and it was in the extensional state during Mesoproterozoic too. These are well evidenced geologically. But there was a discontinuity between the two extensional processes, which is also basic geological reality. In conclusion, there definitely existed an unextensional tectonic process in the end of Paleoproterozoic, which could be collisional tectonics.

According to Sm-Nd age dating, the HP metamorphism occurred in the end of Paleoproterozoic. It was the time of assembly of the North China craton by collisional tectonics. The process may be similar to that of the Laurentia craton created[34].

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