Age of the Miyun dyke swarm: Constraints on the maximum depositional age of the Changcheng System

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A group of NE-trending (~30°) mafic dykes, termed Miyun swarm herein, are distributed around the Miyun Reservoir, northern China, and have individual widths of over 40 m, and lengths of up to 8000 m. Baddeleyite grains were extracted from a ~40 m wide dyke. Using an isotope dilution thermal ionization mass spectrometry method, these grains yield an average 207Pb/206Pb age of 1731±4 Ma (n = 4; or 1731±1 Ma, n = 3). Because this dyke is overlain unconformably by conglomerates of the Changzhougou Formation, the lowermost formation of the Changcheng Group, the maximum depositional age of this group is constrained to be no earlier than 1731 Ma. This result also suggests that the Changcheng System, with the Changcheng Group as its standard stratigraphic section, is younger than 1731 Ma. The Miyun dykes possibly have distinct petrogenesis from the subsequent anorthosite-rapakivi intrusions (1730–1680 Ma), which are thought to be responsible for the opening of the Yan-Liao rift, where the Changcheng Group was deposited. Thus it is reasonable to set the initial boundary of the Changchengian Period at 1730 Ma or slightly younger.

North China Craton, Proterozoic, Changcheng System, Yan-Liao rift system, Mafic dyke swarm, Xiong'er Group

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The Changcheng Group in the Yan-Liao rift of the North China Craton is a standard stratigraphic section of the Changcheng System. It also is one of the main geological records of the Changchengian Period, the first unit from the Mesoproterozoic identified by Chinese geologists. However, debates exist regarding the initial depositional age of the Changcheng Group (e.g. >1800 Ma or ~1950 Ma [1,2], ~1800 Ma or 1800–1750 Ma [3–6], ~1700 Ma [7]). At present, a maximum depositional age between 1800 and 1750 Ma is widely accepted. An age of ~1800 Ma is referred to as the boundary age between the Paleooproterozoic and the Mesoproterozoic in China. This age differs considerably from the boundary age of 1600 Ma as that of in the international geological time scale [8]. In this paper, we provide a new constraint on this boundary, based on dating one of the Miyun mafic dykes, which are unconformably overlain by the Changcheng Group. Characteristics of this Miyun dyke swarm are also described.

1 Regional geology and occurrence of the dykes

The study area is located around the Miyun Reservoir (Beijing) in the middle part of the northern margin of the North China Craton (Figure 1). The rocks in this area include Late Archean complexes (Miyun Complex, traditionally known as the Miyun and Sihetang Groups: constituting granulite-facies supracrustal rocks), Mesoproterozoic Changcheng System (Changcheng Group: comprising conglomerates, pebbly sandstones, sandstones, shales, quartzites, dolostones, and a few high-potassium volcanics of the Changzhougou, Chuanlinggou, Tuanshanzi and Dahongyu formations) and Jixian System (Jixian Group: dominated by carbonates), a Mesoproterozoic rapakivi granitic complex (Shachang), and a Cretaceous granitic pluton [9] (Figure 1). Among them, the Shachang Rapakivi Granite Complex has
an age of ~1680 Ma [10,11]. The volcanic layers (sills) in the Tuanshanzi Formation yield an age of ~1640 Ma [5], and volcanics in the Dahongyu Formation are dated at ~1620 Ma [4,12]. These igneous rocks, as well as the Damiao Anorthosite Complex (~1730–1690 Ma [13], ~200 km north of the study area) and some other anorthosite-syenite-alkaline intrusions [14], constitute a well-known anorogenic magmatic belt in the North China Craton [10–14]. Tectonically, the study area belongs to the western part of the Eastern Hebei Archean domain [9], or the Eastern Block classified by Zhao et al. [15], or the Central Orogenic Belt defined by Li and Kusky et al. [16,17].

The dykes cut the Archean basement and have a NE-trend of ~30° (Figure 1). The individuals have widths of over 40 m and lengths of up to 8000 m. The mineral assemblage is composed of mainly plagioclase and clinopyroxene, with gabbroic-diabasic textures. These dykes have similar petrographic characteristics, magnetic susceptibility values and orientations, and thus can be grouped as one swarm. This swarm is called the Miyun swarm herein. The dyke selected for age dating is located near the Sangyuan village, and it has a width of ~40 m (sample 07MY07). The northeast end is unconformably covered by conglomerates of the Changzhougou Formation, the lowermost formation of the Changcheng Group (inset pictures in Figure 1).

2 Methods

Baddeleyites were separated in the Department of Earth and Ecosystem Sciences, Lund University, Lund, Sweden, using a Wifley shaking table [18]. The grains were brownish, transparent, tabular, and had lengths of ~150 μm (Figure 2, inset). In total, four fractions were selected for U-Pb isotope analyses, with each one containing 10–15 grains. The analyses were completed at the Geological Survey of Canada, Ottawa, using isotope dilution thermal ionization mass spectrometry on a Triton TI instrument. The weight of the baddeleyite grains was estimated using a digital weighing program [19]. A solution of 3 mol/L HNO₃ acid was used to wash the grains. A mixture of 205Pb-233U-235U was chosen, and 48% HF and 16 mol/L HNO₃ under 240–245°C

Figure 1  Simplified geological map of the Miyun Reservoir area. Insets include a map of 1.8–1.6 Ga rift systems in the North China Craton, a diagram showing the dated dyke unconformably covered by strata of the Changcheng System, and a simplified section of the Changcheng Group.
were used to dissolve the baddeleyites. After evaporation, 3.1 mol/L HCl acid was added and heated to drive out relic HF acid after digestion. Finally, the separated Pb and U solutions were loaded on to Re film with pre-placed Si-gel.

### 3 Age results

Table 1 shows both measured and calculated U-Pb of baddeleyites of sample 07MY07. Four fractions had weights of 2.0–4.0 μg, U concentrations of 142 to 218 ppm, radiogenic Pb values of 41 to 58 ppm, and common Pb values from 2 to 5 pg. Figure 2 is the concordant diagram of the four fractions, and it reveals that they are about 0.8%–2.7% discordant. Baddeleyites sometimes show very low discordance during isotope dilution thermal ionization mass spectrometry analyses, possibly due to the overgrowth of minute amounts of zirconolite and/or zircon. Thus 207Pb/206Pb ages are usually applied [23,24]. Among the four fractions, three have 207Pb/206Pb ages of ~1731 Ma, with one of 1725 ± 3 Ma. The four fractions give an average 207Pb/206Pb age of 1731 ± 4 Ma (n = 4, MSWD = 4.8); whereas the three with close ages yielded an average 207Pb/206Pb age of 1731 ± 1 Ma (n = 3, MSWD = 1.12). As baddeleyite can generally reflect the crystallization age of magma [23], this result suggests that the dyke was intruded and solidified at ~1731 Ma.

### 4 Chemical results

The rocks belong to the tholeiitic series, and they have chemical values as follows: SiO$_2$ = 48.8 wt%–50.4 wt%, TiO$_2$ = 1.07 wt%–2.50 wt%, Al$_2$O$_3$ = 12.9 wt%–14.5 wt%, MgO = 5.4 wt%–8.2 wt%, FeO$_{t}$ (total iron) = 13.4 wt%–14.7 wt%, CaO = 9.0 wt%–10.3 wt%, Na$_2$O = 1.8 wt%–2.2 wt%, K$_2$O = 0.2 wt%–1.0 wt%, and P$_2$O$_5$ = 0.1 wt%–0.3 wt% (Table 2). Mg numbers (Mg$^+$/(Fe$^{2+}$+Mg$^{2+}$), in mol) are 51–60 (Table 2). They show weak light rare earth element enrichment (La/Yb$_{chondrite}$ = 0.8–2.8), and no Eu-anomalies (Eu/Eu$^*$ = ~1.0, Eu/Eu$^*$ = Eu$_{chondrite}$/[Sm$_{chondrite}$]$(^\text{Eu}/^\text{Sm})^{1/2}$) (normalized to chondrite [25]) (Table 2). They have distinct Ba positive anomalies, but slightly negative high-field strength element anomalies (e.g. Nb and Ta) (Figure 3(a)). $^{87}$Sr/$^{86}$Sr ($t = 1731$ Ma) values are 0.7025–0.7032 and εNd(t) ($t = 1731$ Ma) values are in the range of 2–5 (Table 3, Figure 3(b)).

### Table 1 U-Pb analytical data of baddeleyites

| Fraction | Weight (μg) | U (ppm) | Pb$^{a}$ (ppm) | $^{207}$Pb/$^{206}$Pb | $^{206}$Pb/$^{207}$U | ±1σ | ±2σ | Correlation coefficient | ±2σ | ±2σ | ±2σ | % discord |
|----------|------------|---------|----------------|----------------------|----------------------|-----|-----|------------------------|-----|-----|-----|-----------|
| B1       | 3.0        | 204     | 60             | 1845                 | 0.020                | 0.0001 | 0.03055 | 0.00003 | 0.89 | 0.10598 | 0.00008 | 1718.6 2.9 1724.4 2.3 1731.4 2.6 0.8 |
| B2       | 2.0        | 218     | 64             | 4834                 | 0.020                | 0.0003 | 0.03035 | 0.00003 | 0.88 | 0.10599 | 0.00006 | 1707.9 3.0 1718.6 2.0 1731.6 2.1 1.6 |
| B3       | 4.0        | 142     | 41             | 1753                 | 0.020                | 0.0001 | 0.02877 | 0.00009 | 0.83 | 0.10564 | 0.00008 | 1685.2 2.9 1703.2 2.3 1725.4 2.9 2.7 |
| B4       | 3.0        | 165     | 48             | 3833                 | 0.010                | 0.0001 | 0.03459 | 0.00007 | 0.91 | 0.10597 | 0.00006 | 1714.1 2.7 1721.8 2.0 1731.2 1.9 1.1 |

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$^{a}$) The isotopic ratios were corrected for blanks and measured common Pb; $^{b}$) radiogenic Pb; $^{c}$) measured ratio, corrected for spike and fractionation; $^{d}$) total common Pb in analysis corrected for fractionation and spike; $^{e}$) correlation coefficients; and $^{f}$) percent discordance.
Table 2  Whole-rock major (wt%) and trace (ppm) element data

| Sample No. | SiO₂  | TiO₂  | Al₂O₃  | FeO  | MnO  | MgO  | CaO  | Na₂O  | K₂O  | P₂O₅  | LOI(*) | Total | Mg[^b] |
|------------|-------|-------|--------|------|------|------|------|-------|------|-------|--------|--------|--------|
| 06MY11     | 50.38 | 1.08  | 12.85  | 14.2 | 0.21 | 8.19 | 10.31| 1.84  | 0.27 | 0.09  | 0.40   | 99.77  | 60     |
| 07MY07     | 50.02 | 1.07  | 13.57  | 13.4 | 0.19 | 6.64 | 10.10| 1.85  | 0.23 | 0.09  | 2.96   | 100.06 | 57     |
| 07MY12     | 49.05 | 2.50  | 13.40  | 14.7 | 0.19 | 6.05 | 9.32 | 2.18  | 0.80 | 0.26  | 1.46   | 99.92  | 52     |
| 07MY13     | 49.58 | 2.22  | 14.49  | 13.8 | 0.17 | 5.41 | 9.15 | 2.24  | 0.97 | 0.28  | 1.70   | 100.02 | 51     |
| 07MY14     | 48.80 | 2.28  | 13.62  | 14.2 | 0.19 | 6.47 | 9.02 | 2.05  | 0.99 | 0.25  | 2.02   | 99.85  | 54     |

| Sample No. | Rb  | Sr  | Ba  | Bi  | Cs  | Ga  | Ge  | Hf  | Hg  | Ho  | Hf  | La  | Ce  | Pr  | Nd  | Sm  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 07MY07     | 6.89| 126 | 88.6| 0.85| 0.19| 2.01| 66.3| 1.92 | 4.47| 0.28 | 46.2 | 297  | 168  |
| 07MY12     | 16.2| 364 | 318 | 2.15| 0.50| 4.72| 143 | 4.00 | 16.5| 1.13 | 38.5 | 380  | 178  |

| Sample No. | Co  | Ni  | Cu  | Be  | Ga  | Cs  | Bi  | Li  | La  | Ce  | Pr  | Nd  | Sm  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 07MY07     | 52.9| 82  | 109 | 0.45| 15.3| 0.28| 0.03| 4.54| 6.39| 14.4| 2.00| 9.25 | 2.72 |
| 07MY12     | 45.4| 82  | 128 | 1.05| 17.3| 0.47| 0.64| 7.67| 21.5| 47.7| 6.29| 26.0 | 5.86 |

| Sample No. | Eu  | Gd  | Tb  | Dy  | Ho  | Er  | Tm  | Yb  | Lu  | YRE | La/Yb | Eu*  |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| 07MY07     | 0.91| 3.03| 0.54| 3.53| 0.75| 2.15| 0.32| 2.09| 0.32| 18.9| 67.2 | 0.8  |
| 07MY12     | 2.02| 5.16| 0.76| 4.37| 0.84| 2.15| 0.31| 1.90| 0.27| 19.7| 145  | 2.8  |

[^a] FeOₜ = total iron; [^b] LOI = loss on ignition; [^c] Mg[^²] = Mg numbers; [^d] normalized to chondite [25]; [^e] Eu/Eu* = Eu anomalies, see text for details. See Figure 1 for sample localities.

Table 3  Whole-rock Sr-Nd isotope data[^a]

| Sample No. | Rb (ppm) | Sr (ppm) | εNd[^f] | εNd[^fR]| Nd[^f] | εNd[^f] | TDM |
|------------|----------|----------|---------|--------|--------|---------|-----|
| 07MY07     | 7.81     | 129.4    | 0.1747  | 0.70628| 0.000010| 0.70248| TDM |
| 07MY12     | 17.6     | 394.6    | 0.1264  | 0.70630| 0.000010| 0.70316| TDM |

[^a] Initial Sr and Nd isotopic ratios were calculated back to 1731 Ma.

5 Discussion

The Miyun dykes show distinct trace element patterns and Sr-Nd isotopic characteristics from the subsequent Damiao Anorthosite Complex (1730–1690 Ma) and Shachang Rapakivi Granite Complex (~1680 Ma) (Figure 3(a), (b)), representatives of the anorogenic magmatic belt in the North China Craton [10–14]. However, they have similar characteristics with the Beitai swarm, which was distributed in the central North China Craton (~1760 Ma, see definition of this swarm from references [26,27]), as well as compatible geometry [27]. In addition, the anorthosite complexes and
rapakivi granite complexes in this area show E-W elongation [28–30], rather than the NE-trend of the Miyun dykes. The above characteristics indicate that the Miyun dykes may have different source regions and stress fields from the Damiao-Shachang associations, but similar to the Beitaizui swarm. This also suggests that the Miyun dykes have had a related or the same genesis as the Beitaizui swarm, and are related to different events from the anorthosite-rapakivi intrusions.

Because the conglomerates of the Changzhougou Formation (Changcheng Group) are unconformably overlying the dated Miyun dyke, the maximum depositional age of this formation may be no earlier than ~1731 Ma. The Changcheng Group is the standard stratigraphic section of the Changcheng System [1–7]. Thus, ~1731 Ma also is the lowermost limit of this system. The Changchengian Period is the first period of the Mesoproterozoic (in Chinese literatures), and is named after the Changcheng System and related geological events [1–7]. Because the Miyun dykes recorded possibly different geological events from the anorthosite-rapakivi intrusions, which are thought to be co-genetic with the Yan-Liao rift, this ~1731 Ma age may also mark a transition of geological events. We suggest the use of 1730 Ma or a slightly younger age (e.g., ~1700 Ma [7]) as the initial boundary of the Changchengian Period.

New age data reveal that the Xiong’er Group volcanics in the Xiong’er rift in the southern of the North China Craton erupted at ~1780 Ma [31,32]. A hypabyssal body intruding the uppermost volcanic layers (Majiahe Formation) of this group indicates ages of ~1780 Ma [33], which limits the volcanism to be no younger than ~1780 Ma. Thus, the Changcheng Group is not coeval with but younger than the Xiong’er Group. As the Xiong’er and Changcheng Groups are the initial deposits in the Xiong’er and Yan-Liao rift systems, respectively, the Xiong’er Rift must have opened earlier than the Yan-Liao Rift.

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