3.6 Ga lower crust in central China: New evidence on the assembly of the North China craton

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ABSTRACT

U-Pb and Hf isotope analyses of zircons from felsic granulite xenoliths in Mesozoic volcanics reveal Early Archean (≥3.6 Ga) lower crust beneath the younger (<2.85 Ga) southern margin of the North China craton, and suggest that the eastern part of the craton formed a coherent block by 3.6 Ga. Hf model ages indicate extraction of protoliths from the mantle ca. 4 Ga or earlier, followed by remelting at 3.6–3.7 Ga. Hf isotope data require both recrystallization of magmatic zircons, and growth of new zircon, up to ca. 1.9 Ga. One sample records 2.1–1.9 Ga remelting of a 2.5 Ga protolith. If large parts of the exposed upper continental crust elsewhere also are underlain by older lower crust, estimates of crustal growth rates through time will require revision.

Keywords: North China craton, Hf isotopes, zircon U-Pb dating, lower crustal granulites, Archean crustal evolution.

INTRODUCTION

The North China craton, one of the major crustal blocks in eastern Eurasia, is made up mainly of Late Archean to middle Proterozoic rocks. Ages older than or ca. 3 Ga are found in the northernmost part (Fig. 1A), but the oldest reported ages in the southern North China craton are 2.50–2.85 Ga (Kröner et al., 1988), and the relationships between the northern and southern parts of the North China craton in Archean time are unclear. We report U-Pb ages and Hf isotope analyses of zircons in felsic granulite xenoliths from Mesozoic volcanic rocks in southern Henan Province. The data demonstrate the existence of Early Archean rocks (older than 3.6 Ga) in the southern part of the North China craton (Fig. 1A), and show that the craton's lower crust may be significantly older than its known surface rocks.

GEOLOGICAL SETTING AND SAMPLES

The basement of the North China craton consists mainly of middle to Late Archean rocks (Qianxi Group and Fuping Complex and equivalents; Jahn et al., 1987; Sun et al., 1992). Early Archean rocks, with ages to 3.8 Ga, have only been reported from eastern Hebei and northern Liaoning Provinces (Liu et al., 1992; Song et al., 1996; Fig. 1A). The craton was stabilized ca. 1.8 Ga, following collision between the Eastern and Western blocks along the Trans-North China orogen (TNCO, Fig. 1A; Zhao et al., 2000). The Yangtze Craton collided with the North China craton in Triassic time along the Qinling-Dabie Shan orogenic belt (Li et al., 1993); the suture is marked by the Xinyang-Mozitan fault (locally known as the Maoji-Hefei fault; Fig. 1B).

The Xinyang area of Henan Province is on the southern margin of the North China craton. Volcanic diatremes ~75 km north of Xinyang city (Figs. 1A, 1B) contain ultramafic to mafic breccias and minor felsic rocks, and intrude supracrustal rocks of the Proterozoic Maoji Group. K-Ar dates indicate Early Jurassic intrusion (178–206 Ma; Zheng et al., 2003).

Rare felsic granulite xenoliths in the largest diatreme (Fig. 1B, no. 7) are angular to rounded, and 10–13 cm in diameter. XY9951 and XY9928 have medium-grained granoblastic microstructures and consist of quartz (Qtz, 35% and 40%, respectively) + plagioclase (Pl, 50% and 44%, $An_{19–26}$) + potassium feldspar (Kfs, 11%, $Or_{84–94}$ $Ab_{6–16}$) + clinopyroxene (Cpx, 5% and 6%). XY9971 has a fine-grained granoblastic microstructure and consists of Qtz (39%) + Pl (39%, An_{26}) + Kfs (13%, $Or_{86}Ab_{14}$) + garnet (Grt, 5%, $Alm_{61}Pyr_{19}Grs_{17}Spe_3$) + Cpx (3%). Clinopyroxene is diopside with ≤1.5 wt% Na_2O. Pyroxene and garnet generally occur as aggregates interpreted as the breakdown products of amphibole and/or biotite. From studies of mafic xenoliths in this pipe, Zheng et al. (2003) concluded that the Mesozoic lower crust consisted of high-pressure granulite and minor eclogitic rocks extending to 41–56 km depth. Estimated pressure-temperature conditions for XY9971 are 740 °C and 9.3 kbar (Ellis and Green, 1979; Newton and Perkins, 1982); these limited data suggest that the felsic granulites are part of this lower crustal section.

Sample XY9928 was too altered for whole-rock analysis. The other two samples (Table DR1[1]) have compositions similar to calc-alkaline igneous rocks, with high SiO_2 and $K_2O + Na_2O$, low CaO + MgO, and negative Eu anomalies. On a plot of Al_2O_3-CaO + Na_2O-K_2O they lie on the join between plagioclase and K-feldspar and within the field of typical igneous rocks. Primitive-mantle-normalized trace-element patterns show negative anomalies in Nb, Ta, P, and Ti, and positive anomalies in K, Ba, Th, Zr, and Hf.

ANALYTICAL METHODS

Zircons were separated by heavy-liquid and magnetic methods. Backscattered-electron

[1]GSA Data Repository item 2004036, Table DR1, xenolith analyses, and Table DR2, zircon U-Pb and Hf isotope data, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

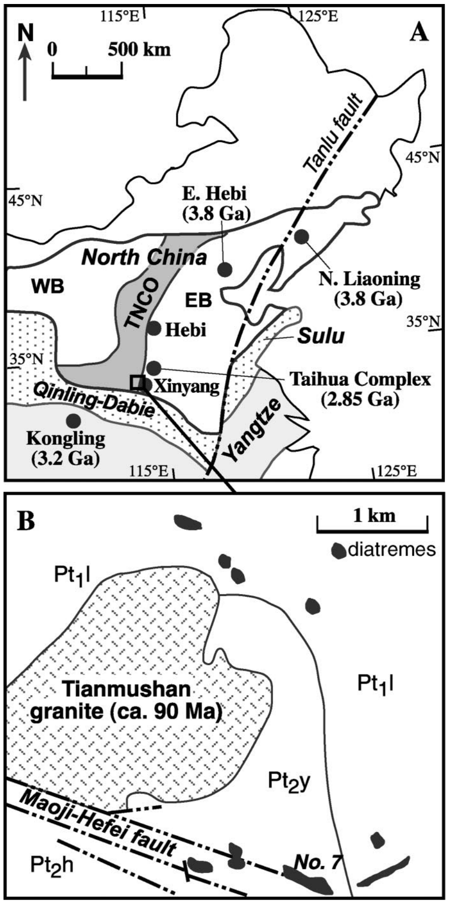

Figure 1. A: Major tectonic units and ages of some Archean rocks in eastern China. WB and EB—west and east blocks of North China craton; TNCO—Trans-North China orogen. Data sources for Archean basement rocks: eastern Hebei, Liu et al. (1992); northern Liaoning, Song et al. (1996); Taihua Complex, Kröner et al. (1988); Kongling Complex, Qiu et al. (2000). Location of map B is shown to northwest of Xinyang. B: Xinyang Mesozoic volcaniclastic diatremes. Maoji-Hefei fault defines part of boundary of North China craton and Qinling-Dabie orogenic belt. Pt_1l, Pt_2y, and Pt_2h are Proterozoic country rocks of Liuzhuang, Yindonggou, and Huilongshi Groups, respectively. No. 7—largest diatreme.

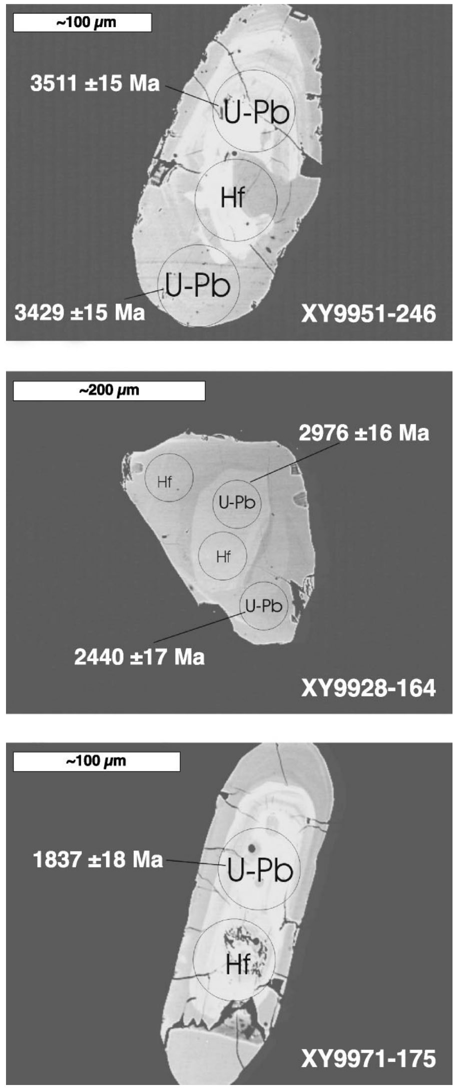

Figure 2. Representative images of zircon morphology and internal structure; circles show positions for laser ablation microprobe–inductively coupled plasma–mass spectrometer (LAM-ICPMS) and LAM-MC-ICPMS analyses (presented in Table DR2; see footnote 1). MC is multicollector.

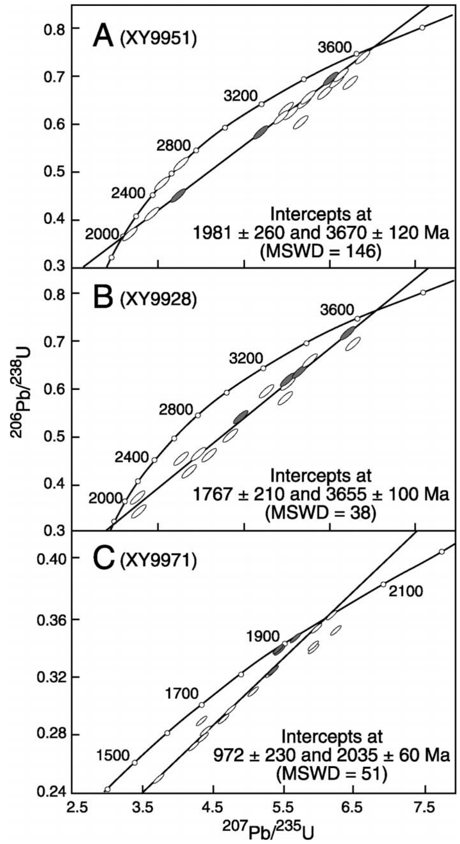

Figure 3. Concordia plots of U-Pb results for Xinyang felsic granulite zircons. MSWD—mean square of weighted deviates.

(BSE-cathodoluminescence [CL]) images taken using a Cameca SX-50 electron microprobe at GEMOC were used to define the internal structures of the grains (Table DR2; see footnote 1) and to select analysis positions (Fig. 2).

In situ U-Pb dating of zircons by laser ablation microprobe–inductively coupled plasma–mass spectometer (LAM-ICPMS) was carried out at GEMOC (Belousova et al., 2001; Jackson et al., 2003). U-Pb dating of single zircons by thermal ionization mass spectrometry (TIMS) was done at the Tianjin Institute of Geology and Mineral Resources, China, using the procedures of Krogh (1982), and a VG-354 TIMS. In situ Hf isotope analyses were done with a Merchantek LUV213 nm laser-ablation microprobe, attached to a Nu plasma multicollector ICPMS (Griffin et al., 2000). The calculation of Hf model ages based on a depleted-mantle source follows Griffin et al. (2000), using the ^{176}Lu decay constant of Blichert-Toft et al. (1997); the conclusions discussed here are not significantly affected by using the alternative values of Bizzarro et al. (2003) or Scherer et al. (2001).

RESULTS

U-Pb Ages

Zircons in XY9951 are transparent, light purple, and 120–250 μm long; forms range from short prismatic to rounded, with mean length/width = 1.4 (Table DR2; see footnote 1). About one-third of the zircons have cores with internal zoning, ranging from clearly oscillatory to irregular, enclosed by an unzoned rim (Fig. 2A); the other two-thirds are structureless. The zircons fall into two groups; one is concordant to mildly discordant, and has $^{207}Pb/^{206}Pb$ ages of 3450–3650 Ma, and the other scatters along or near the concordia between 2850 Ma and 1850 Ma (Fig. 3A). Two TIMS analyses fall in the older group and one in the younger group. Two grains have cores significantly older than their rims (by 98–173 m.y.). Five older grains give a weighted mean $^{207}Pb/^{206}Pb$ age of 3596 ± 26 Ma (95% confidence, mean square of weighted deviates [MSWD] = 1.7); one older grain (3687 ± 30 Ma) with well-preserved oscillatory zoning may indicate that the mean age is a minimum age for magmatic crystallization. The TIMS analyses define a discordia with intercepts of 3578 ± 54 Ma and 1935 ± 140 Ma; the LAM data group around this line, but show a larger scatter, especially in the younger group (lower intercept of 1981 ± 260 Ma).

Zircons in XY9928 are transparent, light yellow to colorless, and 60–150 μm long; forms range from long prismatic to round with mean length/width = 2.1. Half of the analyzed zircons have relict oscillatory or irregular zoning. The LAM analyses scatter along a discordia with intercepts of 3655 ± 100 Ma and 1767 ± 210 Ma (Fig. 3B); the TIMS analyses lie on this line. The oldest and most nearly concordant grains show relict zoning; the most discordant grains tend to be structureless.

Zircons in XY9971 are transparent, colorless to light yellow, and 80–170 μm long; forms range from long well-developed crystals to rounded, with mean length/width = 2.9: ~85% show internal zoning ranging from oscillatory to lamellar or irregular. Most of the data scatter around a discordia with intercepts of 2035 ± 60 Ma and 972 ± 230 Ma (MSWD = 54, Fig. 3C). There are 12 LAM analyses and 4 TIMS analyses that define age peaks at 1900 Ma, 1950 Ma, and 2050 Ma. The four oldest grains all have relict zoning, whereas most of the 1930–1950 Ma grains are structureless. The weighted mean $^{207}Pb/^{206}Pb$ age of 2050 ± 43 Ma (95% confidence, MSWD = 2.2) for the four oldest grains may give the best estimate of a magmatic age.

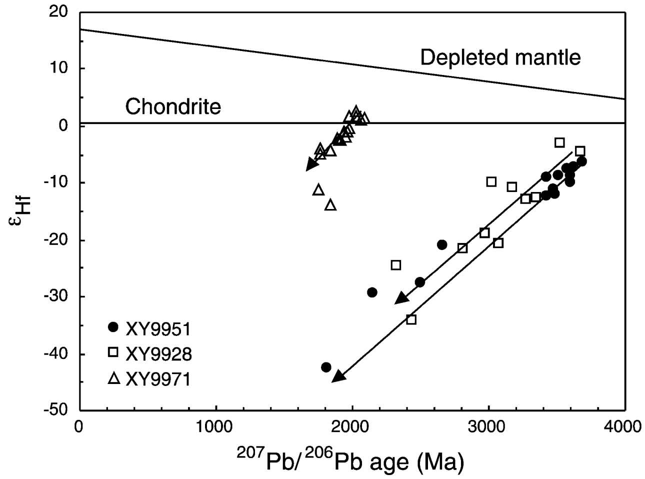

Figure 4. U-Pb age vs. ε_{Hf} for Xinyang zircons. Samples with similar Hf isotope compositions but different ages, reflecting recrystallization and/or Pb loss, will lie along evolution lines indicated. Zircons above such line have more radiogenic Hf than primary zircons, and probably grew from Zr + Hf liberated from higher Lu/Hf phases during metamorphism.

Hf Isotope Data

The in situ Hf isotope analyses (Table DR2; see footnote 1) help to constrain the interpretation of the U-Pb data. Resetting of a zircon's U-Pb age by recrystallization and Pb loss is unlikely to affect its Hf isotope signature, since zircon is the major reservoir for Hf in felsic rocks. However, new zircon that grows after magmatic crystallization can inherit isotopically different Hf that reflects the ingrowth of radiogenic ^{176}Hf over the intervening time, in phases with higher Lu/Hf than the zircons.

In XY9951, 9 of the 10 zircons with $^{207}Pb/^{206}Pb$ ages older than 3.4 Ga have $^{176}Hf/^{177}Hf$ within error of the mean (0.28027 ± 0.00006; 2 s.d.), suggesting that their range in age (3687–3429 Ma) represents the episodic recrystallization of a single population of magmatic zircons, as reflected in the BSE-CL images (Fig. 2A). One 3425 Ma grain, and others with ages of 2.7–2.1 Ga, have higher $^{176}Hf/^{177}Hf$, which suggests that they grew in younger thermal events, from zircon that previously resided in mafic silicates or oxides. Two of these younger zircons have concordant U-Pb ages (2478 Ma, 2660 Ma). The youngest zircon (1808 Ma) has $^{176}Hf/^{177}Hf$ similar to the 2.5–2.7 Ga grains, and may reflect Pb loss from this population (Fig. 4). In sample XY9928, a wide scatter in ε_{Hf} at each age suggests the episodic growth of new zircon. Two zircons (2440 Ma and 2976 Ma) have $^{176}Hf/^{177}Hf$ similar to that of the oldest grains, and may reflect recrystallization and complete Pb loss at these times. The ingrowth of radiogenic ^{176}Hf in these two samples can be produced by a matrix with a mean $^{176}Lu/^{177}Hf = 0.009$. This low value is consistent with the felsic nature of the rocks, which have calculated $^{176}Lu/^{177}Hf = 0.010$–$0.012$ (Table DR1; see footnote 1).

The negative ε_{Hf} values of the oldest zircons in XY9951 and XY9928 indicate a significant prehistory for the protoliths of the felsic magmas. The minimum protolith age, assuming derivation from a depleted-mantle source, is given by the ca. 3.9 Ga model ages (T_{DM}, or mantle extraction age) of the zircons (Table DR2; see footnote 1). If the protolith had the $^{176}Lu/^{177}Hf$ of the average continental crust (0.015; Griffin et al., 2002), its T_{DM} is closer to 4 Ga.

In sample XY9971, all but two of the zircons have $^{176}Hf/^{177}Hf$ values within error of the mean (0.28155 ± 0.00005; 2 s.d.). This homogeneity suggests that the range in $^{207}Pb/^{206}Pb$ ages (2085–1763 Ma) reflects episodic recrystallization and Pb loss, rather than the growth of new zircon; this is consistent with the discordant nature of the younger zircons. Two grains with significantly lower $^{176}Hf/^{177}Hf$ may preserve evidence of an older population. The oldest zircons have $\varepsilon_{Hf} > 0$, and a T_{DM} of ca. 2.3 Ga. If the protolith had an average crustal composition, its T_{DM} is closer to 2.45 Ga.

DISCUSSION

Evolution of the Lower Crust in the Xinyang Area

The Xinyang zircons record a long and complex history for the lower crust beneath the southern edge of the North China craton. The protoliths of samples XY9951 and XY9928 were extracted from the mantle at least 3.9–4 b.y. ago, and were remelted at 3.6–3.7 Ga, as reflected in the upper-intercept ages of both samples. The U-Pb and Hf isotope data indicate that partial recrystallization of primary zircons, and growth of new zircon, continued sporadically up to Late Archean time, and probably well into the early Proterozoic. Unless metasomatism introduced new Hf from more primitive sources, zircon growth must have involved the breakdown of preexisting silicates and oxides, with the liberation of zircon and radiogenic Hf.

Sample XY9971 may represent a middle Proterozoic (2.1–1.9 Ga) addition to the crust, but the protolith of this felsic rock also could be as old as 2.5 Ga. The 2.1–1.9 Ga age corresponds to continental collision in the Trans-North China orogen (Fig. 1A). The discordia defined by the zircons in this sample does not correspond to zero-age Pb loss, which suggests that younger thermal events also have affected the lower crust in the area.

Wilde et al. (2003) presented zircon ages for lower-crustal xenoliths in the Cenozoic (22–10 Ma) Hannuoba basalts on the north end of the Trans-North China orogen. Many samples recorded Precambrian and Paleozoic ages, but all were dominated by Mesozoic ages (180–80 Ma), interpreted as reflecting magmatic events associated with the loss of mantle lithosphere during Gondwana dispersal. The Xinyang samples were erupted before this event, and thus do not record it (Table DR2; see footnote 1), while the absence of Paleozoic ages suggests that these events may have been restricted to the northern edge of the North China craton.

These samples illustrate that lower-crustal xenoliths can record multiple events in the form of different zircon populations (cf. Rudnick and Williams, 1987; Chen et al., 1994, 1998; Wilde et al., 2003). The interpretation of such age populations in terms of process is commonly ambiguous, but the in situ Hf isotope analysis of the zircons provides a basis for more detailed interpretation of the U-Pb ages; this is a powerful new tool for investigating crustal evolution.

Crustal Evolution of the North China Craton

Late Archean (2800–2600 Ma) tonalite-trondhjemite-granodiorite (TTG) gneisses make up more than 80% of the exposure in the eastern block of the North China craton. The oldest basement rocks include 3.8 Ga tonalitic and granitic gneiss (Song et al., 1996; Liu et al., 1992) in eastern Liaoning Province, 3.8 Ga metaquartzite (Liu et al., 1992) and 3.5 Ga and 2.7 Ga amphibolite (Jahn et al., 1987;

Jahn and Ernst, 1990) in eastern Hebei Province, and 2.7 Ga TTG gneisses and amphibolite in Shandong Province (Jahn et al., 1987). The positive ε_{Nd} (+2.7) of 3.5 Ga amphibolites from eastern Hebei implies an earlier depletion event, and thus the possible existence of sialic crust prior to 4 Ga (Jahn et al., 1987). Archean rocks in the eastern block underwent widespread upper amphibolite to granulite facies metamorphism at 2500–2600 Ma (Jahn and Zhang, 1984); the early Proterozoic rocks underwent lower grade metamorphism ca. 1800 Ma (He and Ye, 1998).

The oldest known basement (Taihua Complex) in the southern North China craton has magmatic U-Pb zircon ages of 2.50–2.85 Ga (Kröner et al., 1988). The basement of the Trans-North China orogen includes Late Archean mafic metavolcanics, TTG gneisses and granites, and early Proterozoic metavolcanics and metasedments (Liu et al., 1985). Recent zircon dating of the Fuping Complex in the Trans-North China orogen (Wilde et al., 1998) defined two age groups (2700–2500 Ma, 2000–1800 Ma), interpreted as the protolithic and metamorphic ages (Guan et al., 2002).

Previous records of crustal rocks $\geq$3 b.y. old thus are confined to the far northern part of the North China craton. Our documentation of crust $\geq$3.6 b.y. old in the southern part of the North China craton suggests that the North China craton, east of the Trans-North China orogen, may have formed a coherent block by 3.6 Ga. Reworking and magmatism of the North China craton may have obscured its Early Archean origins, but the xenoliths described here provide a window into the relict ancient crust.

The presence of 3.6 Ga lower crust beneath significantly younger Archean and Proterozoic crust in the North China craton suggests that large volumes of the exposed upper crust in other regions also may be underlain by a preexisting, and still preserved, lower crust. In this case, ancient lower crust could be more widespread in the continents than commonly recognized, and measurements of crustal growth rates based on surface geology would require revision to allow for a higher rate of crustal growth in the Early Archean. This would have implications for the mechanisms of continental growth and lithosphere evolution through time, and for geochemical models.

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