Protoliths of enigmatic Archaean gneisses established from zircon inclusion studies: case study of the Caozhuang quartzite, E. Hebei, China

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Abstract

A diverse suite of Archaean gneisses at Huangbaiyu village in the North China Craton, includes rare fuchsite-bearing (Cr-muscovite) siliceous rocks - known as the Caozhuang quartzite. The Caozhuang quartzite is strongly deformed and locally mylonitic, with silica penetration and pegmatite veining common. It contains abundant 3880-3600 Ma and some Palaeoarchaean zircons. Because of its siliceous nature, the presence of fuchsite and its complex zircon age distribution, it has been until now been accepted as a (mature) quartzite. However, the Caozhuang quartzite sample studied here is feldspathic. The shape and cathodoluminescence petrography of the Caozhuang quartzite zircons show they resemble those found in immature detrital sedimentary rocks of local provenance or in Eoarchaean polyphase orthogneisses, and not those in mature quartzites. The Caozhuang quartzite intra-zircon mineral inclusions are dominated by quartz, with lesser biotite, apatite (7%) and alkali-feldspar, and most inclusions are morphologically simple. A Neoarchaean orthogneiss from near Huangbaiyu displays morphologically simple inclusions with much more apatite (73%), as is typical for fresh calc-alkaline granitoids elsewhere. Zircons were also examined from a mature conglomerate quartzite clast and an immature feldspathic sandstone of the overlying weakly metamorphosed Mesoproterozoic Changcheng System. These zircons have oscillatory zoning, showing they were sourced from igneous rocks. The quartzite clast zircons contain only rare apatite inclusions (<1%), with domains with apatite habit now occupied by intergrowths of muscovite + quartz ± Fe-oxides ± baddeleyite. We interpret that these were once voids after apatite inclusions that had dissolved during Mesoproterozoic weathering, which were then filled with clays ± silica and then weakly metamorphosed. Zircons in the immature feldspathic sandstone show a greater amount of preserved apatite (11%), but with petrographic evidence of replacement of other apatites by quartz and mica. From the zircon morphology and inclusions studies, our studied Caozhuang quartzite is most likely a <3500 Ma immature detrital sedimentary rock of local provenance. This strengthens the case for Eoarchaean rocks with a substantial 3880-3800 Ma component occur close to Huangbaiyu.

Key words: North China Craton; Caozhuang quartzite; Zircon inclusions; Eoarchaean rocks; Archaean crustal evolution
1. Introduction

The world’s oldest rocks (>3600 Ma) are all in gneiss complexes, where their protoliths have been modified usually to a great degree by superimposed ductile deformation and high-grade metamorphism (e.g., Nutman, 2006; Nutman et al., 2007; Horie et al., 2010). These ancient crustal remnants are mostly quartzo-feldspathic gneisses, ranging in composition from tonalite (dominant) to granite. They are important resources to understand the earliest terrestrial processes, before Earth was 1 billion years old. Due to their generally highly modified state, early Earth information via these rocks is extracted by sophisticated, small-scale geochemical methodologies, with an ever-increasing focus on zircons. The reason for the zircon focus is that they are the only mineral that survives without total recrystallisation during often repeated superimposed cycles of ductile deformation and metamorphism (e.g., Nutman et al., 2000, 2007; Izuka et al., 2007). Thus via hafnium radiogenic isotopes, and oxygen stable isotopes (e.g., Valley et al., 2005; Wu et al., 2008; Hiess et al., 2009, 2010; Kemp et al., 2010; Wan et al., 2013), ancient zircons provide direct information on the early Earth, via a substance were domains have not recrystallised since they formed several billion years ago.

The abundance of zircon isotopic data on ancient quartzo-feldspathic rocks occurred subsequent to a late 1960s major re-interpretation of these rocks. Previously, since the dispute between George Barrow on one hand and Benjamin Peach and John Horne on the other at the dawn of the 20th century, ancient (Archaean) banded grey gneisses were largely regarded as having predominantly sedimentary protoliths. However, field observations by the late Vic McGregor in the Nuuk region of Greenland (McGregor, 1973) demonstrated that the majority of these rocks are strongly deformed, polyphase, metaplutonic rocks. McGregor noted strain gradients where small domains preserving cross-cutting plutonic relationships and even igneous textures could be traced into regional strongly banded rocks. Thus from the 1970s onwards there has been a tendency to regard all Archaean banded gneisses as having plutonic rather than sedimentary protoliths.

An exception to this general rule has been to regard high-grade gneisses containing fuchsite (Cr-muscovite) as metasedimentary rocks. These rocks generally contain complex zircon age populations, and thus their major provenance has been regarded as complex older ‘continental’ crust plus the fuchsite derived from chromite sourced from mafic igneous rocks (e.g., Kinny et al., 1988). A case in point regarding such rocks is the Caozhuang quartzite, near Huangbaiyu village, in the North China Craton (NCC) approximately 200 km east of Beijing (Fig. 1). Since the early 1990s it has been recognised that this fuchsitic lithology
carries an inventory of ancient zircons, with ages ranging from ~3550 to 3880 Ma (Liu et al., 1992, 2007; Wu et al., 2005; Wilde et al., 2008; Nutman et al., 2011). Consequently, it has generally been regarded as a €"3550 Ma Archaean sedimentary rock carrying material derived from ancient continental crust. In this paper we examine this presumption, by looking in detail at the inventory of silicate, oxide and phosphate inclusions within both Caozhuang quartzite zircons and zircons from Neoarchaean orthogneisses and unconformable Mesoproterozoic greenschist facies detrital quartzites in the vicinity.

We use the method developed by Rasmussen et al. (2011) to understand the origin and significance of mineral inclusions within Hadean zircons from the Jack Hills quartzite of Western Australia. These zircons have a very low abundance of apatite inclusions compared with ‘fresh’ magmatic zircons in calc-alkaline igneous rocks. Rasmussen et al. (2011) presented an explanation for low apatite abundance in some zircon populations. In their study they compared and contrasted inclusion suites in several Archaean granitoids and orthogneisses, a non-metamorphosed Carboniferous sandstone and the Jack Hills of Western Australia metamorphosed quartzite. In the Carboniferous sandstone they recorded that most apatite inclusions in zircons of igneous origin had been removed by dissolution – along microfractures, to leave voids that became filled with mixtures of very fine grained clay minerals ± silica (Fig. 2). Upon metamorphism, as experienced by the Jack Hills detrital zircons, these infills were recrystallized to give inclusions suggestive to growth of the zircons from very low temperature ‘S-type’ melts derived from melting of sedimentary sources (Fig. 2). In fact, as pointed out by Rasmussen et al. (2011) this is an illusion, caused by the modification of the detrital zircon suite in surficial environments. Thus low abundance of apatite inclusions in zircons plus an increase of polymineralic inclusions unlikely to have developed from silicate melts (e.g. such as baddeleyite + muscovite as found in some of the zircons forming part of our study) can be used as an indicator that zircons have passed through a cycle of weathering and sedimentary transport.

Based on our data and the methodology of Rasmussen et al. (2011) we contend that the best interpretation of the studied Caozhuang quartzite sample (J06/01) is that its protolith was an immature (feldspathic) Archaean sedimentary rock derived from local ancient rocks. This interpretation strengthens the case that in the Huangbaiyu area there is ancient crust that contains a substantial ≥3850 Ma component, and as such would be the oldest in China. Also explored is a less favoured interpretation that the sample of the quartzite is actually a >3500 Ma orthogneiss that has been variably-weathered in the Precambrian.
2. Geological overview of the eastern North China Craton, eastern Hebei

2.1. Regional setting

In eastern Hebei Province, east of Beijing (Fig. 1) early Archaean rocks and zircons have been reported (e.g., Jahn et al., 1987; Liu et al., 1992, 2007; Wu et al., 2005; Wilde et al., 2008; Nutman et al., 2011) but are extremely limited in extent and poorly preserved due to their reworking in subsequent tectonothermal events and their inclusion in younger granitoids. Neoarchaean rocks are extensive, making up >95% of the eastern Hebei NCC basement. These are predominantly 2600-2500 Ma gneisses and deformed granitoids with lesser amounts of supracrustal rocks (e.g. Jahn et al., 1987; Kröner et al., 1988, 1998; Jahn and Ernst, 1990; Wang et al., 1990; Fang et al., 1998; Geng et al., 2006; Yang et al., 2008; Nutman et al., 2011). Strong ductile deformation throughout much of the NCC means that most rocks are foliated, and earlier magmatic, volcanic and sedimentary structures were largely obliterated. Most lithological contacts are now parallel to this foliation, and it is only in rare instances that intrusive contacts and volcanic and sedimentary structures can be recognised. Weakly foliated pink granite bodies up to several tens of metres across intrude all the rock types mentioned above. In the west, there is widespread occurrence of ~2500 Ma granulite facies metamorphism (e.g., Compston et al., 1983; Fang et al., 1998; Nutman et al., 2011), but in the east granulite facies metamorphism is rarer (Yang et al., 2008; Nutman et al., 2011).

2.2. Geology of the Huangbaiyu area

The Qianxi Complex of the Qian’an-Huangbaiyu region is a diverse suite of amphibolite to granulite facies gneissic rocks, all Archaean in age (Liu et al., 1990; Wang et al., 1990; Nutman et al., 2011). Near Huangbaiyu village (Fig. 1), the Caozhuang quartzite occurs with larger volumes of biotite-rich schists (known as ‘leptynites’, that are generally interpreted as sedimentary rocks derived from intermediate to felsic volcanic sources – e.g., Liu (D.Y.) et al., 1990; Liu (S.J.) et al., 2013). Associated with the leptynites are disrupted lenses up to 500 m long and 100 m broad of magnetite-bearing banded iron formation and also bodies of tonalitic orthogneisses with SHRIMP U-Pb zircon ages up to 3287 Ma and also ca. 2936 Ma granitic orthogneisses (Fig. 1; Nutman et al., 2011). All these lithologies are infiltrated by ~2500 Ma pegmatite and granite, which was generally been strongly-deformed under amphibolite facies conditions. Strain is particularly strong in the zone that coincides with the Caozhuang quartzite. Consequently, there are no original contacts
preserved between the leptynites, Caozhuang quartzite, banded iron formations and the 3287-2936 Ma orthogneisses. In the Huangbaiyu area, the boundary between domains affected by ~2500 Ma granulite facies metamorphism and those that were not lies in a zone of strongly deformed rocks along with the Caozhuang quartzite (Fig. 1).

The Archaean gneisses are overlain unconformably by sedimentary rocks belonging to the Mesoproterozoic Changcheng System (Wan et al., 2003 and references therein). These rocks were metamorphosed under (low) greenschist facies conditions and weakly deformed, such that they now dip to the south and west at moderate to steep angles. The lower part of the Changcheng System is dominated by detrital sandstones, and near its base in the Huangbaiyu area there are conglomerates, in which the clasts consist of quartzite.

3. Analytical methods

The detailed examination of the zircon inclusion suites were undertaken on zircon mounts previously prepared for SHRIMP U-Pb zircon geochronology (Nutman et al., 2011). Identification of mineral inclusions exposed at the surface of these zircon mounts was from cathodoluminescence (CL) and reflected light images. Using a Hitachi scanning electron microscope (SEM), Back-Scatter-Electron (BSE) images of the identified grains were acquired, and the phases were identified by energy dispersive spectrometry (EDS).

With the inclusions mapped and identified, the BSE images were loaded into ESRI ArcGIS software at the Spatial Laboratories of the School of Earth & Environmental Sciences at the University of Wollongong, and the areal extent of the different inclusion phases present was quantified. Given the large sample set, we consider that it is a reasonable assumption that the areal proportions correspond to volumetric proportions. Subsequently, these were converted into percentages of the phases. Although no doubt not entirely accurate, this approach does at least lead to a semi-quantitative assessment of the phases present.

4. Neoarchaean orthogneiss

4.1. Geological description, composition and petrography

Sample J06/10 is from a ~1m wide kernel of non-retrogressed granitic granulite facies orthogneiss (Fig. 3A; at 40°04.47’N; 118°34.46’E [WGS84 datum]), in migmatites consisting of orthogneiss and amphibolite lenses within foliated granite (Fig. 1; Nutman et al., 2011). All these rocks show evidence of previous granulite facies metamorphism by hornblende ± biotite replacements after orthopyroxene grains, and more rarely relict
orthopyroxene, particularly in mafic rocks. Analyses of J06/10 high Th/U oscillatory zoned magmatic zircon that dominates the grains yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2548±7 Ma (MSWD=0.8), whereas exterior structureless metamorphic domains bright in CL images yielded a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2506±6 Ma (MSWD=0.6). 2548 Ma is interpreted as the age of the protolith and 2506 Ma as the timing of granulite facies metamorphism (Nutman et al. 2011). Both these protolith and high grade metamorphism ages are common in the Archaean basement of eastern Hebei (e.g., Geng et al., 2006; Yang et al., 2008; Nutman et al., 2011).

4.2. Zircon inclusion suite

J06/10 zircon inclusions are overall structurally simple (Fig. 4). Integration of the reconnaissance cathodoluminescence imaging undertaken prior to SHRIMP U-Pb analysis (Nutman et al., 2011) and the BSE imaging undertaken for this study indicates that this inclusion suite resides primarily in the oscillatory igneous zircon. The most important phases are apatite (73%), quartz (11%), alkali-feldspar (9%) and biotite (7%; Fig. 5A). Also present at <1% are xenotime and amphibole. Most inclusions are mono-mineralic (Fig. 4A), but there are also composite inclusions of biotite ± quartz ± alkali-feldspar (Figs. 4B,C,D). Most mineral inclusions are euhedral, indicating they represent earlier-crystallised phases overgrown by later-crystallised zircon. In the case of the biotite + quartz + alkali-feldspar inclusion shown in Fig. 4D, it might be a globular melt inclusion that crystallised as quartz + alkali-feldspar grown around two biotite laths. Of note is the lack of plagioclase inclusions in the zircons, which are common inclusions in zircons grown from tonalitic magmas (Nutman and Hiess, 2009). The lack of plagioclase inclusions is likely related to the more granitic composition of J06/10. Of note is that despite granulite facies metamorphism, the inclusion suite with the high content of apatite is similar to that found in non-metamorphosed plutonic rocks (Rasmussen et al., 2011). This suggests that high grade metamorphism does not significantly change inclusion suites in igneous zircons, particularly apatite being the dominant phase.

5. Mesoproterozoic Changcheng System low-grade detrital sedimentary rocks

5.1. Geological description, composition and petrography

In the Huangbaiyu area the lower part of the Changcheng System is dominated by detrital sandstones, and near its base there are conglomerates, in which the clasts consist of
quartzite (Fig. 3B). A quartzite clast (J06/09) and a less-mature feldspathic sandstone
(J06/06) were chosen for zircon studies, because they are Huangbaiyu area rocks in which
the zircons were undoubtedly detrital, and that had to different degrees experienced
Precambrian weathering and surficial transport cycles. In this way, their inclusion suites
would be useful to compare between those of J06/10 (a fresh orthogneiss) and those in
J06/01 Caozhuang quartzite zircons. Study of the J06/06 and -09 zircons was undertaken on
grains already mounted and CL-imaged, but upon which U-Pb dating has not been
undertaken.

5.2. Zircon inclusion suites

The J06/09 quartzite clast zircons are generally oval due to abrasion in
sedimentary systems, and CL images show that their internal structures such as
igneous oscillatory zoning is commonly truncated at grain exteriors (Fig. 6A). As
such, they are a population of zircons typical of those found in mature detrital
quartzites (e.g., Cavosie et al., 2006; Nutman et al., 2008). The most important
inclusion phases in the zircons are quartz (73%), muscovite and/or illite (11%),
alkali-feldspar ± illite (9%), Fe-oxides (6%), biotite (1%) and then all at <1% Fe-Ti
oxides, baddeleyite, albite and apatite (Fig. 5B). Thus modally this mineral inclusion
suite is very different from that encountered in nearby Neoarchaean orthogneiss
J06/10, with most striking being the apatite abundance (<1% versus 73%). Only a
few of the inclusions are mono-mineralic, and where they occur they are mostly
quartz. There are a few other instances of mono-mineralic inclusions, for example
very rare apatite (Fig. 7E) or alkali-feldspar (Fig. 7D). Instead, most inclusions are
poly-mineralic. Some consist of quartz + biotite ± Fe-Ti oxides (Fig. 7C). However,
many of the poly-mineralic inclusions have an apatite habit (e.g., Fig. 7A; consisting
of muscovite and/or illite + quartz), suggesting that apatite has been replaced by the
poly-mineralic silicate assemblages. In some cases acicular baddeleyite occurs on the
edge of the inclusions (Fig. 7B). This petrographic evidence is consistent with
dissolution of apatite (via surficial waters along microfractures; Rasmussen et al.,
2011) and then infill by other mineral phases followed by low grade metamorphism.

The J06/06 feldspathic sandstone zircons are only slightly rounded and CL
images show that their internal structures such as igneous oscillatory zoning is
generally more or less parallel to the grain exteriors (Fig. 6B). The much lesser
degree of rounding and truncation of internal features compared with the J06/09
quartzite zircons limited sedimentary transport and abrasion. The most important
inclusion phases are quartz (33%), muscovite and/or illite (40%), alkali-feldspar ±
illite (16%), apatite (11%) and biotite (<1%; Fig. 5C). There is much more apatite
preserved in the zircons of this less mature sedimentary rock than in mature quartzite
clast J06/09 (Fig. 8A; 11% versus <1%), but it is still considerably less than the 73%
in fresh orthogneiss J06/10 zircons, or as found in other Archaean granitoids
(Rasmussen et al., 2011). There are bi-mineralic inclusions of quartz + muscovite
with the habit of apatite (Fig. 8B), which might be occupying voids once filled by
apatite. Other mono-mineralic inclusions are quartz, alkali feldspar (Fig. 8C) and rare
biotite. Some irregular-shaped inclusions consist of quartz + muscovite and/or altered
alkali feldspar (Fig. 8D) and could represent altered melt inclusions.

6. Caozhuang quartzite

6.1. Geological description, composition and petrography

The Caozhuang quartzite crops out near Huangbaiyu village (Fig. 1). It contains some
fuchsitic mica, but ordinary muscovite is more common. Although portions of the
Caozhuang quartzite are very quartz rich, the sample J06/01 investigated here is quartzo-
feldspathic, rather than being a pure quartzite. In thin section plagioclase grains occur as
porphyroclasts, partly altered to epidote, white mica and quartz, residing in a layered
granular matrix in which quartz commonly forms ribbons (Fig. 3C). Within the J06/01
Caozhuang quartzite are lenses and veins of course-grained pegmatite, and also pods of
altered (mica-bearing) amphibolite. These can also carry fuchsitic mica. Clearly, the protolith
of the Caozhuang quartzite was not a homogeneous mature quartzite, but instead contains
layers of quartzo-feldspathic rock, for which an arkosic sedimentary or an orthogneiss
protolith are feasible.

6.3. Zircon morphology and age

Sample J06/01 (39°56.007’N; 118°33.499’E) yielded abundant zircons, of overall
slightly rounded euhedral prismatic habit (Fig. 6C). Igneous oscillatory zoning is
widespread. In most grains with high contrast in CL images, this layering is widely disrupted
by recrystallisation domains and can be truncated near grain margins by domains that appear
brighter and less structured in CL. However, in most cases the oscillatory zoning is broadly
concordant to the exterior of the grains (Fig. 6C), unlike is generally found in for detrital
zircons from mature quartzites (e.g., Cavosie et al., 2006; Nutman et al., 2008). A large minority of the grains are dull in CL images, but nonetheless low-contrast oscillatory zoning can be discerned. In such grains the zoning is also generally concordant to the grain exteriors (e.g., grains 36 and 42, Fig. 6C). SHRIMP U-Pb zircon ages determinations were undertaken on 56 grains (Nutman et al., 2011). The grains with higher contrast in CL images and lower U+Th contents gave ages between 3880-3640 Ma (Nutman et al., 2011). The grains that appear duller in CL images have higher U+Th contents and thus tended to give discordant ages due to greater radiation damage. However, a minority yielded concordant ages of ~3550 Ma (Nutman et al., 2011). The zircons do not show the degree of rounding and truncation of internal structures that would be expected if the protolith was a mature quartzite (compare Figs. 6A and C).

6.3. Zircon inclusion suites

The zircon inclusion suite in J06/01 is quartz 59%, biotite 10%, alkali feldspar 12%, apatite 7%, muscovite and/or chlorite 4%, monazite 2% and other accessory minerals including baddeleyite totalling 6% (Fig. 5D). There is a greater occurrence of inclusions in the stubby prismatic grains with dull oscillatory zoning which where dated belong to the ~3550 Ma population. These include monazite (monaz) and baddeleyite (Fig. 9A); these phases are not found in grains that appear bright in CL, of the type that have yielded >3600 Ma ages. There are some apatite inclusions (e.g., Fig. 9B), but these are much less abundant than the >50% proportion found in unaltered calc-alkaline granitoid igneous zircons (Rasmussen et al., 2011). There are also alkali-feldspar, quartz, biotite inclusions (Figs. 9C,D) typical of unaltered inclusions in granitoid zircons. Some muscovite occurs along microfractures, as evidence of incursion of mica/clay minerals into the zircons (Fig. 9E).

7. Discussion

7.1. Comparison of the zircon inclusion suites in the four samples

In samples J06/01 and J06/10 where there is SHRIMP U-Pb dating (Nutman et al., 2011), there is little congruence between dated grains and those with mineral inclusions. The reason for this is that the presence of inclusions can often promote recrystallisation of the zircon in their hinterland, and hence such grains are rarely selected for U-Pb dating. This issue has been noted in other intra zircon studies, such as of a ~3800 Ma tonalite from Greenland (Nutman and Hiess, 2009).
Fresh orthogneiss sample J06/10 has a zircon inclusion suite typical of unaltered granitoids, with >50% apatite present (Rasmussen et al., 2011). The quartzite clast J06/09 detrital zircon population is dominated by oscillatory-zoned zircons derived from granitoids, but the grains are rounded and apatite inclusions are present at only <1%. The Caozhuang quartzite (J06/01) and the Changcheng System immature sandstone sample (J06/06) show lesser degrees of rounding and intermediate abundance of apatite inclusions (~7 and 11%) with evidence of some replacement of apatite by silicates. As such, the Caozhuang quartzite sample J06/01 cannot be regarded as either a mature sedimentary quartzite, whose detritus had a protracted residence/recycling in the surficial environment, nor can it be regarded as a completely fresh, unaltered orthogneiss.

7.2. Protolith of the Caozhuang quartzite J06/01

The field characteristics, petrography (Fig. 3C) and particularly the zircon studies (Figs. 4-9) presented here show that the protolith of the Caozhuang quartzite sample J06/01 was not a mature sedimentary quartzite. If it were a mature quartzite, then the zircons would be more abraded/rounded, the abundance of apatite inclusions within them would be <1%, and the rock would be devoid of feldspar. On the other hand, because it contains <10% apatite inclusions, it is unlikely to be an entirely fresh/unaltered orthogneiss. Instead two options remain. First, it is an extant early Archaean orthogneiss migmatite with 3550-3880 Ma crustal components, which was affected by Precambrian surficial alteration processes, such that some apatite was leached out of the zircons, and then the rock was subsequently metamorphosed. The second option is that its protolith was a feldspathic, immature, detrital sedimentary rock, where residence time of the detritus in the surficial environment was short, such that feldspar is preserved in the rock and also not all apatite was leached out of the zircons. This latter explanation would probably require that the protolith sedimentary rock was deposited at >3300 Ma, because in the Huangbaiyu area there are orthogneisses with ages up to 3280 Ma (Nutman et al., 2011), which could have been potential source materials if the sediment was deposited at a later time. In the immature detrital quartzite scenario this would then give a window for age of deposition between ~3300 Ma and ~3550 Ma, the latter being the age of the youngest zircons in the Caozhuang quartzite. This second option, that the Caozhuang quartzite has an immature feldspathic detrital sediment protolith is in accord with the documentation by Liu et al. (2013) that some mica schists at Huangbaiyu contain 3840-3340 Ma detrital zircons. Therefore we currently favour that the protolith of the Caozhuang quartzite J06/01 is an immature detrital sediment associated with
more quartz-rich metasedimentary rocks and with mica schists (Liu et al., 2013), not an orthogneiss that was affected by Precambrian weathering.

The immature sedimentary nature of the J06/01 protolith indicates that the source early Archaean gneisses should be close to Huangbaiyu. However, the Caozhuang quartzite lies in a highly tectonised zone between a southern domain that contains 2940-3280 Ma orthogneisses intruded by late Neoarchaean granitic rocks and not affected by ~2500 Ma granulite facies metamorphism and a northern domain where the oldest rocks are ~2550 Ma, and there was ~2500 Ma granulite facies metamorphism (Fig. 1; Nutman et al., 2011). Because the quartzite lies in a significant zone of early Precambrian (pre Changcheng System) tectonic disruption, makes harder the search for the source early Archaean rocks.

7.3. Eoarchaean crust ~200 km from Beijing

Because of the low degree of sedimentary abrasion of the zircons, and also the survival of some apatite (at the 11% level) there was a proximal source for the Caozhuang quartzite detritus, implying that that Eoarchaean crust occurs in the vicinity of Caozhuang, ~200 km from Beijing. Furthermore, the results presented here and by Nutman et al., (2011) and Liu et al. (2013) thus strengthen the case for correlation of the early Archaean crustal remnants at Huangbaiyu with those at Anshan (Liaoning Province), where rocks ranging in age from 3800 to 2500 Ma are present (e.g., Song et al., 1996; Wan et al., 2005; Liu et al., 2007).

7.4. Implications for identifying the protoliths in other Precambrian gneiss complexes

For the past 4 decades, there has been a working assumption that quartzo-feldspathic rocks in gneiss complexes overwhelming have plutonic igneous protoliths. This is probably generally true, as shown by structural studies where low strain domains with relict igneous features are located in general ‘seas’ of banded gneisses where ductile deformation has destroyed all protolith structures (e.g., McGregor, 1973; Nutman et al., 2000). However, this case study of the Caozhuang quartzite zircons shows that intra-zircon techniques can be used to distinguish between possible protoliths of strongly deformed quartzo-feldspathic gneisses as being fresh plutonic rocks, surficially-altered plutonic or volcanic rocks, immature or mature sediments.


8. Conclusions

(1) The protolith of all the Caozhuang quartzite is not a mature sedimentary quartzite.

(2) The most likely protolith of parts represented by sample J06/01 is an immature feldspathic detrital sediment deposited between 3300 and 3500 Ma.

(3) The results indicate the presence of Eoarchaean crust in the vicinity of Huangbaiyu, ~200 km from Beijing. The results presented here and by Nutman et al., (2011) and Liu et al. (2013) strengthen the case for correlation of the early Archaean crustal remnants at Huangbaiyu with those at Anshan.

(4) The zircon inclusions methodology used on the Caozhuang quartzite can be used to determine the protolith of other strongly deformed Precambrian gneisses whose origin is debated.

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References


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Figure captions

Figure 1. Geological sketch map of the Caozhuang-Huangbaiyu area, adapted from Chen (1988).

Figure 2. Cartoon portraying the dissolution of apatite inclusions via surface water dissolution along microfractures, infill by silica and microscopic grains of clay, followed by low grade metamorphism (following process documented by Rasmussen et al., 2011).

Figure 3. (A) Field setting of granulite orthogneiss sample J06/10. (B) Quartzite clast (J06/09) from basal parts of the Changcheng System. (C) Photomicrograph of Caozhuang quartzite J06/01. Note the altered plagioclase porphyroclasts (plag), the quartz ribbon texture (qtz) and fuchsite (f).

Figure 4. BSE (back-scattered electron) images of orthogneiss J01/10 zircon inclusions. Insets show low-resolution reconnaissance cathodoluminescence images. (A) Example of apatites (ap), the most voluminous inclusions. (B) Biotite (bio) + quartz (qtz) inclusion (C) alkali-feldspar (alk-feld) and other inclusions (D) possible melt inclusion, consisting of alkali feldspar + quartz coalesced around two blades of biotite.

Figure 5. Pie charts of showing relative volumes of the inclusion phases.

Figure 6. Representative cathodoluminescence images of zircons. (A) Changcheng System quartzite clast J06/09. (B) Changcheng System feldspathic sandstone J06/06. (C) Caozhuang quartzite J06/01.

Figure 7. BSE images of Changcheng System quartzite clast J06/09 zircon inclusions. Abbreviations are the same as in Fig. 3. (A) Apatite replaced by quartz + muscovite/illite (ill). (B) Muscovite/illite + quartz with baddeleyite (baddel) growing orthogonal to inclusion wall. (C) quartz + biotite + ilmenite (ilm) inclusion (left) and quartz + muscovite/illite (right). Bright areas are vestiges of an earlier thick gold coat. (D) alkali-feldspar and quartz + muscovite/illite inclusions. (E) Rare remnant apatite inclusion.

Figure 8. BSE images of Changcheng System feldspathic sandstone J06/06 zircon inclusions. Abbreviations are the same as in Fig. 3. (A) Apatite replaced by quartz + alkali-feldspar. (B) Irregular composite inclusion, perhaps originally a melt inclusion.

Figure 9. BSE images of Caozhuang quartzite J06/01 zircon inclusions. Insets show low-resolution reconnaissance cathodoluminescence images. (A) Grain with diverse
inclusions, including one consisting of monazite (monaz) + baddel. (B) Preserved apatite inclusions (C) Alkali-feldspar (alk-feld) in grain with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3655 Ma. (D) Quartz + biotite inclusion. (E) Muscovite developed along a crack.
The image contains a geological map of the North China Craton (NCC) with various rock formations marked. The map highlights the Proterozoic sedimentary rocks, Neoarchaean granites (undivided), Neoarchaean monzonites, Neoarchaean banded iron formation, Neoarchaean 'leptynites' (qtz-plag-bio schists), and Meso- and Neoarchaean orthogneisses (undivided). The map includes specific locations and geological samples such as Caozhuang, Huangbaiyu, Bailongguang, and Qian'an gneisses. The map also shows the Trans-North China Orogen and various cities like Beijing, Anshan, Xian, and Shanghai.
(a) igneous zircon never been in a surficial environment

(b) zircon in surficial environment influx of mildly acidic waters: dissolution of apatite; infill by clay and silica etc. alteration of plagioclase

(c) metamorphism metamorphic assemblage mosaics infilling apatite
J06/10 orthogneiss

- Apatite 73%

J06/09 quartzite clast

- Apatite 1%

J06/06 sandstone

- Apatite 7%

J06/01 Caozhuang quartzite

- Apatite 11%

**Legend:**

- Apatite
- Quartz
- Alkali-feldspar ± muscovite
- Biotite
- Muscovite ± chlorite
- Monazite
- Baddeleyite
- Fe-Ti oxides
A: qtz, musc/ill
B: musc/ill, qtz, baddel
C: ilm, bio, qtz, qtz + musc/ill
D: 20 microns, alk-feld, musc/ill + qtz
E: 20 microns, ap