

# Zircon U–Pb and Hf isotopic study of gneissic rocks from the Chinese Altai: Progressive accretionary history in the early to middle Palaeozoic

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## Abstract

Gneissic rocks in the Chinese Altai Mountains have been interpreted as either Paleozoic metasedimentary rocks or Precambrian basement. This study reports geochemical and geochronological data for banded paragneisses and associated gneissic granitoids collected along a NE–SW traverse in the northwestern Chinese Altai. Petrological and geochemical data suggest that the protoliths of the banded gneisses were possibly immature sediments with significant volcanic input and that the gneissic granitoids were derived from I-type granites formed in a subduction environment. Three types of morphological features can be recognized in zircons from the banded gneisses and are interpreted to correlate with different sources. Zircons from five samples of banded paragneiss cluster predominantly between 466 and 528 Ma, some give Neoproterozoic ages, and a few yield discordant Paleoproterozoic to Archean ages. Zircon Hf isotopic compositions indicate that both juvenile/mantle and crust materials were involved in the generation of the source rocks from which these zircons were derived. In contrast, zircons occur ubiquitously as elongated euhedral prismatic crystals in the four samples of the gneissic granitoids, and define single populations for each sample with mean ages between 380 and 453 Ma. The general absence of Precambrian inheritance and positive zircon  $\epsilon_{\text{Hf}}$  values for these granitoids suggest insignificant crustal contribution to the generation of the precursor magmas. Our data can be interpreted in terms of a progressive accretionary history in early to middle Palaeozoic times, and the Chinese Altai may possibly represent a magmatic arc built on a continental margin dominated by Neoproterozoic rocks.

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**Keywords:** U–Pb age; Hf isotope; Gneiss; Zircon; Altaids

## 1. Introduction

The Central Asian Orogenic Belt (CAOB or Altaids or Altaid collage) is the largest Phanerozoic orogenic

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belt in the world, extending from the Urals in the west to the Pacific in the east and from Siberia in the north to the Tianshan in the south (Zonenshain et al., 1990; Mossakovsky et al., 1993; Şengör et al., 1993; Jahn et al., 2000a,b; Şengör and Natl'in, 2004; Windley et al., 2007). About 5.3 million km<sup>2</sup> of crustal materials were added to Asia along this belt, now found as fragments of island arcs, ophiolites, accretionary prisms, seamounts, and micro-continents, which were distributed in the Paleo-Asian Ocean, a long-lived ocean existed for 800 Ma from the late Mesoproterozoic to the Mesozoic (Khain et al., 2002; 2003; Windley et al., 2007; Kröner et al., *in press*, and references cited therein). In addition, voluminous granitoids from juvenile sources were emplaced in this region (Jahn, 2004 and references therein). Thus, this belt provides an excellent opportunity to study an accretionary orogen formed by continuous, long-lived subduction. However, unraveling the tectonic evolution of the CAOB is difficult because

of the allochthonous nature of many terranes and their complicated amalgamation history. The tectonic settings of these terranes are controversial, thus leading to several competing models. For example, Şengör et al. (1993) proposed a single arc chain model that reconstructed the entire CAOB by oroclinally bending of the single Kipchak–Tuva–Mongol arc. In contrast, Didenko et al. (1994) and Mossakovsky et al. (1993) viewed the CAOB as a mosaic of exotic, and mostly unrelated arc terranes and microcontinents, a scenario similar to the present-day SW Pacific archipelago, which is in the process of becoming amalgamated to form an extensive new orogenic belt.

The Chinese Altai lies in the southern part of the CAOB and contains blocks of ophiolites, volcanic rocks, high-grade metamorphic rocks, and sedimentary sequences (Fig. 1). This varied assemblage makes the Chinese Altai not only an excellent natural laboratory in which to test the different models outlined above, but

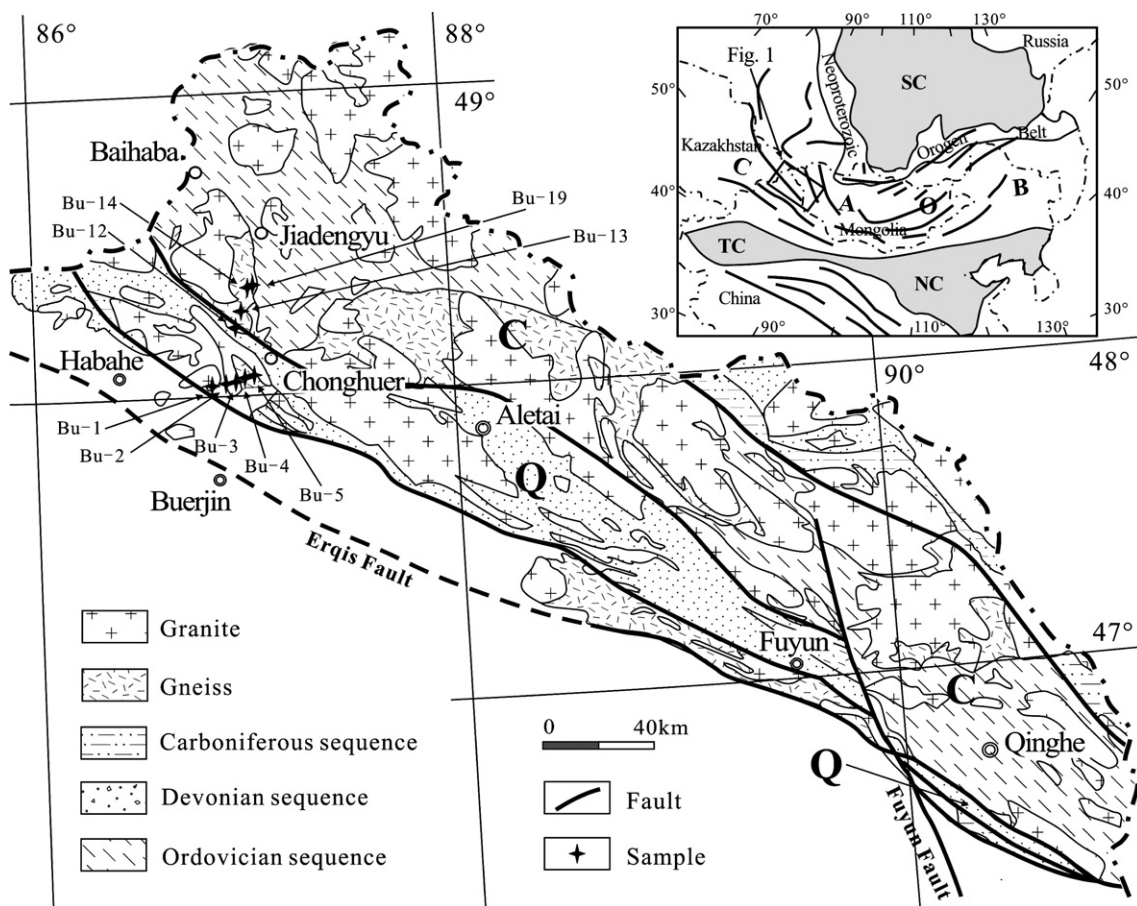


Fig. 1. Simplified geologic map of the Chinese Altai (He et al., 1990; Li et al., 1996; Windley et al., 2002). C — Central Domain, Q — Qiongkuer Domain. Inset figure shows the extension of the CAOB. The Chinese Altai is represented by a box. SC — Siberia Craton, TC — Tarim Craton, NC — North China Craton.

also to study accretionary orogenic processes in general. Although the tectonic subdivision of the Chinese Altai is reasonably well understood (He et al., 1990; Windley et al., 2002), precise geochronological data are rare and firm tectonic constraints have not been provided. Consequently, the tectonic setting of the Chinese Altai has long been controversial, being variously envisaged as an island arc (Şengör and Natal'in, 1996), a passive continental margin (He et al., 1990), or a Precambrian micro-continent (e.g. Li et al., 2006). The high-grade metamorphic rocks within this region are a key element in understanding the tectonic history of the Chinese Altai. These rocks were previously considered to be the metamorphic equivalents of early Paleozoic sedimentary rocks (Habahe Group), but were re-assigned in the early 1990s as the Paleo-to Meso-proterozoic Kemuqi and Neoproterozoic Fuyun Groups (e.g. Li et al., 1996; Chen et al., 2003), and thus were interpreted to represent the Proterozoic basement of the Chinese Altai (e.g. He et al., 1990, 1994; Windley et al., 2002) or a Precambrian microcontinent (Li et al., 2006).

The Precambrian ages for these high-grade metamorphic rocks are based on Sm–Nd whole rock isotopic data (Hu et al., 2001, 2002; Wang et al., 2002), and Nd model ages (e.g. Hu et al., 2000), as well as on xenocrystic zircon dates for associated granitoids (e.g. Windley et al., 2002). Thus, it is imperative to obtain more reliable geochronological data for the high-grade metamorphic rocks in order to test the controversial tectonic models and to correctly understand the accretionary history of this part of the CAOB. This paper reports zircon U–Pb and Hf isotopic data for banded gneisses and gneissic granitoids collected along a NE–SW traverse in the northwestern part of the Chinese Altai. These results shed light on the evolutionary history of the Chinese Altai.

## 2. Geological background

The Chinese Altai, in northernmost Xinjiang Province, is situated between the south Siberian Sanyan block to the north and the Junggar block to the south. Based on recent geological investigations the region has been divided into six NW–SE trending terranes (e.g. Windley et al., 2002; Xiao et al., 2004). This study focuses on two adjacent tectonic domains, namely the Central Altai and Qiongkuer Domains (Fig. 1). The *Central Altai Domain* (Terranes 2 and 3 of Windley et al., 2002) contains low-grade quartzose-feldspathic clastic turbidites and pyroclastic rocks of the Habahe Group (He et al., 1990; Li et al., 2006). These rocks are isoclinally folded with steep axial planes and metamor-

phosed to low greenschist-facies schist and phyllite (Windley et al., 2002). This group was originally assigned to the middle to late Ordovician, but recent workers favor a Sinian (Vendian) to middle Ordovician age (e.g. BGMRX, 1993; Chen and Jahn, 2002; Windley et al., 2002; Li et al., 2006), and consider it to be a passive continental margin deposit (e.g. He et al., 1990; Li and Poliyangsjiji, 2001; Li et al., 2006). However, new data do not support this interpretation since whole-rock geochemical data indicate formation in an active continental margin and detrital zircons from this group have dominant U–Pb ages between 460 and 570 Ma (Long et al., 2006; 2007). The *Qiongkuer Domain* (Terrane 4 of Windley et al., 2002) consists of late Silurian to early Devonian island arc-type volcanic and pyroclastic rocks (Kangbutiebao Formation) and the overlying middle Devonian turbiditic sandstone-shale sequence (Altai Formation) that is considered to be a fore-arc basin deposit (Windley et al., 2002). These two terranes are separated by nearly vertical, NE-dipping fault zones composed of highly deformed rocks with inverted metamorphic gradients (Windley et al., 2002).

High-grade gneissic rocks crop out extensively in these two terranes (Fig. 1) and are currently assigned to the Kemuqi and Fuyun Groups (Chen et al., 2003). The former group consists of coarse- and fine-grained gneiss, migmatite, amphibolite and mica schist, whereas the latter is composed of amphibolite, hornblende gneiss and sericite schist (Li et al., 1996). Their presumed Precambrian age is widely accepted by many workers (e.g. Chen et al., 2003) and led to the proposal of an Altai-Mongolia Precambrian microcontinent (Li et al., 2006). However, the above interpretation is not supported by SHRIMP zircon U–Pb data for high-grade metamorphic rocks from the southeastern part of the Chinese Altai ( $281 \pm 3$  Ma and  $279 \pm 6$  Ma for Qinghe gneiss and Fuyun granulite, respectively; Chen et al., 2006; Hu et al., 2006). In order to firmly constrain the nature and age of the high-grade metamorphic rocks, banded gneisses and associated gneissic granitoids were collected from the Buerjin–Hanasi traverse for this study (Fig. 1).

## 3. Sample description

The rocks in the study area include intensely deformed, banded gneisses, gneissic granitoids and mylonites. Samples used in this study were collected near the road between Buerjin and Jiadengyu. The banded gneisses are generally dark-grey in color, variably migmatized and their prominent leucosomes form folded banding (Fig. 2a and b). The leucosomes



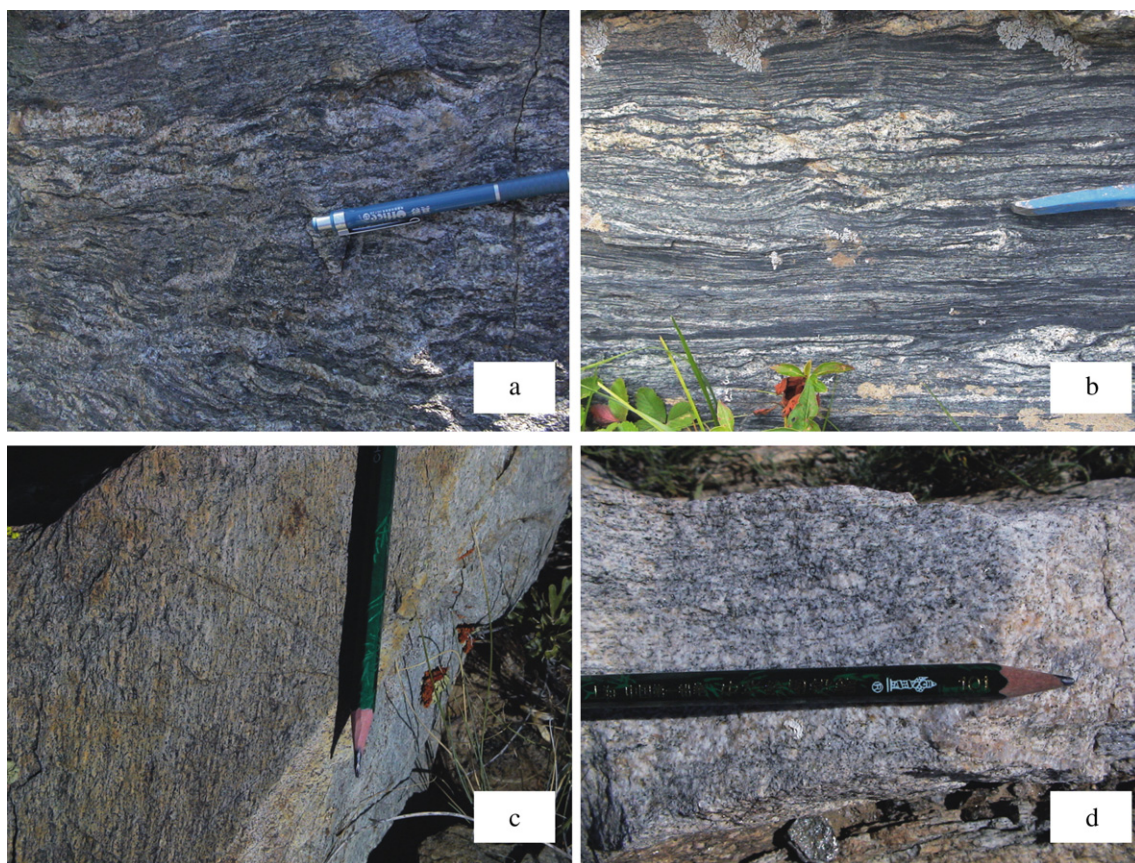


Fig. 2. Field photos of banded paragneisses (a and b) and gneissic granitoids (c and d) in the Chinese Altai.

were avoided during sampling. The banded gneisses are made of coarse to medium-grained quartz, plagioclase, K-feldspar, and biotite. Minor minerals are mainly sillimanite, garnet, tourmaline and zircon (Table 1). The mineral compositions of the gneisses suggest that their protoliths were either feldspathic sandstones or highly deformed granitoids.

The gneissic granitoids also have well-developed foliations, but can be distinguished from the banded gneisses by their more massive structure, uniform mineralogical compositions and occasionally preserved intrusive relationships (Fig. 2c and d). The gneissic granitoids have light grey color, and are mainly composed of coarse to medium-grained quartz, Na-rich plagioclase, K-feldspar, biotite and muscovite (Table 1). Granitic texture is apparent in some thin sections, and the plagioclase phenocrysts may be surrounded by oriented, recrystallized, fine-grained quartz. A fine-grained mylonite sample (Bu-2, Table 1) has granitic compositions and anhedral recrystallized quartz is locally stretched by deformation. Plagioclase laths show simple or polysynthetic twinning and K-feldspar typically

possesses Carlsbad twinning. The mylonite is in sharp contact with the surrounding coarse-grained gneiss, and its fabric is concordant with that of the gneiss (Strike N40°W, Dip 68°NE).

#### 4. Analytical methods

##### 4.1. Major and trace element analysis

Major oxides were determined by wavelength-dispersive X-ray fluorescence spectrometry (XRF) on fused glass beads using a Philips PW2400 spectrometer at the University of Hong Kong. Matrix correction followed the procedure of Norrish and Hutton (1969), and G2 and G3 (granites) were used as reference materials. The accuracies of the XRF analyses are estimated to be ca. 1% (relative) for SiO<sub>2</sub>, ca. 2% (relative) for other major oxides present in concentrations greater than 0.5 wt.% and ca. 5% (relative) for MnO and P<sub>2</sub>O<sub>5</sub>. The trace elements, including REE, were determined by inductively coupled plasma mass spectrometry (ICP-MS) of nebulized solutions using a VG Plasma-Quad Excell ICP-MS at

Table 1  
General description of banded gneiss and gneissic granitoid in the Chinese Altai

Banded gneisses	BU-4	BU-5	BU-13	BU-14	BU-19
Rock name	Coarse grained gneiss	Medium-grained gneiss	Coarse grained gneiss	Coarse grained gneiss	Coarse grained schist
GPS coordinates	48° 03' 12.3" N 87° 00' 02.1" E	48° 03' 13.5" N 87° 00' 04.0" E	48° 16' 11.4" N 87° 03' 58.0" E	48° 19' 14.8" N 87° 06' 41.0" E	48° 21' 21.1" N 87° 08' 13.4" E
Color and Structure	Dark-grey	Dark-grey, with light reddish bands in the weathered surface	Dark-grey, slightly migmatized, quartz shows undulatory extinction	Dark-grey, alternating quartz-feldspar and biotite-amphibole bands	Dark-grey, with minor folded leucosome veins and augen structure
Major minerals (modal %)					
Quartz	30	30	50	40	45
plagioclase	25	35	20	30	30
K-feldspar	15	15	10	18	10
Minor minerals	Sillimanite, garnet, tourmaline, zircon	Sillimanite parallel to the foliation	Sillimanite and tourmaline	Blue–green amphibole	Biotite and muscovite
Gneissic granitoids:	BU-1	BU-2	BU-3	BU-12	
Rock name	Coarse grained leucogranite	Fine-grained mylonite	Medium-grained granite	Coarse grained granodiorite	
GPS coordinates	48° 02' 02.3" N; 86° 52' 51.8" E	48° 02' 27.2" N; 86° 57' 36.4" E	48° 02' 58.9" N; 86° 58' 10.4" E	48° 13' 33.9" N; 87° 01' 28.0" E	
Major minerals (modal %)					
Quartz	35	50	40	30	
plagioclase	50	25	45	40	
K-feldspar	10	10	12	15	
Minor phases	Biotite and muscovite	Biotite, garnet	Biotite	biotite	

the University of Hong Kong after a 2-day closed beaker digestion using a mixture of HF and HNO<sub>3</sub> acids in high-pressure “bombs” (Qi and Gregoire, 2000). Two multi-element solutions were prepared for external calibration, with one containing Li, Be, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Cs, Ba, Pb, Th, U, Sc, Y and fourteen REEs and the other containing W, Mo, Nb, Ta, Zr, and Hf, respectively. G2 and G3 (granites) were used as reference materials. The accuracies of the ICP–MS analyses are estimated to be better than ca.5% (relative) for most elements. Geochemical data are presented in Table 2.

#### 4.2. Zircon separation and CL imaging

After sample crushing, zircons were separated by standard heavy liquid and magnetic techniques. Zircon grains from the >25 μm non-magnetic fractions were hand-picked and mounted on adhesive tape, then enclosed in epoxy resin and polished to about half of their thickness. After being photographed under reflected and transmitted light, the samples were prepared for Cathodoluminescence (CL) imaging, U–Pb dating and Hf isotope analysis.

In order to investigate the origin and structure of zircons and to choose target sites for U–Pb and Hf isotopic analyses, CL imaging was carried out using a

JXA-8100 Electron Probe Microanalyzer with a Mono CL3 Cathodoluminescence System for high resolution imaging and spectroscopy at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences.

#### 4.3. U–Pb zircon geochronology

The U–Pb isotopic composition of zircon was analyzed on a VG PQ Excel IC-PMS equipped with New Wave Research UV213 laser ablation system, installed in the Department of Earth Sciences, the University of Hong Kong. The laser system delivers a beam of 213 nm UV light from a frequency-quintupled Nd:YAG laser. Most analyses were carried out with a beam diameter of 40 μm, 10 Hz repetition rate, and energy of 0.6–1.3 mJ per pulse. This gave a <sup>238</sup>U signal of 3 × 10<sup>4</sup> to 200 × 10<sup>4</sup> counts per second, depending on U contents. Typical ablation time was 30–60 s, resulting in pits 20–40 μm deep. The instrumental settings and detailed analytical procedures were described by Xia et al. (2004). U–Pb ages of zircons were calculated using the U decay constants of <sup>238</sup>U = 1.55125 × 10<sup>-10</sup> year<sup>-1</sup>, <sup>235</sup>U = 9.8454 × 10<sup>-10</sup> year<sup>-1</sup> and the Isoplot 3 software (Ludwig, 2003). Individual analyses are presented with 1σ errors in Table 3 and in concordia diagrams, and uncertainties in age results are quoted at the 95% level

Table 2  
Geochemical composition of banded gneiss and gneissic granitoid in the Chinese Altai

Sample	Banded gneiss					Gneissic granitoid			
	BU-4	BU-5	BU-13	BU-14	BU-19	BU-1	BU-2	BU-3	BU-12
SiO <sub>2</sub>	64.5	63.5	75.7	71.1	77.3	72.6	81.6	73.9	69.8
TiO <sub>2</sub>	0.71	0.73	0.54	0.63	0.37	0.31	0.14	0.36	0.48
Al <sub>2</sub> O <sub>3</sub>	15.8	16.1	10.9	13.1	9.59	13.9	10.0	13.8	14.1
ΣFe <sub>2</sub> O <sub>3</sub>	6.62	7.02	4.61	5.14	2.88	3.37	1.77	2.05	3.94
MnO	0.14	0.11	0.06	0.06	0.05	0.13	0.06	0.09	0.07
MgO	3.87	4.04	2.40	2.53	1.39	1.28	0.56	0.53	1.05
CaO	2.41	1.81	1.25	1.34	3.27	0.59	0.49	2.02	2.81
Na <sub>2</sub> O	2.16	2.43	1.92	2.15	1.46	5.15	4.08	4.40	3.26
K <sub>2</sub> O	2.55	2.81	1.67	2.32	0.98	0.97	0.28	1.84	2.62
P <sub>2</sub> O <sub>5</sub>	0.23	0.18	0.14	0.16	0.26	0.05	0.01	0.09	0.13
LOI	0.96	0.94	0.73	0.95	1.21	1.33	0.92	0.62	1.64
TOTAL	99.9	99.7	99.9	99.5	98.7	99.7	99.9	99.7	99.9
Sc	15.1	15.6	12.2	13.1	7.81	15.7	6.92	8.63	11.7
V	93.0	108	71.5	79.6	51.1	10.8	7.94	11.7	40.3
Cr	136	142	127	150	77.6	4.87	15.4	6.39	23.4
Co	17.6	18.4	13.0	13.9	7.50	3.40	1.97	2.09	6.23
Ni	89.5	94.5	62.1	74.2	33.5	9.34	12.0	7.83	18.0
Ga	17.7	18.7	12.7	15.1	11.4	12.7	6.92	15.0	16.3
Rb	104	108	70.6	93.2	51.0	28.3	5.18	80.8	105
Sr	209	187	169	193	172	157	107	141	141
Ba	447	330	232	306	127	109	15.5	506	400
Y	40.7	36.9	25.2	29.8	27.2	68.7	47.4	39.1	45.7
Nb	9.67	8.32	6.92	8.91	6.69	4.17	4.23	13.8	9.56
Ta	1.12	0.74	0.56	0.89	0.57	0.29	0.33	0.60	0.71
Zr	121	125	150	164	132	156	162	218	227
Hf	3.93	4.15	4.62	5.11	4.08	5.46	5.67	7.09	6.52
Pb	23.1	18.2	16.9	19.6	16.1	7.44	7.60	13.5	15.9
Th	8.96	9.24	9.76	11.3	10.3	4.37	3.33	12.9	14.0
U	4.47	2.54	2.49	3.45	2.93	1.37	1.30	1.08	1.24
La	25.5	23.0	26.7	29.7	19.9	10.4	6.9	30.0	38.3
Ce	55.6	49.5	58.2	64.5	47.3	36.2	21.9	65.9	92.5
Pr	6.27	5.82	6.62	7.51	4.74	4.33	3.17	7.93	10.2
Nd	25.7	23.5	26.9	28.3	20.0	22.4	19.1	32.8	41.6
Sm	5.39	5.10	5.24	5.74	4.23	6.75	5.16	7.07	8.44
Eu	1.07	1.15	1.04	1.09	0.71	1.27	0.70	1.37	1.38
Gd	5.35	5.01	5.23	5.70	4.17	7.64	4.57	6.87	8.53
Tb	0.74	0.71	0.62	0.70	0.59	1.34	0.76	0.89	1.08
Dy	5.34	5.14	4.15	4.74	4.24	10.3	6.45	6.09	7.13
Ho	1.14	1.03	0.76	0.90	0.80	2.13	1.40	1.12	1.35
Er	3.61	3.34	2.40	2.84	2.49	6.46	4.66	3.25	4.00
Tm	0.76	0.68	0.44	0.55	0.50	1.33	0.99	0.57	0.75
Yb	3.91	3.33	2.27	2.71	2.43	6.70	5.39	2.78	3.67
Lu	0.59	0.51	0.33	0.39	0.37	1.04	0.80	0.42	0.53
Mg#	53.7	53.5	50.9	49.4	49.0	43.0	38.4	34.0	34.6
A/NK	2.49	2.29	2.19	2.15	2.77	1.46	1.42	1.50	1.72
A/CNK	1.47	1.56	1.50	1.54	1.02	1.32	1.26	1.07	1.06
DF	-3	-3	-5	-3	-4	1	-1	2	1
ΣREE	140	127	140	155	112	116	80.5	166	218
(La/Yb) <sub>N</sub>	4.40	4.67	7.95	7.41	5.52	1.05	0.87	7.27	7.05
Eu/Eu*	0.61	0.69	0.60	0.58	0.51	0.54	0.44	0.60	0.50
Sr/Y	5.13	5.05	6.72	6.48	6.34	2.28	2.26	3.60	3.08
Nb/Zr	0.08	0.07	0.05	0.05	0.05	0.03	0.03	0.06	0.04
Th/U	2.00	3.63	3.92	3.28	3.50	3.20	2.57	12.0	11.2

(continued on next page)



Table 2 (continued)

Sample	Banded gneiss					Gneissic granitoid			
	BU-4	BU-5	BU-13	BU-14	BU-19	BU-1	BU-2	BU-3	BU-12
Rb/Sr	0.50	0.58	0.42	0.48	0.30	0.18	0.05	0.57	0.75
Zr/Sc	7.99	7.97	12.2	12.5	16.9	9.90	23.5	25.2	19.5
Th/Sc	0.59	0.59	0.80	0.87	1.31	0.28	0.48	1.50	1.20

Note: LOI: weight loss between 120 and 900 °C; A/NK=molar ratio of  $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ ; A/CNK=molar ratio of  $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ ;  $df=0.55 \text{ CaO}+1.46\text{Na}_2\text{O}+0.54 \text{ K}_2\text{O}-0.21\text{SiO}_2-0.32\sum\text{Fe}_2\text{O}_3-0.98 \text{ MgO}+10.44$ .

(2 $\sigma$ ). In this study,  $^{207}\text{Pb}/^{206}\text{Pb}$  ages are used for zircons older than 1000 Ma, but  $^{206}\text{Pb}/^{238}\text{U}$  ages are used for zircons younger than 1000 Ma, because the relative small amount of  $^{207}\text{Pb}$  accumulated in young zircons does not permit precise  $^{207}\text{Pb}/^{206}\text{Pb}$  dating (Black et al., 2003).

#### 4.4. Hf isotope analysis

Hf isotope analyses were carried out using an ArF excimer laser ablation system, attached to a Neptune Plasma multi-collector ICP–MS, at the Institute of Geology and Geophysics, Chinese Academy of Science in Beijing. The analyses for zircons from paragneiss were conducted with a beam diameter of 32  $\mu\text{m}$ , 8 Hz repetition rate, and energy of 15  $\text{mJ}/\text{cm}^2$ , whereas a beam diameter of 63  $\mu\text{m}$  and 6 Hz repetition rate were used for gneissic granitoids. All of the settings yielded a signal intensity of  $\sim 10$  V at  $^{180}\text{Hf}$  for the standard zircon 91500. Typical ablation time was 26 s, resulting in pits 20–30  $\mu\text{m}$  deep. Masses 172, 173, 175–180 and 182 were simultaneously measured in static-collection mode. Data were normalized to  $^{176}\text{Hf}/^{177}\text{Hf}=0.7325$ , using exponential correction for mass bias. Due to the extremely low  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio in zircon (normally  $<0.002$ ), the isobaric interference of  $^{176}\text{Lu}$  on  $^{176}\text{Hf}$  is negligible (Iizuka and Hirata, 2005). The mean  $\beta_{\text{Yb}}$  value was applied for the isobaric interference correction of  $^{176}\text{Yb}$  on  $^{176}\text{Hf}$  in the same spot. The ratio of  $^{176}\text{Yb}/^{172}\text{Yb}$  (0.5887) was also applied for the Yb correction. Detailed instrumental settings and analytical procedures were described by Wu et al. (2006). In order to evaluate the reliability of the analytical data, standard zircon 91500 was analyzed during the course of this study and a weighted mean  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio of  $0.282306\pm 25$  (2 $\sigma$ ) was yielded, which is the same as a weighted mean  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio of  $0.282306\pm 10$  (2 $\sigma$ ) by solution analysis of Woodhead et al. (2004). More reference zircons were analyzed in the same laboratory by Wu et al. (2006), giving results of  $0.282680\pm 31$  (2SD) for TEMORA,  $0.281729\pm 21$

(2SD) for CZ3,  $282177\pm 17$  (2SD) for CN92-1,  $0.282983\pm 17$  (2SD) for FM0411 and  $0.281234\pm 11$  (2SD) for Phalaborwa.

The measured  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios and the  $^{176}\text{Lu}$  decay constant of  $1.865\times 10^{-11} \text{ yr}^{-1}$  reported by Scherer et al. (2001) were used to calculate initial  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios. The chondritic values of  $^{176}\text{Hf}/^{177}\text{Hf}=0.0332$  and  $^{176}\text{Lu}/^{177}\text{Hf}=0.282772$  reported by Blichert-Toft and Albarede (1997) were used for the calculation of  $\epsilon_{\text{Hf}}$  values. The depleted mantle Hf model ages ( $T_{\text{DM}}$ ) were calculated using the measured  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios of zircon based on an assumption that the depleted mantle reservoir has a linear isotopic growth from  $^{176}\text{Hf}/^{177}\text{Hf}=0.279718$  at 4.55 Ga to  $0.283250$  at present, with  $^{176}\text{Lu}/^{177}\text{Hf}=0.0384$  (Griffin et al., 2000). However this  $T_{\text{DM}}$  model age can only give a minimum age for the source material of the magma from which the zircon crystallized because the fractionation between Lu and Hf has taken place when zircons formed. In order to circumvent such a problem, Hf model age  $T_{\text{DM}}^{\text{C}}$  was calculated, which is derived from projecting the initial  $^{176}\text{Hf}/^{177}\text{Hf}$  of a zircon (after determination of its U/Pb age) back to the depleted mantle model growth line by using a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.008, the mean value for upper continental crust (Rudnick and Gao, 2004). The upper continental crust Lu/Hf ratio, other than the average ratio of the whole continent ( $^{176}\text{Lu}/^{177}\text{Hf}=0.015$ ; e.g. Griffin et al., 2004) or mafic crust ( $^{176}\text{Lu}/^{177}\text{Hf}=0.019$ ), is adopted here because the residence time of mafic crust is usually short and especially since Archean granitoids appear to be derived by partial melting of young subducted oceanic crust (Martin 1986). The discussion in this study is based on  $T_{\text{DM}}^{\text{C}}$  model ages.

## 5. Geochemical results

The Chemical Index of Alteration [ $\text{CIA}=\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{CaO}^*+\text{Na}_2\text{O}+\text{K}_2\text{O})\times 100$ , molar ratio] and Index of Compositional Variability [ $\text{ICV}=(\text{Fe}_2\text{O}_3+\text{K}_2\text{O}+\text{Na}_2\text{O}+\text{CaO}+\text{MgO}+\text{TiO}_2)/\text{Al}_2\text{O}_3$ , molar ratio] have been frequently used to study the weathering

Table 3

U–Pb isotopic data for zircons from banded gneiss and gneissic granitoid in the Chinese Altai

Grain no.	Contents		Ratios						Ages (Ma)						Disc. (%)	
	Th	U	Th/U	Pb <sup>207</sup> / Pb <sup>206</sup>	1 $\sigma$	Pb <sup>207</sup> / U <sup>235</sup>	1 $\sigma$	Pb <sup>206</sup> / U <sup>238</sup>	1 $\sigma$	Pb <sup>207</sup> / Pb <sup>206</sup>	1 $\sigma$	Pb <sup>207</sup> / U <sup>235</sup>	1 $\sigma$	Pb <sup>206</sup> / U <sup>238</sup>		1 $\sigma$
<i>Banded gneiss BU-4</i>																
1	56	156	0.36	0.06109	0.00156	0.64912	0.01574	0.07707	0.00150	642	54	508	10	479	9	29
2	218	280	0.78	0.05943	0.00154	0.63345	0.01564	0.07731	0.00152	583	55	498	10	480	9	19
3	149	551	0.27	0.06024	0.00152	0.64204	0.01564	0.07734	0.00154	612	54	504	10	480	9	24
4	72	135	0.54	0.06071	0.00210	0.66439	0.02236	0.07942	0.00170	629	73	517	14	493	10	24
5	145	388	0.37	0.06303	0.00172	0.68982	0.01816	0.07942	0.00160	709	57	533	11	493	10	36
6	98	141	0.70	0.05643	0.00148	0.61817	0.01562	0.07948	0.00158	469	57	489	10	493	9	-5
7	86	132	0.65	0.05994	0.00214	0.65854	0.02284	0.07973	0.00170	601	75	514	14	495	10	20
8	65	104	0.62	0.06149	0.00160	0.67609	0.01666	0.07973	0.00156	656	55	524	10	495	9	28
9	20	209	0.10	0.05971	0.00246	0.65638	0.02616	0.07975	0.00176	593	87	512	16	495	10	18
10	59	114	0.52	0.05872	0.00162	0.65263	0.01734	0.08064	0.00162	557	59	510	11	500	10	11
11	13	138	0.10	0.05865	0.00166	0.65242	0.01786	0.08072	0.00162	554	61	510	11	500	10	10
12	48	155	0.31	0.05768	0.00190	0.64318	0.02046	0.08091	0.00168	518	71	504	13	502	10	3
13	22	105	0.21	0.05778	0.00210	0.64741	0.02260	0.08126	0.00170	521	78	507	14	504	10	3
14	56	94	0.60	0.05988	0.00184	0.67428	0.02010	0.08172	0.00168	599	65	523	12	506	10	17
15	105	188	0.56	0.05908	0.00164	0.66851	0.01798	0.08211	0.00166	570	59	520	11	509	10	11
16	241	698	0.34	0.06023	0.00140	0.69025	0.01500	0.08309	0.00158	612	49	533	9	515	9	17
17	57	43	1.31	0.05902	0.00182	0.67746	0.02002	0.08327	0.00168	568	66	525	12	516	10	10
18	60	72	0.83	0.05871	0.00186	0.67514	0.02052	0.08340	0.00170	556	68	524	12	516	10	7
19	5	50	0.09	0.05935	0.00200	0.68694	0.02224	0.08395	0.00174	580	72	531	13	520	10	11
20	137	262	0.52	0.05748	0.00140	0.66827	0.01536	0.08434	0.00164	510	53	520	9	522	10	-2
21	37	49	0.75	0.06067	0.00190	0.70698	0.02118	0.08454	0.00172	628	66	543	13	523	10	18
22	85	127	0.67	0.05861	0.00184	0.68781	0.02104	0.08516	0.00178	553	67	531	13	527	11	5
23	275	732	0.38	0.05992	0.00162	0.70866	0.01836	0.08580	0.00170	601	57	544	11	531	10	12
24	491	287	1.71	0.05916	0.00152	0.70293	0.01750	0.08621	0.00172	573	55	541	10	533	10	7
25	47	50	0.94	0.05968	0.00184	0.75845	0.02266	0.09222	0.00190	592	65	573	13	569	11	4
26	213	422	0.50	0.05994	0.00150	0.76530	0.01844	0.09265	0.00184	601	53	577	11	571	11	5
27	91	1121	0.08	0.05870	0.00140	0.75425	0.01714	0.09322	0.00182	556	51	571	10	575	11	-3
28	27	241	0.11	0.06276	0.00196	0.81661	0.02436	0.09439	0.00192	700	65	606	14	581	11	19
29	34	82	0.41	0.06244	0.00218	0.89588	0.03004	0.10402	0.00218	689	73	650	16	638	13	8
30	16	106	0.15	0.06601	0.00192	1.10939	0.03122	0.12194	0.00248	807	60	758	15	742	14	8
31	290	881	0.33	0.06898	0.00152	1.25502	0.02590	0.13191	0.00250	898	45	826	12	799	14	12
32	66	241	0.27	0.07112	0.00198	1.50669	0.04082	0.15375	0.00314	961	56	933	16	922	18	4
33	131	370	0.35	0.07616	0.00218	1.80484	0.05022	0.17197	0.00356	1099	56	1047	18	1023	20	7
34	35	36	0.99	0.12254	0.00306	6.05008	0.14552	0.35822	0.00718	1994	44	1983	21	1974	34	1
35	150	299	0.50	0.16583	0.00366	8.76234	0.18154	0.38308	0.00732	2516	37	2314	19	2091	34	18
<i>Banded gneiss BU-5</i>																
1	49	216	0.23	0.05794	0.00158	0.61651	0.01662	0.07722	0.00158	527	59	488	10	480	9	10
2	206	335	0.61	0.06113	0.00152	0.67186	0.01602	0.07980	0.00156	644	53	522	10	495	9	26
3	31	89	0.35	0.05828	0.00176	0.64963	0.01894	0.08091	0.00166	540	65	508	12	502	10	7
4	119	217	0.55	0.05765	0.00172	0.65760	0.01902	0.08281	0.00170	516	64	513	12	513	10	1
5	104	396	0.26	0.05726	0.00168	0.65405	0.01854	0.08293	0.00166	502	63	511	11	514	10	-2
6	155	208	0.74	0.05758	0.00160	0.65760	0.01722	0.08294	0.00162	514	60	513	10	514	10	0
7	89	225	0.40	0.05848	0.00158	0.66957	0.01792	0.08310	0.00170	548	58	520	11	515	10	6
8	121	203	0.59	0.05846	0.00162	0.67576	0.01836	0.08390	0.00172	547	59	524	11	519	10	5
9	318	686	0.46	0.06682	0.00180	0.77397	0.02112	0.08404	0.00178	832	55	582	12	520	11	46
10	6	291	0.02	0.05795	0.00142	0.67261	0.01554	0.08428	0.00162	528	53	522	9	522	10	1
11	102	274	0.37	0.06561	0.00242	0.76674	0.02850	0.08477	0.00196	794	76	578	16	525	12	41
12	269	1016	0.26	0.06496	0.00182	0.75937	0.02158	0.08481	0.00182	773	58	574	12	525	11	38
13	227	510	0.44	0.05917	0.00166	0.69959	0.02008	0.08577	0.00184	573	60	539	12	530	11	8
14	77	103	0.75	0.06327	0.00226	0.75146	0.02574	0.08625	0.00180	717	74	569	15	533	11	29
15	441	822	0.54	0.06237	0.00168	0.74271	0.02042	0.08639	0.00182	687	56	564	12	534	11	25
16	288	590	0.49	0.06099	0.00182	0.73250	0.02328	0.08711	0.00198	639	63	558	14	538	12	17
17	75	141	0.54	0.06187	0.00198	0.82009	0.02722	0.09615	0.00216	670	67	608	15	592	13	12

(continued on next page)



Table 3 (continued)

Grain no.	Contents		Ratios						Ages (Ma)						Disc. (%)	
	Th	U	Th/U	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>	1σ	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>		1σ
<i>Banded gneiss BU-5</i>																
18	94	569	0.17	0.06006	0.00206	0.82168	0.03196	0.09921	0.00248	606	73	609	18	610	15	-1
19	363	1042	0.35	0.06047	0.00172	0.83651	0.02482	0.10034	0.00220	620	60	617	14	616	13	1
20	740	1259	0.59	0.06361	0.00208	0.89018	0.03236	0.10149	0.00246	729	68	646	17	623	14	16
21	268	1222	0.22	0.06320	0.00198	0.93624	0.03198	0.10743	0.00252	715	65	671	17	658	15	8
22	40	127	0.31	0.06245	0.00212	0.93752	0.03098	0.10897	0.00232	690	71	672	16	667	13	3
23	107	303	0.35	0.06354	0.00198	0.95984	0.03174	0.10955	0.00252	726	65	683	16	670	15	8
24	53	145	0.37	0.06533	0.00208	1.00472	0.03278	0.11156	0.00250	785	65	706	16	682	14	14
25	90	109	0.82	0.06708	0.00212	1.09220	0.03526	0.11812	0.00262	840	64	750	17	720	15	15
26	47	86	0.55	0.06517	0.00180	1.08389	0.02858	0.12077	0.00240	780	57	746	14	735	14	6
27	134	727	0.18	0.06567	0.00204	1.11362	0.03730	0.12298	0.00286	796	64	760	18	748	16	6
28	12	36	0.34	0.06723	0.00222	1.20326	0.03900	0.12990	0.00278	845	67	802	18	787	16	7
29	35	64	0.55	0.06901	0.00220	1.38397	0.04260	0.14559	0.00304	899	64	882	18	876	17	3
30	257	473	0.54	0.12637	0.00426	5.85888	0.22124	0.33621	0.00834	2048	58	1955	32	1868	40	9
31	112	693	0.16	0.13458	0.00426	7.74017	0.26930	0.41709	0.00992	2159	54	2201	31	2247	45	-4
<i>Banded gneiss BU-13</i>																
1	25	69	0.37	0.05678	0.00238	0.55697	0.02060	0.07159	0.00138	483	90	450	13	446	8	8
2	15	149	0.10	0.05763	0.00146	0.57589	0.01386	0.07242	0.00140	516	55	462	9	451	8	13
3	95	194	0.49	0.05880	0.00198	0.59471	0.01796	0.07350	0.00138	560	72	474	11	457	8	20
4	24	46	0.52	0.05952	0.00232	0.61228	0.02156	0.07485	0.00146	586	82	485	13	465	9	23
5	12	52	0.23	0.05603	0.00320	0.57785	0.03104	0.07503	0.00168	454	122	463	20	466	10	-3
6	31	99	0.32	0.05877	0.00252	0.60695	0.02280	0.07538	0.00146	559	91	482	14	468	9	18
7	89	177	0.50	0.06029	0.00228	0.62553	0.02074	0.07562	0.00142	614	80	493	13	470	9	27
8	6	21	0.31	0.06506	0.00310	0.67928	0.02944	0.07612	0.00158	776	97	526	18	473	9	49
9	48	109	0.44	0.05897	0.00242	0.61782	0.02270	0.07631	0.00148	566	87	488	14	474	9	18
10	86	245	0.35	0.05706	0.00190	0.60119	0.01918	0.07639	0.00156	494	72	478	12	475	9	4
11	26	49	0.54	0.05993	0.00232	0.63274	0.02214	0.07680	0.00148	601	82	498	14	477	9	23
12	19	43	0.44	0.06155	0.00266	0.65633	0.02590	0.07762	0.00156	659	90	512	16	482	9	31
13	216	293	0.74	0.05817	0.00130	0.64539	0.01360	0.08041	0.00154	536	48	506	8	499	9	7
14	90	202	0.45	0.05742	0.00206	0.64178	0.02086	0.08126	0.00154	508	77	503	13	504	9	1
15	93	85	1.10	0.06551	0.00324	0.73973	0.03492	0.08183	0.00186	791	100	562	20	507	11	44
16	33	49	0.68	0.06177	0.00224	0.71072	0.02364	0.08357	0.00162	666	76	545	14	517	10	25
17	119	331	0.36	0.05781	0.00134	0.66648	0.01484	0.08358	0.00162	523	50	519	9	517	10	1
18	69	93	0.74	0.06062	0.00224	0.69937	0.02354	0.08381	0.00162	626	78	538	14	519	10	19
19	87	500	0.17	0.05929	0.00142	0.76069	0.01678	0.09298	0.00174	578	51	574	10	573	10	1
20	159	931	0.17	0.06216	0.00154	0.81507	0.01904	0.09502	0.00182	680	52	605	11	585	11	15
21	14	20	0.70	0.06807	0.00304	1.06487	0.04378	0.11375	0.00236	871	90	736	21	694	14	23
22	19	40	0.48	0.06928	0.00206	1.09874	0.03036	0.11495	0.00222	907	60	753	15	701	13	26
23	39	54	0.72	0.06852	0.00224	1.11410	0.03340	0.11795	0.00228	884	66	760	16	719	13	21
24	15	63	0.24	0.06823	0.00212	1.12092	0.03180	0.11923	0.00226	876	63	763	15	726	13	19
25	10	58	0.17	0.07087	0.00264	1.27541	0.04164	0.13114	0.00248	954	74	835	18	794	14	18
26	3	22	0.11	0.06839	0.00302	1.25462	0.05284	0.13295	0.00298	880	89	825	24	805	17	9
27	173	255	0.68	0.07353	0.00178	1.62196	0.03658	0.15986	0.00300	1029	48	979	14	956	17	7
28	25	65	0.38	0.09769	0.00290	2.92428	0.08162	0.21691	0.00440	1580	55	1388	21	1266	23	22
29	31	91	0.33	0.11907	0.00366	4.00898	0.11326	0.24417	0.00482	1942	54	1636	23	1408	25	32
30	13	15	0.87	0.15012	0.00644	5.63089	0.21284	0.27353	0.00588	2347	72	1921	32	1559	30	40
31	5	35	0.15	0.17709	0.00494	10.78572	0.26970	0.44199	0.00824	2626	46	2505	23	2360	37	11
<i>Banded gneiss BU-14</i>																
1	70	460	0.15	0.05866	0.00254	0.55200	0.02002	0.06833	0.00138	555	92	446	13	426	8	26
2	121	790	0.15	0.05815	0.00250	0.54911	0.01966	0.06857	0.00138	535	91	444	13	428	8	22
3	11	625	0.02	0.06092	0.00188	0.58596	0.01718	0.06977	0.00140	636	65	468	11	435	8	38
4	259	1336	0.19	0.06284	0.00234	0.60790	0.01962	0.07022	0.00138	703	77	482	12	437	8	47
5	128	571	0.22	0.06161	0.00228	0.59948	0.01994	0.07062	0.00142	661	77	477	13	440	9	40

Table 3 (continued)

Grain no.	Contents		Ratios						Ages (Ma)						Disc. (%)	
	Th	U	Th/U	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>	1σ	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>		1σ
<i>Banded gneiss BU-14</i>																
6	139	244	0.57	0.06113	0.00246	0.60434	0.02178	0.07176	0.00146	644	84	480	14	447	9	36
7	341	1289	0.26	0.06572	0.00270	0.65229	0.02254	0.07207	0.00144	797	84	510	14	449	9	56
8	199	459	0.43	0.05754	0.00210	0.57949	0.01970	0.07308	0.00150	512	78	464	13	455	9	12
9	134	261	0.51	0.05984	0.00212	0.60533	0.01928	0.07341	0.00146	598	75	481	12	457	9	27
10	562	1049	0.54	0.05530	0.00174	0.55968	0.01630	0.07344	0.00144	424	69	451	11	457	9	-7
11	247	1246	0.20	0.05733	0.00216	0.58213	0.01928	0.07370	0.00146	504	81	466	12	458	9	10
12	210	657	0.32	0.05909	0.00216	0.60071	0.01918	0.07379	0.00146	570	78	478	12	459	9	22
13	98	434	0.23	0.06062	0.00266	0.61814	0.02358	0.07403	0.00152	626	92	489	15	460	9	30
14	71	533	0.13	0.05677	0.00210	0.58513	0.02046	0.07478	0.00156	483	80	468	13	465	9	4
15	518	1121	0.46	0.06446	0.00254	0.67041	0.02256	0.07550	0.00150	757	81	521	14	469	9	47
16	573	693	0.83	0.06621	0.00278	0.69580	0.02492	0.07630	0.00154	813	85	536	15	474	9	53
17	55	139	0.39	0.05947	0.00210	0.62881	0.02072	0.07672	0.00156	584	75	495	13	477	9	20
18	79	153	0.51	0.05807	0.00262	0.61954	0.02468	0.07745	0.00162	532	96	490	15	481	10	10
19	365	716	0.51	0.06006	0.00188	0.64425	0.01878	0.07783	0.00154	606	66	505	12	483	9	23
20	57	1206	0.05	0.05552	0.00164	0.60684	0.01676	0.07930	0.00156	433	64	482	11	492	9	-13
21	136	295	0.46	0.05777	0.00168	0.64373	0.01804	0.08083	0.00164	521	63	505	11	501	10	4
22	247	481	0.51	0.05908	0.00228	0.66835	0.02320	0.08211	0.00166	570	82	520	14	509	10	11
23	60	200	0.30	0.06175	0.00278	0.71535	0.02752	0.08411	0.00174	665	94	548	16	521	10	24
24	235	654	0.36	0.05931	0.00166	0.69202	0.01844	0.08464	0.00168	578	60	534	11	524	10	10
25	146	292	0.50	0.06367	0.00190	0.91607	0.02578	0.10438	0.00210	731	62	660	14	640	12	13
26	70	191	0.36	0.06688	0.00242	1.10698	0.03556	0.12014	0.00238	834	74	757	17	731	14	13
27	75	167	0.45	0.06650	0.00206	1.12207	0.03222	0.12243	0.00244	822	63	764	15	745	14	10
28	76	340	0.22	0.07091	0.00272	1.23325	0.04080	0.12626	0.00250	955	77	816	18	766	14	22
29	20	57	0.34	0.06720	0.00382	1.18013	0.06246	0.12749	0.00316	844	114	791	29	774	18	9
30	213	535	0.40	0.07126	0.00212	1.33412	0.03648	0.13584	0.00266	965	60	861	16	821	15	16
31	264	1231	0.21	0.06735	0.00202	1.33085	0.03684	0.14338	0.00282	849	61	859	16	864	16	-2
32	140	499	0.28	0.07129	0.00194	1.48527	0.03826	0.15113	0.00300	966	55	924	16	907	17	6
33	42	140	0.30	0.17806	0.00710	7.81979	0.26564	0.31884	0.00646	2635	65	2210	30	1784	31	39
34	701	2203	0.32	0.11563	0.00374	5.15090	0.14834	0.32331	0.00628	1890	57	1845	24	1806	31	5
35	161	422	0.38	0.16154	0.00498	9.39939	0.27598	0.42213	0.00912	2472	51	2378	27	2270	41	9
<i>Banded gneiss BU-19</i>																
1	125	350	0.36	0.05879	0.00172	0.62229	0.01890	0.07685	0.00174	559	63	491	12	477	10	16
2	569	930	0.61	0.05568	0.00126	0.59697	0.01324	0.07776	0.00154	440	50	475	8	483	9	-9
3	149	461	0.32	0.05792	0.00134	0.64205	0.01484	0.08041	0.00164	527	50	504	9	499	10	5
4	191	538	0.35	0.06165	0.00146	0.68918	0.01658	0.08111	0.00170	662	50	532	10	503	10	27
5	375	1119	0.34	0.05930	0.00128	0.66832	0.01398	0.08174	0.00160	578	46	520	8	507	10	13
6	502	751	0.67	0.05992	0.00134	0.68176	0.01526	0.08253	0.00168	601	48	528	9	511	10	16
7	367	665	0.55	0.05923	0.00132	0.68368	0.01510	0.08373	0.00168	576	48	529	9	518	10	10
8	154	239	0.64	0.05897	0.00156	0.69117	0.01884	0.08506	0.00186	566	57	534	11	526	11	7
9	257	573	0.45	0.05850	0.00126	0.68734	0.01450	0.08523	0.00168	549	46	531	9	527	10	4
10	385	985	0.39	0.06247	0.00156	0.73994	0.01978	0.08601	0.00194	690	52	562	11	532	12	26
11	450	605	0.74	0.05786	0.00140	0.68683	0.01748	0.08617	0.00190	524	52	531	10	533	11	-2
12	291	758	0.38	0.05639	0.00138	0.67613	0.01788	0.08707	0.00196	468	53	524	11	538	12	-14
13	95	344	0.27	0.06131	0.00180	0.74908	0.02182	0.08865	0.00192	650	62	568	13	548	11	17
14	1419	791	1.79	0.05747	0.00140	0.70554	0.01818	0.08912	0.00196	510	53	542	11	550	12	-8
15	104	161	0.64	0.06348	0.00270	0.78473	0.03272	0.08968	0.00212	724	88	588	18	554	13	27
16	155	295	0.52	0.06069	0.00170	0.77411	0.02128	0.09251	0.00192	628	59	582	12	570	11	10
17	183	541	0.34	0.05736	0.00144	0.74427	0.02022	0.09424	0.00216	505	54	565	12	581	13	-14
18	512	1199	0.43	0.05802	0.00138	0.76798	0.01912	0.09608	0.00210	531	51	579	11	591	12	-11
19	685	743	0.92	0.05868	0.00144	0.78491	0.02036	0.09711	0.00216	555	53	588	12	597	13	-7
20	93	456	0.20	0.06533	0.00148	1.07867	0.02392	0.11976	0.00240	785	47	743	12	729	14	7
21	323	726	0.44	0.06557	0.00144	1.14372	0.02542	0.12654	0.00262	793	45	774	12	768	15	3
22	188	156	1.20	0.06980	0.00168	1.21925	0.02918	0.12671	0.00262	922	49	809	13	769	15	18
23	1125	2468	0.46	0.06434	0.00150	1.17424	0.02808	0.13242	0.00280	753	48	789	13	802	16	-6

(continued on next page)

Table 3 (continued)

Grain no.	Contents		Ratios						Ages (Ma)						Disc. (%)	
	Th	U	Th/U	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>	1σ	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>		1σ
<i>Banded gneiss BU-19</i>																
24	235	637	0.37	0.06954	0.00150	1.47128	0.03150	0.15347	0.00310	915	44	919	13	920	17	-1
25	231	536	0.43	0.06943	0.00180	1.49429	0.04210	0.15631	0.00362	912	52	928	17	936	20	-3
<i>Gneissic granitoid BU-1</i>																
1	220	353	0.62	0.05929	0.00142	0.52484	0.01252	0.06420	0.00130	578	51	428	8	401	8	36
2	398	474	0.84	0.06250	0.00132	0.55488	0.01436	0.06439	0.00164	691	44	448	9	402	10	53
3	141	255	0.55	0.06033	0.00164	0.53482	0.01734	0.06429	0.00156	616	58	435	11	402	9	42
4	315	446	0.71	0.05769	0.00176	0.51427	0.02706	0.06465	0.00226	518	66	421	18	404	14	25
5	120	215	0.56	0.05815	0.00166	0.52065	0.01464	0.06494	0.00134	535	61	426	10	406	8	28
6	703	594	1.18	0.06261	0.00134	0.56398	0.01222	0.06533	0.00136	695	45	454	8	408	8	52
7	178	289	0.62	0.05595	0.00214	0.51078	0.02702	0.06621	0.00196	450	83	419	18	413	12	9
8	610	567	1.08	0.06281	0.00158	0.57438	0.01420	0.06632	0.00136	702	53	461	9	414	8	52
9	192	331	0.58	0.05752	0.00190	0.52780	0.05008	0.06655	0.00400	512	71	430	33	415	24	21
10	209	491	0.43	0.05622	0.00150	0.52289	0.01322	0.06745	0.00134	461	58	427	9	421	8	9
11	356	388	0.92	0.06129	0.00302	0.57714	0.02638	0.06830	0.00130	649	102	463	17	426	8	42
12	360	558	0.65	0.05672	0.00142	0.54338	0.01926	0.06948	0.00202	481	54	441	13	433	12	10
13	685	685	1.00	0.06009	0.00132	0.63209	0.01786	0.07629	0.00204	607	47	497	11	474	12	25
14	1666	1635	1.02	0.05763	0.00122	0.61107	0.02386	0.07690	0.00288	516	46	484	15	478	17	8
15	616	473	1.30	0.05745	0.00224	0.63020	0.02214	0.07956	0.00148	509	84	496	14	493	9	3
16	140	102	1.38	0.06129	0.00248	0.70693	0.02798	0.08366	0.00184	649	85	543	17	518	11	23
17	232	650	0.36	0.05681	0.00174	0.66700	0.05014	0.08515	0.00428	484	66	519	30	527	25	-8
18	75	77	0.98	0.06321	0.00160	0.76031	0.01412	0.08724	0.00134	715	53	574	8	539	8	28
19	1125	711	1.58	0.06576	0.00122	0.89853	0.01704	0.09910	0.00206	799	38	651	9	609	12	27
20	790	677	1.17	0.06311	0.00192	0.93094	0.04692	0.10699	0.00372	712	63	668	24	655	22	8
21	742	562	1.32	0.06848	0.00122	1.31937	0.02064	0.13973	0.00248	883	36	854	9	843	14	5
22	660	522	1.26	0.06529	0.00140	1.31286	0.02814	0.14583	0.00294	784	44	851	12	878	17	-11
<i>Gneissic granitoid BU-2</i>																
1	19	35	0.55	0.05923	0.00478	0.47791	0.03694	0.05848	0.00166	576	166	397	25	366	10	44
2	58	102	0.57	0.06864	0.00308	0.55818	0.02366	0.05896	0.00128	888	90	450	15	369	8	83
3	17	32	0.53	0.05736	0.00362	0.46925	0.02846	0.05933	0.00146	505	133	391	19	372	9	31
4	26	42	0.61	0.06294	0.00280	0.52066	0.02196	0.05997	0.00130	706	92	426	15	375	8	61
5	55	77	0.72	0.05372	0.00156	0.44604	0.01220	0.06022	0.00116	359	64	375	9	377	7	-5
6	48	56	0.86	0.05867	0.00256	0.48767	0.02014	0.06025	0.00128	555	92	403	14	377	8	38
7	20	30	0.68	0.05656	0.00272	0.47059	0.02156	0.06031	0.00130	474	103	392	15	378	8	23
8	38	57	0.68	0.05941	0.00310	0.49503	0.02464	0.06040	0.00138	582	109	408	17	378	8	43
9	36	67	0.53	0.05944	0.00190	0.49618	0.01508	0.06057	0.00120	583	68	409	10	379	7	42
10	26	48	0.55	0.05475	0.00200	0.45770	0.01576	0.06063	0.00122	402	80	383	11	379	7	6
11	26	38	0.70	0.05582	0.00226	0.46723	0.01814	0.06071	0.00124	445	88	389	12	380	8	16
12	25	44	0.58	0.05925	0.00408	0.49959	0.03290	0.06113	0.00158	576	143	411	22	382	10	40
13	24	44	0.55	0.05528	0.00380	0.46703	0.03092	0.06128	0.00158	424	146	389	21	383	10	10
14	29	43	0.68	0.05985	0.00572	0.50576	0.04646	0.06129	0.00196	598	195	416	31	383	12	44
15	37	58	0.63	0.06123	0.00302	0.52011	0.02458	0.06162	0.00138	647	103	425	16	385	8	51
16	30	44	0.69	0.06579	0.00282	0.56061	0.02274	0.06180	0.00132	800	87	452	15	387	8	70
17	28	39	0.73	0.06158	0.00256	0.52728	0.02068	0.06206	0.00130	660	87	430	14	388	8	52
18	30	37	0.81	0.05547	0.00240	0.47482	0.01966	0.06210	0.00132	431	94	395	13	388	8	10
19	45	62	0.73	0.05657	0.00228	0.48962	0.01872	0.06278	0.00130	475	87	405	13	393	8	19
20	24	29	0.82	0.06238	0.00332	0.54032	0.02736	0.06280	0.00144	687	110	439	18	393	9	55
21	32	34	0.94	0.05920	0.00294	0.52135	0.02460	0.06383	0.00142	574	104	426	16	399	9	36
22	28	36	0.77	0.05368	0.00212	0.49194	0.01864	0.06649	0.00134	358	87	406	13	415	8	-15
23	45	49	0.92	0.06428	0.00292	0.59933	0.02610	0.06764	0.00148	751	93	477	16	422	9	56
24	61	84	0.73	0.06283	0.00252	0.58674	0.02226	0.06771	0.00140	702	83	469	14	422	8	50
25	21	23	0.90	0.06445	0.00306	0.60525	0.02718	0.06806	0.00150	756	97	481	17	424	9	56
26	30	36	0.84	0.05874	0.00498	0.55125	0.04504	0.06807	0.00196	557	175	446	29	425	12	27

Table 3 (continued)

Grain no.	Contents		Ratios						Ages (Ma)						Disc. (%)	
	Th	U	Th/U	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>	1σ	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>		1σ
<i>Gneissic granitoid BU-2</i>																
27	20	23	0.87	0.06620	0.00792	0.62478	0.07176	0.06846	0.00268	813	232	493	44	427	16	62
28	19	19	1.00	0.06452	0.00464	0.60892	0.04198	0.06848	0.00186	759	145	483	26	427	11	56
29	49	60	0.82	0.06014	0.00392	0.57014	0.03576	0.06878	0.00176	609	135	458	23	429	11	35
30	41	47	0.88	0.06811	0.00270	0.64786	0.02416	0.06896	0.00144	872	80	507	15	430	9	68
31	14	16	0.88	0.06140	0.00366	0.64813	0.03696	0.07654	0.00184	653	123	507	23	475	11	32
32	49	37	1.30	0.05945	0.00660	0.64396	0.06884	0.07856	0.00282	584	224	505	42	488	17	18
33	33	35	0.94	0.05941	0.00446	0.64747	0.04686	0.07906	0.00216	582	155	507	28	491	13	17
<i>Gneissic granitoid BU-3</i>																
1	166	298	0.56	0.05574	0.00194	0.43111	0.01490	0.05612	0.00126	442	76	364	11	352	8	23
2	313	503	0.62	0.05388	0.00116	0.41937	0.00920	0.05645	0.00118	366	48	356	7	354	7	3
3	20	86	0.23	0.05608	0.00148	0.44570	0.01176	0.05768	0.00124	456	58	374	8	362	8	23
4	87	174	0.50	0.05412	0.00126	0.43906	0.01026	0.05885	0.00124	376	52	370	7	369	8	2
5	47	84	0.56	0.05818	0.00156	0.50210	0.01338	0.06258	0.00132	537	58	413	9	391	8	31
6	553	453	1.22	0.05791	0.00138	0.50982	0.01232	0.06390	0.00136	526	51	418	8	399	8	27
7	91	149	0.61	0.05909	0.00154	0.52043	0.01356	0.06393	0.00136	570	56	425	9	399	8	35
8	60	141	0.43	0.05510	0.00130	0.48881	0.01170	0.06436	0.00136	416	52	404	8	402	8	3
9	54	151	0.36	0.05636	0.00144	0.51120	0.01304	0.06577	0.00138	467	56	419	9	411	8	13
10	96	197	0.48	0.05811	0.00138	0.53344	0.01280	0.06658	0.00140	534	51	434	8	416	8	25
11	91	111	0.82	0.05631	0.00132	0.51820	0.01232	0.06675	0.00140	465	51	424	8	417	8	11
12	69	54	1.27	0.05781	0.00170	0.53614	0.01578	0.06730	0.00146	523	63	436	10	420	9	22
13	118	226	0.52	0.05720	0.00128	0.53732	0.01224	0.06812	0.00142	499	49	437	8	425	9	16
14	112	156	0.72	0.05514	0.00126	0.51854	0.01204	0.06820	0.00142	418	50	424	8	425	9	-2
15	32	32	1.00	0.06008	0.00218	0.56758	0.02034	0.06857	0.00156	606	77	456	13	428	9	35
16	70	69	1.02	0.05889	0.00146	0.55852	0.01384	0.06880	0.00146	563	53	451	9	429	9	27
17	32	52	0.62	0.05512	0.00156	0.52883	0.01496	0.06964	0.00150	417	62	431	10	434	9	-4
18	92	193	0.48	0.05737	0.00136	0.55741	0.01330	0.07050	0.00148	506	51	450	9	439	9	14
19	368	332	1.11	0.05573	0.00120	0.54233	0.01176	0.07056	0.00146	442	47	440	8	440	9	0
20	141	211	0.67	0.05651	0.00142	0.54969	0.01388	0.07060	0.00150	472	55	445	9	440	9	7
21	49	64	0.77	0.05781	0.00176	0.56287	0.01710	0.07068	0.00156	523	65	453	11	440	9	17
22	56	65	0.85	0.05837	0.00156	0.56941	0.01514	0.07077	0.00150	544	57	458	10	441	9	21
23	85	135	0.63	0.05665	0.00138	0.55392	0.01362	0.07091	0.00150	478	53	448	9	442	9	8
24	129	148	0.87	0.05749	0.00162	0.56296	0.01576	0.07101	0.00152	510	61	453	10	442	9	14
25	74	84	0.89	0.05655	0.00148	0.55454	0.01458	0.07118	0.00152	474	57	448	9	443	9	7
26	69	171	0.41	0.05865	0.00146	0.57851	0.01440	0.07151	0.00150	554	53	464	9	445	9	22
27	16	23	0.71	0.05648	0.00198	0.55946	0.01952	0.07191	0.00162	471	76	451	13	448	10	5
<i>Gneissic granitoid BU-12</i>																
1	42	56	0.75	0.05503	0.00138	0.52436	0.01266	0.06911	0.00136	413	55	428	8	431	8	-4
2	56	82	0.68	0.05633	0.00130	0.54005	0.01200	0.06954	0.00136	465	50	438	8	433	8	7
3	29	55	0.53	0.06282	0.00224	0.60264	0.02068	0.06958	0.00148	702	74	479	13	434	9	47
4	33	66	0.50	0.05907	0.00138	0.57181	0.01288	0.07022	0.00138	570	50	459	8	437	8	26
5	45	106	0.42	0.05419	0.00140	0.52488	0.01308	0.07025	0.00140	379	57	428	9	438	8	-14
6	42	114	0.37	0.06292	0.00190	0.60984	0.01784	0.07030	0.00144	706	63	483	11	438	9	47
7	21	61	0.34	0.05732	0.00134	0.55596	0.01252	0.07035	0.00138	504	51	449	8	438	8	14
8	132	135	0.97	0.05627	0.00132	0.54710	0.01244	0.07052	0.00138	463	51	443	8	439	8	5
9	26	97	0.26	0.05652	0.00126	0.54994	0.01170	0.07057	0.00138	473	49	445	8	440	8	7
10	31	190	0.16	0.05850	0.00174	0.57227	0.01646	0.07096	0.00144	549	64	459	11	442	9	22
11	18	67	0.28	0.05714	0.00132	0.55926	0.01238	0.07099	0.00138	497	50	451	8	442	8	12
12	22	29	0.74	0.06016	0.00160	0.59496	0.01536	0.07174	0.00144	609	56	474	10	447	9	31
13	24	55	0.43	0.05710	0.00136	0.56472	0.01304	0.07174	0.00140	495	52	455	8	447	8	10
14	51	116	0.44	0.05649	0.00138	0.56122	0.01314	0.07206	0.00142	472	53	452	9	449	9	5
15	71	162	0.44	0.05877	0.00124	0.58716	0.01192	0.07247	0.00140	559	45	469	8	451	8	21
16	28	45	0.62	0.06041	0.00190	0.60482	0.01836	0.07262	0.00150	618	66	480	12	452	9	31
17	46	104	0.45	0.06575	0.00148	0.65932	0.01434	0.07273	0.00142	798	46	514	9	453	9	55

(continued on next page)



Table 3 (continued)

Grain no.	Contents		Ratios						Ages (Ma)						Disc. (%)	
	Th	U	Th/U	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>	1σ	Pb <sup>207</sup> / Pb <sup>206</sup>	1σ	Pb <sup>207</sup> / U <sup>235</sup>	1σ	Pb <sup>206</sup> / U <sup>238</sup>		1σ
<i>Gneissic granitoid BU-12</i>																
18	95	186	0.51	0.05642	0.00122	0.56582	0.01176	0.07274	0.00142	469	47	455	8	453	9	4
19	20	51	0.40	0.05478	0.00136	0.55307	0.01330	0.07324	0.00144	403	55	447	9	456	9	-12
20	52	109	0.47	0.05852	0.00148	0.59103	0.01446	0.07325	0.00146	549	54	472	9	456	9	19
21	11	20	0.53	0.06439	0.00390	0.65061	0.03816	0.07329	0.00192	754	123	509	23	456	12	49
22	36	47	0.77	0.06128	0.00162	0.62031	0.01582	0.07343	0.00146	649	56	490	10	457	9	35
23	51	115	0.45	0.05683	0.00126	0.57561	0.01218	0.07347	0.00142	485	48	462	8	457	9	6
24	30	79	0.38	0.06030	0.00168	0.61321	0.01640	0.07376	0.00148	614	59	486	10	459	9	29
25	142	350	0.41	0.06539	0.00158	0.66529	0.01536	0.07379	0.00146	787	50	518	9	459	9	53
26	186	345	0.54	0.05575	0.00114	0.57023	0.01126	0.07418	0.00142	442	45	458	7	461	9	-4
27	18	43	0.42	0.05847	0.00164	0.60097	0.01620	0.07456	0.00150	547	60	478	10	464	9	17
28	33	38	0.87	0.05618	0.00156	0.57766	0.01544	0.07459	0.00150	459	60	463	10	464	9	-1
29	95	180	0.53	0.06409	0.00174	0.65982	0.01728	0.07468	0.00150	745	56	515	11	464	9	46
30	80	157	0.51	0.05584	0.00118	0.57975	0.01184	0.07530	0.00146	446	46	464	8	468	9	-5
31	38	87	0.44	0.06324	0.00168	0.66075	0.01700	0.07579	0.00152	716	55	515	10	471	9	41
32	43	250	0.17	0.05982	0.00128	0.62697	0.01298	0.07602	0.00148	597	46	494	8	472	9	23
33	72	188	0.38	0.06053	0.00126	0.63583	0.01276	0.07619	0.00148	623	44	500	8	473	9	27
34	24	46	0.53	0.05467	0.00136	0.58278	0.01390	0.07732	0.00152	399	55	466	9	480	9	-19
35	41	106	0.38	0.05508	0.00124	0.58924	0.01274	0.07760	0.00152	415	50	470	8	482	9	-15
36	103	297	0.35	0.05869	0.00122	0.62889	0.01258	0.07772	0.00150	556	45	495	8	482	9	14

intensity of the sedimentary source and the nature of the sedimentary provenance (Nesbitt and Young, 1982; Cox et al., 1995; Fedo et al., 1995). If elements were mobile during the metamorphism for the banded gneiss, CIA would increase and ICV would decrease because Na<sub>2</sub>O and K<sub>2</sub>O would be more easily removed than other elements from the system. However, the banded gneisses in this study all have low CIA and high ICV values (Fig. 3), indicating that metamorphism took place in a closed system and their chemical compositions, including CIA and ICV values, can be used to study the nature of their protoliths.

The banded gneisses have SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and CaO compositions similar to the associated gneissic granitoids (Table 2). However, the banded gneisses have higher A/NK [molar ratio of Al<sub>2</sub>O<sub>3</sub>/(Na<sub>2</sub>O+K<sub>2</sub>O), 2.15–2.77] and A/CNK values [molar ratio of Al<sub>2</sub>O<sub>3</sub>/(CaO+Na<sub>2</sub>O+K<sub>2</sub>O), mostly ~1.5]. These rocks are moderately enriched in light rare earth elements (LREE) (La<sub>N</sub>/Yb<sub>N</sub>=4.4–8.0), have negative Eu anomalies (Eu/Eu\*=0.5–0.7) and show Nb, Ta, and Sr troughs on a continental crust-normalized diagram (Fig. 4a and b). The occurrence of Al-rich minerals such as sillimanite and garnet is consistent with the chemical composition of the gneissic rocks. However, these rocks have relatively high contents of MgO, Ni, Cr, and U (Table 2), not favoring a pelitic source. The banded gneisses have Th/U ratios (2.0–3.9), lower than, or close to, the average value of the upper crust (3.8, McLennan and Taylor,

1980). These rocks also have relatively low Zr/Sc ratios (8–16.9, Table 2), lower than, or close to, those for the associated gneissic granitoids (9.9–25.3, Table 2).

The gneissic granitoids are chemically metaluminous to weakly peraluminous (A/CNK=1.06–1.32, Table 2), and biotite is the major mafic mineral. These rocks show an I-type granite trend in the SiO<sub>2</sub>–P<sub>2</sub>O<sub>5</sub> diagram of Chappell and White (1992) (not shown). They have negative Eu anomalies (Eu/Eu\*=0.4–0.6) and show two types of REE patterns, one with moderately LREE enrichment (La<sub>N</sub>/Yb<sub>N</sub> ~ 7) and the other without LREE enrichment but with some tetrad effect (La<sub>N</sub>/Yb<sub>N</sub> ~ 1) (Fig. 4c), possibly due to extensive differentiation with strong hydrothermal interaction (e.g. Basu, 1996; Irber, 1999; Jahn et al., 2001; Monecke et al., 2002; Wu et al., 2004). These granitoids are depleted in Nb, Ta, and Sr on a continental crust-normalized diagram, a pattern broadly similar to that of the banded gneisses (Fig. 4d), are characterized by low Sr/Y ratios (2.3–3.6, Table 2) and fall in the volcanic arc field in discrimination diagrams [such as the Rb–(Y+Nb) and Nb–Y diagrams of Pearce et al. (1984) and the Rb/10–Hf–Ta\*3 diagram of Harris et al. (1986), not shown].

## 6. Zircon U–Pb ages and Hf isotopic systematics

Zircon U–Pb and Hf isotopic results are presented in Tables 3 and 4 respectively. Hf isotopic analyses were performed on selected large zircon grains. Zircon

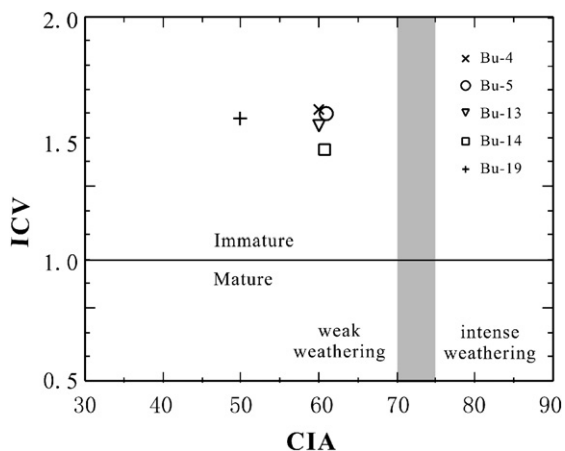
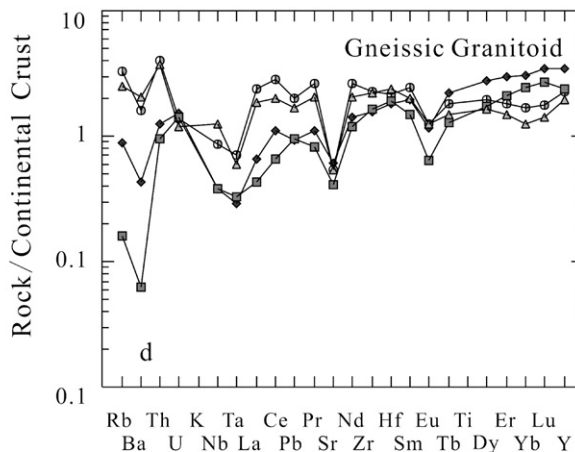
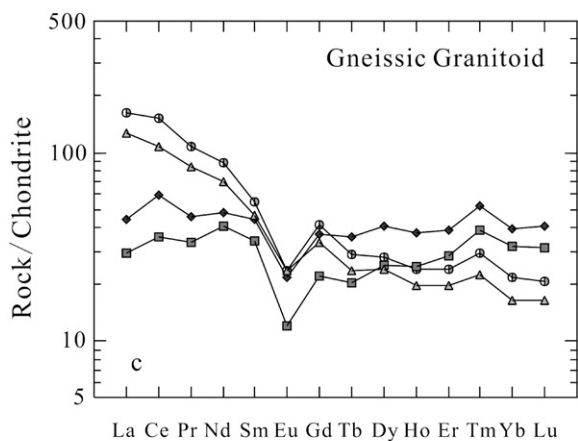
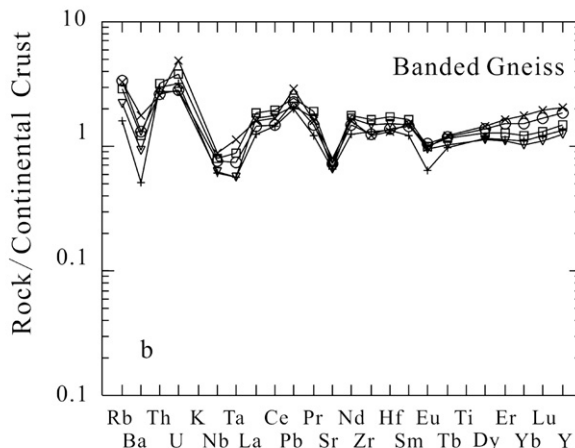
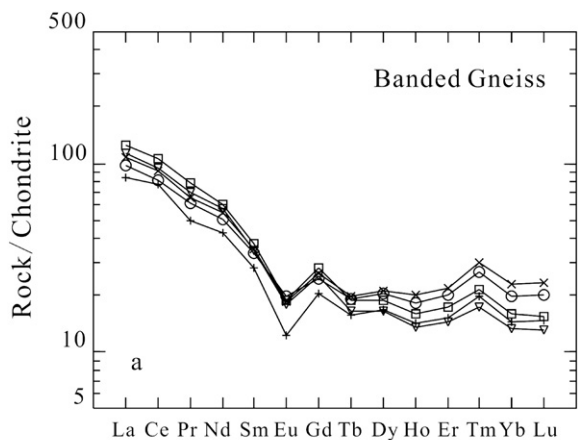


Fig. 3. CIA–ICV diagram for the banded paragneisses.

U and Th contents, Th/U ratios, morphological features, U–Pb ages and Hf isotopic compositions for each population of the analyzed samples are summarized in Table 5.

6.1. Banded gneisses

Three types of zircons are recognized from samples of banded paragneiss. Type-I zircons occur as euhedral, stubby, prismatic crystals (length/width ratio < 2.5), with concentric oscillatory zoning (Fig. 5a–f), and lack inherited cores. Their Th/U ratios are dominantly in the range of 0.1 to 1.0, implying an igneous origin (Hanchar and Rudnick, 1995) (Table 3). We interpret these zircons as possibly having been derived from nearby igneous rocks, with a very short sedimentary



× Bu-4 ○ Bu-5 ▽ Bu-13 □ Bu-14 + Bu-19 ◆ Bu-1 ■ Bu-2 ▲ Bu-3 ⊙ Bu-12

Fig. 4. Chondrite-normalized REE patterns and trace element spider variation diagrams for the banded paragneiss (a and b, respectively) and gneissic granitoids (c and d, respectively). Normalized values are from Sun and McDonough (1989).

transport. Type-II zircons are generally granular, with large, rounded cores surrounded by structureless, low-luminescence rims (Fig. 5g–j). Some cores show oscillatory zoning. One zircon grain in this group displays three stages of growth (Fig. 5h). The rounded zircon cores suggest derivation from a more distant source. Type-III zircons are also granular, but their cores appear to be broken fragments of an earlier generation, surrounded by low-luminescence, structureless rims (Fig. 5k–o). We suggest that the broken zircon cores may have been derived from pyroclastic rocks. Zircons from all analyzed samples of banded gneiss show large variations in U and Th contents, irrespective of their age (Table 3).

#### 6.1.1. Sample Bu-4

The majority of zircons from this sample give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $505 \pm 7$  Ma (Table 5 and Fig. 6a). These zircons have Type-I morphological features (Fig. 5) and yield  $\varepsilon_{\text{Hf}}(t)$  values from  $-7.0$  to  $+7.6$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.90 to 1.59 Ga (Table 4 and Fig. 7a).

In addition, four zircon grains give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $574 \pm 11$  Ma. Five zircons yield Neoproterozoic or late Mesoproterozoic ages ( $^{206}\text{Pb}/^{238}\text{U}$  ages from 638 to 1023 Ma, Tables 3 and 5 and Fig. 6a). These zircons have Type-I or Type-III characteristics and the Proterozoic zircons have been analysed for Hf isotopic compositions, giving  $\varepsilon_{\text{Hf}}(t)$  values from  $-1.8$  to  $+2.6$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 1.45 to 1.81 Ga (Table 4 and Fig. 7a).

Two rounded cores of Type-II zircons were analysed and give one concordant and one highly discordant data, i.e.  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1994 \pm 44$  Ma and  $2516 \pm 37$  Ma, respectively (Table 3 and Fig. 6a). The 1994 Ma zircon has an  $\varepsilon_{\text{Hf}}(t)$  value of  $-11.2$  and a  $T_{\text{DM}}^{\text{C}}$  model age of 3.04 Ga (Table 4 and Fig. 7a).

#### 6.1.2. Sample Bu-5

The majority of zircon populations of this sample give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $517 \pm 8$  Ma (Fig. 6b and Table 5). These zircons have Type-I or Type III morphological features, and yield  $\varepsilon_{\text{Hf}}(t)$  values from  $-17.5$  to  $+12.6$ , and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.64 to 2.12 Ga (Table 4 and Fig. 7b).

Additional 13 zircon grains yield Neoproterozoic  $^{206}\text{Pb}/^{238}\text{U}$  ages between 592 and 876 Ma,  $\varepsilon_{\text{Hf}}(t)$  values from  $-5.5$  to  $+10.7$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.83 to 1.71 Ga. One largely discordant analysis yielded a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $2048 \pm 58$  Ma, with an  $\varepsilon_{\text{Hf}}(t)$  value of  $+2.2$  and a  $T_{\text{DM}}^{\text{C}}$  model age of 2.43 Ga (Table 4 and Fig. 7b), and one slightly reversed point gave a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $2159 \pm 54$  Ma (Fig. 6b, Table 3).

#### 6.1.3. Sample Bu-13

The major population of zircons from this sample give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $481 \pm 11$  Ma (Fig. 6c and Table 5). These zircons have Type-I features and give  $\varepsilon_{\text{Hf}}(t)$  values from  $-6.4$  to  $+14.7$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.54 to 1.55 Ga (Table 4 and Fig. 7c).

One concordant and one discordant analysis gave  $^{206}\text{Pb}/^{238}\text{U}$  ages of  $573 \pm 10$  Ma and  $585 \pm 11$  Ma, respectively. Seven zircons with Type-I or Type-III features give Neoproterozoic  $^{206}\text{Pb}/^{238}\text{U}$  ages between 694 and 956 Ma,  $\varepsilon_{\text{Hf}}(t)$  values from  $-15.8$  to  $+7.19$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 1.07 to 2.21 Ga (Table 4 and Fig. 7c). One Type-I and one Type-III zircon give discordant Meso- and Paleo-proterozoic  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of  $1580 \pm 55$  and  $1942 \pm 54$  Ma, respectively (Fig. 6c and Table 3). Two Type-II zircons yield discordant  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of  $2347 \pm 72$ , and  $2626 \pm 46$  Ma, respectively (Fig. 6c and Table 3), and the 2347 Ma zircon yields an  $\varepsilon_{\text{Hf}}(t)$  value of  $-4.7$  and a  $T_{\text{DM}}^{\text{C}}$  model age of 3.01 Ga (Table 4 and Fig. 7c).

#### 6.1.4. Sample Bu-14

The majority of zircons from this sample give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $466 \pm 11$  Ma (Fig. 6d and Table 5). These zircons have Type-I structural features, and yield  $\varepsilon_{\text{Hf}}(t)$  values from  $-17.4$  to  $+3.8$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 1.03 to 2.07 Ga (Table 4 and Fig. 7d).

Other Type-I zircons are mostly Neoproterozoic ( $^{206}\text{Pb}/^{238}\text{U}$  ages between 640 and 907 Ma), with  $\varepsilon_{\text{Hf}}(t)$  values from  $-12$  to  $+10$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.99 to 1.96 Ga (Table 4 and Fig. 7d). Two Type-II zircons yield Paleoproterozoic or Archean  $^{207}\text{Pb}/^{206}\text{Pb}$  ages ( $1890 \pm 57$ ,  $2472 \pm 51$  and  $2634 \pm 65$  Ma, respectively, Fig. 6d and Table 3), and the 2472 Ma zircon gives an  $\varepsilon_{\text{Hf}}(t)$  value of  $-0.9$  and a  $T_{\text{DM}}^{\text{C}}$  model age of 2.93 Ga (Table 4 and Fig. 7d).

#### 6.1.5. Sample Bu-19

The major population give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $528 \pm 16$  Ma (Fig. 6e and Table 5). These zircons have Type-I morphological features, and their  $\varepsilon_{\text{Hf}}(t)$  values vary from  $-16.7$  to  $+11.8$ , and their  $T_{\text{DM}}^{\text{C}}$  model ages range from 0.72 to 2.09 Ga (Table 4 and Fig. 7e).

Five zircons with Type-I and one with Type-II features give Neoproterozoic  $^{206}\text{Pb}/^{238}\text{U}$  ages (729–936 Ma, Fig. 6e and Table 3),  $\varepsilon_{\text{Hf}}(t)$  values from  $-4.2$  to  $+9.5$  and  $T_{\text{DM}}^{\text{C}}$  model ages from 1.0 to 1.8 Ga (Table 4 and Fig. 7e).

### 6.2. Gneissic granitoids

Zircons from the gneissic granitoids are long, euhedral prisms (length/width ratio up to 4.5) (Fig. 8), similar to the Type-I morphology of zircons from the banded

Table 4

Lu–Hf isotopic data for zircons from banded gneiss and gneissic granitoid in the Chinese Altai

Grain no.	U–Pb age*	1 $\sigma$	<sup>176</sup> Yb/ <sup>177</sup> Hf	2 $\sigma$	<sup>176</sup> Lu/ <sup>177</sup> Hf	2 $\sigma$	<sup>176</sup> Hf/ <sup>177</sup> Hf	2 $\sigma$	( <sup>176</sup> Hf/ <sup>177</sup> Hf) <sub>i</sub>	$\epsilon$ Hf	$T_{DM}$ (Ga)	2 $\sigma$	$T_{DM}^C$ (Ga)	2 $\sigma$
<i>Banded gneiss BU-4</i>														
3	480	9	0.047227	0.000567	0.001559	0.000010	0.282404	0.000023	0.282390	-2.93	1.22	0.03	1.38	0.02
4	493	10	0.060872	0.001073	0.001430	0.000025	0.282461	0.000041	0.282447	-0.64	1.13	0.06	1.28	0.02
5	493	10	0.030111	0.000132	0.000827	0.000005	0.282277	0.000019	0.282269	-6.95	1.37	0.03	1.59	0.02
8	495	9	0.022433	0.000135	0.000678	0.000005	0.282434	0.000026	0.282428	-1.29	1.15	0.04	1.31	0.02
10	500	10	0.035897	0.000406	0.001113	0.000027	0.282569	0.000022	0.282558	3.45	0.97	0.03	1.08	0.02
13	504	10	0.059931	0.000468	0.002002	0.000032	0.282290	0.000022	0.282271	-6.65	1.40	0.03	1.58	0.02
14	506	10	0.023860	0.000240	0.000717	0.000011	0.282456	0.000023	0.282449	-0.28	1.12	0.03	1.27	0.02
18	516	10	0.030841	0.000128	0.001001	0.000015	0.282302	0.000018	0.282292	-5.62	1.34	0.02	1.54	0.02
19	520	10	0.061513	0.000216	0.001945	0.000011	0.282681	0.000021	0.282662	7.57	0.83	0.03	0.90	0.02
29	638	13	0.042875	0.000521	0.001569	0.000027	0.282344	0.000029	0.282325	-1.76	1.30	0.04	1.45	0.02
32	922	18	0.040659	0.000507	0.001086	0.000022	0.282289	0.000043	0.282270	2.61	1.36	0.06	1.48	0.02
33	1099	20	0.036440	0.001345	0.001135	0.000063	0.282073	0.000066	0.280490	-1.24	1.67	0.09	1.81	0.02
34	1994	34	0.011828	0.000138	0.000314	0.000004	0.281211	0.000020	0.281199	-11.20	2.80	0.03	3.04	0.02
<i>Banded gneiss BU-5</i>														
3	502	10	0.026313	0.001689	0.000922	0.000061	0.282416	0.000036	0.282407	-1.88	1.18	0.05	1.35	0.05
4	513	10	0.044306	0.000967	0.001594	0.000025	0.282499	0.000048	0.282484	1.11	1.08	0.07	1.21	0.07
5	514	10	0.024182	0.002315	0.000910	0.000091	0.281966	0.000075	0.281958	-17.52	1.81	0.10	2.12	0.10
7	515	10	0.067432	0.003282	0.002561	0.000118	0.282833	0.000209	0.282808	12.62	0.62	0.31	0.64	0.31
8	519	10	0.062453	0.001430	0.001913	0.000028	0.282714	0.000043	0.282695	8.73	0.78	0.06	0.84	0.06
10	522	10	0.018257	0.001843	0.000652	0.000071	0.282181	0.000051	0.282175	-9.64	1.50	0.07	1.74	0.07
12	525	11	0.042776	0.001479	0.001405	0.000049	0.282788	0.000091	0.282774	11.63	0.67	0.13	0.70	0.13
13	530	11	0.024129	0.001438	0.000816	0.000050	0.282535	0.000038	0.282527	3.01	1.01	0.05	1.13	0.05
14	533	11	0.047413	0.003850	0.001721	0.000131	0.282325	0.000035	0.282307	-4.70	1.34	0.05	1.51	0.05
16	538	12	0.041964	0.000858	0.001321	0.000021	0.282589	0.000035	0.282575	4.89	0.95	0.05	1.04	0.05
17	592	13	0.038650	0.001450	0.001214	0.000054	0.282590	0.000038	0.282576	6.11	0.94	0.05	1.03	0.05
18	610	15	0.046207	0.001041	0.001452	0.000023	0.282386	0.000048	0.282369	-0.83	1.24	0.07	1.39	0.07
20	623	14	0.024491	0.000126	0.000787	0.000011	0.282695	0.000023	0.282686	10.69	0.79	0.03	0.83	0.03
22	667	13	0.020278	0.001605	0.000760	0.000059	0.282230	0.000054	0.282220	-4.82	1.43	0.08	1.63	0.08
25	720	15	0.029156	0.000547	0.000913	0.000018	0.282181	0.000028	0.282168	-5.50	1.51	0.04	1.71	0.04
26	735	14	0.034249	0.000732	0.001146	0.000024	0.282344	0.000033	0.282328	0.50	1.29	0.05	1.42	0.05
28	787	16	0.019504	0.000528	0.000686	0.000018	0.282545	0.000034	0.282535	8.99	0.99	0.05	1.05	0.05
29	876	17	0.021296	0.000334	0.000759	0.000021	0.282531	0.000045	0.282518	10.39	1.01	0.06	1.05	0.06
30	2048	40	0.026698	0.000243	0.000947	0.000010	0.281577	0.000026	0.281540	2.17	2.34	0.04	2.43	0.04
<i>Banded gneiss BU-13</i>														
1	446	8	0.038181	0.000781	0.001232	0.000020	0.282469	0.000045	0.282458	-1.29	1.12	0.06	1.27	0.06
2	451	8	0.041609	0.000484	0.001480	0.000025	0.282801	0.000035	0.282788	10.50	0.65	0.05	0.69	0.05
3	457	8	0.025574	0.000279	0.001012	0.000010	0.282545	0.000027	0.282536	1.71	1.00	0.04	1.13	0.04
4	465	9	0.044046	0.001008	0.001598	0.000050	0.282663	0.000043	0.282649	5.91	0.85	0.06	0.93	0.06
5	466	10	0.026232	0.001916	0.000941	0.000070	0.282486	0.000033	0.282478	-0.15	1.08	0.05	1.23	0.05
6	468	9	0.032288	0.000556	0.001166	0.000023	0.282555	0.000040	0.282545	2.26	0.99	0.06	1.12	0.06
11	477	9	0.025591	0.001076	0.000949	0.000044	0.282304	0.000038	0.282296	-6.35	1.34	0.05	1.55	0.05
14	504	9	0.013696	0.000650	0.000640	0.000030	0.282753	0.000076	0.282747	10.22	0.70	0.11	0.75	0.11
15	507	11	0.029167	0.001320	0.001023	0.000059	0.282548	0.000038	0.282538	2.88	1.00	0.05	1.12	0.05
16	517	10	0.026767	0.001594	0.000890	0.000047	0.282340	0.000039	0.282331	-4.22	1.29	0.05	1.47	0.05
17	517	10	0.031689	0.000702	0.001011	0.000022	0.282874	0.000036	0.282864	14.67	0.54	0.05	0.54	0.05
19	573	10	0.036148	0.001281	0.001141	0.000042	0.282216	0.000053	0.282203	-7.50	1.47	0.07	1.68	0.07
22	701	13	0.013533	0.000734	0.000544	0.000032	0.282545	0.000037	0.282538	7.19	0.99	0.05	1.07	0.05
23	719	13	0.020339	0.000622	0.000703	0.000017	0.281887	0.000043	0.281878	-15.80	1.90	0.06	2.21	0.06
24	726	13	0.055304	0.001645	0.001704	0.000047	0.282542	0.000085	0.282518	7.05	1.03	0.12	1.09	0.12
25	794	14	0.034504	0.001869	0.001101	0.000058	0.282218	0.000041	0.282202	-2.64	1.46	0.06	1.63	0.06
27	956	17	0.057136	0.003901	0.001605	0.000087	0.282315	0.000043	0.282286	3.95	1.35	0.06	1.44	0.06
30	2347	30	0.006214	0.000983	0.000218	0.000039	0.281163	0.000063	0.281154	-4.72	2.85	0.08	3.01	0.08

(continued on next page)



Table 4 (continued)

Grain no.	U–Pb age*	1 $\sigma$	<sup>176</sup> Yb/ <sup>177</sup> Hf	2 $\sigma$	<sup>176</sup> Lu/ <sup>177</sup> Hf	2 $\sigma$	<sup>176</sup> Hf/ <sup>177</sup> Hf	2 $\sigma$	( <sup>176</sup> Hf/ <sup>177</sup> Hf) <sub>i</sub>	$\epsilon$ Hf	$T_{DM}$ (Ga)	2 $\sigma$	$T_{DM}^C$ (Ga)	2 $\sigma$
<i>Banded gneiss BU-14</i>														
3	435	8	0.059109	0.001909	0.002104	0.000079	0.282584	0.000034	0.282567	2.32	0.97	0.05	1.09	0.05
5	440	9	0.061922	0.001128	0.002123	0.000021	0.282549	0.000035	0.282532	1.17	1.03	0.05	1.15	0.05
6	447	9	0.037358	0.001736	0.001256	0.000057	0.282091	0.000037	0.282081	-14.64	1.65	0.05	1.92	0.05
7	449	9	0.028654	0.000748	0.000974	0.000031	0.282314	0.000029	0.282305	-6.65	1.33	0.04	1.54	0.04
8	455	9	0.032742	0.000996	0.001222	0.000035	0.282608	0.000030	0.282597	3.83	0.92	0.04	1.03	0.04
9	457	9	0.044209	0.001932	0.001661	0.000081	0.282325	0.000069	0.282311	-6.27	1.33	0.10	1.52	0.10
10	457	9	0.030293	0.000323	0.000980	0.000013	0.282418	0.000033	0.282410	-2.77	1.18	0.05	1.35	0.05
13	460	9	0.020041	0.001032	0.000722	0.000041	0.282001	0.000033	0.281995	-17.37	1.75	0.04	2.07	0.04
15	469	9	0.029765	0.000331	0.001086	0.000009	0.282436	0.000028	0.282427	-1.90	1.16	0.04	1.32	0.04
16	474	9	0.078844	0.003733	0.002888	0.000139	0.282601	0.000035	0.282575	3.48	0.97	0.05	1.06	0.05
19	483	9	0.036941	0.000702	0.001194	0.000010	0.282311	0.000056	0.282300	-6.06	1.34	0.08	1.54	0.08
23	521	10	0.051747	0.000904	0.001683	0.000028	0.282206	0.000032	0.282189	-9.16	1.50	0.05	1.72	0.05
24	524	10	0.023180	0.000274	0.000857	0.000011	0.282301	0.000033	0.282293	-5.42	1.34	0.05	1.54	0.05
25	640	12	0.113708	0.002535	0.003733	0.000093	0.282076	0.000036	0.282031	-12.13	1.79	0.05	1.96	0.05
27	745	14	0.033239	0.000385	0.001289	0.000019	0.282183	0.000036	0.282165	-5.05	1.52	0.05	1.70	0.05
28	766	14	0.017388	0.000301	0.000554	0.000009	0.282215	0.000031	0.282207	-3.09	1.45	0.04	1.63	0.04
29	774	18	0.017559	0.000392	0.000651	0.000011	0.282580	0.000028	0.282571	9.96	0.94	0.04	0.99	0.04
30	821	15	0.066782	0.001307	0.002251	0.000061	0.282467	0.000062	0.282432	6.12	1.15	0.09	1.22	0.09
32	907	17	0.040129	0.003047	0.001241	0.000068	0.282442	0.000037	0.282421	7.63	1.15	0.05	1.21	0.05
35	2472	41	0.036894	0.000421	0.001215	0.000014	0.281238	0.000033	0.281180	-0.90	2.83	0.05	2.93	0.05
<i>Banded gneiss BU-19</i>														
1	477	10	0.109696	0.008804	0.002806	0.000222	0.282655	0.000055	0.282630	5.48	0.89	0.08	0.96	0.02
2	483	9	0.038299	0.002504	0.000962	0.000049	0.282559	0.000021	0.282550	2.78	0.98	0.03	1.10	0.02
3	499	10	0.035754	0.000554	0.001095	0.000029	0.282432	0.000022	0.282422	-1.42	1.16	0.03	1.32	0.02
4	503	10	0.052423	0.001505	0.001698	0.000053	0.282399	0.000051	0.282383	-2.69	1.23	0.07	1.39	0.02
9	527	10	0.042901	0.000780	0.001012	0.000019	0.281983	0.000024	0.281973	-16.68	1.79	0.03	2.09	0.02
12	538	12	0.063694	0.003244	0.001964	0.000092	0.282712	0.000024	0.282692	9.04	0.79	0.03	0.84	0.02
15	554	13	0.033317	0.001441	0.001183	0.000054	0.282772	0.000125	0.282759	11.76	0.68	0.18	0.72	0.02
16	570	11	0.106679	0.000957	0.002378	0.000033	0.282485	0.000059	0.282459	1.50	1.13	0.09	1.24	0.02
17	581	13	0.023812	0.000173	0.000837	0.000010	0.282469	0.000018	0.282459	1.73	1.10	0.03	1.24	0.02
18	591	12	0.029093	0.000190	0.000862	0.000008	0.282299	0.000024	0.282290	-4.04	1.34	0.03	1.53	0.02
21	768	15	0.030391	0.001248	0.001020	0.000046	0.282574	0.000049	0.282560	9.45	0.96	0.07	1.01	0.02
24	920	17	0.048214	0.000503	0.001521	0.000021	0.282105	0.000029	0.282079	-4.20	1.64	0.04	1.81	0.02
<i>Gneissic granitoid BU-1</i>														
3	402	9	0.158440	0.002550	0.005005	0.000114	0.282639	0.000026	0.282601	2.79	0.97	0.04	1.03	0.04
4	404	14	0.081314	0.001776	0.002263	0.000050	0.282645	0.000026	0.282628	3.78	0.89	0.04	0.99	0.04
5	406	8	0.048478	0.000580	0.001521	0.000026	0.282693	0.000025	0.282681	5.72	0.80	0.04	0.89	0.04
7	413	12	0.108331	0.001434	0.003771	0.000043	0.282628	0.000035	0.282598	2.95	0.96	0.05	1.04	0.05
8	414	8	0.088701	0.002463	0.003066	0.000069	0.282784	0.000052	0.282760	8.69	0.70	0.08	0.75	0.08
9	415	24	0.091991	0.001105	0.002979	0.000034	0.282667	0.000024	0.282643	4.59	0.88	0.04	0.96	0.04
10	421	8	0.065373	0.001157	0.002116	0.000034	0.282632	0.000024	0.282616	3.73	0.90	0.03	1.00	0.03
11	426	8	0.083904	0.002672	0.002854	0.000101	0.282734	0.000034	0.282711	7.21	0.77	0.05	0.84	0.05
12	433	12	0.102582	0.001228	0.002928	0.000029	0.282682	0.000022	0.282658	5.50	0.85	0.03	0.93	0.03
13	474	12	0.138062	0.006301	0.004463	0.000223	0.282711	0.000032	0.282671	6.86	0.85	0.05	0.89	0.05
14	478	17	0.119203	0.000882	0.003863	0.000036	0.282649	0.000025	0.282614	4.92	0.93	0.04	0.99	0.04
15	493	9	0.062764	0.000316	0.001840	0.000005	0.282668	0.000024	0.282651	6.58	0.85	0.03	0.92	0.03
17	527	25	0.077826	0.000669	0.002324	0.000011	0.282637	0.000022	0.282614	6.01	0.90	0.03	0.98	0.03
18	539	8	0.072571	0.001591	0.002425	0.000062	0.282707	0.000050	0.282682	8.70	0.80	0.07	0.86	0.07
19	609	12	0.136141	0.004302	0.004441	0.000115	0.282681	0.000151	0.282630	8.40	0.89	0.23	0.93	0.23
21	843	14	0.083924	0.001583	0.002388	0.000029	0.282721	0.000027	0.282683	15.50	0.78	0.04	0.77	0.04
<i>Gneissic granitoid BU-2</i>														
1	366	10	0.104634	0.000825	0.002822	0.000023	0.282877	0.000035	0.282858	11.09	0.56	0.05	0.60	0.05
3	372	9	0.109093	0.001252	0.003048	0.000057	0.282980	0.000036	0.282959	14.79	0.41	0.05	0.42	0.05
4	375	8	0.129068	0.001300	0.003282	0.000061	0.282981	0.000043	0.282957	14.82	0.41	0.07	0.42	0.07

Table 4 (continued)

Grain no.	U–Pb age*	1 $\sigma$	<sup>176</sup> Yb/ <sup>177</sup> Hf	2 $\sigma$	<sup>176</sup> Lu/ <sup>177</sup> Hf	2 $\sigma$	<sup>176</sup> Hf/ <sup>177</sup> Hf	2 $\sigma$	( <sup>176</sup> Hf/ <sup>177</sup> Hf) <sub>i</sub>	$\epsilon_{\text{Hf}}$	$T_{\text{DM}}$ (Ga)	2 $\sigma$	$T_{\text{DM}}^{\text{C}}$ (Ga)	2 $\sigma$
<i>Gneissic granitoid BU-2</i>														
5	377	7	0.116985	0.001125	0.003337	0.000054	0.283043	0.000043	0.283019	17.03	0.32	0.07	0.31	0.07
8	378	8	0.093337	0.000882	0.002584	0.000040	0.282907	0.000043	0.282888	12.44	0.51	0.06	0.54	0.06
15	385	8	0.164779	0.005204	0.004820	0.000257	0.283028	0.000084	0.282993	16.31	0.35	0.13	0.35	0.13
16	387	8	0.183991	0.008856	0.004851	0.000195	0.282933	0.000035	0.282898	12.95	0.50	0.05	0.52	0.05
25	424	9	0.167217	0.004162	0.004586	0.000096	0.283007	0.000043	0.282970	16.35	0.38	0.07	0.38	0.07
<i>Gneissic granitoid BU-3</i>														
2	354	7	0.123238	0.003613	0.003195	0.000070	0.282666	0.000027	0.282645	3.28	0.88	0.04	0.97	0.04
3	362	8	0.085645	0.005231	0.002858	0.000159	0.282720	0.000052	0.282701	5.43	0.79	0.08	0.87	0.08
4	369	8	0.094213	0.002815	0.002550	0.000129	0.282787	0.000035	0.282769	8.01	0.69	0.05	0.75	0.05
5	391	8	0.073664	0.002381	0.002019	0.000075	0.282672	0.000026	0.282657	4.53	0.85	0.04	0.94	0.04
7	399	8	0.064554	0.001622	0.001998	0.000060	0.282707	0.000024	0.282692	5.96	0.79	0.03	0.88	0.03
12	420	9	0.054435	0.000717	0.001503	0.000017	0.282654	0.000026	0.282642	4.65	0.86	0.04	0.96	0.04
14	425	9	0.062717	0.001987	0.001714	0.000093	0.282828	0.000061	0.282814	10.86	0.61	0.09	0.66	0.09
15	428	9	0.121308	0.001984	0.004100	0.000067	0.282629	0.000035	0.282596	3.18	0.96	0.05	1.04	0.05
16	429	9	0.111849	0.002614	0.003505	0.000073	0.282732	0.000034	0.282704	7.02	0.79	0.05	0.85	0.05
18	439	9	0.051958	0.001413	0.001426	0.000034	0.282703	0.000024	0.282691	6.80	0.79	0.03	0.87	0.03
19	440	9	0.100275	0.003193	0.002756	0.000084	0.282653	0.000024	0.282631	4.67	0.89	0.04	0.97	0.04
21	440	9	0.066258	0.000660	0.001910	0.000016	0.282682	0.000029	0.282666	5.94	0.83	0.04	0.91	0.04
22	441	9	0.060804	0.000439	0.001637	0.000007	0.282727	0.000024	0.282714	7.64	0.76	0.03	0.83	0.03
23	442	9	0.062626	0.002447	0.002188	0.000072	0.282625	0.000050	0.282607	3.89	0.92	0.07	1.01	0.07
25	443	9	0.047914	0.002322	0.001261	0.000043	0.282678	0.000021	0.282667	6.04	0.82	0.03	0.91	0.03
27	448	10	0.068735	0.000500	0.002313	0.000038	0.282707	0.000026	0.282688	6.88	0.80	0.04	0.87	0.04
<i>Gneissic granitoid BU-12</i>														
2	433	8	0.081821	0.001577	0.002328	0.000048	0.282733	0.000031	0.282714	7.49	0.76	0.05	0.83	0.05
3	434	9	0.067204	0.002345	0.002181	0.000103	0.282707	0.000048	0.282689	6.62	0.80	0.07	0.87	0.07
4	437	8	0.067539	0.001758	0.001944	0.000051	0.282580	0.000039	0.282564	2.25	0.98	0.06	1.09	0.06
6	438	9	0.025383	0.001661	0.000820	0.000053	0.282791	0.000039	0.282784	10.08	0.65	0.05	0.70	0.05
7	438	8	0.064264	0.002857	0.001950	0.000086	0.282642	0.000031	0.282626	4.48	0.89	0.04	0.98	0.04
8	439	8	0.272317	0.008354	0.007947	0.000240	0.282694	0.000037	0.282628	4.58	0.97	0.06	0.98	0.06
10	442	9	0.063565	0.003692	0.001707	0.000093	0.282608	0.000027	0.282593	3.41	0.93	0.04	1.04	0.04
11	442	8	0.041940	0.000826	0.001395	0.000041	0.282865	0.000047	0.282854	12.62	0.55	0.07	0.58	0.07
12	447	9	0.069840	0.003146	0.002131	0.000088	0.282585	0.000028	0.282568	2.60	0.97	0.04	1.08	0.04
16	452	9	0.049197	0.002016	0.001484	0.000074	0.282605	0.000034	0.282592	3.59	0.93	0.05	1.04	0.05
17	453	9	0.061585	0.003372	0.001811	0.000111	0.282722	0.000029	0.282706	7.64	0.77	0.04	0.84	0.04
18	453	9	0.046743	0.001724	0.001436	0.000064	0.282782	0.000030	0.282770	9.88	0.67	0.04	0.73	0.04
20	456	9	0.067361	0.001834	0.001956	0.000056	0.282674	0.000033	0.282657	5.97	0.84	0.05	0.92	0.05
21	456	12	0.069153	0.002504	0.002089	0.000078	0.282599	0.000027	0.282581	3.28	0.95	0.04	1.06	0.04
22	457	9	0.066344	0.003577	0.001977	0.000095	0.282641	0.000033	0.282624	4.81	0.89	0.05	0.98	0.05
24	459	9	0.050849	0.001130	0.001427	0.000031	0.282690	0.000025	0.282678	6.76	0.81	0.04	0.89	0.04
25	459	9	0.050475	0.000664	0.001454	0.000024	0.282706	0.000036	0.282694	7.34	0.78	0.05	0.86	0.05
27	464	9	0.066283	0.001576	0.002000	0.000044	0.282652	0.000034	0.282635	5.36	0.87	0.05	0.96	0.05
28	464	9	0.069818	0.003294	0.002088	0.000090	0.282657	0.000030	0.282639	5.50	0.87	0.04	0.95	0.04
29	464	9	0.047566	0.000412	0.001413	0.000014	0.282620	0.000056	0.282608	4.41	0.91	0.08	1.01	0.08
30	468	9	0.075254	0.000492	0.002114	0.000012	0.282705	0.000026	0.282686	7.27	0.80	0.04	0.87	0.04
31	471	9	0.109054	0.002125	0.003696	0.000073	0.282704	0.000067	0.282671	6.80	0.84	0.10	0.89	0.10
32	472	9	0.049612	0.003276	0.001603	0.000089	0.282757	0.000026	0.282743	9.37	0.71	0.04	0.77	0.04
36	482	9	0.052730	0.001255	0.001573	0.000047	0.282667	0.000030	0.282653	6.40	0.84	0.04	0.92	0.04

paragneisses. They show concentric, oscillatory zoning, and have Th/U ratios from 0.2 to 1.6 (Tables 3 and 5). Compared to zircons from the banded gneisses, those from the granitoids lack inherited cores and overgrowth rims, and have lower U and Th contents (Table 3).

### 6.2.1. Sample BU-1

Most zircons cluster together and give a weighted mean <sup>206</sup>Pb/<sup>238</sup>U age of 412±5 Ma (Fig. 9a and Table 5), interpreted to be the crystallization age of the granitoid. Their  $\epsilon_{\text{Hf}}(t)$  values vary from +2.8 to +8.7,

Table 5

Summary of zircon U–Pb and Hf isotopic results for the banded gneiss and gneissic granitoid in the Chinese Altai

	No. of analysis	$^{206}\text{Pb}/^{238}\text{U}$ age (Ma)	Weighted mean (Ma)	Zircon type	U ppm	Th ppm	Th/U	$\varepsilon_{\text{Hf}}(t)$	$T_{\text{DM}}^{\text{C}}$ (Ga)
<i>Banded gneiss</i>									
BU-4	24	479–533	505±7	I	5–491	49–732	0.09–1.71	–7.0 to +7.6	0.90–1.59
	4	569–581	574±11	I or III	27–213	50–1121	0.08–0.94		
	5	638–1023		I or III	16–290	82–881	0.15–0.41	–1.8 to +2.6	1.45–1.81
	2	1994±44 <sup>a</sup> 2516±37 <sup>a</sup>		II	35–150	36–299	0.5–0.99	–11.2	3.04
BU-5	16	480–538	517±8	I or III	6–441	89–1016	0.02–0.75	–17.5 to +12.6	0.64–2.12
	13	592–876		I or III	12–740	36–1259	0.17–0.82	–5.5 to +10.7	0.83–1.71
	2	2048±58 <sup>a</sup> 2159±54 <sup>a</sup>		II	112–257	473–693	0.54–0.16	+2.2	2.43
BU-13	18	446–519	481±11	I	6–216	21–331	0.1–1.1	–6.4 to +14.7	0.54–1.55
	2	573–585		I	87–159	500–931	0.17		
	7	694–956		I or III	3–173	20–255	0.11–0.72	–15.8 to +7.2	1.07–2.21
	2	1580±55 <sup>a</sup> 1942±54 <sup>a</sup>		I or III	25–31	65–91	0.33–0.38		
	2	2347±72 <sup>a</sup> 2626±46 <sup>a</sup>		II	5–13	15–35	0.15–0.87	–4.7	3.01
BU-14	24	426–524	466±11	I	11–573	139–1336	0.02–0.83	–17.4 to +3.8	1.03–2.07
	8	640–907		I	20–264	57–1231	0.21–0.50	–12.1 to +10.0	0.99–1.96
	3	1890±57 <sup>a</sup> 2472±51 <sup>a</sup> 2634±65 <sup>a</sup>		II or I	42–701	140–2203	0.30–0.38	–0.9	2.93
BU-19	19	477–597	528±16	I	95–1419	161–1199	0.27–1.79	–16.7 to +11.8	0.72–2.09
	5	729–936		I	93–1125	156–2468	0.2–1.2	–4.2 to +9.5	1.0–1.8
<i>Gneissic granitoid</i>									
BU-1	12	401–433	412±5		120–703	215–594	0.43–1.18	+2.8 to +8.7	0.75–1.04
	6	474–539	505±23		75–1666	77–1635	0.36–1.38	+4.9 to +8.7	0.86–0.99
	4	609–878			660–1125	522–711	1.17–1.58	+8.4 to +15.5	0.77–0.93
BU-2	21	366–399	381±4		17–58	29–102	0.53–0.94	+11 to +17	0.31–0.60
	9	415–430	424±3		19–61	19–84	0.73–1.0	+16	0.38
	3	475–494	482±15		14–49	16–37	0.88–1.3		
BU-3	23	391–448	425±8		16–553	23–453	0.36–1.27	+3.2 to +10.9	0.66–1.04
	4	352–369	359±7		20–313	86–503	0.23–0.62	+3.3 to +8.0	0.75–0.97
BU-12	36	431–482	453±5		11–186	20–350	0.16–0.97	+2.3 to +12.6	0.58–1.09

<sup>a</sup>  $^{207}\text{Pb}/^{206}\text{Pb}$  age.

and their  $T_{\text{DM}}^{\text{C}}$  model ages range from 0.75 to 1.04 Ga (Table 4 and Fig. 10a).

Six zircons form a minor population with a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of 505±23 Ma (Fig. 9a, Table 3), and give  $\varepsilon_{\text{Hf}}(t)$  values from +4.9 to +8.7 and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.86 to 0.99 Ga. Four additional grains give Neoproterozoic  $^{206}\text{Pb}/^{238}\text{U}$  ages (609–878 Ma) (Fig. 9a, Table 3),  $\varepsilon_{\text{Hf}}(t)$  values from +8.4 to +15.5 and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.77 to 0.93 Ga (Table 4 and Fig. 10a). We note that zircon  $\varepsilon_{\text{Hf}}(t)$  values of this sample decrease linearly with zircon age (Fig. 10a).

### 6.2.2. Sample BU-2

The majority of zircons give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of 381±4 Ma (Fig. 9b, Table 3), considered to represent the crystallization age of the granitoid. The  $\varepsilon_{\text{Hf}}(t)$  values of these zircons vary from

+11.1 to +17.0, and their  $T_{\text{DM}}^{\text{C}}$  model ages are from 0.31 to 0.60 Ga (Table 4 and Fig. 10b).

A minor population is defined by nine analyses which give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of 424±3 Ma. One zircon from this group was analysed for Hf isotopic composition, giving a  $\varepsilon_{\text{Hf}}(t)$  value of +16 and a  $T_{\text{DM}}^{\text{C}}$  model age of 0.38 Ga (Table 4 and Fig. 10b). Three additional zircons yielded a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of 482±15 Ma. (Fig. 9b, Table 3).

### 6.2.3. Sample BU-3

Most zircons from this sample form a dense population and give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of 425±8 Ma (Fig. 9c and Table 3),  $\varepsilon_{\text{Hf}}(t)$  values from +3.2 to +10.9, and  $T_{\text{DM}}^{\text{C}}$  model ages from 0.66 to 1.04 Ga (Table 4 and Fig. 10c). This  $^{206}\text{Pb}/^{238}\text{U}$  age is considered to represent the crystallization age of this granitoid. The remaining

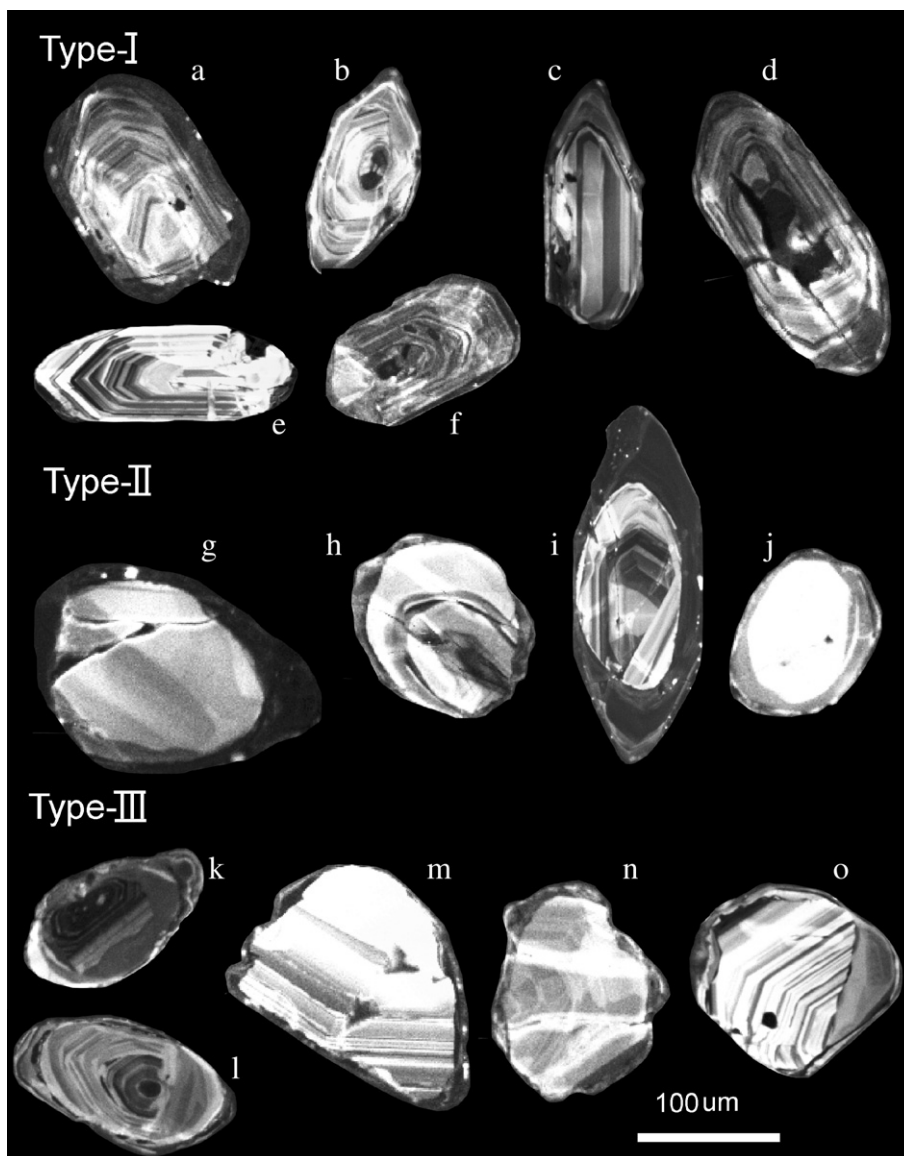


Fig. 5. Representative cathodoluminescence images for detrital zircons from the banded paragneisses. Three types of structural features are recognized: Type-I zircons are euhedral prismatic crystals without obvious cores, Type-II zircons are characterized by rounded cores and Type-III zircons have fragmented cores with overgrowth rims. The zircon grains with alphabetic order are BU-4(14), BU-5(1), BU-5(4), BU-13(15), BU-14(26), BU-14(12), BU-4(34), BU-13(31), BU-13(30), BU-5(30), BU5(22), BU-14(29), BU-13(29), BU-5(29). Numbers in bracket refer to grain numbers in Table 3.

four grains give a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $359 \pm 7$  Ma (Fig. 9c and Table 3), interpreted to be a result of a later thermal disturbance. Their  $\epsilon_{\text{Hf}}(t)$  values range from +3.3 to +8.0 and their  $T_{\text{DM}}^{\text{C}}$  model ages range from 0.75 to 0.97 Ga (Table 4 and Fig. 10c).

#### 6.2.4. Sample Bu-12

All the thirty six analysed zircons cluster together and yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $453 \pm 5$  Ma (Fig. 9d and Table 3),  $\epsilon_{\text{Hf}}(t)$  values from +2.3 to +12.6 and

$T_{\text{DM}}^{\text{C}}$  model ages from 0.58 to 1.09 Ga (Table 4 and Fig. 10d).

## 7. Discussion

### 7.1. Protoliths of the banded gneisses

This study shows that the banded gneisses of the Central Altai and Qiongkuer Domains are indistinguishable in geochemistry, zircon U–Pb age and Hf isotopic



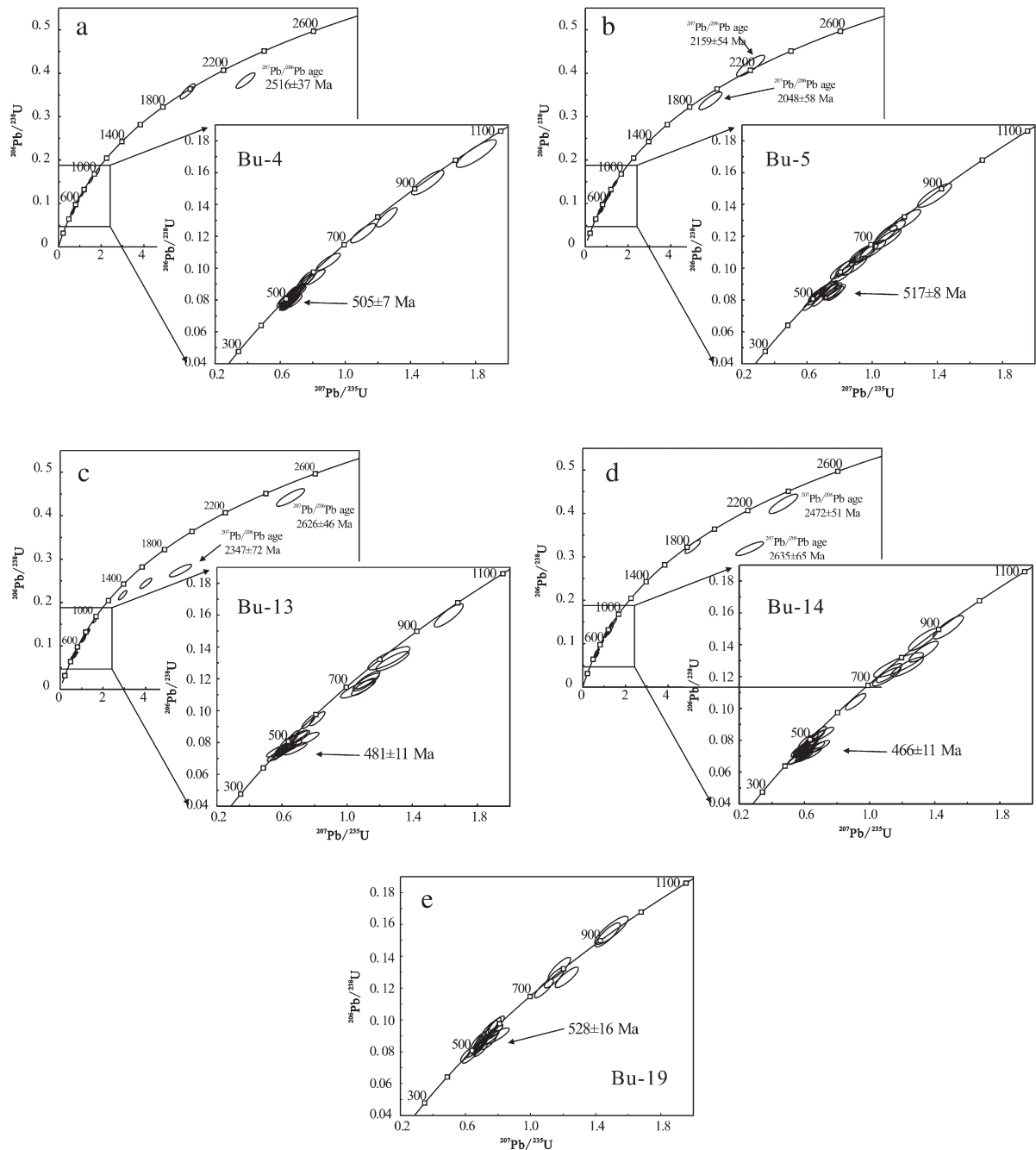


Fig. 6. U–Pb concordia diagrams for detrital zircons from the banded paragneisses.

composition. They have felsic compositions similar to the associated gneissic granitoids in terms of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{Sr}$ ,  $\text{Nb}$ ,  $\text{Y}$ , and  $\text{Zr}$  (Table 2). However, the banded gneisses can be distinguished from the gneissic granitoids by their banded structure, occurrence of sillimanite, relatively high A/NK and A/CNK values, negative DF values of Shaw (1972), and higher MgO contents (Table

2). Their protoliths cannot be mature sediments, because they have relatively high MgO, Ni, Cr, and U contents (Table 2). Removal of labile cations such as  $\text{K}^+$ ,  $\text{Na}^+$  and  $\text{Ca}^{2+}$  relative to stable residual constituents ( $\text{Al}^{3+}$ ,  $\text{Ti}^{4+}$ ) will result in high CIA values. For example, Phanerozoic shales generally have CIA values from 70 to 75 (Nesbitt and Young, 1982; 1984). On the other hand, because of

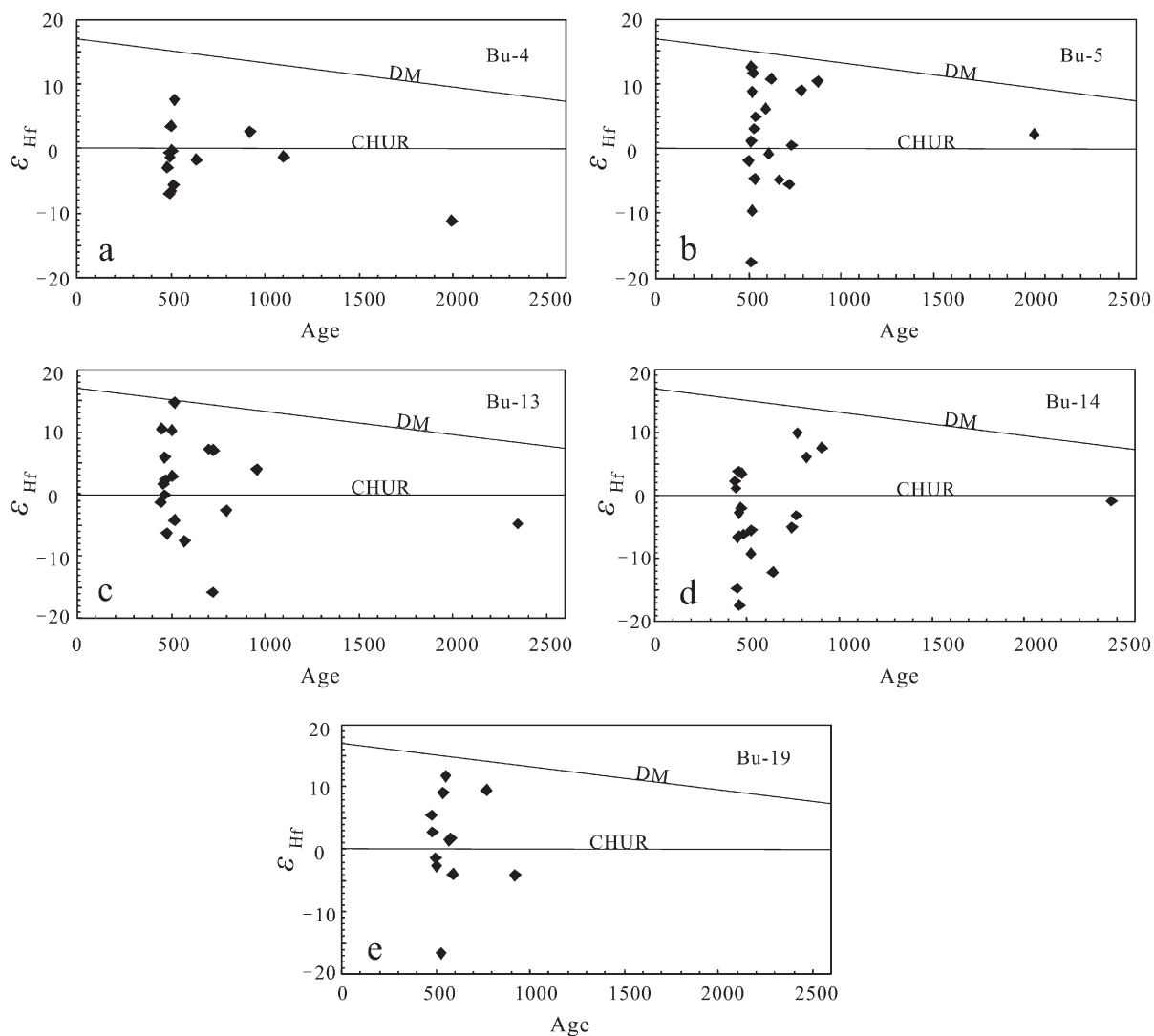


Fig. 7. Diagram of  $\epsilon_{\text{Hf}}$  values vs. U–Pb ages for zircons from the banded paragneisses.  $^{206}\text{Pb}/^{238}\text{U}$  ages are used for gains < 1000 Ma, and  $^{207}\text{Pb}/^{206}\text{Pb}$  ages are used for gains > 1000 Ma.

the high contents of  $\text{Al}_2\text{O}_3$  in clay minerals, mature sediments such as passive continental margin deposits have low ICV values (Cox et al., 1995). The banded gneisses in this study all have low CIA and high ICV values (Fig. 4), indicating the immature nature of their protoliths. Their low Zr/Sc and Th/U ratios also suggest the immature nature of these rocks, because these ratios will increase significantly in sediment recycling due to zircon enrichment and formation and removal of highly soluble  $\text{U}^{+6}$ -bearing species, respectively (McLennan and Taylor, 1980). In summary, our geochemical data suggest that the protoliths of these banded gneisses were immature clastic sediments, possibly containing significant amounts of volcanic material.

These paragneisses contain three different types of zircons (Fig. 5). Type-I zircons are interpreted to have had very short sedimentary transport and possibly derived from nearby igneous rocks, based on their euhedral prismatic shape, concentric oscillatory zoning, high Th/U ratios and the lack of inherited cores. Type-II zircons possibly underwent longer transport as shown by their large, rounded cores. The fragmental cores of Type-III zircons are considered to be a result of volcanic eruption and therefore we interpret this type of zircons originally came from a pyroclastic source. We did not study the thin structureless, low-luminescence rims on Type-II and Type-III zircons, which are possibly metamorphic in origin. These variations in zircon

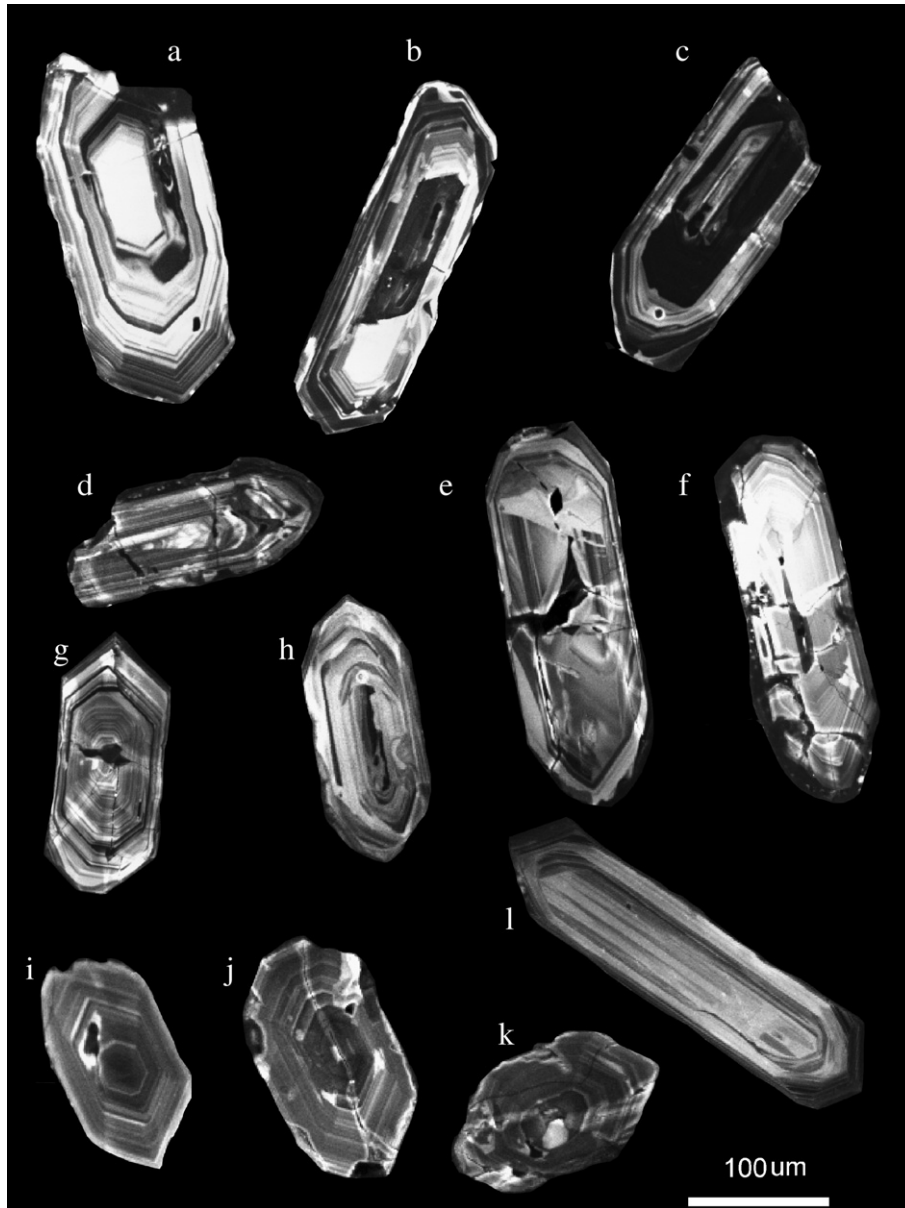


Fig. 8. Representative cathodoluminescence images for magmatic zircons from the gneissic granitoids. All zircons are euhedral prismatic. The zircon grains with alphabetic order are BU-1(18), BU-1(17), BU-1(22), BU-3(21), BU-3(5), BU-3(16), BU-12(36), BU-12(25), BU-2(9), BU-2(4), BU-2(3), BU-12(22). The numbers in bracket refer to the grain numbers in Table 3.

structure suggest a variety of sources for the banded gneisses, possibly including local magmatic rocks, input of contemporaneous volcanic material, and contributions from remote sedimentary sequences. Compared with the gneissic granitoids, which have zircons with relatively low and narrow ranges of U contents and Th/U ratios, the banded gneisses have zircons with large variations in both Th and U (Table 3, Fig. 11). This feature may also imply diverse sources for their protoliths. Hence, we suggest that

the protoliths were immature clastic sediments with significant input from nearby magmatic rocks and minor contributions from distant sedimentary sequences.

### 7.2. Age of banded paragneisses and significance of early Paleozoic zircons

The high-grade metamorphic rocks in the region were previously considered to be the high-grade metamorphic

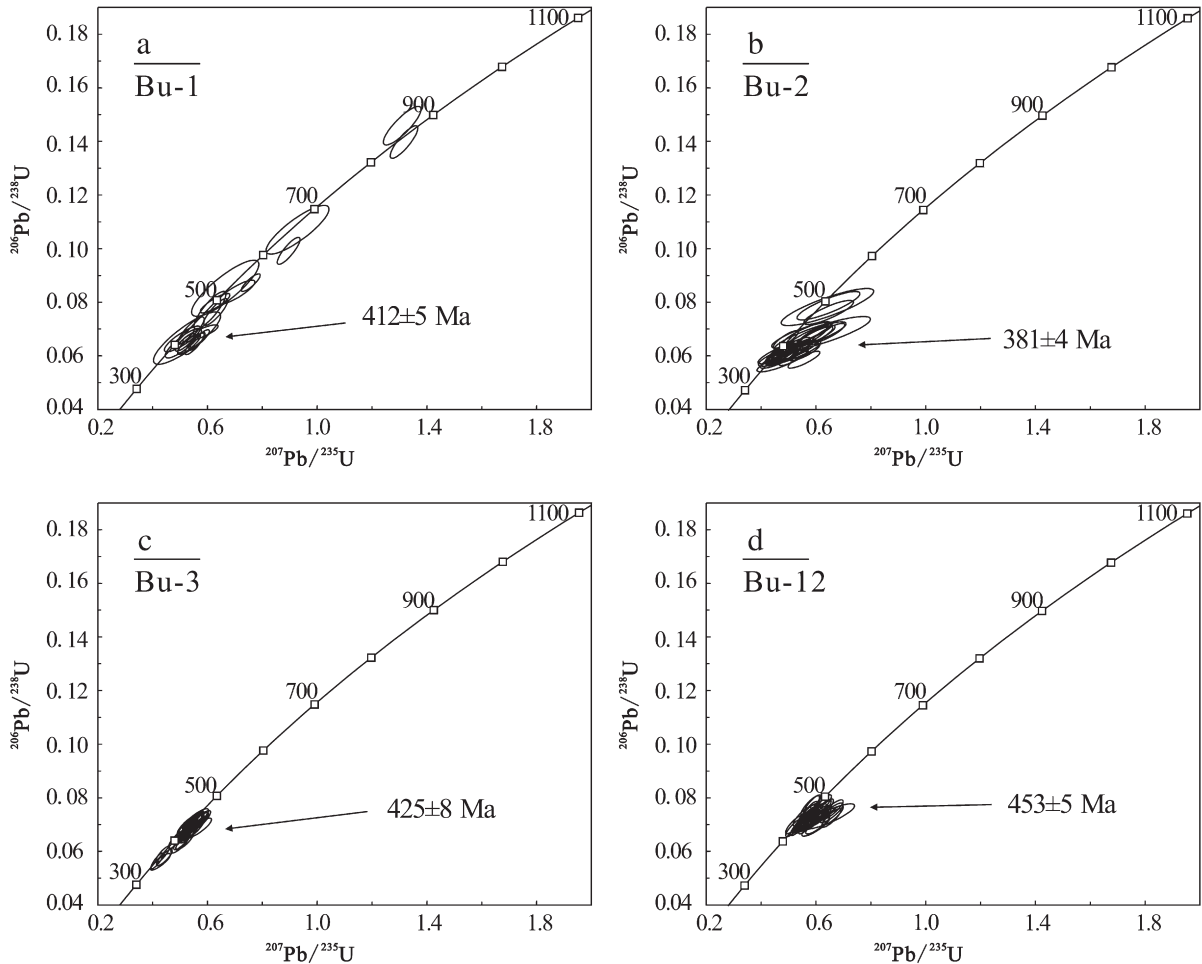


Fig. 9. U–Pb concordia diagrams for zircons from the gneissic granitoids.

equivalents of the Habahe Group, but more recently have been assigned Proterozoic ages (e.g. Li et al., 1996, 2006). Consequently, they were considered to represent a Precambrian basement (e.g. Windley et al., 2002; Li et al., 2003) or a microcontinent that may extend southwards and also underlie the Junggar Basin (Li et al., 2006). Our data indicate that the sedimentary protoliths of the banded gneisses cannot be older than 466 Ma, the youngest zircon population age of these rocks, and cannot be younger than 453 Ma, the oldest intrusive gneissic granitoid dated in this study. Therefore, the banded gneisses cannot represent a Precambrian basement, but, instead, were probably deposited in the Ordovician.

The youngest zircons from each sample of the banded gneisses always form a dominant  $^{206}\text{Pb}/^{238}\text{U}$  age population (Table 3 and Fig. 6), i.e. 466, 481, 505, 517, and 528 Ma, respectively for the analyzed samples. Because these zircons mostly have Type-I, with minor

Type-III, morphological features (Table 5 and Fig. 5), we suggest that Early Paleozoic igneous rocks could have been the major source for the banded gneiss protoliths. Indeed, volcanic rocks of this age exist in the Central Altai, such as the  $505\pm 2$  Ma rhyolite (Pb–Pb zircon evaporation age) dated by Windley et al. (2002) and the  $475\pm 5$  Ma dacite (zircon U–Pb age) dated by Shan et al. (2005).

The Early Paleozoic zircons from the banded gneisses have a large variation in Hf isotopic compositions, i.e. their  $\epsilon\text{Hf}(t)$  values ranging continuously from  $-17$  to  $+15$  (Table 5). Such a large isotopic variation indicates both juvenile and old materials were involved in the generation of magmas in which these zircons crystallized. The continuous  $\epsilon\text{Hf}(t)$  variation and the large number of zircons with positive  $\epsilon\text{Hf}(t)$  values suggest a possible magma mixing process with juvenile magma as the major component. A subduction

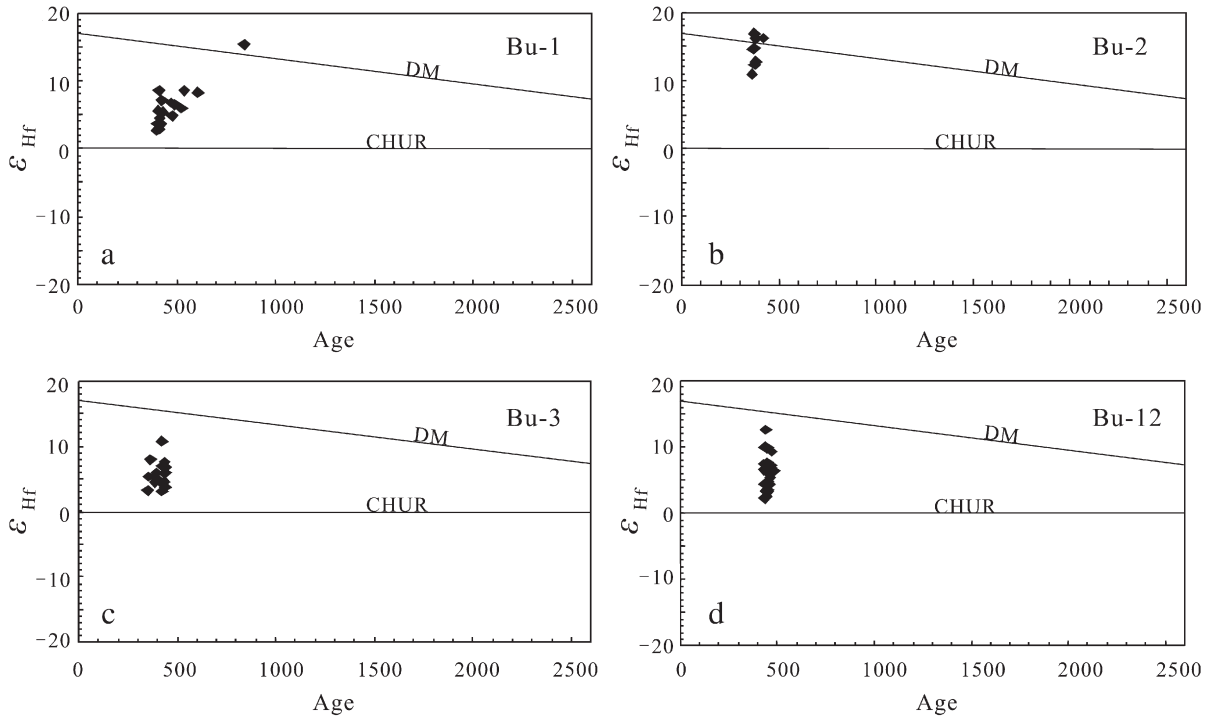


Fig. 10. Diagram of  $\epsilon_{\text{Hf}}$  values vs.  $^{206}\text{Pb}/^{238}\text{U}$  ages for zircons from the gneissic granitoids.

environment would be ideal for such a magmatic activity, therefore, our data may imply an important crustal accretionary process in the Early Paleozoic. The calcalkaline geochemical compositions of the above mentioned Early Paleozoic felsic volcanic rocks in the Chinese Altai support this interpretation (Windley et al., 2002; Shan et al., 2005).

Our recent geochemical and geochronological studies demonstrate that the Habahe Group metasediments contain detrital zircons with ages dominantly in the

range of 460 to 570 Ma and may have been deposited in a continental arc or an active continental margin setting (Long et al., 2006, 2007, in press). Results of this study suggest some genetic link between the banded gneisses and the Habahe Group metasedimentary rocks: the banded gneisses are possibly high-grade metamorphic equivalent of the Habahe Group, they both deposited in a continental arc or active continental margin environment. Our data do not support a simple basement-cover relationship in the Chinese Altai.

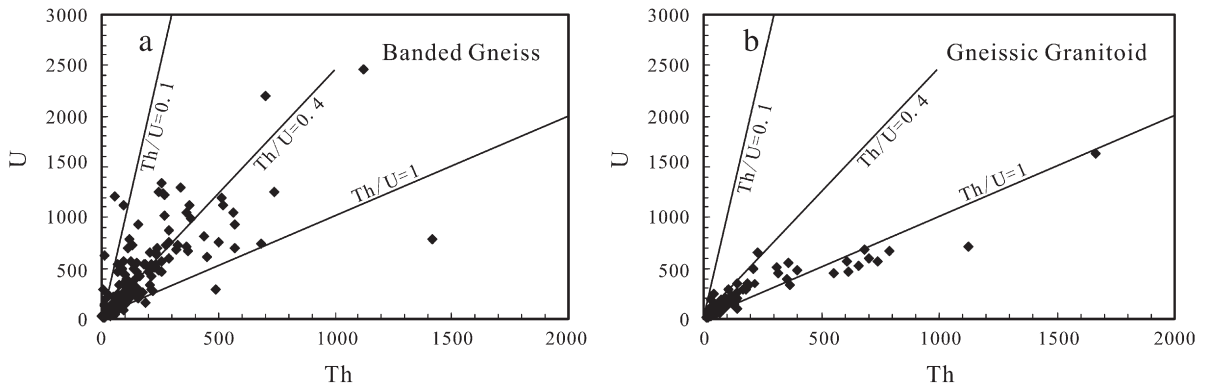


Fig. 11. U–Th diagram for zircons from the banded paragneisses and gneissic granitoids.



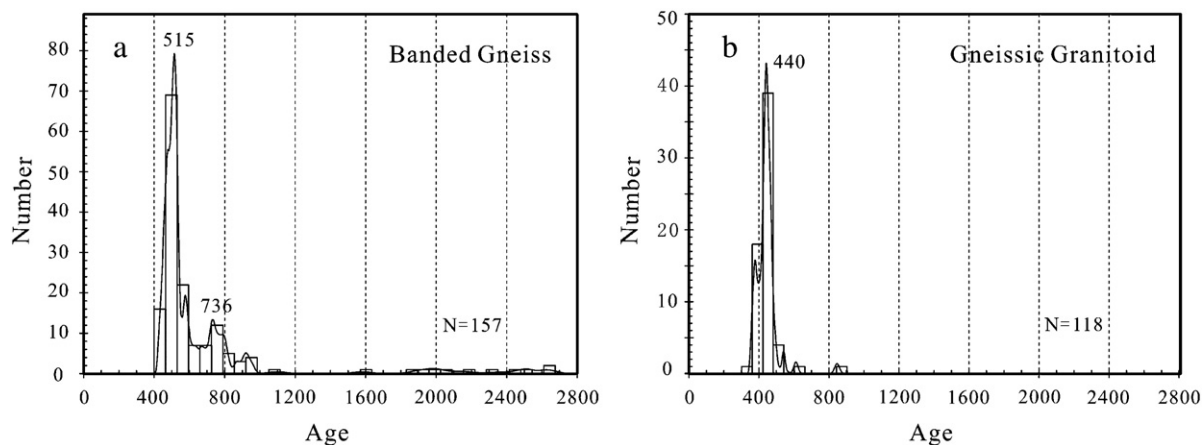


Fig. 12. Zircon age histogram for the banded paragneisses and gneissic granitoids.

### 7.3. Origin and significance of the gneissic granitoids

The gneissic granitoids are metaluminous, show characteristics of I-type granites, and plot in arc field in tectonic discrimination diagrams. Our zircon Hf data clearly indicate contribution of juvenile materials in their petrogenesis. Therefore we suggest that these granitoids were emplaced in a subduction-related environment. Our data indicate that the gneissic granitoids were emplaced between 453 and 381 Ma (Fig. 9 and Table 3). This age range is systematically, but only slightly, younger than the dominant early Paleozoic zircon populations of the banded paragneisses (528 to 466 Ma, Fig. 12 and Table 3). However, zircons from the gneissic granitoids are geochemically different from the Paleozoic zircons of the banded gneisses: (1) they generally have low U contents (mostly <700 ppm)

and high Th/U ratios (mostly >0.4), whereas those from the banded gneisses have more variable U contents and Th/U ratios (Fig. 11); and (2) they all have positive  $\epsilon\text{Hf}(t)$  values and the highest ones plot on the depleted mantle evolution line, whereas those from the banded gneisses have more variable  $\epsilon\text{Hf}(t)$  values (–17.5 to +14.7) (Figs. 7 and 10). These features may imply a significant increase in the contribution of juvenile material to the magma source in the middle Paleozoic (453–380 Ma). This is also reflected in the Hf model ages ( $T_{\text{DM}}^{\text{C}}$ ); those for the gneissic granitoids are generally younger than 1.0 Ga, whereas those for the early Paleozoic zircons are mostly older than 1.0 Ga (Table 4, Fig. 13).

The gneissic granitoids represent an important episode of magmatic activity in the region, because other large gneissic plutons were also emplaced in the

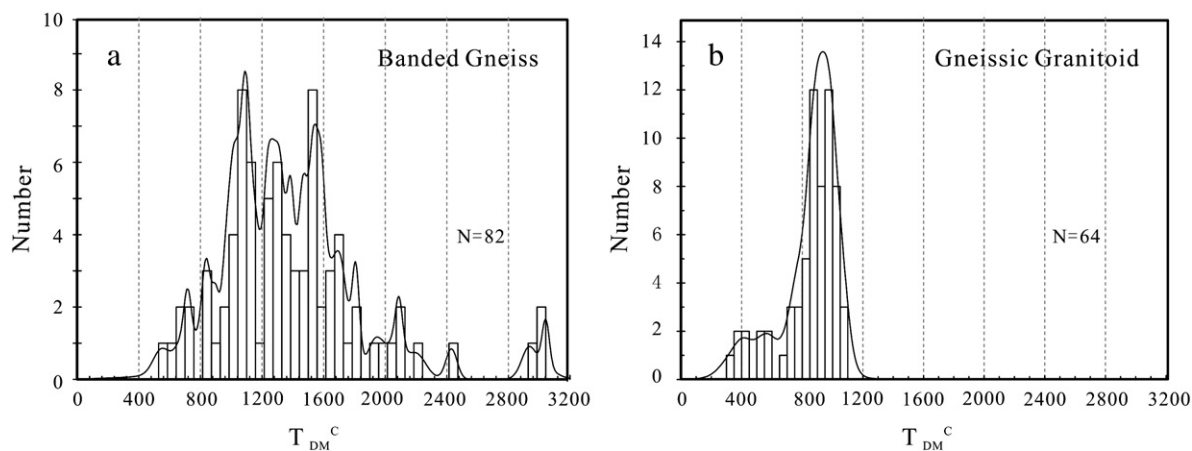


Fig. 13. Hf isotope model age ( $T_{\text{DM}}^{\text{C}}$ ) histogram for zircons from the banded paragneisses and gneissic granitoids.

Chinese Altai during the same time period, e.g. 402–386 Ma (Wang et al., 1998),  $380 \pm 1$  Ma (Windley et al., 2002),  $409 \pm 5$  Ma (Tong et al., 2005) and 460–375 Ma (Wang et al., 2006).

#### 7.4. Prolonged magmatic activity in the Chinese Altai and its tectonic significance

Our study demonstrates a prolonged period of magmatic activity, from the Neoproterozoic to early–middle Palaeozoic, throughout the Central Altai and Qiongkuer Domains. Neoproterozoic detrital zircons are relatively common in the banded paragneisses (Table 3 and Fig. 6), but their sources have not yet been identified although their Type-II and Type-I morphological features imply relatively short sedimentary transport and a nearby origin (Fig. 5). Early and middle Paleozoic magmatic activity is manifested by the dominant zircon populations of the banded paragneisses (466–528 Ma) (Fig. 6 and Table 3) and the associated gneissic granitoids (381–453 Ma) (Fig. 9 and Table 3).

Wang et al. (2006) recently dated six gneissic granite plutons in the Central Altai and Qiongkuer Domains and defined three phases of plutonic activity at ca. 460, 408, and 375 Ma. They concluded that the Altai orogen mainly developed in the early to middle Paleozoic and not in the late Paleozoic as previously proposed (e.g. He et al., 1990, 1994). Our data support this interpretation. Based on the apparent age gap between 460 and 408 Ma, Wang et al. (2006) proposed a model involving the opening and closure of a back-arc basin along the southern margin of the Central Altai Domain. If this model is correct, the Silurian–early Devonian volcanic and pyroclastic rocks of the Kangbutiebo Formation in the Qiongkuer Domain (Fig. 1) should have been formed in this back-arc basin. However, geochemical data suggest an arc setting for the Kangbutiebo Formation (e.g. Windley et al., 2002; Xiao et al., 2004). The four samples of gneissic granitoid dated in this study provided mean  $^{206}\text{Pb}/^{238}\text{U}$  zircon ages of 453, 426, 412, and 381 Ma respectively. These data are in the same range as those reported by Wang et al. (2006) but disprove the assumed age gap in magmatic activity and instead show quasi continuous magmatic activity from the early to middle Palaeozoic in the Central Altai and Qiongkuer Domains. The Kangbutiebao volcanic rocks apparently represent just one eruptive member of the magmatic sequence in the middle Palaeozoic.

We propose the following tectonic scenario for the development of the Chinese Altai. In the early Palaeozoic (528–466 Ma), a magmatic arc was built on a Neoproterozoic continental margin which, in turn, may

represent a Neoproterozoic arc system on a still older continental margin. Some zircons from the banded paragneiss have negative  $\epsilon\text{Hf}(t)$  values, implying the involvement of some older lower crust in the magma source (Fig. 7), but the dominant Mesoproterozoic zircon Hf model ages from the banded gneiss do not support an Archaean basement (Fig. 13). We emphasize that even if an old basement exists in the Chinese Altai, it is not represented by the banded gneisses studied here. These gneisses represent supracrustal material deposited in an early Palaeozoic active margin setting, and their protoliths may represent contemporaneous volcanic material mixed with components derived from pre-existing Neoproterozoic rocks.

The protoliths of the banded paragneiss were carried to depths of possibly 20 km or more (Wei et al., 2007), probably by subduction along the southern margin of the Qiongkuer Domain, and were intruded by the gneissic granitoids at 453–380 Ma during an on-going tectono-metamorphic process. This plutonic activity is characterized by magma derived predominantly from juvenile (i.e., mantle-derived) sources, as demonstrated by the positive  $\epsilon\text{Hf}(t)$  values and mean crustal residence ages younger than 1.0 Ga (Figs. 10 and 13).

#### 7.5. Constraints on the tectonic evolution of the Chinese Altai

The evolutionary history of the Chinese Altai is controversial and currently debated. Its early tectonic setting has been envisaged as an island arc (Şengör and Natal'in, 1996), passive continental margin (He et al., 1990), or a Precambrian microcontinent (Li et al., 2006). The traditional opening-closure model proposed for the Altai inferred the existence of a Precambrian microcontinent in the Junggar or Junggar–Altai region (e.g. He et al., 1990, 1994; Huang et al., 1990; Xiao et al., 1990, 1992; Yuan, 1995; Li et al., 1996; Liu et al., 1998; Li and Poliyangsi, 2001). However, recent studies do not support the microcontinent model (e.g. Zhou, 1994; Han et al., 1997; Chen and Jahn, 2002; Wang et al., 2002; Hu and Wei, 2003; Yuan et al., 2006; Zheng et al., 2007; Long et al., 2007). Our data suggest that the banded paragneisses from the Central Altai and Qiongkuer Domains were formed on an active continental margin in the early Paleozoic, and thus do not represent an old continental fragment. Recent Pb isotopic data for magmatic and sedimentary rocks and ore deposits from this region also show predominantly juvenile characteristics (Chiaradia et al., 2006).

Although Neoproterozoic and sparse Paleoproterozoic–Archaean detrital zircons are present in the banded

paragneisses, Precambrian rocks have not been identified in the Chinese Altai. The Neoproterozoic zircons mostly have Type-III or Type-I morphological features (Table 3 and Fig. 5), possibly suggesting a nearby source. These data suggest that nearby Neoproterozoic felsic pyroclastic or intrusive rocks were also a source for the protolith of the banded gneisses. We identified some zircons with discordant Paleoproterozoic to Archean  $^{207}\text{Pb}/^{206}\text{Pb}$  ages (1890 to 2634 Ma, Table 3). Most of these have Type-II structural features (e.g., rounded cores), indicating long transport from a remote source. These old zircons may have been derived from a nearby continent or a continental sliver. In the Central Asian Orogenic Belt, Precambrian slivers are interpreted to have been rifted off the Siberia Craton (Berzin and Dobretsov, 1994; Şengör and Natal'in, 1996), or off Eastern Gondwana and drifted across the Paleo-Asian ocean (Zonenshain et al., 1990; Mossakovsky et al., 1993; Kheraskova et al., 2003). There are three major Precambrian cratons in the vicinity of the Chinese Altai, i.e. the Siberia Craton to the north, the North China Craton to the southeast, and the Tarim Craton to the south. Abundant U–Pb age data have been published for zircons from these three cratons. The main magmatic events at 2.9–2.7, 2.6–2.45 and 2.35–1.95 Ga and important metamorphic events have been identified at 2.6–2.4 Ga and 1.9–1.8 Ga for the North China Craton (e.g. Zhang et al., 1996; Zhao et al., 2000; Guan et al., 2002; Zhai and Liu, 2003; Kröner et al., 2005; Wilde and Zhao, 2005; Wan et al., 2006). This craton was tectonically stable from 1.65 to 0.16 Ga (Zhai and Liu, 2003). The Tarim Craton has a basement with ages of 2.6–2.3 Ga intruded by 1.94-Ga granitoids. Neoproterozoic volcanic rocks (700–800 Ma) on its margin have been interpreted to record rifting from Rodinia (e.g. Guo et al., 2003; Xu et al., 2005; Zhang et al., 2006; Hu and Wei, 2006; Lu et al., in press). Early magmatic events on the Siberian Craton are confined to two periods at  $\sim 3.4$ –2.6 Ga and 2.2–1.7 Ga (e.g. Bibikova et al., 1981; Kuzmin et al., 1995; Bruguier, 1996; Frost et al., 1998; Jahn et al., 1998; Ross and Villeneuve, 1998; Khudoley et al., 2001). Zircon ages indicate that the Siberian Craton was bordered, along its present southern margin, by a  $\sim 1.0$  Ga ophiolite belt (Khain et al., 1997; 2002; Ritsk et al., 1999), and several island arcs, seamounts, accretionary wedges were formed and accreted to the margin of the Siberia Craton between *c.* 900 and 544 Ma (Gladkochub et al., 2006; Windley et al., 2007). The available data show age peaks at 880–860,  $\sim 800$ , 760–720, 700–630 and 536–464 Ma (Gladkochub et al., 2006 and references therein). The zircon age spectra of the banded paragneisses of this

study are compatible with a model in which the Precambrian zircons were derived from (a sliver of?) the southern margin of the Siberian Craton. The occurrence of Ordovician ophiolites in the southern, but not northern margin, of the Chinese Altai may also favor this interpretation (Khain et al., 2003; Wang et al., 2003; Xiao et al., 2006). The Tuva–Mongolian block in Mongolia is a nearby microcontinent with a Paleoproterozoic–Archean basement (e.g. Bardarch and Tomurtogoo, 2001; Kuzmichev et al., 2001; Badarch et al., 2002). Paleomagnetic data suggest that this block was still adjacent to Siberia in the Vendian and early Cambrian (Kravchinsky et al., 2001). Early Paleozoic granitoids were emplaced on this block at 536–465 Ma (Salnikova et al., 2001), about the same time as the deposition of the protoliths of the paragneisses from the Chinese Altai (528–466 Ma, this study), possibly implying some genetic link.

## 8. Conclusions

Banded paragneisses from the Chinese Altai contain zircons with diverse chemical and Hf isotopic compositions [ $\epsilon\text{Hf}(t)$  from  $-17$  to  $+15$ ]. These zircons dominantly crystallized in the early Palaeozoic (466–528 Ma), some were formed in the Neoproterozoic, and Paleoproterozoic to Archean zircons are rare. The gneissic granitoids intruded the paragneisses at 380–450 Ma, and their zircons show a juvenile magma source ( $\epsilon\text{Hf}(t)$  from  $+2.3$  to  $+17$ ). Our data suggest that the Chinese Altai does not contain a Precambrian microcontinent, but the gneissic rocks constitute an early to middle Palaeozoic magmatic arc built on a Neoproterozoic continental margin. In the long accretionary history of this region, both juvenile/mantle material and old crust were involved in the early Palaeozoic magmatism, whereas juvenile/mantle material was the dominant ultimate source for the middle Palaeozoic magmatism.

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