Tracking deep ancient crustal components by xenocrystic/inherited zircons of Palaeozoic felsic igneous rocks from the Altai–East Junggar terrane and adjacent regions, western Central Asian Orogenic Belt and its tectonic significance

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\textbf{Abstract}

The deep crustal continental components and architecture of the western Central Asian Orogenic Belt (CAOB) have long been a matter of debate. This article presents an integrated study of published geochronological and Hf-in-zircon isotopic data for inherited zircons from the Palaeozoic granitoid rocks and associated felsic volcanic rocks of the Chinese Altai, East Junggar, and nearby regions. The aim is to trace the age spatial distribution of deep old crustal components. Our data set comprises 463 published age data obtained by SHRIMP and LA-ICP-MS from felsic igneous rocks in these areas. Among these samples, zircon xenocrysts were observed in 69 granitic rocks and 15 felsic volcanic rocks from the Chinese Altai and 30 granitoid rocks and five felsic volcanic rocks in the East Junggar, respectively.

Three major zircon xenocrysts provinces are defined based on the distribution of these inherited zircon ages, combined with Hf-in-zircon isotopes. Province I, mainly situated in the eastern part of the central Chinese Altai, is characterized by the abundant inherited zircons with Meso-Proterozoic and Palaeo-Proterozoic ages (1000–1600 and 1600–2500 Ma, respectively), and variable $\epsilon_{\text{Hf}}(t)$ values ranging from $-15$ to $+7$ with ancient Hf crustal model ages ($T_{DMC}$) ranging from 1.5 to 2.9 Ga. A few scattered parts of province I are scattered situated in the East Junggar (individual areas, e.g. Taheir and Shuangchagou). Province II, situated mostly in the central Chinese Altai, is characterized by abundant xenocrystic zircons with Neo-Proterozoic ages (542–1000 Ma), $\epsilon_{\text{Hf}}(t)$ values ranging from $-6.8$ to $+8.1$, and corresponding Hf crustal model ages of $\approx1.0$–$1.3$ Ga. Province III contains abundant Phanerozoic (<541 Ma) xenocrystic zircons that show highly positive $\epsilon_{\text{Hf}}(t)$ values ranging from $+5$ to $+16$ and the youngest Hf crustal model ages (0.4–0.95 Ga). The main part of Province III occupies most areas of the East Junggar and the southernmost and northern parts of the Chinese Altai. Identification of the ancient (pre-Neo-Proterozoic) Hf crustal model ages in the eastern part of the central Chinese Altai (Province I) supports the suggestions that ancient concealed crustal components exist in the Chinese Altai. In contrast, Province III in the East Junggar predominantly displays young model ages, which indicates that it is mainly composed of juvenile components and likely a typical accretionary belt. Besides, a few small areas with ancient model ages are recognized in the East Junggar, providing evidence for the local existence of Precambrian crust or micro-blocks within the accretionary belt. The zircon xenocrysts provinces are consisted with the Nd isotopic province and provide further evidence for the ancient and juvenile compositions in deep. In addition, the tectonic division of the region is discussed based on the distribution of deep crustal components. The Erquis fault zone can be regarded as the boundary between the Chinese Altai and East Junggar regions and its western extension is constrained to be closer to the Altai–Qinghe Fault than previously considered. The central Chinese Altai can be subdivided into two distinct tectonic units.

\section{Introduction}

The Central Asian Orogenic Belt (CAOB), situated between the Siberian Craton in the north and the Tarim and North China Cratons in the south (Figure 1, inset), is the world’s largest Phanerozoic accretionary orogenic belt and has been interpreted as the most...
important site of voluminous continental growth (e.g. Sengör et al. 1993; Jahn et al. 2000; Hong et al. 2004; Kovalenko et al. 2004; Windley et al. 2007; Wilhem et al. 2012; Xiao et al. 2015). Sengör et al. (1993) first proposed that almost half of the large CAOB is composed of juvenile crust, and this is supported by subsequent Nd isotopic studies on compositions of massive granitic rocks (e.g. Jahn et al. 2000; Kovalenko et al. 2004; Wang et al. 2009; Yang et al. 2017). Recently, however, Kröner et al. (2014) argued that the production of juvenile continental crust has been grossly overestimated because of the neglect of ancient crustal reworking and mixing. Central to this debate is an understanding of the occurrence and distribution of both ancient (e.g. Precambrian microcontinental blocks/fragments) and juvenile continental components in the CAOB. Therefore, it is crucial to solve this issue by tracking deep crust, including reworked and mixed parts and juvenile components, besides surface mapping of the Precambrian and Phanerozoic rocks (Safonova 2017).

The Chinese Altai and East Junggar as well as adjacent areas (Figure 1), located in the western part of the CAOB, contain several distinct terranes, and these are vital to understand the accretionary orogenic processes and continental growth (e.g. Jahn et al. 2000, 2004; Xiao et al., 2010). Several studies have been carried out to understand the crustal compositions and tectonic division of these areas (e.g. Xiao et al. 2008, 2013; Wang et al. 2009, 2014; Cai et al. 2011a, 2011b, 2012; Xu et al. 2015; Yu et al. 2017); however, on a regional scale, the deep crustal composition, particularly whether ancient Precambrian basements existed, remains controversial. Previously, several researchers proposed the existence of a Precambrian basement in the Chinese Altai orogen (Li et al. 2006; Zhou et al. 2006; Wang et al. 2009; Song et al. 2010; Liu et al. 2010; Yang et al. 2013; Zhang et al. 2014, 2015a; Zhang et al. 2015b). However, many other studies argued that no Precambrian basement exists in the Chinese Altai (e.g. Sun et al. 2009; Cai et al. 2011a, 2011b, 2012; Yu et al. 2017). Similarly, for the East Junggar, many studies suggested that it has a Precambrian basement as its continental block (e.g. Xu et al. 2015 and references therein); however, others emphasized that the Junggar terrane has a basement.
of Palaeozoic oceanic crust (e.g. Dobretsov et al. 2003; Windley et al. 2007; Zheng et al. 2007) or consists of oceanic island arc complexes (e.g. Chen and Jahn 2004).

Whole-rock neodymium and Hf-in-zircon isotopes of magmatic rocks have been applied as powerful tools to constrain the age of the deep crust and trace the distribution of both ancient and juvenile continental components at depth (e.g. Wang et al. 2009, 2016; Mole et al. 2013, 2014; Hou et al. 2015; Champion and Huston 2016; Yang et al. 2017). Nevertheless, in some cases, there is apparent inconsistent information obtained from whole-rock Nd and Hf-in-zircon isotopic data (e.g. Kröner et al. 2014), which will lead to contradictory interpretations regarding the basement nature (e.g. in the Chinese Altai there are negative to weakly positive $\varepsilon_{\text{Nd}}(t)$ values and variably high positive zircon $\varepsilon_{\text{Hf}}(t)$ values for granitic rocks; Wang et al. 2009; Sun et al. 2008; Cai et al., 2011; Yu et al. 2017). Such discrepancies may result from decoupling between the Sm–Nd and Lu–Hf isotopic systems (e.g. Yu et al. 2017). Generally, both the whole-rock Nd and Hf-in-zircon isotopic data are calculated by using crystallization/emplacement zircon ages and they dominantly reflect the information on the eutectic materials of magma source. However, if zirconium is oversaturated in intermediate to felsic silicate melts mush (parental magma), many pre-magmatic zircon (cores) from refractory materials will survive during partial melting of a crustal source (Clemens 2014; Bindeman and Melnik 2016). Therefore, information based only on crystallized zircon from the cooling magma does not always reflect the complete information on magma source components. It is therefore crucial to obtain all available information on zircon grains from magmatic rocks. ‘Inherited’ zircons, or ‘zircon xenocrysts’ from igneous rocks, are derived from a magmatic source or country rocks appreciably older than that of the host igneous rock (Miller et al. 2003, 2007; Stern et al. 2010). Since these ‘pre-magmatic’ zircon grains are generally excluded when calculating crystallization ages for host igneous rocks, their geochronological and Hf isotopic features have mostly been neglected in previous studies. However, increasing numbers of studies have documented that the old inherited zircon populations contain valuable information on the age and composition of the deep continental crust (Wright and Wyld 1986; Hoskin and Ireland 2000; Horie et al. 2010; Kröner et al. 2014; Liu et al. 2014) and thereby provide additional constraints on understanding crustal evolution (Condie et al. 2009, 2011; Siebel et al. 2009; Stern et al. 2010). In some cases, detailed studies on zircon xenocrysts have extended our knowledge on unexposed parts of the crust through which the host magmas have passed (e.g. Smithies et al. 2001; Hargrove et al. 2006; Bea et al. 2007; Demoux et al. 2009b; Nasdala et al. 2014; Buys et al. 2014; Jeon et al. 2014), and the nature of pre-magmatic continental fragments (Iizuka et al. 2006; Smyth et al. 2007; Siebel et al. 2009; Gaschnig et al. 2013; Torsvik et al. 2013). Moreover, statistical analysis of the regional distribution, ages, and Hf isotopic compositions of zircon xenocrysts within juvenile igneous rocks has been proposed as an effective way to trace deep crustal components (Stern et al. 2010; Zhang et al. 2015).

In the past decade, a large number of zircon ages and Hf-in-zircon isotopic data have been reported for felsic igneous rocks from the Chinese Altai, the East Junggar, and nearby regions (see Supplemental Tables 1 and 5 for data sources), and numerous inherited zircons have been recognized (e.g. Wang et al. 2006; Sun et al. 2009; Cai et al. 2011a; He et al. 2015; Xu et al. 2013b, Xu et al. 2015). These xenocrystic zircons provide a rare opportunity to trace the age and composition of the deep continental crust.

In this article, we collected the published geochronological and Hf isotopic data of xenocrystic/inherited zircons and combined them with our new data, aiming at presenting a new perspective on tracing the crustal compositions of variable tectonic units in the Chinese Altai–East Junggar region and adjacent areas. Based on this compilation, we discuss the nature of the basement and the division of tectonic units.

2. Geological and geochronological background

2.1. Tectonic framework

The Chinese Altai and Junggar orogens are important tectonic units of the southwestern CAOB. They are separated by the Erquis Fault (alternatively known as the Irtish, Ertix, or Erquis fault) zone. This zone (surface-exposed) extends for >1000 km from NE Kazakhstan to NW China and is connected to the Bulgan Fault in western Mongolia. It is one of the largest dextral strike-slip faults (late Carboniferous–Early Permian) of central Asia (Sengőr et al. 1993; Briggs et al. 2007; Buslov 2011) and is regarded as a suture of an arc–continent or continent–continent collision between the Altai and Junggar terranes (Briggs et al. 2007; Xiao et al. 2015).

The Chinese Altai, lying to the north of the Erquis zone, consists of numerous terranes or tectonic units (Windley et al. 2002), and can be geologically divided into three parts (Figure 1). The northern part (Unit 1 = terrane 1 of Windley et al. 2002) largely consists of
Middle–Late Devonian andesites, dacites, and Late Devonian to early Carboniferous metasediments (shale, siltstone, greywacke, sandstone, limestone). The Middle–Late Devonian volcanic rocks were considered to have formed in an island arc setting, and the metasediments were deposited in fore-arc basins. The central part (terrane 2 and terrane 3) predominantly consists of Neoproterozoic (Silurian) to Middle–Late Ordovician low-grade sedimentary and volcanic rocks in the northwest (Long et al. 2007, 2010), and Middle–Ordovician to Silurian amphibolite- and greenschist-facies metasediments and metavolcanics in the southwest. Some high-grade metamorphic rocks were suggested to be Neoproterozoic in age (e.g. Windley et al. 2002; Xiao et al. 2004), which was considered to constitute the most important part of a proposed ‘Altai microcontinent’ (Xiao et al. 2004; Wang et al. 2009). The southern part includes units 4 and 5. Traditionally, this part contains two formations, i.e. the Kangbutiebao and the Altai Formations (Windley et al. 2002). The Kangbutiebao Formation mainly consists of arc-type volcanic and pyroclastic rocks, and minor basic volcanic rocks and splulates, which were believed to have been deposited during the Late Silurian to early Devonian (Chai et al. 2009). The Altai Formation is predominantly composed of low-grade metamorphic rocks such as a turbiditic sandstone-shale sequence, together with minor basalts, siliceous volcanics, and limestones that contain Middle Devonian fossils. Based on the field occurrence and geochemical studies of clastic and volcanic rocks, the two formations probably formed in a fore-arc basin (Windley et al. 2002; Long et al. 2007). In addition, magmatic rocks with adakitic composition, mafic complexes, high-Mg andesites, and boninites are also widespread in this area (Wong et al. 2010; Cai et al. 2012). All these features together suggest an active continental margin setting (Sengör et al. 1993; Yuan et al. 2007).

The East Junggar terrane is located to the south of the Erqis zone and to the north of the Tianshan Orogen, and extends eastwards into Mongolia. Tectonically, the East Junggar comprises a series of arcs, accretionary complexes, and ophiolites generated by subduction–accretion processes during the Palaeo-Asian Ocean (Long et al. 2009). It consists, from the north to the south, of the Dulate composite island arc (unit 6), the Aermantai ophiolite mélangé belt, the Yemaquan composite island arc (unit 7), the Kalamaili ophiolite mélangé belt, and the Harlik arc (unit 8) (Figure 1). The Dulate arc extends along the northern side of the Armantai ophiolite and mainly consists of Devonian–Carboniferous volcanic rocks (Long et al. 2012). The Yemaquan arc is located south of the Armantai ophiolite and is dominated by Ordovician–Carboniferous rocks. The Harlik arc is located south of the Kalamaili ophiolite, and it is considered to be a Devonian to late Carboniferous island arc, resulting from the consumption of the Kelameili ocean basin.

### 2.2. Igneous rocks of the Chinese Altai, East Junggar, and nearby regions

Numerous geochronological studies have been carried out on the widespread granitoid rocks and associated felsic volcanic successions (rhyolite, andesite, dacite, etc.) in the Chinese Altai, East Junggar, and adjacent areas (e.g. Mongolia Altai, Russian Altai, and Kazakh Altai). More than 600 zircon ages have been published for these rocks. In this study, only high-quality zircon ages (476) obtained by TIMS, SIMS, and LA-ICP-MS methods (184 granitoid rocks and 28 felsic volcanic rocks in the Chinese Altai, 116 granitoid rocks and 37 felsic volcanic rocks in the East Junggar, and 111 for the nearby regions) were collected and compiled in a data set (Supplemental Table 1), based on preliminary assessment of the published data. Locations of the 476 samples with zircon ages are shown in Figure 2. Based on the available zircon U–Pb ages in the data set (Supplemental Table 1), the Palaeozoic granitoid rocks and associated felsic volcanic rocks can be subdivided into nine age populations (540–496, 486–436, 432–400, 400–382, 382–360, 359–330, 330–296, 296–275, and 274–252 Ma), corresponding to discrete magmatic events. The most prominent activities were at ca. 420–360 Ma (Figure 2). The temporal-spatial distribution of Palaeozoic principal felsic igneous suites in the Chinese Altai, East Junggar, and the nearby regions is illustrated in Figure 2.

### 3. Age and Hf isotopic data of inherited zircons

#### 3.1. Geochronological data of zircon xenocrysts

We summarize the U–Pb age and the Hf-in-zircon isotopic data of inherited zircons from dated granitic and associated felsic volcanic rocks from the Chinese Altai (84 samples), East Junggar (35 samples), Mongolian Altai (eight samples), and Russian Altai (12 samples) (Supplemental Table 2). In the Chinese Altai, inherited zircons were identified in 69 of the 179 granitoid samples and 15 of the 38 felsic volcanic rocks (andesite, dacite, rhyolite). In the East Junggar, zircon xenocrysts were observed in 30 of the 116 dated granitoid rocks and five of the 37 felsic volcanic rocks. Accordingly, a total of 375 zircon xenocrysts and their U–Pb isotopic
data were compiled (Supplemental Table 3) from 84 samples in the Chinese Altai, and a total of ~250 zircon xenocrysts and their U–Pb isotopic data were compiled (Supplemental Table 3) from 35 samples of the East Junggar. In addition, a few U–Pb ages of zircon xenocrysts from adjacent regions (10 for the Mongolian Altai, 10 for the Russian Altai) were also compiled. About ~86% of these xenocrysts were identified in granitoids and ~14% in associated felsic volcanic rocks. Xenocrystic zircons with discordance of more than 10% (31 grains from the Chinese Altai, 27 grains from the East Junggar, and two grains from the Mongolian Altai) were excluded (Supplemental Table 3), and two zircon grains with Th/U < 0.05 were also discarded because of their likely metamorphic origin (Rubatto 2002). As illustrated in cathodoluminescence (CL) images (Supplemental Figure 4), xenocrystic zircon grains mostly show morphological features similar to those of magmatic origin zircons (e.g. euhedral grains and clear oscillatory zoning). This feature has also been observed in rocks from Mongolia (Kröner et al. 2007; Kröner et al. 2010).

In the northern Chinese Altai (Unit 1), no zircon xenocrysts have been identified; however, inherited zircon grains were found in 481–413 Ma granitoids of the Russian Altai (Glorie et al. 2011; Cai et al. 2014) and 393–309 Ma granitic rocks in the Mongolian Altai (Cai et al. 2015; Burianek et al. 2016). These zircon xenocrysts show ages (207Pb/206Pb for ages >1000 Ma and 206Pb/238U for <1000 Ma, similarly hereinafter) groupings at around 600–500 and 1900–1800 Ma (Figure 3(a)).

For the western part of the central Chinese Altai (Unit 2), zircon xenocrysts (~50) were reported for the 479–378 Ma granitic rocks (Li et al. 2006; Sun et al. 2009; Cai et al., 2011b) and the 445–411 Ma volcanic rocks (Wang et al. 2011). These xenocrysts yielded mainly two distinct age populations peaked at ~600–400 and ~600 Ma (Figure 3(b)). In the eastern part of the central Altai (Unit 3), the zircon xenocrysts (n = 59) were mainly obtained from 459–372 Ma granitoid rocks (Wang et al. 2006; Yuan et al. 2007; Cai et al. 2011b; Sun et al. 2009; Lv et al. 2012; Zhang et al. 2014; Song et al. 2016; Zhang et al. 2017) and 502 Ma rhyolite (Yang et al. 2011a). The composite U–
Pb age distribution of these zircon xenocrysts yields prominent peaks at around 550–500, ~700, and 900–800 Ma, with minor age clusters in the range of 1000 and 1500 Ma (Mesoproterozoic peaks), and around ~2000 Ma (Fig. 3c).

In the southern Chinese Altai (Unit 4), zircon xenocrysts (~154) were observed in 453–363 Ma granitoid rocks (Wang et al. 2006; Sun et al. 2009, 2009; Cai et al. 2011b; Yang et al. 2013; He et al. 2015; Zhang et al. 2015b; Zhang et al. 2017), and 403–378 Ma felsic volcanic rocks (Yang et al. 2014b; He et al. 2015; Wu et al. 2015a). These xenocrysts exhibit composite age distributions peaking at around 550–400 Ma, scattered peaks between 1000 and 800 Ma, and an Archaean peak at 2500 Ma (Fig. 3d).

In the southern Chinese Altai and along the Erquis zone (Unit 5), the zircon xenocrysts (~14) were mainly found within 379–265 Ma granitoid rocks (Briggs et al. 2007; Cai et al. 2012; Tong et al. 2014; Yang et al. 2014a; Xue et al. 2016). These xenocrysts show age groupings at around 550–350 Ma and ~900 Ma, and further peaks between 1900 and 2200 Ma (Figure 3e).

In the East Junggar, many zircon ages for felsic igneous rocks have been reported, but only a few samples show inherited grains, much fewer than those of the Chinese Altai (Figure 4), and these samples are mainly located in Unit 7.

In Unit 6, the zircon xenocrysts (~19) were mainly found within 379–252 Ma granitoid rocks (Zhang et al. 2006; Tong et al. 2012; Zhang et al. 2012; Li et al., 2015c; Liang et al. 2016) and 413 Ma andesite (Liu and Liu 2014). The composite age distribution of zircon xenocrysts yielded prominent clusters at around 600–400, ~900, and ~1100 and further peaks between 2000 and 1800 Ma (Figure 3f).
In Unit 7 of the East Junggar, zircon xenocrysts (~145) were mainly found within 419–276 Ma granitoid rocks (Lin et al. 2007; Yang et al. 2009; Li et al. 2009; Du et al. 2010; Zhang et al. 2010; Shen et al. 2011; Yang et al. 2011b; Liu et al. 2016). These xenocrysts show age groupings at around 500–400, ~600–1200, and 1500–2000 Ma, and further peaks at 2100 and 2300 Ma (Figure 3(g)).

In Unit 8, the zircon xenocrysts (~52) were mainly found within 341–297 Ma granitoid rocks (Shanlin and Qingyou 2013; Zhang et al. 2014; Wu et al. 2015b) and 314–307 Ma rhyolite (Su et al. 2012). These xenocrysts show age groupings at around ~400, ~650–500, and ~1500 Ma (Figure 3(h)).

In Unit 8, the zircon xenocrysts (~52) were mainly found within 341–297 Ma granitoid rocks (Shanlin and Qingyou 2013; Zhang et al. 2014; Wu et al. 2015b) and 314–307 Ma rhyolite (Su et al. 2012). These xenocrysts show age groupings at around ~400, ~650–500, and ~1500 Ma (Figure 3(h)).

In addition, as illustrated in Figure 4, the distribution of the oldest xenocrystic zircon ages from the granitoid rocks and associated felsic volcanic rocks from the Chinese Altai, East Junggar, and nearby regions was especially compared. The locations of samples without xenocrystic zircons have been marked by white dots (Figure 4). Pre-Neoproterozoic (>1000 Ma) zircon xenocryst abundances in the Palaeozoic felsic igneous rocks show strong compositional dependence, and they are more common in granitoid rocks than in felsic volcanic rocks (Figure 4).

3.2. Hf isotopic data of xenocrystic zircons

We compiled and recalculated the available Hf isotopic data of 323 individual xenocrystic zircons from the Chinese Altai, and 189 individual zircons from the East Junggar and adjacent areas (four from the Mongolian Altai). The data set includes our unpublished results and the literature data (see Supplemental Figure 4). The initial $^{176}$Hf/$^{177}$Hf ratios and crustal Hf model ages were calculated with the corresponding zircon ages ($^{207}$Pb/$^{206}$Pb >1000 Ma and $^{206}$Pb/$^{238}$U <1000 Ma).

The zircon xenocrysts from Palaeozoic granitoid rocks in the Chinese Altai are characterized by variable $\varepsilon_{\text{Hf}(t)}$ values (−12.4 to +18.7) with Hf model ages ($t_{\text{DMC}}$) of 0.2–3.7 Ga, whereas the zircon xenocrysts from felsic volcanic rocks have $\varepsilon_{\text{Hf}(t)}$ values ranging from −28 to +10.5, and Hf model ages ($t_{\text{DMC}}$) of 0.8–3.0 Ga. The zircon xenocrysts within Palaeozoic granitoid rocks in the East Junggar are also characterized by variable $\varepsilon_{\text{Hf}(t)}$ values (−25 to +16) with Hf model ages ($t_{\text{DMC}}$) of 0.4–3.2 Ga, whereas the xenocrysts from felsic volcanic rocks in the East Junggar have $\varepsilon_{\text{Hf}(t)}$ values in the range from +6.3 to +18.7 with Hf model ages ($t_{\text{DMC}}$) of 0.17–0.95 Ga.

As illustrated in Figure 5, in the Chinese Altai, the Hf isotope values of <542 Ma zircon xenocrysts in Units 1,
Figure 5. (a) Distribution of Hf-in-zircon studies for samples of Palaeozoic granitoids and felsic volcanic rocks of the Chinese Altai and East Junggar. (b) Plots of $\epsilon_{\text{Hf}}(t)$ versus $t$ (Ma) diagram showing the Hf isotopic compositions of compiled xenocrystic zircons. Hf-in-zircon isotopic data of magmatic zircons from previous studies were also recalculated and are shown for comparison. CHUR, chondritic uniform reservoir. $(^{176}\text{Lu} / ^{177}\text{Hf})_{\text{CHUR}} = 0.0332$ and $(^{176}\text{Hf} / ^{177}\text{Hf})_{\text{CHUR}} \approx 0.282772$ (Blichert-Toft and Albarède, 1997), $(^{176}\text{Lu} / ^{177}\text{Hf})_{\text{DM}} = 0.0384$ and $(^{176}\text{Hf} / ^{177}\text{Hf})_{\text{DM}} = 0.28325$ (Griffin et al. 2000); $t$, U–Pb age of the magmatic zircons, or age $(^{207}\text{Pb} / ^{206}\text{Pb} > 1000 \text{ Ma}$ and $(^{206}\text{Pb} / ^{238}\text{U} < 1000 \text{ Ma})$ of xenocrystic zircons. The ‘new crust’ (island arc) evolutionary curve is defined by isotopic growth from $^{176}\text{Hf} / ^{177}\text{Hf} = 0.27903$ at 4.55–0.283145 at present, with $(^{176}\text{Lu} / ^{177}\text{Hf}) = 0.0375$ (Dhuime et al. 2011). The Hf evolution line is based on $(^{176}\text{Lu} / ^{177}\text{Hf}) = 0.0125$ (Chauvel et al. 2014). Data sources for these Hf-in-zircon isotopic data are listed in Supplemental Table 5. Data sources for typical xenocrystic Hf-in-zircon compositions for the Chinese Altai (from our studies and Yang et al., 2011a, 2014b, Zhang et al. 2017) and for East Junggar (Xu et al., 2013, Xu et al. 2015) are labelled.
2, and 5 mainly have $\varepsilon_{\text{Hf}(t)}$ values of $-3$ to $+15$, similar to those of magmatic zircons in the Chinese Altai. However, some xenocrysts with Neoproterozoic ages in Unit 3 have $\varepsilon_{\text{Hf}(t)}$ varying from $-25$ to $+15$ and mostly fall in the category defined by 2.5 Ga and 1.4 Ga evolution trends (Figure 5(b)).

In the East Junggar, the <542 Ma xenocrysts in Units 6, 7, and 8 mainly have $\varepsilon_{\text{Hf}(t)}$ values of $+7$ to $+17$ (Figure 5), consistent with those of magmatic zircons in the East Junggar. On the contrary, some xenocrysts with U–Pb ages >542 Ma in Unit 7 of the East Junggar are characterized by negative $\varepsilon_{\text{Hf}(t)}$ values varying from $-25$ to 0 and mostly fall in the categories defined by 2.2 and 1.4 Ga, 2.5 and 2.2 Ga, and 3.0 and 2.5 Ga evolution trends (Figure 5(b)).

In addition, some inherited zircons from the Chinese Altai and East Junggar have negative $\varepsilon_{\text{Hf}(t)}$ values and plot far away from the evolution line for the new continental crust, indicating the involvement of ancient source components. In contrast, most magmatic zircons of granitoid rocks and associated felsic volcanic rocks from the East Junggar have $\varepsilon_{\text{Hf}(t)}$ values much closer to the ‘new continental crust’ evolution line than those of the Chinese Altai, implying significant involvement of mantle-derived mafic magmas or newly formed juvenile crustal material.

4. Age provinces and Hf isotopic signatures defined by the zircon xenocrysts

Considering (1) the age and spatial distribution (Figure 4 and Supplemental Table 3) and available Hf isotopic signatures of xenocrystic zircon grains (Figure 5) and (2) the tectonic units in which they occur, we now divide the Altai–East Junggar terrane and adjacent regions into three inherited zircon provinces (Figure 6).

4.1. Province I (containing 1000–2500 Ma xenocrystic zircons)

Province I is defined by abundant xenocrystic zircons with Mesoproterozoic and Palaeoproterozoic ages (1000–1600 and 1600–2500 Ma, respectively), and their ancient crustal Hf model ages ($t_{\text{DMC}} = 1.5$–2.9 Ga) with variable $\varepsilon_{\text{Hf}(t)}$ values ranging from $-15$ to $+7$. 

![Figure 6](image-url)

*Figure 6.* The inferred framework of old zircon xenocryst provinces, based on the variations in spatial characteristics of age and Hf isotopic compositions ($t_{\text{DMC}}$) of xenocrystic zircons within Palaeozoic felsic igneous rocks. For detailed description for Provinces I, II, and III see text. Data sources as in Figures 4 and 5.
(Figure 5). Province I mainly occupies the eastern part of the central Chinese Altai and is also discretely distributed in the Qinghe, Qinggeli, and Keketuohai areas (Units 3 and 4, to the east of the Fuyun Fault), where the distribution is mainly defined by the extent of outcrop areas that contain more than 12 zircon xenocryst samples (with ages $>1000$ Ma) distributed closely (Figure 6). A few parts of Province I are scattered in the East Junggar (individual areas in and around unit 7, e.g. Taheir and Shuangchagou areas), where they are defined by the outcrops of the pluton with only one zircon xenocryst sample. The felsic igneous rocks in Province I are dominated by $\sim$400–382 and 380–360 Ma granitoid rocks (mainly I- and A-types) and dacites and rhyolites (Figure 2; blue and green dots), with subordinate 486–400 Ma varieties (Figure 2; purple dots).

4.2. Province II (containing 541–1000 Ma xenocrystic zircons)

Province II is characterized by abundant xenocrystic zircons with Neoproterozoic ages (542–1000 Ma), which exhibit $\varepsilon_{\text{Hf}}$ values ranging from $-6.8$ to $+8.1$ and corresponding to $t_{\text{DMC}}$ values from $\sim1.0$ to 1.3 Ga. It is widespread in the central part (units 2 and 3) and southern part (unit 4) of the Chinese Altai, and is defined by more than five samples with 1000–542 Ma zircon xenocrysts, and 12 samples with Cambrian zircon xenocrysts. The felsic igneous rocks in Province II are dominated by $\sim432$–400 and 486–436 Ma granitoid rocks (mainly I-type), with subordinate 400–382 Ma varieties as well as dacites and rhyolites (Figure 2; light purple dots, dark purple dots, and blue dots, respectively). It is worth noting that some $<542$ Ma zircon xenocrysts were also identified within the Palaeozoic igneous rocks of Province II (Figure 6).

4.3. Province III ($<541$ Ma xenocrystic zircons)

Province III is defined by abundant Palaeozoic felsic igneous rocks either containing xenocrystic zircons with Phanerozoic ($<541$ Ma) ages (no Precambrian age record) or not containing zircon xenocrysts, and the youngest highly positive $\varepsilon_{\text{Hf}}$ values (ranging from $+5$ to $+16$) with $t_{\text{DMC}}$ values of 0.4–0.95 Ga. It is the largest province and is situated mainly in most areas of the East Junggar (units 6, 7, and 8; Figure 6), and a few parts occur in the southernmost (unit 5) and the northern (unit 1) part of the Chinese Altai. In the East Junggar, this province is defined by ca. 20 samples, and in the southernmost Chinese Altai by five samples. The felsic igneous rocks in Province III are dominated by $\sim330$–300 Ma and 359–330 Ma granitoid rocks (mainly I-type) as well as dacites and rhyolites (Figure 2; yellow and light blue dots, respectively), with subordinate 486–436, 432–400, 380–360, and 296–275 Ma granitoid rocks (Figure 2; dark purple, light purple, green, and red dots, respectively).

5. Discussion

5.1. Implications of xenocrystic zircons for tracing the source of igneous rocks

Hf-in-zircon and whole-rock Nd isotopes have been widely used to trace the source of felsic igneous rocks. However, in many studies, Hf-in-zircon isotopes are often inconsistent with whole-rock Nd isotopic signatures. For example, granitoids from western Antarctica and the Northern Tibetan Plateau exhibit negative to positive $\varepsilon_{\text{Hf}}$ values, whereas the whole-rock $\varepsilon_{\text{Hf}}$ values are significantly negative (Brown et al. 2016; Huang et al. 2017). The early Palaeozoic granitoid rocks in the central Altai also exhibit strongly positive zircon $\varepsilon_{\text{Nd}}$ values and young model ages ($+3$ to $+15$, 0.9–1.4 Ga) (e.g. Sun et al. 2009; Cai et al. 2011a, 2011b, 2012; Yu et al. 2017). These are distinct from negative to weakly positive $\varepsilon_{\text{Nd}}$ Values ($-6$ to $+2$), corresponding to $t_{\text{DMC}}$ model ages of 1.6–1.1 Ga (Wang et al. 2009). There may be several reasons or interpretations for such discrepancy. Decoupling of Nd–Hf isotopes, which may result from disequilibrium melting processes or inherited from the magma source, has been the prevailing interpretation (e.g. Cai et al. 2011b; Long et al. 2012; Yu et al. 2017).

We emphasize that negligence and loss of information recorded in the xenocrystic zircons of felsic igneous rocks could be one of the major reasons for such discrepancy. This is because zircon Hf isotopic compositions are generally obtained and reported from crystallized zircons, or crystallized domains of zircon, and sometimes may not always reflect the whole-rock Hf isotopic information on magma sources (e.g. Farina et al. 2014; Barth et al. 2016) due to loss of information on pre-magmatic zircon (cores) derived from refractory material. Thus, negligence of zircon Hf compositions of xenocrystic zircons must result in significantly higher positive $\varepsilon_{\text{Hf}}$ values compared with the $\varepsilon_{\text{Nd}}$ values due to the loss of information on the ancient age of the crust. Two examples from the Chinese Altai are given here. (1) Granodiorite sample 380205, 363 Ma now shows a mean value of 17 magmatic zircons of $\varepsilon_{\text{Hf}}(t = 363)$ of $+6.45$ (with $t_{\text{DMC}} = 896$ Ma), but if two Hf isotopic data for inherited zircons (1293 and 1854 Ma) are calculated to $\varepsilon_{\text{Hf}}(t = 363)$ and added to the mean Hf composition, the $\varepsilon_{\text{Hf}}(t = 363)$ decreases to $+3.68$, and the mean $t_{\text{DMC}}$ value increases to 1054 Ma (Song et al. 2011a).
2016; Supplemental Table 5). (2) Granite sample Areletuobi-West; 484 Ma has mean value for 12 magmatic zircons $\varepsilon_{\text{HF}}(t = 484)$ of +4.84 (with $t_{\text{DMC}} = 1084$ Ma), but if three xenocrystic/inherited zircons (981, 665, and 981 Ma) found in this sample are added to this value, the mean $\varepsilon_{\text{HF}}(t = 484)$ value will decreases to ~0.58 (with average $t_{\text{DMC}} = 1392$ Ma) (Zhang et al. 2017).

Felsic igneous rocks often contain not only magmatic zircons from the cooling magma, but also numerous xenocryst or inherited zircons from the melt mush (e.g. Clemens 2014; Zhang et al. 2015c; Bindeman and Melnik 2016). Generally, xenocrystic zircons in magmatic systems record information on crustal contamination, whereas inherited zircons indicate ancient materials input from source components during the partial melting processes. For a long time, xenocrystic/inherited zircons have been considered as bothersome that hinder the precise estimate of emplacement and the eruption age of granitoid rocks and associated felsic volcanic rocks. Accordingly, the available age and detailed Hf isotopic data for these xenocrystic zircons are often neglected. There are numerous Precambrian xenocrystic zircons in Palaeozoic felsic igneous rocks, especially those with Precambrian age, but their Hf isotopic data are often not reported (Supplemental Table 2), although zircon xenocrysts may appear frequently in the CL images of our and other samples. Therefore, information recorded in xenocrystic zircons should also be considered, combined with magmatic zircons, when we discuss the source components of felsic igneous rocks.

5.2. Geological significance of the provinces

Age and Hf isotopic information recorded in xenocrystic zircons could provide unique/additional constraints on the existence of ancient crustal components, despite uncertainties in possible provenance/source. Based on this, we traced old zircons derived from the deep crust by considering their age and Hf isotope spatial characteristics.

The three zircon xenocryst Provinces I, II, and III described above provide information on the distribution of ancient and juvenile crustal components in the region. Province I, with abundant pre-1000 Ma xenocrystic zircons and the oldest $t_{\text{DMC}}$ values for the xenocrystic and magmatic zircons (Figure 6), exhibits typical characteristics of ancient crustal components. It may reflect the oldest crust in the region at depth.

Province II, with 542–1000 Ma xenocrystic zircons and somewhat younger $t_{\text{DMC}}$ values (Figure 6), is considered to reflect mixed sources composed of juvenile and old crustal materials. This is evidenced by the occurrence of zircon xenocrysts with ancient and juvenile isotopic characteristics (many 542–500 Ma and < 488 Ma zircon xenocrysts also occur).

Provinces I and II demonstrate that the central Chinese Altai contain old (pre-Neoproterozoic) crustal components. This provides new information on a possible Precambrian basement. As mentioned above, there are different viewpoints on the basement nature in the Chinese Altai. Previously, a Precambrian basement represented by high-grade gneisses was suggested, and the central Chinese Altai was regarded as a Precambrian continental block (Hu et al. 2000; Li et al. 2003; Xiao et al. 2004). Wang et al. (2009) employed whole-rock Nd and Sr isotopic mapping of granitoid rocks and proposed that the central Altai contains widespread ancient components in deep crust as suggested by Nd isotopes, whereas the southern Altai reflects a higher proportion of juvenile crust. However, some authors argued against the existence of Precambrian basement in the Chinese Altai (e.g. Sun et al. 2008, 2009; Long et al. 2007, 2010; Cai et al. 2011a, 2011b, 2012), based on geochronological and Hf-in-zircon (magmatic) studies of gneissic granitic rocks, detrital zircon U–Pb and Hf-isotope compositions of Palaeozoic sedimentary sequences, and suggested the Altai possibly represented an accretionary prism in the early Palaeozoic.

There are at least two reasons for such contradictory interpretations. First, the sample distribution of these studies was different. Some studies show magmatic rocks samples collected from the northwestern and southern Chinese Altai (e.g. Habahe Groups rocks) and interpreted those to be of juvenile origin (e.g. Sun et al. 2008; Yuan et al. 2007; Cai et al. 2011a, 2011b, 2012; Shen et al. 2014). However, samples from our and other authors (e.g. Wang et al. 2009; Song et al. 2010; Liu et al. 2010; Yang et al. 2013; Zhang et al. 2015a, 2015b; Song et al. 2016) cover most parts of the central Altai, particularly the eastern part, as shown in Province I (Figure 6), where we show the exhibits’ existence of the oldest crustal compositions.

Second, as discussed above, negligence of xenocrystic zircons in establishing the origin of some rocks resulted in such discrepancy. It is still questionable whether the ancient (Neoproterozoic) xenocrystic zircons from Palaeozoic igneous rocks can be used to deduce the existence of an old (Neoproterozoic) basement. Before exploring the implication of the age and Hf isotopic composition recorded in these xenocrystic zircons, it is important to consider their source. They could have been acquired from (1) Neoproterozoic sediments sourced from a neighbouring old crustal block, such as the Tuva-Mongolian microcontinent (e.g.
Kuzmichev et al. 2001; Demoux et al. 2009; Ivanov et al. 2014), or the Chinese Alai region; (2) sediment recycling and input of ancient crustal material into subduction zones that later contributed to arc magmatism (including residual zircon crystals derived from the melting of oceanic sediments) (Zhang et al. 2017); or (3) an unexposed ancient basement (possibly underling the Palaeozoic felsic igneous rocks).

The first possibility can probably be ruled out due to the following: (1) the old zircon source (Provinces I and II) is only located in the central-southern Altai, far away from the Tuva–Mongolian microcontinent, and particularly there is no or little old source in the northern Altai (Province III) and the Lake zone to the north of the Altai is juvenile; (2) lack of Neoproterozoic sediments in the Chinese Altai; and (3) the morphology of the xenocrysts is characterized by subhedral to euhedral (not like detrital zircons). The second possibility can also be possibly ruled out because our sample locations cover the entire Chinese Altai, and Precambrian xenocrystic zircons have only been identified in the eastern part of the central Chinese Altai (Province I).

The third possibility is the most likely explanation because there are concealed fragments of ancient basement at depth. Province I also preliminarily constrains the extent of possible ancient (Archaean) basement in the deep crust. This is further supported by the following evidence. (1) Widespread distribution of relative homogenous old components in Province I. Large areas consisting of homogenous old components seem to be best explained as buried Precambrian basement. (2) Dong et al. (Zengchan et al. 2016) have recently reported the oldest age of felsic rocks (~2.6 Ga quartzite) from the Supute rock group in Qinghe area, Chinese Altai, which is consistent with the existence of pre-Neoproterozoic zircon xenocryst within Province I. (3) The composite zircon age distribution in Province I includes zircons of Gondwana affinity, characterized by similar age peaks around 2.5 Ga and 1.8 Ga, and in the range of 500–1200 Ma and around 1600 Ma (e.g. Ireland et al. 1998; Gehrels et al. 2011; Zhu et al. 2013). This supported the fact that the proposed Altai possibly represents a microcontinent that was derived from the northern margin of the Gondwana continent (e.g. Buslov et al. 2001; Yang et al. 2011a).

Province III (no magmatic and xenocrystic zircons have a Precambrian age record and yielded the youngest \(t_{\text{DMC}}\) values; Figure 6) indicates that the southwestern part of the central Chinese Altai and most areas of the East Junggar are juvenile, rather than ancient. This is consistent with the Nd isotopic studies (e.g. Zheng et al. 2007; Wang et al. 2009; Liang et al. 2016).

However, some researchers emphasized that the East Junggar constitutes an old (Palaeoproterozoic–Archaean) block (e.g. Xu et al. 2013, Xu et al. 2015). Our map exhibits that these old compositions only occur locally (Figure 6), suggesting that only small ancient continental fragments were involved in the juvenile accretionary orogeny. This shows that the regional mapping of old ages is effective for an evaluation of old and juvenile crustal distribution.

Kröner et al. (2014) have recently confirmed the presence of numerous segments of predominantly juvenile, mixed, and reworked crust (microcontinents) in the CAOB based on the available whole-rock Nd and Hf-in-zircon isotopic data. According to their study, the central (units 2 and 3) and northern Chinese Altai (unit 1) were recognized as a reworked crustal segment (characterized by mixed isotopic signatures) and an isotopically juvenile segment, respectively, which is in good agreement with the present study as shown by Provinces I, II, and III (Figure 6). Safonova (2017) interpreted the reworked crustal features exhibited by Provinces I and II as the presence of microcontinents or as mixed sources for the primary magmas.

In summary, the basement nature in the Chinese Altai and East Junggar regions is distinct. Precambrian (pre-Neoproterozoic) basement could exist in the eastern part of central Chinese Altai and local areas in the East Junggar, whereas the East Junggar is juvenile. This conclusion is also crucial to understand the geodynamic evolution and crustal growth rate of the CAOB. If the Chinese Altai and East Junggar regions prove to be ‘less juvenile’ than previously thought, then revision of the crustal growth rate (e.g. Jahn et al. 2004; Kovalenko et al. 2004) in the CAOB is required.

Thus, it is important to re-evaluate the occurrence and distribution of Precambrian continental fragments by isotopic mapping of xenocrystic zircons. Obviously, a detailed distribution of juvenile, ancient, and reworked crustal components in the Chinese Altai, East Junggar, and nearby regions is difficult to be accurately determined, because the western CAOB has a complex geological history (e.g. Kröner et al. 2010; Xu et al., 2013; Xiao et al. 2015). Therefore, more multidisciplinary studies are required to evaluate our interpretation concerning the distribution of ancient components by: 1) more detailed geological mapping (large-scale mapping based on surface geology) for basement rocks in our study region; 2) more geochronology, Hf-in-zircon, and O isotopic studies of zircons (including xenocrystic zircons) from granitoid intrusions and associated felsic volcanic rocks in the Chinese Altai and East Junggar.
5.3. Implications for the tectonic subdivision of the region

The defined three xenocrystic zircon Provinces I, II, and III (Figure 6) provide new evidence for understanding the tectonic units and their boundaries extension. The Erquis Fault zone (Late Carboniferous–early Permian) is one of the largest dextral strike-slip faults of Asia (Sengör et al. 1993; Briggs et al. 2007; Buslov 2011). Its western extension, however, is still not clear (Briggs et al. 2007), probably due to the cover of Quaternary sediments (Figure 1). Our study indicates that the boundary between Provinces II and III, i.e., the boundary between the old and juvenile terranes, is consistent with the Erquis Fault zone and displays distinctive deep compositions at two sides on the fault (Figure 6). Our study also indicates that the zone and to the south of the Erquis zone constitutes the youngest crust in this part of the CAOB. This confirms that the Erquis zone is a subduction zone to the north, and the Erquis ocean was subducted to the south, forming a large accretionary wedge of Junggar juvenile crust by accretionary orogenic processes. This is consistent with previous studies (e.g., Li et al. 2015b; Xiao et al. 2015), particularly our Nd isotopic mapping (Wang et al. 2009). Moreover, the boundary between Provinces II and II shows that the western extension of the Erquis Fault zone in the northwestern and southeastern parts of the central Chinese Altai should be closer to the north (near the Altai–Qinghe Fault) than previously considered (Figure 6).

The tectonic attribution of units 3 and 4 of the Chinese Altai is different from a previous suggestion (Windley et al. 2002), and they can possibly be subdivided into two different tectonic units. This inference is evidenced by Provinces I and II, showing that the northwestern and southeastern parts of the central Chinese Altai contain different crustal components at depth.

6. Conclusions

Based on the spatial characteristics of ages and Hf isotopic compositions of xenocrystic zircons within Palaeozoic felsic igneous rocks of the Chinese Altai, East Junggar, and nearby regions, several conclusions can be drawn.

1. The Chinese Altai, East Junggar, and nearby regions can be subdivided into three provinces, based on the distribution of xenocrystic zircon ages from igneous rocks, combined with Hf-in-zircon isotopic compositions. Province I is characterized by abundant xenocrystic zircons with ages of 1000–1600 and 1600–2500 Ma, and variable $\varepsilon_{Hf(t)}$ values ($-15$ to $+7$), corresponding to old crustal model ages (1.5–2.9 Ga). Province II contains abundant xenocrystic zircons with ages of 1000–541 Ma, and $\varepsilon_{Hf(t)}$ values ranging from $-6.8$ to $+8.1$, corresponding to $t_{DMC}$ of ~1.0 to 1.3 Ga. Province III is characterized by abundant <541 Ma xenocrystic zircons, and high positive $\varepsilon_{Hf(t)}$ values (+5 to +16) with the youngest $t_{DMC}$ values of 0.4–0.95 Ga.

2. These provinces reveal the architecture and distribution of deep continental components and provide additional constraints on the tectonic subdivision of the region. Ancient compositions (1000–1600 and 1600–2500 Ma) exist in the eastern segment of central Chinese Altai. Similar ancient components were also identified in some local areas in the East Junggar. These ancient compositions may be interpreted as reflecting Precambrian basement or fragments of continental micro-blocks. Province III indicates that most parts of the East Junggar terrane are juvenile. Distinct deep crustal compositions between two sites along the Erquis Fault zone confirm the importance of this fault as a regional crustal boundary. Different deep crustal compositions in the northwestern and southeastern parts of the central Chinese Altai (units 2 and 3) suggest that this tectonic unit should be subdivided into two parts.

3. Xenocrystic or inherited zircon is frequently neglected in the study of zircon Hf compositions, resulting in the overestimation of positive epsilon Hf(t) values and juvenile compositions in magmatic rocks and loss of information on ancient crustal compositions. The age and Hf isotopic statistical study of this xenocrystic zircon can provide additional constraints on tracing deep crustal compositions.

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Appendix Methodology

Hf-in-zircon isotope data interpretation

In situ geochronology and Hf isotopic compositions of xenocrystic zircon from igneous rocks may provide significant information on the unexposed crustal levels through which the host magma passed (e.g. magma source and obscured basement rocks), but caution must be exercised in interpreting such data. As a first step, we must check whether these zircon xenocrysts are magmatic or metamorphic in origin before we interpret the zircon ages and Hf isotopic compositions. CL images reveal that most zircon xenocrysts of this study exhibit magmatic textures (Supplemental Figure 4). This interpretation is in good agreement with the high Th/U ratios (Supplemental Table 3). These xenocrystic zircons should be ultimately sourced from felsic igneous rocks.

Zircon Lu–Hf isotopic data are expressed using the $\varepsilon_{Hf(t)}$ notation, representing deviation of the measured $^{176}\text{Hf}/^{177}\text{Hf}$ ratio from that of chondritic meteorites (CHUR) in parts per 10,000 (Wu et al. 2006). The $\varepsilon_{Hf(t)}$ values can be used to distinguish juvenile sources with positive $\varepsilon_{Hf(t)}$ values from ancient continental sources with negative $\varepsilon_{Hf(t)}$ values (e.g. Kemp et al. 2006). The crustal Hf model ages ($t_{DMC}$) provide an estimate of the age when the magmatic source was extracted from a depleted mantle reservoir (Griffin et al. 2000). We use the terms ‘juvenile’ and ‘reworked’ to describe crustal evolution (e.g. Mole et al. 2014). The term ‘juvenile’ refers to crustal material that plots on or close to the depleted mantle evolution line, indicating ultimate derivation from a depleted mantle source (Hawkesworth et al. 2010). In addition, the new continental crust evolutionary line, besides the depleted mantle evolutionary line, is plotted in Figure 5 as another reference to discuss continental crust growth (Dhuime et al. 2011). The subduction zone, which has been widely considered as one of the most dominant tectonic settings for the formation of ‘juvenile continental crust’, has enriched Hf isotopic compositions relative to the depleted upper mantle (Dhuime et al. 2011, 2012).

Thematic maps for information on xenocrystic zircons

The maps (Figures 2, 4, 5, and 6) showing the spatial characteristics of age and Hf-in-zircon isotopic compositions of xenocrystic zircons contained within Palaeozoic felsic igneous rocks were first produced in ArcGIS using the compiled data set and then further edited in Adobe Illustrator. All point data shown in the thematic maps represent the average $\varepsilon_{Hf(t)}$ value of zircon grains, which were used to infer the spatial extent of crustal blocks with specific Hf isotopic character and their evolution through time.