Journal of Earth Science, *Vol. 31*, *No. 1*, *p. 102–114*, *February 2020* *ISSN 1674-487X*
Printed in China
https://doi.org/10.1007/s12583-019-1217-x

Nd-Hf Isotopic Decoupling of the Silurian–Devonian Granitoids in the Chinese Altai: A Consequence of Crustal Recycling of the Ordovician Accretionary Wedge?

Yanqiong Huang[1, 2], Yingde Jiang*[1], Yang Yu[1], Stephen Collett[3], Sheng Wang[1, 2], Tan Shu[1, 2], Kang Xu[1, 2]
1. *State Key Laboratory of Isotope Geochemistry*, *Guangzhou Institute of Geochemistry*, *Chinese Academy of Sciences*, *Guangzhou* 510640, *China*
2. *University of Chinese Academy of Sciences*, *Beijing* 100049, *China*
3. *Center for Lithospheric Research*, *Czech Geological Survey*, *Prague*, *Czech Republic*
Yanqiong Huang: https://orcid.org/0000-0002-5059-3081; Yingde Jiang: https://orcid.org/0000-0002-9533-0146

ABSTRACT: Voluminous Silurian–Devonian granitoids intruded a greywacke-dominated Ordovician accretionary wedge in the Chinese Altai. These granitoids are characterized by significant Nd-Hf isotopic decoupling, the underlying mechanism of which, so far, has been poorly understood. This issue is addressed in this study by the integration of our new and regional published geological and geochemical data. Geological studies indicated a close spatial relationship between the regional anatexis of the Ordovician wedge and the formation of the granitoids, which is characterized by a gradual textural evolution from the partial molten Ordovician wedge sedimentary rocks (the Habahe Group) to the granitoid bodies. Compositionally, these granitoids and the Ordovician Habahe Group rocks displayed close geochemical similarities, in the form of arc-like trace elemental signatures as well as comparable Nd isotopic characteristics. Combined with regional available data, we suggest that the Silurian–Devonian granitoids originated from the immature and chemically primitive Habahe Group rocks. Since Nd and Hf isotopic data for the Habahe Group rocks show significant Nd-Hf isotopic decoupling, we propose that the Silurian–Devonian granitoids inherited the Nd and Hf isotopic signatures from their sources, i.e., the Habahe Group rocks. In other words, the Nd-Hf decoupling in the Habahe Group rocks is the primary causative factor leading to the prevailing Nd-Hf isotopic decoupling of the Silurian–Devonian granitoids in the Chinese Altai.
KEY WORDS: granitoids, crustal recycling, Ordovician wedge sediments, partial melting, Nd-Hf decoupling, Chinese Altai, geochemistry.

0 INTRODUCTION

Long-lived radiogenic isotope systems, in particular, those of neodymium, have proved invaluable tracers of the crustal evolution on Earth (Vervoort and Patchett, 1996; McCulloch and Bennett, 1994; Bennett et al., 1993; Galer and Goldstein, 1991; Bowring et al., 1989; Chase and Patchett, 1988; DePaolo et al., 1982). Compared to the Sm-Nd isotopic system, the Lu-Hf system displays a larger fractionation of Lu/Hf in planetary magmatic processes (Salters and Longhi, 1999; Patchett, 1983) due to the greater sensitivity of Lu-Hf to residual garnet and accessory minerals during magmatic differentiation (Ionov et al., 2005) and is less sensitive to metasomatism (Bizimis et al., 2004), therefore providing a potential fingerprint for crustal growth history. It has been known for a long time that the Lu-Hf system closely mirrors the Sm-Nd isotope system during magmatic processes (Vervoort et al., 1999; Vervoort and Blichert-Toft, 1999; Vervoort and Patchett, 1996). This has led to a high degree of correlation between Hf and Nd isotope ratios, also known as coupled behavior of the Nd-Hf isotopic systems (Vervoort et al., 1999; Vervoort and Blichert-Toft, 1999; Vervoort and Patchett, 1996; Patchett, 1983; Patchett and Tatsumoto, 1980). While the Sm-Nd and Lu-Hf isotopes behave similarly in many geological processes, decoupling between these two isotopic systems has been increasingly reported worldwide since the 2000's (Tang et al., 2012; Yu et al., 2009; Ionov et al., 2005; Bizimis et al., 2004; Schmitz et al., 2004; Schmidberger et al., 2002). Since then, the underlying mechanism (s) of Nd-Hf isotopic decoupling has been a subject of many discussions. Various causes for this Nd-Hf isotopic decoupling have been considered, including (1) redistribution of isotopic systems related to metasomatism, high-grade metamorphism and partial melting (Yu et al., 2009; Wittig et al., 2007; Ionov et al., 2005; Bizimis et al., 2004; Vervoort et al., 2000, 1999; Scherer et al., 1997; Vervoort and Patchett, 1996); (2) involvement of garnet in magma genesis resulting in significant fractionation between Lu/Hf and Sm/Nd ("garnet effect", Ionov et al., 2005; Schmidberger et al., 2002); (3) recycling of sedimentary materials in the

*Corresponding author: jiangyd@gig.ac.cn

Manuscript received November 14, 2018.
Manuscript accepted April 10, 2019.

Huang, Y. Q., Jiang, Y. D., Yu, Y., et al., 2020. Nd-Hf Isotopic Decoupling of the Silurian–Devonian Granitoids in the Chinese Altai: A Consequence of Crustal Recycling of the Ordovician Accretionary Wedge? *Journal of Earth Science*, 31(1): 102–114. https://doi.org/10.1007/s12583-019-1217-x. http://en.earth-science.net

magma source (“zircon effect”, Patchett et al., 1984). Suggesting that the mechanism varies from case to case; however, there seems a consensus that decoupling of the Nd-Hf isotopes can provide critical clues to decipher the geochemical characteristics of magma sources and to understand the complexity of the evolution of crust.

The Chinese Altai orogenic belt represents a high-grade core of the Central Asian orogenic belt (CAOB), which is considered to be the Earth’s largest area of Phanerozoic crustal growth (Windley et al., 2007; Şengör et al., 1993). The Chinese Altai is mainly composed of variably metamorphosed Ordovician wedge sediments (Jiang et al., 2019, 2017) and voluminous Silurian–Devonian granitoids that occupy nearly 40% area of the outcropped area (Zou et al., 1989; Fig. 1). Decoupling of Nd-Hf isotopic systems in these granitoids has been increasingly noted. For example, these granitoids have whole-rock $\varepsilon_{Nd}(t)$ values ranging from -4 to +5 (Yu et al., 2017a; Jiang et al., 2016; Liu et al., 2012; Wang et al., 2009; Chen and Jahn, 2002), while their zircon $\varepsilon_{Hf}(t)$ values are significantly higher, mostly in the range from +2 to +9 (Cai et al., 2011a, b; Sun et al., 2008). Such decoupled isotopic signatures have become problematic since contrasting interpretations might be drawn for the mechanism of crustal evolution. For example, on the basis of generally negative $\varepsilon_{Nd}(t)$ values of the local Silurian–Devonian granitoids, some authors envisaged that the Chinese Altai had a Precambrian continental basement (Wang et al., 2009). On the other hand, the prevailing positive zircon $\varepsilon_{Hf}(t)$ values of these granitoids led many to suggest that the crust in the region is juvenile (Cai et al., 2011a; Sun et al., 2008). The latter is further advocated by the findings that most detrital zircons (more than 70%) from the metasedimentary rocks have positive $\varepsilon_{Hf}(t)$ values, implying the existence of a large volume of young and geochemically primitive component (Jiang et al., 2017, 2016, 2011; Long et al., 2008, 2007; Sun et al., 2008).

Thus far, our knowledge of the Nd-Hf isotopic decoupling in the Chinese Altai still remains rather fragmented. Yu et al. (2017a, b) proposed that the observed isotopic decoupling in the granitoids was inherited from the arc magma, which was extracted from the lithospheric mantle where Nd was selectively enriched over Hf due to metasomatism in the mantle wedge. This may be the case for the subordinate hornblende-bearing I-type granitoids. Apart from these I-type granitoids, a large volume of granitoids are peraluminous which were recently considered as typical Circum-Pacific S-type granitoids and to be originated from regional-scale anatexis of the local chemically immature Ordovician wedge sediments (Jiang et al., 2016). The possibility as to whether the Nd-Hf isotopic decoupling of these granitoids reflects the nature of the source rocks is worth further investigation.

In this study, new and published geological, geochemical, Nd and Hf isotopic characteristics of the metasedimentary rocks of the Ordovician wedge as well as the regional Silurian–Devonian granitoids in the Chinese Altai are integrated. The expanded database may allow us to compare the chemical similarities between the sedimentary rocks and the granitoids. Our data suggest that the pervasive Nd-Hf decoupling in the Silurian–Devonian granitoids is inherited from their crustal magma source, i.e., Ordovician wedge sediments.

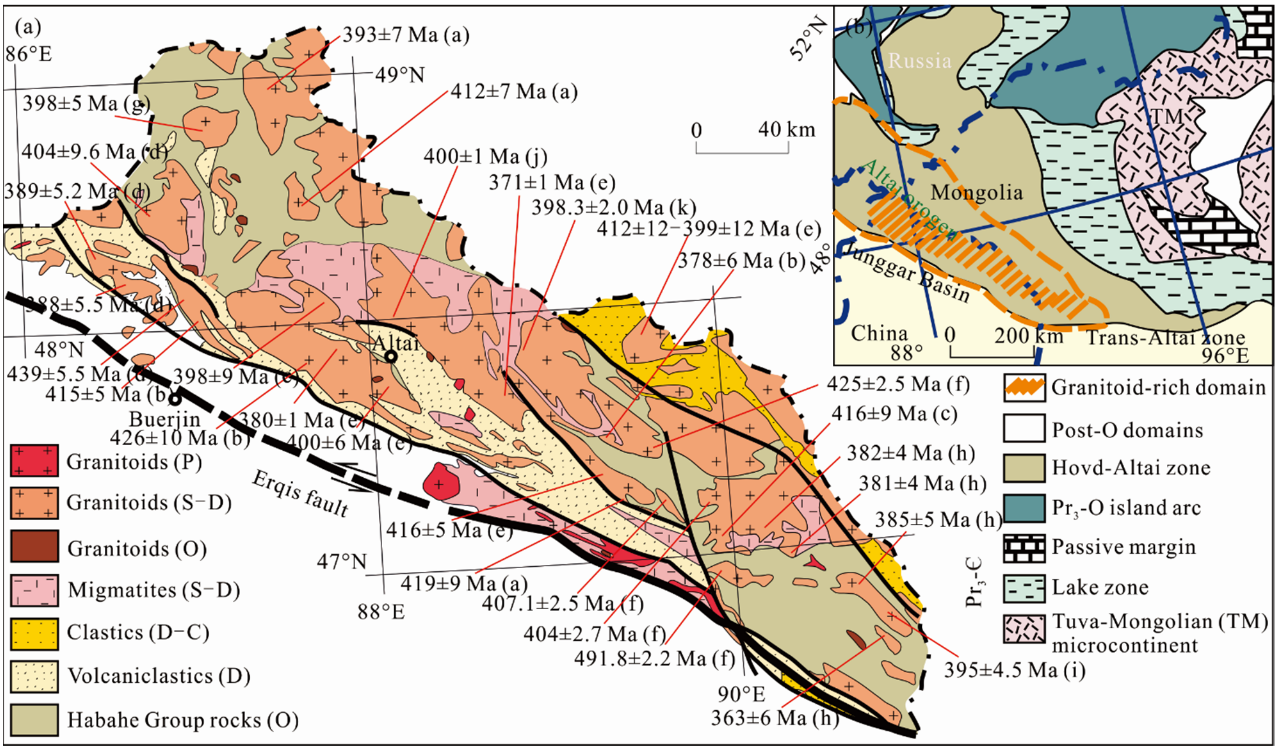

Figure 1. (a) Geological map of the Chinese Altai and (b) geological map of the NW Chinese and western Mongolian tract of the CAOB (after Jiang et al., 2016). Geochronological data: a. Cai et al., 2011a; b. Sun et al., 2009; c. Yuan et al., 2007; d. Cai et al., 2011b; e. Wang et al., 2006; f. Zhang et al., 2017; g. Tong et al., 2007; h. Song et al., 2017; I. Shi et al., 2015; j. Zheng et al., 2016; k. Zhang et al., 2016.

1 GEOLOGICAL SETTING

The central Asian orogenic belt extends from the Urals in the west to the Pacific in the east and from the Siberian cratons in the north to the North China and Tarim cratons in the south (Windley et al., 2007; Jahn et al., 2000; Şengör et al., 1993, Fig. 1). It is one of the largest and most complex accretionary collages in the world and contributes substantially to the enlargement of the Asian continent by subduction and accretion of juvenile materials from the Neoproterozoic to the Late Paleozoic (Windley et al., 2007; Şengör et al., 1993). This giant orogenic system consists of magmatic arcs, ophiolites, accretionary wedges, passive margins, and microcontinents (Wilhem et al., 2012; Şengör et al., 1993). Controversies are centered on its tectonic evolution, and two major competing tectonic models were proposed: long-lived subduction and oroclinal bending of a single arc (Şengör and Natal'in, 1996; Şengör et al., 1993) versus amalgamation of multiple terranes, similar to the geology of the modern SW Pacific (Xiao et al., 2010, 2009, 2004; Windley et al., 2007, 2002). The Altai orogenic belt mainly consists of a thick low-grade greenschist- to amphibolite-facies Late Cambrian to Ordovician meta-volcano-sedimentary succession, located in the hinterland of the CAOB (Safonova et al., 2009; Badarch et al., 2002, Fig. 1). The sedimentary succession extends for about 2 000 km, from Mongolia, through China to Kazakhstan and Russia, and is irregularly covered by the Silurian basalt, tuff, and siliciclastic sediments (Jiang et al., 2017; Xiao et al., 2009), which has recently been considered as a giant Early Paleozoic accretionary wedge along the active margin of Mongolian continental blocks (Jiang et al., 2017; Long et al., 2010, 2007; Xiao et al., 2010, 2009, 2004; Windley et al., 2002; Fig. 1). Its Chinese segment, namely the Chinese Altai, is composed of a greywacke-dominant Ordovician wedge sedimentary sequence and Devonian turbiditic to clastic sedimentary sequences, alternating with NW-SE trending elongated magmatite-migmatite domes (Broussolle et al., 2019; Jiang et al., 2019, 2015; Xiao et al., 2009). The Chinese Altai is separated from the southern Junggar arc domain that is composed of folded and weakly metamorphosed Silurian–Carboniferous ocean floor sediments and volcanic rocks by the Erqis fault zone (Li et al., 2015; Zhang et al., 2012; Xiao et al., 2009; Windley et al., 2002). Here, we summarize the available petrological, geochronological and geochemical data on the Ordovician sedimentary sequences and the Silurian–Devonian granitoids of the Chinese Altai in the following text for further study.

1.1 Ordovician Sedimentary Sequence of the Habahe Group

The Ordovician sedimentary sequence represents the oldest and most extensive lithological unit in the region, which constitutes the basement of the Chinese Altai, namely the Habahe Group. This sequence is mainly comprised of terrigenous-clastic components associated with subordinate volcanogenic components including volcanoclastic rocks, tuffaceous sediments, and volcanic rocks (Jiang et al., 2017; Xiao et al., 2009; Windley et al., 2002). The terrigenous sedimentary components display chemically immature signatures and are compositionally similar to those sediments deposited in active continental margins (see also Jiang et al., 2016; Long et al., 2008; Fig. 2). The trace element characteristics of these terrigenous sediments, resemble those of the Pacific trench sediments but show lower concentrations of large-ion lithophile elements (LILEs) (Rb, Sr, Ba, Th, U and Pb) and high field strength elements (HFSEs) (Zr, Hf, Nb and Ta) than the mature post-Archean Australian shale (PAAS) (Jiang et al., 2016). The volcanogenic rocks are characterized by intermediate-basic interbedding layers or admixtures in the quartz-feldspar dominant terrigenous components (Fig. 3a). These intermediate-basic components display sub-parallel REE patterns with enrichment in LREE (La_N/Yb_N=2.06–6.99), flat HREE (Gd_N/Yb_N=1.66–2.09) and weak negative Eu anomalies, on a primitive mantle (PM)-normalized variation diagram (Huang et al., 2018). The volcanogenic components also show enrichment in LILEs and pronounced negative Sr, Nb, Ta and Ti anomalies, similar to those of the terrigenous components (Huang et al., 2018).

There have been extensive discussions regarding the provenance of the Habahe Group during the last two decades (Sun et al., 2009; Long et al., 2008, 2007; Windley et al., 2002). The whole-rock Nd-Sr isotopic compositions as well as the Proterozoic Nd model ages (T_{2DM}: 1.5–1.8 Ga) once led many to think that the Habahe Group is mostly comprised of the evolved continental materials (Chen and Jahn, 2002). Later on, detrital zircon U-Pb data from this sedimentary sequence showed prominent ca. 540–460 Ma ages with subordinate Neoproterozoic and rare pre-Neoproterozoic ones (Broussolle et al., 2019; Jiang et al., 2011; Long et al., 2007), indicating the significance of Ordovician components. Zircon Hf isotopic data of the Habahe Group showed that more than 70% had positive $\varepsilon_{Hf}(t)$ values, suggesting input of abundant young and geochemically primitive components (Cai et al., 2011a). These new findings support the interpretation that the Habahe Group rocks probably represent detritus deposited in an active margin setting with significant volcanic input (Jiang et al., 2016; Long et al., 2008). It is also revealed that the Early Paleozoic zircons are euhedral and displayed oscillatory zoning, in contrast to the Precambrian ones that are generally rounded with complicated magmatic-metamorphic internal structures (Jiang et al., 2011; Sun et al., 2008; Long et al., 2007). These features suggest that the detritus of the Habahe Group is mainly derived from both the nearby Early Paleozoic arc-proximal sources with minor contributions from perhaps more distant Precambrian continental sources (Jiang et al., 2017).

Recently, an ~1 800 km long Cambro–Ordovician Ikh-Mongol arc system was identified by Janoušek et al. (2018) to the northeast of the Altai. The related arc magmatism was found to rework the accreted Neoproterozoic island arc of the Lake Zone and the Precambrian blocks in western Mongolia. Further study by Jiang et al. (2017) showed that the published detrital zircon age patterns of the Habahe Group resembled the ages of the Neoproterozoic–Early Paleozoic arc-related rocks in the Lake Zone and its adjacent Precambrian blocks to the west. This is in line with the view that the Habahe Group and its equivalents represent a huge accretionary wedge riming the active margin of the Mongolian Precambrian blocks (Jiang et al., 2017; Xiao et al., 2009). The Altai wedge reworked by extensive magmatism and metamorphism during the Devonian orogeny (Broussolle et al., 2018; Jiang et al., 2010; Wang et al., 2006). Recent petrological observations and thermodynamic modelling indicated that the Habahe Group was buried to a depth of 30 km or more, and, developed Barrovian-type metamorphism during the early phase of the orogeny (Jiang et al., 2016, 2015; Wei et al., 2007). It was also indicated that the crust of the Chinese Altai was affected by high-temperature metamorphism associated with the Devonian lithospheric extension, marked by a high field geothermal gradient about 30 °C/km (Jiang et al., 2019, 2010; Li et al., 2014, Figs. 3c, 3d). This tectono-thermal event gave rise to the regional-scale anatexis of the Habahe Group at a temperature range of 700–1 000 °C (Jiang et al., 2015; Li et al., 2014; Wei et al., 2007). Recent studies revealed that detrital zircons from the terrigenous components of the Habahe Group had $\varepsilon_{\rm Hf}(t)$ values ranging from -21.3 to +13.5, mostly -8.1 to 6.8 and $\varepsilon_{\rm Nd}(t)$ ranging from -0.3 to -5.9, mostly -5.5 to -2.5 (Jiang et al., 2016, 2011; Long et al., 2012, 2010, 2007; Sun et al., 2008; Chen and Jahn, 2002; Hu et al., 2000).

1.2 Silurian–Devonian Granitoids

Voluminous Silurian–Devonian granitoids intruded into the Ordovician Habahe Group and occupy more than 40% of the map surface of the Chinese Altai (Zou et al., 1989, Fig. 1). These granitoids formed a series of isolated circular or elongate bodies in contrast to the Late Paleozoic granitoids which are spatially concentrated along the southern flank of the Chinese Altai (Fig. 1). In the following text, detailed geochronological and geochemical features of the Silurian–Devonian granitoids are summarized.

Recent geochronological studies indicate the Silurian–Devonian granitoids have crystallization U-Pb zircon ages ranging from 420 to 370 Ma, with a prominent peak at around 400–390 Ma (Cai et al., 2011b), coeval with the high-temperature anatexis in the region (Broussolle et al., 2019; Jiang et al., 2010). Inherited zircons of these granitoids are marked by a high proportion of ~500 Ma grains, which is comparable with detrital zircon age patterns of the Ordovician Habahe Group metasediments that are characterized by Early Paleozoic ages, predominantly peaked at 500 Ma (Broussolle et al., 2019; Jiang et al., 2017, 2011; Sun et al., 2008).

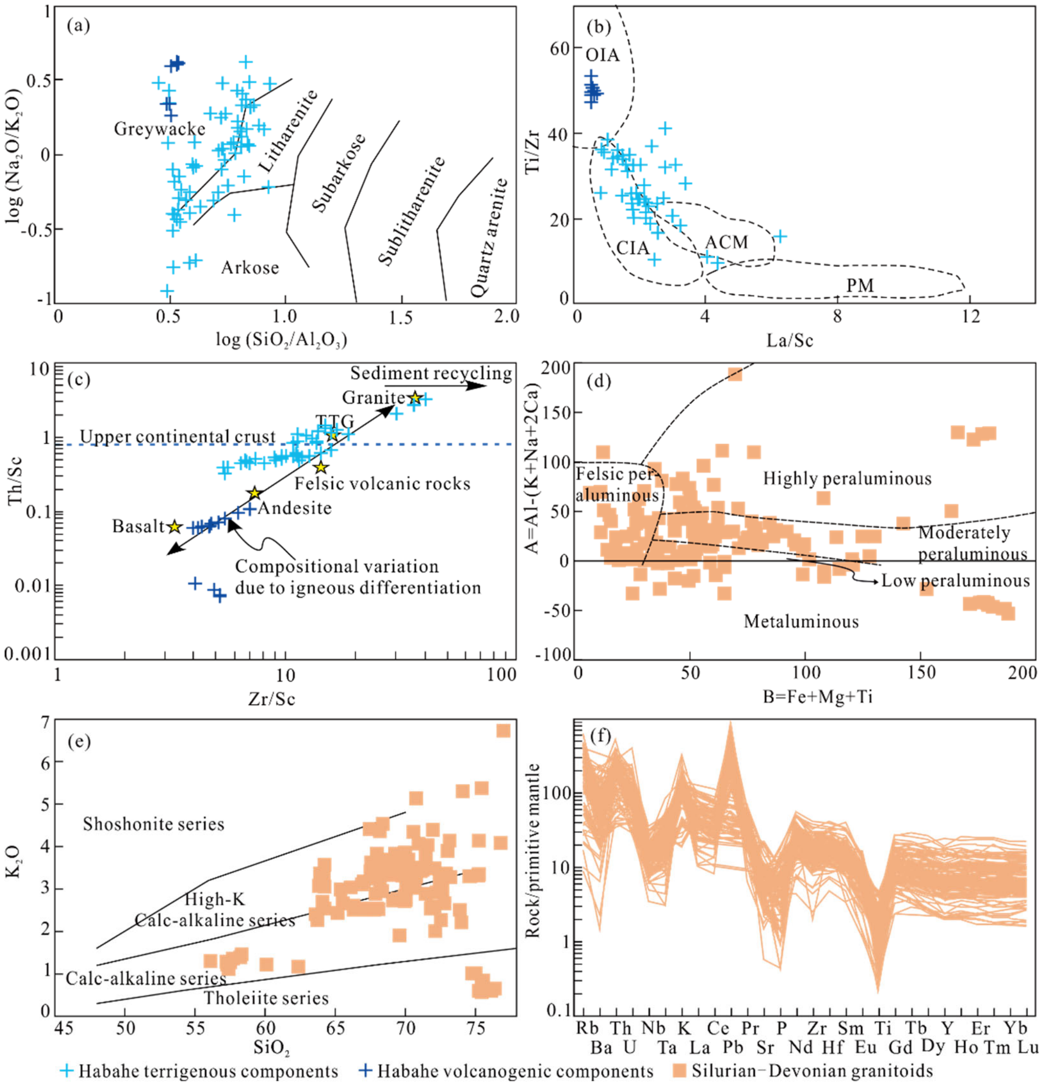

Figure 2. Geochemical characteristics of Habahe Group sediments and Silurian–Devonian granitoids. (a) Classification diagram after Pettijohn et al. (1987); (b) La/Sc vs. Ti/Zr diagram after Bhatia and Crook (1986) (outlined fields: OIA. oceanic island arc; CIA. continental arc; ACM. active continental margin; and PM. passive margin); (c) Zr/Sc vs. Th/Sc diagram after McLennan et al. (1984), TTG. trondhjemite-tonalite-granodiorite; (d) B-A diagram of Villaseca et al. (1998) modified from Debon and Le Fort (1983) showing that majority of the Silurian–Devonian granitoids from the Chinese Altai are peraluminous compositions; (e) K_2O vs. SiO_2 diagram after Peccerillo and Taylor (1976); (f) primitive mantle normalized trace element patterns for granitoids. Primitive mantle normalizing values are from Sun and McDonough (1989). Details and data sources are available in Table S1.

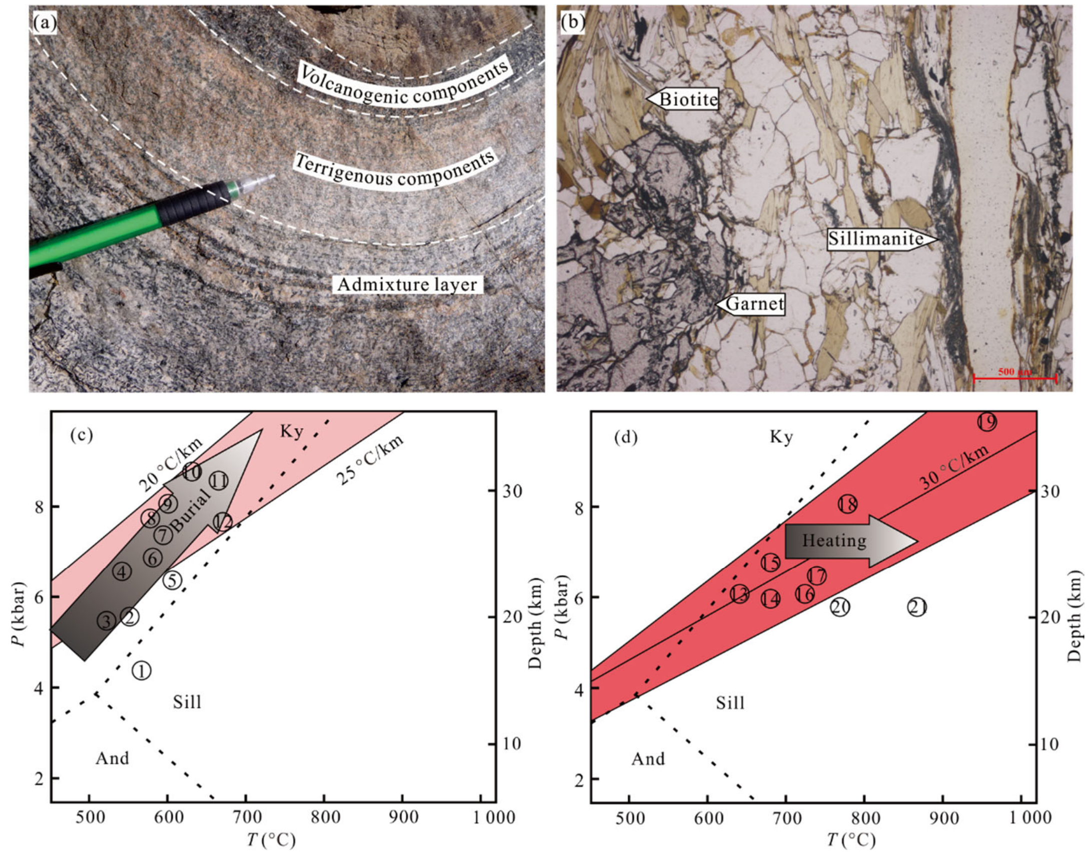

Figure 3. (a) Field photograph showing the terrigenous and volcanogenic components of the Habahe Group; (b) sillimanite and garnet as peritectic minerals; (c) and (d) geothermal gradients and published *P-T* paths for peak metamorphic assemblages of the two different Paleozoic metamorphic events (after Jiang et al., 2016): (c) Early Paleozoic burying; (d) Middle Paleozoic heating. Published data of *P-T* conditions are presented in Table S2.

The Silurian–Devonian granitoids in the Chinese Altai are mainly granodiorites to granites, more than 85% of them are biotite-bearing granodiorites and granites and the remaining 15% are hornblende-bearing granodiorites and tonalites (Huang et al., 2018; Jiang et al., 2016). The first group granitoids have moderate to high SiO_2 contents (65.20 wt.%–81.60 wt.%), moderate total alkalis (Na_2O+K_2O, 4.27 wt.%–8.60 wt.%), and high Al_2O_3 contents (10.0 wt.%–16.7 wt.%) (Shi et al., 2015; Cai et al., 2011a; Sun et al., 2008; Tong et al., 2007; Yuan et al., 2007; Wang et al., 2006; Chen and Jahn, 2002, Figs. 2d, 2e, Table S1). They have calc-alkaline, predominantly peraluminous compositions (Figs. 2d, 2e). They show differentiated REE patterns, and are enriched in LILE and depleted in HFSE (especially Ta, Nb and Ti), closely resembling the patterns of the Habahe Group metasediments and considered to be S-type granitoids (see also Jiang et al., 2016; Cai et al., 2011a; Yuan et al., 2007; Wang et al., 2006, Fig. 2f). The remaining subordinate hornblende-granodiorites and tonalites have moderate-high SiO_2 (56.80 wt.%–76.08 wt.%), moderate total alkalis (3.65 wt.%–7.84 wt.%), and high Al_2O_3 (11.25 wt.%–17.10 wt.%). They are generally peraluminous to metaluminous and classically considered as "I-type" granitoids (Yu et al., 2017b). However, our recent study pointed out that these so-called "I-type" granitoids could be derived from the partial melting of the volcanogenic components of the Habahe Group and previously inferred significant extraction of source magma from the mantle is unnecessary (Huang et al., 2018).

A large variation of zircon $\varepsilon_{Hf}(t)$ values (-7.0 to +9.0) and generally negative whole-rock $\varepsilon_{Nd}(t)$ values (-4.2 to +4.8) were reported from the bulk granitoids (Zhang and Wang, 2017; Wang et al., 2009; Yuan et al., 2007; Chen and Jahn, 2002).

2 FIELD RELATIONSHIPS

Most of the Silurian–Devonian granitoids are associated with migmatites that structurally correspond to partially molten Habahe Group rocks (Jiang et al., 2019). It is quite often that granitoids and migmatites form composite migmatite-magmatite domes in the region (Fig. 4a). There is no clear boundary between the granitoids and the migmatites, but, in general, the granitoids center the domes and the migmatites show inward textural evolution of migmatite types from ophthalmitic gneiss, through stromatites to nebulites (see also Jiang et al., 2019, 2015; Figs. 4a–4f). The migmatites are characterized by a granulite-facies mineral assemblage of granet+sillimanite+K-feldspar+cordierite (Fig. 3b), but relics of an early phase Barrovian-type metamorphic assemblage, such as kyanite+staurolite, are locally present (Jiang et al., 2019, 2016, 2015). These petrological observations imply that the Habahe metasediments were buried to deep crustal levels where they thereby underwent extensive anatexis (Figs. 3c, 3d). This is consistent with the notion that the Silurian–Devonian migmatite-magmatite composite complexes are considered as the exhumed Chinese Altai orogenic lower crust (Jiang et al., 2019, 2016; Broussolle et al., 2018).

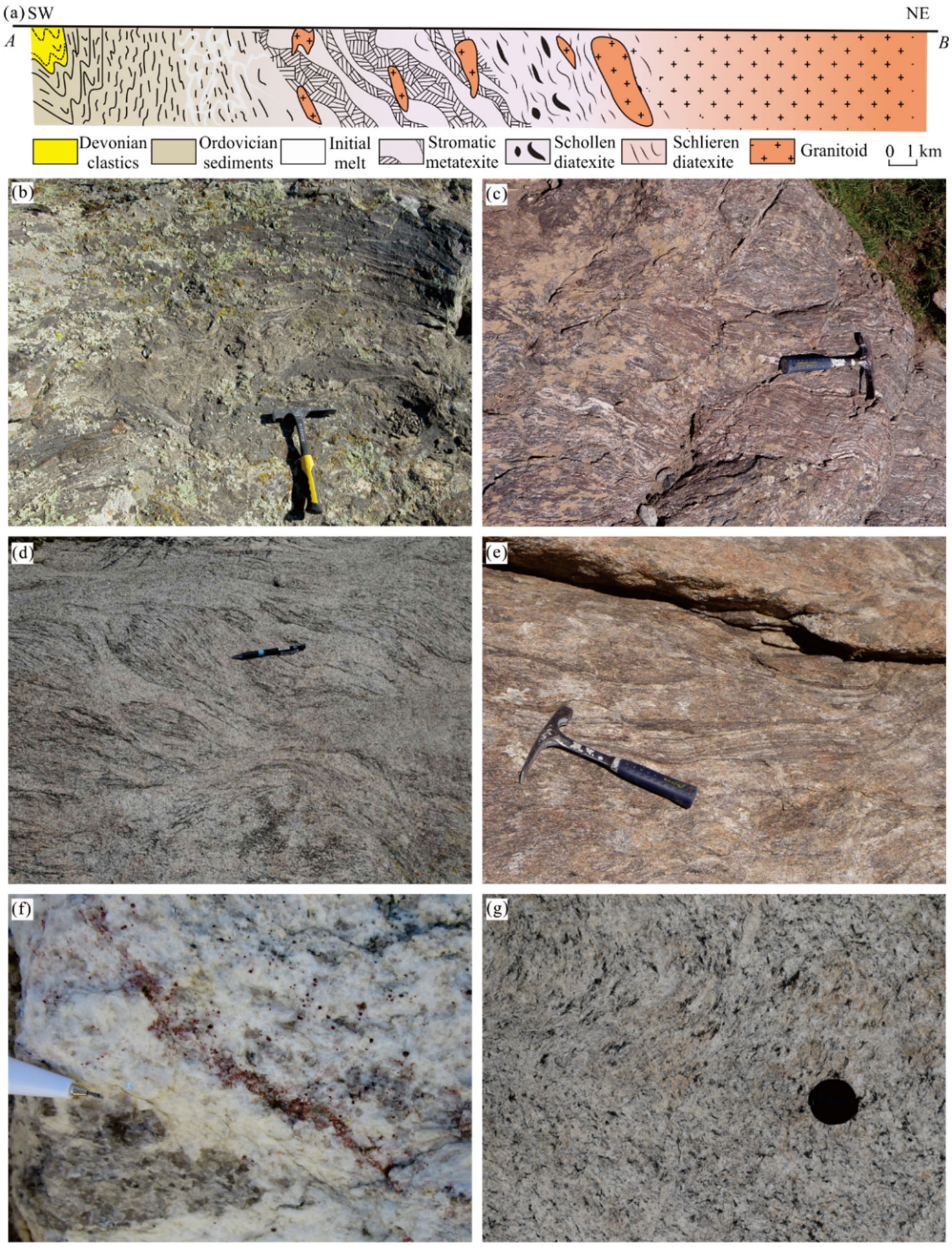

Figure 4. (a) Simplified geological profile showing the textures of migmatites and their spatial relationships with the Silurian–Devonian granitoids; (b), (c), (d) and (e) photographs show transition from stromatic metaxite, metaxite to diatexite; (f) garnet-bearing granite; (g) granitoids.

3 Nd ISOTOPIC CHARACTERISTICS: SAMPLING, METHODS AND RESULTS

In this section, Nd isotopic signatures from both the Habahe Group metasediments and the Silurian–Devonian granitoids are investigated. Four samples from Habahe terrigenous components (sandstone and siltstone), three from migmatites and another four from granitoids were collected (Figs. 3, 4). The terrigenous samples (17CA90-1, 17CA90-2, 17CA125-1 and 17CA125-2) are mainly comprised of grainy quartz (70 vol.%), plagioclase (20 vol.%) and some fine clay minerals (10 vol.%). Volcanogenic components are locally present in the form of actinolite/amphibole rich interbedded or admixture layers (Fig. 3a; Huang et al., 2018). The other three migmatite samples 16CA31, 16CA33 and 17BC26 are comprised of quartz (60 vol.%), plagioclase (30 vol.%) and biotite (10 vol.%) with accessory sillimanite and garnet (Fig. 3b). The 3 granite samples 16CA30, 17BC29 and 17BC34 are comprised of quartz (50 vol.%), plagioclase (30 vol.%), mica (15 vol.%) and minor garnets. The GPS coordinates and the general descriptions of samples are included in Table 1.

The experiments of Nd isotope measurements were performed at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry (SKLIG-GIG), on a micromass isoprobe multi-collector mass spectrometer (MC-ICP-MS), following the procedures described by Li et al. (2004). Measured $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd=0.721\,9$. The $^{143}Nd/^{144}Nd$ ratio of the BCR-2 standard measured during this study was 0.512 628±15 (2σ). The Nd isotopes results are presented in Table 1.

The Nd isotopic analysis of terrigenous samples from this study gave ε_{Nd}(400 Ma) values varying from -4.2 to -2.7, and two-stage depleted mantle model ages (T_{2DM}) ranging from 1.5 to 1.4 Ga (Figs. 5a, 5b). Migmatite samples from this study have almost the same Nd isotopic characteristics as the Habahe Group terrigenous samples, with ε_{Nd}(400 Ma) and T_{2DM} values varying from -4.3 to -2.2, and from 1.5 to 1.4 Ga, respectively (Fig. 5a). This is consistent with the suggestion that the protoliths of the migmatites are indeed the Habahe Group rocks (Jiang et al., 2015). The ε_{Nd}(400 Ma) values of granites vary from -1.9 to 0, slightly more radiogenic than Habahe terrigenous samples, and the T_{2DM} varies from 1.1 to 1.3 Ga.

Published Nd isotopic data, including both terrigenous and volcanogenic components of the Habahe Group as well as from Silurian–Devonian granitoids from the Chinese Altai were collected for further comparison. Interestingly, the ε_{Nd}(400 Ma) values of 34 datasets of the Habahe Group terrigenous components vary from -5.5 to -2.5 (mostly negative, Fig. 5a, Table S3), a range overlapping with, or somewhat less radiogenic than, most local granitoids. In contrast, the ε_{Nd}(400 Ma) dataset of the Habahe volcanogenic components are in a range of +4.1 to +9.1, chemically more primitive than the granitoids. Similarly, the T_{2DM} values of the granitoids are mostly 1.4–1.0 Ga, exactly falling in the gap between those of the Habahe Group terrigenous and volcanogenic components (Fig. 5b). It is obvious that the Nd isotopic signatures of nearly all granitoids can be attained by mixing in the source of terrigenous and volcanogenic components in various proportions, supporting the view that the Habahe Group rocks could potentially be the source of the local Silurian–Devonian granitoids, as discussed in the following section.

4 DISCUSSION

4.1 Silurian–Devonian Granitoids: Recycling of the Habahe Group

The Silurian–Devonian granitoids in the Chinese Altai were classically interpreted as a product of arc magmatism, on the basis of their arc-like geochemical characteristics, such as depleted HFSE and enriched LILE on the N-MORB normalized spidergram (Cai et al., 2010; Yuan et al., 2007; Wang et al., 2006). The related magmatic arc was thought to be a continental-type arc since an old Precambrian basement was believed to exist in the region (Tong et al., 2007; Wang et al., 2006). However, this idea is not supported by recent findings that have reinterpreted the so-called "continental block" of the Chinese Altai as a variably metamorphosed accretionary wedge without any pieces of continental basement (Jiang et al., 2017, 2011; Xiao et al., 2009; Long et al., 2008; Sun et al., 2008). It is therefore highly speculative regarding the proposed whole petrogenetic model of the granitoids.

Alternatively, the geochemical features of the granitoids could be inherited from magmatic recycling of geochemically immature wedge sediments, i.e., the Habahe Group. This scenario has been emphasized by recent studies where geochemical similarities were found between granitoids and the Habahe Group rocks (Huang et al., 2018; Jiang et al., 2016; Liu et al., 2012). As shown in Figs. 6a, 6b, the bulk of the Silurian–Devonian granitoids in the Chinese Altai are compositionally comparable to partial melts derived from immature sediments dominated by metagreywackes, with subordinate contribution from intermediate-to-mafic source, but only a few resemble the compositions of pelite-derived melts as well as the Himalayan peraluminous granites. It is worth noting that the Habahe Group is mainly constituted by greywacke and intermediate-mafic volcanogenic components (Jiang et al., 2017, 2016). In addition, partial melts derived from immature sediments, i.e., the Habahe Group in this case, would tend to have higher Rb/Sr and Rb/Ba ratios than their source, since greywacke-like sediments contain large amounts of plagioclase and, Sr and Ba are compatible in plagioclase while Rb is incompatible (Sylvester, 1998; Harris and Inger, 1992). This is consistent with the fact that the local Silurian–Devonian granitoids have systematically higher Rb/Sr and Rb/Ba ratios than their prospective sources, i.e., the Habahe Group (Fig. 6b). Such a scenario is also supported by similar isotopic compositions between the granitoids and the Habahe Group (Huang et al., 2018; Jiang et al., 2016; Figs. 6c, 6d). Furthermore, recent studies demonstrated that zircons from the Silurian–Devonian granitoids have high $\delta^{18}O$ values (from +8.49‰ to +13.82‰), much higher than the mantle value of 5.3‰±0.3‰ (Zhang et al., 2019; Kong et al., 2018), suggesting reworking of crustal material in the magma source.

Table 1 Nd isotope of the Habahe Group rocks and Silurian–Devonian granitoids in Chinese Altai (CA)

Sample	Lithology	Location	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	±2σ	$(^{143}Nd/^{144}Nd)_t$	$\varepsilon_{Nd}(t)$	T_{DM} (Ga)	T_{2DM} (Ga)	$f_{Sm/Nd}$
17CA90-1	Sandstone	48°27'24.35"N, 87°10'9.61"E	4.2	24.9	0.101 6	0.512 232	11	0.511 966	-3.1	1.2	1.4	-0.5
17CA90-2	Sandstone	48°27'24.35"N, 87°10'9.61"E	5.7	39.0	0.088 9	0.512 218	7	0.511 985	-2.7	1.1	1.4	-0.5
17CA125-1	Siltstone	47°49'56.07"N, 88°3'3.96"E	5.6	27.0	0.125 5	0.512 238	7	0.511 909	-4.2	1.6	1.5	-0.4
17CA125-2	Siltstone	47°49'56.07"N, 88°3'3.96"E	5.8	26.5	0.132 9	0.512 281	7	0.511 933	-3.7	1.6	1.4	-0.3
17BC26	Migmatite	48°3'44.30"N, 86°58'29.50"E	4.0	20.8	0.116 6	0.512 258	8	0.511 953	-3.3	1.4	1.4	-0.4
16CA33	Migmatite	48°3'34.79"N, 87°0'18.45"E	5.1	26.2	0.118 9	0.512 214	9	0.511 903	-4.3	1.5	1.5	-0.4
16CA31	Migmatite	48°5'3.32"N, 87° 3'56.42"E	4.9	24.3	0.121 2	0.512 329	8	0.512 012	-2.2	1.4	1.3	-0.4
16CA30	Grt-granites	48°5'28.70"N, 87° 5'2.39"E	4.0	19.7	0.124 0	0.512 429	7	0.512 104	-0.4	1.2	1.2	-0.4
17BC29	Granites	48°6'5.40"N, 87° 2'36.60"E	2.1	11.6	0.111 5	0.512 417	7	0.512 125	0.0	1.1	1.1	-0.4
17BC34	Granites	48°3'34.84"N, 87°4'7.60"E	11.1	51.3	0.131 0	0.512 367	6	0.512 024	-1.9	1.4	1.3	-0.3

$^{147}Sm/^{144}Nd$ are calculated using whole-rock Sm and Nd contents; $(^{143}Nd/^{144}Nd)_t=(^{143}Nd/^{144}Nd)_S-(^{147}Sm/^{144}Nd)_S\times(e^{\lambda Sm\times t}-1)$; $\varepsilon_{Nd}(t)=[(^{143}Nd/^{144}Nd)_S/(^{143}Nd/^{144}Nd)_{CHUR}-1]\times 10\ 000$; in the calculation, $(^{143}Nd/^{144}Nd)_{CHUR}=0.512\ 638$; $(^{147}Sm/^{144}Nd)_{CHUR}=0.196\ 7$; $\lambda_{Sm}=6.54\times10^{-6}$; where S, CHUR are the sample and chondritic uniform reservoir; t is using the age of 400 Ma, because the initial $^{143}Nd/^{144}Nd$ ratios, $\varepsilon_{Nd}(t)$ values and model ages of the Habahe rocks with those of magmatic rocks in the region, which have predominant ca. 400 Ma emplacement ages.

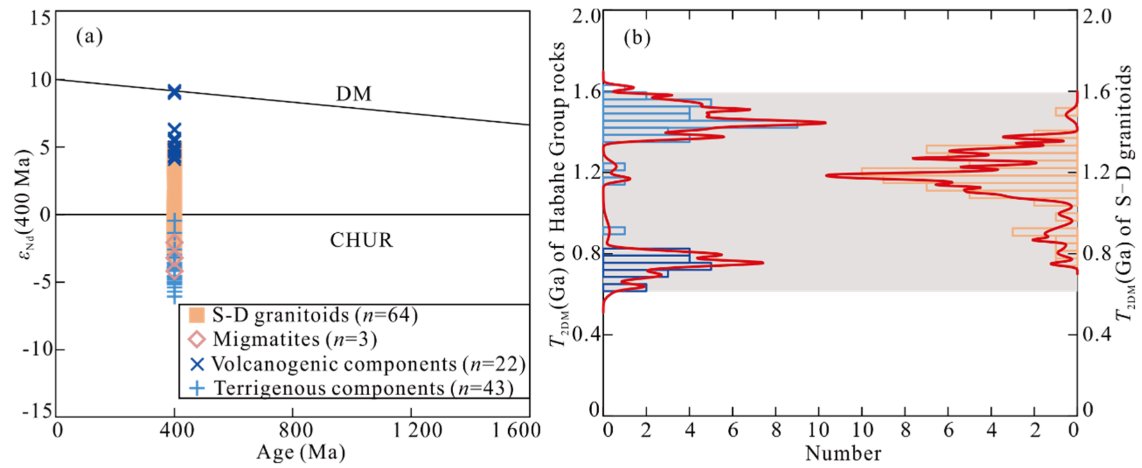

Figure 5. (a) Diagram of ε_{Nd}(400 Ma) vs. age (Ma) for the Habahe Group rocks, migmatites and Silurian–Devonian granitoids; (b) two stage Nd model ages of Habahe Group rocks and the granitoids. Details on data sources are available in Tables 1, S3.

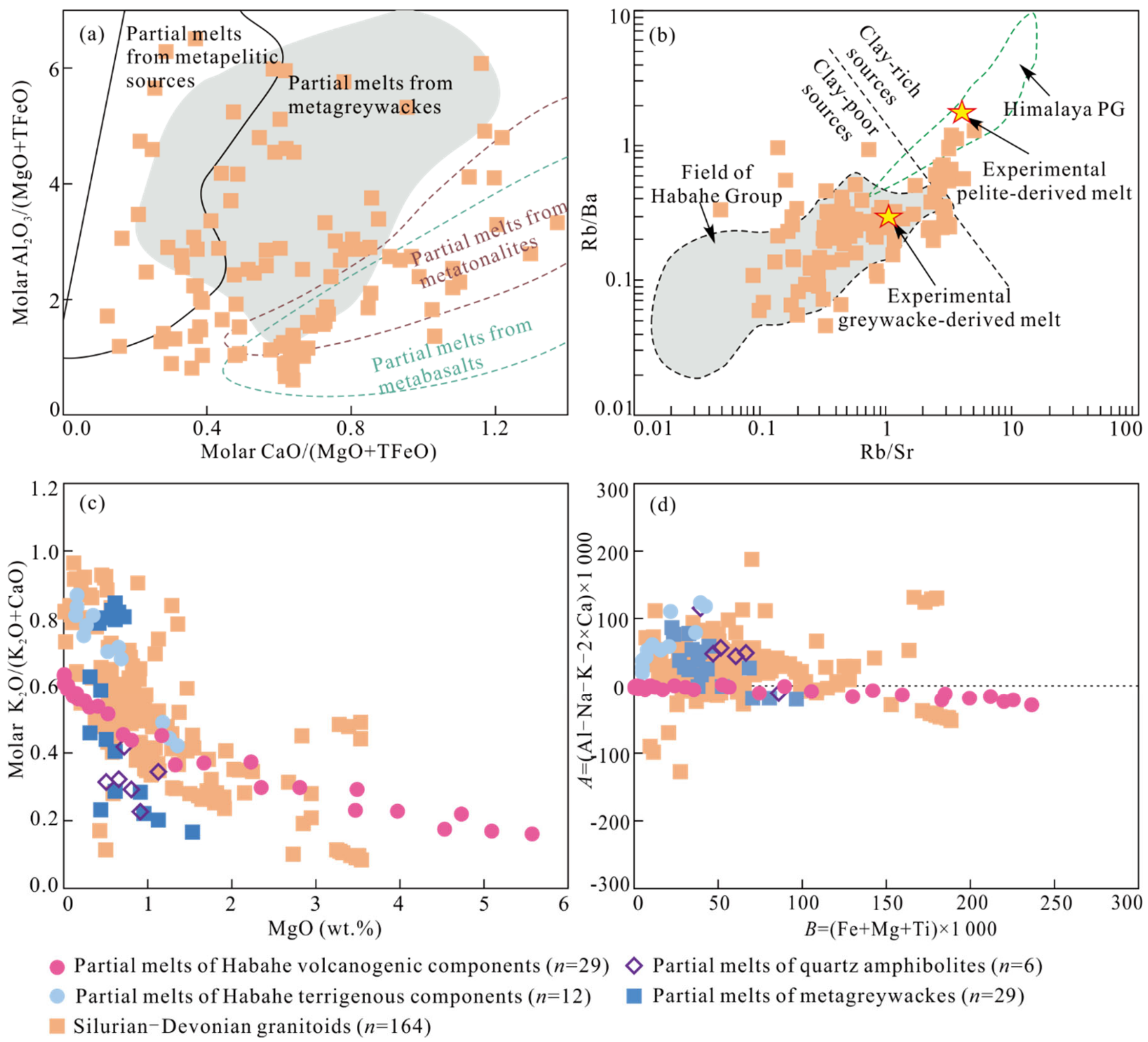

Figure 6. (a) Binary plot (CaO/(MgO+TFeO)) vs. Al_2O_3/(MgO+TFeO) (mol.%) after Gerdes et al. (2002) to distinguish granitic melts derived from various crustal sources; (b) plots of Rb/Sr vs. Rb/Ba after Sylvester (1998) to constrain the possible origin of the Altai granitoids; (c) whole-rock chemical comparison for modelled melts from partial melting of terrigenous and volcanogenic components and Silurian–Devonian granitoids; (d) multicationic (a)-(b) diagram after Castro et al. (2010). Compositions of partial melts from melting experiments of quartz amphibolites (Patiño Douce and Beard, 1995), and metagreywackes (Montel and Vielzeuf, 1997; Conrad et al., 1988) are shown for comparison, data of partial melts of Habahe terrigenous components and volcanogenic components are from Jiang et al. (2016) and Huang et al. (2018), respectively. Data sources are presented in Table S4.

In addition, lines of geological evidence support the magmatic recycling of the Habahe Group rocks: (1) metamorphic petrological features indicated that these rocks were buried into deep crustal levels and re-equilibrated during high-temperature metamorphism (Jiang et al., 2019, 2016, 2015); and (2) partial melting of Habahe Group rocks has shown gradual textural evolution evolving from ophthalmitic gneiss, though stromatites, nebulites to granitoid bodies (Fig. 4). Recent pseudosection modelling shows that partial melting of the Habahe Group sediments at regional attainable *P-T* conditions could have produced a large number of melts that show a good chemical match, in terms of major element contents and trace element patterns, with those of the local granitoids (see also Huang et al., 2018; Jiang et al., 2016, Figs. 6c, 6d); All these features have provided strong evidence that the Silurian–Devonian granitoids have originated from the magmatic recycling of the young, immature and chemically primitive Habahe rocks.

4.2 Nd-Hf Decoupling of the Habahe Group Rocks and Silurian–Devonian Granitoids

As mentioned above, decoupling between Nd and Hf isotopic systems of the Silurian–Devonian granitoids has resulted in hot debates on the nature of the lower crust. This has also led to different views on the tectonic setting of the Chinese Altai in the Early to Middle Paleozoic. To address this issue, Yu et al. (2017a, b) suggested that the Nd-Hf isotopic decoupling observed in the granitoids of the Chinese Altai were most likely inherited from the lithospheric mantle beneath the Chinese Altai. These authors suggested that the prolonged subduction and significant crust-mantle interaction caused the Nd-Hf isotopic decoupling in the mantle wedge where Nd was selectively enriched over Hf due to their distinctive behaviors during metasomatism (Yu et al., 2017b). This interpretation is quite similar to those exemplified in some modern island arcs (Hermann and Rubatto, 2009; Pearce et al., 1999). Alternatively, other authors suggested the Nd-Hf decoupling occurred as a consequence of disequilibrium between zircon and whole-rock during melting of the source (Kong et al., 2018). During such a process, they believed that residual zircons preferred to preserve and retain large amounts of Hf, whereas the resultant melts were Hf-depleted (Kong et al., 2018). The model of Yu et al. (2017b) may satisfactorily explain the Nd-Hf isotopic decoupling in the subordinate "I-type" granitoids in the region, which was possibly derived from arc magmas extracted from the mantle wedge. However, this may be not the case for the dominant biotite granidiorites and granites of the Chinese Altai. Moreover, recent findings of Huang et al. (2018) indicated that the so-called "I-type" granitoids could also be derived from the volcanogenic components of the Habahe Group rocks, a petrogenesis similar to that of the predominant biotite granodiorites to granites (see details in Jiang et al., 2016). The model of Kong et al. (2018) is possible but needs further mineralogical and petrological constraints. More importantly, the possibility that the Nd and Hf isotopic systems were already decoupled in the source rocks has never been considered yet in the region. The isotopic decoupling features of the granitoids could be due to the "zircon effect" during the magmatic process, but also could be inherited from the source.

As discussed above, our data supports that the bulk Silurian–Devonian granitoids in the Chinese Altai were derived from magmatic recycling of the Habahe Group rocks. The hypothesis of Nd-Hf isotopic signatures of the granitoids could be inherited from the Habahe Group rocks could hence be evaluated. For such a purpose, regional avaliable Nd-Hf isotopic data of the terrigenous and volcanogenic components were integrated (Tables S3, S5). It should be noted that zircon Hf isotopes sometimes may not represent those of their host rocks because of possible disequilibrium between zircon and whole-rock (Farina et al., 2014). In the Chinese Altai, whole-rock Hf isotope data for the Habahe Group rocks are not available. As a result, we could only gather a large number of zircon Hf isotopic data. However, given that hafnium was predominantly held in zircons in sediments, we tentatively propose that the zircon Hf isotopic data could broadly represent the isotopic compositions of the whole-rock, i.e., the Habahe Group.

It is shown that the terrigenous components of the Habahe Group have ε_{Hf}(400 Ma) values ranging from -21.3 to +13.5, with more than 70% falling between -8.1 to +6.8, and ε_{Nd}(400 Ma) values ranging from -5.9 to -0.3, with ~90% varying from -5.5 to -2.5, and averaging in -4.0 (Fig. 7). Apparently, more than 80% of those data plot above the Terrestrial Array (Fig. 7). On the other hand, the volcanogenic components have $\varepsilon_{Nd}(t)$ values ranging from +4.1 to +9.1, mostly varying from +4.1 to +6.5, with an average of +4.8. Hf-in-zircon isotopic data for the volcanogenic components in the Chinese Altai are currently unavailable, and data from their potential source, i.e., gabbros to diorites from the Lake Zone, western Mongolia (Janoušek et al.,

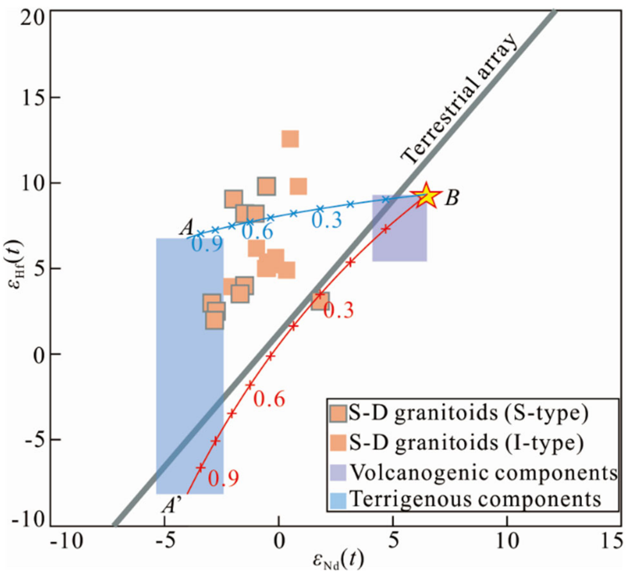

Figure 7. Diagram of $\varepsilon_{Nd}(t)$ vs. $\varepsilon_{Hf}(t)$ showing Nd-Hf decoupling of Silurian–Devonian granitoids. *t* is calculated using 400 Ma, the age peak of the Altai granitoids. The Hf isotope data of volcanogenic components were collected from gabbros and diorites of the Lake Zone after Janoušek et al. (2018) and data of granitoids after Yu et al. (2017b). See detailed explanations in the text. Data are presented in Table S5. Mixing hyperbolae for in source magma mixing is shown and proportions of the terrigenous components are indicated (see further explanations in text). The partition coefficients are from Bédard (2006), Irving and Frey (1978) and Dudas et al. (1971). Details on the calculation are presented in Table S6, data of melting fraction and mineral proportion are from thermodynamic modelling of Huang et al. (2018) and Jiang et al. (2016).

2018; Jiang et al., 2017) were collected. They have ε_{Hf}(400 Ma) ranging from +1.5 to +12.1, ~90% of which vary from +5.4 to +9.3 with an average value of +8.1, slightly below the Terrestrial Array (Fig. 7). It is notable that the Nd and Hf isotopic data of all the Silurian–Devonian granitoids fall within the gap between terrigenous and volcanogenic components (Fig. 7).

This advocates the notion, again, that the Nd-Hf decoupling isotopic signatures of nearly all granitoids can be attained by mixing in the source of these two components in various proportions. The proportions of the volcanogenic and terrigenous components in the in-source mixing model cited above were further evaluated. A binary mixing mode between the terrigenous components and the volcanogenic component was applied using the equation as follow

$$\varepsilon_m=[f_A\times C_A\times\varepsilon_A+f_B\times C_B\times\varepsilon_B]/(f_A\times C_A+f_B\times C_B)$$

where ε_m, ε_A and ε_B refer to the epsilon isotopic values of mixing melts, melts of Habahe terrigenous and volcanogenic components, and, C_A and C_B refer to the related element concentrations in partial melts of Habahe terrigenous and volcanogenic components. The compositions of melts and residue were inferred from thermodynamic modelling of Huang et al. (2018) and Jiang et al. (2016) for terrigenous and volcanogenic components, respectively.

Given that the anatexis of the Habahe Group in the deep crust was thought to have a thermal condition of 10 kbar and 900 °C (Jiang et al., 2016), melts from such reference point in the phase diagrams of Jiang et al. (2016) and Huang et al. (2018) were selected for further Nd and Hf isotopic modelling. It was shown by Jiang et al. (2016) that the terrigenous components under such conditions would have 25 vol.% of melts in equilibrium with a granulite-facies residual assemblage mainly consisting of garnet, plagioclase, K-feldspar and quartz (Table S6). Similarly, with the same metamorphic condition, the volcanogenic components would have 20 vol.% of melts in equilibrium with the residual assemblage mainly with amphibole, plagioclase and clinopyroxene (Huang et al., 2018, Table S6). According to the modelled results, the mineral proportions could be adjusted to plagioclase: K-feldspar: garnet (0.3 : 0.3 : 0.4) for the terrigenous components, and amphibole: plagioclase: clinopyroxene (0.3 : 0.4 : 0.3) for the volcanogenic components, respectively. Two possible hyperbolae were considered for the binary mixing between the most primitive volcanogenic component ($\varepsilon_{Nd}(t)$=+6.5, $\varepsilon_{Hf}(t)$=+9.3, "B" in Fig. 7) and two terrigenous end-members with contrasting $\varepsilon_{Hf}(t)$ values (i.e., "A": $\varepsilon_{Nd}(t)$=-4.0, $\varepsilon_{Hf}(t)$=+6.8 and "A": $\varepsilon_{Nd}(t)$ =-4.0 and $\varepsilon_{Hf}(t)$=-8.1, Fig. 7). Details about the calculation were presented in Table S6.

It shows that the granitoids could be generated by magma mixing in the source of 50 vol.%–90 vol.% terrigenous components with 50 vol.%–10 vol.% volcanogenic components (Fig. 7). In any cases, the results of this simple binary mixing model should be taken only as a guide in the evaluation of an approximate amount of these two components, since the nature of the real magmatic process could be different. However, we can tentatively conclude that the decoupled Nd-Hf isotopic signatures may have been inherited from their magma source, i.e., the Habahe Group rocks.

5 CONCLUSIONS

Geological and geochemical data are combined to decipher the nature of the Nd-Hf decoupling of the Silurian–Devonian granitoids in the Chinese Altai. The principal conclusions are as follows.

(1) The Silurian–Devonian granitoids in the region was possibly originated from the partial melting of the immature, young, and chemically primitive Ordovician Altai wedge sediments, i.e., the Habahe Group rocks.

(2) The dominant terrigenous components of the Habahe Group have relatively high $\varepsilon_{Hf}(t)$ and low $\varepsilon_{Nd}(t)$ values whereas the subordinate volcanogenic components of the Habahe Group are characterized by relatively high $\varepsilon_{Nd}(t)$ and low $\varepsilon_{Hf}(t)$ values. Both of them show significant Nd-Hf isotopic decoupling.

(3) The Nd-Hf isotopic decoupling for the Silurian–Devonian granitoids in the Chinese Altai can be ultimately inherited from their source rocks, i.e., the Habahe Group.

ACKNOWLEDGMENTS

This study was supported by the National Key R & D Program of China (No. 2017YFC0601205), the Strategic Priority Research Program (B) of the CAS (No. XDB18020203), the NSF China (No. 41672056), the Guangdong Special Support Program and GIG-CAS 135 Project (No. 135TP201601). A 100 Talents Program of the CAS to Yingde Jiang and a China Postdoctoral Science Foundation to Yu Yang (No. 2018M633172) are also acknowledged. Constructive reviews from two anonymous reviewers helped us to greatly improve the paper. The final publication is available at Springer via https://doi.org/10.1007/s12583-019-1217-x.

Electronic Supplementary Materials: Supplementary materials (Tables S1, S2, S3, S4, S5, S6) are available in the online version of this article at https://doi.org/10.1007/s12583-019-1217-x.

REFERENCES CITED

Badarch, G., Dickson Cunningham, W., Windley, B. F., 2002. A New Terrane Subdivision for Mongolia: Implications for the Phanerozoic Crustal Growth of Central Asia. *Journal of Asian Earth Sciences*, 21(1): 87–110. https://doi.org/10.1016/s1367-9120(02)00017-2

Bédard, J. H., 2006. A Catalytic Delamination-Driven Model for Coupled Genesis of Archaean Crust and Sub-Continental Lithospheric Mantle. *Geochimica et Cosmochimica Acta*, 70(5): 1188–1214. https://doi.org/10.1016/j.gca.2005.11.008

Bennett, V. C., Nutman, A. P., McCulloch, M. T., 1993. Nd Isotopic Evidence for Transient, Highly Depleted Mantle Reservoirs in the Early History of the Earth. *Earth and Planetary Science Letters*, 119(3): 299–317. https://doi.org/10.1016/0012-821x(93)90140-5

Bhatia, M. R., Crook, K. A. W., 1986. Trace Element Characteristics of Graywackes and Tectonic Setting Discrimination of Sedimentary Basins. *Contributions to Mineralogy and Petrology*, 92(2): 181–193. https://doi.org/10.1007/bf00375292

Bizimis, M., Sen, G., Salters, V. J. M., 2004. Hf-Nd Isotope Decoupling in the Oceanic Lithosphere: Constraints from Spinel Peridotites from Oahu, Hawaii. *Earth and Planetary Science Letters*, 217(1/2): 43–58. https://doi.org/10.1016/s0012-821x(03)00598-3

Bowring, S. A., King, J. E., Housh, T. B., et al., 1989. Neodymium and Lead Isotope Evidence for Enriched Early Archaean Crust in North America.

Nature, 340(6230): 222–225. https://doi.org/10.1038/340222a0

Broussolle, A., Aguilar, C., Sun, M., et al., 2018. Polycyclic Paleozoic Evolution of Accretionary Orogenic Wedge in the Southern Chinese Altai: Evidence from Structural Relationships and U-Pb Geochronology. *Lithos*, 314–315: 400–424. https://doi.org/10.1016/j.lithos.2018.06.005

Broussolle, A., Sun, M., Schulmann, K., et al., 2019. Are the Chinese Altai "Terranes" the Result of Juxtaposition of Different Crustal Levels during Late Devonian and Permian Orogenesis?. *Gondwana Research*, 66: 183–206. https://doi.org/10.1016/j.gr.2018.11.003

Cai, K. D., Sun, M., Yuan, C., et al., 2010. Geochronological and Geochemical Study of Mafic Dykes from the Northwest Chinese Altai: Implications for Petrogenesis and Tectonic Evolution. *Gondwana Research*, 18(4): 638–652. https://doi.org/10.1016/j.gr.2010.02.010

Cai, K. D., Sun, M., Yuan, C., et al., 2011a. Geochronology, Petrogenesis and Tectonic Significance of Peraluminous Granites from the Chinese Altai, NW China. *Lithos*, 127(1/2): 261–281. https://doi.org/10.1016/j.lithos.2011.09.001

Cai, K. D., Sun, M., Yuan, C., et al., 2011b. Prolonged Magmatism, Juvenile Nature and Tectonic Evolution of the Chinese Altai, NW China: Evidence from Zircon U-Pb and Hf Isotopic Study of Paleozoic Granitoids. *Journal of Asian Earth Sciences*, 42(5): 949–968. https://doi.org/10.1016/j.jseaes.2010.11.020

Castro, A., Gerya, T., Garcia-Casco, A., et al., 2010. Melting Relations of MORB-Sediment Melanges in Underplated Mantle Wedge Plumes; Implications for the Origin of Cordilleran-Type Batholiths. *Journal of Petrology*, 51(6): 1267–1295. https://doi.org/10.1093/petrology/egq019

Chase, C. G., Patchett, P. J., 1988. Stored Mafic/Ultramafic Crust and Early Archean Mantle Depletion. *Earth and Planetary Science Letters*, 91(1/2): 66–72. https://doi.org/10.1016/0012-821x(88)90151-3

Chen, B., Jahn, B. M., 2002. Geochemical and Isotopic Studies of the Sedimentary and Granitic Rocks of the Altai Orogen of Northwest China and Their Tectonic Implications. *Geological Magazine*, 139(1): 1–13. https://doi.org/10.1017/s0016756801006100

Conrad, W. K., Nicholls, I. A., Wall, V. J., 1988. Water-Saturated and -Undersaturated Melting of Metaluminous and Peraluminous Crustal Compositions at 10 Kb: Evidence for the Origin of Silicic Magmas in the Taupo Volcanic Zone, New Zealand, and other Occurrences. *Journal of Petrology*, 29(4): 765–803. https://doi.org/10.1093/petrology/29.4.765

Debon, F., le Fort, P., 1983. A Chemical-Mineralogical Classification of Common Plutonic Rocks and Associations. *Transactions of the Royal Society of Edinburgh*: *Earth Sciences*, 73(3): 135–149. https://doi.org/10.1017/s0263593300010117

DePaolo, D. J., Manton, W. I., Grew, E. S., et al., 1982. Sm-Nd, Rb-Sr and U-Th-Pb Systematics of Granulite Facies Rocks from Fyfe Hills, Enderby Land, Antarctica. *Nature*, 298(5875): 614–618. https://doi.org/10.1038/298614a0

Dudas, M. J., Schmitt, R. A., Harward, M. E., 1971. Trace Element Partitioning between Volcanic Plagioclase and Dacitic Pyroclastic Matrix. *Earth and Planetary Science Letters*, 11(1–5): 440–446. https://doi.org/10.1016/0012-821x(71)90206-8

Farina, F., Stevens, G., Gerdes, A., et al., 2014. Small-Scale Hf Isotopic Variability in the Peninsula Pluton (South Africa): The Processes that Control Inheritance of Source $^{176}Hf/^{177}Hf$ Diversity in S-Type Granites. *Contributions to Mineralogy and Petrology*, 168(4): 1065. https://doi.org/10.1007/s00410-014-1065-8

Galer, S. J. G., Goldstein, S. L., 1991. Early Mantle Differentiation and Its Thermal Consequences. *Geochimica et Cosmochimica Acta*, 55(1): 227–239. https://doi.org/10.1016/0016-7037(91)90413-y

Gerdes, A., Montero, P., Bea, F., et al., 2002. Peraluminous Granites Frequently with Mantle-Like Isotope Compositions: The Continental-Type Murzinka and Dzhabyk Batholiths of the Eastern Urals. *International Journal of Earth Sciences*, 91(1): 3–19. https://doi.org/10.1007/s005310100195

Harris, N. B. W., Inger, S., 1992. Trace Element Modelling of Pelite-Derived Granites. *Contributions to Mineralogy and Petrology*, 110(1): 46–56. https://doi.org/10.1007/bf00310881

Hermann, J., Rubatto, D., 2009. Accessory Phase Control on the Trace Element Signature of Sediment Melts in Subduction Zones. *Chemical Geology*, 265(3/4): 512–526. https://doi.org/10.1016/j.chemgeo.2009.05.018

Hu, A. Q., Jahn, B. M., Zhang, G. X., et al., 2000. Crustal Evolution and Phanerozoic Crustal Growth in Northern Xinjiang: Nd Isotopic Evidence. Part I. Isotopic Characterization of Basement Rocks. *Tectonophysics*, 328(1/2): 15–51. https://doi.org/10.1016/s0040-1951(00)00176-1

Huang, Y. Q., Jiang, Y. D., Collett, S., et al., 2018. Nd Isotope Characteristics of the Chinese Altai Accretionary Wedge: Implications of Syn-Tectonic Granitoids Petrogenesis, 2018 Annual Meeting of Chinese Geoscience Union, Beijing. 341

Ionov, D. A., Blichert-Toft, J., Weis, D., 2005. Hf Isotope Compositions and HREE Variations in Off-Craton Garnet and Spinel Peridotite Xenoliths from Central Asia. *Geochimica et Cosmochimica Acta*, 69(9): 2399–2418. https://doi.org/10.1016/j.gca.2004.11.008

Irving, A. J., Frey, F. A., 1978. Distribution of Trace Elements between Garnet Megacrysts and Host Volcanic Liquids of Kimberlitic to Rhyolitic Composition. *Geochimica et Cosmochimica Acta*, 42(6): 771–787. https://doi.org/10.1016/0016-7037(78)90092-3

Jahn, B. M., Wu, F. Y., Chen, B., 2000. Granitoids of the Central Asian Orogenic Belt and Continental Growth in the Phanerozoic, In: Barbarin, B., Stephens, W. E., Bonin, B., eds., Transactions of the Royal Society of Edinburgh-Earth Sciences. *Geological Society of America*, 181–193

Janoušek, V., Jiang, Y. D., Buriánek, D., et al., 2018. Cambrian–Ordovician Magmatism of the Ikh-Mongol Arc System Exemplified by the Khantaishir Magmatic Complex (Lake Zone, South-Central Mongolia). *Gondwana Research*, 54: 122–149. https://doi.org/10.1016/j.gr.2017.10.003

Jiang, Y. D., Schulmann, K., Kröner, A., et al., 2017. Neoproterozoic–Early Paleozoic Peri-Pacific Accretionary Evolution of the Mongolian Collage System: Insights from Geochemical and U-Pb Zircon Data from the Ordovician Sedimentary Wedge in the Mongolian Altai. *Tectonics*, 36(11): 2305–2331. https://doi.org/10.1002/2017tc004533

Jiang, Y. D., Schulmann, K., Sun, M., et al., 2016. Anatexis of Accretionary Wedge, Pacific-Type Magmatism, and Formation of Vertically Stratified Continental Crust in the Altai Orogenic Belt. *Tectonics*, 35(12): 3095–3118. https://doi.org/10.1002/2016tc004271

Jiang, Y. D., Schulmann, K., Sun, M., et al., 2019. Structural and Geochronological Constraints on Devonian Suprasubduction Tectonic Switching and Permian Collisional Dynamics in the Chinese Altai, Central Asia. *Tectonics*, 38(1): 253–280. https://doi.org/10.1029/2018tc005231

Jiang, Y. D., Štípská, P., Sun, M., et al., 2015. Juxtaposition of Barrovian and Migmatite Domains in the Chinese Altai: A Result of Crustal Thickening Followed by Doming of Partially Molten Lower Crust. *Journal of Metamorphic Geology*, 33(1): 45–70. https://doi.org/10.1111/jmg.12110

Jiang, Y. D., Sun, M., Zhao, G. C., et al., 2011. Precambrian Detrital Zircons in the Early Paleozoic Chinese Altai: Their Provenance and Implications for the Crustal Growth of Central Asia. *Precambrian Research*, 189(1/2): 140–154. https://doi.org/10.1016/j.precamres.2011.05.008

Jiang, Y. D., Sun, M., Zhao, G., et al., 2010. The 390 Ma High-*T* Metamorphic Event in the Chinese Altai: A Consequence of Ridge-Subduction?.

American Journal of Science, 310(10): 1421–1452. https://doi.org/10.2475/10.2010.08

Kong, X. Y., Zhang, C., Liu, D. D., et al., 2018. Disequilibrium Partial Melting of Metasediments in Subduction Zones: Evidence from O-Nd-Hf Isotopes and Trace Elements in S-Type Granites of the Chinese Altai. *Lithosphere*, 11(1): 149–168. https://doi.org/10.1130/l1039.1

Li, P. F., Sun, M., Rosenbaum, G., et al., 2015. Structural Evolution of the Irtysh Shear Zone (Northwestern China) and Implications for the Amalgamation of Arc Systems in the Central Asian Orogenic Belt. *Journal of Structural Geology*, 80: 142–156. https://doi.org/10.1016/j.jsg.2015.08.008

Li, X. H., Liu, D. Y., Sun, M., et al., 2004. Precise Sm-Nd and U-Pb Isotopic Dating of the Supergiant Shizhuyuan Polymetallic Deposit and Its Host Granite, SE China. *Geological Magazine*, 141(2): 225–231. https://doi.org/10.1017/s0016756803008823

Li, Z. L., Yang, X. Q., Li, Y. Q., et al., 2014. Late Paleozoic Tectono-Metamorphic Evolution of the Altai Segment of the Central Asian Orogenic Belt: Constraints from Metamorphic P–T Pseudosection and Zircon U-Pb Dating of Ultra-High-Temperature Granulite. *Lithos*, 204: 83–96. https://doi.org/10.1016/j.lithos.2014.05.022

Liu, W., Liu, X. J., Xiao, W. J., 2012. Massive Granitoid Production without Massive Continental-Crust Growth in the Chinese Altay: Insight into the Source Rock of Granitoids Using Integrated Zircon U-Pb Age, Hf-Nd-Sr Isotopes and Geochemistry. *American Journal of Science*, 312(6): 629–684. https://doi.org/10.2475/06.2012.02

Long, X. P., Sun, M., Yuan, C., et al., 2007. Detrital Zircon Age and Hf Isotopic Studies for Metasedimentary Rocks from the Chinese Altai: Implications for the Early Paleozoic Tectonic Evolution of the Central Asian Orogenic Belt. *Tectonics*, 26(5): TC5015. https://doi.org/10.1029/2007tc002128

Long, X. P., Sun, M., Yuan, C., et al., 2008. Early Paleozoic Sedimentary Record of the Chinese Altai: Implications for Its Tectonic Evolution. *Sedimentary Geology*, 208(3/4): 88–100. https://doi.org/10.1016/j.sedgeo.2008.05.002

Long, X. P., Yuan, C., Sun, M., et al., 2010. Detrital Zircon Ages and Hf Isotopes of the Early Paleozoic Flysch Sequence in the Chinese Altai, NW China: New Constrains on Depositional Age, Provenance and Tectonic Evolution. *Tectonophysics*, 480(1–4): 213–231. https://doi.org/10.1016/j.tecto.2009.10.013

Long, X. P., Yuan, C., Sun, M., et al., 2012. Geochemistry and Nd Isotopic Composition of the Early Paleozoic Flysch Sequence in the Chinese Altai, Central Asia: Evidence for a Northward-Derived Mafic Source and Insight into Nd Model Ages in Accretionary Orogen. *Gondwana Research*, 22(2): 554–566. https://doi.org/10.1016/j.gr.2011.04.009

McCulloch, M. T., Bennett, V. C., 1994. Progressive Growth of the Earth's Continental Crust and Depleted Mantle: Geochemical Constraints. *Geochimica et Cosmochimica Acta*, 58(21): 4717–4738. https://doi.org/10.1016/0016-7037(94)90203-8

McLennan, S. M., Taylor, S. R., McGregor, V. R., 1984. Geochemistry of Archean Metasedimentary Rocks from West Greenland. *Geochimica et Cosmochimica Acta*, 48(1): 1–13. https://doi.org/10.1016/0016-7037(84)90345-4

Montel, J. M., Vielzeuf, D., 1997. Partial Melting of Metagreywackes, Part II. Compositions of Minerals and Melts. *Contributions to Mineralogy and Petrology*, 128(2/3): 176–196. https://doi.org/10.1007/s004100050302

Patchett, P. J., 1983. Importance of the Lu-Hf Isotopic System in Studies of Planetary Chronology and Chemical Evolution. *Geochimica et Cosmochimica Acta*, 47(1): 81–91. https://doi.org/10.1016/0016-7037(83)90092-3

Patchett, P. J., Tatsumoto, M., 1980. Lu-Hf Total-Rock Isochron for the Eucrite Meteorites. *Nature*, 288(5791): 571–574. https://doi.org/10.1038/288571a0

Patchett, P. J., White, W. M., Feldmann, H., et al., 1984. Hafnium/Rare Earth Element Fractionation in the Sedimentary System and Crustal Recycling into the Earth's Mantle. *Earth and Planetary Science Letters*, 69(2): 365–378. https://doi.org/10.1016/0012-821x(84)90195-x

Patiño Douce, A. E., Beard, J. S., 1995. Dehydration-Melting of Biotite Gneiss and Quartz Amphibolite from 3 to 15 Kbar. *Journal of Petrology*, 36(3): 707–738. https://doi.org/10.1093/petrology/36.3.707

Pearce, J. A., Kempton, P. D., Nowell, G. M., et al., 1999. Hf-Nd Element and Isotope Perspective on the Nature and Provenance of Mantle and Subduction Components in Western Pacific Arc-Basin Systems. *Journal of Petrology*, 40(11): 1579–1611. https://doi.org/10.1093/petroj/40.11.1579

Peccerillo, A., Taylor, S. R., 1976. Geochemistry of Eocene Calc-Alkaline Volcanic Rocks from the Kastamonu Area, Northern Turkey. *Contributions to Mineralogy and Petrology*, 58(1): 63–81. https://doi.org/10.1007/bf00384745

Pettijohn, F. J., Potter, P. E., Siever, R., 1987. Sand and Sandstone. Springer, New York

Safonova, I. Y., Utsunomiya, A., Kojima, S., et al., 2009. Pacific Superplume-Related Oceanic Basalts Hosted by Accretionary Complexes of Central Asia, Russian Far East and Japan. *Gondwana Research*, 16(3/4): 587–608. https://doi.org/10.1016/j.gr.2009.02.008

Salters, V. J. M., Longhi, J., 1999. Trace Element Partitioning during the Initial Stages of Melting beneath Mid-Ocean Ridges. *Earth and Planetary Science Letters*, 166(1/2): 15–30. https://doi.org/10.1016/s0012-821x(98)00271-4

Scherer, E. E., Cameron, K. L., Johnson, C. M., et al., 1997. Lu-Hf Geochronology Applied to Dating Cenozoic Events Affecting Lower Crustal Xenoliths from Kilbourne Hole, New Mexico. *Chemical Geology*, 142(1/2): 63–78. https://doi.org/10.1016/s0009-2541(97)00076-4

Schmidberger, S. S., Simonetti, A., Francis, D., et al., 2002. Probing Archean Lithosphere Using the Lu-Hf Isotope Systematics of Peridotite Xenoliths from Somerset Island Kimberlites, Canada. *Earth and Planetary Science Letters*, 197(3/4): 245–259. https://doi.org/10.1016/s0012-821x(02)00491-0

Schmitz, M. D., Vervoort, J. D., Bowring, S. A., et al., 2004. Decoupling of the Lu-Hf and Sm-Nd Isotope Systems during the Evolution of Granulitic Lower Crust beneath Southern Africa. *Geology*, 32(5): 405–408. https://doi.org/10.1130/g20241.1

Şengör, A. M. C., Natal'in, B. A., 1996. Turkic-Type Orogeny and Its Role in the Making of the Continental Crust. *Annual Review of Earth and Planetary Sciences*, 24(1): 263–337. https://doi.org/10.1146/annurev.earth.24.1.263

Şengör, A. M. C., Natal'in, B. A., Burtman, V. S., 1993. Evolution of the Altaid Tectonic Collage and Palaeozoic Crustal Growth in Eurasia. *Nature*, 364(6435): 299–307. https://doi.org/10.1038/364299a0

Shi, W. X., Zhang, J. D., Liu, W. G., et al., 2015. Hronology and Petrology Characteristics of Early Devonian Gnessic Granites from East Altai Orogenic Belt. *Xinjiang Geology*, 33(4): 456–462. https://doi.org/10.3969/j.issn.1000-8845.2015.04.008 (in Chinese with English Abstract)

Song, P., Tong, Y., Wang, T., et al., 2017. Zircon U-Pb Ages and Genetic Evolution of Devonian Granitic Rocks in the Southeastern Chinese Altai and Its Tectonic Implications: New Evidence for Magmatic Evolution of Calc-Alkaline-High-K Calc-Alkaline-Alkaline Rocks. *Acta Geologica Sinica*, 91(1): 55–79 (in Chinese with English Abstract)

Sun, M., Long, X. P., Cai, K. D., et al., 2009. Early Paleozoic Ridge Subduction in the Chinese Altai: Insight from the Abrupt Change in Zircon Hf Isotopic Compositions. *Science in China Series D*: *Earth Sciences*, 52(9): 1345–1358. https://doi.org/10.1007/s11430-009-0110-3

Sun, M., Yuan, C., Xiao, W. J., et al., 2008. Zircon U-Pb and Hf Isotopic Study of Gneissic Rocks from the Chinese Altai: Progressive Accretionary History in the Early to Middle Palaeozoic. *Chemical Geology*, 247(3/4): 352–383. https://doi.org/10.1016/j.chemgeo.2007.10.026

Sun, S. S., McDonough, W. F., 1989. Chemical and Isotopic Systematics of Oceanic Basalts: Implications for Mantle Composition and Processes. *Geological Society*, *London*, *Special Publications*, 42(1): 313–345. https://doi.org/10.1144/gsl.sp.1989.042.01.19

Sylvester, P. J., 1998. Post-Collisional Strongly Peraluminous Granites. *Lithos*, 45(1–4): 29–44. https://doi.org/10.1016/s0024-4937(98)00024-3

Tang, G. J., Wang, Q., Wyman, D. A., et al., 2012. Recycling Oceanic Crust for Continental Crustal Growth: Sr-Nd-Hf Isotope Evidence from Granitoids in the Western Junggar Region, NW China. *Lithos*, 128–131: 73–83. https://doi.org/10.1016/j.lithos.2011.11.003

Tong, Y., Wang, T., Hong, D. W., et al., 2007. Ages and Origin of the Early Devonian Granites from the North Part of Chinese Altai Mountains and Its Tectonic Implications. *Acta Petrologica Sinica*, 23(8): 1933–1944 (in Chinese with English Abstract)

Vervoort, J. D., Blichert-Toft, J., 1999. Evolution of the Depleted Mantle: Hf Isotope Evidence from Juvenile Rocks through Time. *Geochimica et Cosmochimica Acta*, 63(3/4): 533–556. https://doi.org/10.1016/s0016-7037(98)00274-9

Vervoort, J. D., Patchett, P. J., 1996. Behavior of Hafnium and Neodymium Isotopes in the Crust: Constraints from Precambrian Crustally Derived Granites. *Geochimica et Cosmochimica Acta*, 60(19): 3717–3733. https://doi.org/10.1016/0016-7037(96)00201-3

Vervoort, J. D., Patchett, P. J., Albarède, F., et al., 2000. Hf-Nd Isotopic Evolution of the Lower Crust. *Earth and Planetary Science Letters*, 181(1/2): 115–129. https://doi.org/10.1016/s0012-821x(00)00170-9

Vervoort, J. D., Patchett, P. J., Blichert-Toft, J., et al., 1999. Relationships between Lu-Hf and Sm-Nd Isotopic Systems in the Global Sedimentary System. *Earth and Planetary Science Letters*, 168(1/2): 79–99. https://doi.org/10.1016/s0012-821x(99)00047-3

Villaseca, C., Barbero, L., Herreros, V., 1998. A Re-Examination of the Typology of Peraluminous Granite Types in Intracontinental Orogenic Belts. *Transactions of the Royal Society of Edinburgh*: *Earth Sciences*, 89(2): 113–119. https://doi.org/10.1017/s0263593300007045

Wang, T., Hong, D. W., Jahn, B. M., et al., 2006. Timing, Petrogenesis, and Setting of Paleozoic Synorogenic Intrusions from the Altai Mountains, Northwest China: Implications for the Tectonic Evolution of an Accretionary Orogen. *The Journal of Geology*, 114(6): 735–751. https://doi.org/10.1086/507617

Wang, T., Jahn, B. M., Kovach, V. P., et al., 2009. Nd-Sr Isotopic Mapping of the Chinese Altai and Implications for Continental Growth in the Central Asian Orogenic Belt. *Lithos*, 110(1/2/3/4): 359–372. https://doi.org/10.1016/j.lithos.2009.02.001

Wei, C. J., Clarke, G., Tian, W., et al., 2007. Transition of Metamorphic Series from the Kyanite- to Andalusite-Types in the Altai Orogen, Xinjiang, China: Evidence from Petrography and Calculated KMnFMASH and KFMASH Phase Relations. *Lithos*, 96(3/4): 353–374. https://doi.org/10.1016/j.lithos.2006.11.004

Wilhem, C., Windley, B. F., Stampfli, G. M., 2012. The Altaids of Central Asia: A Tectonic and Evolutionary Innovative Review. *Earth-Science Reviews*, 113(3/4): 303–341. https://doi.org/10.1016/j.earscirev.2012.04.001

Windley, B. F., Alexeiev, D., Xiao, W. J., et al., 2007. Tectonic Models for Accretion of the Central Asian Orogenic Belt. *Journal of the Geological Society*, 164(1): 31–47. https://doi.org/10.1144/0016-76492006-022

Windley, B. F., Kröner, A., Guo, J. H., et al., 2002. Neoproterozoic to Paleozoic Geology of the Altai Orogen, NW China: New Zircon Age Data and Tectonic Evolution. *The Journal of Geology*, 110(6): 719–737. https://doi.org/10.1086/342866

Wittig, N., Baker, J. A., Downes, H., 2007. U-Th-Pb and Lu-Hf Isotopic Constraints on the Evolution of Sub-Continental Lithospheric Mantle, French Massif Central. *Geochimica et Cosmochimica Acta*, 71(5): 1290–1311. https://doi.org/10.1016/j.gca.2006.11.025

Xiao, W. J., Huang, B. C., Han, C. M., et al., 2010. A Review of the Western Part of the Altaids: A Key to Understanding the Architecture of Accretionary Orogens. *Gondwana Research*, 18(2/3): 253–273. https://doi.org/10.1016/j.gr.2010.01.007

Xiao, W. J., Windley, B. F., Yuan, C., et al., 2009. Paleozoic Multiple Subduction-Accretion Processes of the Southern Altaids. *American Journal of Science*, 309(3): 221–270. https://doi.org/10.2475/03.2009.02

Xiao, W., Windley, B. F., Badarch, G., et al., 2004. Palaeozoic Accretionary and Convergent Tectonics of the Southern Altaids: Implications for the Growth of Central Asia. *Journal of the Geological Society*, 161(3): 339–342. https://doi.org/10.1144/0016-764903-165

Yu, S. Y., Xu, Y. G., Huang, X. L., et al., 2009. Hf-Nd Isotopic Decoupling in Continental Mantle Lithosphere beneath Northeast China: Effects of Pervasive Mantle Metasomatism. *Journal of Asian Earth Sciences*, 35(6): 554–570. https://doi.org/10.1016/j.jseaes.2009.04.005

Yu, Y., Sun, M., Huang, X. L., et al., 2017a. Sr-Nd-Hf-Pb Isotopic Evidence for Modification of the Devonian Lithospheric Mantle beneath the Chinese Altai. *Lithos*, 284–285: 207–221. https://doi.org/10.1016/j.lithos.2017.04.004

Yu, Y., Sun, M., Long, X. P., et al., 2017b. Whole-Rock Nd-Hf Isotopic Study of I-Type and Peraluminous Granitic Rocks from the Chinese Altai: Constraints on the Nature of the Lower Crust and Tectonic Setting. *Gondwana Research*, 47: 131–141. https://doi.org/10.1016/j.gr.2016.07.003

Yuan, C., Sun, M., Xiao, W. J., et al., 2007. Accretionary Orogenesis of the Chinese Altai: Insights from Paleozoic Granitoids. *Chemical Geology*, 242(1/2): 22–39. https://doi.org/10.1016/j.chemgeo.2007.02.013

Zhang, C. L., Santosh, M., Zou, H. B., et al., 2012. Revisiting the "Irtish Tectonic Belt": Implications for the Paleozoic Tectonic Evolution of the Altai Orogen. *Journal of Asian Earth Sciences*, 52: 117–133. https://doi.org/10.1016/j.jseaes.2012.02.016

Zhang, C., Liu, D. D., Zeng, J. H., et al., 2019. Nd-O-Hf Isotopic Decoupling in S-Type Granites: Implications for Ridge Subduction. *Lithos*, 332–333: 261–273. https://doi.org/10.1016/j.lithos.2019.03.009

Zhang, J. J., Wang, T., Tong, Y., et al., 2017. 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. *International Geology Review*, 59(16): 2021–2040. https://doi.org/10.1080/00206814.2017.1308841

Zhang, X., Zhang, H., Ma, Z. L., et al., 2016. A New Model for the Granite-Pegmatite Genetic Relationships in the Kaluan-Azubai-Qiongkuer Pegmatite-Related Ore Fields, the Chinese Altay. *Journal of Asian Earth Sciences*, 124: 139–155. https://doi.org/10.1016/j.jseaes.2016.04.020

Zheng, J. H., Chai, F. M., Yang, F. Q., 2016. The 401–409 Ma Xiaodonggou Granitic Intrusion: Implications for Understanding the Devonian Tectonics of the Northwest China Altai Orogen. *International Geology Review*, 58(5): 540–555. https://doi.org/10.1080/00206814.2015.1095131

Zou, T. R., Chao, H. Z., Wu, B. Q., 1989. Orogenic and Anorogenic Granitoids in the Altay Mountains of Xinjiang and Their Discrimination Criteria. *Acta Geologica Sinica-English Edition*, 2(1): 45–64. https://doi.org/10.1111/j.1755-6724.1989.mp2001005.x