Two-Stage Mafic-Felsic Magma Interactions and Related Magma Chamber Processes in the Arc Setting: An Example From the Enclave-Bearing Calc-Alkaline Plutons, Chinese Altai

Xing Cui1, Min Sun1, Guochn Sun1,2, Yunying Zhang3,4, and Jinlong Yao2

1Department of Earth Sciences, The University of Hong Kong, Hong Kong, China, 2Department of Geology, Northwest University, Xi’an, China, 3Key Laboratory of Ocean and Marginal Sea Geology, South China Sea Institute of Oceanology, Innovation Academy of South China Sea Ecology and Environmental Engineering, Chinese Academy of Sciences, Guangzhou, China, 4Southern Marine Science and Engineering Guangdong Laboratory, Guangzhou, China

Abstract A systematic data set of petrography, mineralogy, geochronology, and geochemistry is reported for typical arc granitoids and associated mafic microgranular enclaves (MME) from the Chinese Altai, Central Asian Orogenic Belt. Zircon U-Pb dating indicates that they crystallized coevally at ~395 Ma. Magma hybridization modeling suggests that the granitoid parental magma formed by mixing between a mafic and a felsic endmember. The sharp decrease of An values from cores to rims (e.g., from ca. 80 to 40) of plagioclase crystals points to polybaric crystallization accompanied by degassing. Petrographic evidence and plagioclase in situ Sr isotopic compositions (ε87Sr/ε86Sr) = 0.7053–0.7071 confirm the interaction of at least two isotopically different magmas during the mineral crystallization. A model for the formation of the enclave-bearing calc-alkaline plutons in arc settings is presented: At depth, mantle and crustal melting and efficient magma mixing controlled the principal chemical compositions of the granitoid intrusions. Then in the higher level chamber, decomposition-dominated crystallization and the mingling and limited mixing between blobs of mafic magma and the enclosing granitoid magma ultimately determined the texture, mineral composition, and enclave morphology. The MME have ε87Sr/ε86Sr of 0.7048–0.7062, εNd(t) of −0.5 to +2.6, and zircon εHf(t) of +2.3 to +5.4, while the host granitoids have similar Sr isotopic compositions (ε87Sr/ε86Sr) = 0.7054–0.7064, but generally lower whole-rock εNd(t) and zircon εHf(t) values (~2.2 to +0.4 and +0.6 to +4.6, respectively). The petrogenetic analysis and isotopic characters suggest that granitoid emplacement was a means of crustal growth in the Chinese Altai orogen.

1. Introduction

Granitoids are principal constituents of the felsic continental crust, and their formation is of fundamental significance in interpreting the generation, growth, and reworking of the continents. The petrogenesis of granitoids has long been hotly debated, involving multiple parental magma sources and the complex interplay between various magmatic processes. Specifically, some interpret that most post-Archean granitoids are of dominantly crustal origin, while others contend that there is mantle involvement, leading to the controversy over patterns of crustal growth (e.g., Arndt, 2013; Dhuime et al., 2012). The relative importance of fractional crystallization, crustal melting, and magma mixing is rather complex and may require case-by-case analysis. Calc-alkaline plutons in arc settings are special in that many of them retain textural and field evidence indicating the hybridization of compositionally diverse magmas (e.g., Wiebe, 1993). For example, widespread mafic microgranular enclaves (MME) within the calc-alkaline granitoids are mostly of igneous origin and sometimes associated with mafic dykes, representing quenched globules of a mafic magma (Blundy & Sparks, 1992; Browne et al., 2006; Cheng et al., 2012; Dorais et al., 1990; Kumar & Rino, 2006; Perugini et al., 2003; Vernon, 1983, 1984; K. Yu et al., 2018). Large batholiths from the Cordilleran arcs, such as the Sierra Nevada batholith in California (Barbarin, 2005; Coleman et al., 2004; Ratajewski et al., 2001) and the Coast Ranges in British Columbia (Brown & McClelland, 2000; Gehrels et al., 2009) were proposed to grow incrementally with frequent recharge by mafic magmas on million-year time scales. Consequently, the importance of mafic magmatism for the generation of calc-alkaline plutons and batholiths in convergent-margin settings is widely recognized. Debate has thus been centered on the role of magma hybridization in the petrogenesis (e.g., Barbarin, 2005; Chappell, 1996; Janoušek et al., 2004; Slaby & Martin, 2008; Wiebe et al., 1997, 2002). For example, it is unclear whether, how, when, and where two
streams of compositionally different magma can mix. With additional difficulties to ascertain the magma source and generation, and the magma chamber geometry and processes, contrasting models have been proposed for the formation and evolution of granitoid suites in arc settings (e.g., Annen et al., 2006; Castro et al., 2010; Chappell & White, 2001; Grove et al., 2003; Janoušek et al., 2004; Poli et al., 1996; Sisson et al., 2005; Turnbull et al., 2010; Vernon, 1984; Zhang et al., 2016).

The Chinese Altai is an element of the Central Asian Orogenic Belt (CAOB), which is a typical accretionary orogenic belt and an important area of Phanerozoic crustal growth. Early Paleozoic I-type granitoids, widely distributed in the Chinese Altai, have been interpreted as products of subduction at an active continental margin (Sun et al., 2008; T. Wang et al., 2006; Yu, Sun, Long, et al., 2017; Yuan et al., 2007). Like all intermediate-silicic plutons in arc settings, the origin of these granitoids is also subject to uncertainty and controversy over magma sources and magmatic processes. Such problems hinder our deep understanding of the crustal growth pattern for this orogen and also the whole CAOB.

The Tuerhongnan Batholith (TB) and Chaergan Pluton (CP) are typical arc granitoid examples in the Chinese Altai, containing abundant MME and are associated with mafic dykes. In this study, we have two primary research objectives. First and foremost, the magmatic processes of TB and CP is studied in detail by using a multi-faceted approach. We aim to unravel the mechanism of felsic-mafic magma interactions and define an overall framework for the genesis of arc-related, enclave-bearing granitoid suites. The general pattern is in turn combined with regional data to better refine the integrated evolutionary model of arc granitoids in the Chinese Altai, which advances our understanding of the crustal growth and internal differentiation of accretionary orogenic belts.

2. General Geology of the TB and CP and Samples

The TB and CP are located in the eastern range of the Chinese Altai, CAOB (Figure 1a; e.g., Şengör et al., 1993; Windley et al., 2007; Xiao et al., 2009). Comprehensive research on the Chinese Altai orogen involving studies of magmatism, metamorphism, and structural deformation has revealed its formation by northward subduction-accretion of the Paleo-Asian Ocean in the early Paleozoic, which continued until the collision with the Junggar arc in the Carboniferous-Permian (e.g., Broussolle et al., 2018; Li et al., 2017; Sun et al., 2008, 2009; Y. Wang...
et al., 2014). Prolonged orogenic history since the Cambrian produced extensive magmatic activities, including voluminous granitoids and subordinate mafic intrusions, which characterize the Chinese Altai orogenic belt.

The TB is one of the typical syn-subduction intrusive complexes of the Chinese Altai (Figure 1a). It is a composite batholith composed of multiple magma batches emplaced from ca. 410 to 360 Ma, occupying a huge area of about 1,200 km² (Yuan et al., 2007), and in this study we focus on its southern part (Figure 1b). It intruded into the early Paleozoic Habahe Group, which represents the oldest terrigenous and volcano-sedimentary rocks in the Chinese Altai orogen (Jiang et al., 2016; Long et al., 2008). MME are unevenly distributed in the TB, with a mafic complex (called Keketuohai mafic complex, Cai et al., 2012) exposed in the northern region (Figure 1b). The MME in the TB cluster as swarms in some places while scattered or absent in other locations. They are typically ellipsoidal, rounded or irregular in shape with varying sizes ranging from ca. 4 to 50 cm, showing either sharp or diffusive contacts with the host granitoids (Figure 2). To the southeast of the TB, the CP outcrops as a NW-SE elongated body and intrudes into the Habahe Group as well (Figure 1c). MME in the CP do not significantly differ in shape or size from those in the TB, and associated gabbroic dyke intrudes the CP.

The light-colored host rocks and dark-colored enclaves/dyke are respectively referred to as felsic granitoids and MME/mafic dyke in this study, although in each group they have a gradual transition to intermediate chemical compositions. Granitoids from the TB can be classified into dominant biotite-granodiorite and subordinate quartz diorite according to the relative proportions of biotite and amphibole. The amphibole-free samples (19XJ63-1, 65-1, 68-1, 69-1, and 70-1) are porphyritic with large phenocrysts of plagioclase and biotite (ca. 1–2.5 mm) enclosed in a matrix of plagioclase, quartz, and K-feldspar. Averaged mineral proportions are ca. 35 vol% plagioclase, 20 vol% K-feldspar, 25–30 vol% quartz, 10–15 vol% biotite, with minor accessories including apatite, titanite, zircon, and Fe-Ti oxides (Figure 3a). Plagioclase phenocrysts are euhedral to subhedral, zoned prismatic crystals, and sometimes show synneusis grouping. Many of them have distinct core-rim textures, with the core more severely altered into secondary minerals (Figures 3g, 3h, 16a, and 16b). Biotites appear in two different forms (Figure 3a). One type is large subhedral bladed crystals with small mineral inclusions, showing a primary magmatic origin. The other type appears as aggregates of fine-grained flakes, intergrown with opaque minerals and secondary epidote, and usually adjacent to the tabular biotite phenocrysts. It suggests that they are most likely hydrothermal biotites (Idrus, 2018) that have replaced the early primary ones. Unzoned plagioclase, cross-hatched K-feldspar, and quartz in the matrix are subhedral, granular, and 0.1–0.5 mm in diameter. Amphiboles appear in one biotite-granodiorite sample (19XJ64-6; Figure 3b) as subhedral phenocrysts (about 5 vol%). Quartz diorite samples (19XJ66-1, 66-4, 67-1, and 67-2) have more amphibole than biotite, with average mineral assemblages of plagioclase (40–45 vol%), amphibole (20 vol%), quartz (15 vol%), K-feldspar (5–8 vol%), biotite

Figure 2. Field photographs of the enclave-granitoid associations from the Tuerhongnan Batholith and Chaergan Pluton. Panel (a) shows the enclave swarm. Panels (b–d) show the various shapes of the mafic microgranular enclaves and their contact relationships with host rocks.
Figure 3. Cross-polarized light photomicrographs of the granitoids, mafic microgranular enclaves (MME), and mafic dyke from the Tuerhongnan Batholith (TB) and Chaergan Pluton (CP). All the images are on the same scale. (a) Biotite-granodiorite sample (19XJ63-1) from the TB. Primary biotite with resorption surface is juxtaposed with hydrothermal biotites, which appear as aggregates of fine-grained flakes intergrown with tiny epidote. (b) Amphibole-bearing biotite-granodiorite sample (19XJ64-6) from the TB. (c) Quartz diorite sample (19XJ66-1) from the TB. Large, tabular amphiboles show blue-green and yellow-brown pleochroism. (d) Gabbro-dioritic MME sample (19XJ64-1) from the TB. Amphiboles are isolated subhedral crystals. (e) Hornblende-gabbroic MME sample (19XJ119-4) from the CP. Lath-shaped plagioclase show some alignment and cumulative texture. (f) Hornblende-gabbroic dyke sample (19XJ119-7) intruding into the CP. Large plagioclase phenocrysts are xenocrysts and interspersed in the fine-grained matrix. Panels (g and h) are thin sections where enclave and host rocks coexist, with host granitoids on the left, transition zone in the middle, and MME on the right. Panel (g) (sample 19XJ64-4) is biotite-granodiorite and associated MME, and plagioclase phenocrysts in the transition zone and enclave side suggest crystal transfer between the two sides. Panel (h) (sample 19XJ63-3) is quartz diorite and associated MME, showing planar interface with obvious crystal size difference between the two sides. Mineral abbreviations: Am, amphibole; Ap, apatite; Bt, biotite; Ep, epidote; Kfs, K-feldspar; Pl, plagioclase; Q, quartz; Ttn, titanite.
Amphiboles show blue-green and yellow-brown pleochroism, appearing either as euhedral isolated crystals or large, tabular, and poikilitic crystals encasing plagioclase. Granitoids from the CP have similar mineral assemblages to biotite-granodiorite from the TB, with varied mineral proportions of plagioclase (35–50 vol%), K-feldspar (10–30 vol%), quartz (20–30 vol%), biotite (3–15 vol%), and minor accessories (<3 vol%).

The mafic enclaves from both TB (Figures 3c and 3d) and CP (Figure 3e) have identical mineral associations to their respective host rocks but are richer in mafic minerals and finer-grained. They are mostly inequigranular, consisting of 0.2–1 mm plagioclase and amphiboles with micro inclusions, and <0.2 mm anhedral plagioclase, quartz, minor biotite, and scarce K-feldspar. Magmatic foliations and typical igneous textures such as interstitial and poikilitic minerals with oscillatory zoning suggest that they were crystallized from magmas (Barbarin, 2005; Y. Yu et al., 2018) and do not represent restite fragments (Chappell et al., 1987). As shown in thin sections with enclave and host rock in contact (Figures 3g and 3h), felsic materials often penetrate into the enclave, and the interface between them is typically planar with contrasts of mineral proportion and grain size. The mafic dyke intruding the CP has the same modal mineralogy as the enclaves. It shows a porphyritic texture (Figure 3f), characterized by a homogeneous matrix composed of finer-grained plagioclase and amphibole crystals (ca. 0.1–0.2 mm) interspersed with ca. 3–5 mm plagioclase phenocrysts, suggesting a possible crystal transfer with host rocks and thus a syn-plutonic character.

Common accessory titanite in both granitoids and MME shows euhedral-subhedral wedge or irregular shapes with lengths of ca. 0.5–0.8 mm, while apatite displays either tiny acicular habits as inclusions in most major mineral phases or isolated intergranular tabular shapes with lengths up to 0.7 mm. Epidote stands out with high interference color, typically <0.2 mm inside the plagioclase cores or intergrown with biotite clots, suggesting a secondary origin. Other trace minerals include sericite, muscovite, and kaolinite, which are also products of secondary alteration and often replace the core of feldspar. Petrographic observation demonstrates that the TB was more severely altered than the CP, while the MME were more severely altered than the host granitoids.

3. Analytical Methods

We performed the following chemical analyses on selected samples from the TB and CP: whole-rock major trace elements and Sr-Nd isotopes, zircon U-Pb and Lu-Hf isotopes, mineral in situ elements, and plagioclase in situ Sr isotopes. Full details of analytical methods are provided in Supporting Information S1.

4. Results

4.1. Whole-Rock Major and Trace Element

Because of the close spatial-temporal relationship, similar mineral compositions, and tectonic setting, we discuss the TB and CP together and only differentiate them when necessary. The host granitoids have SiO$_2$ contents ranging from 54.0 to 72.5 wt%, K$_2$O from 1.30 to 4.66 wt%, Na$_2$O from 2.04 to 3.75 wt%, and Al$_2$O$_3$ from 14.1 to 16.8 wt% (Figure 4). They plot into gabbroic diorite to granite in the TAS diagram (Figure 5a), while mostly in the granodiorite range in the Q'-ANOR diagram (Figure 5b). The high K$_2$O contents make them medium- to high-K calc-alkaline series (Figure 5c), and they are metaluminous to weakly peraluminous with A/CNK all below 1.1 (Figure 5d). They display generally smooth compositional trends in the Harker diagrams (Figure 4).

The mafic enclaves and dyke samples have low SiO$_2$ contents of 45.2–58.3 wt%. Variable K$_2$O (0.17–3.75 wt%) and Na$_2$O (1.63–5.09 wt%) contents make them plot into gabбро-diorite or monzogabbro-monzonite series in the TAS diagram (Figure 5a) and tholeiite to shoshonitic series in the Si-K diagram (Figure 5c). All of them are metaluminous with low A/CNK values (0.70–0.91; Figure 4d). Most of the major elements for these mafic rocks are scattered in the Harker diagram (Figure 4), which is explained later in Section 5.

Regarding the trace elements, samples of the host granitoids from both TB and CP show relatively homogeneous compositions. They are characterized by variable V contents from 13 to 266 ppm, low Cr (0.2–77.2 ppm) and Ni (0.2–31.4 ppm) contents, and total REE of 91–187 ppm. The consistent REE patterns show LREE enrichment with (La/Yb)$_N$ ratios of 3.05–15.0 and flat HREE, with negative or positive Eu anomalies (Eu/Eu* = 0.66–1.23; Figures 6a and 6b). The enrichment in LILE and depletion in Nb, Ta, and Ti are shown in the spider diagrams (Figures 6c and 6d). As for the MME and mafic dykes, some samples show comparable REE concentrations...
with the host granitoids, together with similar LREE enrichment and flat HREE distribution patterns (Figures 6a and 6b). Other samples, however, have much higher contents of REE (302–401 ppm), with variable LREE distribution ranging from the positive slope (19XJ63-4, 64-1, 64-2, 64-3, and 69-2) through flat (19XJ119-3, 119-4, and 119-5) to the negative slope (19XJ63-3 and 69-3). As shown in the spider diagrams (Figures 6c and 6d), Nb, Ta, and Ti are also depleted for these mafic rocks, while the LILE, Th, and U are variably enriched or depleted.

4.2. Zircon U-Pb Geochronology and In Situ Hf Isotope

Zircons from the granodiorite sample (19XJ63-1) from the TB are short prismatic euhedral crystals with lengths of ca. 80–120 μm. They are characterized by clear oscillatory zonings with thin dark rims and Th/U ratios of 0.14–1.12. Twenty-one of them have clustered 206Pb/238U ages of 382–402 Ma, giving a weighted mean of ca. 394.6 ± 2.6 Ma (Figure 7a). The clustered magmatic zircons of ca. 395 Ma give εHf(t) values of +1.6 to +4.5.
Three additional analyses yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 611, 617, and 1,044 Ma, which are thought to be xenocrysts from country rocks, and their variable $\varepsilon_{\text{Hf}}(t)$ values range from −4.3 to +5.4.

Zircons from the enclave (19XJ64-2) of the TB have mostly euhedral, elongated lath shapes (100–200 μm) with visible zonings and high Th/U ratios of 0.34–1.59. Twenty-three analyses give well-grouped concordant $^{206}\text{Pb}/^{238}\text{U}$ ages, which range from 387 to 406 Ma and yield a weighted mean of ca. 393.3 ± 2.1 Ma (Figure 7b). In situ Hf isotopic analyses yielded $\varepsilon_{\text{Hf}}(t)$ values of 2.8–5.4 (Figure 8).

Zircons from the tonalite (19XJ119-1) of the CP are euhedral, granular or elongated with variable lengths of 80–250 μm. They have clear oscillatory zonings with Th/U ratios of 0.59–1.06. Twenty-four dated grains give consistent $^{206}\text{Pb}/^{238}\text{U}$ ages of 390–399 Ma, with a weighted mean of 393.6 ± 2.6 Ma (Figure 7c). Zircons from this sample have $\varepsilon_{\text{Hf}}(t)$ values of 0.6–4.6 (Figure 8).

Zircons from the MME (19XJ119-3) of the CP have prismatic shapes, 80–200 μm long, with slightly rounded margins or erosional boundaries. Oscillatory zonings and Th/U ratios of 0.59–1.25 are consistent with a magmatic origin. Twenty-five zircon grains have limited $^{206}\text{Pb}/^{238}\text{U}$ ages between 386 and 401 Ma, with a weighted mean of 392.6 ± 2.0 Ma (Figure 7d). The thirty zircon-Hf analyses show restricted variations of $\varepsilon_{\text{Hf}}(t)$ values of 2.3–4.2 (Figure 8).

High-resolution zircon U-Pb dating of the above four representative samples reveals that: (a) the MME and their host granitoids from both the TB and CP have the same crystallization ages within analytical error and (b) the...
emplacements of the TB and CP were coeval, possibly responding to one common tectono-magmatic event in the Chinese Altai.

4.3. Whole-Rock Sr-Nd Isotopes

Whole-rock Sr-Nd isotopic compositions for selected host granitoids and mafic enclaves from the TB and CP are shown in Figure 9. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are between 0.704790 and 0.706420, with the lowest for the mafic dyke (19XJ119-7) of the CP and the highest for a host granodiorite (19XJ65-1) of the TB. These two samples yield the highest and lowest $\varepsilon_{\text{Nd}}(t)$ values of +2.6 and −2.2, respectively, while other samples have near-chondrite Nd isotopic compositions with consistent $\varepsilon_{\text{Nd}}(t)$ of −0.5 to +0.5.

4.4. Mineral Compositions

Amphibole and biotite in the felsic and mafic rocks have overlapping compositions. The analyzed amphiboles are all calcic ($Ca_{2}>1.5$), ranging from tschermakite through magnesio-hornblende to actinolite (Figure 10a). They have low and variable TiO$_2$ contents of 0–1.5 wt% and Fe number of 0.1–0.5, showing a differentiation trend and some alteration (Figure 10c). Tabular phenocrysts of biotites were analyzed, while tiny biotite aggregates were avoided for testing. They have FeO contents of 15.9–18.7 wt%, MgO of 10.3–13.3 wt%, and TiO$_2$ of 1.4–2.6 wt%, plotting into the re-equilibrated primary biotite field in the discrimination diagram, suggesting a cation exchange in the later stage (Figures 10b and 10c). Plagioclase from the host granitoids ranges from oligoclase to bytownite with An values between 22.1 and 80.7, while those from the enclaves have a larger variation from oligoclase to anorthite with An of 23.1–91.6 (Figure 11a). They show a continuous compositional trend from the most mafic enclave to the most felsic host granite despite large variations within individual samples (Figure 11b).

Chondrite-normalized REE patterns of the zircons are generally parallel with steep positive slopes defined by HREE enrichment over LREE, accompanied by positive Ce and negative Eu anomalies (Figures 12a and 12b).
The temperature dependency of Ti solubility in zircon allows an estimation of zircon crystallization temperature, based on the revised calibrations for Ti-in-zircon thermometer in Ferry and Watson (2007). We first excluded the captured xenocrysts and some with abnormally high values that may be associated with unexpected inclusions. By adopting $a\text{SiO}_2 = 1$ and $a\text{TiO}_2 = 1$ due to the appearance of quartz and rutile, Ti concentrations in the zircons from granite sample 19XJ63-1 (4.67–19.3 ppm) yield temperatures from 679 to 812°C. For MME sample 19XJ64-2, $a\text{SiO}_2 = 1$ and $a\text{TiO}_2 = 0.7$ were set due to the appearance of quartz and absence of rutile, and Ti contents of 1.51–12.3 ppm give temperatures between 620 and 801°C. As for samples from the CP, the enclave (19XJ119-3) and host rock (19XJ119-1) show identical zircon compositions with nearly overlapping REE patterns. We set the $a\text{SiO}_2 = 1$ and $a\text{TiO}_2 = 1$, and the restricted variations of Ti contents (6.5–12.2 ppm and 6.4–14.7 ppm, respectively) yield consistent temperatures of 707–765°C and 705–763°C.

Titanite crystals from the host and enclave of the TB give similar REE patterns with positive LREE slopes and relatively flat MREE-HREE slopes (Figure 12c). The high REE concentrations in the range of 2.61–4.38 wt% account for the large amount of REE in the whole rock. Their Zr contents range from 416 to 889 ppm. The high trace element contents, prominent negative Eu anomalies, high Th/U ratios as well as crystal shapes indicate a magmatic origin. Meanwhile, similar crystal habit, size, and element compositions suggest possible crystal transfer between the host and enclave rocks, considering the lack of modal titanite in some granites.

Figure 7. Concordant plots of LA-ICP-MS zircon U-Pb dating results for host granitoids and mafic microgranular enclaves from the (a and b) Tuerhongnan Batholith and (c and d) Chaergan Pluton.
4.5. Plagioclase In Situ Sr Isotope

Sr isotopic analyses were performed on different positions within individual plagioclase phenocrysts including cores, mantles, and rims, and on plagioclase in the matrix. Overall, plagioclase throughout the TB show relatively large variations in \(\frac{\delta^{87}Sr}{\delta^{86}Sr}\) values between 0.7054 and 0.7089, with the highest value from sample 19XJ63-3. Plagioclase from the CP, in contrast, show limited variations in \(\frac{\delta^{87}Sr}{\delta^{86}Sr}\) of 0.7053–0.7063. Given that some of the MME from the TB were severely altered, it is reasonable to infer that the very high values (above 0.7075; Figure 13) are due to local alteration by crust-derived hydrothermal fluids and are thus omitted from further discussion. From the analytical results, there is no systematic or regular variation in isotopic values of plagioclase in host rocks and enclaves, possibly due to the similarity or partial equilibrium of Sr isotopes between mafic and felsic magmas (Figure 13). However, the large variations in the grain- or sub-grain scale suggest that the isotope system was not fully homogenized by diffusion but still preserves the magma source information.

Figure 8. Zircon Hf isotopic data for the dated granitoid and mafic microgranular enclaves samples from the Tuerhongnan Batholith (TB) and Chaergan Pluton (CP). On the left are histograms of the \(\varepsilon Hf(t)\) values of zircons (TB in the top and CP in the bottom). On the right is the \(\varepsilon Hf(t)\) values versus Age (Ma). CHUR, chondritic uniform reservoir. The sample symbols are consistent with Figure 6. \(T_{2DM}\) represents the two-stage depleted mantle model ages. Data for Keketohai mafic complex are from Yu, Sun, Huang, et al. (2017), and for granitoids in the Chinese Altai are from Cai et al. (2011).

Figure 9. Whole-rock Sr-Nd isotopic compositions of the early Paleozoic mafic-felsic rocks from the Chinese Altai. (a) \((\delta^{87}Sr/\delta^{86}Sr)\) versus \(\varepsilon Nd(t)\) diagram. (b) \(\varepsilon Nd(t)\) values versus Age (Ma). \(T_{2DM}\) represents the two-stage depleted mantle model ages. Data sources are from Cai et al. (2012), Yu, Sun, Huang, et al. (2017), and Cui et al. (2020).
5. Discussion

5.1. Crystal Accumulation and Late-Stage Alteration

Crystal accumulation and late-stage alteration are common in our studied rocks, and these processes need to be first evaluated on account of their significant impact on whole-rock chemical compositions.

The crystal alignment in some MME (19XJ119-3, 119-4, and 119-5) from the CP could indicate crystal accumulation (Figure 3e). These enclaves are characterized by very low SiO$_2$ contents (45.2–47.9 wt%) inconsistent with their mineral assemblages (Figure 4). Their low Mg$#$ of 43–45, low Cr and Ni, and high TiO$_2$, Fe$_2$O$_3$, Al$_2$O$_3$, P$_2$O$_5$, and Zr contents further suggest that they were not simply crystallized basaltic liquids, but formed in more evolved liquids with accumulations of plagioclase, hornblende, apatite, Fe-Ti oxides, and zircon. The high abundance of REE is possibly a combined effect of apatite and hornblende accumulation (Barbarin, 2005).

The high water content of many calc-alkaline magmas makes them susceptible to late-stage chemical and/or mineral alteration caused by magmatic-hydrothermal fluids, as was the case with our samples from the TB. First, there are many examples of auto-metasomatism of both enclave and host granite by the hydrous and enriched residual melt at the final stage of granitic differentiation (Bédard, 1990; Sisson et al., 1996). The abnormally high K$_2$O and Rb in the MME from the TB may be due to concentration of these elements in the newly formed or altered biotites, which is consistent with the presence of abundant biotite clots (Figure 3a). High K$_2$O samples are simultaneously characterized by high abundances of REE and other incompatible elements such as Zr, Nb,

![Figure 10](image-url). Chemical compositions of amphibole and biotite from mafic-felsic rocks of the Tuerhongnan Batholith and Chaergan Pluton. (a) Plot of calcic amphibole compositions from Leake et al. (1997), (b) FeO – $10 \times$ TiO$_2$ – MgO ternary diagram from Nachit et al. (2005), (c) Variation of Ti versus Fe number for biotite and amphibole after Slaby and Martin (2008).

![Figure 11](image-url). Chemical compositions of plagioclase from mafic-felsic rocks of the Tuerhongnan Batholith and Chaergan Pluton. The sample symbols are consistent with Figure 6. In panel (b), analytical spots in the sample 19XJ66-3 with co-existent enclave and host rocks are represented by red triangle symbols for the granitoid side and blue diamond symbols for the MME side. Their WR (whole-rock) SiO$_2$ contents adopt the value for 19XJ66-1 (granitoid) and 19XJ66-2 (MME), respectively.
Ta, etc. The distinctive LREE distribution patterns with positive slopes are compatible with those of the titanite (Figures 6a and 12c), which thus should be a late-stage reaction product between enclaves and their host granitoid magmas. Second, the evidence for the effect of a hydrothermal fluid under sub-solidus condition comes from the ubiquity of epidote (Figure 3), formed at ca. 300°C (Parsapooy et al., 2015). Such hydrothermal alteration is also reflected by mild sericitization and/or clayization of some feldspar, appearance of actinolite (Figure 10a), and re-equilibration of primary biotites (Figure 10b). Enclaves with relatively small volumes inevitably experienced more intense alteration (e.g., Perugini et al., 2003), as suggested by their vastly scattered chemical compositions compared with more uniform ones of the host granitoids.

5.2. Magmatic Processes in the Deep Source Zone

5.2.1. The Parental Magma Generation Process

5.2.1.1. Host Granitoids

Linear correlations of major and trace elements in the Harker diagrams for the host granitoids can be explained by fractional crystallization (FC) or assimilation-fractional crystallization (AFC) from more mafic magma, or magma mixing between mafic and felsic ones. To distinguish these magmatic processes, trace elements with high resistance to alteration were selected for elemental modeling using the PetroGram and partition coefficients therein (Gündüz & Asan, 2021). The most mafic gabbroic enclave (19XJ66-5) and the most felsic granite (19XJ65-1) from the TB are selected as two endmembers. Sample 19XJ66-5 is characterized by a lack of accumulation textures, an arc-like REE distribution pattern and Eu/Eu* value (1.02), no significant deviation in the Harker diagram, and no abnormally high trace-element abundances. The weak accumulation and alteration
characteristics for this selected MME sample make it an approximation of actual mafic liquid and an appropriate end-member candidate. The modeling results are shown in Figure 14, and the host granitoids generally fall on the magma mixing line, whereas crystallization from the mafic endmember with possible crustal assimilation cannot explain the compositional variations. The lack of country rock xenoliths and rarity of zircon xenocrysts, and relatively low whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$ ratios also support that crustal assimilation was insignificant during the magma evolution. REE patterns for the host granitoids are in agreement with our mixing model (Figure 6a), as they have intermediate REE concentrations between the postulated two endmembers. We further conducted a hybrid testing for the major elements using mass balance calculation following the method of Fourcade and Allegre (1981). Concentrations for each element in hybrid rocks should follow the expression: $C_{\text{hi}} = C_{\text{f}} \times X_{\text{f}} + C_{\text{m}} \times (1-X_{\text{f}})$, and a straight line would form in the $C_{\text{f}} - C_{\text{M}}$ diagram, whose slope gives the mass proportion of the mixture. As shown in Figure 15, host granitoids from the TB mostly fit a hypothetical mixing model with good linear correlations ($R^2$ close to unity), except for the quartz diorite sample 19XJ66-1 (Figure 15c), whose low correlations may be ascribed to some crystal accumulation as inferred by its low SiO$_2$ and high P$_2$O$_5$ contents (Figure 4).

Overall, combined major and trace element modeling strongly suggests that mixing between mafic and felsic magmatic endmembers is the most likely process accounting for the compositional trend displayed by the host granitoids and thus indicates a hybrid origin for their parental magmas.

---

**Figure 14.** Trace element plots for the granitoids, mafic microgranular enclaves, and mafic dyke from the Tuerhongnan Batholith and Chaergan Pluton, showing models of fractional crystallization (FC), crustal assimilation and fractional crystallization (AFC), and magma mixing. The excel-based software PetroGram and method in the Gündüz and Asan (2021) were applied. Gabbroic enclave 19XJ66-5 and host granite 19XJ65-1 were selected as the two endmembers for magma mixing, with ticks along the mixing curve show increments of 10% in the relative proportions. The FC and AFC trends were modeled based on the simplified mineral phase mode of 60% plagioclase and 40% amphibole, with whole-rock partition coefficients of $D(\text{Co}) = 8.86$, $D(\text{Ta}) = 0.276$, $D(\text{Sr}) = 1.8$, $D(\text{Nb}) = 0.294$, and $D(\text{Zr}) = 0.295$ for an intermediate-silicic melt (partition coefficients are from PetroGram and GERM database). The averaged chemical composition of metasedimentary rocks from the Habahe Group in the Qinghe area (Dong et al., 2018) is regarded as an approximation for the chemical composition of country rock and thus the assimilant in the AFC. The ticks along the FC and AFC model curves show increments of 6% mass removal.
5.2.1.2. MME and Mafic Dyke

The petrographic characters indicate igneous origins for the MME. The parental magma of these mafic rocks may represent either the differentiated product of pristine mantle-derived magma, or the hybrid product that is cogenetic with the granitoid magma (Barbarin, 2005; Cheng et al., 2012; Kumar & Rino, 2006; Perugini et al., 2003; Turnbull et al., 2010; Wiebe et al., 1997). Because of the strong interference of late-stage alteration and crystal accumulation, the chemical compositions of most studied mafic rocks do not represent the composition of the original melt in which they were crystallized. This explains why MME samples did not plot along any differentiation trend in the elemental modeling (Figure 14). Here we prefer the first explanation based on the following evidence. Samples with high contents of Cr and Ni, and no distinct accumulation textures (19XJ120-3 and 120-4) may approximate the early liquids of the MME. The melt with high Cr-Ni values, if mixed with a low Cr-Ni melt, would result in a continuous decline for the mixed melt. Therefore, a magma mixing model cannot account for the homogeneously low Cr-Ni values for other mafic rocks (Figures 4j and 4k), whereas fractional crystallization could rapidly decrease their concentrations. The melt compositions are similar to the Keketuohai gabbros, whose parental magma was possibly differentiated from the primitive mantle-derived magma, leaving behind the cumulated Keketuohai mafic-ultramafic complex (Cai et al., 2012). Thus we infer that fractionation probably played the dominant role in the mafic magma evolution in the source region, although the influence of mixing cannot be excluded.

5.2.2. The At-Depth Magma Hybridization Process

The interaction between magmas is affected by many parameters, including relative volume and composition contrast of the two components, temperature, volatile content, and initial crystallinity of the magma (Kumar & Rino, 2006; Snyder & Tait, 1995). The magma origin analysis above indicates that mantle-derived mafic magmas were well mixed with the felsic magmas to form parental magmas for the host granitoids. The felsic endmember represents either advanced fractionation products of cogenetic mantle-derived magma, low-degree partial melts of continental crust, remelts of shortly antecedent deep mafic intrusions, or probably an irresolvable combination of all three processes. For our samples, a juvenile lower crust is inferred from the new and existed isotopic data, which is discussed further in the last section about the Chinese Altai regional geological evolution. Such a thorough mixing of mantle- and lower crust-derived magmas can happen at-depth, which has been referred to as a deep crustal hot zone (DCHZ) in Annen et al. (2006) or melting-assimilation-storage-hybridization (MASH) zone in Hildreth and Moorbath (1988). In the current study, the lack of HREE depletion for the mafic rocks suggests a primitive magma differentiation depth shallower than the garnet-stable condition. The high Al₂O₃ in
the residual basaltic magma indicates the restricted earlier fractionation of plagioclase, consistent with relatively high-H$_2$O condition. The mantle-derived magma ascends and ponds at the lower crust or crust/mantle boundary, inducing partial melting of the lower crust. In the DCHZ, the larger volumes of evolved mafic magmas, high-$T$, and high-H$_2$O conditions facilitate the magma mixing process. Hybrid melts can detach and ascend into the shallow level due to the lower density, as represented by the host granitoid rocks of this study. A pulse of the residual mafic magma could also ascend directly with less hybridization in the deep, which is represented by the enclave/dyke magma.

5.3. Evolution in the High-Level Magma Reservoir

5.3.1. Intensive Parameters

The Al-in-amphibole geobarometer was established by Anderson and Smith (1995) for the appropriate buffering mineral assemblage of hornblende, plagioclase, biotite, orthoclase, quartz, Fe-Ti oxides, titanite, plus a vapor. The estimated pressures for our samples using this approach yield values of 0.3–1.9 kbar (Table 1 and Table S7-3 in Supporting Information S1). Due to the uncertainty of actual mineral assemblages at the time of amphibole crystallization, we do not agree with the accuracy of these data, but it is reasonable to infer that the crystallization pressure is relatively low. Such a shallow crustal emplacement level is consistent with the widespread hydrothermal alteration of many samples.

Temperature estimation using the hornblende-plagioclase geothermometer of Holland and Blundy (1994) gives values between 682 and 786°C. Zircon saturation temperatures reflect the minimum $T$ for those inheritance-free, zircon-unsaturated melts before extensive crystallizations (Miller et al., 2003), which yield 764–828°C for the host granitoids, whereas those mafic rocks are out of the experimental calibration. Ti-in-zircon (Fu et al., 2008) and Zr-in-titanite (Hayden et al., 2007) thermometers give variable values of ca. 648–811°C and 727–764°C, respectively (Table 1), suggesting relatively late growth at low magmatic $T$.

The primitive arc magma is originally H$_2$O-rich, generally confined in the range of 2–6 wt% (e.g., Cervantes & Wallace, 2003; Müntener et al., 2001; Sisson & Grove, 1993). With differentiation in the deep source region, the water content increases and remains in the melt. Plagioclase-liquid hygrometer in Waters and Lange (2015) is based on the plagioclase-liquid exchange reaction between the An and Ab components in the melt and plagioclase. Samples with strong chemical modification may not represent true liquid/melt compositions following the criteria outlined in Section 5.1, and thus were not used in this calculation. The valid calculated water contents.

| Sample | Rock type | Rock composition | $P$ (kbar; Al-in-hb) | $T$ (°C; hb-pl) | H$_2$O (wt%) | $T$ (°C; zircon saturation) | $T$ (°C; Ti-in-zircon) | $T$ (°C; Zr-in-titanite) |
|--------|-----------|------------------|----------------------|----------------|-------------|-----------------------------|----------------------|------------------------|
| 19XJ63-1 | Felsic host | Biotite granodiorite | – | – | 3.9–4.6 | 764 | 811–719 | 764 |
| 19XJ64-6 | Felsic host | Tonalite | 0.3–1.9 | 786 | 4.7–5.1 | 779 | – | 727 |
| 19XJ63-3 | Mafic enclave | Monzodiorite | – | – | – | – | – | 749 |
| 19XJ64-1 | Mafic enclave | Monzodiorite | 0.1–3.1 | 682 | – | – | – | – |
| 19XJ64-2 | Mafic enclave | Monzodiorite | – | – | – | 801–648 | – | – |
| 19XJ64-5 | Mafic enclave | Monzodiorite | – | 705 | – | – | – | – |
| 19XJ66-1 | Felsic host | Quartz diorite | 1.7–3.3 | 703 | – | 710 | – | – |
| 19XJ119-1 | Felsic host | Granodiorite | – | 4.5–4.9 | 828 | 764–707 | – | – |
| 19XJ119-3 | Mafic enclave | Diorite | – | – | – | 783–705 | – | – |
| 19XJ119-4 | Mafic enclave | Diorite | 1.4–2.4 | 763 | – | 785 | – | – |
| 19XJ120-3 | Mafic enclave | Diorite | 1.9–2.3 | 738 | 5.1–5.6 | – | – | – |

**Table 1**

$P$-T-H$_2$O Estimation of Host Granitoids and Mafic Microgranular Enclaves From the Tuerhongnan Batholith and Chaergan Pluton

*Note.* Pressures of crystallization calculated using the Al-in-hornblende geobarometer of Anderson and Smith (1995). Temperatures calculated using the Holland and Blundy (1994) plagioclase geothermometer. H$_2$O contents calculated using the Waters and Lange (2015) plagioclase-melt hygrometer. Other calibrations used are described in the text.
Figure 16. Cross-polarized light photomicrographs. An and Sr isotope profiles of plagioclase phenocrysts from host granitoids of the (a–d) Tuerhongnan Batholith and (e) Chaergan Pluton (CP), and (f) mafic microgranular enclaves form the CP. Error bars for the Sr isotope are at 2σ. White circles in the phenocrysts are locations of EPMA analysis. Yellow circles and numbers are Sr isotope analytical spots and results.
in granites from TB and CP are of 3.9–5.1 wt% and 4.5–4.9 wt%, respectively, while the MME from CP yield values
between 4.1 and 4.6 wt% (Table 1 and Table S7-1 in Supporting Information S1). The standard error estimate
on the hygrometer model is 0.35 wt% H$_2$O (Waters & Lange, 2015). The water content at crystallization of
these feldspars should be lower than the original melt water content at segregation from the source region due to
degassing at low pressure conditions (Annen et al., 2006).

A combination of P-T-H$_2$O estimation for studied rocks is provided in Table 1.

5.3.2. Magma Evolution and Hybridization History: Plagioclase Records

5.3.2.1. Plagioclase Characteristics

The slow CaAl–NaSi diffusion and high resistance to high-T recrystallization allow plagioclase zoning to be well
preserved, which can be used to monitor the long-lived magma evolution relating to the changing crystallization
conditions (e.g., Ginibre et al., 2002; Grove et al., 1984; Janoušek et al., 2000, 2004; Waight et al., 2000). The
composition and stability of the plagioclase is a function of melt composition and intensive parameters such as
P, T, and H$_2$O (Ginibre & Wörner, 2007; Putirka, 2005; Ruprecht & Wörner, 2007; Ustunisik et al., 2014).
Plagioclase crystallized from the mafic magma tends to be more calcic with high An values (e.g., Panjasawatwong
et al., 1995), and the An values are positively correlated with temperature and negatively with pressure (e.g.,
Ginibre et al., 2002). As constrained by the experimental research in Ustunisik et al. (2014), the magnitude of
the variation caused by P is relatively small on the order of 3% An per kbar, and a T decrease of 100°C at 1 bar
(from 1100 to 1000°C) resulted in 20 mol% decrease in An (An$_{54}$-An$_{34}$). On the contrary, the water content of
the melt strongly controls the liquidus and solidus for mineral phases, and an addition of 1.5 wt% water at 1 kbar
and 1050°C induces an increase of 30 mol% An content in the plagioclase. Experimental results from Pichavant
et al. (2002) show that the plagioclase An values can reach as high as 80–90 in basaltic andesite and andesite
melt under H$_2$O-saturated conditions (with up to 8 wt% dissolved H$_2$O) at 4 kbar and 950°C. On the other hand,
in an open-system, magma recharge with different compositions may yield changes in both the physical condition
and the chemical composition of the existing magma if mixing occurs, which will be reflected in the An values
of plagioclase grown in the newly equilibrated magma. Plagioclase An variations alone thus cannot distinguish
between closed- and open-system behaviors. In situ Sr isotope analysis of plagioclase has the ability to record
inhomogeneity at grain- or sub-grain scale in relation to open-system operations. For example, isotope hetero-
genicity in plagioclase can be caused by incomplete homogenization of various melt batches from heterogeneous
or contrasting sources (e.g., Braschi et al., 2014; Ferrara et al., 1985; Ginibre & Davidson, 2014; Karykowski
et al., 2017; Wilson et al., 2017). However, country rock assimilation and/or late-stage alteration can also change
the isotopic composition and should be taken into account when interpreting isotopic data. Therefore, a combi-
nation of morphological, chemical, and Sr isotopic characteristics of plagioclase was analyzed to provide impli-
cations for the recharge event in the magma chamber and the complete process of long-lived magma evolution
(Gagnevin et al., 2005; Ginibre & Davidson, 2014).

5.3.2.2. Plagioclase Phenocryst Profiles

As shown in Figure 16a, the phenocryst from 19XJ64-6 displays clear zonation as reflected by the brightness
of interference colors. A bright core with a curving resorption surface is bordered by a dark zone 200 μm wide,
then a very thin bright zone, and finally a euhedral dark rim. Compositional profile from A$_1$ to B$_1$ reveals that
the brightness zonation correlates well with the An value. The high An value of the plagioclase core (ca. 80)
indicates equilibrium with a high- H$_2$O melt, consistent with the calculated dissolved water of 5.1 wt% by pl-liq-
uid hydrometer (Table S7-1 in Supporting Information S1). The sharp decrease of An (An$_{80}$-An$_{46}$) to the mantle
cannot be explained by the changing total P or T, as it is impossible to have such a big pressure increase within
the high-level magma chamber or temperature decrease for the large volume of host granitic magma. Instead, it
may reflect a degassing-induced crystallization that commonly occurs during the rapid ascent with decompression,
especially for those magmas with high volatile contents and moderate melt viscosities (Annen et al., 2006; Blundy
& Cashman, 2001; Cashman & Blundy, 2000; Crabtree & Lange, 2011). A water content of 4.7 wt% equilibrated
with low An (An$_{42-46}$) possibly reflect a downward trend, but the uncertainty of parameters and standard error of
the hygrometer inhibit our determination on the actual situation. The very thin calcic ring with An spike most
likely reflects an impinge of another pulse of mafic magma, during which the possibly local melt mixing affected
the plagioclase composition. The thin high-An zone is immediately followed outward by a low An rim equilibrat-
ed with the final host magma, possibly due to rapid chemical and thermal equilibrium concerning the very low
relative abundance of mafic to felsic magma. This scenario is manifested in another large phenocryst from this sample (Figure 16b). In this plagioclase, the high-An core (ca. 80) is not present. It may be absent and replaced by Anₙ₋₀ that corresponds to the mantle region of the former phenocryst, suggesting that it started to crystallize at the second stage after degassing. The relatively low initial $^{87}$Sr/$^{86}$Sr ratio in the rim may represent the isotope equilibration after mixing with a low $^{87}$Sr/$^{86}$Sr mafic magma due to the fast diffusion of Sr isotopes in melts (e.g., Lesher, 1990; Poli et al., 1996).

Figures 16c and 16d show phenocrysts from 19XJ66-1. Analytical spots were selected respectively from the bright and dark zones shown in the microphotographs, and the measured An contents correspond to high and low values. Unlike sample 19XJ64-6, these two phenocrysts lack regular zonation but have spot-like or irregularly corroded fillings surrounded by a dark rim. This phenomenon is also consistent with a decompression-degassing process, during which the resorbed high-An plagioclase was followed by more sodic plagioclase, which was newly precipitated and stable in a low-P and low-$\text{H}_2\text{O}$ condition. Although no An spikes are discovered, the low ($^{87}$Sr/$^{86}$Sr) values in the dark zone (Figure 16c) possibly reflect some mafic magma assimilation during the second-stage crystallization. The distinctly high isotopic values in the rim (Figure 16d), however, may represent a late-stage alteration.

With regard to the CP, a similar explanation for the two populations of An values can be applied to the phenocryst from granite 19XJ119-1 (Figure 16e), where low An mantle surrounds the high-An inner core, and the rim with the lowest An is related to later alteration. The general core-rim texture of the phenocryst from the enclave sample 19XJ119-4 is manifested by a calcic core with more intense alteration and a rim characterized by alternating high- and low-An values (Figure 16f). The high An core (as high as 90) is considered to have crystallized from a hydrous mafic magma prior to its injection into the acidic magma chamber (Browne et al., 2006). The variable An in the narrow rim may result from degassing, convection, cooling, and successive assimilation with the felsic host magma. The fine-grained matrix possibly marked the fast cooling of the enclave magma upon intruding into a relatively low-$T$ felsic magma. Because the chemical exchange is not as efficient as the thermal equilibration, the matrix records two populations of the An values (e.g., 53 and 62), with the lower one recording the equilibrium re-equilibration with locally mixed melt during the crystallization history of the enclave magma.

### 5.3.3. Ascent and Crystallization Path Accompanied by Magma Hybridization

The $P$-$T$-$t$ path followed by individual magma batches controls the resulting phase assemblage, chemistry, and texture. Based on detailed analysis of plagioclase profiles involving chemical composition, Sr isotope, and mineral morphology and textures, the possible crystallization path of the granitoid and enclave magma is here proposed. The hydrous parental magma possibly ascended near adiabatically into the shallow level (Annen et al., 2006), where the decompression of a water-saturated melt inevitably induced degassing with decreased capacity of accommodating volatiles in solution at lower pressure. When the melt intersected the water-saturated liquidus, it started to crystallize amphibole and/or plagioclase as the liquidus phase according to the chemical compositions. Crystal size and shape are closely related to the interplay of nucleation and growth of crystals, which is then strongly controlled by magma undercooling, the depression of temperature below the equilibrium freezing temperature ($\Delta T = T_{\text{liquidus}} - T_{\text{magma}}$). It has been suggested that large undercooling induces an increased nucleation rate, whereas small undercooling leads to an increased growth rate (Dowty, 1980; Kirkpatrick, 1981; Vernon, 2018). Widely developed core-rim textures of plagioclase phenocrysts from both the granitoids and MME yield two populations of An values. The relatively large cores with high An of 80–90 should be homogeneously formed in the early stage with higher $\text{H}_2\text{O}$, in which condition the small undercooling (low $T_{\text{liquidus}}$ and low $\Delta T$) resulted in a high growth rate. The crystal-carrying magma ascended further into the final emplacement level with continuous degassing. At that moment, the large undercooling caused by degassing and moderate cooling changed the crystallization mode from growth-controlled to nucleation-controlled (Vernon, 2018), which is compatible with the sodic mantle-rim overgrowth and small, unzoned plagioclase of matching composition in the groundmass.

Magma hybridization during crystallization in the high-level chamber differed from the thorough mixing at depth. During the magma interaction at shallow levels, thermal equilibration and isotope exchange were relatively efficient between the mixing melts. Especially for samples from the CP, smaller variations of Sr isotopic data, comparable zircon $\epsilon$Hf(t) values, and overlapping zircon trace element compositions suggest a more thorough re-equilibration. Meanwhile, the partial chemical equilibration is reflected by the similarity in mineral compositions but heterogeneity in major elements. Interactive crystal transfer is evidenced by the penetration of some
plagioclase phenocrysts from the host into the enclave side and the transfer of some titanite from the mafic to felsic magma. Meanwhile, the effects of magma interaction on the two engaging magmas are different due to the difference in relative proportions. For the host granitoid, it was locally disturbed by mafic input during the emplacement, and only a few plagioclase phenocrysts recorded such a replenishment event by increased An content as shown in Figures 16a and 16b. However, the relatively large variation in the plagioclase Sr isotopes between two possible end members does indicate the disturbance of the mafic magma and isotope diffusion. For the MME, in addition to the effect of decompression upon ascent, the rapid heat loss of the enclave magma to the enclosing granite magma resulted in a larger undercooling (high Δ7), with needle-like apatite and tiny matrix crystals formed (Baxter & Feely, 2002; Coombs et al., 2003). The large difference in mineral sizes shown in the transition zone between the enclave and host granite also supports a rapid crystallization of the mafic magma (Figures 3g and 3h). Further processing in the shallow magma chamber, including more advanced fractional crystallization, may take place in tandem with crystal transfer and chemical mixing/assimilation with host magma, making it compositionally grade toward the felsic end.

5.4. Implications for the Granitic Magmatism in the Chinese Altai

The origin of the early Paleozoic arc-related granitoids that are widely distributed in the Altai area is not yet well defined. Do mafic magmas simply provide heat for crustal melting or are they also involved in other magmatic processes? Is the source of magma crustal material, mantle material, or both, and what is the isotopic composition of the source? Do the granitoids signify the continental growth in this orogen? Here we combine the above general model with the whole-rock and zircon isotopic composition, along with the existing regional data to further constrain the origin of arc-related granitic magmatism in the Chinese Altai.

First, the most mafic sample (19XJ120-3) has an evolved composition with low Mg# (59.9), which cannot represent mantle-equilibrated primary basaltic melt before earlier fractionation of olivine and pyroxene. The ca. 409 Ma Keketuohai mafic complex outcrops in the northern part of the TB, and represents a set of magmatic series formed through fractional crystallization from an inferred high-Mg tholeiitic basaltic melt. The primitive magma was derived from the sub-continental lithospheric mantle (SCLM) that had been enriched by the previous subduction (Cai et al., 2012; Yu, Sun, Huang, et al., 2017). Our mafic rocks (enclaves and dyke) possess identical εNd(t) values to this complex (Figure 9), and their proximity in time and space, similarities in mineral assemblages and chemical compositions suggest a genetic correlation. Thus, we infer that the mafic magma likewise represents a differentiated component from partial melts of the SCLM. The host granitoid samples representing hybrid melts have εNd(t) values identical to or slightly lower than the mafic rocks (Figure 9). It suggests that the felsic endmember should be isotopically similar to the mafic one with near chondritic Nd isotopic compositions, or that they may have experienced Nd isotopic equilibration. Zircon Hf isotopic ratios can provide information for the original magma composition from which zircons crystallized (Kinny & Maas, 2003). The host granitoid from the TB (19XJ63-1) has depleted zircon Hf isotopic ratios, but overall more enriched than the associated MME (19XJ64-2) despite some overlapping (Figure 8). It confirms the existence of two (or more) isotopically different melts and precluding a simple origin by closed-system fractionation from a common mantle-derived magma. The changing plagioclase Sr isotopes (Figure 13) likewise support such a conclusion. Therefore, a juvenile lower crust extracted from the mantle could be the source of the felsic magma.

Such interpretation is consistent with the isotopic and geochemical data for the high-grade metamorphic rocks in the region, which indicate that there is no Precambrian crustal basement underneath the Chinese Altai (e.g., Broussolle et al., 2019). Subordinate Precambrian detrital zircons from the meta-sedimentary rocks were transported from the old continental blocks of western Mongolia (e.g., Long et al., 2008). Addition of such enriched components is also the cause of somehow more enriched isotopic composition for the crust-derived melts relative to the mantle-derived melts. The Proterozoic Hf and Nd model ages for both the MME and granitoids thus are hybrid values, and do not negate the contribution of mantle material. Widespread coeval syn-subsidence granitic rocks in the Chinese Altai are generally characterized by calc-alkaline, metaluminous chemical compositions, and slightly depleted Nd and zircon Hf isotopic compositions (Figures 8 and 9; Broussolle et al., 2019; Cui et al., 2020; Yu, Sun, Long, et al., 2017; Yuan et al., 2007). Some of them show homogeneous textures with no distinct association with MME or mafic dykes, and their generally low Mg numbers (Mg# < 40) is within the range of crustal melts. According to previous research on their petrogenesis, such type of granitoids were formed by dehydration melting of a juvenile lower crust with little addition of mantle materials (See data summary in
Broussolle et al. [2019]). It represents the reworking and internal differentiation of the crust, facilitating its further maturation. Those enclave-bearing ones are relatively rare in this region and typified by TB and CP in this study. Based on our general model and supplementary data, their parental magmas were generated by mixing between SCLM-derived magma and juvenile lower crustal-derived magma, suggesting some crustal growth with direct mantle addition. As a result, the Chinese Altai orogen has experienced substantial crustal growth during the early Paleozoic, either through juvenile lower crustal accretion or through addition into middle-upper crustal granitoids by magma mixing.

6. Conclusions

The TB and CP represent discrete portions active in the subduction stage of the Chinese Altai and can be typified as calc-alkaline arc-related intrusions. A combination of petrography, whole-rock chemical analysis, and in situ elemental and isotopic composition determination for minerals allow us to establish an evolutionary path of the studied granitoids and associated mafic rocks (Figure 17), which involves mafic-felsic magma interplay and other magmatic processes in deep and shallow chambers respectively:

1. High-Mg tholeiitic magma generated by partial melting of the SCLM underplated and ponded at the base of the arc crust, where it experienced extensive crystallization accumulation. The hot mafic magma induced partial melting of the existing juvenile crustal rocks. Under the high-\(T\) and hydrous condition, the evolved residual basaltic magma and the crustal-derived felsic magma could extensively mix to form the hybrid magma in the DCHZ.

2. Due to the relatively low viscosity and density, the hybrid magma with varying mixture proportions may segregate and ascend near adiabatically to upper crustal levels, forming the granitic magma chamber. The rarity of inherited-zircons suggests a nearly crystal-free ascent path, and the fully molten state of the magma is a consequence of high water content. The very calcic cores of some plagioclase phenocrysts (An~80) mark the onset of crystallization at high \(\text{pH}_2\text{O}\) condition. After a brief stagnation, the further rise at the emplacement.

Figure 17. Schematic diagram showing the generation and evolution of the Tuerhongnan Batholith and Chaergan Pluton in the Chinese Altai, involving magma generation, hybridization in the deep crustal hot zone, magma ascent and crystallization in shallow level, and late-stage alteration. See text descriptions in conclusion for the complete scenario.
Acknowledgments

This work was financially supported by Hong Kong RGC GRF (17302317), National Key R&D Program of China (2017YFC0601205), NSFC Projects (41730213, 42072264, 41902229, and 41972237), and the International Partnership Program of Chinese Academy of Sciences (Grant No. 132744KYSB20190039). This is a contribution of the Joint Laboratory of Chemical Geodynamics between The University of Hong Kong and Guangzhou Institute of Geochemistry, Chinese Academy of Science. The authors thank Prof. Simon Williams for polishing the manuscript. The authors also thank Mr. Zhou Ningchao from the Xi’an Geological Survey Center of China Geological Survey for the EPMA experiment assistance, and all members from the Wuhan Sample Solution Analytical Technology Co., Ltd and Nanjing FocuMS Technology Co., Ltd for other experimental assistance. Brandon Browne, Tom Sisson, and one anonymous reviewer are highly appreciated for their constructive suggestions, as well as careful handling by editor Janne Blichter-Toft.

References

Anderson, J. L., & Smith, D. R. (1995). The effects of temperature and fO2 on the Al-in-hornblende barometer. American Mineralogist, 80(5–6), 549–559. https://doi.org/10.2138/am-1995-5-615

Amen, C., Blundy, J. D., & Sparks, R. S. J. (2006). The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology, 47(3), 505–539. https://doi.org/10.1093/petrology/egi084

Arndt, N. T. (2013). The formation and evolution of the continental crust. Geochemical Perspectives, 2(3), 405–533. https://doi.org/10.7185/geochempersp.2.3

Barbarin, B. (2005). Mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada batholith, California: Nature, origin, and relations with the hosts. Lithos, 80(1–4), 155–177. https://doi.org/10.1016/j.lithos.2004.05.010

Baxter, S., & Feely, M. (2002). Magma mixing and mingling textures in granitoids: Examples from the Galway Granite, Connemara, Ireland. Mineralogy and Petrology, 76(1–2), 63–74. https://doi.org/10.1007/s007100200032

Bédard, J. (1990). Enclaves from the A-type granite of the Mégantic Complex, White Mountain Magma Series: Clues to granite magmatism. Journal of Geophysical Research: Solid Earth, 95(B11), 17797–17819. https://doi.org/10.1029/JB095iB11p17797

Blundy, J., & Cashman, K. (2001). Ascent-driven crystallisation of dacite magmas at Mount St Helens, 1980–1986. Contributions to Mineralogy and Petrology, 140(6), 631–650. https://doi.org/10.1007/s004100000219

Blundy, J., & Sparks, R. (1992). Petrogenesis of mafic inclusions in granitoids of the Adamello Massif, Italy. Journal of Petrology, 33(5), 1039–1104. https://doi.org/10.1093/petrology/33.5.1039

Braecli, F., Francalanci, L., Tommasini, S., & Vougioukalakis, G. E. (2014). Unraveling the hidden origin and migration of plagioclase nocrysts by in situ Sr isotopes: The case of final dome activity at Nisyros volcano, Greece. Contributions to Mineralogy and Petrology, 167(3). https://doi.org/10.1007/s00410-014-0988-4

Brousolles, A., Aguilar, C., Sun, M., Schulmann, K., Štípská, P., Jiang, Y., et al. (2019). Polycyclic Palaeozoic evolution of accretionary orogenic wedge in the southern Chinese Altai: Evidence from structural relationships and U–Pb geochronology. Lithos, 314, 400–424. https://doi.org/10.1016/j.lithos.2018.06.005

Brousolles, A., Sun, M., Schulmann, K., Guy, A., Aguilar, C., Štípská, P., et al. (2019). Are the Chinese Altai “terranes” the result of juxtaposition of different crustal levels during Late Devonian and Permian orogenism? Gondwana Research, 66, 183–206. https://doi.org/10.1016/j.gr.2018.11.003

Brown, E., & McClelland, W. (2000). Pluton emplacement by sheeting and vertical ballooning in part of the southeast Coast Plutonic Complex, British Columbia. Geological Society of America Bulletin, 112(5), 7082–7719. https://doi.org/10.1130/0016-7606(2000)112<7082:pebsav>2.0.co;2

Browne, B. L., Eichelberger, J. C., Patino, L. C., Vogel, T. A., Dehn, J., Uto, K., et al. (2006). Generation of porphyritic and equigranular mafic enclaves during magma recharge events at Unzen Volcano, Japan. Journal of Petrology, 47(2), 301–328. https://doi.org/10.1093/petrology/egd076

Data Availability Statement

All of the analytical data mentioned in the study are available at EarthChem Library data repository via http://doi.org/10.26022/IEDA/112081.
Idrus, A. (2018). Petrography and mineral chemistry of magmatic and hydrothermal biotite in porphyry copper-gold deposits: A tool for understanding mineralizing fluid compositional changes during alteration processes. Indonesian Journal on Geoscience, 5(1). https://doi.org/10.17014/jog.5.1.47-64

Janoušek, V., Bowes, D., Braithwaite, C. J., & Rogers, G. (2000). Microstructural and mineralogical evidence for limited involvement of magma mixing in the petrogenesis of a Hercynian high-K calc-alkaline intrusion: The Kožárvice granodiorite, Central Bohemian Pluton, Czech Republic. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 91(1-2), 15–26. https://doi.org/10.1017/S0263593300007264

Janoušek, V., Braithwaite, C. J. R., Bowes, D. R., & Gerdes, A. (2004). Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: An integrated petrographic and geochemical study of the Sázava intrusion, Central Bohemian Pluton, Czech Republic. Lithos, 78(1–2), 67–99. https://doi.org/10.1016/j.lithos.2004.04.046

Jiang, Y., Schulmann, K., Sun, M., Štípská, P., Guy, A., Janoušek, V., et al. (2016). Anaxiosis of accretionary wedge, Pacific-type magmatism, and formation of vertically stratified continental crust in the Altai Orogenic Belt. Tectonics, 35(12), 3099–3118. https://doi.org/10.1002/2016TC004271

Karykowski, B. T., Yang, S. H., Maier, W. D., Lahaye, Y., Lissenberg, C. J., & O’Brien, H. (2017). In situ Sr isotope compositions of plagioclase from a complete stratigraphic profile of the Bushveld Complex, South Africa: Evidence for extensive magma mixing and percolation. Journal of Petrology, 58(11), 2285–2308. https://doi.org/10.1093/petrology/egy008

Kinny, P. D., & Maas, R. (2003). Lu–Hf and Sm–Nd isotope systems in zircon. Reviews in Mineralogy and Geochemistry, 53(1), 327–341. https://doi.org/10.2113/0530327

Kirkpatrick, R. J. (1981). Kinetics of crystallization of igneous rock. In A. Lasaga & R. Kirkpatrick (Eds.), Reviews in Mineralogy, Kinetics of Geochemical Processes (Vol. 8, pp. 98–321). Mineralogical Society of America.

Kumar, S., & Rino, V. (2006). Mineralogy and geochemistry of microgranular enclaves in Palaeoproterozoic Malanjkhand granitoids, central India: Evidence of magma mixing, mingling, and chemical equilibration. Contributions to Mineralogy and Petrology, 152(5), 591–609. https://doi.org/10.1007/s00410-006-0122-3

Leake, B. E., Woolley, A. R., Arps, C. E., Birch, W. D., Gilbert, M. C., Grice, J. D., et al. (1997). Nomenclature of amphiboles; report of the subcommittee on amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. The Canadian Mineralogist, 35(1), 219–246. https://doi.org/10.1188/minmag.1997.061.405.13

Le Maître, R., Bateman, P., Dudek, A., Keller, J., Lameyre, J., Le Bas, M., et al. (1989). A classification of igneous rocks and glossary of terms. Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks. Blackwell Scientific Publications.

Lesher, C. (1990). Decoupling of chemical and isotopic exchange during magma mixing. Nature, 344(6263), 235–237. https://doi.org/10.1038/344235a0

Li, P., Sun, M., Rosenbaum, G., Jourdan, F., Li, S., & Cai, K. (2017). 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

Miller, C. F., McDowell, S. M., & Mapes, R. W. (2003). Hot and cold granites? Implications of zircon saturation temperatures and preservation of inheritance. Geology, 31(6). https://doi.org/10.1130/0091-7613(2003)31<0631:COCGIC>2.0.CO;2

Münntener, O., Klemken, P. B., & Grove, T. L. (2001). The role of H2O during crystallization of primitive arc magmas under uppermost mantle conditions and genesis of igneous pyroxenites: An experimental study. Contributions to Mineralogy and Petrology, 141(6), 643–658. https://doi.org/10.1007/s004100100266

Nachit, H., Ibhi, A., & Ouhoud, M. B. (2005). Discrimination between primary magmatic biotites, reequilibrated biotites and neofomed biotites. Comptes Rendus Geoscience, 337(16), 1415–1420. https://doi.org/10.1016/j.crd.2005.09.002

Panjasawatwong, Y., Danuyushchev, L. V., Crawford, A. J., & Harris, K. L. (1995). An experimental study of the effects of melt composition on plagioclase-melt equilibria at 5 and 10 kbar: Implications for the origin of the magmatic high-An plagioclase. Contributions to Mineralogy and Petrology, 118(4), 420–432. https://doi.org/10.1007/BF00300524

Parasporo, A., Khalili, M., Tepley, F., & Maghami, M. (2015). Mineral chemistry and isotopic composition of magmatic, re-equilibrated and hydrothermal biotites from Darreh-Zar porphyry copper deposit, Kerman (Sistan and Baluchestan). Ore Geology Reviews, 66, 200–218. https://doi.org/10.1016/j.oregeorev.2014.10.015

Perugini, D., Poli, G., Christofides, G., & Elefteriadis, G. (2003). Magma mixing in the Siftonia Plutonic Complex, Greece: Evidence from mafic microgranular enclaves. Minerals, Rocks and Petrology, 78(3–4), 173–200. https://doi.org/10.1016/S0263-5835(03)00029-0

Pichavant, M., Martel, C., Boudier, J. L., & Scaillet, B. (2002). Physical conditions, structure, and dynamics of a zoned magma chamber: Mount Pelée (Martinique, Lesser Antilles Arc). Journal of Geophysical Research: Solid Earth, 107(B5), ECV 1-1–ECV 1-28. https://doi.org/10.1029/2001JB000315

Poli, G., Tommasini, S., & Halliday, A. (1996). Trace element and isotopic exchange during acid–basic magma interaction processes. Transactions of the Royal Society of Edinburgh: Earth Sciences, 87(1), 225–232. https://doi.org/10.1017/S0308137195000225

Putikka, K. D. (2005). Igneous thermometers and barometers based on plagioclase+ liquid equilibria: Tests of some existing models and new calibrations. American Mineralogist, 90(2–3), 336–346. https://doi.org/10.2138/am.2005.1449

Ratajeski, K., Glazner, A. F., & Miller, B. V. (2001). Geology and geochemistry of mafic to felsic plutonic rocks in the Cretaceous intrusive suite of Yosemite Valley, California. Geological Society of America Bulletin, 113(11), 1486–1502. https://doi.org/10.1130/0016-76062001113<1486:GAGOM2.0.CO;2

Ruprecht, P., & Wörner, G. (2007). Variable regimes in magma systems documented in plagioclase zoning patterns: El Misti stratovolcano and Andahuay monogenetic cones. Journal of Volcanology and Geothermal Research, 163(3–4), 142–162. https://doi.org/10.1016/j.jvolgeores.2007.06.002

Şençir, A., Natařin, B., & Burttman, V. (1993). Evolution of the Altai tectonic collage and Palaeozoic crustal growth in Eurasia. Nature, 364(6435), 299–307. https://doi.org/10.1038/364299a0

Sisson, T. W., & Grove, T. (1993). Experimental investigations of the role of H2O in calc-alkaline differentiation and subduction zone magmatism. Contributions to Mineralogy and Petrology, 113(2), 143–166. https://doi.org/10.1007/BF00283225

Sisson, T. W., Grove, T., & Coleman, D. (1996). Hornblende gabbro sill complex at Onion Valley, California, and a mixing origin for the Sierra Nevada batholith. Contributions to Mineralogy and Petrology, 126(1–2), 81–108. https://doi.org/10.1007/s00410010050237

Sisson, T. W., Ratajeski, K., Hankins, W. B., & Glazner, A. F. (2005). Voluminous granitic magmas from common basaltic sources. Contributions to Mineralogy and Petrology, 148(6), 635–661. https://doi.org/10.1007/s00410-004-0632-9
Slaby, E., & Martin, H. (2008). Mafic and felsic magma interaction in granites: The Hercynian Karkonosze Pluton (Suethes, Bohemian Massif). *Journal of Petrology, 49*(2), 353–391. https://doi.org/10.1093/petrology/egn085

Snyder, D., & Tait, S. (1995). Replenishment of magma chambers: Comparison of fluid-mechanic experiments with field relations. *Contributions to Mineralogy and Petrology, 122*(3), 230–240. https://doi.org/10.1007/BF00380512

Streckeisen, A., & Le Maitre, R. (1979). A chemical approximation to the modal QAPF classification of the igneous rocks. *Neues Jahrbuch für Mineralogie - Abhandlungen, 139*, 169–206.

Sun, M., Long, X., Cai, K., Jiang, Y., Wang, B., Yuan, C., 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*(5), 1345–1358. https://doi.org/10.1007/s11430-009-0110-3

Sun, M., Yuan, C., Xiao, W., Long, X., Xia, X., Zhao, G., 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 Paleozoic. *Chemical Geology, 247*(3–4), 352–383. https://doi.org/10.1016/j.chemgeo.2007.10.026

Sun, 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

Turnbull, R., Weaver, S., Tulloch, A., Cole, J., Handler, M., & Ireland, T. (2010). Field and geochemical constraints on mafic-felsic interactions, and processes in high-level arc magma chambers: An example from the Halfmoun Pluton, New Zealand. *Journal of Petrology, 51*(7), 1477–1505. https://doi.org/10.1093/jpetro/jeg026

Ustunisk, G., Kizil, A., & Nielsen, R. L. (2014). New insights into the processes controlling compositional zoning in plagioclase. *Lithos, 200–201*, 80–93. https://doi.org/10.1016/j.lithos.2014.03.021

Vernon, R. H. (1983). Restite, xenoliths and microgranoid enclaves in granites. *In Paper presented at the Journal and Proceedings of the Royal Society of New South Wales*. Royal Society of New South Wales.

Vernon, R. H. (1984). Microgranoid enclaves in granites—Globules of hybrid magma quenched in a plutonic environment. *Nature, 309*(5967), 438–439. https://doi.org/10.1038/309438a0

Vernon, R. H. (2018). *A practical guide to rock microstructure*. Cambridge University Press.

Wiebe, R. A. (1993). The Pleasant Bay layered gabbro-diorite, coastal Maine: Ponding and crystallization of basaltic injections into a silicic magma chamber. *Journal of Petrology, 114*(6), 735–751. https://doi.org/10.1086/507617

Wang, Y., Long, X., Wilde, S. A., Xu, H., Sun, M., Xiao, W., et al. (2014). Provenance of Early Paleozoic metasediments in the central Chinese Altai: Implications for tectonic affinity of the Altai-Mongolia terrane in the Central Asian Orogenic Belt. *Lithos, 210–211*, 57–68. https://doi.org/10.1016/j.lithos.2014.09.026

Waters, L. E., & Lange, R. A. (2015). An updated calibration of the plagioclase-liquid hygrometer-thermometer applicable to basaltic through rhyolitic. *American Mineralogist, 100*(10), 2172–2184. https://doi.org/10.2138/am.2015-5232

Wiebe, R. A. (1993). The Pleasant Bay layered gabbro-diorite, coastal Maine: Ponding and crystallization of basaltic injections into a silicic magma chamber. *Journal of Petrology, 34*(3), 347–383. https://doi.org/10.1093/petrology/34.3.461

Wiebe, R. A., Blair, K., Hawkins, D., & Sabine, C. (2002). Mafic injections, in situ hybridization, and crystal accumulation in the Pyramid Peak granite, California. *Geological Society of America Bulletin, 114*(7), 909–920. https://doi.org/10.1130/0016-7606(2002)114<909:MISHI2.CO;2

Wiebe, R. A., Smith, D., Sturman, M., King, E., & Beckler, M. (1997). Enclaves in the Cadillac mountain granite (Coastal Maine): Samples of hybrid magma from the base of the chamber. *Journal of Petrology, 38*(3), 393–423. https://doi.org/10.1093/petrology/38.3.393

Wilson, A. H., Zeh, A., & Gerdes, A. (2017). In situ Sr isotopes in plagioclase and trace element systematics in the lowest part of the eastern Bushveld Complex: Dynamic processes in an evolving magma chamber. *Journal of Petrology, 58*(2), 327–360. https://doi.org/10.1093/petrology/egx018

Windley, B. F., Alexiev, D., Xiao, W., Kröner, A., & Badarch, G. (2007). Tectonic models for accretion of the Central Asian Orogenic Belt. *Journal of the Geological Society, 164*(1), 31–47. https://doi.org/10.1144/1470-6649/2006-022

Windley, B. F., Kröner, A., Guo, J., Qu, G., Li, Y., & Zhang, C. (2002). Neo-protoreozoic 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/10.1086/542866

Xiao, W., Windley, B., Yuan, C., Sun, M., Han, C., Lin, S., et al. (2009). Paleozoic multiple subduction-accretion processes of the southern Altays. *American Journal of Science, 309*(3), 221–279. https://doi.org/10.2475/03.2009.02

Yu, K., Liu, Y., Hu, Q., Ducea, M. N., Hu, Z., Zeng, K., et al. (2018). Magma recharge and reactive bulk assimilation in enclave-bearing granitoids, Tonglu, South China. *Journal of Petrology, 59*(5), 795–824. https://doi.org/10.1093/petrology/egy044

Yu, Y., Sun, M., Huang, X., Zhao, G., Li, P., Long, X., et al. (2017). 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., Li, P., Zhao, G., Kröner, A., et al. (2017). 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

Yu, Y., Sun, M., Yuan, C., Zhao, G., Huang, X., Rojas-Agramonle, Y., et al. (2018). Evolution of the middle Paleozoic magmatism in the Chinese Altai: Constraints on the crustal differentiation at shallow depth in the accretionary orogen. *Journal of Asian Earth Sciences, 175*, 230–246. https://doi.org/10.1016/j.jseaes.2018.07.026

Yuan, C., Sun, M., Xiao, W., Li, X., Chen, H., Lin, S., 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, J., Wang, T., Castro, A., Zhang, L., Shi, X., Tong, Y., et al. (2016). Multiple mixing and hybridization from magma source to final emplacement in the Permian Yamato pluton, the Northern Alxa Block, China. *Journal of Petrology, 57*(5), 933–980. https://doi.org/10.1093/petrology/egw028

Reference From the Supporting Information

Liew, T., & Hofmann, A. (1988). Precambrian crustal components, plutonic associations, plate environment of the Hercynian Fold Belt of central Europe: Indications from a Nd and Sr isotopic study. *Contributions to Mineralogy and Petrology, 98*(2), 129–138. https://doi.org/10.1007/BF00402106