Research Article

The Pennsylvanian Composite Volcanism in the Bogda Mountains, NW China: Evidence for Postcollisional Rift Basins

Jialin Wang,1 Chaodong Wu,1,2 Zhuang Li,3 Tianqi Zhou,1,2 Yanxi Zhou,1,2 Geng Feng,1,2 and Yue Jiao1,2

1Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University, Beijing 100871, China
2Institute of Oil and Gas, Peking University, Beijing 100871, China
3State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing), Beijing 102249, China

Correspondence should be addressed to Chaodong Wu; cdwu@pku.edu.cn

Received 2 April 2020; Accepted 13 August 2020; Published 6 October 2020

Academic Editor: Matt Steele-MacInnes

Copyright © 2020 Jialin Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In this paper, we present new petrological, zircon U–Pb–Hf isotopic, bulk-rock geochemical, and Sr–Nd isotopic data for the rocks from the Pennsylvanian Liushugou and Qijiagou Formations, Bogda Mountains (BMs), northwest China. The new data help in understanding the petrogenesis and geodynamic background of the two formations, further constraining the evolution of BMs during the Pennsylvanian. The eastern Liushugou Formation is composed mainly of bimodal volcanic rocks, while the western Liushugou Formation is dominated by pillow basalts with interstitial limestones, peperites, and pyroclastic rocks. The Qijiagou Formation consists principally of bioclastic limestones, peperites, and volcanic and volcaniclastic rocks with turbidites. Depositional environment analyses of the Liushugou and Qijiagou Formations reveal subaqueous volcanism and a progressively deepening shallow marine environment with time. Zircon LA-ICP-MS U–Pb dating of felsic volcanic rocks from the Liushugou Formation indicates that the subaqueous volcanism occurred at ca. 310–302 Ma, viz., the Pennsylvanian era. The basaltic rocks from the Liushugou and Qijiagou Formations are high-K calc-alkaline, enriched in light rare earth elements and large-ion lithophile elements, and depleted in high-field-strength elements (Nb, Ta, and Ti). The above characteristics, together with their depleted isotopic signature (εNd(t) = 3.0–8.1, εHf(t) = 8.0–15.6, and I0Sr = 0.703–0.707), suggest the derivation from a depleted mantle source metasomatized by slab-derived fluids and sediment-derived melts. Most felsic volcanic rocks of the high-K calc-alkaline to shoshonite series from the Liushugou and Qijiagou Formations show features of the A2-type granites and have similar trace and isotopic composition to the basaltic rocks, which were probably generated from the partial melting of juvenile continental crust. Combining the newly acquired data with the regional geology, we propose that the Pennsylvanian volcanic and sedimentary rocks in the BMs were formed in a series of postcollisional rift basins which were related to local strike-slip faulting. Moreover, the volcanic rocks in the east were derived from a relatively deeper mantle source (thick lithosphere) due to their smaller rifting.

1. Introduction

The postcollisional setting is distinctive and not integrated into the model of plate tectonics (e.g., [1]). However, how to distinguish the characteristic of postcollisional magmatism remains questionable [1, 2]. Liegeois [1] proposed that geochemical discrimination diagrams cannot characterize the postcollisional tectonic setting due to a variety of magma types generated coevally. The postcollisional magmatism is so complex, but they still share some common characteristics: (1) They mainly belong to the high-K calc-alkaline to shoshonitic series, of which the felsic volcanic rocks are usually peraluminous and have attributes of A2-type granites [3–8]. (2) Their magma sources are generated from the crust or lithospheric/asthenospheric mantle during the preceding subduction and collision period [1, 8, 9]. Moreover, the sources commonly contain a sizeable juvenile component which has similar geochemical and isotopic attributes to the
lithospheric mantle (e.g., [1] and reference therein). (3) They are usually linked to large horizontal movements along major shear zones [1, 10–13]. The most typical examples of the postcollisional setting are Neogene Tibet (northern Tibet at Songpan-Ganzi, Kunlun, and western Qiangtang terranes, southern Tibet at Lhasa terrane; [1, 4, 6–8, 14, 15]).

The Central Asian Orogenic Belt (CAOB) is one of the largest Phanerozoic accretionary orogens which was formed by a long accretionary history that interacted through microcontinents, island arcs, seamounts, and accretionary wedges (Figure 1; [16]). In the CAOB, scholars suggested a Late Paleozoic postcollisional process, but the beginning time and the geodynamic mechanism are controversial [17, 18]. Some have believed that the subduction processes have continued to the Pennsylvanian [19–21] and subsequently transferred to the postcollisional extensional setting in the Permian [17, 22–24]. Besides, scholars also thought that the Tarim-Tianshan-Junggar ocean was still active, and the subduction processes have lasted to the Permian-Triassic [25–28]. Others have suggested that the Pennsylvania is a tectonic transitional regime from arc to postcollision due to their transitional characteristics in geochemistry [20, 29–33]. Due to the controversy on the beginning time of the postcollisional process, the Late Paleozoic (especially the Pennsylvanian) geodynamic mechanism of the CAOB is disputed. The Late Paleozoic Bogda Mountains (BMs) in the southern CAOB have been interpreted to represent a subduction-related island arc [34, 35] or back-arc [13, 17], mantle plume [36], ridge subduction [37, 38], postcollisional extension ([39]; Zhang et al., 2014; [40]), and local strike-slip faulting [41, 42]. These disputes suggest the need to find more solid evidence to interpret the tectonic evolution of the CAOB.

The Liushugou and Qijiagou Formations of the BMs in the southern CAOB (Figure 2), belonging to the Late Paleozoic [41, 43], could give constraint on this controversial period. The completed successions, exposed along the western and eastern BMs, provided an excellent opportunity to uncover their petrogenesis and geodynamic background. Thus, this study reports new geochronological, geochemical,
Figure 2: Geological map of (a) the Urumqi Range and (b) the Qijiaojing Range in the Bogda Mountains with the locations of sampling sites (modified after [43]).
and isotopic data for the volcanic and sedimentary rocks to study their petrogenesis, and provides a model to explain the Late Paleozoic geodynamic background of the North Xinjiang, as well as that of the CAOB.

2. Geological Background

The CAOB is a large accretionary orogenic belt surrounded by the continent Baltica in the northwest, the Siberian Craton in the northeast, and the Tarim and North China Cratons in the south (Figure 1(a); [44]). The BMs, as the southern segment of CAOB, function as a pivotal tectonic belt separating the Turpan-Hami Basin from the Junggar Basin (Figure 1(b); [45]). The BMs, located in the northern part of the NTS (Figure 1(b)), are mainly comprised of Devonian to Quaternary sedimentary rocks with some igneous rocks [19]. Of these, the Carboniferous bimodal volcanic rocks are widely distributed [13, 46–48]. The sedimentary rocks consist mainly of fine-grade clastic rocks, limestones, and volcanic breccias, with no ophiolites [49]. The present average elevation of the BMs is above 4000 m, which is induced by the late Cenozoic India-Asia collision [50]; the Carboniferous strata were deposited in an intracontinental rift basin [36] or a subduction-related forearc or back-arc basin [13, 17, 34, 35, 41].

The Haxiongou section, located in the central peak of the western BMs, is composed of the Mississippian Qiergou-sitao Group, and the Pennsylvanian Liushugou and Qijiaojing Formations from bottom to top, with no Devonian or even older strata (Figure 2(a); [43]). The Mississippian Qiergousi-tao Group is located mainly at the peak of the BMs and is not involved in this study. The Liushugou Formation is dominated by pillow basalts with interstitial limestones (Figures 3(a) and 3(b)), peperites (Figure 3(c)), vesicular-dominated by pillow basalts with interstitial limestones involved in this study. The Liushugou Formation is dominated by volcanic rocks, marine clastic rocks, and volcaniclastic rocks with a small amount of volcanic lavas (Figures 3(e)–3(g)). The volcanic rocks mainly consist of basalts, dacites, and rhyolites, similar to a "bimodal" volcanic assemblage (Figure 3(e); [13, 52]). The Pennsylvanian Qijiaojing Formation mainly consists of felsic volcanic rocks mixed with volcaniclastic rocks (Figures 3(h) and 3(i)). The marine bioclastic is distributed in sandstones and limestones (Figure 3(h)).

3. Petrology

In the Haxiongou section, the volcanic rocks of the Liushugou Formation mainly include basalts, andesites, dacites, and rhyolites with some peperites (Figures 4(a)–4(e)). In the Qijiaojing section, the Liushugou Formation consists of bimodal volcanic rocks with minor or no andesites (Figures 4(f)–4(i)).

The basaltic rocks are greyish-green or black grey; have a massive, pillow or vesicular structure; and exhibit no porphyry or less porphyritic textures with 10–30% content of clinopyroxene and plagioclase (Figure 4(a)). The clinopyroxene phenocrysts are euhedral and are up to 2 mm long. The plagioclase phenocrysts are subhedral, have a long columnar shape, and are 0.2–1.0 mm long. The groundmasses consist of fine-grained plagioclases, clinopyroxenes, and opaque oxides (Figures 4(a) and 4(g)).

The gabbros are greyish-green and have a gabbro texture in which the basic plagioclases and clinopyroxenes are irregularly interlaced with each other (Figure 4(f)). Clinopyroxene phenocrysts are subhedral, granular shaped, and 0.2–1.0 mm long. Basic plagioclase phenocrysts are euhedral to subhedral, have a long columnar shape, and are 0.2–1.0 mm long. The plagioclase and clinopyroxene phenocrysts have similar grain shapes, probably the products of the same period of crystallization.

The andesites and basaltic andesites are grey or greyish-green and commonly show a porphyritic texture with clinopyroxene, plagioclase, and hornblende phenocrysts (Figure 4(b)). The clinopyroxene phenocrysts are euhedral to subhedral, and some crystals have epidote alteration. The plagioclase phenocrysts are subhedral and tabular shaped, and some crystals are altered. The hornblende phenocrysts are few, commonly euhedral, and 0.1–0.5 mm long. The matrix consists mainly of plagioclase, clinopyroxene, volcanic glass, and opaque oxides, some of which have a trachytic texture (Figure 4(b)).

The dacites are grey and greyish brown and show nonporphyritic to porphyritic textures with plagioclase, hornblende, and quartz phenocrysts (Figures 4(c) and 4(h)). The plagioclase phenocrysts are subhedral and 0.1–1.0 mm long, and some of them have a polysynthetic twin and a Carlsbad twin. The matrix is mainly composed of plagioclases, quartzes, and volcanic glasses.

The rhyolites are generally grey or greyish-white and have an apparent rhyolite structure, with nonporphyritic cryptocrystalline and porphyritic textures (Figures 4(d) and 4(i)). The phenocrysts consist mainly of quartzes and plagioclases, with a content of about 10%. The quartz phenocrysts are hypidiomorphic to xenomorphic, with a diameter of...
Figure 3: Representative photos of the Pennsylvanian strata in the Bogda Mountains. (a) Pillow basalt with interstitial limestone (the lenticular limestone is distributed in pillow basalt); Liushugou Formation of the Haxionggou section, west Bogda Mountains; telegraph pole (scale) is 10 m high. (b) Pillow basalt; Liushugou Formation of the Haxionggou section, western Bogda Mountains; person (scale) is 1.7 m tall. (c) Peperite composed of limestone and volcanic rocks; Liushugou Formation of the Haxionggou section, western Bogda Mountains; hammer (28 cm long) shows the scale. (d) Vesicular basalt; Liushugou Formation of the Haxionggou section, western Bogda Mountains; coin (scale) has a diameter of 20 cm. (e) The bimodal volcanic assemblage of the Liushugou Formation in the Qijiaojing section, eastern Bogda Mountains; person (scale) is 1.7 m tall. (f) Dark grey shale; Liushugou Formation of the Qijiaojing section, eastern Bogda Mountains; hammer (28 cm long) shows the scale. (g) Greyish-green vesicular basalt; Liushugou Formation of the Qijiaojing section, eastern Bogda Mountains; coin (scale) has a diameter of 20 cm. (h) Sandstone is rich in biodetritus, including marine brachiopods, corals, gastropods, and crinoid biological fossils; Qijiagou Formation of the Qijiaojing section, eastern Bogda Mountains; coin (scale) has a diameter of 20 cm. (i) Grey volcanic breccia; Qijiagou Formation of the Qijiaojing section, eastern Bogda Mountains; coin (scale) has a diameter of 20 cm.
0.1–0.5 mm. The plagioclase phenocrysts are euhedral, tabular shaped, and 0.1–1.0 mm long, with a polysynthetic twin and zonal texture. The matrix mainly consists of quartzes, plagioclases, and glasses.

Besides, there are also some peperites in the Liushugou and Qijiagou Formations which were formed by magma-sediment mingling (magma and unconsolidated limestone, [41]). The main components of the flowing slurry are plagioclase and quartzes, and the host sediments are mainly calcites. Some slurry particles have condensation edges and recrystallized calcite baking edges (Figure 4(e)).

4. Analytical Methods and Data Collection

The studied volcanic rocks were collected from the Haxiongou and Qijiaojing sections in the BMs (Figure 2). Two samples (16HXG-12 and 16 HXG-13) from the Haxiongou section and one sample (16QJJ-15) from the Qijiaojing section have been collected for Zircon U–Pb dating and Hf isotope analyses. Fourteen samples from the Haxiongou section (all of these are collected from the Liushugou Formation) and 27 samples from the Qijiaojing section (9 samples are collected from the Liushugou Formation and 18 samples...
from the Qijiagou Formation) have been collected for bulk-rock geochemical analysis and Sr–Nd isotope analyses.

Zircon U–Pb isotope analyses were conducted using a Laser Ablation Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS) instrument (Agilent 7500c ICP-MS coupled with a 193 nm ArF excimer laser) at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, Peking University. Detailed analysis procedures follow Yuan et al. [53]. Isotopic ratios and elemental contents of samples were calculated by the GLITTER 4.0 program [54]. Common lead correction was calculated by the program given by Andersen [55]. The weighted average age and Concordia plot were drawn using ISOPLOT 3 [56]. Zircon in-situ Lu–Hf isotopic analysis is based on the preceding zircon U–Pb isotope, and the test was conducted at the State Key Laboratory of Continental Tectonics and Dynamics, Institute of Geology, Chinese Academy of Geological Sciences using the Neptune Multi-collector Plasma-Mass Spectrometer and New Wave UP-213 UV Laser Ablation Multi-collector Inductively Coupled Plasma-Mass Spectrometer. See Hou et al. [57] for operating conditions and detailed analysis procedures of relevant instruments.

The 12 basaltic rocks, 11 andesitic rocks, and 18 felsic rocks were milled to a mesh size of less than 200 for elemental geochemical analysis. Major element determinations were performed by inductively coupled plasma optical emission spectrometry analysis at the China University of Geoscience (Beijing). Preliminary treatment and measurement of trace elements were undertaken at OBCE. Then, these bulk samples were analyzed by the VG Axiom multicollector, high-resolution ICP-MS. Detailed method descriptions follow Liu et al. [58].

Bulk-rock Sr–Nd isotope separation and purification of Rb, Sr, Sm, and Nd were completed in the OBCE mainly by the conventional ion-exchange method. The isotopic ratios of Sr and Nd were measured by LA–MC–ICP-MS in OBCE. The ratios of \( ^{87}\text{Rb}/^{86}\text{Sr} \) and \( ^{143}\text{Sm}/^{144}\text{Nd} \) were calculated mainly based on trace test results of Rb, Sr, Sm, and Nd. Mass fractionation is mainly conducted by normalizing the tested \( ^{87}\text{Rb}/^{86}\text{Sr} \) and \( ^{143}\text{Sm}/^{144}\text{Nd} \) with \( ^{86}\text{Sr}/^{88}\text{Sr} \) (0.1194) and \( ^{146}\text{Nd}/^{144}\text{Nd} \) (0.7219), respectively. Standard rock sample BCR-2 (basalt; \( ^{87}\text{Rb}/^{86}\text{Sr} = 0.704992 \pm 7 \) (2\( \sigma \), \( n = 94) \), \( ^{147}\text{Sm}/^{144}\text{Nd} = 0.512634 \pm 1 \) (2\( \sigma \), \( n = 97) \) was used to evaluate the degree of isolation and purification of Rb, Sr, Sm, and Nd.

In comparison, we also collected the major and trace element data from the Andean Arc, the Cascade Arc, the Lesser Antilles Arc, Hawaii, the Izu Arc, the East African Rift, and the Lau Back-Arc Basin for comparison. The data are collected from PetDB (http://www.earthchem.org/petdb) and GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/). Due to a large number of data, we performed principal component analysis (PCA). PCA is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components (PCs). The detailed analysis software employed is PAST—Palaontological Statistics [59, 60]; introductions follow Wang et al. [42]. The main parameters are set as follows:

matrix—correlation; groups—between group; and missing values—mean value imputation.

5. Results

5.1. Zircon U–Pb Ages and Hf Isotopes. Three felsic volcanic rocks were collected from the Haxiongou section for zircon LA-ICP-MS U–Pb dating. 16HXG-12 and 16HXG-13 were chosen from the western Liushugou Formation (Haxiongou section). 16QJJ-15 was selected from the eastern Liushugou Formation (Qijiaojing section). All these analytic data are listed in Supplementary Table 1. Almost all the zircons are euhedral to subhedral, show typical oscillatory growth zoning, and have Th/U ratios > 0.2 (0.29–1.36), indicating a magmatic origin [61]. Nineteen analyses from 16HXG-12 (N43°49.596′, E87°57.360′) were concordant, yielding \( ^{206}\text{Pb}^{238}\text{U} \) ages ranging from 317 Ma to 302 Ma with a weighted mean \( ^{206}\text{Pb}^{238}\text{U} \) age of 301 ± 3 Ma (Figure 5(a); MSWD = 1.5, \( n = 19 \)). This age was interpreted as the crystallization age of the dacite. All the twenty zircons from 16HXG-13 (N43°49.677′, E87°57.247′) yielded concordant \( ^{208}\text{Pb}^{238}\text{U} \) ages ranging from 317 Ma to 290 Ma. Except for 4 zircons of preeruptive units (inherited zircon) and 3 zircons of post-eruptive units, the rest of the analyses gave a weighted mean \( ^{206}\text{Pb}^{238}\text{U} \) age of 301 ± 3 Ma (Figure 5(b); MSWD = 1.6, \( n = 13 \)), which represents the formation time (syneruptive time) of the tuff. Twenty zircon grains from 16QJJ-15 (N43°40.979′, E91°38.937′) yielded concordant \( ^{206}\text{Pb}^{238}\text{U} \) ages ranging from 371 Ma to 294 Ma. Except for 6 zircons of pre-eruptive units (inherited zircon) and 1 zircon of post-eruptive units, the rest of the analyses gave a weighted mean \( ^{206}\text{Pb}^{238}\text{U} \) age of 308 ± 4 Ma (Figure 5(c); MSWD = 1.4, \( n = 13 \)), which was interpreted as the formation time (syneruptive time) of the tuff.

The results of zircon Hf isotopic data are listed in Supplementary Table 2 and shown in Figure 5. The zircons from 16HXG-12, 16HXG-13, and 16QJJ-15 have positive \( \epsilon_{\text{Hf}(t)} \) values which plot below the depleted chondrite line (Figure 5(d)). After excluding seven incorrect data (16HXG-13-07, 16HXG-13-10, 16HXG-13-12, 16HXG-13-17, 16HXG-13-20, 16QJJ-15-05, and 16QJJ-15-13), the remaining 30 zircon grains have lower \( \epsilon_{\text{Hf}(t)} \) values which plot below the depleted mantle evolutionary line (Figure 5(e); Supplementary Table 2).

5.2. Bulk-Rock Geochemistry. The result of bulk-rock major and trace elements from the Liushugou and Qijiaojing Formations in the BMs are presented in Supplementary Table 3. The samples of the Liushugou Formation from the Haxiongou section have SiO₂ contents ranging from 47.31 to 76.87 wt.%, classified as basalt, andesite, basaltic
Figure 5: (a–c) Zircon LA-ICP-MS U–Pb dating results of 16HXG-12, 16HXG-13, and 16QJJ-15 which were collected from the Liushugou Formation. (d) Histograms of the Hf-depleted mantle model ages of $T_{DM2}$ for zircons derived from the Liushugou Formation. (e) Plots of $\epsilon_{Hf}(t)$ versus $^{206}\text{Pb}/^{238}\text{U}$ ages of zircons for these samples from the Bogda Mountains. CHUR: Chondrite Uniform Reservoir.

Mean = 310 ± 2 Ma (95% conf.)
(n = 19, MSWD = 1.5)

Mean = 301 ± 3 Ma (95% conf.)
(n = 13, MSWD = 1.6)

Mean = 309 ± 3 Ma (95% conf.)
(n = 13, MSWD = 1.4)

570–326 Ma
737–615 Ma

16HXG-12
16HXG-13
16QJJ-15

Depleted mantle
Bogda
CHUR
North Tianshan
Yili-Central Tianshan

$\epsilon_{Hf}(t)$ versus $^{206}\text{Pb}/^{238}\text{U}$ ages of zircons for these samples from the Bogda Mountains. CHUR: Chondrite Uniform Reservoir.

Figure 5: (a–c) Zircon LA-ICP-MS U–Pb dating results of 16HXG-12, 16HXG-13, and 16QJJ-15 which were collected from the Liushugou Formation. (d) Histograms of the Hf-depleted mantle model ages of $T_{DM2}$ for zircons derived from the Liushugou Formation. (e) Plots of $\epsilon_{Hf}(t)$ versus $^{206}\text{Pb}/^{238}\text{U}$ ages of zircons for these samples from the Bogda Mountains. CHUR: Chondrite Uniform Reservoir.
trachyandesite, trachyandesite, dacite, trachydacite, and rhyolite in the Total Alkalis and Silica (TAS) diagram (Figure 6(a)), and subalkaline basalt, andesite, dacite/rhyodacite in the Zr/TiO$_2$–Nb/Y diagram (Figure 6(b)). On the K$_2$O–SiO$_2$ and FeO T–Na$_2$O+K$_2$O–MgO (AFM) diagrams, most samples plot in the high-K and medium-K calc-alkaline areas, and a minority plot in the tholeiite areas (Figures 6(c) and 6(d)). In the Harker diagrams, SiO$_2$ values correlate negatively with MgO, Al$_2$O$_3$, CaO, TiO$_2$, and Fe$_2$O$_3$ contents, with no clear correlations with Na$_2$O, P$_2$O$_5$, Sr, Ni, and Co contents (Figure 7). The basaltic rocks have moderate light rare earth element (LREE) enrichment with no Eu anomalies in the chondrite-normalized diagram (Figure 8(a)). On the N-MORB-normalized spider diagrams, the basaltic rocks show enrichment of large-ion lithophile elements (LILEs; e.g., Rb, Ba, Sr, and U) and depletion of high-field-strength elements (HFSEs; e.g., Nb and Ta) (Figure 8(b)). The andesites, dacites, and rhyolites have similar trace element patterns to the basaltic rocks which exhibit enriched LREEs and LILEs and depleted HREEs and HFSEs (Figures 8(c)–8(h)). Furthermore, the felsic rocks have a little more LREE fractionation and negative Eu anomaly (Figures 8(e)–8(h)).

The samples of the Liushugou Formation from the Qijiaojing section are composed mainly of basalts, trachybasalts, dacites, and rhyolites, forming as the bimodal volcanic rocks (Figure 6(a)). The basaltic rocks show moderate LREE enrichment with Nb depletion (Figures 8(a) and 8(b)). The dacites and rhyolites show LREE and LILE enrichment with Nb, Ta, and Ti depletion (Figures 8(e)–8(h)). The major and trace characteristics are similar to the Haxiongou section but have relatively higher REE contents (Figures 6–8).

The samples of the Qijiagou Formation from the Qijiaojing section have SiO$_2$ contents ranging from 47.31 to 70.15.
The bulk-rock initial $^{143}$Nd/$^{144}$Nd ($I_{\text{Nd}}$) and $\varepsilon_{\text{Nd}}(t)$ values were calculated based on the results of the zircon U–Pb ages (Figure 9), and the results are listed in Supplementary Table 4.

The basaltic rocks of the Liushugou Formation from the Haxionggou section have high $I_{\text{Nd}}$ (0.7048–0.7058) and positive $\varepsilon_{\text{Nd}}(t)$ values (from +6.7 to +7.6), and the felsic volcanic rocks have similar Sr–Nd isotopic characteristics to the basaltic rocks with $I_{\text{Nd}}$ values ranging from 0.7051 to 0.7059 and $\varepsilon_{\text{Nd}}(t)$ values from +3.0 to +8.0. The basaltic rocks of the Liushugou Formation from the Qijiaojing section have high $I_{\text{Nd}}$ (0.7038–0.7042) and positive $\varepsilon_{\text{Nd}}(t)$ values (+6.1 to +8.0), and the felsic volcanic rocks have similar Sr–Nd isotopic characteristics to the basaltic rocks with $I_{\text{Nd}}$ values ranging from 0.7032 to 0.7044 and $\varepsilon_{\text{Nd}}(t)$ values from +5.3 to +7.2.

5.4. Principal Component Analysis (PCA) of Geochemical Data. The major and trace elements of representative tectonic settings and the Carboniferous-Permian basaltic rocks from the BMs were all collected for PCA analysis (Figure 10). PC1 accounts for 41.8% of the variance and shows high positive loadings for Fe$_2$O$_3$, MgO, and TiO$_2$ and negative loadings for SiO$_2$ and Al$_2$O$_3$ when ten major elements are used as variables (Figures 10(a), 10(c), and 10(e)). PC2 (34.0% of variance) gives distinct positive loadings for Na$_2$O, P$_2$O$_5$, and K$_2$O and negative loadings for CaO. When the trace elements are used as variables, PC1 (49.2% of variance) has strong positive loadings for Rb, Sr, Ba, Nb, Ta, Zr, Hf, and LREEs compared to the negative loadings of V and Cu. PC2 (21.5% of variance) yields positive loadings for Sc, Pb, and HREEs and shows negative loadings for Cu, Co, Ni, Cr, and Zn (Figures 10(b), 10(d), and 10(f)).

Compared to the data of representative tectonic settings (collected from PetDB and GEOROC), the Carboniferous–Permian basaltic rocks from the BMs share some similar features with the Andean Arc, the Cascade Arc, the Lau Back-Arc Basin, the Izu Arc, and the Lesser Antilles Arc which were considered as continental arc, back-arc basin, and island arc in some aspects (Figure 10). But the Pennsylvanian basaltic rocks are rather complex and have composite
compositions (Figure 10). On the principal compositional biplot diagrams, the Mississippian basaltic rocks show the same characteristics as the arc-related basaltic rocks, which overlap with the Lau Back-Arc Basin, as well as with the Andean Arc, the Cascade Arc, and the Lesser Antilles Arc in large part (Figure 10). Although some of the

Figure 8: Chondrite-normalized REE patterns and N-MORB-normalized trace element spider diagrams for (a and b) basalts, (c and d) andesites, (e and f) dacites, and (g and h) rhyolites of the Pennsylvanian volcanic rocks in the Bogda Mountains. Chondrite and N-MORB values are after Sun and McDonough [82].
Pennsylvanian basaltic rocks from the BMs plot in the areas of the Andean Arc, the Cascade Arc, the Lau Back-Arc Basin, the Izu Arc, or the Lesser Antilles Arc, none of the tectonic settings overlap completely. All these features reveal that the Pennsylvanian basaltic rocks have a wide variety of magma types, and the geochemical features probably were mobilized from the original source or decoupled from the tectonic setting.

6. Discussions

6.1. Subaqueous Volcanism in a Progressively Deepening Basin. The Carboniferous strata are subdivided as the Mississippian Qiergusitao Group (C1qr) and the Pennsylvanian Liushugou (C2l) and Qijiagou (C2q) Formations. These formations mainly consist of sandstones, mudstones, limestones, bioclastic limestones, tuffs, basalts, and andesites intercalated with rhyolites. Also, they have different fossil assemblages developed in these rocks. The biological fossils include marine brachiopods, corals, gastropods, and crinoids, indicating a shallow marine depositional environment [40, 43, 51]. Moreover, the pillow lavas, limestones, and siliceous rocks, together with peperites, suggest that the volcanic and volcanioclastic rocks were the result of subaqueous volcanism (Figures 3 and 4; [41]). Besides, the Mississippian Qiergusitao Group is composed predominantly of shoreline sandstones and mudstones, with minor or no pillow lavas and peperites. Above the Qiergusitao Group, the pillow lavas and peperites began to appear in the Pennsylvanian Liushugou and Qijiagou Formations. Up to the upper part of the Qijiagou Formation, the clastic rock units show a conglomerate-sandstone-siltstone-siliceous mudstone sequence, with the characteristics of rhythmically bedded turbidite sequences [51]. Therefore, the Carboniferous succession in the BMs is deposited in a progressively deepening basin, from a shallow marine to a semideep marine environment.

6.2. Basaltic Rocks: High-K Calc-Alkaline with Arc-like Signature. To assess the influence of the postmagmatic alteration and crustal contamination before speculating as to their source is very important (e.g., [62, 63]). Basaltic rocks are a good indicator for their mantle source and petrogenesis (e.g., [64]). The studied basaltic rocks have relatively high LOI contents (2.58–8.22 wt.%), revealing that the effect of alteration cannot be ignored. PCA analysis suggests that Zr and Ti are some of the least mobile elements (e.g., [65]); MnO, Fe2O3T, and TiO2 are the immobile elements; and Na2O, K2O, and Al2O3 are the mobile elements (Figures 10(a), 10(c), and 10(e)). Likewise, REEs, Rb, Sr, Th, Nb, Ta, and Hf are immobile elements due to their positive correlations with Zr, while Ba, Cs, and V are mobile elements as they are inversely correlated to Zr in the PCA biplots (Figures 10(b), 10(d), and 10(f)). Thus, the mobile elements cannot be used for the study of petrogenesis. Still, the immobile elements (e.g., REEs, Zr, and Ti) can reflect their petrogenetic processes.

6.2.1. Undergone Minor or No Crustal Contamination. Crustal contamination generally causes a decrease in εNd(t), Nb/La ratios, and Nb/Th ratios but causes an increase in Istr because crustal materials have low εNd(t) and Nb values but have high Istr and Th contents (Rudnick and Fountain, 1995). All the studied volcanic rocks have relatively homogeneous Sr–Nd isotopic compositions, and their εNd(t) and Istr values do not vary with Mg#, SiO2, and Al2O3 (Figure 11), which are inconsistent with crustal contamination. Also, the constant Nb/La and Nb/Th ratios irrespective of SiO2 indicate insignificant crustal contamination.

6.2.2. Fractionation of Olivine and Clinopyroxene from Parental Magma. Although the genesis of the basaltic rocks is controlled mainly by the mantle component due to their low SiO2 (47.0–51.2 wt.%) contents and high Mg# (mostly
Figure 10: Principal compositional biplot for the Carboniferous volcanic rocks in the Bogda Mountains and representative tectonic setting around the world with major and trace elements as variables. The geochemical data of the Andean Arc, Cascade Arc, Lesser Antilles Arc, Hawaii, Izu Arc, East African Rift, and Lau Back-Arc Basin are collected from PetDB (http://www.earthchem.org/petdb) and GEOROC (http://georoc.mpch-mainz.gwdg.de/georoc/).
The lower Cr (21.3–661 ppm), Co (26.4–56.6 ppm), and Ni (5.1–178 ppm) contents related to primary mantle-derived magmas [66] indicate that their parental magma has experienced various degrees of fractional crystallization. The negative correlations between MgO, CaO, Al₂O₃, Fe₂O₃, and SiO₂, together with the positive correlation between Cr and Ni, are compatible with the fractionation of clinopyroxene and olivine (Figure 7). The basaltic rocks have positive Eu and Sr anomalies (Figure 8) and have no correlation between Na₂O, K₂O, and SiO₂ (Figure 7), suggesting...
Figure 12: Discrimination diagrams for the Carboniferous basaltic rocks of the Bogda Mountains with data of representative tectonic setting for comparison: (a) 3Tb–Th–2Ta (after [87]); (b) Hf/3–Th–Ta (after [88]); (c) Th/Yb–Nb/Yb (after [64]); (d) Zr/Y–Zr [63]; (e) (Hf/Sm)N–(Ta/La)N (after [62]); (f) Th/Ce–Sr/Th [89]. ICA: island arc calc-alkaline basalt; IAT: island arc tholeiites; PIAT: primitive island arc tholeiites; N-MORB: N-type middle ocean ridge basalt; E-MORB: E-type middle ocean ridge basalt; OIB: ocean island basalt; TH: tholeiitic series; TR: transitional series; ALK: alkaline series.
minor or no fractionation of plagioclase. There is no correlation between Dy/Yb and Mg further reflecting the little effect of amphibole fractionation ([67]; Supplemental Table 3).

6.2.3. Depleted Mantle Source Metasomatized by Slab-Derived Fluids and Sediment-Derived Melts. The basaltic rocks have positive $\epsilon_{\text{Nd}}(t)$ (3.0–8.1) and $\epsilon_{\text{Hf}}(t)$ (4.3–17.7) values with relatively lower $I_{\text{Sr}}$ values (0.703–0.707), suggesting that they were derived from an isotopically depleted mantle source (Figure 9). In the chondrite-normalized REE patterns and N-MORB-normalized trace element spider diagrams, these basaltic rocks show the geochemical affinity between oceanic island basalt (OIB) and enriched middle ocean ridge basalt (E-MORB) (Figure 8). Compared to OIB, their lower Nb/Ta, Nb/La, Ce/Pb, and Nb/Yb ratios also indicate that they are not originated from an OIB-like mantle plume but mostly had a MORB-like mantle source (Figures 12(a) and 12(b)). However, enrichment in LREEs and LILs and depletion in HREEs and HFSEs with negative Nb–Ta anomalies of the samples are indicative of arc-related magmatism and reflect a depleted mantle source previously hybridized by fluids or melts from a subducted slab [68]. On the Th/Yb–Nb/Yb diagram (Figure 12(c)), some of the basaltic rocks plotted above the MORB-OIB array, further suggesting the involvement of an arc-related component [64]. On the Zr/Y–Zr diagram, most basaltic rocks plot in an intraplate setting and a minority plot in an island arc setting, implying the influence of an arc-related component (Figure 12(d)). The depletion in Nb and Ta is attributed to their derivation from a mantle source modified by slab-derived fluids (Figure 12(e)) and sediment-derived melts (Figure 12(f)). These characteristics probably indicate that the magma is derived from a subduction-related fluid/melt-modified mantle source.

The basaltic rocks are characterized by flat chondrite-normalized HREE patterns (Figure 8(a)), indicating that they were derived from a spinel-garnet mantle. This can be further evaluated by REE contents and ratios (e.g., Sm/Yb and Sm; [69]). On the Sm/Yb–Sm diagram, the basaltic rocks from the Qijiaojing section plotted near the (garnet+spinel)-bearing lherzolite melting trend, indicating a spinel-garnet lherzolite mantle source with partial melting of 10%–25%, from a depth of about 60–80 km [70]. On the other hand, the basaltic rocks from the Haxionggou section have lower Sm/Yb ratios and plot below the garnet-spinel lherzolite (1 : 1) melting curve, implying a magma source in a transition zone between spinel lherzolite and garnet-spinel lherzolite (Figure 13). The degree of partial melting is about 15%–35%, from a depth of slightly about 60 km, which contains more spinel. Most basaltic rocks from the Qijiaojing section have higher Sm/Yb ratios than those from the Haxionggou section, suggesting that they are generated from the partial melting of relatively deep mantle sources with LREE-enriched mantle components (Figures 8(a) and 8(b)).
6.3. Felsic Volcanic Rocks: High-K Calc-Alkaline and Shoshonitic Rocks with Characteristics of A2-Type Granite.

The Pennsylvanian felsic volcanic rocks in the BMs included basaltic andesites, basaltic trachyandesites, andesites, trachyandesites, dacites, trachydacites, and rhyolites, constituting a successive magmatic evolution sequence (Figure 6(a)). The basaltic and felsic volcanic rocks share similar REE patterns and have identical Sr–Nd isotopic compositions (Figures 10 and 11), implying that they probably share a common mantle-derived parental magma. Chen et al. [46] and Xie et al. [71] have suggested that the felsic volcanic rocks are generated by coeval basaltic magma, but the modeling results using MELTS did not support the fractionation hypothesis [13]. Instead, the Carboniferous zircons from these felsic volcanic rocks have positive $\varepsilon_{\text{Hf}}(t)$ values (16HXG-12, 16HXG-13, and 16QJJ-15 have positive $\varepsilon_{\text{Hf}}(t)$ values concentrated in the range from +8.0 to +9.8, +13.1 to +15.6, and +10.8 to +13.2, respectively), young two-stage Hf model ages (major peaks < 800 Ma), and approximate $T_{DM1}$ and $T_{DM2}$ ages (Supplementary Table 2) suggesting that they are primarily derived from a juvenile continental crust. The published data also show that isotopes of the juvenile continental crust are almost indistinguishable from those of the depleted mantle source (Figure 5(e)). Therefore, the felsic volcanic rocks were probably generated by partial melting of the juvenile arc crust as suggested by Zhang et al. [13].

The Pennsylvanian felsic volcanic rocks in the BMs have high SiO$_2$ and K$_2$O content, belonging to the high-K calc-alkaline and shoshonitic series (Figure 6(c)). Most samples also exhibit high Zr, Rb, and Ga/Al, akin to A-type granites (Figure 14(a); [72]). These A-type-like felsic volcanic rocks can be classified into the A2 Group (Figure 14(b)), suggesting that their source has been through a cycle of continent-continent collision or island arc magmatism [73, 74]. On the tectonomagmatic discrimination diagram [75], the felsic
volcanic rocks were plotted within an area of overlap among the volcanic arc (VAG), ocean ridge (ORG), and within-plate (WPG) granite fields (Figure 14(c)). Besides, almost all samples are plotted in the postcollisional area on the Rb–Y+Nb diagram (Figure 14(d)).

6.4. Implication for a Pennsylvanian Postcollisional Rift Basin. The mantle plume [36], island arc [34, 35, 71], subduction-torn-type rift [48], and back-arc rift [13] models have been proposed to explain the Carboniferous-Permian tectonic setting of the BMs. In recent years, the Mississippian (ca. 345–330 Ma; [13, 46]), Pennsylvanian (ca. 315 Ma; [76]; this study), and Cisuralian (ca. 295 Ma; [2]) bimodal volcanic rocks were recognized in the Heishankou-Dashitou, Sepikou, and Qijiaojing regions, respectively. Bimodal volcanism commonly occurs in an extensional setting related to intraplate, postcollisional, or back-arc rifting tectonic regimes ([13] and references therein). Xia et al. [36] have proposed that Carboniferous-Permian volcanism is a large igneous province related to an intracontinental rift, whereas more and more researchers demonstrate that the mantle plume is not appropriate due to the different geochemical features, low magma temperature, and long erupted period [13, 22]. Instead, accumulating evidence suggests that the Mississippian volcanic rocks are formed in an arc-related setting (island arc or back-arc; [13] and references therein), and the Permian high-K calc-alkaline and alkaline rocks were related to the postcollisional setting [22]. The main controversy is concentrated on the Pennsylvanian period [34–36] due to their individual characteristics.

Firstly, the Pennsylvanian volcanic rocks of the BMs are composed of various types of high-alumina basaltic rocks, peperites, bimodal volcanic rocks, and A2-type rhyolites, almost all of which have arc-related signatures, such as Nb-Ta negative anomalies (Figure 8). Secondly, except for the basaltic rocks of the Liushugou Formation from the Haxiongou section which have the characteristics of island arc basalts, others plot in the areas of within-plate basalts or E-MORB (Figures 12(b)–12(d)). The felsic volcanic rocks are predominated by high-K calc-alkaline and shoshonitic rocks with characteristics of A2-type granite (Figures 14(a) and 14(b)), and most of them are plotted in complicated tectonic settings, including within-plate, volcanic arc, syncollisional, and ocean ridge settings (Figures 14(c) and 14(d)). Thirdly, petrogenesis analyses revealed that the Pennsylvanian basaltic rocks are mainly derived from a lithospheric mantle source metasomatized by slab-derived fluids and sediment-derived melts, so this naturally explains why these volcanic rocks have arc-like signatures. The zircons acquired from the Pennsylvanian felsic volcanic rocks have lower zircon saturation temperatures ($T_{Zr}$ is about 810°C) compared with those from the Mississippian felsic volcanic rocks ($T_{Zr}$ is about 960°C) [2, 13, 46, 71]. We agree with the viewpoint that the Mississippian volcanic rocks of the BMs have erupted in a back-arc basin [13, 41, 46]. However, the Pennsylvanian volcanic rocks of the BMs are rather composite and have three unique characteristics which we mentioned above. These three characteristics indicate that they were formed in an intraplate extensional setting and were affected by preceding subduction-related fluids. The collected evidences suggest that it is very challenging to explain these phenomena using the model of plate tectonics. Instead, the postcollisional setting is more suitable for deciphering their geodynamic background. This is consistent with the features of felsic volcanic rocks, which plot in the areas of postcollisional setting (Figures 14(c) and 14(d)). Therefore, we proposed that the Pennsylvanian volcanic rocks of the BMs are formed in a series of postcollisional rift basins (Figure 15), and the eastern BMs have smaller rifting which have a relatively thicker crust and lithospheric mantle (Figure 15).
The postcollisional setting can also be demonstrated by the 316 Ma Sikeshu stitching pluton [39], widespread 315–270 Ma A-type granitoid and mafic intrusions in the continental arc [77], Pennsylvaniaan-Permian molasse deposits ([78], Zhang et al., 2014), and 310 Ma intracontinental bimodal volcanic rocks [58]. The geodynamic mechanism is probably related to the large-scale rotation and displacement that occurred in the southwestern CAOB during the Pennsylvaniaan to the earliest Mesozoic [17, 79–81] or during local strike-slip faulting [41].

7. Conclusions

The Pennsylvaniaan volcanic rocks of the BMs have a composite composition deposited in a shallow to semideep marine environment with subaqueous volcanism and a progressively deepening process. Of these, the basaltic rocks are derived from the isotopically depleted mantle source (lithosphere mantle) hybridized by subduction-related fluids and sediment-derived melts. The felsic volcanic rocks are derived from the partial melting of the juvenile continental crust. The volcanic and volcano-sedimentary rocks were probably related to a series of postcollisional rift basins, and the eastern BMs were in a relatively shallower basin due to their smaller rifting.

Data Availability

All the raw data are listed in Supplementary Tables 1–4.

Conflicts of Interest

The authors declare no conflict of interest regarding this publication.

Acknowledgments

We are grateful to Zhaojie Guo, Qiugen Li, Yuming Qi, Jian Ma, Yi Zhu Wang, Jiaxuan Leng, Yue Jiao, Qingyun Li, and Qi Zhao for their assistance in the field and in indoor experiments. This study was financially supported by a National Science and Technology Major Project of China grant (2017ZX05008-001).

Supplementary Materials

Supplementary 1. Table 1: zircon LA-ICP-MS U–Pb dating data for the selected Pennsylvaniaan volcanic rocks of the Bogda Mountains.

Supplementary 2. Table 2: zircon Lu–Hf isotopic data for the selected Pennsylvaniaan volcanic rocks of the Bogda Mountains.

Supplementary 3. Table 3: bulk-rock major element (wt.% and trace element (×10⁶) contents for the selected Pennsylvaniaan volcanic rocks of the Bogda Mountains. Note: BA = basaltic andesite; BTA = basaltic trachyandesite; TB = trachybasalt; Fe₂O₃ represents the total amount of iron; δEu = 2EuN/(SmN + GdN); N is chondrite-normalized [82].

Supplementary 4. Table 4: bulk-rock Sr–Nd isotopic data for the selected Pennsylvaniaan volcanic rocks of the Bogda Mountains. Note: BA = basaltic andesite; BTA = basaltic trachyandesite; TB = trachybasalt.

References

[1] J. P. Liegeois, "Preface — Some words on the post-collisional magmatism," Lithos, vol. 45, pp. xv–xvii, 1998.
[2] X. J. Chen, L. S. Shu, and M. Santosh, "Late Paleozoic post-collisional magmatism in the Eastern Tianshan Belt, Northwest China: new insights from geochemistry, geochronology and petrology of bimodal volcanic rocks," Lithos, vol. 127, no. 3–4, pp. 581–598, 2011.
[3] B. Bonin, "Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal sources? A review," Lithos, vol. 78, no. 1-2, pp. 1–24, 2004.
[4] Z. F. Guo, M. Wilson, L. H. Zhang, M. Zhang, Z. Cheng, and J. Liu, "The role of subduction channel mélanges and convergent subduction systems in the petrogenesis of post-collisional K-rich mafic magmatism in NW Tibet," Lithos, vol. 198-199, pp. 184–201, 2014.
[5] B. A. Litvinovskiy, A. A. Tsygankov, B. M. Jahn, Y. Katzir, and Y. Be’eri-Shlevin, "Origin and evolution of overlapping calc-alkaline and alkaline magmas: the Late Palaeozoic post-collisional igneous province of Transbaikalia (Russia)," Lithos, vol. 125, no. 3–4, pp. 845–874, 2011.
[6] P. Wang, G. C. Zhao, Y. G. Han et al., "Post-collisional potassic rocks in Western Kunlun, NW Tibet Plateau: insights into lateral variations in the crust-mantle structure beneath the India–Asia collision zone," Lithos, vol. 370-371, article 105645, 2020.
[7] L. Q. Xia, X. M. Li, Z. P. Ma, X. Y. Xu, and Z. C. Xia, "Cenozoic volcanism and tectonic evolution of the Tibetan plateau,” Gondwana Research, vol. 19, no. 4, pp. 850–866, 2011.
[8] H. B. Zou, J. Vazquez, and Q. C. Fan, "Timescales of magmatic processes in post-collisional potassic lavas, northwestern Tibet," Lithos, vol. 358-359, article 105418, 2020.
[9] S. Li, S. A. Wilde, and T. Wang, "Early Permian post-collisional high-K granitoids from Liuyuan area in southern Beishan orogen, NW China: petrogenesis and tectonic implications," Lithos, vol. 179, pp. 99–119, 2013.
[10] S. Laurent-Charvet, J. Charvet, L. Shu, R. Ma, and H. Lu, "Palaeozoic late collisional strike-slip deformations in Tianshan and Altay, Eastern Xinjiang, NW China," Terra Nova, vol. 14, no. 4, pp. 249–256, 2002.
[11] I. Seghedi, L. Besutiu, V. Mirea et al., "Tectono-magmatic characteristics of post-collisional magmatism: case study East Carpathians, Călimani-Gurghiu-Harghita volcanic range," Physics of the Earth and Planetary Interiors, vol. 293, article 106270, 2019.
[12] R. Seltmann, D. Konopelko, G. Biske, F. Divaev, and S. Sergeev, "Hercynian post-collisional magmatism in the context of Palaeozoic magmatic evolution of the Tien Shan orogenic belt," Journal of Asian Earth Sciences, vol. 42, no. 5, pp. 821–838, 2011.
[13] Y. Y. Zhang, C. Yuan, X. P. Long et al., "Carboniferous bimodal volcanic rocks in the Eastern Tianshan, NW China: evidence for arc rifting,” Gondwana Research, vol. 43, pp. 92–106, 2017.
[14] S. Turner, N. Arnaud, J. Liu et al., "Post-collision, shoshonitic volcanism on the Tibetan plateau: implications for convective thinning of the lithosphere and the source of ocean island basalts," Journal of Petrology, vol. 37, no. 1, pp. 45–71, 1996.

[15] H. M. Williams, S. P. Turner, J. A. Pearce, S. P. Kelley, and N. B. W. Harris, "Nature of the source regions for post-collisional, potassic magmatism in southern and northern Tibet from geochemical variations and inverse trace element Modelling," Journal of Petrology, vol. 45, no. 3, pp. 555–607, 2004.

[16] B. F. Windley, D. Alexeev, W. Xiao, A. Kröner, and G. Badarch, "Tectonic models for accretion of the Central Asian Orogenic Belt," Journal of the Geological Society London, vol. 164, no. 1, pp. 31–47, 2007.

[17] Y. G. Han and G. C. Zhao, "Final amalgamation of the Tian Shan and Junggar orogenic collage in the southwestern Central Asian Orogenic Belt: constraints on the closure of the Paleo-Asian Ocean," Earth-Science Reviews, vol. 186, pp. 129–152, 2018.

[18] L. S. Shu, B. Wang, W. B. Zhu, Z. J. Guo, J. Charvet, and Y. Zhang, "Timing of initiation of extension in the Tian Shan, based on structural, geochemical and geochronological analyses of bimodal volcanism and olistostrome in the Bogda Shan (NW China)," International Journal of Earth Sciences, vol. 100, no. 7, pp. 1647–1663, 2011.

[19] G. Jun, L. Maosong, X. Xuchang, T. Yaoqing, and H. Huoqi, "Paleozoic tectonic evolution of the Tian Shan Orogen, northwestern China," Tectonophysics, vol. 287, no. 1–4, pp. 213–231, 1998.

[20] J. L. Wang, C. D. Wu, Z. Li et al., "Geochronology and geochemistry of volcanic rocks in the Arbasay Formation, Xinjiang Province (Northwest China): implications for the tectonic evolution of the North Tian Shan," International Geology Review, vol. 59, no. 10, pp. 1324–1343, 2017.

[21] J. L. Wang, C. D. Wu, X. Jiang et al., "Age assignment of the upper Carboniferous Arbasay Formation in Shichang Region, North Tianshan (NW China)," Journal of Palaeogeography-English, vol. 7, no. 1, pp. 272–282, 2018.

[22] J. He, Y. Zhang, Y. Wang, X. Qian, and L. Sun, "Late Paleozoic post-collisional setting of the North Tianshan, NW China: new insights from geochronology, geochemistry and Sr–Nd isotopic compositions of the Permian Nileke volcanic rocks," Lithos, vol. 318-319, pp. 314–325, 2018.

[23] J. L. Wang, C. D. Wu, Z. Li et al., "Whole-rock geochemistry and zircon Hf isotope of Late Carboniferous-Triassic sediments in the Bogda region, NW China: clues for provenance and tectonic setting," Geologic Journal, vol. 54, no. 4, pp. 1853–1877, 2019.

[24] Y. Y. Zhang, Z. J. Guo, G. Pe-Piper, and D. J. W. Piper, "Geochemistry and petrogenesis of Early Carboniferous volcanic rocks in East Junggar, North Xinjiang: implications for post-collisional magmatism and geodynamic process," Gondwana Research, vol. 28, no. 4, pp. 1466–1481, 2015.

[25] W. J. Xiao, C. M. Han, C. Yuan et al., "Middle Cambrian to Permian subduction-related accretionary orogenesis of Northern Xinjiang, NW China: implications for the tectonic evolution of central Asia," Journal of Asian Earth Sciences, vol. 32, no. 2–4, pp. 102–117, 2008.

[26] W. J. Xiao, B. F. Windley, M. B. Allen, and C. M. Han, "Paleozoic multiple accretionary and collisional tectonics of the Chinese Tian Shan orogenic collage," Gondwana Research, vol. 23, no. 4, pp. 1316–1341, 2013.

[27] P. P. Yu and Y. Zheng, "Pb-Zn-Cu accumulation from seafloor sedimentation to metamorphism: constraints from ore textures coupled with elemental and isotopic geochemistry of the Tiemuit in Chinese Altay Orogen, NW China," Gondwana Research, vol. 72, pp. 65–82, 2019.

[28] Y. Zheng, Y. J. Chen, P. A. Cawood et al., "Late Permian-Triassic metallogeny in the Chinese Altay Orogen: constraints from mica 40Ar/39Ar dating on ore deposits," Gondwana Research, vol. 43, pp. 4–16, 2017.

[29] Y. P. Su, J. P. Zheng, W. L. Griffin et al., "Geochemistry and geochronology of Carboniferous volcanic rocks in the eastern Junggar terrane, NW China: implication for a tectonic transition," Gondwana Research, vol. 22, no. 3–4, pp. 1009–1029, 2012.

[30] G. J. Tang, Q. Wang, D. A. Wyman et al., "Geochemistry and geochronology of Late Paleozoic magmatic rocks in the Lamasu-Dabate area, northwestern Tianshan (west China): evidence for a tectonic transition from arc to post-collisional setting," Lithos, vol. 119, no. 3–4, pp. 393–411, 2010.

[31] B. Wang, D. Cluzel, L. S. Shu et al., "Evolution of calc-alkaline to alkaline magmatism through Carboniferous convergence to Permian transient tectonics, western Chinese Tian Shan," International Journal of Earth Sciences, vol. 98, no. 6, pp. 1275–1298, 2009.

[32] J. Yu, N. Li, N. Qi, J. P. Guo, and Y. J. Chen, "Carboniferous-Permian tectonic transition envisaged in two magmatic episodes at the Kuruer Cu-Au deposit, Western Tianshan (NW China)," Journal of Asian Earth Sciences, vol. 153, pp. 395–411, 2018.

[33] X. R. Zhang, G. C. Zhao, P. R. Eizenhöfer et al., "Tectonic transition from Late Carboniferous subduction to Early Permian post-collisional extension in the Eastern Tianshan, NW China: insights from geochronology and geochemistry of mafic-intermediate intrusions," Lithos, vol. 256-257, pp. 269–281, 2016.

[34] W. Xie, Z. Y. Luo, Y. G. Xu et al., "Petrogenesis and geochemistry of the Late Carboniferous rear-arc (or back-arc) pillow basaltic lava in the Bogda Mountains, Chinese North Tian Shan," Lithos, vol. 244, pp. 30–42, 2016.

[35] W. Xie, Y. G. Xu, Y. B. Chen et al., "High-alumina basalts from the Bogda Mountains suggest an arc setting for Chinese Northern Tianshan during the Late Carboniferous," Lithos, vol. 256-257, pp. 165–181, 2016.

[36] L. Q. Xia, Z. C. Xia, X. Y. Xu, M. X. Li, and Z. P. Ma, "Relative contributions of crust and mantle to the generation of the Tianshan Carboniferous rift-related basic lavas, northwestern China," Journal of Asian Earth Sciences, vol. 31, no. 4-6, pp. 357–378, 2008.

[37] H. Y. Geng, M. Sun, C. Yuan et al., "Geochemical and geochronological Sr–Nd and zircon U–Pb–Hf isotopic studies of Late Carboniferous magmatism in the West Junggar, Xinjiang: implications for ridge subduction?", Chemical Geology, vol. 266, no. 3–4, pp. 364–389, 2009.

[38] J. Y. Yin, X. P. Long, C. Yuan, M. Sun, G. C. Zhao, and H. Y. Geng, "A Late Carboniferous–Early Permian slab window in the West Junggar of NW China: geochronological and geochemical evidence from mafic to intermediate dikes," Lithos, vol. 175-176, pp. 146–162, 2013.

[39] B. F. Han, Z. J. Guo, Z. C. Zhang, L. Zhang, J. F. Chen, and B. Song, "Age, geochemistry, and tectonic implications of a late Paleozoic stitching pluton in the North Tian Shan suture zone, western China," Geological Society of America Bulletin, vol. 122, no. 3–4, pp. 627–640, 2010.
[40] J. Wang, C. Wu, Z. Li et al., “The tectonic evolution of the Bogda region from Late Carboniferous to Triassic time: evidence from detrital zircon U–Pb geochronology and sandstone petrography,” Geological Magazine, vol. 155, no. 5, pp. 1063–1088, 2018.

[41] M. Memtimin, Y. Y. Zhang, H. Furnes, G. Pe-Piper, D. J. W. Piper, and Z. J. Guo, “Facies architecture of a subaqueous volcano-sedimentary succession on Bogda Mountains. NW China—evidence of extension in Late Carboniferous,” Geological Journal, vol. 55, no. 4, pp. 3097–3111, 2020.

[42] J. L. Wang, C. D. Wu, T. Q. Zhou, W. Zhu, X. Y. Li, and T. Zhang, “Source and sink evolution of a Permian-Triassic rift-drift basin in the southern Central Asian Orogenic Belt: perspectives on sedimentary geochemistry and heavy mineral analysis,” Journal of Asian Earth Sciences, vol. 181, article 103965, 2019.

[43] BGMRXUAR (Bureau of Geology and Mineral Resources of Xinjiang Uyug Autonomous Region), Regional Geology of Xinjiang Uyug Autonomous Region, Geological Publishing House, Beijing, 1993.

[44] A. M. Ç. Şengör, B. A. Natal’ín, and U. S. Burtman, “Evolution of the Altdai tectonic collage and Palaeozoic crustal growth in Eurasia,” Nature, vol. 364, no. 6435, pp. 299–307, 1993.

[45] M. B. Allen, A. M. C. Şengör, and B. A. Natal’ín, “Junggar, Turfan and Alakol basins as Late Permian to Early Triassic extensional structures in a sinistral shear zone in the Altdai orogenic collage, Central Asia,” Journal of the Geological Society, vol. 152, no. 2, pp. 327–338, 1995.

[46] X. J. Chen, L. S. Shu, M. Santosh, and X. X. Zhao, “Island arc-type bimodal magmatism in the Eastern Tianshan Belt, North-west China: geochemistry, zircon U–Pb geochronology and implications for the Palaeozoic crustal evolution in Central Asia,” Lithos, vol. 168-169, pp. 48–66, 2013.

[47] L. X. Gu, S. X. Hu, C. S. Yu, H. Y. Li, X. J. Xiao, and Z. F. Yan, “Carboniferous volcanites in the Bogda orogenic belt of eastern Tianshan: their tectonic implications,” Acta Petrologica Sinica, vol. 16, no. 3, pp. 305–316, 2000.

[48] L. X. Gu, S. X. Hu, C. S. Yu, M. Zhao, C. Z. Wu, and H. Y. Li, “Intrusive activities during compression-extension tectonic conversion in the Bogda intracontinental orogen,” Acta Petrologica Sinica, vol. 17, no. 2, pp. 187–198, 2001.

[49] A. R. Carroll, S. A. Graham, M. S. Hendrix, D. Ying, and D. Zhou, “Late Paleochoic tectonic amalgamation of northwestern China: sedimentary record of the northern Tarim, northwestern Turfan, and southern Junggar basins,” Geological Society of America Bulletin, vol. 107, no. 5, pp. 571–594, 1995.

[50] J. Charrueau, C. Gumiaux, J. P. Avouac et al., “The Neogene Xiyu Formation, a diachronous prograding gravel wedge at front of the Tianshan: climatic and tectonic implications,” Earth and Planetary Science Letters, vol. 287, no. 3–4, pp. 298–310, 2009.

[51] J. L. Wang, C. D. Wu, W. Zhu et al., “Tectonic-depositional environment and prototype basin evolution of the Permian-Triassic in the southern Junggar Basin,” Journal of Palaeogeography, vol. 18, no. 4, pp. 643–660, 2016.

[52] Y. X. Wang, L. X. Gu, Z. Z. Zhang et al., “Geochronology and Nd–Sr–Pb isotopes of the bimodal volcanic rocks of the Bogda rift,” Acta Petrologica Sinica, vol. 22, no. 5, pp. 1215–1224, 2006.

[53] H. L. Yuan, S. Gao, X. M. Liu, H. M. Li, D. Günther, and F. Z. Wu, “Accurate U–Pb age and trace element determinations of zircon by laser ablation-inductively coupled plasma-mass spectrometry,” Geostandards and Geoanalytical Research, vol. 28, no. 3, pp. 353–370, 2004.

[54] S. E. Jackson, N. J. Pearson, W. L. Griffin, and E. A. Belousova, “The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology,” Chemical Geology, vol. 211, no. 1–2, pp. 47–69, 2004.

[55] T. Andersen, “Correction of common lead in U–Pb analyses that do not report 206Pb,” Chemical Geology, vol. 192, no. 1–2, pp. 59–79, 2002.

[56] K. R. Ludwig, ISOPLOT 3: A Geochronological Toolkit for Microsoft Excel, Berkeley Geochronology Centre Special Publication, 2003.

[57] K. J. Hou, Y. H. Li, T. R. Zou, X. M. Qu, Y. R. Shi, and G. Q. Xie, “LA-MC-ICP-MS zircon Hf isotope analysis method and its geological application,” Acta Petrologica Sinica, vol. 23, no. 5, pp. 2595–2604, 2007.

[58] F. Liu, J. S. Yang, T. F. Li et al., “Geochemical characteristics of Late Carboniferous volcanic rocks in northern Tianshan, Xinjiang, and their geological significance,” Geology in China, vol. 38, no. 4, pp. 868–889, 2011.

[59] R. Heiny, D. A. T. Harper, and P. D. Ryan, “PAST: paleontological statistics software package for education and data analysis,” Palaeoelectronica, vol. 4, no. 1, pp. 1–9, 2001.

[60] I. T. Jolliffe, Principal Component Analysis, Springer-Verlag, New York, 1986.

[61] F. Corfu, J. M. Hanchar, P. W. O. Hoskin, and P. Kinny, “Atlas of zircon textures,” Reviews in Mineralogy and Geochemistry, vol. 53, no. 1, pp. 469–500, 2003.

[62] M. R. La Flèche, G. Camiré, and G. A. Jenner, “Geochemistry of post-Acadian, Carboniferous continental intraplate basalts from the Maritimes Basin, Magdalen islands, Québec, Canada,” Chemical Geology, vol. 148, no. 3–4, pp. 115–136, 1998.

[63] J. A. Pearce and M. J. Norry, “Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks,” Contributions to Mineralogy and Petrology, vol. 69, no. 1, pp. 33–47, 1979.

[64] J. A. Pearce, “Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust,” Lithos, vol. 100, no. 1–4, pp. 14–48, 2008.

[65] J. A. Pearce and F. W. Peate, “Tectonic implications of the composition of volcanic arc magmas,” Annual Review of Earth and Planetary Sciences, vol. 23, no. 1, pp. 251–285, 1995.

[66] F. A. Frey, D. H. Green, and S. D. Roy, “Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilitites from South Eastern Australia utilizing geochemical and experimental petrological data,” Journal of Petrology, vol. 19, no. 3, pp. 463–513, 1978.

[67] J. M. Garrison and J. P. Davidson, “Dubious case for slab melting in the Northern volcanic zone of the Andes,” Geology, vol. 31, no. 6, pp. 565–568, 2003.

[68] J. A. Pearce, J. R. Stern, S. H. Bloomer, and P. Fryer, “Geochemical mapping of the Mariana arc-basin system: implications for the nature and distribution of subduction components,” Geochimica, Geophysics, Geosystems, vol. 6, no. 7, article Q07006, 2005.

[69] D. McKenzie and R. K. O’Nions, “Partial melt Distributions from inversion of rare earth element concentrations,” Journal of Petrology, vol. 32, no. 5, pp. 1021–1091, 1991.

[70] D. McKenzie and M. J. Bickle, “The volume and composition of melt generated by extension of the lithosphere,” Journal of Petrology, vol. 29, no. 3, pp. 625–679, 1988.
M. J. L. Bas, R. W. L. Maitre, A. Streckeisen, B. Zanettin, and S. S. Sun and W. F. McDonough, "Igneous Rocks: A Classification and Glossary of Terms. Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks," Cambridge University Press, Cambridge, 2nd edition, 2002.

J. A. Winchester and P. A. Floyd, "Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks," Earth and Planetary Science Letters, vol. 28, no. 3, pp. 459–469, 1976.

T. N. Irvine and W. R. A. Baragar, "A guide to the chemical classification of the common volcanic rocks," Canadian Journal of Earth Sciences, vol. 8, no. 5, pp. 523–548, 1971.

P. B. Cabanis and D. Thieblemont, "La discrimination des tholeiites continentales et des basaltes arriere-arc; proposition d’un nouveau diagramme, le triangle Th-3xTb-2xTa," Bulletin de la Société Géologique de France, vol. IV, no. 6, pp. 927–935, 1988.

D. A. Wood, "The application of a Th–Hf–Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province," Earth and Planetary Science Letters, vol. 50, no. 1, pp. 11–30, 1980.

Y. F. Zhu, L. F. Zhang, L. Gu, X. Guo, and J. Zhou, "The zircon SHRIMP chronology and trace element geochemistry of the Carboniferous volcanic rocks in western Tianshan Mountains," Chinese Science Bulletin, vol. 50, no. 19, pp. 2201–2212, 2005.

D. M. Shaw, "Trace element fractionation during anatexis," Geochimica et Cosmochimica Acta, vol. 34, no. 2, pp. 237–243, 1970.

E. Aldanmaz, J. A. Pearce, M. F. Thirwall, and J. G. Mitchell, "Petrogenetic evolution of late Cenozoic, post-collision volcanism in western Anatolia, Turkey," Journal of Volcanology and Geothermal Research, vol. 102, no. 1–2, pp. 67–95, 2000.

J. A. Pearce, "Sources and settings of granitic rocks," Episodes, vol. 19, no. 4, pp. 120–125, 1996.