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Early Devonian Arc-Related Volcanic Rocks in the Haerdaban, North Margin of the Yili Block: Constraint on the Southward Subduction of the Junggar Ocean

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Abstract: The origin and tectonic implication of Early–Middle Devonian magmatism in the northern margin of YB (Yili Block) remain enigmatic and are important for understanding Late Paleozoic evolution of the Junggar Ocean and southern Kazakhstan Orocline. Here, we present the systematic study of whole-rock geochemical and Sr–Nd isotope features as well as U–Pb–Hf isotope characteristics of zircon crystals for newly identified Early Devonian volcanic rocks from the northern margin of YB. The volcanic rocks are composed of rhyolite, rhyolite porphyry, and rhyolitic tuff. Zircon U–Pb age dating indicates they were formed at ca. 407–418 Ma. They have high SiO₂ (70.16–77.52 wt.%) and alkali (5.10–9.56 wt.%) contents, and high Zr + Nb + Ce + Y content (~456 ppm), indicative of A-type magma. Their relative depletion of Nb, Ta, and Ti, and enrichment of LILEs show arc affinity. Their low initial ⁸⁷Sr/⁸⁶Sr ratios (0.699708–0.709822) and negative ε_{Nd}(t) values (−1.8 to −4.0) indicate a mainly continental magma source and their positive ε_{Hf}(t) values (+6.13 to +14.81) are possibly due to the garnet effect. All these above reveal that volcanic rocks were generated by re-melting of lower crust under a high temperature condition, which was induced by long-lived heat accumulation with no or minimal basalt flux. Combined with active continental margin inference evidenced by contemporaneous sedimentary rocks, we attribute the generation of the volcanic rocks to a continental arc setting related to the southward subduction of Junggar oceanic crust. Thus, we infer the Early–Middle Devonian arc-related magmatic rocks in the northern margin of YB are eastward counterparts of the southern limb of the Devonian Volcanic Belt, which resulted from a relatively steady-state southward subduction.

Keywords: Central Asian Orogenic Belt; northern margin of Yili Block; the Early Devonian; volcanic rocks; subduction

1. Introduction

The Kazakhstan Orocline is one of the major oroclines in the Central Asian Orogenic Belt (CAOB), which was formed by the bending of the originally linear Kazakhstan composite arc in the Carboniferous to Early Permian and further tightened to form the present orocline in the Late Permian to Early Triassic [1]. It contains a collage of Precambrian continental fragments and several Paleozoic island arcs [2,3]. The major Cambrian and Early Ordovician arc systems distribute along the northern limb [3], and the Late Paleozoic

arc systems along the southern limb, which is characterized by the occurrences of Early or Middle to Late Ordovician arc-related rocks in the Chinese West Tianshan [4–6]. The Late Paleozoic arc systems were built on the margin of the Kazakhstan microcontinent, and mainly contain the Balkhash–Yili arc (BY) and Devonian Volcanic Belt (DVB). The BY is mainly composed of Late Devonian to Carboniferous volcanic rocks and its southeastern part extends to the Yili Block (YB) [1]. The DVB, a Japanese-type volcanic arc, is mainly composed of Early to Middle Devonian plutonic and volcanic rocks [7,8] and the eastward extension of its southeastern part is still unclear. Additionally, the geodynamic mechanism for the formation of the Late Paleozoic arc magmatism is unclear, especially whether it has a continuous subduction of the Junggar–Balkhash Ocean with trench retreating [9] or not [10,11]. Bodies of Middle Ordovician to Carboniferous magmatites outcrop in the north margin of the YB, which was attributed to the southward subduction of the Junggar (or North Tianshan) oceanic crust beneath the YB [4,9,11–16]. The Middle to Late Ordovician [4,5,17,18] and the Middle to Late Devonian [11,13,19,20] arc-type magmatism were both reported in the northern margin of YB. However, during the Caledonian and Hercynian orogenic periods, whether a magmatic gap occurred in the Late Silurian–Early Devonian or not is little known and their origin and tectonic implication are unclear in the northern margin of YB. The petrologic features of the sedimentary sequence shows that the northern margin of the YB was an active continental margin during roughly the whole Paleozoic, although the tectonic regime changed in the Paleozoic [21], while other authors consider that there was a collision orogenic events in the Silurian or early Devonian periods [22]. Furthermore, this tectonic setting, i.e., an active continental margin, probably still existed in the Late Silurian, evidenced by coeval sedimentary rocks deposited in the back-arc basin showing low-maturity source area with weak weathering degree and near-source rapid accumulation [23]. However, the status in the Early Devonian is puzzled due to the absence of Early Devonian strata in the northern margin of YB. Thus, the contemporaneous magmatite of the northern margin of YB is key to understanding the tectonic setting during that time.

Here, we report newly identified Early Devonian rhyolitic rocks in the Haerdaban area, northern margin of the YB. We obtained whole-rock major and trace element and Sr–Nd isotopic compositions, as well as zircon U–Pb age and Hf isotopic compositions of Early Devonian volcanic rocks. This new dataset enables us to examine the exact age, origin and tectonic setting of the volcanic rocks. Our results indicate that a continuous arc-related magmatism occurred in the early Devonian and thus we argue that there is a late Silurian–early Devonian magmatic gap in the northern margin of the YB.

2. Geological Setting and Petrographic Characteristics

The CAOBS is one of the largest and best-preserved Phanerozoic accretionary orogenic belts, and it is separated by the Siberian Craton to the north, Tarim–North China Craton to the south, and the Baltic Craton to the west (Figure 1a). It was formed by the accretion and amalgamation of microcontinents, magmatic arcs, accretionary complexes, seamount and oceanic plateaus, and ophiolitic mélanges during the period from the Neoproterozoic to the Late Permian [1,2,10,24–26]. The Chinese Tianshan is located in the southwest part of the CAOBS and extends from east to west for about 1500 km and is bordered by the Tarim Craton in the south and the Junggar Terrane in the north. It can be subdivided into four parts, namely, the North Tianshan Accretionary Complex (NTAC), Kazakhstan–Yili Block (KYB), Central Tianshan Block (CTB), and South Tianshan Accretionary Complex (STAC), which are separated by the North Tianshan Suture, North Nalati Suture, and South Central Tianshan Suture, respectively (Figure 1b). The NTAC is mainly composed of the Devonian–Carboniferous turbidites and the ophiolite component, which was formed by the southward subduction of the North Tianshan Ocean in the Late Paleozoic [19,27–29]. The STAC was formed by the northward subduction of the South Tianshan Ocean in the Paleozoic and it mainly composed of lower Cambrian to Carboniferous sedimentary rocks,

ophiolites and metamorphic rocks [28,30,31]. KYB and CTB are two major microcontinents with Precambrian metamorphic basements in the westernmost of the Chinese Tianshan.

Figure 1. (a) Simplified map of the Central Asia Orogenic Belt and the location of the Tianshan orogen (modified after [32]). (b) Simplified geological map of the Chinese Tianshan belt (modified after [33]). (c) Geological map of the Biezhen Tao Mountain area and location of the study area (modified after [34–36]).

The YB, an important Precambrian continental fragment in the southern limb of the Kazakhstan collage system, is a triangular area that extends westward into Kazakhstan, and it is bordered by the North Tianshan Suture to the north and North Nalati Suture to the south (Figure 1b). The Precambrian rocks are mainly exposed in the north and south margin of YB, and unconformably overlain by the Paleozoic sedimentary and volcanic rocks, which are intruded by the voluminous Ordovician–Permian granitoids [11,28,31,34,35,37,38]. The Precambrian rocks mainly outcrop in its northern and southern margins discontinuously, for example, the amphibolite, migmatite, quartzite, marble, and various schist in the Wenquan and Sayram areas [34]. The Cambrian–Silurian rocks consist mainly of cherts, siltstones, carbonates, felsic pyroclastic rocks, and normal clastic sedimentary rocks, and outcrop mainly in the Boluokenu Mountain and the sedimentary sequences are complete, although the exposed area of Cambrian–Ordovician strata is limited. Late Paleozoic to Mesozoic strata have wide distribution in the YB and is characterized by sandstone, siltstone, and shale interbedded with volcanic rocks [35]. As mentioned above, volumes of Paleozoic magmatic rocks including both volcanic and intrusive rocks distribute along the north margin of YB, but the Late Silurian to Early Devonian magmatism is poorly reported.

The study area is located in southern region of the Boertala River, Wenquan County. The Proterozoic strata are widely distributed along the Biezhen Tao Mountain, and the Neoproterozoic gneissic granites were recognized in the Wenquan Complex (Figure 1c). The Precambrian strata are overlain unconformably by the Paleozoic rocks and they are intruded by the Paleozoic plutons. As shown in the geological map of Baskan Pass–Huocheng Sheet, the Late Paleozoic strata distribute in the Haerdaban area and mainly comprise sandstone, conglomerate, and limestone, which was originally divided into Upper Devonian and Low Carboniferous [34]. Recently, our investigation found that volcanic rocks can be recognized in the Agutu area (Figure 2a) and Buergasite area (Figure 2b), which includes rhyolite, rhyolite porphyry, and rhyolitic tuffs. The outcrops

of volcanic rock are mostly domed and a few are intercalated (Figure 3a). The lava and clasolite are mostly in gradual contact and it is difficult to draw a boundary.

Figure 2. Detailed geological map of Early Devonian volcanic rocks in Agutu area (a) and Buergasite area (b) with sampling locations.

Figure 3. Field and microscopic photographs of the Early Devonian volcanic rocks. (a) Overview of the Early Devonian volcanic outcrop. (b) Fluidal structures in rhyolite samples. (c) Rhyolitic tuffs with rhyolitic gravel. (d) The mylonite structure in rhyolitic tuffs. (e,f) Microscope photographs of rhyolite and rhyolitic tuffs, respectively. Q: quartz, Pl: plagioclase.

Fifteen samples of volcanic rocks from two areas were collected, including rhyolite, rhyolite porphyry, and rhyolitic tuffs (Figure 3a,b). Rhyolite samples are gray to dark gray, porphyritic, and have typical flow structures (Figure 3b). The phenocrysts (~15%) are mainly composed of quartz and K-feldspar and range in size from 0.2 to 1.5 mm (Figure 3e). The groundmass is mainly composed of aphanitic feldspar and quartz, and

minor amounts of biotite and sericite (Figure 3f). The rhyolitic tuffs samples are gray to tawny and contain ~45% volcanic ash, ~35% rhyolite detritus, and ~25% crystal fragments (Figure 3c,d,f). Sometimes, the augen or mylonite structure develops in the volcanic rocks after the experience of later deformation (Figure 3d).

3. Analytical Methods

The detailed analytical methods involved in this study including zircon U–Pb dating, whole-rock major and trace element analyses, zircon Lu–Hf, and Sr–Nd isotopes analyses.

3.1. Zircon U–Pb and Hf Isotope Analyses

Zircon crystals were selected from rhyolitic samples and embedded in epoxy resin, and then polished down to expose the interior of the crystals. Cathodoluminescence (CL) images were taken and used to demonstrate the internal texture of the zircons and to select optimum spot locations during the laser-ablation inductively coupled plasma mass spectrometry (LA–ICP–MS). Zircon U–Pb isotopic data were collected from 32 µm diameter regions of single grains by use of ICP–MS (Agilent 7700) and a laser-ablation system at the Key Laboratory for the Study of Focused Magmatism and Giant Ore Deposits, MNR, Xi'an. The adopted laser-ablation system is a GeoLas 200M equipped with a 193 nm laser. Harvard zircon 91,500 was used as the external standard for isotopic fractionation, NIST SRM610 glass was used as the external calibration standard, and ^{29}Si was used as the internal standard for the elemental analyses. Isotopic ratios and element concentrations for zircons were calculated with the software Glitter 4.0 (Macquarie University). The ages were calculated with the program Isoplot (ver. 2.94), an add-in for Microsoft Excel [39]. The detailed analytical procedures for age and trace element determinations of zircons were similar to those described in the references [40].

Zircon Hf isotope compositions were examined simultaneously from the same spot. The 193 nm laser ablation system attached to a Neptune Plasma Multicollector–ICP–MS at the same laboratory. The analysis was undertaken under a laser repetition rate of 10 Hz at 200 mJ and an ablated spot size of 60 µm. The measured $^{176}\text{Lu}/^{177}\text{Hf}$ ratios and the ^{176}Lu decay constant of $1.867 \times 10^{-11} \text{ yr}^{-1}$ were used to calculate initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios [41]. The present-day $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ values were used to calculate the depleted mantle model age (T_{DM}) [42]. The chondritic values of $^{176}\text{Hf}/^{177}\text{Hf} = 0.0332$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.282772$ were used for the calculation of ϵ_{Hf} values [43]. The detailed analytical procedures were described by reference [44].

3.2. Whole-Rock Major and Trace Element Analyses

Samples were analyzed for whole-rock chemical composition at the Key Laboratory for the Study of Focused Magmatism and Giant Ore Deposits, MNR, Xi'an. The major elements were analyzed by wet chemical techniques and X-ray fluorescence spectroscopy (XRF-1500). The analytic precision of major elements ranged from 1% to 5%. Trace and rare earth elements (REEs) were determined by ICP–MS (Element II) and the analytic precision was generally better than 5%.

3.3. Whole-Rock Sr and Nd Isotopes Analyses

The Rb–Sr and Sm–Nd isotopic analysis followed procedures similar to those described by reference [45]. Whole-rock powders for Sr and Nd isotopic analyses were dissolved in Savillex Teflon screw-top capsule after being spiked with the mixed ^{87}Rb – ^{84}Sr and ^{149}Sm – ^{150}Nd tracers prior to $\text{HF} + \text{HNO}_3 + \text{HClO}_4$ dissolution. Rb, Sr, Sm, and Nd were separated by use of the classical two-step ion exchange chromatographic method and the isotopic compositions were obtained using a Thermo Fisher Scientific Triton Plus multi-collector thermal ionization mass spectrometer at IGGCAS (State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China). The whole procedure blank was lower than 250 pg for Rb–Sr and 100 pg for Sm–Nd. The isotopic ratios were corrected for mass fractionation by

normalizing to $^{88}\text{Sr}/^{86}\text{Sr} = 8.375209$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. The international standard samples, NBS-987 and JNdi-1, were employed to evaluate instrument stability during the period of data collection. The measured values for the NBS-987 Sr standard and JNdi-1 Nd standard were $^{87}\text{Sr}/^{86}\text{Sr} = 0.710264 \pm 0.000012$ ($n = 4$, 2SD) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512114 \pm 0.000009$ ($n = 3$, 2SD), respectively. USGS reference material BCR-2 was measured to monitor the accuracy of the analytical procedures, with the following results: $^{87}\text{Sr}/^{86}\text{Sr} = 0.705022 \pm 0.000011$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512632 \pm 0.000010$. The $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ data of BCR-2 show good agreement with previously published data by TIMS technique [45].

4. Results

The analytical results are listed in the Supplementary Tables S1–S4, respectively.

4.1. Zircon U-Pb Dating and Hf Isotopic Composition

The sampling locations for U-Pb and Hf isotope analyses are shown in Figure 2. The U-Pb isotopic data samples include rhyolite (PM9-19-TW1 and ZJ-TW1) and rhyolite porphyry (D4189-TW1 and PM 17-16-TW1). Additionally, Lu–Hf isotopic compositions of zircons from three samples (ZJ-TW1, D4189-TW1, and PM17-16-TW1). The results are shown in the Figures 4 and 5a and listed in the Supplementary Tables S1 and S2.

The zircon grains from the sample PM9-19-TW1 are generally hypidiomorphic prismatic crystals that are 80–130 μm long with aspect ratios of 1:1–2:1. They are typically transparent, colorless to gray, and show magmatic oscillatory zoning in CL images (Figure 4a) with Th/U ratios of 0.40–0.71. Analysis of nineteen grains yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 408 Ma to 437 Ma, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 418.7 ± 4.6 Ma (MSWD = 1.7, Figure 4e).

Zircon grains from the sample ZJ-TW1 are 60–150 μm long and 40–80 μm wide, with length/width ratios of 1:1 to 3:1. In CL images (Figure 4b), these zircon grains show obvious oscillatory zoning with high Th/U ratios (0.29 to 0.79) indicating a magmatic origin. Seventeen grains yielded concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 436 Ma to 389 Ma, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 414.1 ± 6.9 Ma (MSWD = 2.3, Figure 4f). One inherited zircon grain yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1465 Ma. They have $^{176}\text{Hf}/^{177}\text{Hf}$ ranging from 0.282758 to 0.282950, and high ϵ_{Hf} (t) (from +8.69 to +14.53) value, as well as the calculated two-stage Hf model ages (T_{DM^2}) ranging from 469 to 865 Ma.

Zircon grains from the sample D4189-TW1 have sizes of 80–130 μm and aspect ratios between 2:1 and 1:1. The grains are primarily euhedral in shape and display oscillatory zoning in CL images (Figure 4c). Nineteen spots were analyzed on zircon grains. These data points yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 406.5 ± 6.1 Ma (MSWD = 1.7, Figure 4g), with high Th/U ratios of 0.39–0.75, representing a magmatic origin. They yield high $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (ranging from 0.282710 to 0.282942), and high ϵ_{Hf} (t) value (from +6.61 to +14.81), with the two-stage Hf model ages ranging from 467 to 982 Ma.

Zircon grains from the sample PM17-16-TW1 are colorless, transparent, or translucent grains. Their lengths are mostly in the range 70–120 μm with aspect ratios of 1:1–2:1. The grains are euhedral prismatic crystals with a zoning structure indicative of magmatic origin (Figure 4d). Sixteen spots have concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of 421–388 Ma with high Th/U ratios (0.42–0.76) and clear oscillatory zoning, confirming their magmatic origin. The weighted mean age of 408.3 ± 5.8 Ma (MSWD = 3.3, Figure 4h) are interpreted as the crystallization age of the rhyolite porphyry. They yield high $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (ranging from 0.282692 to 0.282911), and high ϵ_{Hf} (t) value (from +6.13 to +12.99) with Hf model ages ranging from 554 to 1015 Ma.

Figure 4. Photomicrographs (a–d) of representative zircon grains analyzed for U–Pb ages and Hf isotopes, and Zircon U–Pb concordant diagrams (e–h) for the volcanic rocks in the Haerdaban area. The white or blue circles indicate the analytical spots for U–Pb isotopes and yellow circles denote the analytical spots for Hf isotopes. (a,e): the sample PM9-19-TW1; (b,f): the sample ZJ-TW1; (c,g): the sample D4189-TW1(d,f): the sample PM17-16-TW1

Figure 5. (a) In situ zircon $\epsilon_{\text{Hf}}(t)$ values versus U–Pb ages and (b) whole-rock $\epsilon_{\text{Nd}}(t)$ values versus initial $^{87}\text{Sr}/^{86}\text{Sr}$ diagrams for the volcanic rocks in the Haerdaban area (previous data are collected from [11] and its references).

4.2. Whole-Rock Geochemical Composition

Fifteen samples of volcanic rocks, including thirteen rhyolite and rhyolite porphyry samples and two rhyolitic tuff samples from the Haerdaban area, were selected to analyze the whole-rock major and trace elemental compositions. Results are listed in Supplementary Table S3. All samples have similar chemical composition and are characterized by high SiO_2 (70.16 to 77.52 wt.%), high K_2O (2.13 to 6.44 wt.%), Al_2O_3 (11.27 to 16.36 wt.%), and low MgO (0.10 to 0.22 wt.%), TiO_2 (0.13 to 0.38 wt.%), and FeO^T (1.38 to 3.79 wt.%). The samples are subalkaline affinity and mainly plot in the field of rhyolite in the TAS diagram (Figure 6a), as well as the result in the diagram of Nb/Y versus Zr/TiO_2 (Figure 6b). They have relatively high K_2O and $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ consistent with high-K calc-alkalic series (Figure 6c). The rocks are metaluminous to peraluminous with A/CNK values of 0.94 to 2.53, similar to the peraluminous granite (Figure 6d).

Figure 6. Geochemical diagrams for the Early Devonian volcanic rocks from Haerdaban area in the northern margin of Yili Block. (a) Total alkalis versus SiO_2 diagram (reference line after [46]). (b) Zr/TiO_2 versus Nb/Y diagram (reference lines after [47]). (c) $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ versus SiO_2 diagram (reference lines and fields after [48]). (d) Plot of A/NK versus A/CNK (reference lines and fields after [49]).

They have high total rare earth element (REE) concentrations of 146–482 ppm. The total light rare earth element (LREE) content is between 128 and 395 ppm, and the total heavy rare earth element (HREE) content is 18.28 to 86.93 ppm with LREE/HREE ratios varying from 4.55 to 8.78. They show chondrite-normalized REE patterns enriched in LREE with $(\text{La}/\text{Yb})_N$ of 4.38 to 11.35 and medium negative Eu anomalies with δEu values of 0.26 to 0.66 (Figure 7a). The samples have low Sr contents with a range from 41.2 to 120 ppm. On the primitive mantle-normalized spider diagram (Figure 7b), the rocks are rich in large ion lithophile elements (LILE) relative to high field strength elements (HFSE). The samples exhibit Rb, Th, U, Zr, and Hf enrichments, Ba, Sr, P, Ti, Nb, and Ta depletions, and arc-likely magma characteristics.

Figure 7. (a) Chondrite-normalized REE patterns and (b) primitive mantle-normalized trace element patterns of the Early Devonian volcanic rocks from Haerdaban area in the northern margin of Yili Block. Normalizing values are from [50]. Values of the upper continental crust (UCC) and lower continental crust (LCC) are from [51].

Six rhyolite/rhyolite porphyry samples were selected to analyze the whole-rock Sr and Nd isotopic compositions. The results are listed in the Supplementary Table S4. The samples have relatively low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.699708 to 0.709822), and show lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios comparing with the Middle to Late Devonian granite in the study area (0.711603–0.712615) [11]. They have initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios from 0.511909 to 0.512008 and negative $\varepsilon_{\text{Nd}}(t)$ values (−1.8 to −4.0) (Figure 5b), with two-stage Nd model ages ranging from 1305 to 1476 Ma.

5. Discussion

5.1. Petrogenesis

The Early Devonian volcanic rocks from the Haerdaban area in the northern margin of YB are characterized by high SiO_2 (70.16 to 77.52 wt.%), $\text{Na}_2\text{O}+\text{K}_2\text{O}$ (5.10 to 9.56 wt.%), and Zr (156–411 ppm) contents, as well as low concentrations of Al_2O_3 (11.27 to 16.36 wt.%), CaO (0.21 to 2.57 wt.%), and MgO (0.1 to 1.22 wt.%). On the primitive mantle-normalized spider diagram (Figure 7b), these samples show the strong depletion of Ba, Sr, P, and Ti, and the enrichment of Th, U, and K indicates that they have experienced a notably fractional crystallization. The high differentiation index ($\text{DI} = 82.6\text{--}96.8$) and the Zr/Hf ratios (27.1–36.5) suggest the moderately evolved granites attribute [52–54]. Whole-rock Zr saturation temperatures (T_{Zr}) were calculated and the results have a range from 783 °C to 952 °C (average $T_{\text{Zr}} = 860$ °C). It is similar to those of typical A-type granites (800–900 °C) [55], but lower than those plume-related A-type granites (930–1050 °C,) [56] and higher than I-type granites and S-type granites [57]. These geochemical signatures, including high SiO_2 and Zr contents, as well as the high zircon saturation temperatures, are consistent with their classification as A-type granite [52,54,58]. In the discrimination diagrams (Figure 8a,b), the rocks fall into the field of A-type granites. Sometimes, the high-Si A-type granites may show the similar geochemical characteristics with the high fractionated I-type granites [58]. The high $\text{Fe}^\#$ values ($\text{Fe}^\# = \text{FeO}^\text{T}/(\text{FeO}^\text{T} + \text{MgO})$, from 0.67 to 0.93) and high Zr + Nb + Ce + Y (average 456 ppm) content are obviously different from those high fractionated I-type granites [48,59,60].

Figure 8. Plot of $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ versus $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$, FeOT/MgO versus $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y}$ discrimination diagrams for the Early Devonian volcanic rocks from Haerdaban area in the northern margin of Yili Block (a,b, reference area after [58]).

The petrogenesis of A-type alkaline magmas is still a matter of debate. Commonly, the A-type granites can be produced by the fractionation of mantle-derived magma, crust anatexis, or mixing of mantle-derived magma and crustal rock [58,61,62]. Fractionation of mantle-derived magma or re-melting of under-plating basaltic rocks generally produces small amounts of silicic magma [63]. Therefore, a significant quantity of mafic magma and mafic residues were required in such a model [64,65]. The metaluminous to weakly peraluminous composition of the samples are inconsistent with the peralkaline attribute of fractionation mantle-derived magma (Figure 6d) [53,57]. The lack of mafic rocks, high SiO_2 content with low Ni and Co of samples is indicative of the minor contribution from mantle-derived material in generation. Therefore, we can predict that the volcanic rocks did not directly generate by the fractionation mantle-derived magmas or mixing origin. The low $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (36–96) and high $\text{CaO}/\text{Na}_2\text{O}$ ratios (0.07–1.37), as well as the negative whole-rock $\varepsilon_{\text{Nd}}(t)$ values (−1.8 to −4.0) indicate a lower crustal source [66]. Moyen [67] proposed that the pure crust can melt and form the granite induced by long-lived heat accumulation with no or minimal basalt flux and the heat source chiefly from the radioactive and basal heat flux on the basis of heat budget calculation. In the heat balance models, more than 20 Ma is necessary to accumulate heat and induce the crust melting at a thick crust [67]. As shown in previous studies, there is little or no magmatic event from Early Silurian to Late Silurian (440 Ma to 420 Ma) in the northern margin of YB [9,18], representing a long-time relatively stable condition. Despite no or little basalt flux during the Early Devonian, the long-lived heat accumulation in a thick crust could induce a magmatic burst after more than 20 Ma [67,68]. Therefore, the Haerdaban volcanic rocks were mainly derived from the partial melting of felsic crustal rocks induced by the long-lived heat accumulation with no or minimal basalt flux.

The low Sr (41.2 to 120 ppm) and high Rb (56.2 to 372 ppm) concentrations of the samples imply that the fractional crystallization may be involved in the production of the A-type volcanics. The depletion of Ba, Sr, P, Ti, and Eu anomalies in the trace element patterns, as well as the high differentiation index also supported the fractional crystallization. The fractional crystallization of plagioclase and K-feldspar minerals can account for the depletion of Ba, Sr, and Eu. The P and Ti anomalies can be attributed to the fractionation of apatite and Fe-Ti oxides. It is noted that the $\varepsilon_{\text{Nd}}(t)$ values of samples range from −1.8 to −4.0, but $\varepsilon_{\text{Hf}}(t)$ values of zircon range from +6.13 to +14.8, showing that Nd and Hf isotopic compositions are decoupled. The Nd–Hf isotopic decoupling may be related to the elevated Lu/Hf of the rocks, which could be attributed to the removal of zircon with low Lu/Hf, or the involvement of garnet with high Lu/Hf during the re-melting of the crust [69–71]. The characteristic of positive Zr and Hf anomalies, crust-like Lu/Hf ratios (0.06 to 0.16), do not support the removal of zircon during the re-melting of the crust. The HREE of samples much higher than the upper continental crust (UCC) and lower

continental crust (LCC) (Figure 7a), combined with the high zircon saturation temperatures ($T_{Zr} = 783\text{ }^{\circ}\text{C}$ to $952\text{ }^{\circ}\text{C}$), showing that the breakdown of garnet may have been involved during crustal re-melting. The breakdown of garnet would likely affect the Lu–Hf rather than the Sm–Nd isotopic systematics, so the Nd isotopic compositions may be more consistent with the source rocks [71]. The oldest inherited zircon age (1465 Ma, sample ZJ-TW1) is in agreement with the two-stage Nd model ages (1305–1476 Ma), which further emphasizes that the breakdown of garnet during crustal re-melting results in the elevated HREE and $\varepsilon_{\text{Hf}}(t)$ values of the melts.

In summary, the Early Devonian volcanic rocks from Haerdaban area are considered to be generated by re-melting of lower crust induced by the long-lived heat accumulation with no or minimal basalt flux and subsequently fractional crystallization is significant.

5.2. Tectonic Setting and Implications

The Cambrian to Early Ordovician strata distributed in the northern margin of YB reveal a passive continental margin environment [27,72]. The Middle to Late Ordovician arc-related plutons were reported in the northern margin of YB and indicated that the Junggar Ocean is likely to have begun southwards subduction at least in the Middle Ordovician [4,5,18,72]. The Middle Devonian to Carboniferous arc-related volcanic and intrusive rocks produced by the southward subduction of the Junggar Ocean combined with Late Paleozoic accretionary complexes in the northern margin of YB indicate an active continental margin [37,73–75].

The Early Devonian volcanic rocks from Haerdaban area show relative depletion of Nb, Ta, and Ti, and enrichment of LILEs, which are similar to the arc magmas typically generated in subduction-related settings [76–78]. In the Nb versus Y and Rb versus Y + Nb tectonic discrimination diagrams, these samples plot in the volcanic arc granite (VAG) and within plate granite (WPG) fields (Figure 9). Besides, the samples have relatively high HREE concentrations and low Ti contents, unlikely formed in the rift- or plume-related settings. The Middle–Late Devonian arc-related magmatism are exposed along the northern margin of YB, which were generated in a continental arc setting, indicating the continuous southward subduction of Junggar oceanic crust (or North Tianshan oceanic crust) beneath the Northwestern Chinese Tianshan [11]. This is also supported by the sedimentary evidence. Our investigation found that the Late Paleozoic sedimentary strata in the Biezhentao mountain area, including Lower Devonian Dahalajunshan Formation, Middle Devonian Hanjiga Formation, and Upper Devonian Tuosikuertawu Formation, which are characterized by near-source deposition and contain amounts of arc-related volcanic debris, suggest an active continental margin [79]. Additionally, the Devonian Tulasu Formation in the Tulasu basin also reflected an active margin [14]. Thus, we infer that the northern margin of the YB is an active continental margin in the Early Devonian.

Figure 9. Tectonic discrimination diagrams for the Early Devonian volcanic rocks in the Haerdaban area. (a) Nb versus Y and (b) Rb versus Y + Nb (reference area after [76,77]). Syn-COLG: syn-collision granites; WPG: within plate granites; VAG: volcanic arc granites; and ORG: ocean ridge granites.

The Early Devonian granites (our unpublished data), Early Devonian volcanic rocks (this study), and previous reported magmatism [11,13,19] have similar geochemical characteristics (such as enrichment in LILEs relative to HFSEs, and depletion of Nb, Ti, and P) to that of continental arc magma, which can be related to the southward subduction of the Junggar Ocean. The Early–Middle Devonian magmatism suggests a relatively extensive magmatism in the northern margin of YB [11], which is the eastward counterpart of southern limb of the DVB. The DVB and BY magmatic belts were superimposed together in the northern margin of YB, which are different from the spatial–temporal distributions in the western and northern margins, implying a continuous arc-related magmatism. The $\epsilon_{\text{Nd}}(t)$ and $\epsilon_{\text{Hf}}(t)$ values of these Early Devonian to Permian arc magmatic rocks increase steadily, which are different from that of magmatic rocks generated during the slab retreating (Figure 10a,b) [80–82]. Therefore, the ~E–W linear trending of arc magmatism in the northern margin of YB combined with the geochemical and Nd–Hf isotope data in this study and previous studies indicate that they were generated in a relatively steady-stated subduction setting without significant slab retreat or advance. The Early Devonian volcanic rocks in this study formed in a continental arc setting related to the southward subduction of Junggar oceanic crust (Figure 11).

Figure 10. (a) In situ zircon $\epsilon_{\text{Hf}}(t)$ values versus U-Pb ages and (b) whole rock $\epsilon_{\text{Nd}}(t)$ values versus U-Pb ages diagrams for the Paleozoic magmatic rocks in the northern margin of Yili Block (previous data are collected from [9] and its references).

Figure 11. Tectonic model of the north margin of Yili Block during the Early-Middle Devonian.

6. Conclusions

1. A suit of Early Devonian (ca. 418–406 Ma) volcanic rocks were identified from Haerdaban area in the northern margin of the YB. These rocks have compositions similar to A-type granitoids and formed in a high temperature setting, and were generated by re-melting of low crust associated with the breakdown of garnet.
2. They are formed in a continental arc setting related to the southward subduction of Junggar oceanic crust, which was induced by the long-lived heat accumulation with no or minimal basalt flux.
3. The Early–Middle Devonian arc-related magmatic rocks in the northern margin of YB are the eastward counterpart of southern limb of DVB, which indicate a relatively steady-state southward subduction in the southern limb of Kazakhstan Orocline during the Early–Middle Devonian.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/min11111248/s1>, Table S1: LA-ICP-MS zircon U-Pb analyses for the volcanic rocks in the Haerdaban area. Table S2: Zircon Lu–Hf isotopic data for the volcanic rocks in the Haerdaban area, northern margin of Yili Block. Table S3: Major and trace element data for the volcanic rocks in the Haerdaban area, northern margin of Yili Block. Table S4: Whole-Rock Sr–Nd isotopic compositions of the volcanic rocks in the Haerdaban area, northern margin of Yili Block.

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