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Research Article

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The timing of Barleik Formation and its implication for the Devonian tectonic evolution of Western Junggar, NW China

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Abstract: The timing of Barleik Formation in Xinjiang, NW China, has not been constrained by accurate geochronology yet, while this work is of great significance to help reconstruct the geological tectonic evolution of Western Junggar. Based on the LA-ICP-MS U–Pb geochronology study, the weighted average age of magmatic zircons collected from the tuff in Barleik Formation, which reflects the formation age of the tuff, is 372 ± 2 Ma ($N = 57$, mean square of weighted deviates (MSWD) = 1.15). The first report in this study of the zircon U–Pb dating result indicates that Barleik Formation along the West Junggar tectonic belt occurred in the Late Devonian rather than in the middle Devonian period as previously claimed. Meanwhile, chronology data and the geochemical features comparing with the Island Arc-related rocks in the adjacent area, as well as stratigraphic structural relationship, suggest that volcanic activities may exist in the Late Devonian, and the relevant volcanic ash deposited in the Barleik forearc basin may be derived from the adjacent island arc (current geographic coordinate). In addition, the fossil assemblage dominated by bathyal-abyssal invertebrate fossils and bathyal-abyssal facies indicates that the Barleik Formation is a bathyal-abyssal sedimentary environment.

Keywords: Barleik Formation, tuff, magmatic zircons, U–Pb isotope chronology, tectonic settings

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1 Introduction

The central Asian orogenic belt (CAOB) adjacent to the Siberian plate to the north, the Tarim-North China plate to the south, the eastern European plate to the west, and the Pacific plate to the east (as shown in Figure 1a) were products of accretion around the ancient continent heading into the ocean [1,2]. It represents site of major crustal growth in the Phanerozoic, and half of its growth was because of the addition of juvenile material [3–6]. In addition, the CAOB is one of the remarkable global world-class Cu–Au–Mo metallogenic provinces [7,8]. Therefore, the CAOB is a natural laboratories for studying the continental crust growth and evolution, and huge amount accumulation mechanism of the metallic element.

The Western Junggar region is located in the southwest of the CAOB, and voluminous Paleozoic igneous rocks and associated Cu–Au–Mo deposits occur in the area. There is a heated debate, however, on the tectonic evolution of continental growth, tectonic settings, and tectonic unit division during Devonian period [9–11]. Thus, the temporal-spatial distribution of the magmatic rocks and sedimentary rocks along the West Junggar are vitally important to understanding the transition from lateral growth to the vertical growth of the Western Junggar and its mechanism during Devonian period. The volcanic-sedimentary rock series distributed in the orogenic belt record the regional tectonic evolution, and the corresponding chronology studies could also provide a time constraint for reconstructing the quantitative evolution process.

The Barleik Formation, named after the Barleik mountain by Xinjiang Bureau of Geology and Mineral Resources (XJBGMR) [12,13], is composed of fine-grained clastic rocks distributed in the Western Junggar region. It is overlaid by the Tielieketi Formation with a disconformity and underlain by the Kulumudi Formation with a conformable contact. Moreover, large sets of terrigenous clastic rock, pyroclastic rock, and volcanic rock occur in the

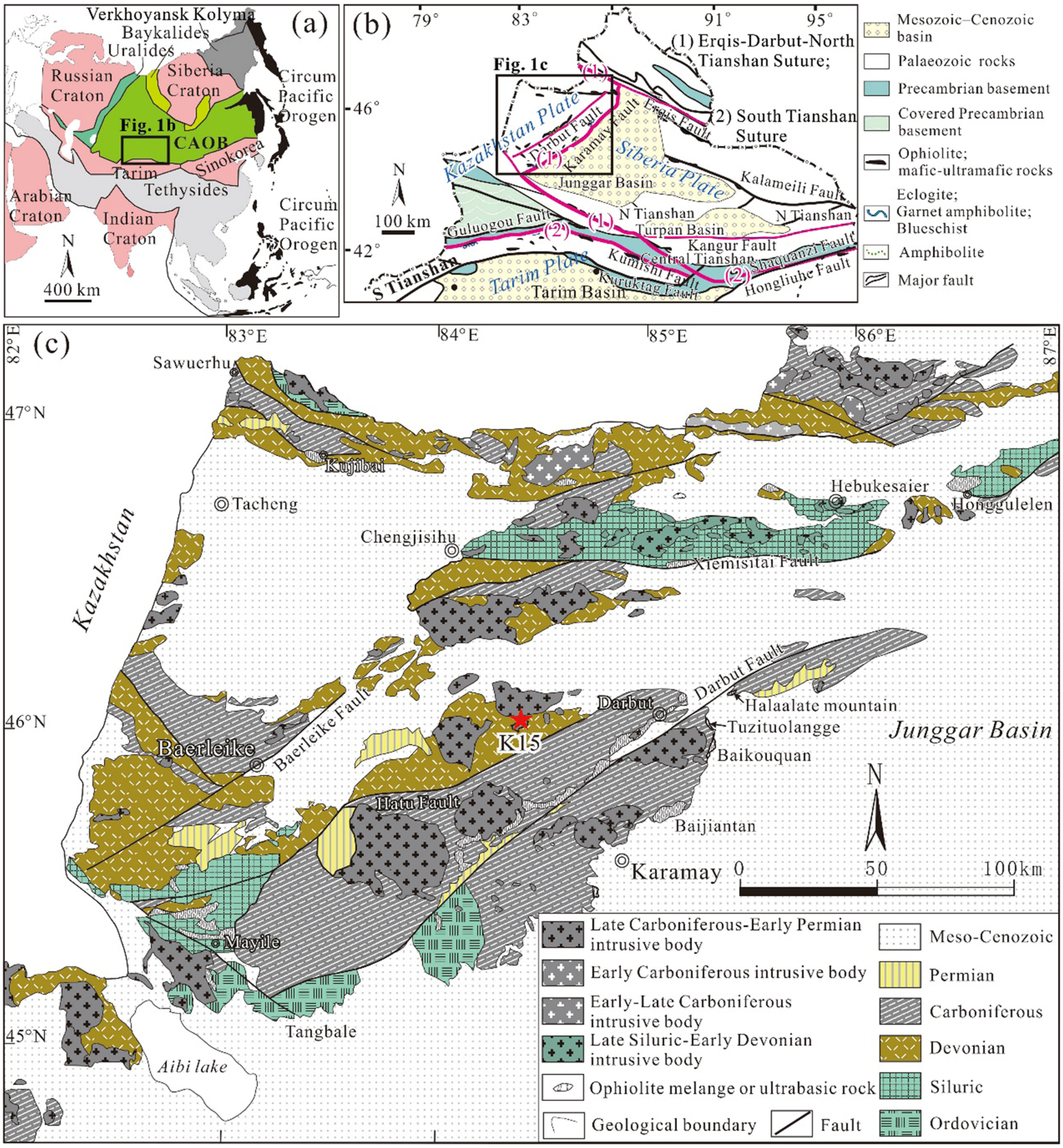

Figure 1: (a) Simplified tectonic units of the central Asian orogenic belt, K15 with five-pointed star showing the sampling location (modified from Li et al. [1,2]); (b) the tectonic map showing the tectonic setting of the Northern Xinjiang [1,2]; (c) location map of the study area and simplified geology of Southern West Junggar, NW China (modified from XJBGME [12,16]).

Devonian system along West Junggar. Unfortunately, because of scarcity of fossils, mixing of marine zoolites, and terrestrial plant fossils of different ages, lithology comparison turns out to be a particularly tough work [14]. As a result, the relative age of Barleik Formation can only be inferred as Middle Devonian from contact relationship between underlying and overlying strata from fieldwork [12,13]. However, the U–Pb dating age of 379 Ma for zircons from the underlying Kulumudi Formation was recently acquired by Bai et al. [15], which is an important proof to oppose the viewpoint of Middle Devonian Timing for the Barleik Formation. Therefore, a new consideration to the age of Barleik Formation and further discussion of the Western Junggar tectonic evolution are required.

This study collected and sorted zircons from tuff interlayers in the strata, conducted LA-ICP-MS U–Pb dating, and obtained the accurate magmatic zircon age, which has ultimately constrained the stratigraphic age of the Barleik Formation. The deposited age of the Barleik Formation can provide the evidence for tectonic unit division of West Junggar and give a new insight into the

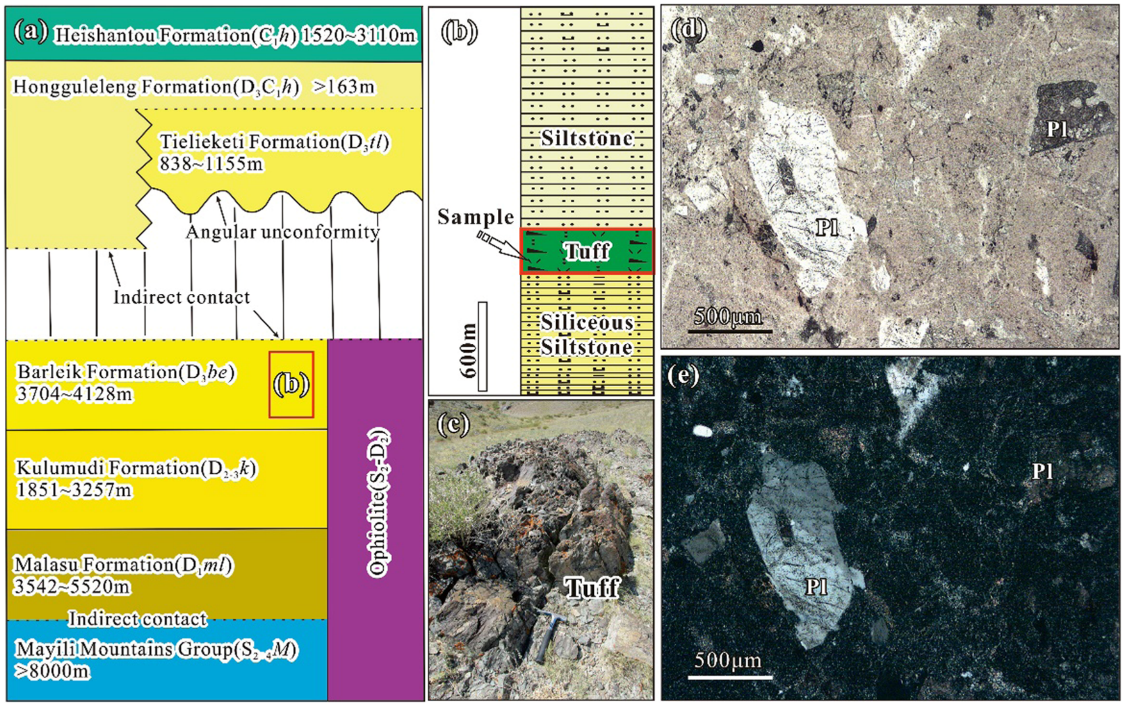

Figure 2: (a) Lithological column figure [25]; (b) the lithostratigraphic columnar section of the Barleik Formation; (c) field photograph; (d) and (e) photomicrographs are taken in orthogonal light of the Devonian tuff rocks. Note: Pl-plagioclase.

provenance of the volcanic ash deposited in the Barliik area by comparing with the northern volcanic rock belts. The goal of this study can not only be used in the regional comparative study of Devonian strata but also provide essential chronological and stratigraphic information for the reconstruction of Paleozoic tectonic evolution in the Western Junggar region.

2 Geological setting

According to ref. [10,11], the West Junggar tectonic unit is bounded on the east by Darbut–Karamay ophiolite zone, on the north by Zhaisang – Irtysh ophiolite zone, and on the south by Abi Fault with the Tianshan Terran and is the eastern edge of the Kazakhstan plate (Figure 1). The post-collisional rifting setting and NE–SW strike-slip fault since Carboniferous had modified the tectonic patterns before Devonian in Western Junggar. Regarding the tectonic reconstruction results [17], pyroclastic rock series in the Tiechanggou area which appears as the sedimentary part of arc-related tectonic system show contact with Darbut–Karamay ophiolite zone at Hatu fault to the southeast [18–24] and Chengjisi-Saerwuer island arc rock belt at Xiemisitai fault to the northwest, respectively [16–25].

The Devonian stratigraphy is composed of the Malasu Formation, the Kulumudi Formation, the Barleik Formation, and the Tielieketi Formation from lower to upper [25], which are mainly made up of terrigenous clastic rocks interbedded with carbonate rocks, volcanic rocks, and clastic rocks. These pyroclastic rocks are mainly distributed in the Western Junggar tectonic belt along NE-striking, paralleling to Darbut–Karamay Devonian ophiolite. The Barleik Formation is in a tectonic contact with the Carboniferous strata at the Hatu fault and a conformable contact with underlying Kulumudi Formation without the occurrence of primary sedimentary boundaries.

In addition, using the regional unconformity to divide tectonic layers, the Barleik Formation belongs to the tectonic layers of the Devonian accretionary arc, which shows an angular unconformity with upper Carboniferous tectonic layer and an unconformable contact with lower Early Paleozoic tectonic layer [12,16]. Moreover, the Karamay–Darbut ophiolite zone are also covered by Carboniferous strata with an unconformity contact [19,27].

3 Materials and methods

Devonian strata, including the Kulumudi Formation and Barleik Formation, are widely exposed in the south of

Western Junggar Tiechanggou town, Xinjiang. In this article, the Barleik Formation profile is mainly composed of three sections, and the sample of grayish and black crystal-lithic tuff was collected from the tuff interlayers in these strata as shown in Figure 2a and b (46°2′40″N; 84°23′25″E).

In terms of the microscopic observation, the sample of crystal-lithic tuff (Sample K15) is composed of crystal fragment (content: 60–65%) with volcanic ash and little lithic as shown in Figure 2c and d. Specifically, the crystal fragments are mainly feldspar, and there are few quartzes with grain size ranging from 0.1 to 1 mm. The rock fragments including andesite rock fragments (content: 10–12%) and tuff rock fragments (content: 10–15%) are subangular to sub-rounded. The rock and crystal fragments are cemented with volcanic ash and altered into cryptocrystalline felsic or micro-scaly chlorite assemblages.

Zircons granules from the sample K15 were separated using traditional method, including gravity separation, purified in a heavy liquid, and handpicked under a binocular microscope. Zircon U–Th–Pb measurements were proceeded at the Xi'an Centre of the China Geological Survey, using analytical procedures described by Yuan et al. [28]. Zircon U–Th–Pb measurements were made on 30 μm diameter regions of single grains using an inductively coupled plasma-mass spectrometry (ICP-MS) (Agilient 7700x) and an excimer laser-ablation system (193 nm, Geolas 200 M, Lambda Physic) at the Xi'an Centre of the China Geological Survey. Isotopic ratios and element concentration of zircons were calculated using ICPMSDataCal software [29,30]. Concordia ages and diagrams were obtained using isoplot/Ex (version 3.23) [31]. The common lead was corrected with LA-ICP-MS Common Lead Correction (version 3.15), using the method of Andersen [32]. The united states geological survey (USGS) standards (AGV-1, BCR-1, and BHVO-1) were used for calibration.

Major element oxides and trace elements were determined by X-ray fluorescence on fused glass beads and ICP-MS with an Thermo-X7 system (power: 1,200 W, nebulizer gas: 0.64 L/min, auxiliary gas: 0.80 L/min, plasma gas: 13 L/min), respectively, at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The fused disks were prepared by mixing 0.5 g of rock powder and 2.5 g of $LiBO_3$ flux following the method of Norrish and Hutton [33]. The error on major element determination is 2–5%. Trace elements were analyzed using the following method. Powdered samples were dissolved using a mixture of $HF\text{-}HNO_3$ and a sinter procedure using Na_2O_2 (for REEs) in a polytetrafluoroethylene (PTFE) bomb as described in Qi et al. [34]. Standard reference materials, SY-2 and MRG-1, were used to monitor the data quality during the course of this study. The precision and accuracy of the trace element analyses are estimated to be better than 5% (relative), except for Nb and Ta (better than 10%). Other volcanic rock data except K15 are from the reference [35–38].

4 Results

The grain sizes of the zircons in tuff sample K15 are between ~100 and ~300 μm, and they all have the length/width ratios of 1.5–2.5. Zircons from the tuff of sample K15 show intermediate to strong cathodoluminescence (CL) brightness, which reveals clear oscillatory zoning and idiomorphic outlines as shown in Figure 3. Several angular granules may be caused by volcanic eruptions.

In the dating analyzed data for the Sample K15 (Supplementary Table S1), Th/U ratios resemble magmatic zircons, and most of them are higher than 0.4, but three spots have the lower value ranging from 0.27 to 0.37. Three spots, including K15-01, K15-28, and K15-52, have older ages than most of the spots (Figure 4a), while the older ages (418–442 Ma) are probably from captured zircons from surrounding rocks during the volcanic eruption and represent the formation age of sedimentary provenance. The $^{206}Pb/^{238}U$ ages of 57 spots are in the range of 357–374 Ma, and the lower intercept age is 371.6 ± 1.6 Ma (Figure 4b). This small variation in the ages suggests a magmatic event. The weighted mean of the radiogenic $^{206}Pb/^{238}U$ age of 372 ± 1 Ma (1σ, MSWD = 1.15, N = 57, see the histogram in Figure 4c) is interpreted as the time of magmatic recrystallization of the zircons from the Barleik tuff.

5 Discussion

The Barleik Formation was named by XJBGMR [12,13] on the Barleik mountain in Yumin county (at the west side of the Watapukan-Bakaique lake) during the 1:2,00,000 regional geological survey. Primary rock assemblage of the Barleik Formation was defined as littoral to neritic faces of mudstone, tuffaceous siltstone, tuffaceous conglomerate, intermediate tuff, jasper rock, and felsite interbedded with limestone. Through literature investigation, Gong and Zong [39,40] believe that there are littoral and neritic invertebrate fossils in the Barrek Formation. Fossil assemblage and sedimentary facies indicate that the area is a littoral and neritic sedimentary environment. The occurrence of the Barleik Formation which appears

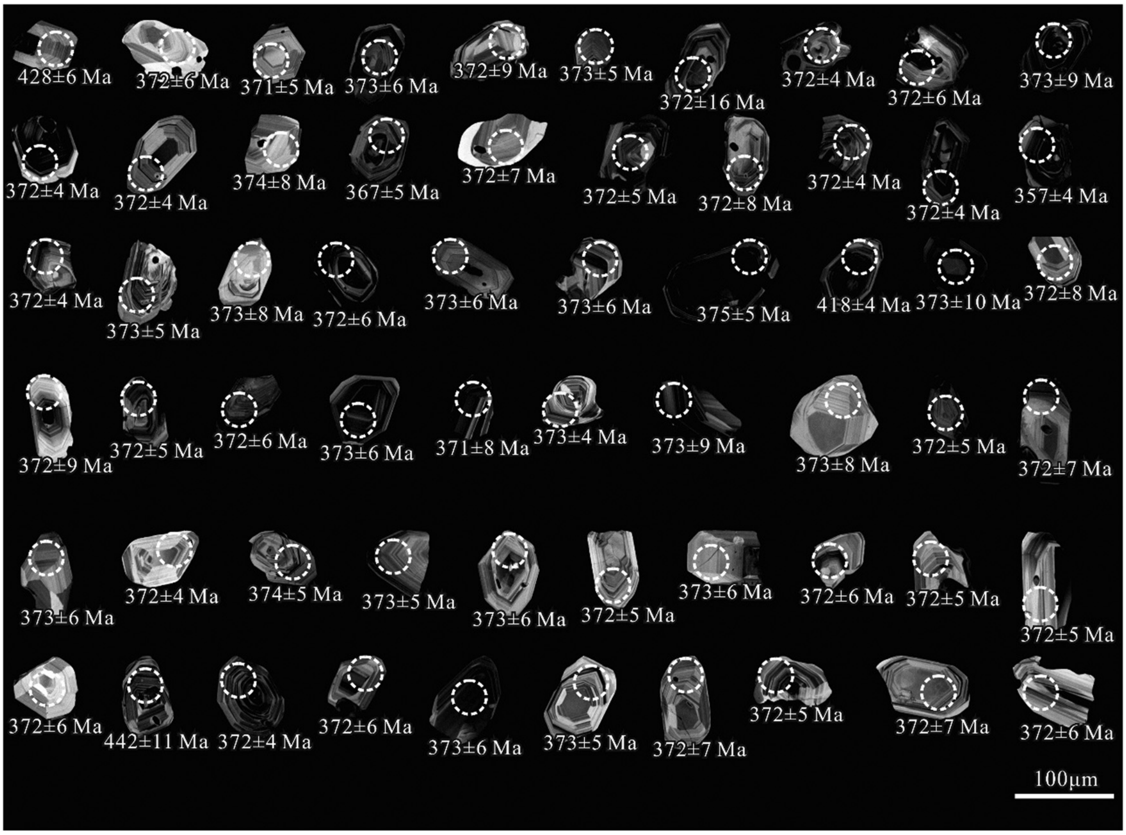

Figure 3: Cathodoluminescence image of selected zircons. Note that the white circles indicate positions of laser denudation.

as a conformity contact with Kulumidi and Tuoerdengakeman Formation, and a disconformity contact with Tielieketi Formation, was restricted to a relative timing of the early Middle Devonian period because of the lack of the accurate chronological evidence. Subsequently, the broad and imprecise timing (early Middle Devonian) of this formation was widely used [41,42].

Then, the Barleik Formation was revised by XJBGMR [13] and further defined as dark gray or gray argillaceous siltstone, siltstone, siliceous rock interbedded with tuffaceous siltstone, tuffaceous conglomerate, intermediate tuff, and sandy limestone. Moreover, the upper stratigraphic contact relationship of the Barleik Formation was retained, while the lower contact relationship was modified to be integrated with the underlying Kulumudi Formation. The researcher still adopted the original broad and imprecise timing, that is, Middle Devonian. However, the age of Barleik Formation, according to the LA-ICP-MS zircon U–Pb age (379.3 ± 5.0 Ma) of the tuff in the Southern Devonian strata of the Tiechanggou town, was updated to Early Devonian, indicating the unreliability of the original relative imprecise timing of Barleik Formation.

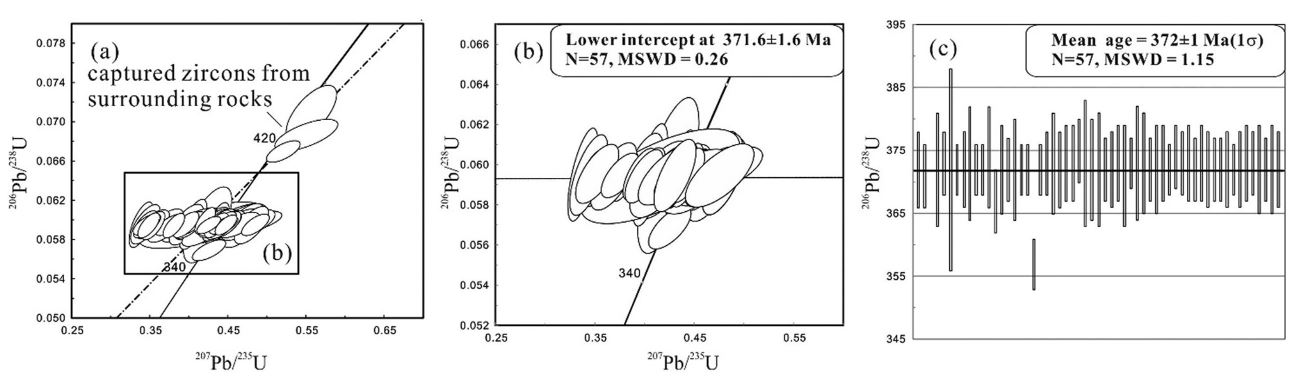

Figure 4: Zircon U–Pb concordia plot and age histogram of the sample. (a) Concordia plot for 60 spots of all of zircons, (b) concordia plot for 57 spots of zircons of magmatic origin, (c) histogram of the radiogenic $^{206}Pb/^{238}U$ ages of 57 spots of zircons of magmatic origin.

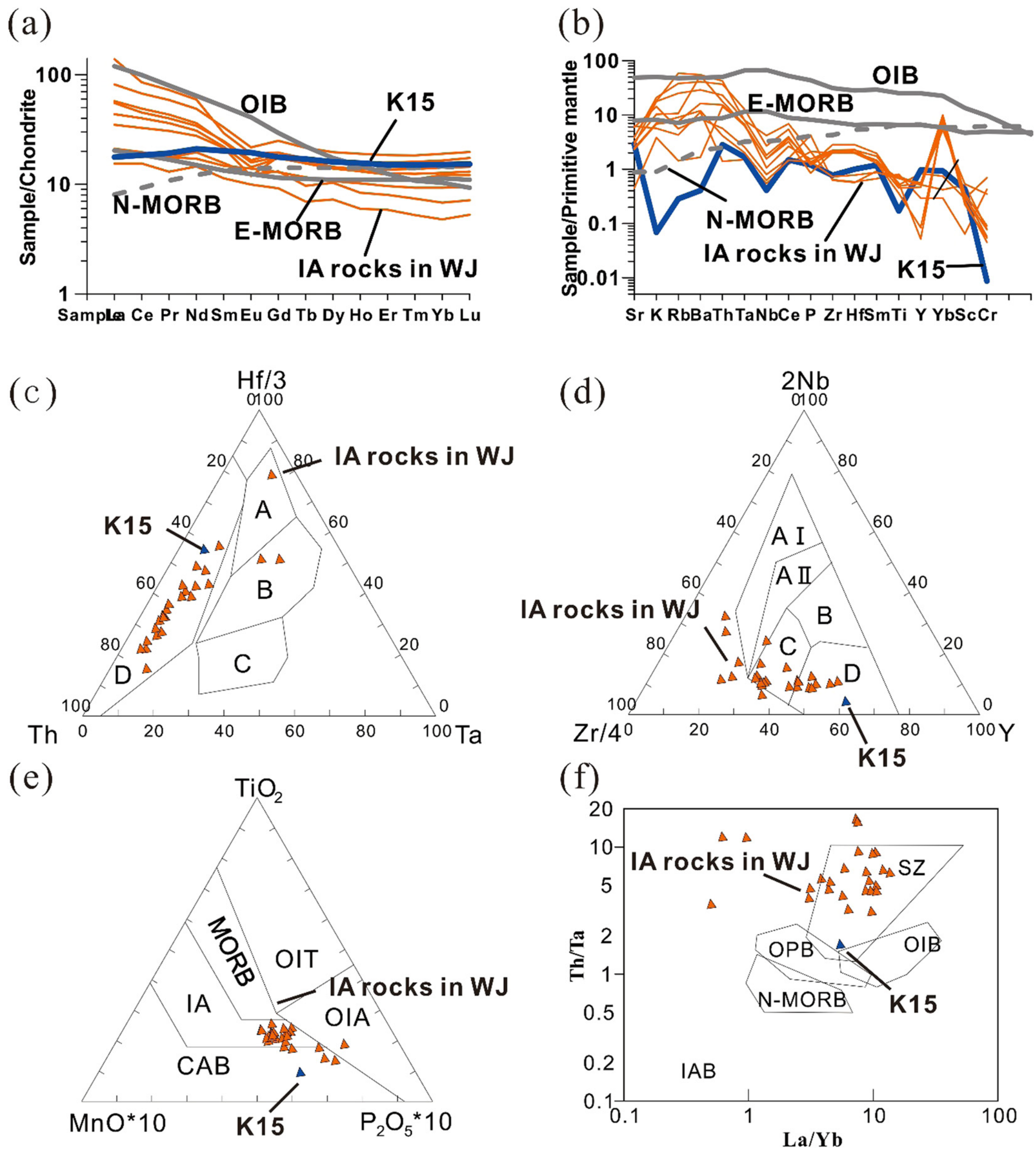

Figure 5: Comparison of geochemical features for the Barleik tuff with the Devonian Volcanic rocks from adjacent areas: (a) normalized REE pattern [43]; (b) trace element spider diagram [44]; (c) Th–Hf/3-Ta discrimination diagram [45]: A, NMORB; B, E-MORB; C, alkaline intraplate basalts; D, volcanic-arc basalts. (d) 2Nb–Zr/4-Y variation diagram [46]: AI, within-plate alkali basalts; AII, within-plate alkali basalts and within-plate tholeiites; B, E-type MORB; C, within-plate tholeiites and volcanic-arc basalts; D, N-MORB and volcanic-arc basalts; (e) Ti–10MnO–10P_2O_5 discrimination diagram [47]; (f) La/Yb vs Th/Ta diagram [48].

The tuff (K15) was sampled at the fine-grained volcanic clastic rock interlayers. Based on the CL image, trace element (such as Th/U ratio > 0.4), and the age distribution characteristics, zircons turned out to be magmatic genesis suggesting the volcanic eruption event. The data from 57 points yielded an average age of 372 ± 2 Ma (N = 57, MSWD = 1.15). Therefore, it is reasonable to verify the sedimentary timing of the Barleik Formation into the Late Devonian.

The tuff (K15) has the Island Arc (IA) affinity with respect to geochemical characteristics. The reasons are as follows: (1) They all have low content of Ti, P, K, and total alkali, belonging to calc-alkaline series (Supplementary Table S2 [35–38]). (2) The rare earth elements (REE) patterns normalized to chondrite are similar to the rocks from IA tectonic settings with respect to the heavy rare earth element (HREE) depletion patterns (Figure 5a), and the Spider Diagrams of trace elements have "TNT" (Nb, Ti, and Ta) negative anomalies (Figure 5b). (3) Tectonic environment discrimination diagrams show that K15 and the volcanic rocks of Devonian period in the adjacent area are also very similar to those rock assemblages formed in the IA tectonic settings and are different from those rocks originated from Mid-Ocean Ridges, within plate tectonic settings (Figure 5c–f). Therefore, these features suggest that the volcanic tuffs sandwiched in the Barleik Formation probably came from IA-related volcanism in the adjacent areas.

The volcanic rocks, ophiolites, and volcanic-sedimentary rocks of Devonian in Figure 1c are distributed along NE-striking, which manifest a pattern of trench-arc-basin tectonic system. During the Devonian period, in the Tiechanggou area of Western Junggar, the terrigenous clastics far away from the source region were deposited in a relatively stable semi-deep-sea sedimentary environment. Therein, the lithic-crystal tuff interbeds may come from the Devonian IA in the north, while the Barleik Formation containing volcanic ash was constructed from the flysch formation of volcanic clastic rock to terrigenous clastic rocks, which indicate a turbidite deposition (a turbidite is the geologic deposit of a turbidity current, which is a type of sediment gravity flow responsible for distributing vast amounts of clastic sediment into the deep ocean). Moreover, the Barleik Formation could originate from the semi-deep-sea to deep-sea environment of deep-sea plain adjacent to IA, indicating the possible genesis of the forearc basin.

6 Conclusions

The first report of the zircon U–Pb dating result suggests that tuff from the Tiechanggou district in the Western Junggar deposited as a result of the volcanic eruption at 372 ± 1 Ma (N = 57, MSWD = 1.15). According to the dating results and the latest international stratigraphic chronology [49], the set of volcanic rocks of Barleik Formation is of Late Devonian age. In addition, the underlying Kulumudi Formation is of Fasnian period of the Late Devonian, and the Hongguleleng or Tielieketi Formation overlying the sandstone of the Barleik Formation is also limited to the Late Devonian. The set of sandstone overlying the tuff within the Barleik Formation may extend to the Famennian period. Therefore, the Barleik Formation must be constrained at the Late Devonian rather than the middle Devonian of the Carboniferous.

The Devonian in study area is mainly a set of volcanic clastic rocks with coarse bottom and fine top, and there are a small amount of clastic rocks, siliceous rocks locally, which contains biological debris such as brachiopods corals. The geochemical compositions of the volcanic clastic rocks interbedded in the Barleik Formation and the volcanic rocks of the adjacent area suggest an IA-related affinity. These characteristics indicate that the study area of the West Junggar tectonic belt was an arc-related sedimentary basin adjacent to an IA during Late Devonian, thereby constraining the Late Paleozoic tectonic evolution of the IA terrain in the southwestern part of the CAOB.

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