

Article

Provenance of Triassic Xiazijie Fan-Delta in Junggar Basin, Northwestern China: Insights from U-Pb Dating of Detrital Zircons

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Abstract: Abundant hydrocarbon resources were discovered in the Xiazijie fan-delta in the Triassic Baikouquan Formation in Mahu sag, Junggar Basin. However, the maximum depositional age of Baikouquan Formation and provenance of this fan-delta are still unclear, which would be unfavourable for further hydrocarbon exploration. In this study, we used detrital zircon U-Pb dating and composition statistics of conglomerate clast and sandstone grain from Baikouquan Formation to constrain the maximum depositional age and provenance of the Xiazijie fan-delta. The results showed that (1) the conglomerate clast compositions of Xiazijie fan-delta mainly consisted of tuff and intermediate-felsic magmatic rocks, and sandstone samples could be classified as litharenite type with the lithic fragments were almost entirely volcanic lithic fragments; (2) the average Qt:F:L values of sandstone samples (M152-S1 and M152-S2) were 26:7:67 and 21:8:71, respectively, and they plotted in the magmatic arc domain in the Qt-F-L ternary diagram, indicating the tectonic setting of source area of Xiazijie fan-delta was magmatic arc; (3) M152-S1 yielded U-Pb ages ranging from 417 Ma to 253 Ma, with a dominant age peak at 313 Ma and two secondary age peaks at 411 Ma and 268 Ma, respectively, while M152-S2 yielded U-Pb ages ranging from 467 Ma to 256 Ma, with a dominant age peak at 307 Ma and two secondary date peaks at 405 Ma and 262 Ma; (4) the mean age of youngest two zircon grains of M152-S1 was 254.8 ± 4.7 Ma, while that of M152-S2 was 257.6 ± 3.8 Ma, suggesting the Baikouquan Formation might be deposited after the Changhsingian to Olenekian; (5) the magmatic rock ages of central West Junggar were distributed mostly between 450–260 Ma, with a dominant age peak at 307 Ma. The ages distribution between magmatic rock of central WJ and detrital zircons of M152-S1 and M152-S2 were similar, indicating the central WJ domain should be the major source area of the Xiazijie fan-delta; (6) the magmatic rock of Hakedun–Hongguleleng area in the Central WJ was characterized by a peak age at 305 Ma, which was consistent with the peak ages of M152-S1 and M152-S2, indicating the Hakedun–Hongguleleng area was likely to be their major source area; and (7) one minor peak age at 411 Ma and another at 405 Ma were obtained from M152-S1 and M152-S2, respectively, and a zircon grain with Middle Ordovician age at 467 Ma was obtained from M152-S2, indicating Late Silurian–Early Devonian Chagankule pluton in the Saier Mountain and Ordovician Hongguleleng ophiolite mélange in the Sharburt mountain were the minor source areas. This research has significant implications for stratigraphic correlation in Junggar Basin and hydrocarbon exploration in the Xiazijie fan-delta conglomerate reservoir.



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Keywords: detrital zircon; fan-delta; Junggar Basin; Mahu sag; provenance; West Junggar

1. Introduction

Over 1.24 billion tons of hydrocarbon geological reserves were discovered in the Triassic Baikouquan Formation in the Mahu sag of Junggar Basin in recent years [1,2]. These hydrocarbon resources accumulated in several large gravelly fan-deltas bodies

around the Mahu sag (Figure 1), which formed the largest conglomerate hydrocarbon reservoirs in the world. Among these fan-deltas, the Xiazijie fan-delta, located in the north area of Mahu sag (Figure 1c), is the most significant hydrocarbon exploration target. Many studies focusing on the sedimentary facies and conglomerate reservoir characteristics of this Xiazijie fan-delta were carried out [1,3]. However, the depositional age of the Baikouquan formation is unclear because of the lack of paleontological fossils in this gravelly stratum. Additionally, the provenance of the Xiazijie fan-delta sediments is still poorly understood, which heavily affected the deep understanding to its subfacies or microfacies distribution rule, and prediction of high-quality hydrocarbon reservoir. Few studies using heavy mineral ZTR index and dip logging showed that the paleo-current direction of Xiazijie fan-delta was from northeast to southwest [3,4]. However, the tectonic setting and precise location of the source area were unknown.

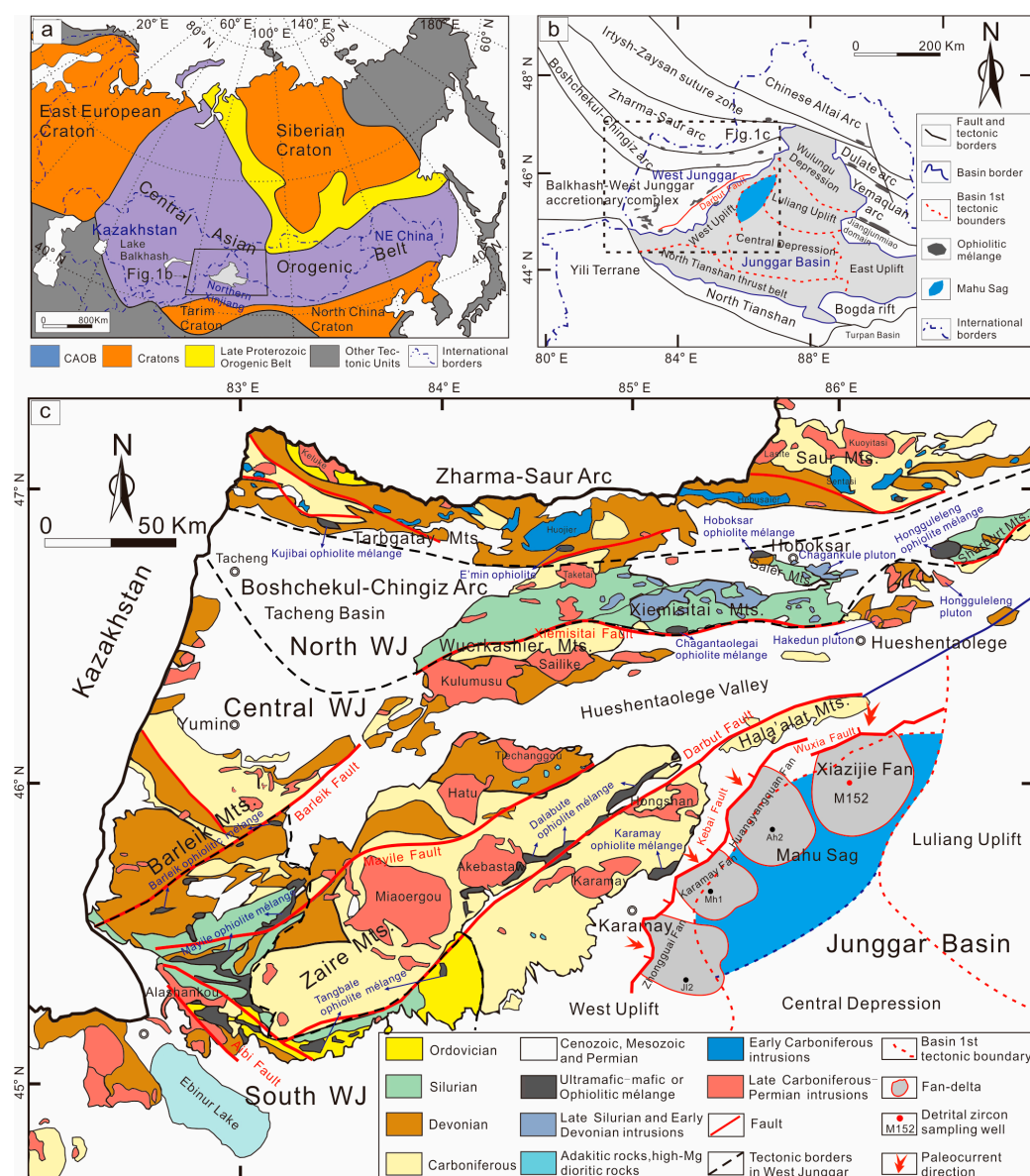


Figure 1. (a) Tectonic outline of the CAOB and environs, modified after reference [5]; (b) tectonic map showing the Junggar Basin and adjacent regions, modified after references [5,6]; (c) Geological map of West Junggar and adjacent northwest margin of Junggar Basin (modified after references [7,8]), showing the location of Mahu sag and the distribution of several fan-deltas in the Triassic Baikouquan Formation. The paleocurrent direction of these fan-deltas are from references [3,4]. Abbreviations: CAOB: Central Asian Orogenic Belt; WJ: West Junggar.

In the last ten years, U-Pb dating of detrital zircon was widely used to infer maximum depositional ages of sedimentary strata, search for the potential source areas of sediments and reconstruct paleogeography [9–11]. Compared with the traditional heavy mineral analysis, the advantage of detrital zircon U-Pb dating is building a quantitative relationship between sediments and source area rocks. In this paper, we present sandstone detrital zircon U-Pb ages and petrology characteristics of conglomerate and sandstone from the Baikouquan Formation of Well M152, aiming to (1) reveal the tectonic setting of the source area of Xiazijie fan-delta; (2) discuss the depositional age of the Baikouquan Formation; (3) ascertain the location of the source area of Xiazijie fan-delta; (4) reconstruct the source-to-sink system of the Xiazijie fan-delta. This research has significant implications for stratigraphic correlation in Junggar Basin and hydrocarbon exploration in Xiazijie fan-delta conglomerate reservoir.

2. Geological Setting

2.1. Tectonic Evolution of Junggar Basin and Mahu Sag

Junggar Basin is a large continentally Carboniferous–Quaternary-imposed basin, located in the south margin of the Central Asian Orogenic Belt (CAOB) (Figure 1a) and northwest margin of China (Figure 1a,b). The Mahu sag, a second-class tectonic unit, is located in the northwest margin of Junggar Basin, with an area of approximately 5000 km² (Figure 1b,c).

The crystalline basement of Junggar Basin formed in the Precambrian before 800 Ma, and deposition started in the Late Carboniferous with volcanic and clastic sequence developed in a remnant ocean basin [12]. Since then, the whole Junggar Basin gradually developed into two single foreland basins because of the eastward thrust of the West Junggar orogenic belt and uplift of the south Tianshan mountains [13].

In the northwest margin of Junggar Basin, a collisional uplift zone and its near foreland depression was formed by the subduction and collision of the ocean crust of Junggar–Turpan plate to the Kazakhstan plate. In the early middle Permian, a huge thickness of volcanoclastic rocks and subaqueous fan, fan delta coarse-sized clastic rocks were developed in the Mahu sag (Figure 2a). In the late Permian, the northwest margin of Junggar Basin was intensely uplifted and a series of high-angle, northeast-trending large-scale thrust fault zones were formed during the late stage of Hercynian movement, which resulted in the erosion of the middle-upper Permian in the hanging wall of Kebai–Wuxia fault zone [14], and the lack of the Upper Urho Formation (P_{3w}) in the north area of Mahu sag (Figure 2a).

In the Triassic-early Jurassic, the northwest margin inherited the former tectonic activity; however, the strength of thrust activity became weaker [3]. Specially, in the early Triassic, large-area basal conglomerates were deposited in several fan deltas around the Mahu sag, including Xiazijie fan, Huangyangquan fan, Karamay fan and Zhongguai fan from north to south (Figure 1c). From the middle Jurassic to Cretaceous period, the thrust activity of the northwest margin of Junggar Basin basically ceased, and relatively finer sandstone and mudstone from braided-river delta and meandering-river delta developed (Figure 2a). From the Oligocene epoch to the Quaternary Period, the whole Junggar Basin evolved into a rejuvenated foreland basin because of the Himalayan Orogeny, and the sedimentation in the Mahu sag basically ceased after the early Cretaceous age (Figure 2a).

2.2. Regional Tectonics of West Junggar

The Central Asian Orogenic Belt (CAOB), surrounded by the European and Siberian cratons to the north and the Tarim and North China cratons to the south (Figure 1a), is a typical Phanerozoic accretionary orogen resulted from multiple episodes of subduction, amalgamation, and collision events in the Paleo–Asian Ocean area [10]. The West Junggar (WJ), an important part of the CAOB [15], is located on the west edge of the Junggar Basin (Figure 1b). West Junggar can be divided into north WJ, central WJ and south WJ domains (Figure 1c), which represent different subduction-accretion history [16].

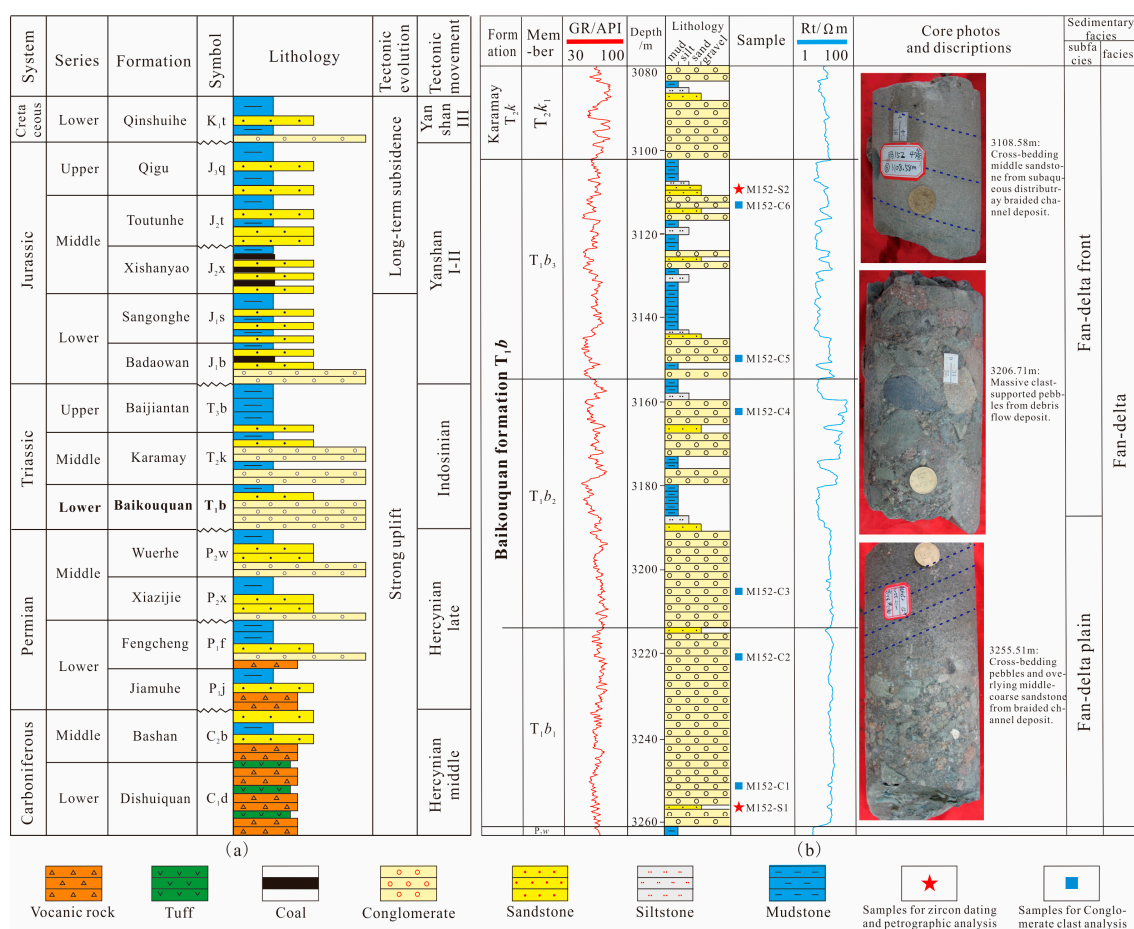


Figure 2. (a) Simplified stratigraphic column of Mahu sag; (b) Stratigraphic column and sedimentary facies of Triassic Baikouquan Formation of Well M152, with the sample locations in this study.

The north WJ is composed of Zharma–Saur arc and Boshchekul–Chingiz arc (Figure 1b,c) [17]. The Zharma–Saur volcanic arc, formed by the southward subduction of the Irtysh–Zaysan oceanic lithosphere during the early carboniferous [18,19], is composed of the Devonian to Early Carboniferous subduction-related magmatic rocks, and Early Carboniferous to Early Permian granitoid plutons [20]. The Boshchekul–Chingiz arc, formed by the northward subduction of the Junggar–Balkhash Ocean during the early Paleozoic age [18], is mainly composed of the Early Silurian to Early Devonian arc magmatic rocks, and a few Late Carboniferous to Early Permian granitoid plutons [21].

The central WJ, a remnant oceanic basin in the Carboniferous, is separated from the north WJ by the east–west striking Xiemisitai strike-slip fault and Cambrian Chagantaolegai ophiolitic mélange (Figure 1c). It consists of Devonian Darbut and Karamay ophiolitic mélange belts (Figure 1c), and Devonian to Carboniferous volcanic-sedimentary successions, intruded by the Late Carboniferous to Early Permian plutons (Figure 1c) [22,23]. The Darbut and Karamay ophiolite mélange belts are distributed along the northeast–southwest striking faults, and were formed in a Late Silurian to Late Devonian back-arc basin [24].

The south WJ, a composite arc-accretionary system resulted from the southward subduction of the Junggar Ocean [25], is separated from the central WJ by the northeast–southwest striking Barleik and Darbut strike-slip faults (Figure 1c). It is characterized by Ediacaran to Cambrian ophiolite mélange belts and Ordovician to Silurian intra-oceanic arc-related magmatic rocks, which are overlain unconformably by Devonian and Carboniferous volcanic-sedimentary successions, or intruded by Late Carboniferous to Early Permian plutons (Figure 1c) [26]. The ophiolite mélange belts, including the Barleike, Mayile and

Tangbale ophiolite mélanges from northwest to southeast direction, developed in a fore-arc environment [25].

2.3. Sedimentation of Xiazijie Fan-Delta

The early Triassic Baikouquan Formation (T₁b) in Mahu sag is constituted of 130–240 m grey and brown conglomerates, sandstone and minor mudstone deposited in a retro-gradation fan-delta environment (Figure 2b). Baikouquan Formation (T₁b) overlies on the Lower Urho Formation (P₂w) unconformably and underlies the middle Triassic Karamay Formation (T₂k) conformably (Figure 2). The Xiazijie fan-delta of the Baikouquan Formation, namely the research target of this paper, located in the north area of the Mahu sag, is a typical and rare large-scale lacustrine fan-delta with area of more than 1000 km² (Figure 1c). This fan-delta is mainly composed of subaerial and subaqueous debris flow and braided channel deposits (Figure 2b). The detrital clasts in the conglomerate and sandstone of Xiazijie fan-delta have moderate-poor sorting and roundness (Figure 2b), indicating the short-distance transportation and rapid deposition process. The gravel components of the Xiazijie fan-delta are tuff, andesite, rhyolite, felsite with minor granite, which are different to that of the Huangyangquan fan-delta, and the latter are granite, tuff with minor sedimentary rocks and metamorphic rocks [4].

3. Sampling Description and Analytical Methods

Six pebbly conglomerate samples (M152-C1, M152-C2, M152-C3, M152-C4, M152-C5 and M152-C6) at the bottom and top of each member of Baikouquan Formation of the Well 152 were observed for gravel compositions counting (Figure 2b); and one massive medium sandstone sample (M152-S1) at the bottom and one cross-bedding fine sandstone sample (M152-S2) at the top of Baikouquan Formation of the Well 152 were collected for petrographical analysis and detrital zircon U-Pb analysis (Figure 2b).

A total of 100 gravel clasts per conglomerate sample were observed and counted for statistics of conglomerate compositions, based on the method proposed by Howard (1993) [27]. Three thin sections per sandstone sample were made. The Gazzi–Dickinson point-counting method was used for sandstone composition statistics [28]. Sandstone detrital grains were classified into different types as follows: monocrystalline quartz (Qm), polycrystalline quartz (Qp), plagioclase feldspar (P), potassium feldspar (K), sedimentary lithic fragments (Ls), metamorphic lithic fragments (Lm) and volcanic lithic fragments (Lv) [29]. Furthermore, the quartzite (Qt), feldspar (F) and lithic fragments (L) were calculated by the following formulas: $Qt = Qm + Qp$, $F = P + K$, $L = Ls + Lm + Lv$ [30].

Zircon grains of two sandstone samples (M152-S1 and M152-S2) were obtained by standard crushing, sieving and conventional heavy liquid and magnetic separation at Langfang Yuneng Rock and Mineral Separation Technology Service Co., Ltd., Langfang, China. Cathodoluminescence (CL) images were attained to observe the internal structures of zircons, determine the origins of the zircons and select the zircon U-Pb analysis positions [31].

Zircon U-Pb isotope analyses were conducted at Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China, by using an Agilent 7700e laser-ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) that was equipped with a GeolasPro laser ablation system. The laser spot diameter for all ablate zircons was 32 µm. Zircon 91500 and glass NIST610 were used as external standards for U-Pb dating and trace element calibration, respectively, and the Plešovice zircon was dated to monitor the measurements. Zircon 91500 and Plešovice zircon yielded a weighted mean ²⁰⁷Pb/²⁰⁶Pb age of 1062.4 ± 8.9 Ma and a weighted mean ²⁰⁶Pb/²³⁸U age of 338.1 ± 1.0 Ma, respectively, which were in good agreement with the recommended age of 1062.6 ± 10.0 Ma and 337.1 ± 3.0 Ma [32]. A detailed experimental process refers to Jackson et al. (2004) and Moizinho et al. (2022) [33,34].

A software ICPMSDataCal was adopted to conduct off-line selection, integration of background and analyte signals, time-drift correction [35]. Concordia diagrams and weighted mean U-Pb age calculations were conducted using ISOPLOT/Ex (version 3.0)

software [36]. The U-Pb ages with discordance larger than 10% were excluded. $^{207}\text{Pb}/^{206}\text{Pb}$ ages for zircons > 1000 Ma and $^{206}\text{Pb}/^{238}\text{U}$ ages for zircons < 1000 Ma would be chosen [37].

4. Results

4.1. Conglomerate Clast and Sandstone Compositions

Fan-delta conglomerate is characterized by short-distance transportation and rapid accumulation, so gravel compositions in conglomerate can directly reflect the rock types of source area [38–40]. The conglomerate clast compositions of these samples mainly consist of pyroclastic rock (tuff) and intermediate-felsic magmatic rocks, probably indicating the magma arc source of the Xiazijie fan-delta sediments (Table 1).

Table 1. Conglomerate clast types identified in the Baikouquan Formation, Well M152.

Sample	Depth/m	Member	Tuff	Ande Site	Granite	Felsite	Trac Hyte	Rhyo Lite	Sand Stone
M152-C6	3112.61	b3	71	5	10	4	0	10	0
M152-C5	3149.08	b3	61	5	12	6	9	7	0
M152-C4	3162.18	b2	66	12	5	7	0	10	0
M152-C3	3205.52	b2	62	7	3	12	6	8	2
M152-C2	3220.61	b1	64	9	1	11	0	12	3
M152-C1	3250.96	b1	77	4	6	6	0	7	1

The average Qt:F:L value of the sample M152-S1 is 26:7:67, and that of the sample M152-S2 is 21:8:71 (Table 2), both of which can be classified as litharenite type, indicating a poor compositional maturity.

Table 2. Sandstone modal composition in the Baikouquan Formation, Well M152.

Sample	Member	Qm	Qp	P	K	Lv	Qt	F	L	Qt + F + L	Qt /%	F /%	L /%
M152-S2-1	b3	176	40	46	37	702	216	83	702	1001	22	8	70
M152-S2-2	b3	130	28	31	39	544	158	70	544	772	21	9	70
M152-S2-3	b3	133	40	16	40	666	173	56	666	895	19	6	75
Total of M152-S2	b3	439	108	93	116	1912	547	209	1912	2668	21	8	71
M152-S1-1	b1	93	38	6	25	384	131	31	384	546	24	6	70
M152-S1-2	b1	107	25	9	31	359	132	40	359	531	25	7	68
M152-S1-3	b1	94	39	8	24	275	133	32	275	440	30	7	63
Total of M152-S1	b1	294	102	23	80	1018	396	103	1018	1517	26	7	67

The lithic fragments are almost entirely volcanic lithic fragments, which mainly consist of tuff. Quartz grains are mainly composed of monocrystalline quartz (Table 2; Figure 3). All the framework grains from these sandstones are characterized by poor sorting and angular to sub-angular roundness, indicating a poor textural maturity (Figure 3).

In the Qt-F-L ternary diagram, M152-S1 and M152-S2 sandstone of the Baikouquan Formation plot in the magmatic arc domain, indicating that the tectonic setting of the source area for Xiazijie fan-delta was magmatic arc (Figure 4).

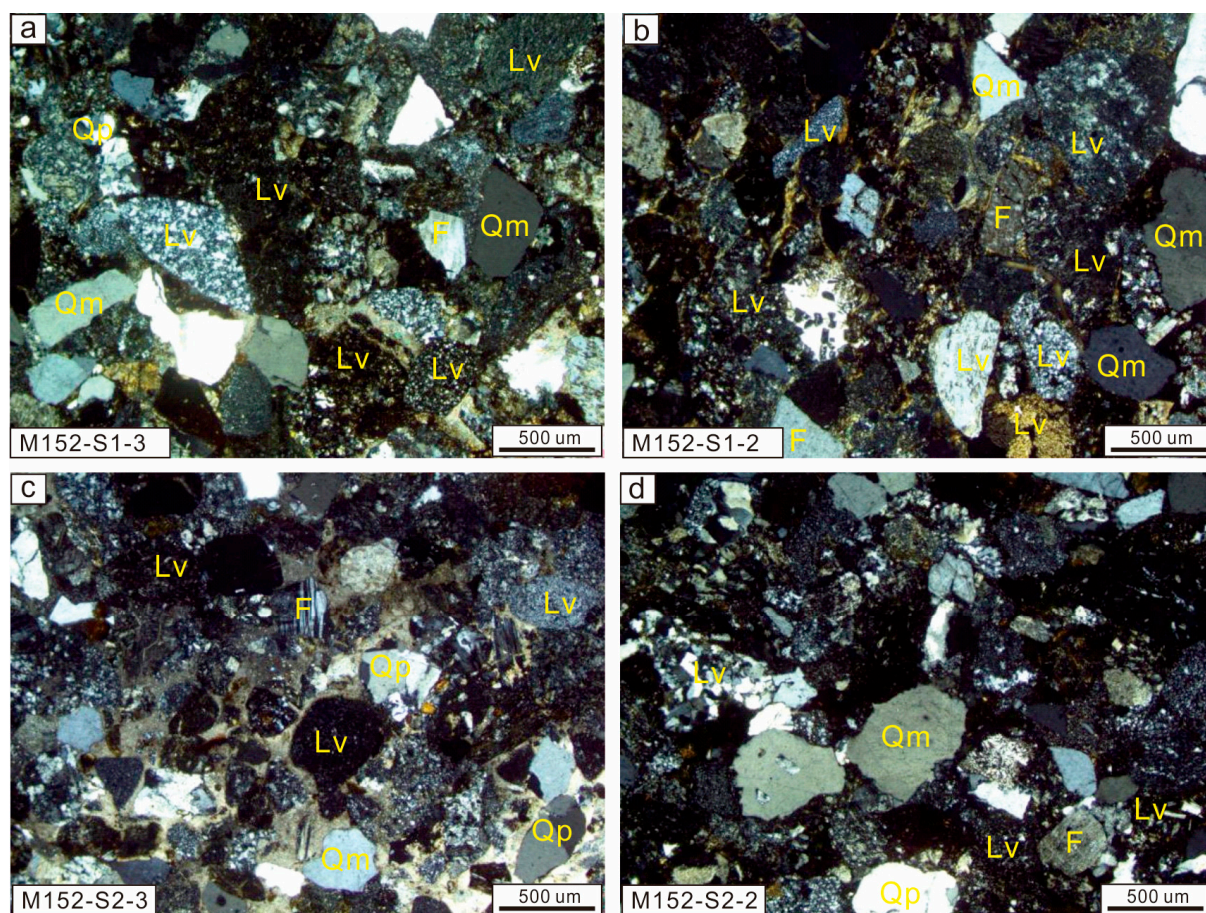


Figure 3. Photomicrographs showing the compositional characteristics of the sandstone M152-S1 (a,b) and M152-S2 (c,d) from Baikouquan Formation of Well M152. Abbreviations: Qm-monocrystalline quartz; Qp-polycrystalline quartz; F-Feldspar; Lv-volcanic lithic fragments.

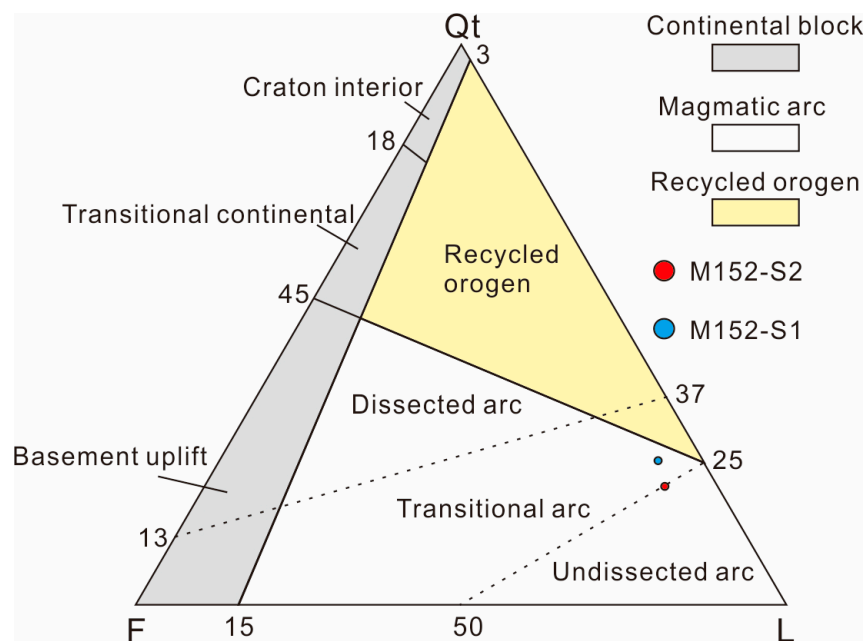


Figure 4. Qt-F-L ternary diagram of modal sandstone grain composition (after reference [29]).

4.2. Zircon Geochronology

Zircon grains from M152-S1 and M152-S2 are euhedral crystals, with clear concentric oscillatory zonings, indicating a magmatic genesis (Figure 5) [41,42]. A total of 89 and 98 effective detrital zircon U-Pb dates from sample M152-S1 and M152-S2 were obtained (Table S1). Considering these U-Pb ages were younger than 1000 Ma, $^{206}\text{Pb}/^{238}\text{U}$ ages were chosen.

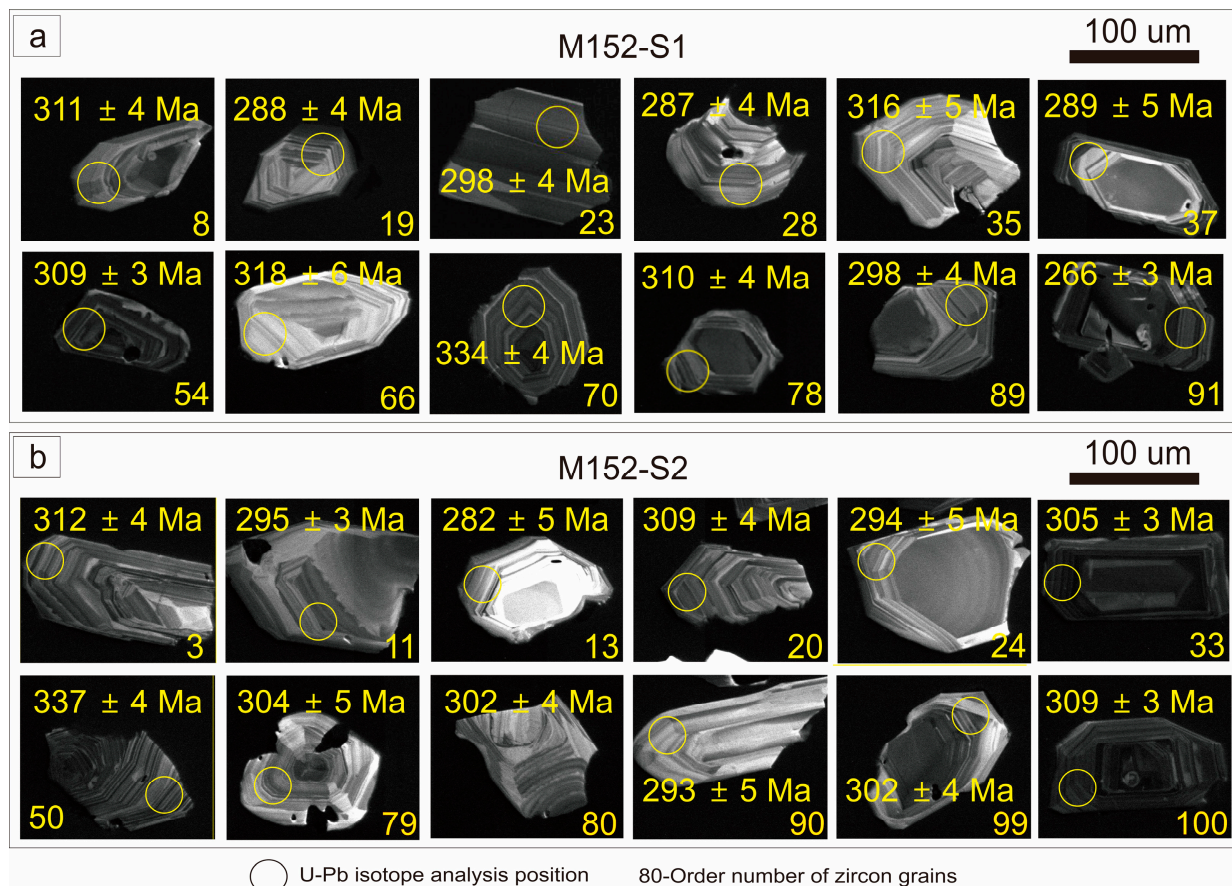


Figure 5. Cathodoluminescence (CL) images and U-Pb dates of representative detrital zircon grains from sandstone samples M152-S1 (a) and M152-S2 (b).

Sample M152-S1: 91 detrital zircon grains were analyzed and 89 concordant dates were obtained (Figure 6a), showing a range between 417 Ma and 253 Ma (Table S1). The dates are characterized by a dominant date peak at 313 Ma and two secondary date peaks at 411 Ma and 268 Ma (Figure 6d).

Sample M152-S2: 100 detrital zircon grains were analyzed and 98 concordant dates were gained (Figure 6b), showing a range between 467 Ma and 256 Ma (Table S1). The dates are characterized by a dominant date peak at 307 Ma and two secondary date peaks at 405 Ma and 262 Ma (Figure 6c).

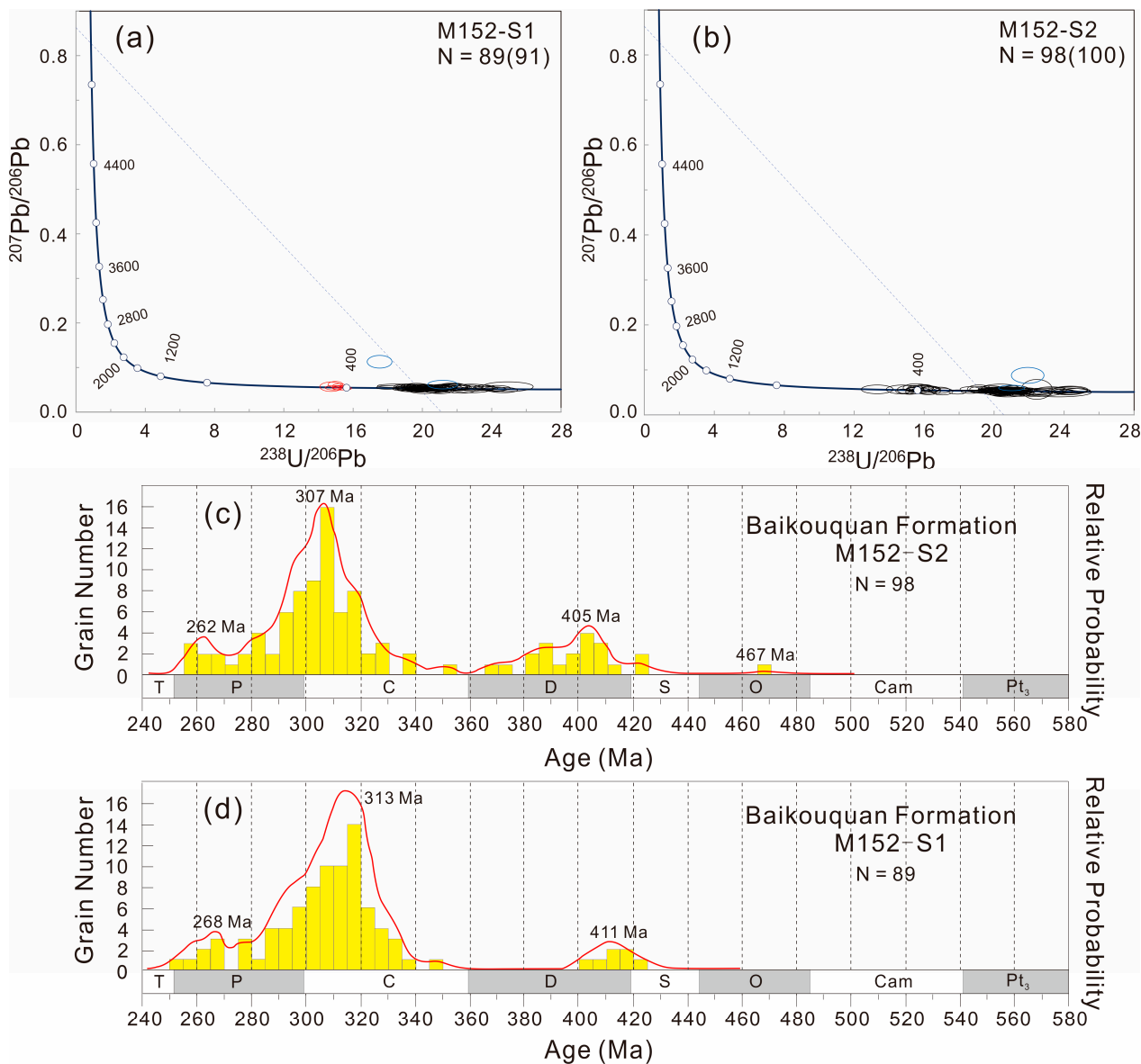


Figure 6. U-Pb dates Tera-Wasserburg plot (a,b) and relative probability density distribution (c,d) for detrital zircons from the Baikouquan Formation sandstone.

5. Discussion

5.1. Maximum Depositional Age of the Baikouquan Formation

The mean age of the youngest two or more detrital zircon grains with ages overlapping at 1σ (YC1 σ [2+]) was always employed to determine the maximum depositional ages [9–11]. Two sandstone samples (M152-S1 and M152-S2) in Baikouquan Formation displayed two youngest mean ages of 254.8 ± 4.7 Ma and 257.6 ± 3.8 Ma, respectively, suggesting that Baikouquan Formation might be deposited after the Changhsingian to Olenekian.

5.2. Regional Magmatism and Potential Sources

Textural and mineralogical immaturity of the sandstone and poor sorting of conglomerate from the Xiazijie fan-delta indicate that these delta sediments underwent a short-distance transportation. Thereby, the northern, central and southern West Junggar domains should be potential sources terranes for this Xiazijie fan-delta. Detrital zircons

ages from sandstone samples M152-S1 and M152-S2 were compared with magmatic rock ages of West Junggar domain (Figures 7 and 8; Table S2).

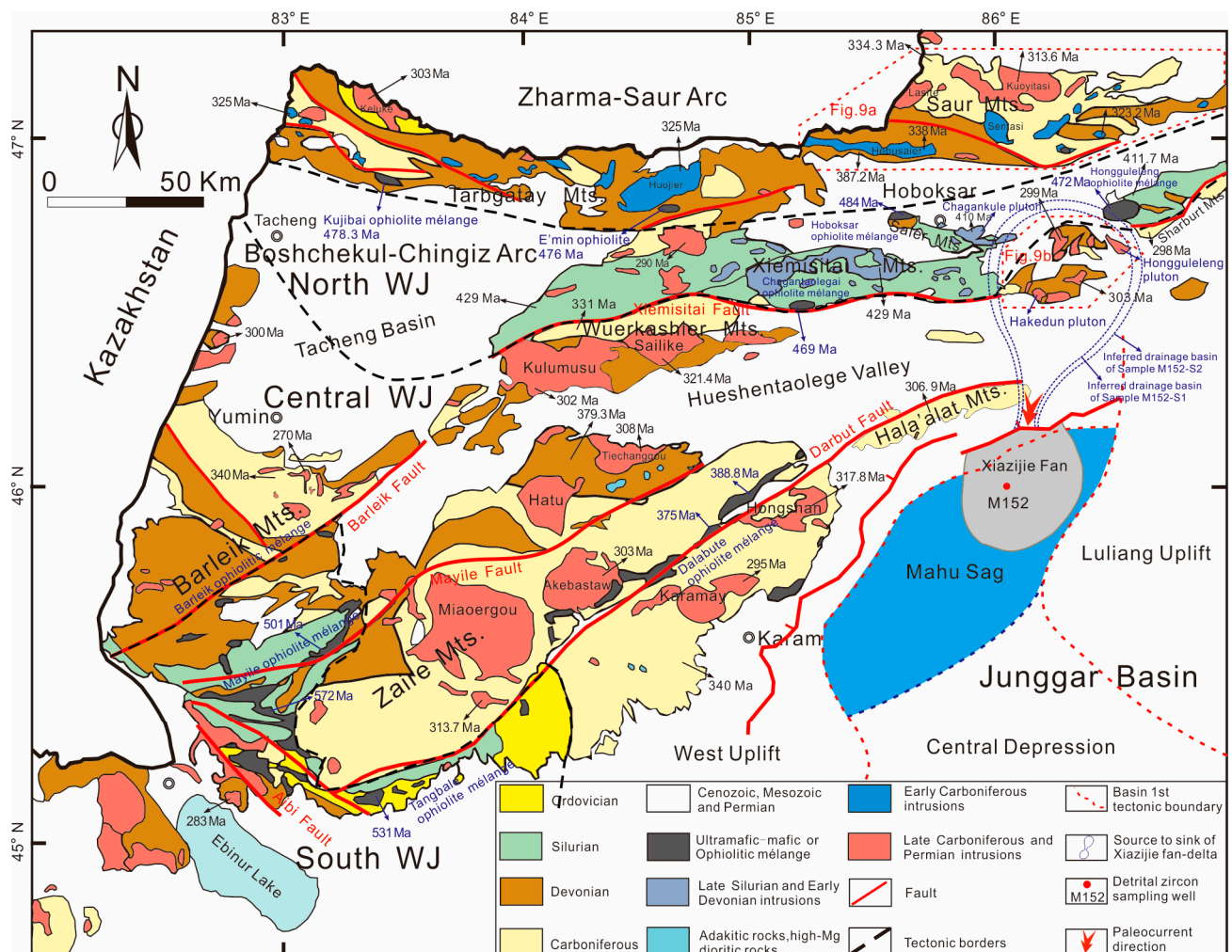


Figure 7. Age distribution map of magmatic rocks in the West Junggar region. Age data for Zharma-Saur arc of the north WJ area are from references [16,19,43,44]; Age data for Boshchekul–Chingiz arc of the north WJ area are from references [21,23,45–48]; age data for central WJ area are from references [5,16,49–52]; age data for south WJ area are from references [26,53–55].

The magmatic rock ages of Zharma–Saur arc of the north WJ domain were distributed mostly between 360–290 Ma, with a few at 480–390 Ma (Figure 8a). The magmatic rock ages of Boshchekul–Chingiz arc of the north WJ domain were distributed mostly between 520 and 360 Ma, with a few at 350–260 Ma (Figure 8b). The magmatic rock ages of central WJ domain were distributed mostly between 450 and 260 Ma (Figure 8c), and that of south WJ domain was dominated by 540–480 Ma and 320–250 Ma (Figure 8d).

5.3. Provenance of Xiazijie Fan-Delta

The detrital zircon U–Pb ages of sample M152-S1 were distributed mostly between 330 and 290 Ma, with a main peak age at 313 Ma (Figure 8f), suggesting intense Late Carboniferous magmatic activity in the provenance area, which is coincident with the Late Carboniferous to Early Permian post-collision magmatic activity in the whole West Junggar area (Figure 7; Table S2).

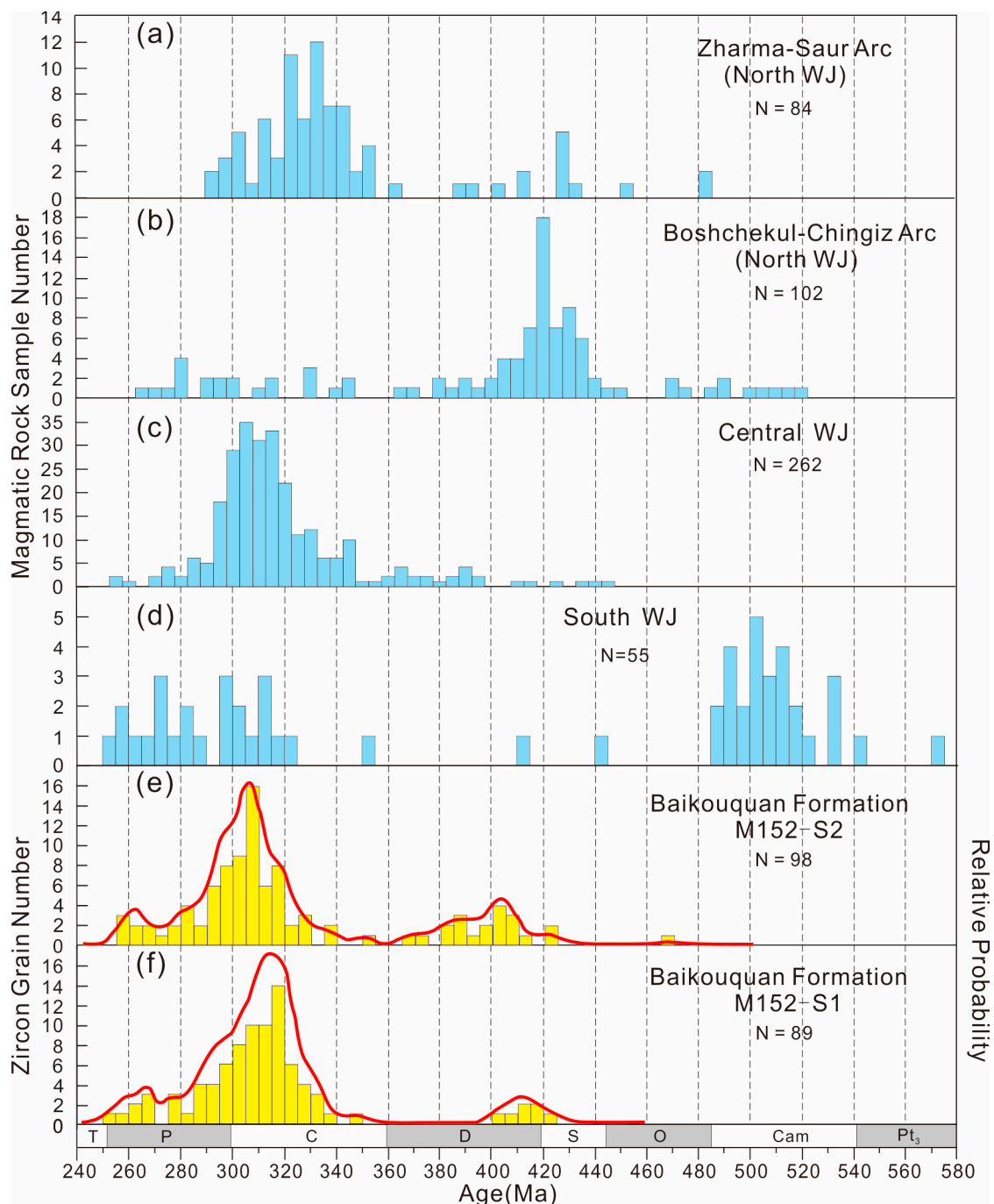


Figure 8. Magmatic rocks age distribution from (a) Zharma–Saur arc of North WJ, (b) Boshchekul–Chingiz arc of North WJ, (c) Central WJ, and (d) South WJ areas. (e,f) Frequency and relative probability density curves for detrital zircons U–Pb ages from the Xiazijie fan-delta.

However, Early Carboniferous intrusions rather than Late Carboniferous intrusions widely developed in the Zharma–Saur arc (Figures 7 and 8a), indicating this arc is not the main provenance area for this sample. The Boshchekul–Chingiz arc contained a large area of the Late Silurian to Early Devonian magmatic rocks and locally distributed Late Carboniferous to Early Permian post-collision magmatic rocks (Figures 7 and 8b), indicating Boshchekul–Chingiz arc also was not the main provenance area. The south West Junggar domain contained many Late Carboniferous to Early Permian post-collision magmatic rocks in the Alashankou area (Figure 7), but it can also be excluded by the following factors: (1) the Alashankou area is located hundred kilometers to the southwest of the Xiazijie area,

which contradicts the short-distance transportation nature of fan-delta deposit and the paleocurrent direction from north to south reconstructed by heavy minerals ZTR index, formation dip logging and the conglomerate thickness/formation thickness ratio [3,4]; (2) Cambrian ophiolite mélanges, such as Mayile ophiolite mélange and Tangbale ophiolite mélange, are widely distributed in the whole south West Junggar domain (Figure 7), but the zircon U-Pb ages more than 480 Ma were absent in this sample (Figure 8f).

Furthermore, the central West Junggar domain contained numerous Late Carboniferous to Early Permian post-collision magmatic rocks, such as Hakedun and Hongguleleng plutons in the east margin of Xiemisitai mountain, Kulumusu pluton in the Wuerkashier mountain and Hatu pluton, Miaoergou pluton in the Zaire mountain (Figures 1c and 7), and the prominent peak age of central West Junggar (303.2 Ma) was very similar to that of the sample M152-S1 (Figure 8c,f), indicating the central West Junggar should be the major source area of this sample M152-Z1.

The zircon U-Pb ages of sample M152-S2 was dominated by 330–290 Ma, with a main peak age at 307 Ma. Similarly, the central West Junggar area was believed to be the major source area of this sample (Figure 8c,e). The highly similarity of the whole age range, dominated peak age and subordinate peak ages between sample M152-S1 and M152-S2 suggest that no great change of source area occurred when Xiazijie fan-delta deposited (Figure 8e,f).

In order to confine the concrete position of the source area, the crystallization ages of magmatic rocks from Saur arc and Hakedun–Hongguleleng region in the east margin of Xiemisitai mountain were compiled (Figures 7 and 9a,b), considering these two regions are located to the north of the Xiazijie fan-delta and Late Carboniferous to Early Permian post-collision magmatic rocks were widely distributed in both of them (Figure 7).

The magmatic rock ages of Saur arc of the north WJ domain were distributed mostly between 360 and 310 Ma, with a few at 310–290 Ma (Figure 9a), which were evidently different from the ages distribution of these two samples (Figure 9c,d). Considering the Late Carboniferous to Early Permian post-collision magmatic rocks (such as Kuoyitasi and Lasite plutons) were located to the north of the Early Carboniferous magmatic rocks (such as Sentasi and Hebusaier plutons) (Figure 7), the Saur arc should not be the provenance area of these samples.

Furthermore, the Hakedun–Hongguleleng area in the east margin of the Xiemisitai mountain was characterized by a peak age at 305 Ma (Figure 9b), which is consistent with the peak ages (313 Ma and 307 Ma) of these two samples (Figure 9c,d), indicating the Hakedun–Hongguleleng area was likely to be their major source area.

Even if no crystallization ages of magmatic rocks younger than 280 Ma were reported from the Hakedun–Hongguleleng area, the detrital zircons with ages < 280 Ma from these samples are still believed to come from this area: (1) Late Carboniferous to Early Permian post-collision magmatic rocks only developed in the Hakedun–Hongguleleng area rather than the nearby Sharburt mountain, Saier mountain or middle part of Xiemisitai mountain (Figure 7); (2) magmatic rocks crystallization ages of 259 Ma, 270 Ma, 272 Ma and 274 Ma were reported from the Late Carboniferous to Early Permian post-collision intrusions in the northern Barleik mountain of the Central West Junggar (Figure 7; Table S2) [8].

Furthermore, one Early Devonian minor peak age at 411 Ma from sample M152-S1 and another minor peak age at 405 Ma from sample M152-S2 were obtained (Figure 6). Considering that abundant Late Silurian–Early Devonian intrusions, such as the Chagankule pluton in the Saier Mountain, developed to the west of the Hakedun–Hongguleleng area (Figure 7), these Late Silurian–Early Devonian intrusions in the east part of the Saier Mountain are likely to be the minor source area.

Based on the above, the paleo-current direction from heavy minerals analysis, and general morphology of drainage basin, the approximate range of the source area or drainage basin of the sample M152-S1 was drawn (Figure 7). The northeast boundary of the drainage basin was located between Hongguleleng pluton and Hongguleleng ophiolite mélange, and the west boundary of which was in the Chagankule pluton of the Saier Mountain.

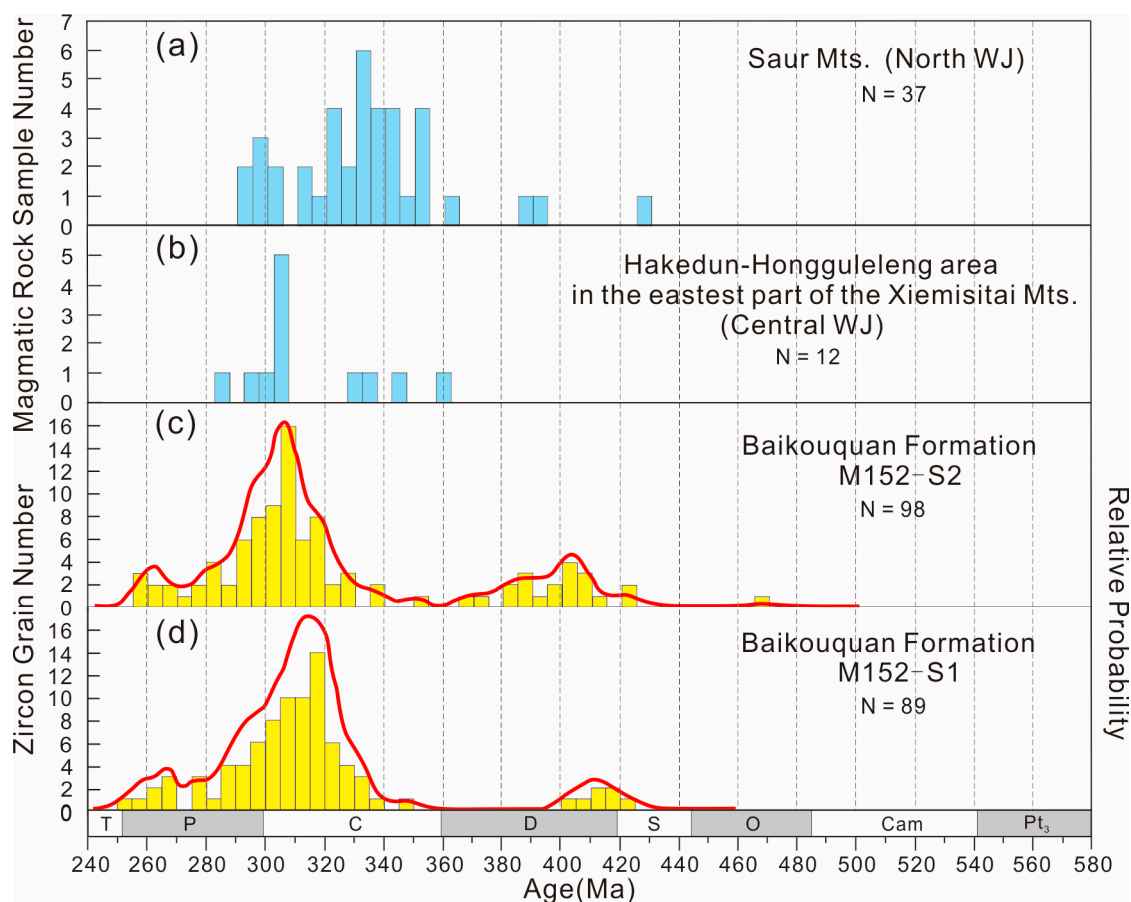


Figure 9. Magmatic rocks age distribution from (a) Saur arc of North WJ, (b) Hakedun-Hongguleleng regions of Central WJ, (c,d) Frequency and relative probability density curves for zircons U-Pb ages from the Xiazijie fan-delta.

Compared with M152-S1, the relative probability of minor peak with Early Devonian age from M152-S2 was higher, and a zircon grain with Middle Ordovician age (467 Ma) was firstly obtained (Figure 6), implying the small northward extension of the drainage basin of Xiazijie fan-delta by a few kilometers, and the part of Hongguleleng ophiolite mélangé in the Sharburt mountain also became the minor source area during the late stage of the Baikouquan Formation sedimentation (Figure 7).

5.4. Source to Sink System of Xiazijie Fan-Delta

Based on the source area analysis in this paper and sedimentary studies of Xiazijie fan-delta by other scholars [2–4], a simplified source to sink system of Xiazijie fan-delta was reconstructed (Figure 10). The drainage basin was bordered by the Hongguleleng ophiolite mélangé in the Sharburt mountain on the northeast and Chagankule pluton in the Saier Mountain on the west, with a long axis of about 75 km and a short axis of about 40 km (Figure 10).

In the early Triassic, the inherited thrusting activity of the WuXia fault resulted in the uplift of the hanging wall regions including the West Uplift area, Central and Northwest Junggar terrane, and the subsidence of the north of Mahu sag [1,2]. Many detrital materials eroded from the Hakedun–Hongguleleng area were transported by braided channels and debris flows to the lake margin of Mahu sag, and were then deposited as a typical large-scale gravelly fan-delta, namely Xiazijie fan-delta, with the long axis more than 40 km (Figure 10).

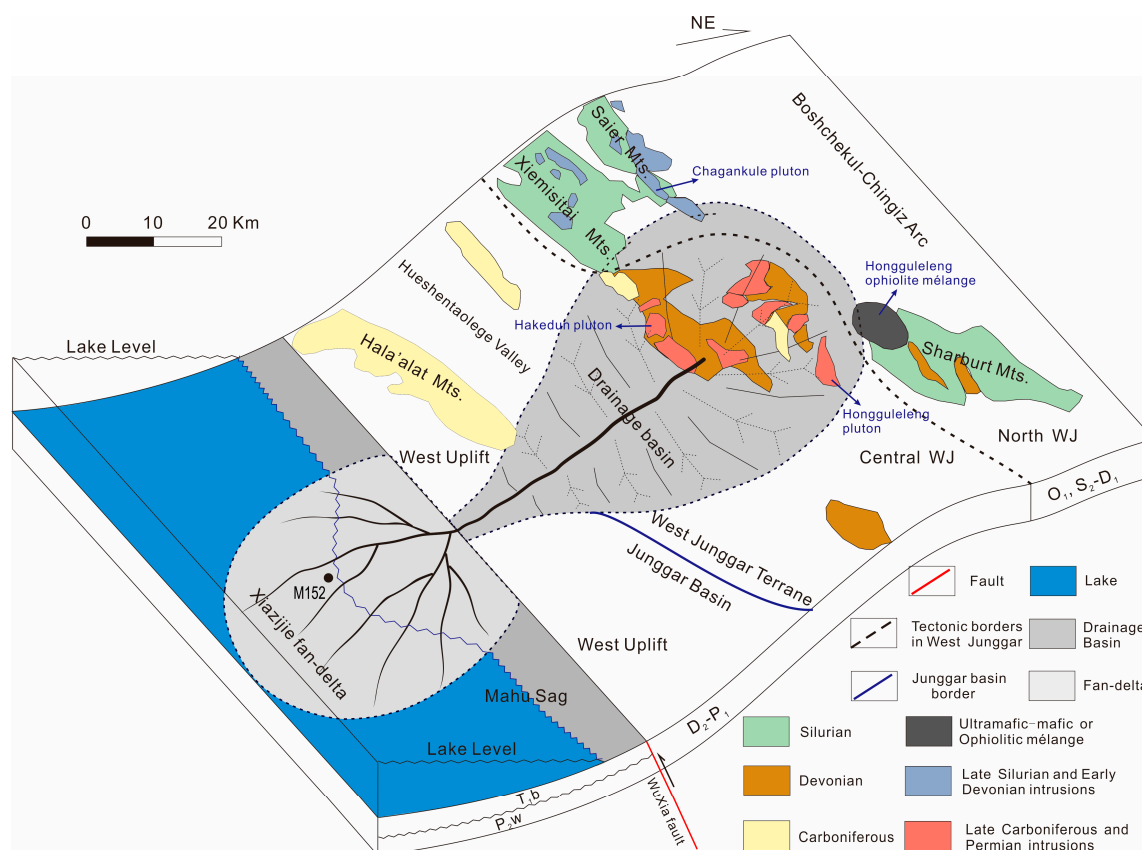


Figure 10. Simplified source to sink system map of the Xiazijie fan-delta.

6. Conclusions

(1) The compositions of conglomerate clasts and sandstone grains, and Qt-F-L ternary diagram plot showed that the source of the Xiazijie fan-delta was primarily arc magmatic rocks.

(2) M152-S1 yielded U-Pb ages ranging from 417 Ma to 253 Ma, with a dominant age peak at 313 Ma and two secondary age peaks at 411 Ma and 268 Ma, while M152-S2 yielded U-Pb ages ranging from 467 Ma to 256 Ma, with a dominant age peak at 307 Ma and two secondary date peaks at 405 Ma and 262 Ma.

(3) Two sandstone samples (M152-S1 and M152-S2) yielded youngest mean ages of 254.8 ± 5 Ma and 257.6 ± 4 Ma, respectively, suggesting the maximum depositional age of Baikouquan Formation might be Changhsingian to Olenekian.

(4) The magmatic rock ages of central West Junggar were distributed mostly between 450 and 260 Ma, with a dominant age peak at 307 Ma. The ages distribution between magmatic rock of central WJ and detrital zircons of M152-S1 and M152-S2 were similar, indicating the central WJ domain should be the major source area of the Xiazijie fan-delta.

(5) The magmatic rock of Hakedun–Hongguleleng area in the Central WJ was characterized by a peak age at 305 Ma, which was consistent with the peak ages of M152-S1 and M152-S2, indicating the Hakedun–Hongguleleng area was likely to be their major source area.

(6) One minor peak age at 411 Ma and another at 405 Ma were obtained from M152-S1 and M152-S2, respectively, and a zircon grain with Middle Ordovician age (467 Ma) was obtained from M152-S2, indicating Late Silurian–Early Devonian Chagankule pluton in the Saier Mountain and Ordovician Hongguleleng ophiolite mélange in the Sharburt mountain were the minor source areas.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min13040467/s1>, Table S1: Detrital zircon LA-ICP-MS U-Pb dating analytical data of the Baikouquan formation. Table S2: Magmatic rock ages of the West Junggar area.

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