

Article

Late Silurian–Early Devonian Magmatism in the Southeastern Sarysu–Teniz Uplift, Central Kazakhstan: Zircon U–Pb Geochronology and Major-Element Geochemistry

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Abstract

The southeastern Sarysu–Teniz Uplift in Central Kazakhstan is partly concealed beneath Cenozoic sediments, which complicates the correlation and age assignment of its Paleozoic magmatic rocks. This study combines new zircon U–Pb ages from four felsic volcanic samples with whole-rock major-element data for volcanic and intrusive rocks to constrain the timing of magmatism and assess their compositional relationships. The principal zircon populations yield concordia ages of 414 ± 3 , 415 ± 2 , 421 ± 2 , and 414 ± 2 Ma, with uncertainties reported at 2σ , indicating Late Silurian–Early Devonian magmatism. Older populations at 440 ± 6 and 438 ± 6 Ma and a single ca. 2.67 Ga zircon document older components, although their provenance remains unresolved. Comparison with previously published intrusive ages supports partial temporal overlap between volcanic and plutonic activity, but does not establish a single magmatic system. Major-element variations are compatible with differentiation involving fractional crystallization, while crustal melting, assimilation, magma mixing, and source heterogeneity remain possible contributors. The available geochemical data do not uniquely identify source lithologies or tectonic setting. These results refine the chronology of the sampled volcanic rocks and provide a basis for revising their regional correlation and relationship with intrusive magmatism.

Keywords: zircon; U–Pb age; petrogenesis; Sarysu–Teniz uplift; Central Kazakhstan; Central Asian Orogenic Belt



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1. Introduction

Central Kazakhstan is one of the country's major ore-bearing regions. It is composed predominantly of Paleozoic, as well as Precambrian and Mesozoic, formations and has been the subject of numerous geological investigations [1–4]. The Sarysu–Teniz Uplift is located in western Central Kazakhstan between the Zhezkazgan and Teniz basins [5]. Most of the uplift is well exposed, except for its southeastern part. The southeastern part of the uplift is

adjacent to the iron–copper Zhezkazgan district and the lead–zinc–iron–manganese Atasu–Zhairem district [6–15]. The proximity to these ore districts has stimulated exploration for concealed ore deposits beneath the sedimentary cover, as has been demonstrated in other regions [16–21].

In recent years, various studies on geophysics, intrusive magmatism, and the petrography of volcano-sedimentary rocks have been carried out in the Sarysu–Teniz region [15,22–27]. However, the age and petrogenesis of the volcanic rocks in the southeastern part of the region remain poorly constrained. The study area is located in the southeastern part of the uplift (Figure 1).



Figure 1. Location of the study area on the administrative map of Kazakhstan.

This study aims to constrain the timing of felsic volcanism in the southeastern Sarysu–Teniz Uplift using zircon U–Pb geochronology and to assess the compositional relationships between volcanic and intrusive rocks using whole-rock major-element data. The volcanic ages are compared with previously published intrusive ages to evaluate their regional temporal relationship. Petrogenetic interpretations are considered within the limitations of the available geochemical dataset.

2. Geological Setting

The Sarysu–Teniz Uplift is located between the Kypshak Trough to the north and the Zhezkazgan Basin to the south, while its eastern part adjoins the Devonian marginal volcanic belt [25]. Tectonically, it represents the northern part of the Chu–Sarysu sedimentary basin [28]. Most of the area is covered by Cenozoic sediments (Figure 2). The oldest rocks are Lower Cambrian (Є_1) green and grayish-green basalts and basaltic porphyrites exposed in the southern part of the area, which formed during oceanic seafloor spreading. From the Middle Ordovician to the end of the Early Devonian, the area evolved in an active continental margin setting. During the Ordovician and Silurian, an island-arc system developed. Middle–Upper Ordovician (O_{2-3}) deposits occur in the southern part of the area and consist predominantly of sandstones interbedded with siltstones and mudstones. The Silurian succession is widespread and comprises two units: a lower terrigenous unit (St) and an upper andesite–basalt unit (Sab). The terrigenous unit is composed mainly of gray

siltstones and sandstones, whereas the andesite–basalt unit (Sab) consists of grayish-green to green basalts, andesibasalts, and their tuffs [27]. The volcanic fields of the andesite–basalt unit are accompanied by subvolcanic bodies of moderately alkaline diabase and gabbro–diabase ($v\beta$, $\varepsilon v\beta S$). Volcanic rocks of the rhyolite–dacite unit, ranging in age from the Pridoli Series of the Silurian to the Lower Devonian, are widely distributed and extend along the western margin of the study area.

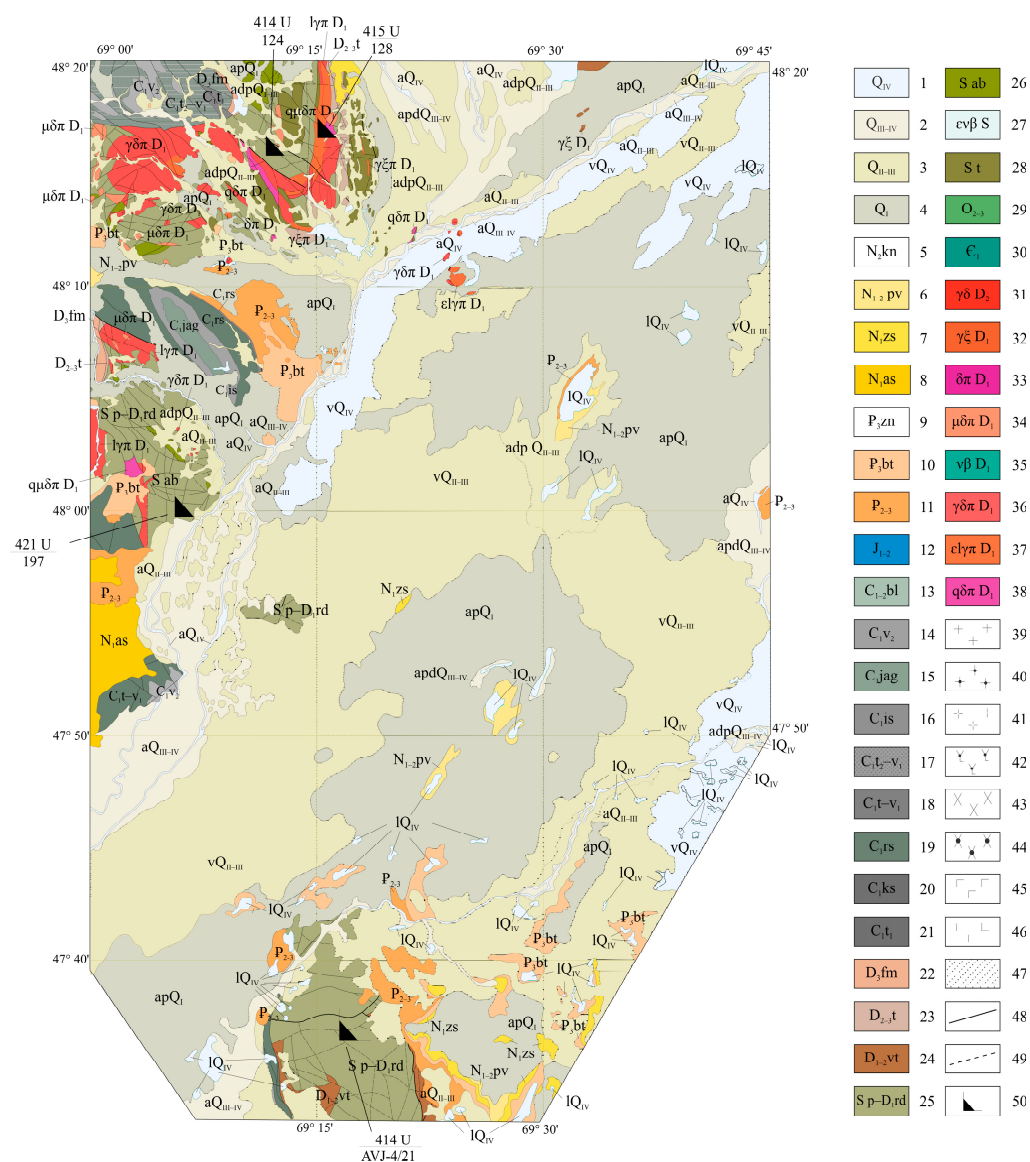


Figure 2. Schematic geological map of the southeastern Sarysu–Teniz Uplift. 1–4—Quaternary deposits: 1—Holocene. Alluvial (a), aeolian (v), lacustrine (l). 2—Upper Pleistocene–Holocene. Alluvial (a) and alluvial–proluvial (ap). 3—Middle–Upper Pleistocene. Alluvial (a), alluvial–proluvial (ap), aeolian (v). 4—Lower Pleistocene. Alluvial–proluvial (ap). 5–8—Neogene formations: 5—Kenshagir Formation. Clays. 6—Pavlodar Formation. Clays. 7—Zhamansarysu Formation. Clays. 8—Aksazansor Formation. Quartz sands and pebble beds. 9–11—Paleogene formations: 9—Zhanaarka Formation. Sands, silty clays, siltstones, sandy loams, and clays. 10—Betpakdala Formation. Clays with interbeds of quartz sands and lignites. 11—Eocene–Oligocene. Clays. 12—Jurassic, Lower–Middle undivided. Sandstones, gravelstones, conglomerates. 13–21—Carboniferous: 13—Lower–Middle undivided. Beleuty Formation. Sandstones, siltstones, and mudstones. 14—Upper Visian. Siltstones and mudstones. 15—Yagovka Formation. Siltstones, mudstones, limestones. 16—Ishim

Formation. Limestones and calcareous siltstones. 17—Upper Tournaisian–Lower Viséan, undivided. Limestones and marls. 18—Tournaisian–Lower Viséan, undivided. Limestones and marls. 19—Rusakov Formation. Limestones and marls. 20—Kassin Formation. Limestones. 21—Lower Tournaisian. Limestones, black and gray chert nodules. 22–24—Devonian: 22—Upper Devonian, Famennian. Limestones and dolomites. 23—Middle–Upper Devonian, undivided. Terrigenous deposits with interbeds of felsic lava and ash tuffs. 24—Lower–Middle Devonian, undivided. Terrigenous deposits with lenses and interbeds of felsic tuffs. 25–29—Silurian: 25—Přídolí (Silurian)–Lower Devonian. Rhyolite–dacite unit. 26—Andesite–basalt unit. 27—Subvolcanic rocks: diabases ($\nu\beta$) and moderately alkaline diabases. 28—Terrigenous unit. 29—Middle–Upper Ordovician, undivided. Sandstones, siltstones, gravelstones, and conglomerates. 30—Lower Cambrian. Basalts, basaltic porphyrites, and picobasalts. Intrusive rocks: 31—Granodiorites; 32—Granosyenites; 33–35—Hypabyssal intrusions: 33—Diorite porphyries, quartz diorites ($q\delta\pi$), monzodiorite porphyries, monzodiorites ($\mu\delta$); 34—Quartz monzodiorite porphyries ($q\mu\delta\pi$); 35—Diabases, gabbro-diorites ($\nu\delta$), gabbro-diorite porphyries ($\nu\delta\pi$). 36–38—Hypabyssal intrusions: 36—Granodiorite porphyries, granite porphyries ($\gamma\pi$); 37—Normal-alkaline and low-alkaline leucogranite porphyries ($l\gamma\pi$), moderately alkaline leucogranite porphyries, granosyenite porphyries ($\gamma\xi\pi$); 38—Quartz diorite porphyries; 39—Granites; 40—Moderately alkaline granites; 41—Leucocratic granites; 42—Granosyenites; 43—Diorites, quartz diorites; 44—Monzonites, monzodiorites; 45—Gabbros; 46—Gabbro-diorites; 47—Intermediate to mafic subvolcanic rocks. Faults: 48—Major; 49—Inferred. 50—Sampling sites for radiometric age determinations.

The subsequent evolution of the active continental margin was associated with the development of the Devonian continental-margin volcano-plutonic belt. The Devonian succession (D) comprises the Lower–Middle Devonian volcano-sedimentary deposits (D_{1-2vt}), the Middle–Upper Devonian terrigenous deposits (D_{2-3}), and the Upper Devonian Famennian carbonate deposits (D_{3fm}). Carboniferous deposits (C) crop out in the eastern and northeastern parts of the study area and are represented by limestones, gray polymictic sandstones, siltstones, and mudstones.

Jurassic sandstones, gravelstones, and conglomerates (J_{1-2}) do not crop out in the study area (Figure 3). Paleogene variegated clays and gray sands are distributed mainly in the southern and eastern parts of the area. Neogene deposits occur predominantly in the east and consist of gray quartz sands, pebble beds, and clays. Quaternary deposits cover the vast majority of the study area and are represented by alluvial–deluvial–proluvial, alluvial, and lacustrine sediments of Pleistocene and Holocene age.

2.1. Magmatic Rocks of the Study Area

Intrusive Rocks

The intrusive rocks are represented by four groups: Lower Devonian (1) predominantly felsic, intermediate-felsic, and intermediate-acid intrusions; (2) intermediate, intermediate-mafic, and mafic intrusions; (3) granosyenites; and (4) Middle Devonian granodiorites.

The Middle Devonian granodiorites form two small plutons in the southern part of the study area, each covering an area of less than 1 km². The first pluton intrudes into the Middle–Upper Ordovician strata, whereas the second intrudes into the Lower–Middle Devonian succession. Both intrusions consist of porphyritic granodiorites and are partially covered by Cenozoic sediments.

Hypabyssal intrusions include quartz diorite porphyries ($q\delta\pi D_1$), granodiorite porphyries ($\gamma\delta\pi D_1$), granosyenite porphyries ($\gamma\xi\pi D_1$), granite porphyries ($\gamma\pi D_1$), leucogranite porphyries, and moderately alkaline leucogranite porphyries. These rocks constitute the most widespread intrusive rocks in the study area. More than ten intrusions have been identified, and their sizes vary considerably. The largest plutons, covering areas of 50–70 km², include the Karasu, Tuyemoynak, Koksengir, South Sarysu, and West Utzhal massifs. Smaller intrusions, with areas not exceeding 10–15 km², are represented by the

Espe, Utzhal, South Espe, East Tuyemoynak, Baisugen, and Moyyn massifs. The remaining bodies have exposed areas ranging from a few square kilometers to less than 1 km².

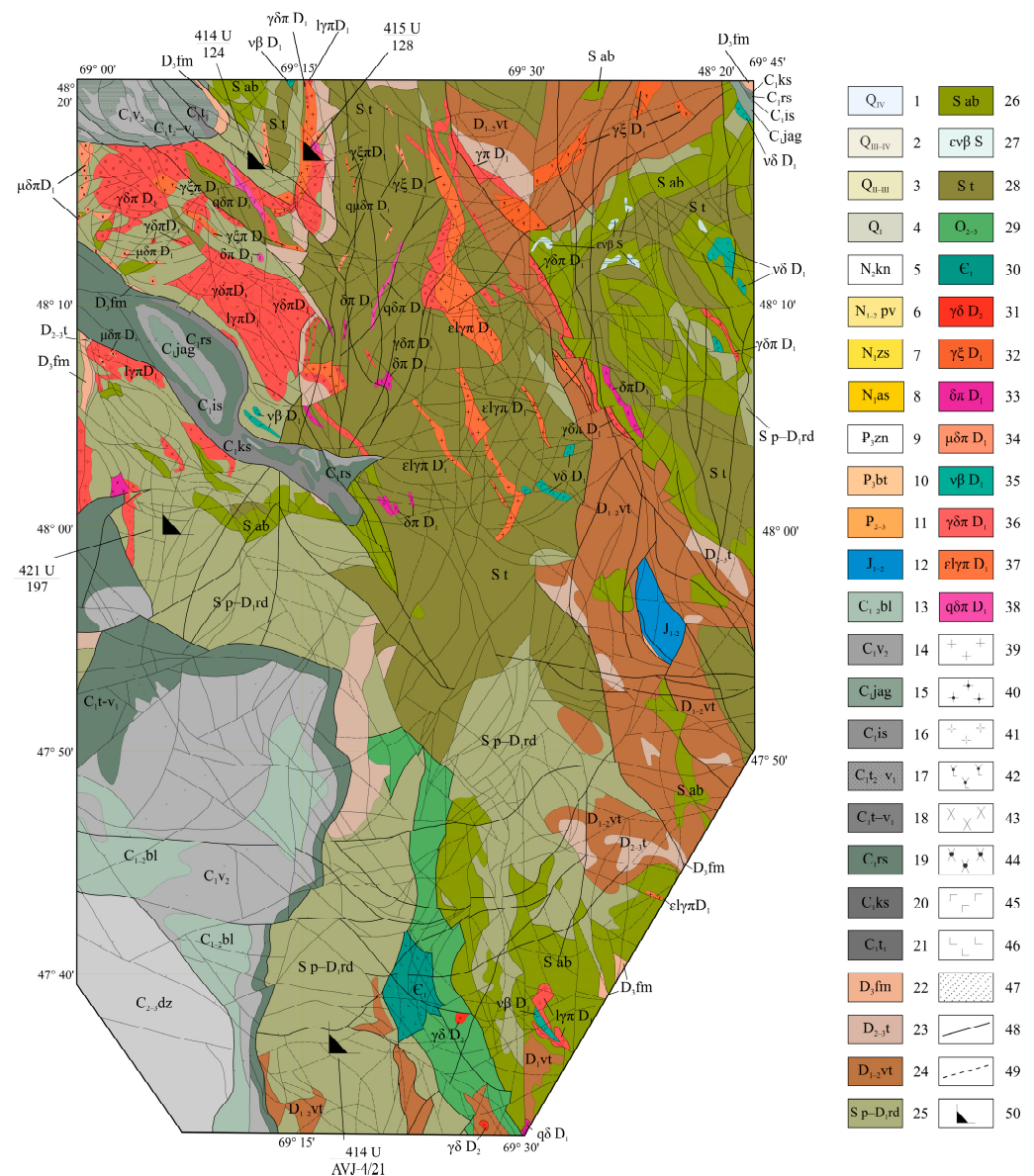


Figure 3. Basement geological map of the study area. Symbols are the same as in Figure 2.

This group comprises porphyritic and porphyritic-like, less commonly aphyric, igneous rocks with a cryptocrystalline, less commonly fine- to medium-grained holocrystalline groundmass. The rocks are divided into two groups, each characterized by the formation of independent intrusive bodies. The dominant petrotype of the first group is granodiorite porphyry (this group also includes quartz diorite porphyries and granosyenite porphyries), whereas the second group is dominated by leucogranite porphyries. Granite porphyries, which represent a transitional variety between these two principal groups, are considerably less common. Granodiorite porphyries are gray, greenish-gray, or purplish-gray rocks of dark shades. Leucogranite porphyries are typically pink, pale yellowish, light gray to nearly white, or lilac in color. Granites are pink, purplish-pink, or lilac.

The hypabyssal intrusive group includes diabases ($v\beta D_1$), gabbro-diorites ($v\delta D_1$), gabbro-diorite porphyries ($v\delta\pi D_1$), diorite porphyries ($\delta\pi D_1$), monzodiorites ($\mu\delta D_1$), monzodiorite porphyries ($\mu\delta\pi D_1$), quartz diorites and quartz diorite porphyries ($q\delta D_1$), and quartz monzodiorite porphyries ($q\mu\delta\pi D_1$). This group comprises intrusive bodies com-

posed of intermediate-composition rocks exhibiting a wide range of petrographic and petrochemical characteristics. In addition to their relatively mafic composition, these intrusions are generally characterized by small sizes, typically not exceeding 1–2 km², and by stock-like and dyke-like forms.

The granosyenite intrusive complex ($\gamma\xi D_1$) comprises relatively small intrusive bodies of heterogeneous composition, ranging from mafic to highly felsic in terms of silica content and from subalkaline to moderately alkaline in terms of total alkali content.

The age of the above-described rocks has been estimated by [25] as ranging from the latest Lochkovian to the Emsian of the Early Devonian.

2.2. Volcanic Rocks of the Study Area

Rhyolite–Dacite Unit (Sp–D₁rd). Deposits of the Přídolí Series of the Silurian to the Lower Devonian are widely distributed throughout the study area. Their main distribution forms a north–south-trending belt 6–20 km wide along the western part of the area (Figure 3). In the eastern part, exposures are less common. In the west, the volcanic rocks of the unit are intruded by numerous hypabyssal intrusions of granodioritic, granitic, and leucogranitic composition. The stratigraphic succession of the unit is highly variable. The common features of rocks exposed in different structures are their predominantly reddish coloration, indicating deposition under continental conditions, and the felsic, more rarely intermediate-felsic, composition of the volcanic rocks. The unit consists of rhyolites, dacites, their porphyritic varieties, and tuffs, locally interbedded with siltstones, sandstones, and gravelstones. In the eastern part of the study area, the unit is characterized by nearly equal proportions of volcanic and terrigenous rocks. It is composed of interbedded purplish-red volcanoclastic rocks, rhyolites of the same color, and their autobreccias [29–31].

3. Materials and Methods

The geological, petrographic, geochemical and geochronological data used in this study were obtained during exploration work carried out by Azimuth Geology LLP with the participation of A. M. Glukhov in 2020–2022 under the project “Prospecting for Atasu-type and other deposits within the southeastern Sarysu–Teniz Uplift over an area of 4500 km²”. The results of this work were compiled in the exploration report prepared by Azimuth Geology LLP in 2022 (Karaganda, Kazakhstan).

Major-element analyses were performed for ten oxides (SiO₂, TiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, P₂O₅, MnO, K₂O, and Na₂O). The analyses were carried out by X-ray fluorescence spectrometry using a SRM-25 multichannel spectrometer (Nauchpribor, Orel, Russia) according to analytical procedure MVI No. KZ.07.00.01859-2015. Certified reference materials with certified oxide contents (GSR-4, GSR-15, and GSO-2798-83) [32–34] were used for quality control. The detection limits of the analytical procedure were as follows: SiO₂ (<1.1%), TiO₂ (<0.01%), Al₂O₃ (<0.95%), Fe₂O₃ (<1.0%), MgO (<0.1%), CaO (<0.1%), P₂O₅ (<0.01%), MnO (<0.01%), K₂O (<0.1%), and Na₂O (<0.1%). Loss on ignition (LOI; detection limit <0.1%) was determined gravimetrically according to GOST 2642.2-2014 [35].

The whole-rock geochemical dataset considered here is restricted to major-element compositions. Trace-element and rare-earth-element data, whole-rock Sr–Nd isotope compositions, and zircon Hf isotope data are not available for the investigated samples. Major-element diagrams are therefore used to characterize compositional variations and assess possible petrogenetic processes; they do not provide a unique identification of magma sources or tectonic setting.

U–Pb dating of zircon grains from volcanic rocks was carried out by D. V. Semenova, A. V. Karpov and I. Yu. Vaskova at the Multi-Element and Isotope Research Center, V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences

(Novosibirsk, Russia). Zircon U–Pb dating using the same Element XR–Analyte Excite instrumental (Thermo Fisher Scientific, Bremen, Germany; Teledyne CETAC Technologies, Omaha, NE, USA) configuration at this centre has previously been described by [36]. Zircon grains were separated using standard magnetic separation and heavy-liquid (bromoform) techniques. Individual zircon grains were handpicked under a binocular microscope and mounted in epoxy resin discs (25 mm in diameter and 5 mm in height). The zircon grains were ground and polished to approximately half of their thickness. Cathodoluminescence (CL) images were used to select analytical spots on the zircon surfaces. CL images were obtained using a MIRA 3 LMU scanning electron microscope equipped with a JSM 6510 LV scanning electron microscope (TESCAN, Brno, Czech Republic) at the V.S. Sobolev Institute of Geology and Mineralogy. Prior to analysis, the mounts were coated with carbon.

U–Pb analyses were performed using a Thermo Scientific Element XR high-resolution inductively coupled plasma mass spectrometer (Thermo Fisher Scientific, Bremen, Germany) coupled to an Analyte Excite laser ablation system (Teledyne CETAC) (Teledyne CETAC Technologies, Omaha, NE, USA) equipped with a two-volume HelEx II ablation cell. The laser system uses a 193 nm excimer source. Instrumental parameters were optimized to achieve maximum ^{208}Pb signal intensity while maintaining a $^{248}\text{ThO}^+ / ^{232}\text{Th}^+$ ratio below 2%, using the NIST SRM 612 standard [37]. The following isotopes were measured: ^{202}Hg , $^{204}(\text{Pb} + \text{Hg})$, ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , and ^{238}U . Analyses were performed in E-scan mode. Signals were acquired in counting mode for all isotopes except ^{238}U and ^{232}Th , which were measured in triple mode. The laser spot diameter ranged from 25 to 35 μm , with a repetition rate of 5 Hz. The laser fluence was 3.0 J/cm² for samples 124 and 128 and 4.5 J/cm² for samples 197 and AVZh-4-21. Mass spectrometric data were processed using the Glitter software package version 4.4 [38,39]. The ^{235}U concentration was calculated from ^{238}U using a $^{238}\text{U} / ^{235}\text{U}$ ratio of 137.818 [40].

A published application of zircon U–Pb dating using the Element XR–Analyte Excite configuration is described by [36]. In that study, Plešovice zircon was used for elemental and isotopic fractionation correction, and GJ-1 zircon was analysed as an independent quality-control material.

Uncertainties of individual isotopic ratios and ages are reported at the 1 σ level. Concordia diagrams and concordia age estimates were obtained using Isoplot [41] from the $^{207}\text{Pb} / ^{235}\text{U}$ and $^{206}\text{Pb} / ^{238}\text{U}$ isotopic ratios. Error ellipses and concordia age uncertainties are shown at the 2 σ level; the original Isoplot outputs specify that the age uncertainties include decay-constant uncertainties. The associated MSWD values are reported specifically as MSWD of concordance, following the original analytical outputs. Discordance was calculated as $D = 100 \times (\text{Age}^{(207\text{Pb}/^{235}\text{U})} / \text{Age}^{(206\text{Pb}/^{238}\text{U})} - 1)$. The numerical discordance threshold and the complete criteria for excluding individual analyses from age calculations are not specified in the source report.

Uncertainties of individual analyses (isotopic ratios and ages) are reported at the 1 σ level, whereas uncertainties of concordia ages are reported at the 2 σ level. Concordia diagrams were constructed using the Isoplot–3 software package [41] based on the $^{207}\text{Pb} / ^{235}\text{U}$ and $^{206}\text{Pb} / ^{238}\text{U}$ isotopic ages. Discordance was calculated using the formula: $D = 100 \times (\text{Age}^{(207\text{Pb}/^{235}\text{U})} / \text{Age}^{(206\text{Pb}/^{238}\text{U})} - 1)$.

Generative artificial intelligence was used during manuscript revision. ChatGPT (OpenAI, GPT-6 Astra) assisted with English-language editing, drafting and restructuring manuscript sections, literature searches, and developing revised formulations of the geological interpretations in response to reviewer comments. The tool was also used to compare numerical values and sample descriptions across the supplied manuscript, analytical tables, and figures and to identify inconsistencies requiring author review.

4. Results

4.1. Major-Element Geochemistry of the Magmatic Rocks

This study presents 58 new whole-rock major-element analyses of volcanic and intrusive rocks from the southeastern Sarysu–Teniz Uplift. The analytical results are provided in Table 1. SiO₂ contents range from 53.46 to 77.72 wt.%, corresponding to compositions from gabbro-diorites and monzodiorites to granites. On the SiO₂ versus (Na₂O + K₂O) diagram (Figure 4), the samples range from gabbro-diorites and monzodiorites to granites. As shown by the A/CNK and A/NK diagrams (Figure 4), A/CNK values range from 0.73 to 2.50. Most samples are metaluminous to weakly peraluminous.

Table 1. Major Element Composition of the Magmatic Rocks.

Sample	Rock Type	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	MnO	P ₂ O ₅	K ₂ O	Na ₂ O	LOI
SJK-50-75.7	gabbro-diorite	53.46	0.94	16.82	6.78	7.61	5.45	0.07	0.37	2.17	2.96	3.32
SJK-256-49	gabbro-diorite	53.81	1.09	15.49	8.04	6.81	5.78	0.16	0.21	0.69	3.72	4.26
119	diorite	56.23	1.00	17.05	6.20	7.75	4.42	0.10	0.27	1.78	2.56	2.66
SJK-133-75	quartz monzodiorite	59.61	0.73	20.26	5.14	0.44	1.97	0.02	0.15	4.01	2.40	5.31
SJK-201-58.0	quartz diorite	62.11	0.72	14.38	5.58	4.61	3.59	0.11	0.16	1.18	4.07	3.63
1032	granodiorite	63.10	0.55	16.76	4.82	4.38	3.54	0.08	0.15	2.94	3.26	0.27
166/1	granodiorite	63.67	0.57	15.42	5.56	3.11	1.58	0.09	0.15	2.95	3.86	2.98
1031	granodiorite	64.81	0.57	15.81	4.15	3.62	2.42	0.07	0.14	3.24	3.44	1.69
SJK-251-66	granodiorite	65.12	0.66	15.87	4.93	0.71	1.94	0.02	0.15	2.66	3.96	4.15
1033	granodiorite	65.90	0.49	15.61	3.81	3.20	2.64	0.07	0.13	3.41	3.12	1.54
130	granodiorite	66.25	0.53	16.03	2.88	3.74	2.95	0.07	0.14	3.06	3.43	0.90
AVJ-9-21	granodiorite	66.48	0.47	15.48	3.84	3.36	2.64	0.08	0.12	2.82	3.12	1.41
SJ-9-101.8	granite	68.21	0.43	13.24	4.02	2.55	2.77	0.12	0.14	2.96	2.94	2.46
SJK-4-37.1	granite	71.66	0.37	15.65	2.61	0.25	1.00	<0.01	0.08	4.08	2.09	2.34
123	leucogranite	73.37	0.28	12.93	3.53	0.70	0.55	0.05	0.05	4.83	3.00	0.66
167a	leucogranite	73.78	0.26	14.28	2.40	0.18	0.44	0.01	0.04	4.71	3.07	0.70
SJK-253-40	subalkaline leucogranite	74.75	0.33	11.92	2.62	0.27	0.42	0.01	0.06	4.99	4.09	0.45
128	trachyrhyolite	74.85	0.26	13.69	1.55	0.13	0.36	0.03	0.04	4.37	3.73	0.89
123/1	subalkaline leucogranite	75.38	0.25	12.93	2.52	0.17	0.27	0.01	0.04	5.32	3.00	0.08
SJK-3-61.7	dacite	64.18	0.55	17.44	2.99	3.75	1.81	0.09	0.11	4.23	1.15	3.81
116	subalkaline dacite	64.98	0.62	17.64	4.81	1.42	3.08	0.05	0.14	2.12	2.50	2.60
SJK-34-47.5	dacite	65.39	0.59	19.72	3.66	0.51	1.04	0.02	0.04	2.66	4.01	2.22
SJK-35-51.0	dacite	65.74	0.80	15.00	4.26	1.38	4.13	0.11	0.23	2.82	3.13	2.51
SJK-211-34.0	dacite	65.80	0.93	13.89	4.76	0.78	4.20	0.11	0.25	2.74	3.10	3.58
SJK-158-32	dacite	65.92	0.60	17.34	4.16	0.26	2.05	0.01	0.13	3.12	2.25	4.12
1035	dacite	65.97	0.57	15.95	4.29	2.76	1.82	0.07	0.15	2.86	3.83	1.87
SJK-125-29	dacite	66.43	0.64	12.71	5.07	2.81	2.03	0.05	0.15	2.94	3.77	3.33
SJK-135-50	trachydacite	66.65	0.83	15.53	3.96	1.97	0.72	0.02	0.22	2.95	4.85	2.39
37	dacite	67.23	0.64	17.37	5.18	0.25	0.76	<0.01	0.08	3.55	2.46	2.53
1016/1	dacite	67.28	0.47	17.15	3.54	1.51	1.46	0.06	0.14	2.53	4.25	1.73
1012	trachydacite	67.70	0.50	16.37	3.72	1.25	0.66	0.05	0.15	3.77	4.09	1.52
1025	dacite	67.73	0.48	15.66	3.51	2.88	1.31	0.10	0.13	3.28	4.04	0.95
123/2a	dacite	68.34	0.51	14.84	3.34	2.12	1.38	0.07	0.13	3.17	4.14	1.98
1026	dacite	68.60	0.49	14.71	3.58	2.79	1.23	0.07	0.15	3.25	4.31	0.78
177	rhyodacite	69.30	0.49	16.17	3.28	0.80	1.18	0.04	0.19	3.03	3.56	2.05
124	rhyodacite	69.36	0.47	15.40	3.84	2.44	0.64	0.08	0.12	3.33	4.11	0.10
125	rhyodacite	69.46	0.48	16.73	3.27	0.40	0.66	0.05	0.17	2.71	4.36	1.71
SJK-212-53	trachyrhyodacite	69.64	0.45	15.04	3.58	0.19	0.47	0.01	0.10	3.58	4.75	2.29
176/2	rhyodacite	69.71	0.48	15.54	3.32	0.70	0.66	0.03	0.14	2.59	3.54	3.35
256	rhyodacite	69.79	0.96	15.49	4.40	0.63	0.81	0.03	0.14	3.02	3.26	1.26
258/1	rhyodacite	70.16	0.53	15.86	3.22	0.77	0.69	0.03	0.18	2.85	3.57	1.99
253/1	rhyodacite	70.98	0.59	12.85	3.63	1.15	0.35	0.03	0.14	3.22	3.08	3.99
AVJ-4-21	rhyodacite	71.06	0.50	16.06	2.53	0.86	0.47	0.01	0.12	2.26	4.18	1.95
177/1	rhyodacite	71.26	0.62	13.18	3.72	1.74	1.79	0.09	0.13	3.64	3.19	0.57
1023	rhyodacite	71.90	0.30	15.20	2.29	0.15	0.79	0.03	0.04	5.57	2.36	1.50
SJK-3-87.5	subalkaline rhyodacite	72.12	0.31	15.98	2.35	0.86	0.68	0.04	0.06	3.95	1.66	2.07
2001/1	trachyrhyodacite	72.27	0.36	14.55	2.63	0.20	0.38	0.02	0.06	4.23	4.34	1.07
41	trachyrhyolite	73.99	0.23	13.18	2.39	0.24	0.48	0.04	0.07	7.03	1.87	0.41
255/1	subalkaline rhyolite	74.60	0.32	13.84	2.63	0.18	0.80	<0.01	0.04	3.72	1.63	2.05
262/1	rhyolite	75.01	0.18	13.67	2.25	0.18	0.35	<0.01	0.03	3.51	3.08	1.51

Table 1. Cont.

Sample	Rock Type	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	MnO	P ₂ O ₅	K ₂ O	Na ₂ O	LOI
187/3	subalkaline rhyolite	75.24	0.15	14.48	2.10	0.13	0.56	<0.01	0.03	3.45	1.11	2.75
187/3a	subalkaline rhyolite	75.49	0.15	14.10	2.37	0.11	0.51	0.02	0.03	3.29	1.79	2.19
189	subalkaline rhyolite	75.53	0.11	14.45	2.24	0.12	0.39	<0.01	0.03	3.32	2.40	1.28
187/2	subalkaline rhyolite	75.58	0.15	15.05	2.19	0.29	0.55	<0.01	0.03	3.40	1.53	1.35
262/1a	rhyolite	76.41	0.25	10.58	2.88	0.28	0.40	<0.01	0.05	5.33	2.16	1.69
261/1	rhyolite	76.77	0.20	11.16	2.54	0.18	0.52	<0.01	0.10	4.53	2.61	1.17
197	rhyolite	77.32	0.19	11.81	2.00	0.27	0.40	<0.01	0.04	4.47	2.23	1.23
260	rhyolite	77.72	0.22	11.23	2.29	0.21	0.50	<0.01	0.06	4.74	1.57	1.54

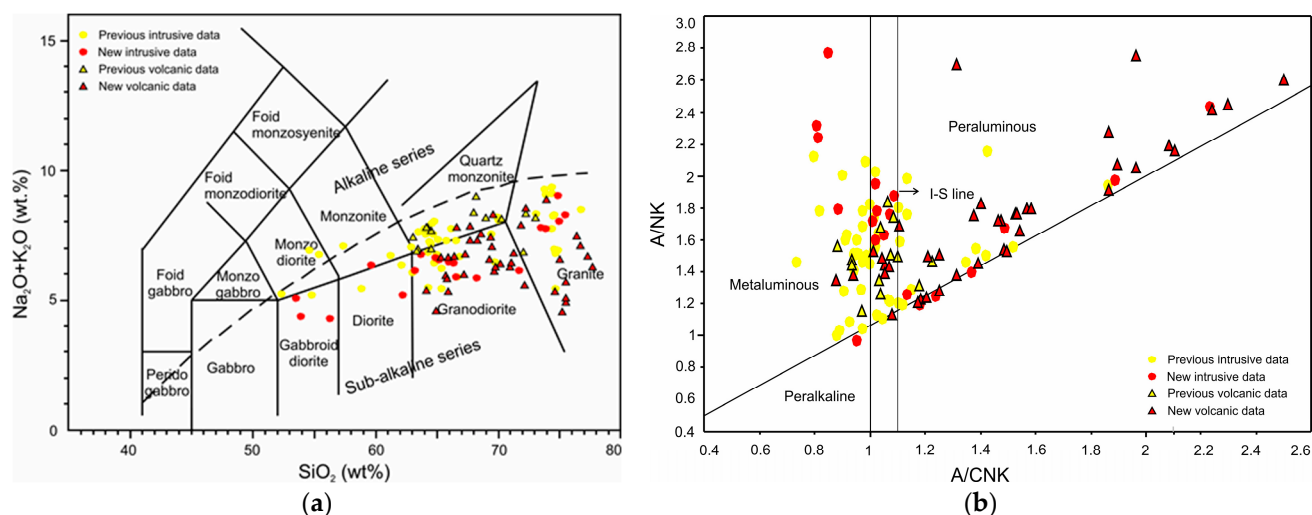


Figure 4. Magmatic rocks on the classification diagrams. (a) Description TAS diagram [42]. (b) A/CNK vs. A/NK diagram [43,44]. The data are from this study and [25,29,45–47].

Granites are characterized by SiO₂ contents of 68.21–75.31 wt.%, Al₂O₃ of 11.92–15.65 wt.%, CaO of 0.13–0.70 wt.% (except one sample with 2.55 wt.%), MgO of 0.27–1.00 wt.% (except one sample with 2.77 wt.%), Fe₂O_{3T} of 1.50–4.02 wt.%, Mg# values of 18–58, and A/CNK values ranging from 0.90 to 1.36. Granodiorites are characterized by SiO₂ contents of 63.10–66.48 wt.%, Al₂O₃ of 15.42–16.76 wt.%, CaO of 3.11–4.38 wt.% (except one sample with 0.71 wt.%), MgO of 1.58–3.54 wt.%, Fe₂O_{3T} of 2.90–5.50 wt.%, Mg# values of 36–67, and A/CNK values ranging from 1.00 to 1.48. Dacites contain 64.18–68.60 wt.% SiO₂, 12.71–19.72 wt.% Al₂O₃, 0.25–3.75 wt.% CaO, 0.72–4.20 wt.% MgO, 2.98–5.17 wt.% Fe₂O_{3T}, Mg# values of 23–66, and A/CNK values of 0.88–2.30. Rhyodacites are characterized by SiO₂ contents of 69.30–72.27 wt.%, Al₂O₃ of 12.85–16.73 wt.%, CaO of 0.15–2.44 wt.%, MgO of 0.35–0.79 wt.% (except one sample with 1.79 wt.%), Fe₂O_{3T} of 2.30–4.40 wt.%, Mg# values of 16–48, and A/CNK values ranging from 1.04 to 1.86. Rhyolites have SiO₂ contents of 73.99–77.72 wt.%, Al₂O₃ of 10.58–15.05 wt.%, CaO of 0.11–0.29 wt.%, MgO of 0.35–0.80 wt.%, Fe₂O_{3T} of 2.00–2.88 wt.%, Mg# values of 21–34, and A/CNK values ranging from 1.08 to 2.50.

4.2. Age of the Magmatic Rocks

The age of the magmatic rocks was investigated based on U–Pb dating of zircon grains from volcanic rocks of the rhyolite–dacite unit, including sample 124 (rhyodacite), sample 128 (trachyrhyolite), sample 197, and sample AVZh-4-21 (rhyolite porphyry).

Sample 124 (rhyodacite). Forty-five zircon analyses are reported in Table S1. The grains are euhedral and prismatic, reach approximately 250 µm in length, and commonly exhibit oscillatory zoning in CL images (Figure 5a). The principal population yields a concordia age of 414 ± 3 Ma (2σ; 31 analyses; MSWD of concordance = 1.6; Figure 6a). An older population

yields a concordia age of 440 ± 6 Ma (2σ ; $n = 6$; MSWD of concordance = 1.4; Figure 6b). Analyses 8, 16, 19, 24, 29, and 31 have individual $^{206}\text{Pb}/^{238}\text{U}$ ages of 433–443 Ma and discordance values between -0.16% and 0.68% . Analysis 33 records a substantially older component, with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2667 ± 32 Ma, a $^{206}\text{Pb}/^{238}\text{U}$ age of 2665 ± 40 Ma, and a $^{207}\text{Pb}/^{235}\text{U}$ age of 2665 ± 18 Ma; the corresponding discordance is -0.02% . Uncertainties of these individual analyses are reported at 1σ .

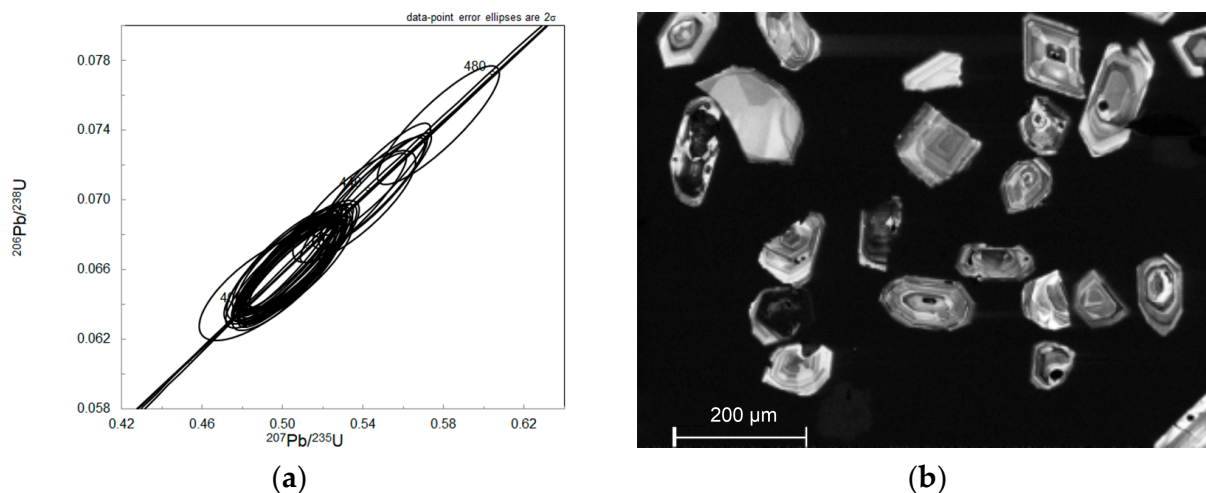


Figure 5. Sample 124: (a) Concordia diagram for zircons with ages ranging from 410 to 460 Ma. (b) Cathodoluminescence (CL) images of zircon grains.

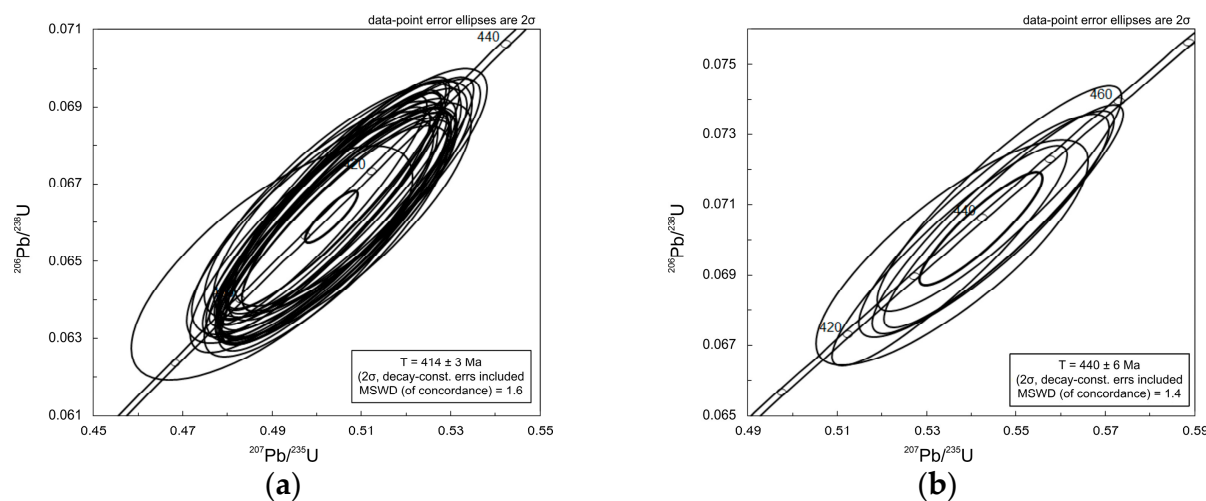


Figure 6. Sample 124: (a) Concordia diagram showing the weighted mean age of Cluster 1. (b) Concordia diagram showing the weighted mean age of Cluster 2.

Sample 128 (trachyrhyolite). Forty-five zircon analyses are reported in Table S2. The grains are euhedral and prismatic, reach approximately $250\ \mu\text{m}$ in length, and commonly exhibit oscillatory zoning (Figure 7a). The principal population yields a concordia age of 415 ± 2 Ma (2σ ; $n = 37$; MSWD of concordance = 1.14; Figure 8a). An older population yields a concordia age of 438 ± 6 Ma (2σ ; $n = 6$; MSWD of concordance = 0.034; Figure 8b). Analyses 1, 5, 10, 15, 19, and 34 have individual $^{206}\text{Pb}/^{238}\text{U}$ ages of 433–445 Ma and discordance values between -0.50% and 0.81% .

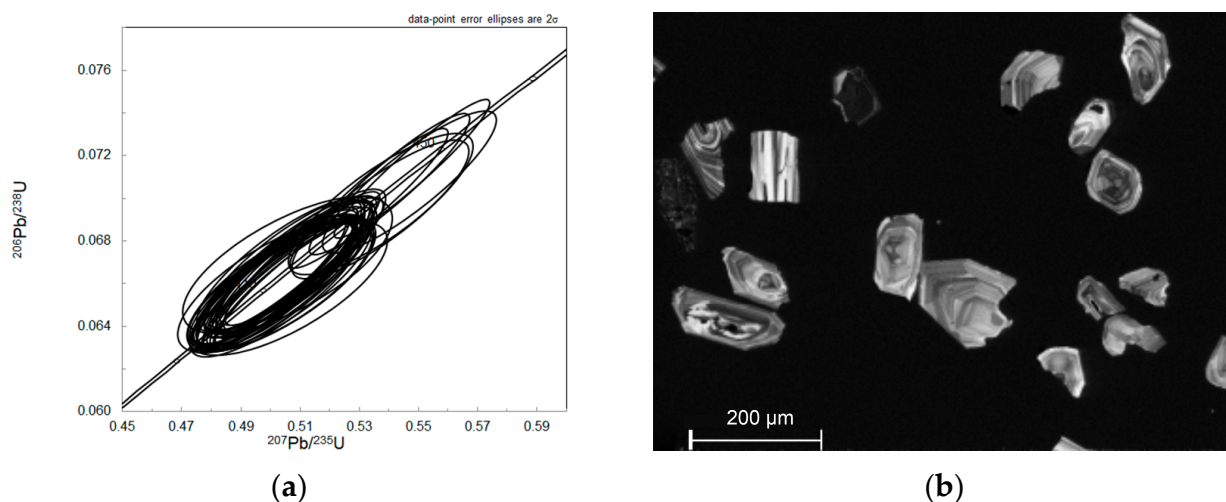


Figure 7. Sample 128: (a) Concordia diagram showing the weighted mean age of Cluster 1. (b) Cathodoluminescence (CL) images of zircon grains.

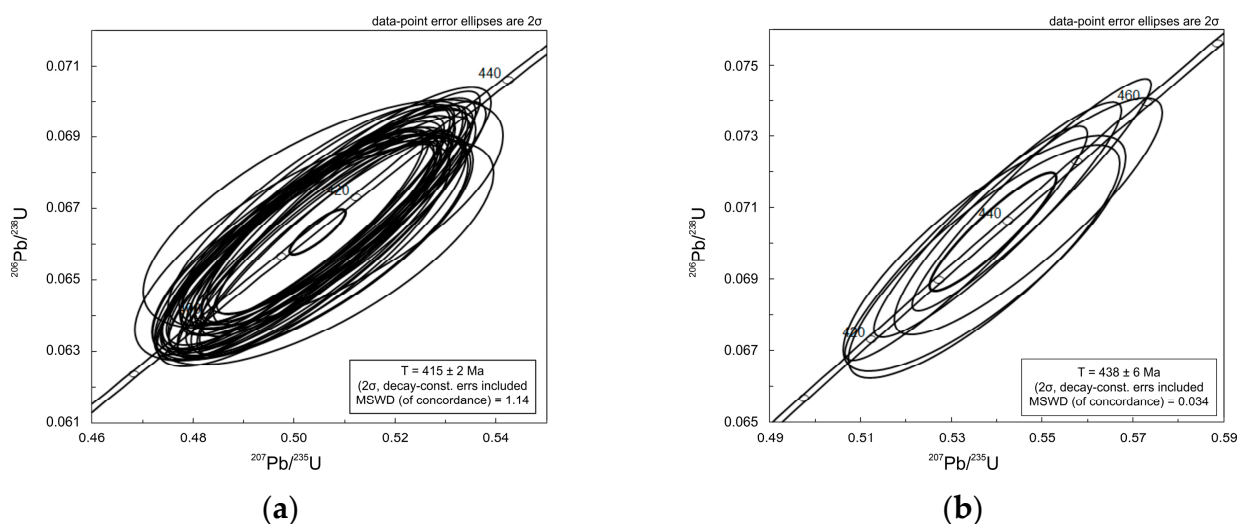


Figure 8. Sample 128: (a) Concordia diagram showing the weighted mean age of zircons from Cluster 1. (b) Concordia diagram showing the weighted mean age of zircons from Cluster 2.

Sample 197 (rhyolite porphyry). Forty zircon analyses are reported in Table S3. The grains are euhedral and prismatic, reach approximately 250 µm in length, and exhibit oscillatory zoning (Figure 9a). The principal population yields a concordia age of 421 ± 2 Ma (2σ ; $n = 32$; MSWD of concordance = 2.3; Figure 9b).

Sample AVZh-4-21 (rhyolite). Forty-five zircon analyses are reported in Table S4. The grains are euhedral and prismatic and commonly exhibit oscillatory zoning (Figure 10a). The principal population yields a concordia age of 414 ± 2 Ma (2σ ; MSWD of concordance = 0.34; Figure 10b). An older analysis, spot 43, yields a $^{206}\text{Pb}/^{238}\text{U}$ age of 453 ± 8 Ma (1σ), with a discordance of 0.53%.

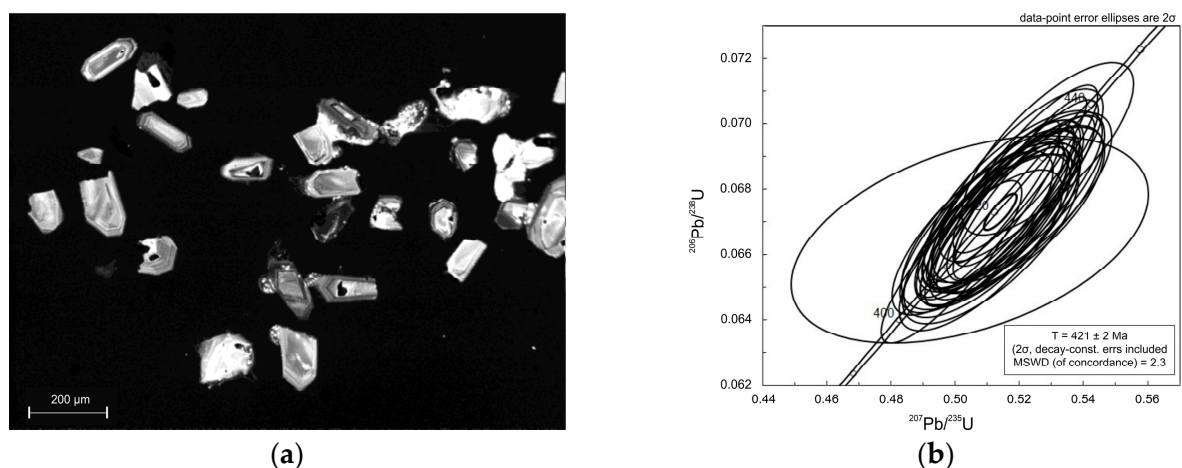


Figure 9. Sample 197: (a) Cathodoluminescence (CL) images of zircon grains. (b) Concordia diagram for zircons from Sample 197.

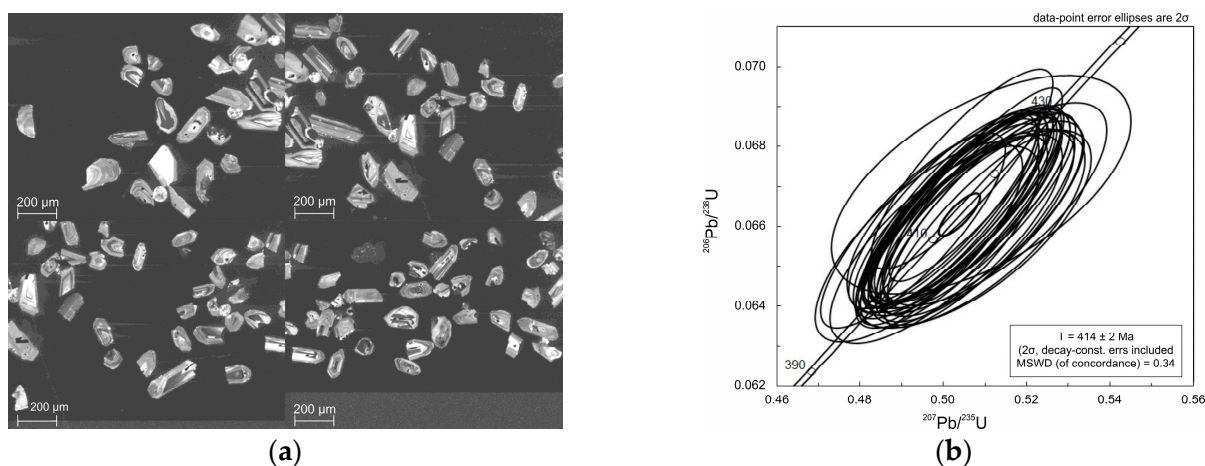


Figure 10. Sample AVZh-4-21: (a) Cathodoluminescence (CL) images of zircon grains. (b) Concordia diagram showing the weighted mean age of zircons.

5. Discussion

5.1. Age of the Volcanic Rocks

Previous studies assigned different ages to the felsic volcanic succession of the study area. These rocks were variously attributed to the Lower, Middle, or Middle–Upper Devonian [29], whereas some occurrences and their eastern equivalents were assigned to the Upper Devonian [46]. In the southern part of the area, the succession was interpreted as Lower–Middle Devonian [47] or Middle Devonian [30,31]. The new zircon U–Pb results provide direct chronological constraints for the sampled volcanic rocks.

The principal zircon populations yield concordia ages of 414 ± 3 Ma for Sample 124, 415 ± 2 Ma for Sample 128, 421 ± 2 Ma for Sample 197, and 414 ± 2 Ma for Sample AVZh-4-21, with uncertainties reported at 2σ . Their central values span 414–421 Ma and indicate Late Silurian–Early Devonian felsic magmatism. The uncertainty interval of Sample 197 extends across the Silurian–Devonian boundary; therefore, an exclusively Early Devonian assignment is inappropriate for the complete dataset. Its reported age interval also does not overlap those of the other three samples at 2σ . Accordingly, the results should not be represented as a single instantaneous volcanic event. The available sampling does not establish whether activity was continuous or episodic within this interval.

The intrusive ages used for comparison are previously published results [25], rather than new measurements presented here. Their principal age estimates range from approximately 412 to 418 Ma. Some volcanic and intrusive ages overlap within their quoted uncertainties: for example, the intervals for volcanic Sample 197 at 421 ± 2 Ma and published granite Sample 272 at 418 ± 3 Ma overlap. This comparison supports temporal overlap between parts of the volcanic and intrusive activity at the reported precision. However, overlapping uncertainty intervals do not establish exact synchrony or demonstrate derivation from a single parental magma.

The older populations in Samples 124 and 128 yield concordia ages of 440 ± 6 and 438 ± 6 Ma, respectively. The small discordance values of the older analyses listed in Tables S1 and S2 support the presence of an older zircon component. However, near-concordance and an older age do not independently establish its geological origin. These populations are interpreted as possible inherited or antecrystic components. Incorporation from older country rocks and recycling from earlier magmatic episodes cannot be distinguished using the present dataset.

The ca. 2.67 Ga zircon in Sample 124 has mutually consistent U–Pb ages and very low discordance (Table S1, analysis 33), supporting the identification of an ancient zircon component. Its presence is compatible with inheritance and possible recycling of Archean crustal material. Nevertheless, a single grain does not identify a tonalitic protolith, establish its derivation from a particular microcontinent, or quantify the crustal contribution to the host magma.

5.2. Petrogenesis of the Magmatic Rocks

The volcanic and intrusive rocks show overlapping compositional affinities on the K_2O – SiO_2 and modified alkali–lime index diagrams (Figure 11) [48,49]. These similarities provide a basis for comparing the rock groups within the regional magmatic association. However, overlapping major-element compositions do not establish derivation from a common parental magma, because comparable compositions can develop through different combinations of source melting and subsequent magmatic differentiation.

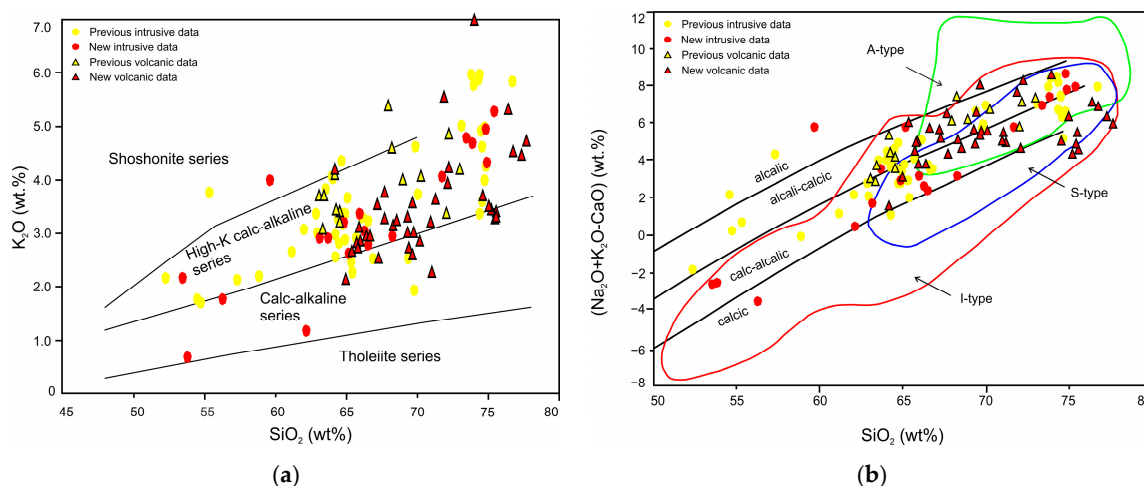


Figure 11. Magmatic rock samples on the classification diagrams. (a) SiO_2 (wt.%) vs. K_2O (wt.%) (after [48]); (b) SiO_2 (wt.%) vs. $Na_2O + K_2O - CaO$ (wt.%) (after [49]). The data are from this study and [25,29,45–47,50].

The Harker diagrams (Figure 12) show broad decreases in MgO , total Fe expressed as Fe_2O_3 , TiO_2 , and CaO with increasing SiO_2 . Such variations are compatible with fractional crystallization involving mafic minerals, Fe–Ti oxides, and plagioclase. Nevertheless, these

trends do not uniquely identify fractional crystallization as the dominant process. Differences in source composition and degree of partial melting, magma mixing, and assimilation of crustal material may also contribute to the observed variations. Furthermore, the combined dataset represents multiple rock groups, so its overall trends cannot automatically be interpreted as the differentiation path of a single magma batch.

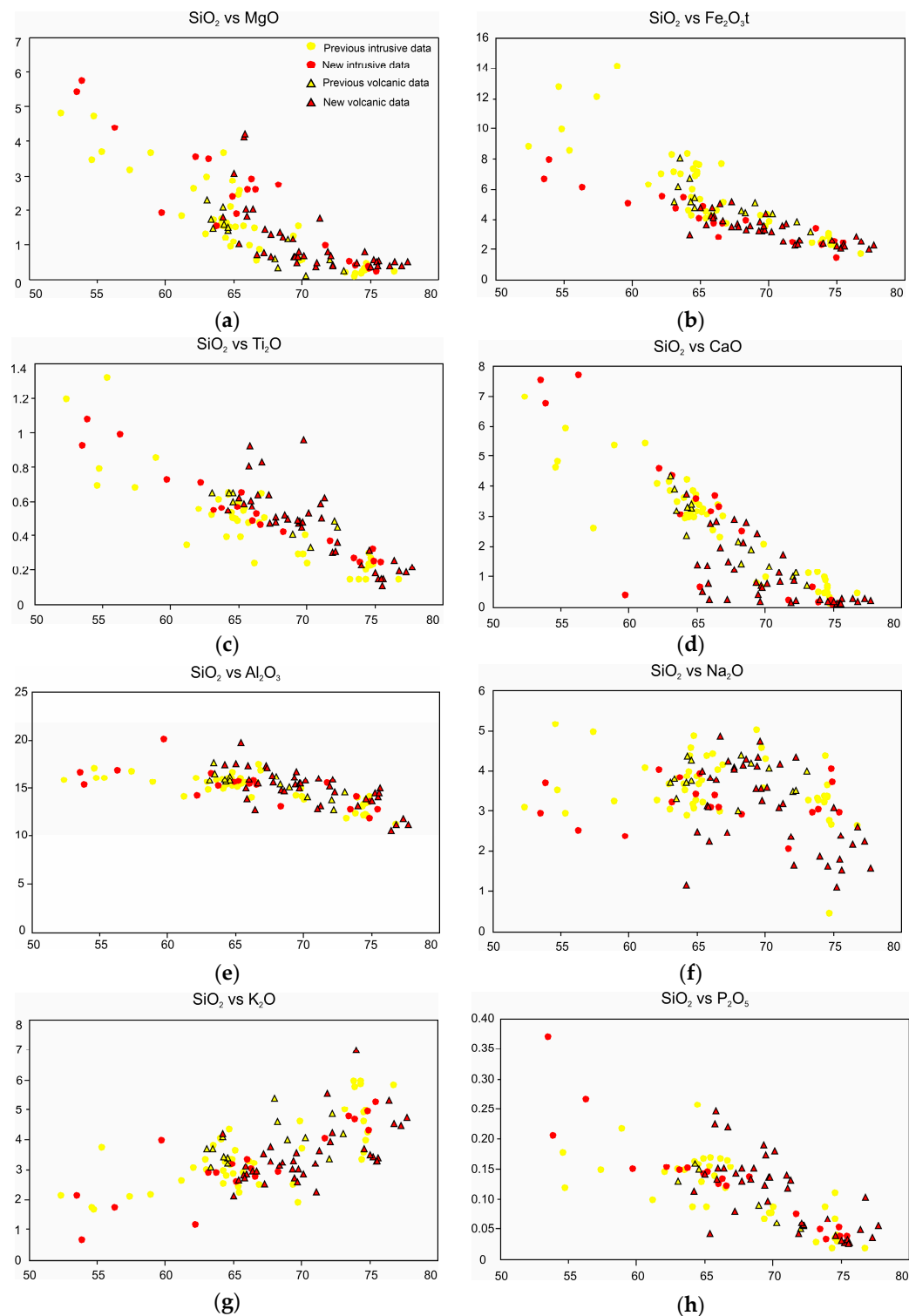


Figure 12. Harker diagrams for major oxides (wt.%) vs. SiO_2 (wt.%). (a) SiO_2 vs. MgO ; (b) SiO_2 vs. $\text{Fe}_2\text{O}_3\text{t}$; (c) SiO_2 vs. TiO_2 ; (d) SiO_2 vs. CaO ; (e) SiO_2 vs. Al_2O_3 ; (f) SiO_2 vs. Na_2O ; (g) SiO_2 vs. K_2O ; (h) SiO_2 vs. P_2O_5 . The data are from this study and [25,29,45–47,50].

Felsic magmas may be generated through differentiation of mafic parental magmas, partial melting of crustal rocks, or interaction between mantle-derived and crust-derived melts [51–57]. Intermediate magmas may likewise develop through differentiation, mixing, or partial melting of mafic protoliths [58–60]. These processes are not mutually exclusive: magmas derived from compositionally different sources may subsequently undergo fractional crystallization, mixing, and assimilation. The present major-element data allow these mechanisms to be considered but do not determine their relative contributions.

The high SiO₂ contents and generally low MgO contents and Mg# values of the felsic rocks indicate evolved compositions. They are compatible with crustal melting, but they may also result from extensive differentiation of less evolved magmas. Accordingly, Mg# variations (Figure 13) are not used here to quantify mantle and crustal contributions. Similarly, peraluminous compositions and variations in P₂O₅ provide useful compositional information but are insufficient on their own to assign the rocks unequivocally to an S-type or I-type petrogenetic category [61–65].

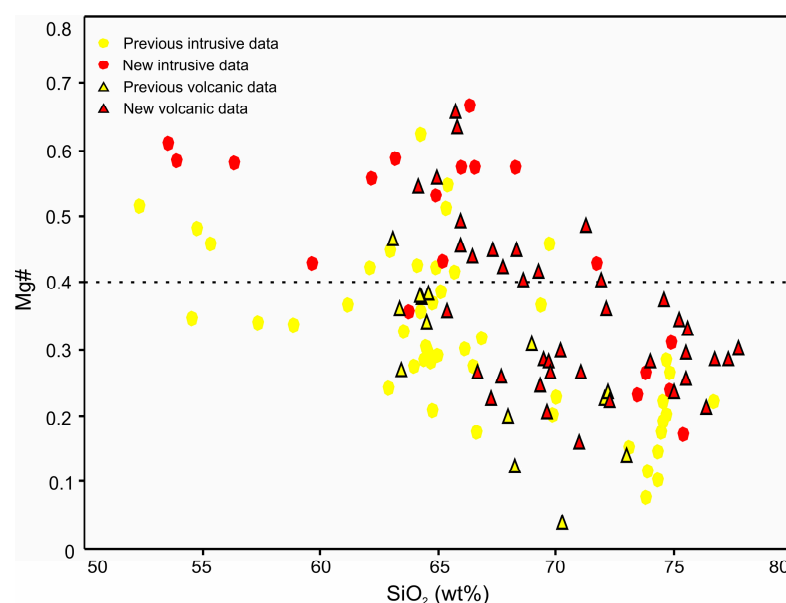


Figure 13. SiO₂ vs. Mg# diagram. The data are from this study and [25,29,45–47,50].

The $3\text{CaO}-(5\text{K}_2\text{O}/\text{Na}_2\text{O})-\text{Al}_2\text{O}_3/(\text{FeO}_{\text{total}} + \text{MgO})$ and $\text{CaO}/(\text{MgO} + \text{FeO}_{\text{total}})$ vs. $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeO}_{\text{total}})$ diagrams (Figures 14 and 15) suggest a mixed origin for most of the magmatic rocks in the study area. The rhyolites and granites could be primarily derived from a tonalitic crustal source with the involvement of a metapelitic component. For the rhyodacites and dacites, the $3\text{CaO}-(5\text{K}_2\text{O}/\text{Na}_2\text{O})-\text{Al}_2\text{O}_3/(\text{FeO}_{\text{total}} + \text{MgO})$ diagram may indicate a low-K mafic source with the participation of tonalitic crust, whereas the $\text{CaO}/(\text{MgO} + \text{FeO}_{\text{total}})$ vs. $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeO}_{\text{total}})$ diagram additionally might indicate the involvement of metapelitic and metagreywacke material, implying a heterogeneous source. The granodiorites and granosyenites are consistent with a crustal source. The inherited zircon grain with an age of $2666 \pm 32 \text{ Ma}$ identified in rhyodacite Sample 124 may be the record of the involvement of Archean crust.

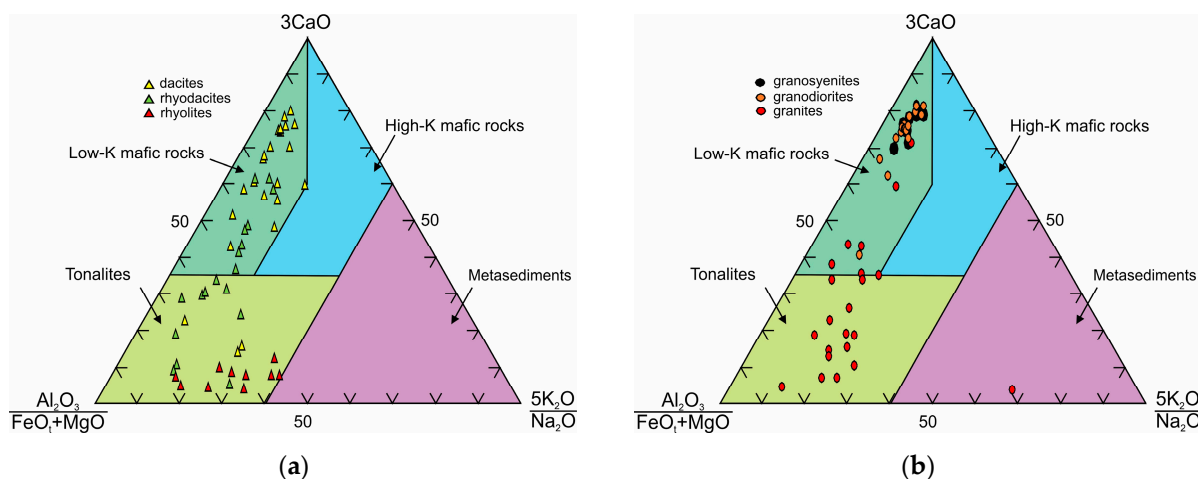


Figure 14. (a,b) $3\text{CaO}-(5\text{K}_2\text{O}/\text{Na}_2\text{O})-\text{Al}_2\text{O}_3/(\text{FeO}_{\text{total}} + \text{MgO})$ diagrams [66]. The data are from this study and [25,29,42–47].

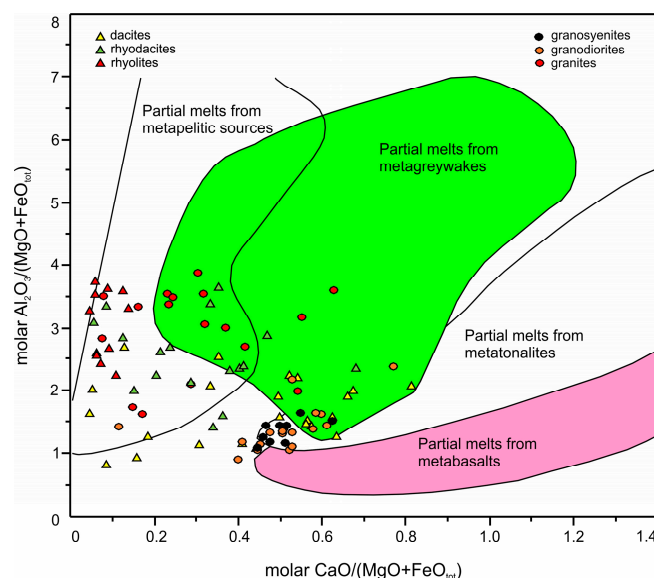


Figure 15. Petrogenetic diagram $\text{CaO}/(\text{MgO} + \text{FeO}_{\text{total}})$ vs. $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeO}_{\text{total}})$ [67,68]. The data are from this study and [25,29,45–47].

The major-element source-comparison diagrams (Figures 14 and 15) [66–68] provide qualitative constraints on possible source affinities. However, the positions of the samples on these diagrams cannot uniquely distinguish tonalitic, metatonalitic, metapelitic, metagreywacke, or low-K mafic protoliths. The apparent affinities may reflect both source characteristics and subsequent differentiation. Contributions from crustal and mafic components therefore remain possible interpretations, while specific source lithologies and their proportions are unresolved.

Loss-on-ignition (LOI) values are available for all 58 samples and range from 0.08 to 5.31 wt.%, with a median of 1.91 wt.%. Eleven samples have LOI values above 3 wt.%. These data provide an additional basis for assessing possible post-magmatic modification, although LOI alone does not uniquely establish the degree of alteration. Potential redistribution of Na, K, and Ca remains relevant to the interpretation of total-alkali classifications, $\text{K}_2\text{O}-\text{SiO}_2$ relationships, aluminum saturation indices, and major-element source-comparison diagrams, particularly for samples with higher LOI values.

Taken together, the major-element data are compatible with variable magmatic differentiation and possible crustal involvement. Fractional crystallization, source heterogeneity,

mixing, and assimilation remain viable processes, but the available evidence does not establish a unique combination of these processes or a single parental magma for all volcanic and intrusive rocks.

5.3. Regional Geological Implications

The principal contribution of this study is the identification of Late Silurian–Early Devonian zircon crystallization ages in felsic volcanic rocks previously assigned a broader range of Devonian ages. These results provide chronological constraints for correlating the sampled volcanic occurrences across the partly concealed southeastern Sarysu–Teniz Uplift. Their comparison with published intrusive ages supports regional temporal overlap between volcanic and plutonic activity, while allowing for multiple magmatic episodes and distinct magma reservoirs.

The older zircon populations document components predating the principal crystallization ages, but do not independently identify the tectonic setting of their sources. Similarly, the major-element compositions and compositional similarities between volcanic and intrusive rocks do not uniquely constrain a geodynamic mechanism. Consequently, regional active-margin interpretations provide a geological framework for discussing these results, rather than a model independently demonstrated by the present dataset. The new findings refine the timing of magmatism and its regional correlation without resolving the specific tectonic processes responsible for magma generation.

6. Conclusions

Zircon U–Pb dating of four felsic volcanic samples from the southeastern Sarysu–Teniz Uplift yields principal concordia ages of 414 ± 3 Ma (Sample 124), 415 ± 2 Ma (Sample 128), 421 ± 2 Ma (Sample 197), and 414 ± 2 Ma (Sample AVZh-4-21), with uncertainties reported at 2σ . These results constrain the sampled magmatism to the Late Silurian–Early Devonian and provide a basis for revising earlier age assignments of the volcanic succession.

Older zircon populations at 440 ± 6 and 438 ± 6 Ma and a single ca. 2.67 Ga zircon record components predating the principal crystallization ages. They are compatible with zircon inheritance or recycling, but do not establish a specific island-arc source, Archean tonalitic protolith, or microcontinental provenance.

The major-element compositions document compositional diversity and trends compatible with magmatic differentiation. Fractional crystallization may have contributed to these variations, but its effects cannot be uniquely separated from partial melting, assimilation, magma mixing, source heterogeneity, and post-magmatic modification. Specific source lithologies and their relative contributions remain unresolved.

Comparison of the new volcanic ages with published intrusive ages supports partial temporal overlap of volcanic and plutonic activity. This relationship improves the regional chronological framework but does not demonstrate that all investigated rocks formed synchronously within a single magmatic system.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min16101069/s1>. Table S1: Zircon LA-ICP-MS U-Pb analytical data from the rhyodacite sample 124; Table S2: Zircon LA-ICP-MS U-Pb analytical data from the trachyrhyolite sample 128; Table S3: Zircon LA-ICP-MS U-Pb analytical data from the rhyolite sample 197; Table S4: Zircon LA-ICP-MS U-Pb analytical data from the rhyolite sample AVJ-4-21; Table S5: Zircon LA-ICP-MS U-Pb analytical data from the rhyolite sample SJK-43-54.3-55.3.

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