Journal of volcanology and geothermal research

Journal of Volcanology and Geothermal Research 112 (2001) 189–220

www.elsevier.com/locate/jvolgeores

Late collision rhyolitic volcanism in the north-eastern part of the Armenian Highland

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Received 18 May 2000; accepted 29 May 2001

Abstract

Plio-Pleistocene acidic volcanism of the northeastern part of the Armenian highland is related to a continental collision zone as a result of convergence between Eurasia and Arabia lithosphere plates. The development of volcanism is divided into three stages of 10–17, 4.5–7.5 and 0.1–2.8 Ma. A crustal origin model is proposed to explain the geochemical and petrogenetic aspects of the acidic volcanism formation. Spatially separated Ba-rich and Rb-rich geochemical types of rhyolites were revealed, indicating more evolved and primitive rhyolitic magma types, respectively. The variation interval of the primary $^{87}Sr/^{86}Sr$ ratio was found to be from 0.70438 to 0.70636. Age and lateral variation of geochemical and isotopic parameters were determined by differences of initial substrates and degrees of their partial melting. The mechanisms of rhyolitic magma evolution were the remelting of heterogeneous sialitic materials and low-pressure fractional crystallization in isolated magmatic chambers. These facts confirm the model of crustal anatexis origin of the eutectic melts. The eutectic rhyolitic magma was generated by an open-system melting in the presence of deep-horizon mobile K–Rb fluids, initiated by mantle resources.

Keywords: late-collision volcanism; Armenia; rhyolites; dacites; obsidians; geochemistry; eutectic melt

1. Introduction

Diversity of types and characters of volcanic processes attributes Armenia to the classical areas of young volcanism. In its entire geological history, this country has been an arena of strong volcanic eruptions. Intensity of the eruptions was the greatest at the late-collision stage of the development of the territory and led to the formation of such magnificent volcanic edifices of the Armenian highland as Ararat, Aragats, Nemrut, Sipan and others. Along with numerous lava and cinder cones placed en echelon, thick lava flows and vast covers of ignimbrite tuffs, these edifices have determined today's volcanic relief of Armenia.

Among the great diversity of the types of volcanic processes, rhyolitic volcanism presents particular interest due to the specific conditions of origin, and fair preservation of eruption centers and their products. Studies of rhyolitic volcanism are of great scientific and applied value, particularly for some general issues of petrogenesis, evolution and depth of acidic magma origin (Kozhemyaka et al., 1980; Shirinyan, Karapetian, 1971; Karapetian, 1970, 1981).

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0377-0273/01/$ - see front matter
PII: S0377-0273(01)00241-4

Fig. 1. The Armenian area with Plio-Pleistocene volcanic districts: I — Ashotsk, II — Aragats, III — Gegham, IV — Vardenis, V — Syunik, VI — Kaphan.

As an independent geological phenomenon, Neogene–Quaternary rhyolitic volcanism is spread widely within the Caucasian segment of the Mediterranean belt, the latter presenting a 'continent–continent' collision orogen. Recent publications have regarded this region as a standard model of mountain belt collision type (Abramowich and Klushin, 1987; Ostroumova et al., 1995; Keskin et al., 1998). In general, this corresponds to the concept of the late orogeny blockwave rise of the Anatolian–Armenian–Iranian subcontinent at the Pliocene–Quaternary stage (Aslanian et al., 1980, 1983; Meliksetyan et al., 1998).

In the conditions of collision and rising of heterogeneous continental geological blocks, the rhyolitic crust magmatism is an indicator of the eutectic nature of acid magma (Meliksetian and Karapetian, 1981; Meliksetyan et al., 1998; Shirinian and Karapetian, 1973).

Considering acid magma origin and geological relationships of rhyolites with associated basic and intermediate rocks, scientists have interpreted differently the ways and mechanism of their formation. Some consider rhyolites to be basic magma differentiates (Adamian, 1961; Amaryan, 1958; Paffengolts, 1947), while the other refer them to independent palingenetic crustal melts (Meliksetian and Karapetian, 1981; Meliksetyan

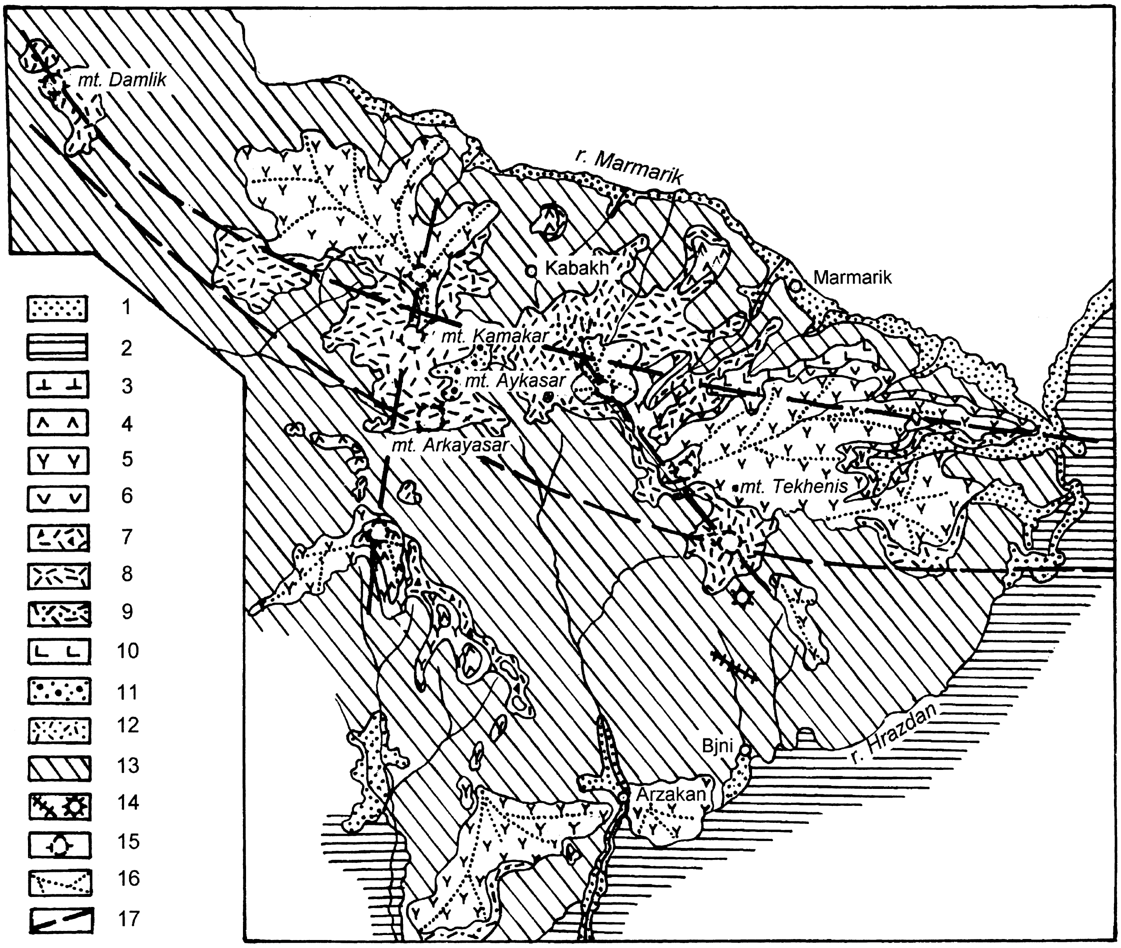

Fig. 2. Geological and petrographical map of the Pliocene volcanic rocks of the Tsakhkuniats Ridge (by Karapetian S.H., Kharazian E.Kh.): 1. Alluvium, delluvium, 2. Quarternary andesite–basalts, 3. Rhyodacites, 4. Andesite–basalts, andesite, 5. Andesite–dacites, 6. Olivine andesite-basalts, 7. Agglomeratic rocks, 8. Rhyodacites, 9. Acid pyroclasts, 10. Andesite–dacites, 11. Andesite agglomeratic rocks, 12. Rhyolitic rocks, 13. Rocks of the basement, 14. Dykes and necks of basic and andesitic composition, 15. Centers of eruptions, 16. Lava flow directions, I–IV Pliocene complexes.

et al., 1998; Shirinian and Karapetian, 1973). Mindful of this problem, we have generally preferred consideration of the geological situation and relationship of the rhyolites with widespread newest basaltic and andesitic formations, using absolute age data (Karapetian, 1968, 1970, 1981; Komarov et al., 1972).

We have created detailed maps of all rhyolite volcanoes and areas of distribution of their products (Figs. 1–10). They are published (Aslanyan et al., 1980; Keller et al., 1994) and are largely used by other scientists (Blackman et al., 1998; Poidevin, 1998).

2. Geological and tectonic setting

Strongly differential movements of the Earth's crust and formation of modern relief characterize the late collision stage in the development of the Armenian highland (Aslanian, 1958; Badalian et al., 1986; Gabrielian et al., 1977; Milanovsky and

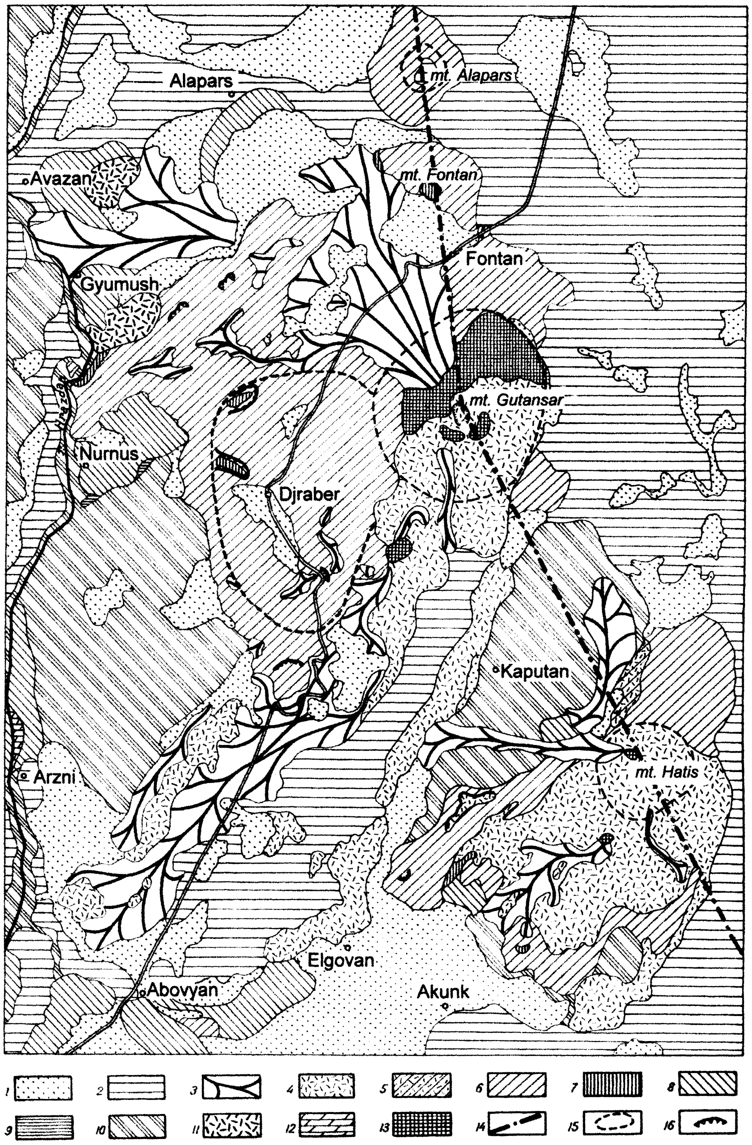

Fig. 3. Geological map of the Atis–Gutansar volcano field. 1 — Alluvial, deluvial and proluvial deposits; 2 — Quaternary andesite-basaltic and basaltic lavas; 3 — Andesitic and andesite-basaltic lavas of Atis and Gutansar groups of Quaternary volcanoes; 4 — Rhyolite, dacite lavas of Atis and Gutansar volcanoes; 5 — Perlite and pumice pyroclastic products of Atis volcano; 6 — Obsidian and perlite lavas of Atis, Gutansar, Fontan and Alapars volcanoes; 7 — Rhyolite lavas -'lower'- of Atis, Gutansar, Fontan volcanoes; 8 — Basalt lavas, mostly of doleritic structure; 9 — Diatomites and diatom clays; 10 — Pliocene dacites, andesite–dacites, andesites and andesite-basalts of the regions of Nurnus and Kaputan villages (Kaputan suite); 11 — Rhyolites, dacites of Gyumush and Avazan domes; 12 — Sarmatian clays, limestones, etc.; 13 — Slags and cinder volcanic cones; 14 — Assumed faults, 15 — Outlines of volcanic structures; 16 — Quarries.

Koronovsky, 1973). This stage was generally accompanied by continental volcanic activity.

In the above publications, two stages of collision volcanism are identified in Armenia: early collision (Oligocene–Early Miocene) and late collision (Late Miocene–Quaternary). The former is characterized by local volcanic eruptions in some residual basins and formation of granitoid intrusions. The latter was

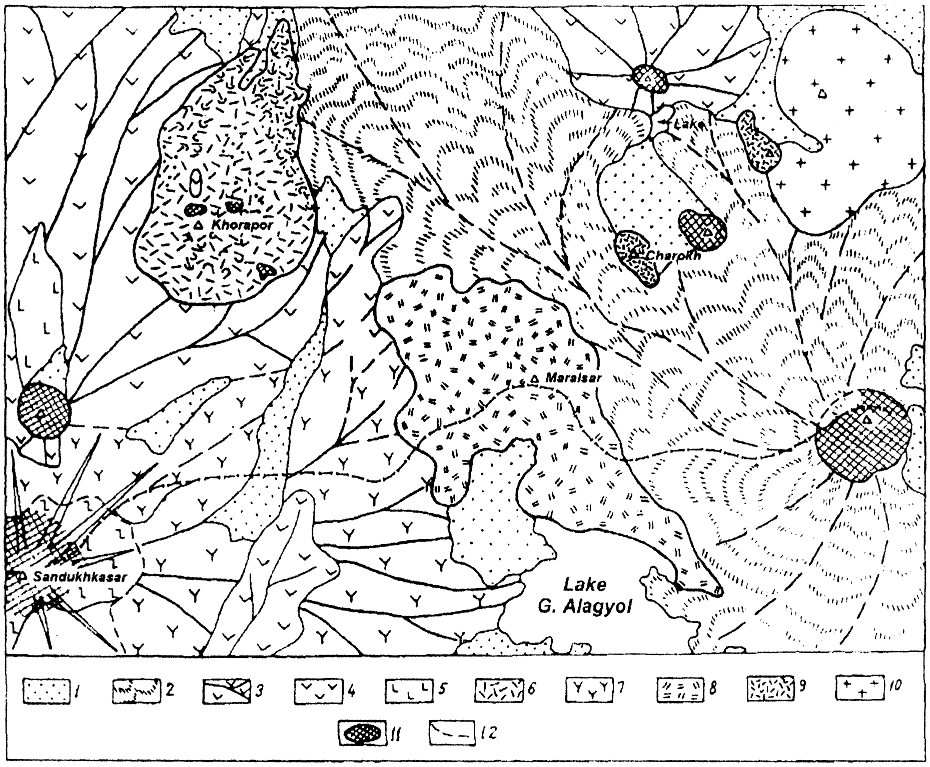

Fig. 4. Geological map of the Choraphor volcano and other volcanic domes (by Karapetian S.H.): 1. Alluvium, delluvium; 2. Quarternary andesitic lavas; 3, 4 Quaternary andesite-basalt lavas from Sarigagat and other volcanoes; 5. Basalt lavas of the Sandukhkasar volcano; 6. Rhyolite–obsidian–perlite rocks of the Choraphor volcano; 7. Andesitic lavas of Sandukhkasar volcano; 8. Rhyolitic and dacitic rocks of the Maralsar volcano; 9. Rhyolitic and dacitic rocks of Girhsar, Charokh and other volcanoes; 10. Porphyrites of Dalisar; 11. Quaternary cinder cones; 12. Lava flow directions.

responsible for intense mountain formation and strong continental volcanism in all volcanic provinces of the Armenian highland.

The late collision stage of volcanism left extensive traces of activity in Armenia; its products occupy a vast area trending from W–NW to SE as a band and forming individual volcanic highlands, ridges and volcanic plateaus (Aslanian, 1958; Gabrielian, 1959; Karapetian, 1972), which are often referred to as sub-zones, or blocks (Shirinian and Adjimamudov, 1966; Shirinian and Karapetian, 1973; Shirinian, 1973) (Fig. 1).

Spatially, these sub-zones are associated with two regional volcanic zones that intersect within Armenia, namely, the Trans-Caucasian transverse uplift zone and the longitudinal Anatolian–Armenian–Iranian zone (Milanovsky and Koronovsky, 1973; Aslanian, 1958; Gabrielian, 1959; Shirinian, 1973). The first zone includes a part of the Ashotsk (Djavakhet, Kechut) ridge, turns into the Akhalkalak volcanic plateau in the north, and joins the Aragats volcanic area in the south-west (Figs. 1, 5). The second zone includes Tsakhkuniats Ridge, Gegham, Vardenis and Syunik Highlands, and Zangezour Ridge (Figs. 1–4, 9, 11). The Aragats region is at the intersection of the two mentioned zones and thus is characterized by some distinctive features (Shirinian and Adjimamudov, 1966; Shirinian and Karapetian, 1973). Amongst the fields of basic and intermediate volcanic rocks of these areas, dome-shaped volcanoes of distinct morphology, formed by rhyolitic lava, obsidians, perlites and pumice, are described and mapped in detail (Karapetian, 1966, 1972).

The development of late collision rhyolitic

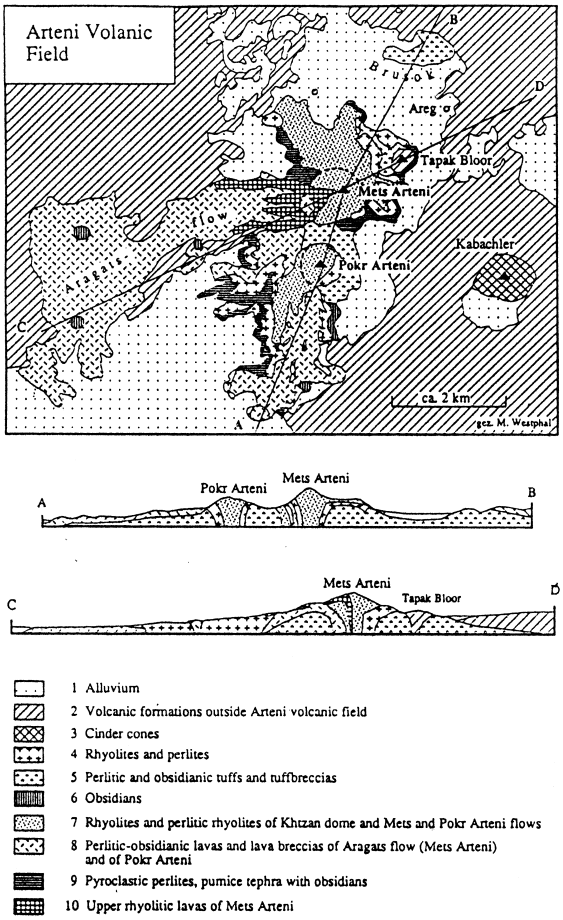

Fig. 5. Geological map of the Arteni volcanic complex.

volcanism can be divided into three phases (Table 1):

The first phase of 10–17 Ma (Mid-to-Late Miocene) includes rhyolites of the Zangezour ridge exposed on its slopes and watershed, as well as rhyolites of the Tsakhkuniats ridge foot (Kabakh River gorge).

The second phase of 4.5–7.5 Ma (Late Miocene–Early Pliocene) encompasses rhyolitic formations of the Tsakhkuniats ridge watershed, some domes of the Vardenis Highland (Gedykvank, Maralsar and others) and two small domes in the Hrazdan structure — Gyumush and Avazan.

The third phase of 0.1–2.8 Ma (Plio-Pleistocene) includes well-preserved rhyolitic volcanoes of the Ashotsk, Gegham, Vardenis and Syunik sub-zones.

Geophysical data imply substantial crust thickness (45–50 km), high heat flow and areas of low seismic velocities in the mantle under the regional zones of rhyolitic volcanism, which proves a lack of consolidation of the Earth's crust (Bagramian et al., 1986; Badalian et al., 1986). The latter is characterized by heterogeneity and block-mosaic structure of the lithosphere, the presence of a system of differently oriented faults and deep flexures, and strong differentiation of geophysical fields. Probably, magma melts were transported to the surface by through-crust and relatively shallow intra-crust fractures.

Different phases of rhyolitic volcanism are not always located within a single sub-zone. In the Tsakhkuniats ridge, for instance, the first and second phases of the volcanism are found; the Zangezour ridge has only the first, whereas the Gegham Highland and Aragats area have only the third phase.

2.1. Phase I rhyolitic formations

These are not found in the western zone of Armenia. In the eastern zone, they occur within the Zangezour ridge, forming whitish zones sporadically exposed on its slopes, and occasional small and distinct dome-shaped bodies on the watershed — Bartsratumb, Soulakar, and Agayargan (Karapetian, 1978). They are formed by rhyolites, perlites, pumice, and rarely by obsidians. Manganese ores are associated with them (Karapetian et al., 1986).

Within the Tsakhkuniats ridge, the rhyolites of this phase are found in the gorge of Kabakh River (tributary of Marmarik River) (Fig. 2). In one of the exposures, they are represented by whitish perlite–pumice pyroclastics, while in the other by a small rhyolitic extrusive body. To this phase, we attribute also pyramid-shaped erosion exposures of obsidians on the bank of another tributary to Marmarik near Kabakh. Karapetian (1968) classified these rhyolites into an individual phase.

2.2. Phase 2 rhyolitic formations

These are also identified only in the eastern zone, within the Tsakhkuniats ridge and Hrazdan structure, and in the Vardenis sub-zone. In the Tsakhkuniats ridge, the rhyolite–dacite formations compose some

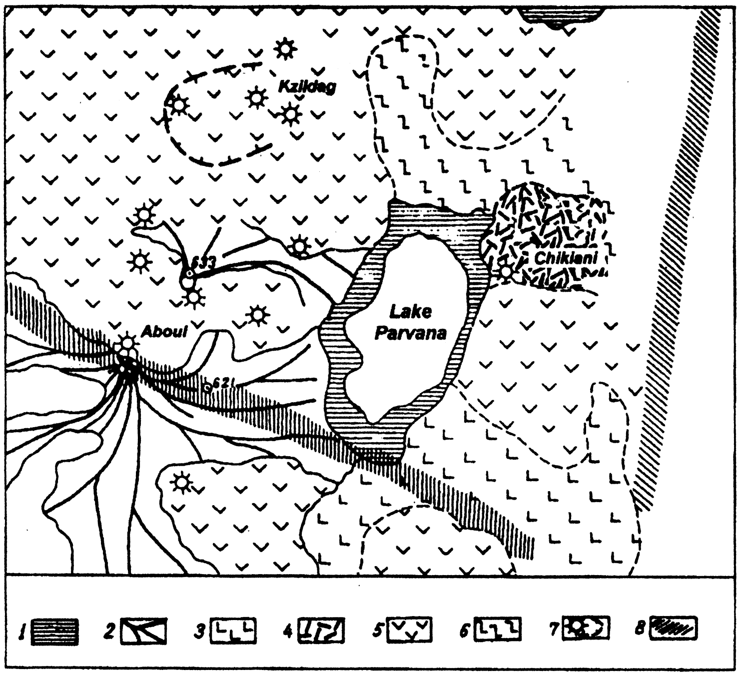

Fig. 6. Geological map of the field of Lake Parvana (by Stankevich E.K., Karapetian S.H.): 1. Alluvium, delluvium; 2. Lavas of the volcanoes Abul, Godoreby and other; 3. Basaltic lavas; 4. Rhyolitic rocks of the Parvana volcano; 5.Andesitic–basaltic lavas of the Injak volcano; 6. Dolerite–basalts, 7. Volcanic cones, caldera; 8. Gravity anomaly zones.

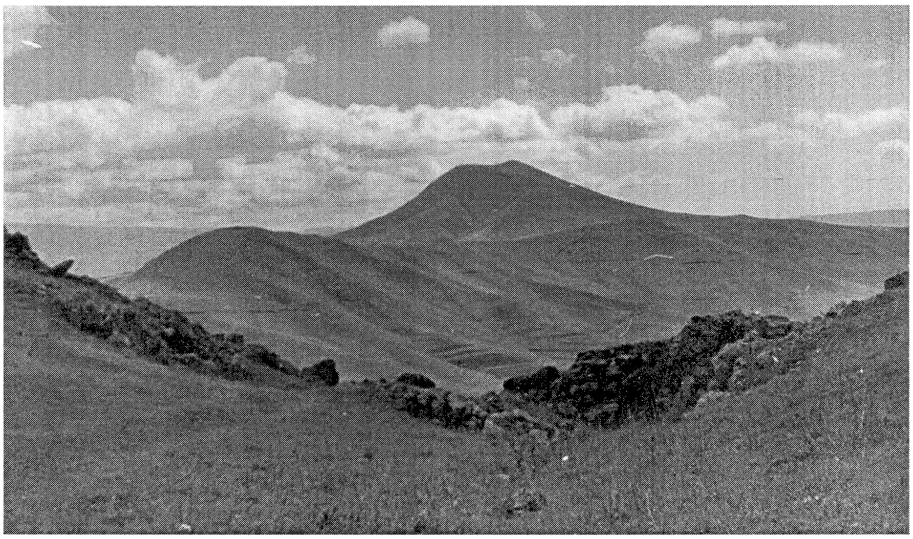

Fig. 7. Atis Volcano.

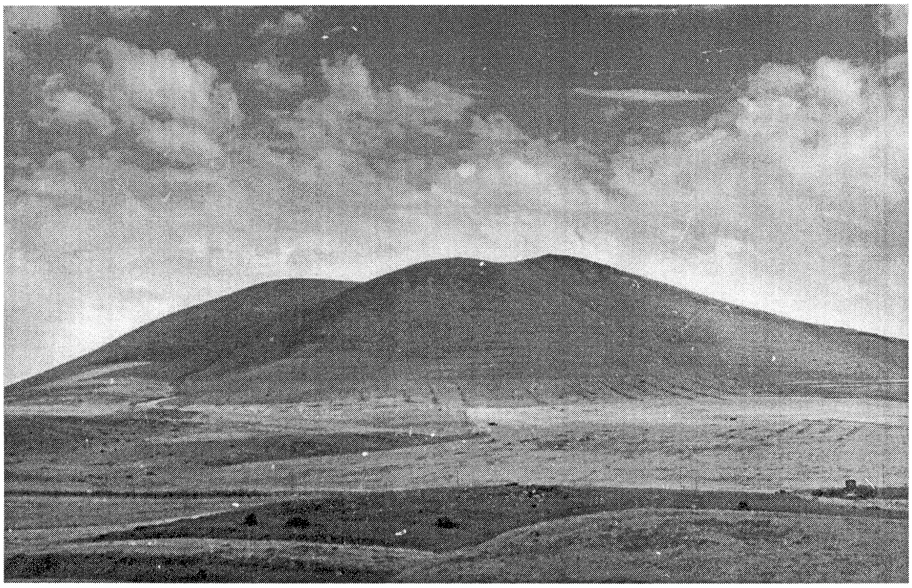

Fig. 8. Gutansar Volcano.

of the slopes and the watershed (more than 85 km^2). There, the centers of rhyolite eruptions are mainly denuded or smoothed. However, several large dome bodies with gentle slopes have remained intact: Tekhenis, Kamakar, Ttvakar, Nakharar, Damlik and others (Fig. 2). Among them, Arkayasar stands out by its morphology and is formed by fluidal rhyolites. Most of these volcanoes are overlaid by younger andesite and basaltic andesite lava. Several examples of coincidence between the centers of acid and basic rock eruptions, and instances of eruption synchronism are revealed, which can be explained by the different depths of several autonomous magma chambers of diverse composition (Karapetian, 1987).

Locations of rhyolite eruption centers mark the fractures coinciding with the 310–320° NW direction of the main Tsakhkuniats and Marmarik faults (Aslanian, 1958; Bagdasarian et al., 1970; Gabrielian, 1959). Besides, there are transverse 10–15° NE fractures crossing the main faults at different angles. The largest eruption centers of Tekhenis, Arkayasar, Damlik, and Kamakar are at the site of possible intersection of these two systems of fractures. The eruption type is multivental.

Apparently, rocks of this phase were widely spread within the Vardenis highland. Their remnants are represented now by the relatively small, dome-shaped volcanoes of Maralsar, Gedykvank, Baydara and others, separated by young flows of basic lava. In addition, rhyolites compose the bases of large peaks of the highland — the Lesser Vardenis, Sandukhkasar and others (Kazarian et al., 1967, 1981).

To this phase we attribute two small domes from the Hrazdan structure — Gyumush and Avazan, which neighbor villages with the same names on the left bank of the Hrazdan River. The domes are formed by quite peculiar rhyolite–dacite lava that is immediately underlaid by dolerite basalts. Besides, Gyumush is covered by rhyolite–obsidian–perlite rocks of the Djraber extrusion. The age of these domes is 4.5–5.5 Ma (Karapetian, 1968; Komarov et al., 1972).

2.3. Phase 3 rhyolitic formations

By the character and volume of eruptions, diversity of types, fair rate of preservation of volcanic edifices, as well as considering practical use of the eruption products, and high-quality perlite and obsidian in particular, rhyolitic volcanism of this phase is rather different from the first two phases and therefore is discussed in greater detail.

This volcanism covered new areas in the western

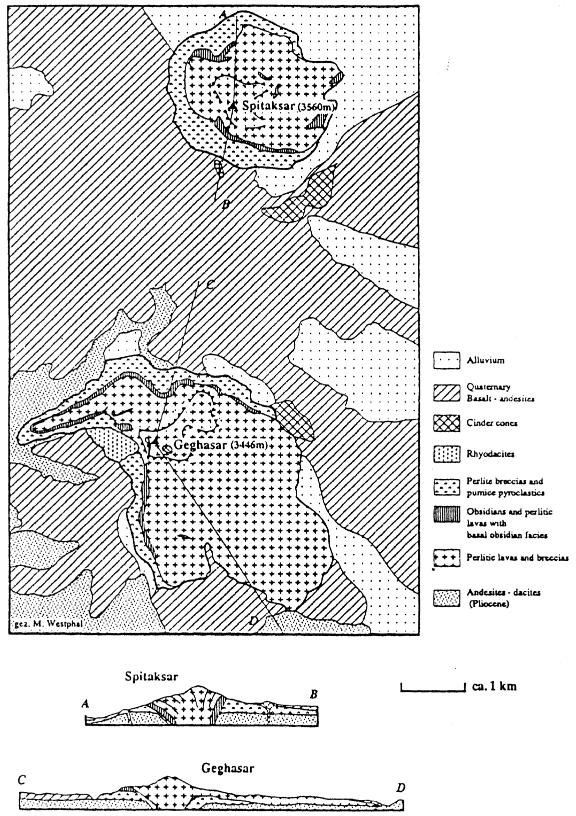

Fig. 9. Geological map of the Spitaksar and Geghasar volcanoes.

and eastern zones, from Ashotsk in the north (Kechut Ridge) to Syunik area in the southeast. In total, the area of these rocks is more than 200 km^2, while the material volume is 32 km^3. In the western zone and in the Hrazdan structure (near Atis volcano, town of Charentsavan and villages of Lusavan and Nurnus), thick layers of acid formations are underlaid by dolerite basalts (Fig. 3). Dolerite basalts are lacking in the eastern zone (Vardenis, Syunik, and Zangezour), and the rhyolites are underlain directly by the Middle Pliocene andesite–dacites. Thus, gradual passage from basalts to rhyolites is found in none of the zones.

Unlike other regions, where young volcanism is represented mainly by tuff and pumice, and associated with calderas and linear fractures, as in Kamchatka, Kuril Islands, Yellowstone Park and Cheghem (Kozhemiaka, 1980), rhyolite eruption centers in Armenia are volcano-dome edifices of distinct morphology that are often large and complex structures (Figs. 7 and 8, Table 2). Formation of the complex of rocks considered is related to multivent type volcanism. Volcano-forming rocks are rhyolites, dacites, obsidian, perlite, pumice, their tuffs and breccias. The last two are frequently interlayered with lava flows, which indicate recurrent activity periods of these volcanoes. For individual volcanoes, the number of eruption events is 4–5 (Atis, Spitaksar and others) and sometimes ranges up to 8 (Arteni).

Normally, the activity of the volcanoes began with strong explosions and depositions of loose perlite and pumice pyroclastics of rhyolitic composition. Zonal rhyolite–obsidian flows were erupted afterwards. The final stage was marked by effusive eruptions, or extrusions of small rhyolite and dacite bodies (Arteni, Atis, Gutanasar, Geghasar). At the Holocene stage of recent volcanism in Armenia, majority of the rhyolitic volcanoes (Atis, Gutansar, Geghasar, Alapars, Sevkar, Mets Satanakar and others) were broken through by small andesite and basaltic andesite volcanoes and connected flows (Amarian, 1964; Badalian et al., 1986; Karapetian, 1987).

Against the background of these basic patterns, Phase 3 volcanoes and eruption products within individual zones or sub-zones display certain peculiarities briefly described below.

2.4. Western zone

Phase 3 rhyolites occur in the two sub-zones: Ashotsk (Kechut Ridge) and Aragats. For Ashotsk, no credible eruption centers are established. The rhyolites form gently sloping heights behind the villages of Agvorik (Kechut) and Sizavet (Kharazian, 1968; Blackman et al., 1998). Rhyolitic lavas and obsidians — black, striped, and spotted, with faded shine — are also found. Within the northern extension of the zone (Akhalkalak area, Georgia), there is a single rhyolitic dome of Parvana (Chikiani) on the NE coast of Lake Parvana (Fig. 6). It is formed by rhyolites, perlites (the northern foot) and predominantly by obsidians, shaping a quite large train in the eastern direction.

The Aragats sub-zone accommodates only the Arteni complex, which is nevertheless of greatest interest and has the most complicated structure. It is famous for the stores of high-quality perlite (Aragats Deposit) and striped and transparent ornamental

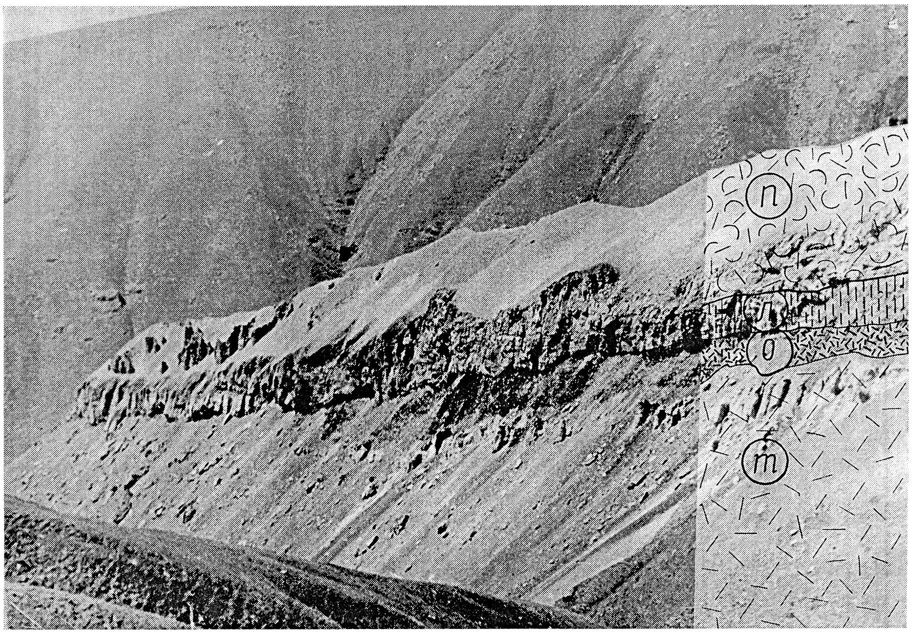

Fig. 10. Section of the Geghasar volcano west spur: m — rhyolitic tuff, o — obsidian, l — rhyolite, p — perlite.

obsidians (Karapetian, 1966, 1972). The complex is formed by products from the two larger Mets Arteni and Pokr Arteni centers, and several smaller ones that are now eroded (Fig. 5). The activity of the volcano began with an eruption of perlite–pumice pyroclastics. That was followed by an eruption of detrital perlite and zonal rhyolite–obsidian and obsidian flows in the western and southern directions; shorter flows went also northward. Finally, the large Khtsan extrusion was squeezed out from the main Mets Arteni volcano channel. A flow of fine-striped rhyolite spread from the extrusion top. Activity within the entire complex ceased with the extruding of the small dome of Tapak Blour.

2.5. Eastern zone

Phase 3 rhyolitic volcanism is present in the Vardenis, Gegham and Syunik sub-zones. Rhyolitic formations of the Hrazdan structure, which is in the central part of the country, are found on the two large volcanoes of Atis and Gutansar, and on the two smaller volcanoes of Alapars and Fontan (Fig. 3).

The locations of the volcanoes form a broken line following a fracture of near-meridian strike (14–16 km). The line coincides with the segment of the Ani–Ordubad deep fault (Aslanian, 1958). Atis and Gutansar basically have the same structure, with activity beginning with eruptions of rhyolitic pyroclastics, followed by later rhyolitic flows and obsidians (western slopes of Atis), and finishing with quite lengthy flows of rhyolite and dacite lava, the final portions of which plugged the volcano channels and formed dome-shaped structures.

In the Holocene, both volcanoes were broken through by volcanoes of andesite and basaltic andesite composition, which also formed lengthy flows. Quite a large crater (600 m in diameter, 5–8 m deep) formed on the Gutanasar summit in the Holocene. The Alapars and Fontan volcanoes differ from Gutanasar in their much smaller size, the characteristics of their products and their activity sequence. We identify them as independent centers (Karapetian, 1972, 1987).

The Large Djraber Extrusion (Fig. 3), taking in the area between the villages of Fontan, Charentsavan, Gyumush, and Djraber, is worthy of notice. All locally known and explored deposits of perlite and lithoid pumice, including Djraber, Fontan, Gyumush and others, are confined to it. In fact, the deposits form

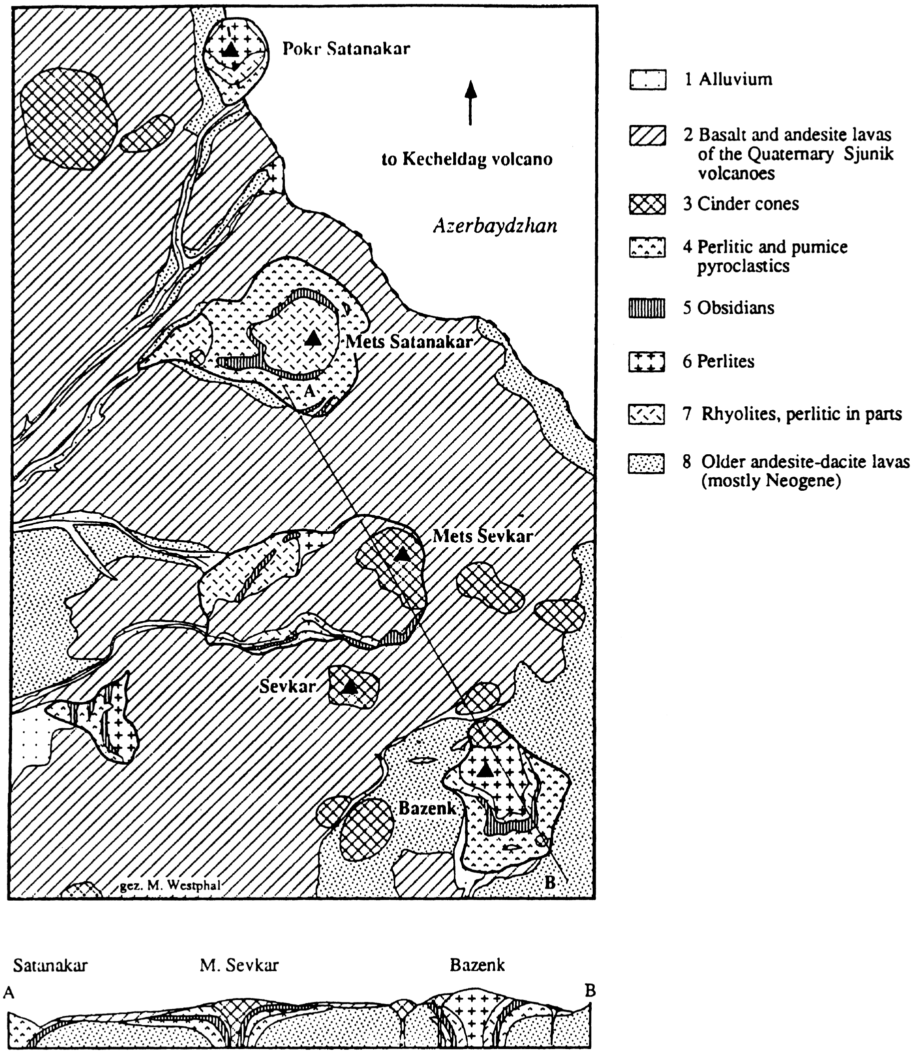

Fig. 11. Geological map of Syunik group volcanoes.

the apex of glassy extrusion. The glassy mass is there inflated to form perlite and pumice. In deep quarry sections, the remains of non-inflated ‘obsidian’ glass, as well as dike-shaped small bodies of the same glass, which had intruded into already inflated whitish perlite–pumice formations, are clearly visible. As a whole, the region is an interesting example of multivent rhyolitic volcanism.

Gegham sub-zone. Rhyolite rocks compose two relatively large volcanoes on the Gegham Ridge watershed — Spitaksar (White Mountain) and Geghasar (Beautiful Mountain). These rocks are mainly rhyolitic lavas, obsidians, perlites and their tuffs and breccia, and small residual flows of dacites (Fig. 9). The activity of both volcanoes was generally the same. It began with explosive eruptions, which formed pyroclastic deposits and tuffs. On Spitaksar, mountain massif borders limited the flows, i.e., there were no lengthy flows, and on Geghasar they spread southward and westward. West of Geghasar, there is an original erosion branch of a zonal flow washed-out on both sides (Fig. 10). At the base of this branch,

Table 1
Absolute age of the late-collision rhyolite rocks of Armenia

No.	No.	Dome volcanoes	Region, sub-zone	Age, Ma	
				K–Ar	By tracks
I	3318	Bartsratumb	Zangezour ridge	17.5	–
	2587	Kabakh canyon	Tsakhkuniats ridge	11.0 ± 0.5	–
II	1858	Damlik, Arkayasar	Tsakhkuniats ridge	5.4 ± 0.4	–
	1916	Sandukhkasar	Vardenis ridge	3.7	–
	1868	Maralsar		3.5	–
	3996	Gizhkar		5.0	–
	3998	Charokh		5.1	–
	4005	Babajan river-1		4.9	–
	4007	Babajan river-2		5.0	–
	4010	Baidara		4.8	–
	965	Avazan	Hrazdan structure	4.7 ± 0.2	–
	968	Gyumush		4.8 ± 0.5	–
III	1514	Arteni	Aragats sub-zone	1.25	1.2
	1161	Atis	Hrazdan structure	0.65	0.33
	1675	Gutansar		0.55	0.33
	1419	Spitaksar	Gegham highland		0.51
	1420	Geghasar			0.11
	1890	Choraphor	Vardenis highland	1.75	–
	3588	Mets Satanakar	Syunik highland		0.61
	3168	Michnek Satanakar		0.43	0.6
	459	Bazenk			0.3
	3223	Sevkar		0.9	0.64
	3605	Merkasar (Kechaldag)		0.7	–
	5933	Agvorak (Kechut)	Ashotsk ridge	2.3 ± 0.2	0.71
	3676	Parvana (Chikiani)	Akhalkalak (Georgia)	2.7 ± 0.1	–
	–	Pokr Ararat	Turkey	0.5	–
	AG-31	Sipan	Turkey	0.6 ± 0.2	–

Middle-Pliocene andesite and andesite–dacite detrital rocks are exposed. These are in turn covered by the tuffs of the first eruptive event on Geghasar and followed by a rhyolitic flow vitrified at the base and roof. Individual obsidian flows are also found: they are multi-colored, clearly striped and of high quality (Karapetian, 1972, 1987). A small patch of rhyolite–dacite lava is preserved on the western slope of the mountain. The Geghasar summit also has a young relict volcano, from which a small flow of basaltic andesite lava can be traced. On the west slope of Spitaksar there is a small patch of biotite–amphibole andesite.

In the Vardenis sub-zone, Phase 3 rhyiolites are represented only by one small Choraphor Volcano (Fig. 4). The volcano is composed of rhyolites and obsidians. Its northern part is of perlites and pumice, to which the Astichanasar perlite deposit is confined.

Syunik sub-zone. We considered this sub-zone, along with the Hrazdan structure, as an area typical for the development of multivent volcanism (Karapetian, 1966, 1972, 1987). It involves large volcanoes of distinct morphology, including Mets Satanakar, Michnek and Pokr Satanakars, Sevkar, and Bazenk (Fig. 11). The northern termination of this group (7 km) includes the similar Merkasar (Kechaldag) Volcano. The volcanoes form a broken line of a NW-striking fracture traced further to the NE for about 22 km.

These volcanoes are of rhyolitic lavas, obsidians, perlites and pumice. Diversities of dacite composition are not found in any of the volcanoes mentioned. Basic lavas broke through the two of them: Mets Satanakar on the western base, and Bazenk on the northern, western and southeastern slopes. The cinder cone, which had formed at the location of Sevkar Volcano, also erupted a basaltic andesite flow to the west,

Table 2
Main characteristics of late-collision rhyolite volcanoes of Armenia*

Sub-zones	Volcano name	H (m)	h (m)	D (m)	P (km)	V (km^3)	Structural-morphological forms	Eruption center
I	Mets Arteni	2047.4	500	2200	37	5.0	Domes, necks, flows	Complicated zonal dome
	Pokr Arteni	1753	300	1500			Flows, pyroclastics	Dome-shaped
II	Atis	2329.2	350	1000	25	3.0	Flows, pyroclastics	Dome-shaped
	Gutansar	2229.2	350	3000	45	5.0	Flows, extrusions	Rhyodacite dome
	Fontan	1791.0	35	170	2.0	0.2	Flows	Rhyodacite dome with crater
	Alapars	1809.5	160	400	2.6	0.2	Flows	Dome
III	Spitakasar	3560.1	500	3500	20	4.5	Flows, extrusions	Dome-shaped
	Geghasar	3446.0	350	1500			Flows, extrusions	Two-head peak
IV	Choraphor	2906.5	200	1000	7.0	2.2	Flows	Dome-shaped
V	Bazenk	3228.7	350	800	5.5	2.0	Extrusions, flows	Dome-shaped
	Mets Satanakar	3174.0	450	1000	5.5	2.0	Flows, extrusions	Dome-shaped
	Michnek Satanakar	2788.4	245	1500	1.5	0.3	Extrusion	Dome-shaped
	Pokr Satanakar	3162.0	200	500	0.7	0.2	Extrusion	Dome
	Sevkar	Volcanic formation destroyed					Flows, dykes	Dome ruins

* H — absolute height; h — relative height; D — foot diameter; P — foot perimeter (of volcano or massif); V — volume of erupted material.

covering most of the rhyolitic rocks. The volcanoes described are rich in perlite: the Vorotan deposit of perlite is confined to Bazenk Volcano.

3. Analytical methods

Chemical analyses of the Pliocene–Quaternary acid volcanics were performed at the Chemical Laboratory of the Institute of Geological Sciences, National Academy of Sciences of Armenia. Bulk rock analysis for major and trace elements in 39 obsidian samples from the main types of Upper Pliocene–Quaternary volcanoes of Armenia (Phase 3) was made by X-ray fluorescent (XRF) method (major elements) and INAA method (minor elements) at the Institute of Mineralogy and Petrography, University of Freiburg, and Max Planck Institute of Nuclear Physics in Geidelberg, Germany (Keller et al., 1994). Exceptional freshness and homogeneity were the criteria for the selection of obsidian samples for precise analytical studies. Also, analyses of Phase 2 obsidians published by Blackman et al. (1998) were used. For comparative studies, recent publications on the geochemistry of the latest acid rhyolites and obsidians of Anatolia and Caucasus were consulted (Keskin et al., 1998; Blackman et al., 1998; Poidevin, 1998; Chataigner, 1988; Yilmaz et al., 1998).

Strontium-isotope composition was determined by R.Kh. Gukasyan at the Laboratory of Isotopic Geology, Institute of Geological Sciences of the Republic of Armenia National Academy of Sciences. Twenty-six samples of acid volcanics representative of all three volcanism phases were studied. In addition, this paper provides isotopic composition determinations for Quaternary dacites from Aragats Volcano carried out by R.Kh. Gukasyan on two samples from the collections of Y.G. Gukasyan and D.S. Djrbashyan.

Rb and Sr concentrations were determined by standard method of isotopic dilution with separation of Sr on an ion-exchange column (Bagdasarian and Ghukasian, 1985). Isotopic ratios in a mixture of a sample with an indicator were measured by MI-309 mass-spectrometer. Direct measurements of Sr isotope composition ($^{87}Sr/^{86}Sr$) were made by MI-1021-T thermo-ionic mass-spectrometry. The measurement program implies also normalization of the measured $^{87}Sr/^{86}Sr$ ratio to the value of $^{88}Sr/^{86}Sr = 8.37521$. For this study, the relative error of the measured $^{87}Sr/^{86}Sr$ averaged $\pm 0.25\%$ according to parallel determinations. The error of Rb/Sr ratio does not exceed $\pm 2\%$. To check the $^{87}Sr/^{86}Sr$ measurements, the SRM-987 Sr Standard of the US Bureau of Standards was tested with each group of samples analyzed. Over the period of analysis, the standard gave the value of $^{87}Sr/^{86}Sr$ of 0.710240 ± 15 (2 SD; $n = 56$).

4. Petrography

Late-collision acid rocks are divided into rhyolite (lava, obsidians, perlites, and lithoid pumice) and dacite (lava, breccia) groups. The eruption sequence was from rhyolites to dacites. The formation of the first and second groups is usually related to the initial and final stages of volcanic activity, respectively (Karapetian, 1972). The rhyolitic group clearly dominates in the formation of the youngest volcanoes in the eastern zone (Gegham, Vardenis, Syunik highland).

The rhyolites include microcrystalline lavas with felsitic, microlithic, granopyric, and spherolithic types of groundmass, and glassy diversities of obsidians (of homogenous, fluidal, striped, or breccial texture and aphire gialine microstructure). In the fine-crystal groundmass of rhyolites, potassium feldspar (45%) and tridymite (up to 55%) are dominant; microlites of oligoclase, biotite and orthopyroxene also occur. Dacites have microlithic, felsitic, or spherolithic quartz–feldspar groundmass.

For both groups, a relatively small content of microphenocrystals is characteristic. In Phase 1 and 2 volcanics rocks, the content is higher and reaches 10–12%; in Phase 3 rocks it does not exceed 2–2.5%. Plagioclase is dominant in phenocrysts (An_{26-34} in rhyolites and An_{38-45} in dacites). There also occur quartz, biotite and amphibole; the content of the last two in Phase 1 and 2 rhyolites is up to 3–4%. Microphenocrysts of sanidine and anorthoclase (0.3–0.8%) are common in young rhyolites of the eastern zone (Choraphor, Geghasar, Spitaksar, Bazenk). Dacites of the eastern zone and Hrazdan structure contain small amounts of ortho- and clinopyroxene.

Table 3
Chemical compositions of recent acid volcanics of Armenia*

Oxides	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	72.20	75.00	67.13	65.81	72.74	72.52	71.54	74.84	72.00	73.79	72.08	72.40	73.69	72.60
TiO_2	0.24	0.21	0.70	1.01	0.07	0.10	0.18	0.05	0.09	0.37	0.12	0.14	0.14	0.13
Al_2O_3	14.80	13.40	15.23	16.42	15.59	14.71	14.45	13.64	16.70	14.46	14.08	14.34	13.96	15.02
Fe_2O_3	1.80	1.30	3.55	3.82	0.12	0.94	1.07	0.97	0.78	0.86	0.92	1.30	1.31	0.72
FeO					0.54	0.89	0.45	0.71		0.21	0.62	1.10	0.78	1.08
MnO	0.06	0.06	0.08	0.09	0.10	0.09	0.10	0.07		0.01	0.08	0.08	0.06	0.07
MgO	0.50	0.40	1.45	1.07	0.61	0.20	0.63	0.26	0.28	0.26	0.21	0.76	0.35	0.49
CaO	1.70	1.40	2.68	2.55	0.58	1.40	1.23	0.97	1.54	1.07	1.31	1.36	1.47	1.25
Na_2O	4.30	4.10	4.43	5.41	4.70	3.90	5.12	3.77	2.70	4.08	3.00	4.45	3.72	4.60
K_2O	4.30	4.10	3.35	2.68	4.60	4.18	2.64	4.06	3.60	4.16	4.25	4.10	4.01	4.66
H_2O^+					1.10			0.09	2.53	0.25	3.50		0.69	
H_2O^-						0.40	2.86	0.65	0.17	0.09	0.29	0.11	0.12	0.24
P_2O_5	0.13	0.05	0.20	0.23	0.07	0.02	0.08	0.01	0.23	0.02	0.05		0.04	
Sum	100.03	100.02	98.80	99.09	100.82	99.35	100.35	100.09	100.62	99.63	100.51	100.14	100.34	100.85
ASI	1.00	0.97	0.96	0.99	1.13	1.08	1.07	1.10	1.49	1.09	1.18	1.00	1.07	1.00
K_2O/Na_2O	1.00	1.00	0.76	0.50	0.98	1.07	0.52	1.08	1.33	1.02	1.42	0.92	1.08	1.01
Oxides	15	16	17	18	19	20	21	22	23	24	25	26	27	28
SiO_2	74.86	69.60	73.92	73.84	70.06	72.07	76.36	76.18	74.42	72.88	72.06	73.59	74.10	76.24
TiO_2	0.11	0.39				0.27			0.10	0.10		0.14		0.07
Al_2O_3	14.19	16.40	14.03	11.03	18.68	15.38	14.43	15.37	15.34	14.45	15.08	12.11	14.68	12.79
Fe_2O_3	0.89	2.40	1.24	2.69	0.69	0.67	0.27	0.52	0.90	0.60	1.90	1.61	0.53	1.22
FeO		0.48	0.48	0.73	0.14	0.43	0.14	0.28		0.54	0.66	0.07	0.28	0.09
MnO	0.06	0.06	0.08	0.02				0.09	0.06	0.05	0.02	0.05	0.05	0.01
MgO	0.24	1.31		0.29	0.60	0.70	0.52			0.20	1.30		1.20	
CaO	0.96	2.19	1.32	0.58	2.09	1.59	1.41	1.15	0.87	0.83	1.56	0.91	1.05	0.94
Na_2O	4.50	4.20	4.20	3.32	4.20	3.50	3.80	3.30	4.25	4.50	4.09	3.60	3.30	4.18
K_2O	4.16	3.20	4.80	4.11	3.70	4.38	3.50	3.50	4.15	4.90	3.40	4.40	3.40	4.15
H_2O^+		0.38		2.48	0.30	1.10	0.25	0.31		0.40	0.17	2.50	2.38	0.12
H_2O^-		0.10	0.40	0.43	0.39	0.47		0.02			0.12	0.86		
P_2O_5	0.03		0.04						0.09		0.04	0.06		0.04
Sum	100.00	100.71	100.51	99.52	100.85	100.56	100.68	100.72	100.18	99.45	100.40	99.90	100.97	99.85
ASI	1.03	1.14	0.96	1.00	1.27	1.14	1.15	1.36	1.12	1.01	1.14	0.98	1.33	0.97
K_2O/Na_2O	0.92	0.76	1.14	1.24	0.88	1.25	0.92	1.06	0.98	1.09	0.83	1.22	1.03	0.99

* 1–28 — ordinal numbers: Ashotsk sub-zone: 1 — sample 4341a, rhyolite. Agvorik (Eniel): 2 — sample 4342, same place; Aragats sub-zone: 3 — sample 153, dacite, Aragats volcano (authors Djerbashian D.S. and Ghukasian Yu.G.); 5 — sample 304a, thyolite ('upper'), summit of Mets Arterni Volcano; 6 — sample 3934, obsidian, Mets Arteni volcano (author Shirinyan K.G.); 7 — 3954, perlite, Mets Arteni volcano; 8 — sample 2, obsidian, Pokr Arteni volcano; Tsakhkuniats ridge: 9 — sample 3782, rhyolite, extrusive body, Kabach canyon; 10 — sample 3387, rhyolite, Arkayasar volcano; 11 — sample 3388, obsidian, same place; Hrazdan structure: 12 — sample 3547, rhyolite, Gutansar volcano; 13 — sample 2384, obsidian, same place; 14 — sample 562, rhyolite, Atis volcano (author Shirinyan K.G.); 15 — sample 3833, obsidian, same place; 16 — sample 765, dacite, break-through body in perlites and obsidians on the summit of Atis volcano; Gegham sub-zone: 17 — sample 3824, rhyolite, Geghasar volcano; Vardenis sub-zone: 18 — sample 1870a, rhyolite, Maralsar volcano; 19 — sample 4380 dacite, Sandukhkasar volcano; 20 — sample 1920, rhyolite, Khorapor volcano; 21 — sample 1880, rhyolite, same place; Syunik sub-zone: 22 — sample 3911, rhyolite, west foot of Bartstratumb volcano; 23 — sample 3824, rhyolite, east slope of Bazenk volcano; 24 — sample 3599, Mets Satanakar volcano; 26 — sample 3627, rhyolite, Pokr Satanakar volcano; 27 — sample 3636, rhyolite, Sevkar volcano; 28 — sample 3634, obsidian, same places.

Table 4
Representative chemical (wt %) and trace element (ppm) compositions of obsidians of Phase 3 acidic volcanism of Armenia*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	75.56	76.46	76.35	76.34	74.37	75.15	72.84	76.31	76.58	77.37	76.54	76.68	76.75	77.01
TiO_2	0.14	0.06	0.06	0.10	0.19	0.11	0.21	0.07	0.07	0.08	0.07	0.10	0.08	0.09
Al_2O_3	13.57	13.40	13.46	13.42	14.08	13.95	14.53	13.51	13.26	12.64	13.17	13.02	12.85	12.67
Fe_2O_3	0.98	0.53	0.53	0.62	1.25	0.94	1.80	0.58	0.56	0.59	0.60	0.74	0.66	0.71
MnO	0.06	0.10	0.10	0.07	0.09	0.07	0.06	0.08	0.09	0.06	0.07	0.06	0.08	0.06
MgO	0.22	0.08	0.07	0.15	0.24	0.22	0.48	0.12	0.09	0.04	0.12	0.12	0.11	0.05
CaO	0.81	0.51	0.51	0.52	1.00	0.99	1.67	0.57	0.58	0.48	0.48	0.48	0.44	0.47
Na_2O	3.96	4.43	4.51	4.21	4.59	4.29	4.56	4.38	4.29	4.18	4.61	4.19	4.44	4.06
K_2O	4.67	4.44	4.42	4.55	4.15	4.26	3.76	4.38	4.48	4.56	4.34	4.61	4.59	4.86
P_2O_5	0.03	0.00	0.00	0.02	0.04	0.03	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Rb	115	147	146	116	135	108	88	200	203	207	184	169	209	174
Sr	117	18	17	35	125	113	233	13	16	10	10	19	10	16
Ba	1042	45	28	338	451	521	590	16	10	10	10	45	10	26
Y	17	34	34	25	24	20	17	24	25	15	10	12	11	11
Nb	16	37	37	28	36	21	20	73	48	33	35	32	37	34
Zr	115	55	52	59	170	83	140	64	60	68	91	99	83	86
Sc	2.57	3.63	3.45	2.53	3.56	2.58	3.31	3.86	3.82	2.02	2.33	1.98	2.52	1.93
Cr	4.03	2.42	2.96	3.17	4.39	3.77	5.16	0.40	3.18	3.63	3.01	3.71	3.13	2.75
Co	0.61	0.44	0.14	0.22	0.80	0.68	0.30	0.54	0.20	0.19	0.10	0.21	0.10	0.20
Zn	40.20	44.50	39.90	34.10	39.20	32.60	39.10	30.90	29.00	22.30	32.60	28.90	31.40	26.10
As	2.25	5.58	4.99	3.57	3.38	2.71	2.88	5.25	5.67	4.99	2.03	1.68	2.19	1.69
Sb	0.19	0.50	0.48	0.42	0.44	0.35	0.34	0.61	0.70	0.62	0.26	0.20	0.34	0.24
Cs	4.38	4.75	4.51	3.48	5.60	5.04	4.08	7.55	7.91	8.08	5.66	4.85	6.38	4.92
Hf	3.61	3.22	2.98	3.00	4.38	3.45	4.02	2.81	2.90	3.33	3.89	3.45	3.87	3.51
Ta	1.39	3.47	3.18	2.56	3.56	1.48	2.24	6.35	5.33	3.32	2.76	2.58	3.11	2.71
Th	16.20	15.90	15.00	15.70	17.60	15.30	16.10	27.60	29.40	36.20	36.70	34.40	37.30	34.50
U	5.30	8.48	7.74	6.10	8.67	4.77	7.39	14.30	15.10	15.30	11.70	10.20	12.10	10.20
La	33.30	12.60	11.40	20.90	32.10	31.50	36.30	16.80	16.60	22.10	18.90	32.70	23.50	30.70
Ce	59.80	29.40	27.30	41.10	56.70	55.80	61.40	35.80	35.20	44.50	32.20	54.30	41.40	53.00
Nd	17.20	12.90	13.00	15.50	21.60	18.50	27.90	15.00	16.30	16.30	9.68	14.80	12.00	12.20
Sm	3.49	3.89	3.78	3.34	3.90	3.47	3.68	4.19	4.37	3.88	2.02	2.56	2.42	2.51
Eu	0.71	0.29	0.26	0.49	0.68	0.69	0.73	0.34	0.22	0.18	0.08	0.18	0.10	0.16
Tb	0.37	0.77	0.78	0.50	0.54	0.39	0.42	0.52	0.53	0.37	0.12	0.19	0.15	0.13
Yb	1.46	3.28	3.77	2.40	2.35	1.20	1.79	2.05	2.33	1.55	1.28	1.39	1.30	1.32
Lu	0.28	0.48	0.53	0.34	0.34	0.22	0.27	0.39	0.34	0.25	0.22	0.24	0.24	0.22

* 1–14 ordinal numbers of samples; analyses according to Keller et al. (1994): 1 — sample KAU 1, Ashotsk range (Parvana); 2 — sample OA 105, Pokr Arteni volcano; 3 — sample OA 102.1, Pokr Arteni volcano; 5 — sample OA 201, Gutansar volcano; 6 — sample KAU 2, Atis volcano; 7 — sample MA 7, Atis volcano; 8 — sample TO 140.1, Spitaksar volcano; 9 — sample OA 401, Geghasar volcano; 10 — sample MA 15, Choraphor volcano; 11 — sample TO 141.1, Bazenk volcano; 12 — sample 142.1, Sevkar volcano; 13 — sample OA 409, Mets Satanakar volcano; 14 — sample MA 19, Mets Satanakar volcano.

A wide diversity of accessory minerals, common in granite magmas, is found in these acid rocks (Karapetian and Meliksetian, 1972). All varieties of the acid rocks contain typical minerals, i.e. magnetite, ilmenite, apatite, garnet, zircon, and titanite. Anatase (rutile), corundum, tourmaline and titanite, along with high concentrations of almandine–spessartine garnet, are specific for the Arteni complex. Barite, allanite, monazite, and high concentrations of zircon and cyrtolite are characteristic for the volcanics of Atis, Gutansar, and Gyumush. The highest concentrations of ilmenite are found in the rhyolites of Spitaksar and Geghasar volcanoes, and of titanite in the volcanoes of Bazenk, Mets and Pokr Spitaksars, and Sevkar.

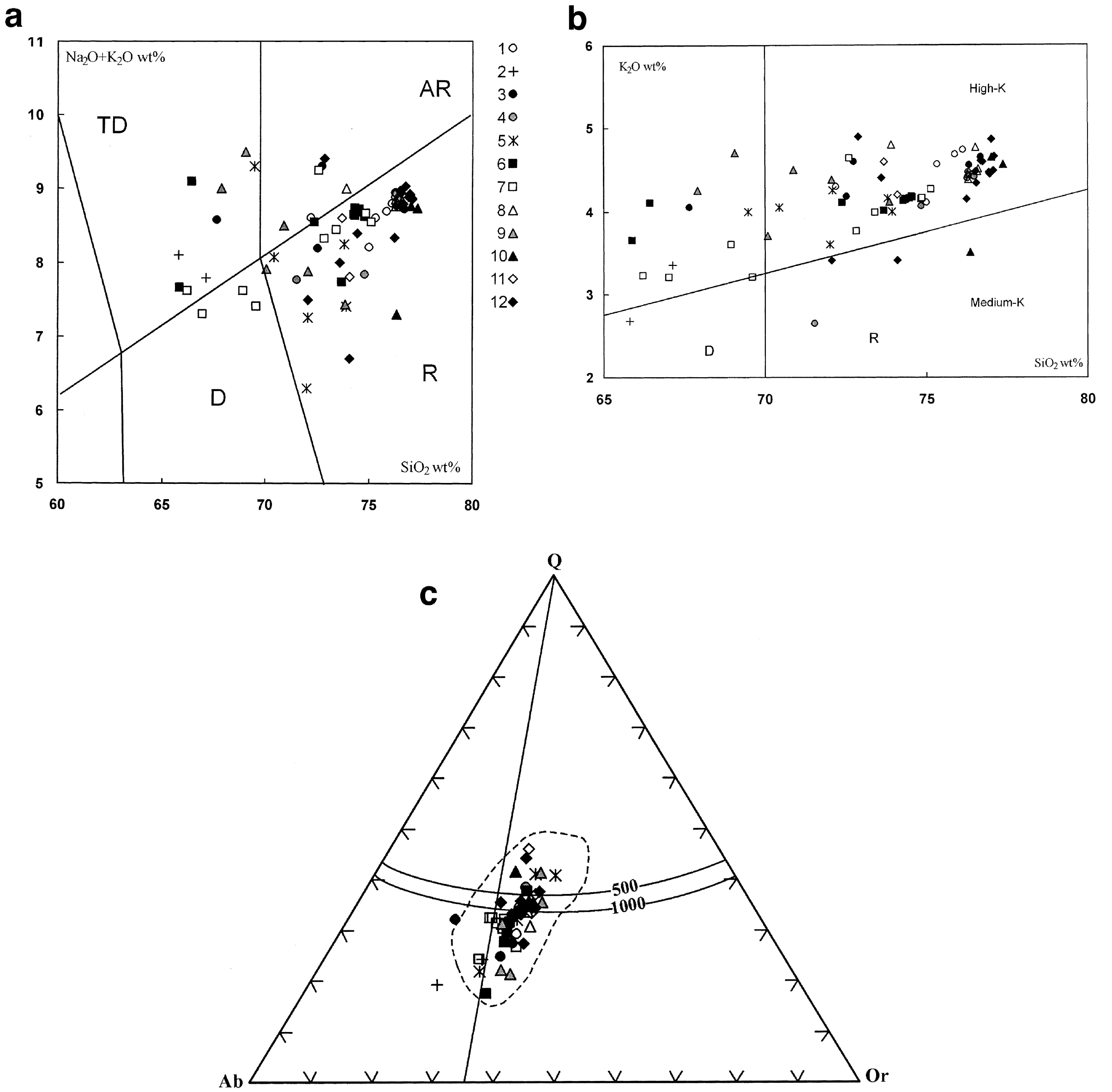

Fig. 12. (a) TAS diagram by Le Bas et al., 1987 and classification of Plio-Pleistocene acid volcanic rocks of Armenia. Data sources are Tables 3 and 4 and publication of Keller et al. (1994). Symbols: 1–12 acid volcanic rocks of separate volcanoes: 1 — Kechut; 2 — Aragats; 3 — Mets Arteni; 4 — Pokr Arteni; 5 — Tsakhkuniats ridge; 6 — Gutansar; 7 — Atis; 8 — Geghasar and Spitaksar; 9 — Maralsar, Sandukhkasar and Gedikvank; 10 — Choraphor; 11 — Bartsratumb; 12 — Basenk, Sevkar, Mets Satanakar, Pokr Satanakar, Merkasar (Kechaldag). Fields: D — dacite; TD — trachydacite; R — rhyolite; AR — alkali rhyolite. (b) K_2O–SiO_2 diagram by Peccereilo and Taylor (1976) for the Plio-Pleistocene acid volcanic rocks of Armenia. Series: II — medium-K calc-alkaline; III — high-K calc-alkali Symbols see on (a). (c) Ab–Or–Q triangular diagram for the Plio-Pleistocene acid volcanic rocks of Armenia. Dotted field represents 180 chemical analyses of Phase 1, 2 and 3 rocks of acidic volcanism of Armenia (Karapetian, 1972, 1987). Points represent compositions in Tables 3 and 4, and publication of Keller et al. (1994). Cotectic curves under P_{H2O} = 500 and 1000 bar are shown. See the symbols in (a).

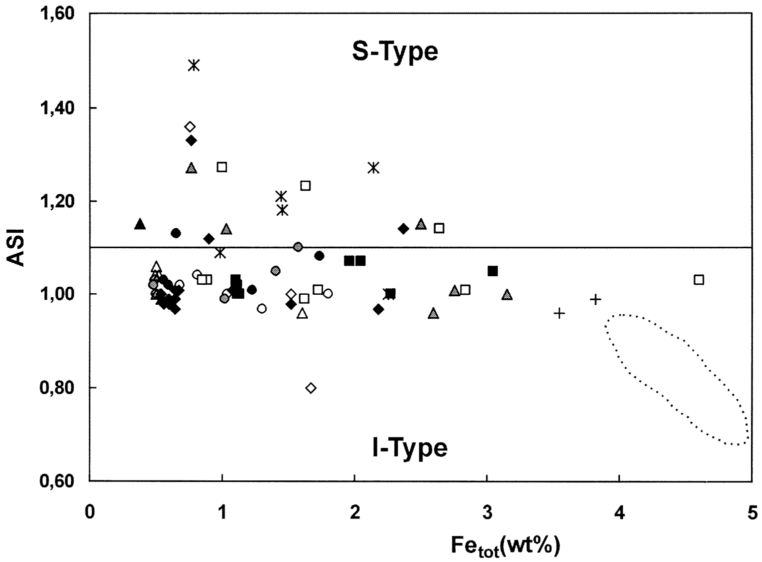

Fig. 13. Relationship between ASI and Fe_{tot} in Plio-Pleistocene acid volcanic rocks of Armenia on the diagram of Norman et al. (1992). ASI = $Al_2O_3/CaO + Na_2O + K_2O$, mol%. Data sources are the same as those for Fig. 12. The straight line 1.1 divides the diagram into S- and I-acid rock type fields. In the right corner of the diagram, composition field of peralkaline obsidians of Anatolia is outlined (Keller et al., 1994; Poidevin, 1998; Keskin et al., 1998; Blackman et al., 1998).

5. Geochemistry

5.1. Major elements

Chemical analyses of representative samples of the main rhyolitic volcano types of all three volcanism phases are presented in Table 3. Major and trace element composition of Phase 3 obsidians analyzed by Keller et al. (1994) is presented in Table 4.

In general, SiO_2 content for both groups of acid volcanics ranges from 76 to 66%. On a TAS classification diagram (Le Bas et al., 1987), they take up the fields of rhyolite, alkali rhyolite, dacite and trachidacite. These compositions are situated mainly along the boundary separating calc-alkaline and alkaline rhyolites (Fig. 12a). The SiO_2–K_2O diagram (Fig. 12b) demonstrates that they belong to the medium- and high-K calc-alkaline series of orogenic and continental collision zones.

The Ab–Or–Q diagram (Fig. 12c) shows a distribution of acid volcanics compositions within a limited field with maximum concentration in the area of the triple eutectic under intermediate and low values of P_{H2O}. Under small changes in orthoclase content, normative quartz and albite ratios are the most variable, which suggests that the depth is the composition-regulating factor of acid melt generation.

Phase 1 and 2 rhyolites have an SiO_2 range from 64 to 78% with clear trachite trend of differentiation and decrease of K_2O contents in parallel with the increase in SiO_2. This age group differs in over-saturation with Al_2O_3 (ASI = 1.06–1.42) (Fig. 13). Also, high contents of normative quartz correspond to the sub-surface eutectic melts.

Phase 3 rhyolites and dacites show considerable regional variations and a different range of SiO_2 variation. The range is relatively wide in volcanic rocks of the western zone and Hrazdan structure (76.5–66.0%). There, volcanics near Agvorik (Kechut) Village cover a narrow range in SiO_2 and corresponds to the rhyolites. At the same time, a clear discontinuity in SiO_2 and division into rhyolites and dacites is established for the Arteni complex. Immediate transition from rhyolites through rhyodacites to dacites is characteristic for the volcanics of Atis and Gutansar. In this group, SiO_2 positively correlates with K_2O, and with 1.08–0.52 variations in K_2O/Na_2O, indicating the increased role of Na_2O. This is particularly clear in dacites erupted at the final stages of Atis Volcano activity.

Volcanic rocks of the eastern zone, from the watershed part of the Gegham Highland to the Syunik Highland, are much less differentiated by SiO_2 (76–72%), and form compact groups of points on all graphs, with calc-alkaline trend under K_2O/Na_2O = 0.83–1.22.

Compared with the earlier phases, Phase 3 volcanics in both western and eastern zones are characterized by lower contents of normative quartz and Al_2O_3/$CaO + K_2O + Na_2O$ ratio (ASI = 1.1–0.95). This corresponds to deeper levels of magma generation and a higher degree of melting of the substrate, which is realized in a rhyolite–dacite sequence of eruptions.

High-K dacites of the polygenic Aragats Volcano present the final members in the consequently differentiated basalt–andesite–dacite (BAD) series and show high concentrations of CaO, low K_2O/Na_2O (0.5–0.85) ratios and moderate content of Al_2O_3. In Fig. 12c the composition of high-K dacites distinctly deviates from the eutectic minimum to the field of albite crystallization.

The diagram of ASI–Fe_{tot} by Norman et al. (1992) proves the noted differences in the age and series of the acid volcanics studied (Fig. 13). Compositions of Phase 1 and 2 volcanics are marked by low values of Fe_{tot} and are projected above the 1.1 separating line, according to their over-saturation in Al_2O_3. Under considerable variations of Fe_{tot}, Phase 3 volcanics, with a few exceptions, fall into a narrow field along the separating line. Compositions of calc-alkaline obsidians of Anatolia studied by Keller et al. (1994), Blackman et al. (1998) and others also fall into the same narrow field. For comparison, the compositions of peralkaline obsidians under-saturated in Al_2O_3 from Nemrut and Bingöl volcanoes (SE Anatolia) are presented. Due to high concentrations of Fe_{tot} and low values of ASI, they take an isolated position in the right lower corner of the diagram. The position of the Aragats volcano dacites with ASI = 1.0 and maximum values of Fe_{tot} is also distinct.

Thus, a description of the chemistry of the recent acid rocks in Armenia leads to the following conclusions. (1) Regardless of age, all studied acidic rocks have a eutectic composition implying low values of P_{H2O} and belong to the medium- and high-K calc-alkaline series. Dacites of the BAD series in the Aragats volcano deviate from the eutectic. (2) In terms of their $Al_2O_3 > 1.33FeO + 4.4$ ratio (Macdonald, 1974), the acid rocks belong to the comendite, low-ferric type. (3) From the early to final phases of volcanism, generation of initial acid melts descended to deeper levels, with increasing degree of melting. (4) In the lateral direction, from the western zone and Hrazdan structure towards the eastern zone, the compositions of acid rocks vary in a smaller range and the rate of their differentiation decreases. (5) The appearance of obsidians with extreme contents of SiO_2 is related to the formation of anhydrous high-temperature melts, which almost avoided crystallization in transient magma chambers. (6) Armenian obsidians belong to the calc-alkaline group of the two major petrochemical groups of obsidians identified by Keller et al. (1994) in Anatolia and the Caucasus (including Armenia), and are comparable to obsidians of the Orta and Yaglar volcanoes in W Anatolia, Hasan Dag, Acigol, and Nenezi Dag in central Anatolia (Cappadocia), areas of Kars–Erzerum in NE Anatolia, and Suphan, and Bingöl in SE Anatolia. Analogues of peralkaline obsidians from Nemrut and Bingöl volcanoes of SE Anatolia are not found in Armenia.

5.2. Trace elements

The geochemical characteristics of acid volcanoes are discussed using the example of the western and eastern zone Phase 3 obsidians studied in detail (Keller et al., 1994). As dry and high-temperature portions of rhyolitic melts, the obsidians most closely match the primary rhyolitic compositions and reflect their initial differences. Despite the similarity of petrographic composition and contents of major elements (SiO_2 = 72.84–77.37%, K_2O/Na_2O = 0.90–1.20), the obsidians from individual volcanic sub-zones show substantial differences in the concentrations of trace elements (Meliksetian and Karapetian, 1981; Keller et al., 1994). This leads to the conclusion that trace elements do not take part in the triple Q–Ab–Or eutectic (Tauson, 1974).

In general, the values obtained are close to those of Pliocene–Quaternary calc-alkaline obsidians of Anatolia and Caucasus (Keller et al., 1994; Blackman et al., 1998; Keskin et al., 1998). As shown below, variations of trace element contents in Armenian obsidians are of clear regional character, determining the geochemical type of individual volcanoes, their

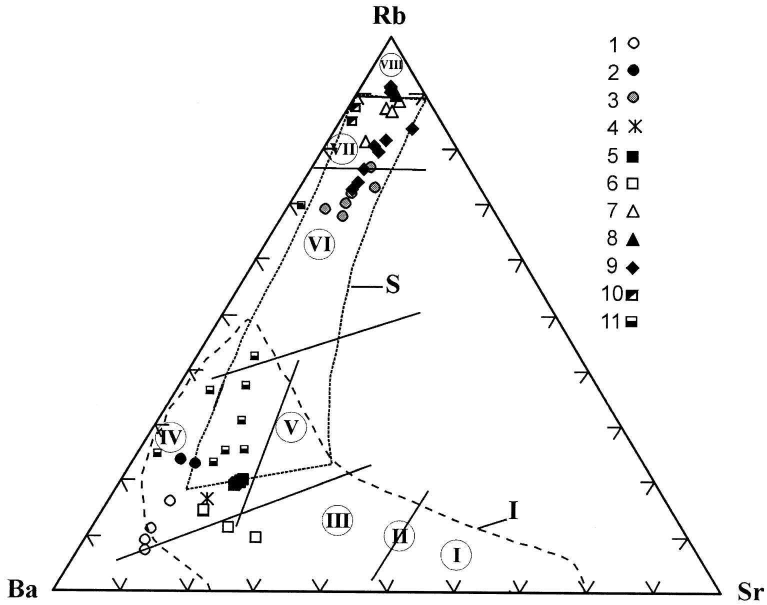

Fig. 14. Rb–Sr–Ba triangular diagram for Phase 3 obsidians of acidic volcanism of Armenia Sources of data are according to Keller et al. (1994). Fields of separate granitic groups are by Tauson (1974): I — plagiogranites of the tholeitic series; II — granite–granodiorites of the calc-alkaline series; III — subalkaline granites of the latite series; IV — ultrametamorpic granites; V — calc-alkaline granites; VI — plumasitic leukogranites; VII — peralkaline granites; VIII — peralkaline granites–alaskites. The fields of S and I granite types are also shown (Ostroumova et al., 1995). Symbols: 1–8 composition of obsidians from some of Armenian volcanoes: 1 — Kechut; 2 — Mets Arteni; 3 — Pokr Arteni; 4 — Tsakhkuniats; 5 — Gutansar; 6 — Atis; 7 — Geghasar, Spitaksar; 8 — Choraphor; 9 — Basenk, Sevkar, Mets Satanakar, Pokr Satanakar, Merkasar (Kechaldag); 10 — calc-alkaline obsidians of Anatolia; 11 — peralkaline obsidians of Anatolia (according to Keller et al., 1994; Blackman et al., 1998; Poidevin, 1998; Chataigner, 1988; Yilmaz et al., 1998; Keskin et al., 1998).

groups and zones. For example, the obsidians of the western zone and Hrazdan structure show much greater differentiation in the content of CaO, MgO and TiO_2 and all trace elements, with a wide range of variation even within the same group of volcanoes. This is reflected in different age trend of the variations, with extreme abundances within individual volcano groups. The obsidians of the eastern zone constitute compact groups of trace element compositions correlating with low concentrations of CaO, MgO and TiO_2.

The triangle plot for Rb–Sr–Ba (Fig. 14) reflects the dividing of the studied rocks into two discrete geochemical types — Ba-rich (Sr, Zr, Hf, LREE) and Rb-rich (Cs, Th, U, Ta, and Nb). The first type takes up the field of ultra-metamorphic granites (IV) and deviates towards the field of calc-alkaline granites (V). Phase 2 rhyolites in the Tsakhkuniats Ridge also belong to the Ba-rich type.

The second geochemical type is projected into the field of plumasite leukogranites (VI), peralkaline granites and alaskites (VII and VIII). The identified types are separated in space. The Ba-rich type is widespread in the western zone and Hrazdan structure with extreme values of Ba found in the Kechut Ridge obsidians, and of Zr and Hf on the Gutansar volcano. Except for the Pokr Arteni volcano, the Rb-rich type is characteristic of the eastern zone and the extreme value of Rb is found on the volcanoes of Gegham and Vardenis Ridges. As follows from the diagram, Anatolian obsidians are also represented by discrete types of Ba-rich and Rb-rich compositions, even though the locations of these types are not so distinct. The Ba-rich type is predominant (Yaglar and Orta-dome volcanoes in western Anatolia, Hasan Dag and Acigol in Cappadocia, and Erzincan, Saricamis, Kars, Bingol-A, and Suphan in eastern Anatolia). The calc-alkaline obsidians from Acigol-ouest and Pasinler, and ultra-alkaline obsidians of Nemrut and Bingol-B belong to the Rb-rich type. As in the case of the

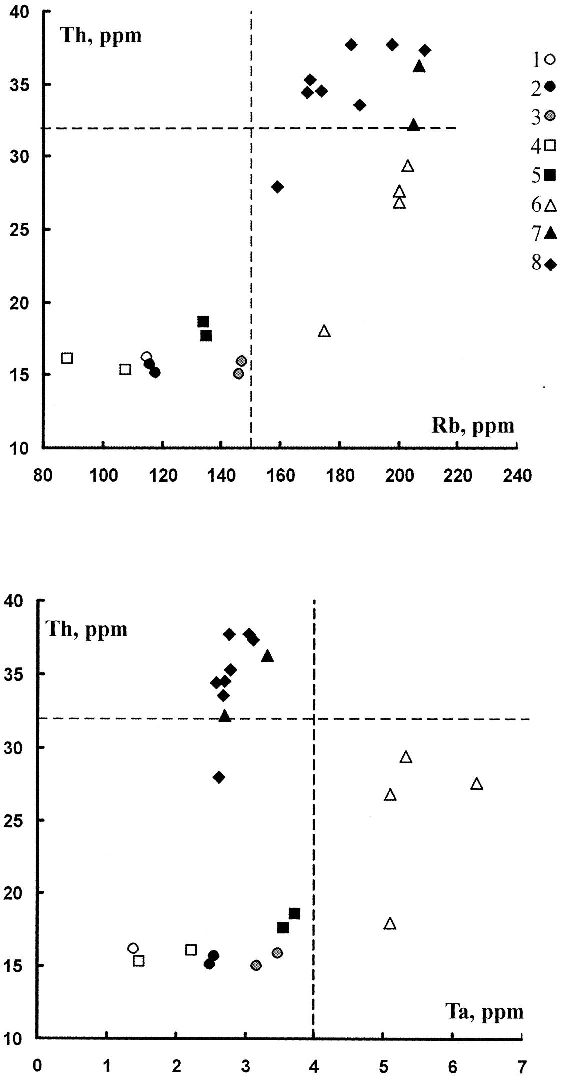

Fig. 15. (a) Th–Rb diagram for obsidians of Phase 3 acidic volcanism of Armenia Data sources are Keller et al. (1994). See the symbols in Fig. 14. (b) Th–Ta diagram for obsidians of Phase 3 acidic volcanism of Armenia. See the symbols in Fig. 14.

complicated Arteni complex, geochemically different obsidians often occur within the same volcano areas (Acigol, Pasinler, Bingol).

The difference between the two types of Armenian obsidians is delineated by the extreme concentrations (in ppm) of Th = 32 (U = 10) and Ta = 4. The Th–Rb (Fig. 15a) and Th–Ta (Fig. 15b) diagrams illustrate this by an extensive trend of increasing concentrations of these elements eastwards from the Kechut and Aragats sub-zones to the Spitaksar and Geghasar volcanoes. Farther, within the eastern zone, obsidians are characterized by maximum concentrations of Th (U) and Rb, forming an independent short trend without sharp differences for the Vardenis and Syunik sub-zones. The extreme abundances of Ta and Nb are found in the obsidians of Spitaksar and Geghasar volcanoes of the Gegham highland. The observed values of Ta and Nb significantly exceed the concentrations of these elements in calc-alkaline obsidians of Anatolia. At the same time, they are several times lower than in ultra-alkaline obsidians of the Nemrut and Bingol volcanoes.

Variations of Th and U show close correlation (Fig. 16) and form two discrete trends along the isolines of Th/U = 2–2.5 (Fig. 16). The first trend corresponds to the obsidians of the western zone and Hrazdan structure, and the second one belongs to the obsidians of the Gegham and Vardenis sub-zones with extreme values of U on Geghasar and Choraphor volcanoes. The third trend along the isoline of Th/U = 3–3.5 belongs to the obsidians of the Syunik group with the highest concentrations of Th. According to Taylor and MacLennan, 1988, Th/U ratios are indicators of the contribution of recycled continental crust sediments to the formation of magmatic melts. High Th/U ratios in obsidians of the Syunik sub-zone volcanoes can thus indicate the substantial increase of sedimentary rock portions in initial substrates.

The low limit of Th/U ratios (1.88–2.37) established for the obsidians of the western zone and Hrazdan structure approximates the respective mantle values. Anatolian obsidians show different Th/U ratios. In particular, high concentrations of Th and Th/U ratio of 3–3.5 in the Yaglar, Hasan Dag, Acigol, Bingol-A and Nemrut obsidians are similar to those in the obsidians from the Syunik sub-zone. Similarly, in significantly higher U concentrations, the obsidians of Spitaksar, Geghasar and Choraphor have no analogs among the geochemical groups of Anatolia and Caucasus.

Y–Rb systematics of Armenian obsidians presented in Fig. 17 reveal negative correlation between these elements, and a decline in Y concentrations along with the increase in Rb from the western zone and Hrazdan structure to the eastern zone. The extremely Y-enriched obsidians of the

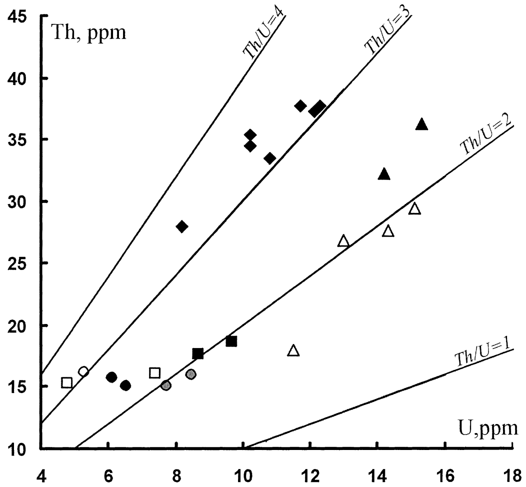

Fig. 16. Th–U diagram for obsidians of Phase 3 acidic volcanism of Armenia. Data sources are Keller et al. (1994). See the symbols in Fig. 14.

Pokr Arteni volcano occupy a separate position. Comparison with the vectors of high-Y and low-Y series of the Erzurum–Kars Plateau (Keskin et al., 1998) plotted on the same diagram clearly shows that the Y–Rb trend of Armenian obsidians is parallel to the trend of low-Y series, even though it is strongly displaced towards the higher Rb concentrations. The obsidians of Pokr Arteni volcano neatly follow the trend of high-Y series, approximating the obsidian compositions of Pasinler, Sarikamis, Bingol-A, and Suphan volcanoes.

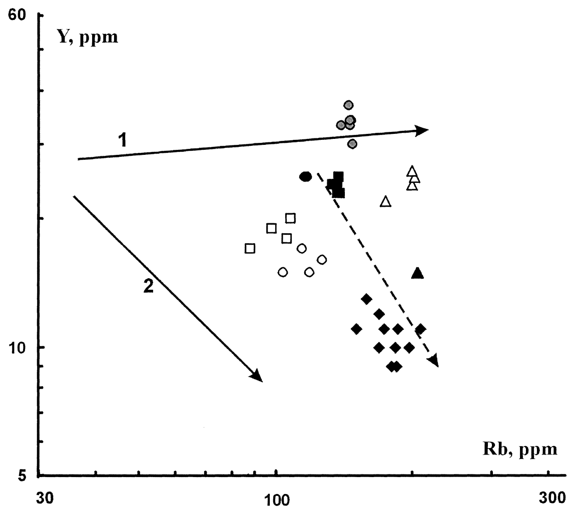

Fig. 17. Y–Rb diagram for obsidians of Phase 3 acidic volcanism of Armenia. Data sources are Keller et al. (1994). See the symbols in Fig. 14. High-Y (1) and low-Y (2) trends for the Erzurum–Kars plateau volcanics according to Keskin et al. (1998).

According to the data of Keller et al. (1994), the average concentration of REE in the Phase 3 obsidians studied varies within the range 61–132 ppm. In Phase 2 obsidians within the Tsakhkuniats Ridge this variation is notably higher ($\sum$REE = 163–185 ppm) (Blackman et al., 1998).

The obsidians of the western zone and Hrazdan structure give quite a wide interval of $\sum$REE variations with maximum concentrations observed in the volcanoes of Kechut Ridge ($\sum$REE = 117 ppm), Gutansar, and Atis in the Hrazdan structure ($\sum$REE = 113–132 ppm), while the minimum values ($\sum$REE = 61–84 ppm) are found in the Arteni complex. In the eastern zone, $\sum$REE varies within much narrower limits (66–116 ppm) with a maximum on Merkasar (Kechaldag) and Sevkar volcanoes (106–119 ppm).

Chondrite-normalized REE patterns for the Phase 3 obsidians studied are presented in Fig. 18. Generally, the variation curves are characterized by high level of fractionation and a steep slope toward HREE, which especially increases from Nd to Sm. With a few exceptions, there is a strong Eu-minimum, which reflects early separation of plagioclase (and alkaline feldspar) from the melt, or their accumulation in the restite. At the same time, the REE spectra reflect regional differences and belonging to certain geochemical types.

The Ba-rich type demonstrates a higher level of concentrations of both LREE and HREE, and a wider range of variations in Tb, Yb and Y, with La^N/Y_{bN} ratios between 1.9 and 5.1. In this type, Ba-enriched obsidians of the Kechut Ridge are an exception, which differ in steeper transition to HREE, without Eu-min. The lowest level of LREE concentrations and, at the same time, the highest level of HREE and Y is established for the obsidians of Pokr Arteni volcano, which can be explained by a high degree of melting of the depleted dry substrate containing such refractory accessory phases as garnet and, possibly, allanite. The variations of HREE and Y concentrations in the obsidians of the western zone, Hrazdan structure and Gegham Ridge are interpreted as the result of at least

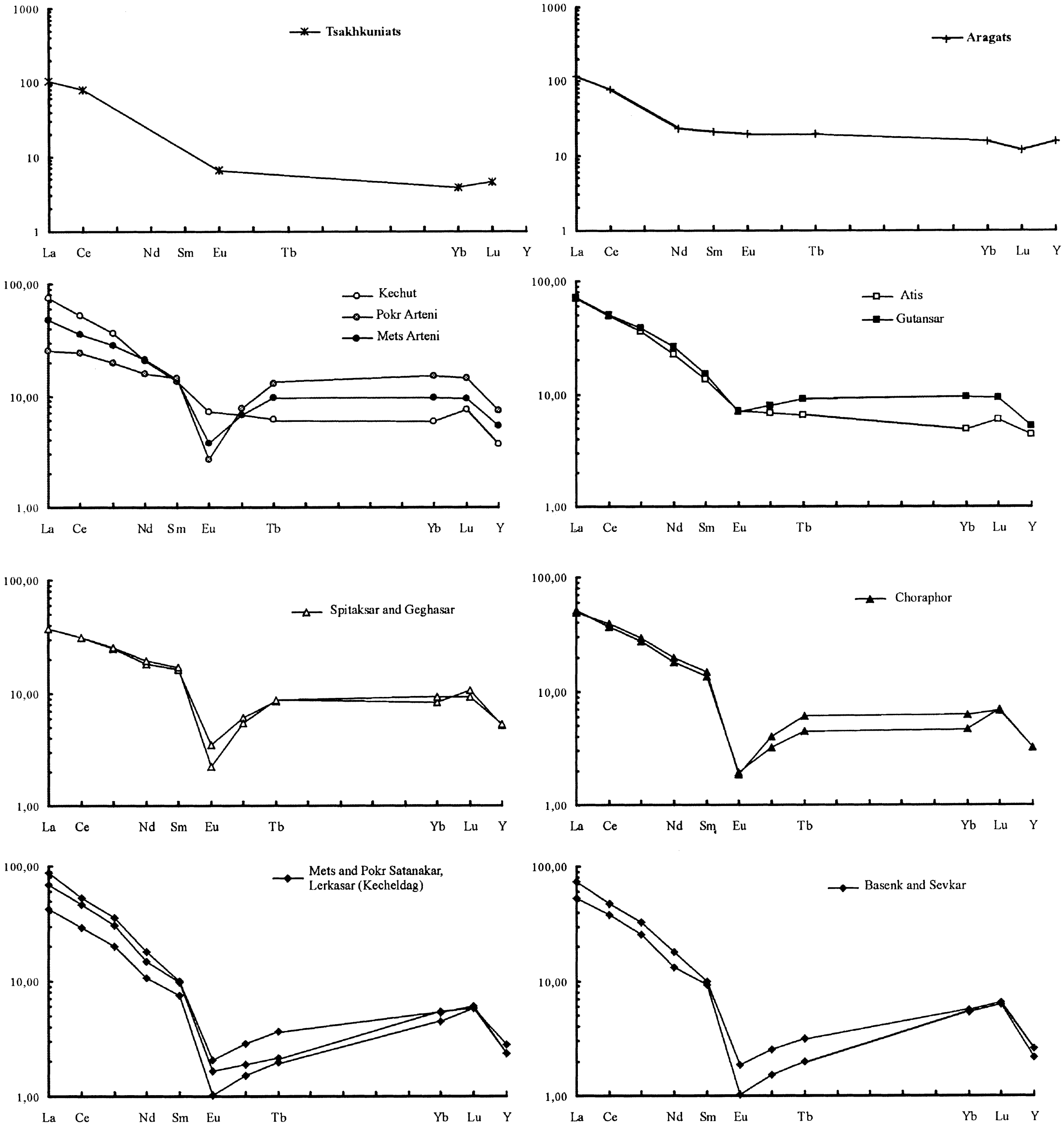

Fig. 18. Chondrite-normalized REE pattern for obsidians of Phase 3 acidic volcanism of Armenia. Data sources are Keller et al. (1994); Poidevin (1998). The chondrite-normalized values are by Anders and Grevesse (1989).

two degrees of melting: the higher (up to 30%) for Pokr Arteni, Gutansar, Spitaksar and Geghasar volcanoes, and the lower one (up to 20–25%) for volcanoes of the Kechut Ridge, Mets Arteni and Atis. The Arteni volcanic complex thus presents an example of spatial coexistence of eruption products which belong to different stages of magmatic chamber evolution.

The Rb-rich geochemical type differs in having a steep profile of LREE decline, deeper Eu-min, depletion in HREE, and increasing of La^N/Yb_N ratios (8.9–15.8). It is necessary to note that the largest negative value of Eu anomalies is observed in the eastern zone obsidians and associated with the greatest abundance of Rb (209–184 ppm). These features can be

Table 5
Correlation coefficient values (r) for some indicator elements in obsidians of Phase 3 acidic volcanism of Armenia (for the 5% level of significance)

Components	Western zone and Hrazdan structure r ($n = 23$)	Eastern zone r ($n = 20$)	Phase of fractionation or accumulation
$CaO–Al_2O_3$	0.6696	0.7736	Plagioclase
CaO–Sr	0.7196	0.1763	Plagioclase
CaO–MgO	0.7709	0.1963	Ortho + clinopyroxene
MgO–Cr	0.7984	− 0.2027	Ortho + clinopyroxene
$CaO–TiO_2$	0.5862	− 0.4835	Titanite
CaO–Ce	0.6140	− 0.6478	Allanite
CaO–Y	− 0.4808	0.8247	Amphibole
$TiO_2–Zr$	0.9820	0.6889	Ilmenite
$TiO_2–Y$	− 0.5485	− 0.4079	Garnet (rutile)
$K_2O–Rb$	− 0.0283	− 0.3237	Biotite, K–feldspar
$K_2O–Ba$	− 0.1046	0.3661	K–feldspar
$SiO_2–Zr$	− 0.5862	− 0.6192	Zircon
Nb–Zr	− 0.0168	− 0.6064	Titanite

explained by a low degree of non-depleted substrate melting under the activity of a volatile phase and the presence of amphibole in the cumulus.

In the same figure, the REE spectrum in the BAD series dacites from the Aragats volcano is shown according to the data of Ostroumova et al. (1995). It differs in high overall concentrations of lanthanides and the absence of a Eu-min, probably as inherited from the initial basalt–andesite differentiates.

The character of distribution and different systems of major and trace element correlation in obsidians from different zones and areas agree with geochemical differences of initial melting substrates and with the two mechanisms of rhyolithic magma evolution (Meliksetian et al., 1998). Table 5 presents correlation coefficients for some indicator elements of the obsidians studied, calculated on the basis of analytical data of Keller et al. (1994). The results can be summarized as follows. The first mechanism of rhyolithic magma evolution is connected with the mineralogical control of fractionating or accumulating phases. From Table 5 it is clear that the dominant fractionation minerals both in the western and eastern zone are plagioclase and accessory ilmenite. In the western zone and Hrazdan structure, additional phases are represented by ortho-clinopyroxenes and accessory titanite and allanite. In the eastern zone, the fractionating assemblage includes amphibole with subordinate K-feldspar. Strong negative correlations of TiO_2–Y, SiO_2–Zr, and Nb–Zr show that restite phases are represented by garnet (rutile) and zircon in the eastern zone, and by titanite in the western zone. In contrast, poor negative K_2O–Rb correlation, as well as Rb–Th, Ta–Th, Th–U, and Y–Rb relationships (Figs. 15a,b, 16 and 17) show that K, Rb (Cs), Th and U generally behave as incompatible elements. This feature can be better explained through the second evolution mechanism connected with the entrance to the melting areas of deep-horizon mobile fluids, disturbing the process of fractionation and consequent differentiation of melts (Balashov, 1985; Puzankov et al., 1990).

6. Isotopic characteristics

The later-collision acid volcanics cover a wide range in $^{87}Sr/^{86}Sr$ ratios from 0.70438 to 0.70636 (Table 6). These data reflect a high-rate influence of a mantle-derived substance on the composition of acid effusives (Balashov, 1985). In the upper limit, the data provided approximate the values determined by crust material.

The Rb/Sr–Rb diagram (Fig. 19) illustrates the concordant increase of these parameters in the acid volcanics studied along with the distinct age trend. The following composition fields are distinguished. Field I with Rb/Sr = 0.2–0.6 and an average value

Table 6
Concentrations of rubidium, strontium and isotopic composition of strontium in the newest acid volcanics of Armenia

No	Sample	Age (Ma)		Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Rb/^{86}Sr$ (atomic ratio)	$(^{87}Rb/^{86}Sr)_0$
		K–Ar	Tracks						
1	4341a	2.10	1.71	91.65	181.36	0.506	1.47	0.70459 ± 9	0.70455
2	4342			90.00	180.00	0.500	1.45	0.70447 ± 15	0.70443
3	153	0–3		38.00	574.00	0.066	0.19	0.70449 ± 10	–
4	642			42.00	585.00	0.072	0.21	0.70432 ± 17	–
5	304a	1.25	1.20	138.26	16.89	8.186	23.74	0.70610 ± 25	0.70569
6	3934			128.37	30.94	4.149	12.03	0.70578 ± 15	0.70557
7	3954			111.36	43.23	2.570	7.47	0.70565 ± 27	0.70552
8	2			124.40	34.50	3.610	10.47	0.70445	0.70435
9	3782	11.00		84.85	384.45	0.221	0.65	0.70458 ± 6	0.70448
10	3387	6.00		85.47	226.11	0.378	1.09	0.70468 ± 30	0.70459
11	3388			87.29	223.15	0.391	1.13	0.70469 ± 6	0.70459
12	3547	0.55	0.33	53.56	33.63	1.596	4.63	0.70476 ± 30	0.70473
13	2384			131.35	119.46	1.100	3.19	0.70456 ± 11	0.70454
14	562		0.40	100.40	191.70	0.520	1.51	0.70435	0.70425
15	3833	0.65	0.33	108.12	109.03	0.992	2.88	0.70439 ± 6	0.70439
16	765		0.90	105.17	113.43	0.927	2.68	0.70441 ± 15	0.70438
17	3824		0.11	190.52	11.89	16.024	46.46	0.70566 ± 25	0.70559
18	1870a		3.50	113.58	342.19	0.332	0.96	0.70467 ± 11	0.70462
19	4380		4.20	96.97	352.89	0.274	0.79	0.70444 ± 8	0.70439
20	1920		3.70	138.28	279.44	0.495	1.44	0.70453 ± 6	0.70446
21	1880	1.75	1.72	197.77	8.15	24.266	70.37	0.70811 ± 28	0.70636
22	3911	12.50		106.50	175.27	0.606	1.76	0.70484 ± 30	0.70453
23	3864		0.30	187.18	8.13	23.023	66.77	0.70583 ± 30	0.70555
24	3599		0.61	180.96	12.46	14.523	42.11	0.70568 ± 26	0.70532
25	3594	0.43	0.60	201.84	12.70	15.893	46.09	0.70593 ± 9	0.70553
26	3627		0.43	164.80	16.78	9.821	28.48	0.70493 ± 18	0.70468
27	3636	0.90	0.64	241.90	22.60	10.704	31.04	0.70522 ± 17	0.70489
28	3634			165.35	21.26	7.778	22.56	0.70494 ± 16	0.70470

of $(^{87}Sr/^{86}Sr)_0 = 0.70448$ corresponds mainly to Phase 1 and 2 volcanics. The younger volcanics of this group includes rhyolites of Agvorik (Kechut) and one sample from the Atis volcano. Field I grades into Field II and is characterized by a Rb/Sr ratio = 0.9–4.5, an average value of $(^{87}Sr/^{86}Sr)_0 = 0.70478$, and includes rhyolites and dacites of the western zone and Hrazdan structure, which, except for Phase 3 of the Pokr Arteni volcano, belong to the Ba-rich type. After a large gap, there follows Field III with Rb/Sr = 7–11 and an average value of $(^{87}Sr/^{86}Sr)_0 = 0.70499$, and Field IV with a maximum of Rb/Sr = 14–24 and an average value of $(^{87}Sr/^{86}Sr)_0 = 0.70567$. The latter two groups include all rhyolites of the eastern zone beginning from the watershed part of the Gegham Ridge to Syunik, and one sample from Mets Arteni. The maximum parameters are established for rhyolites of the Choraphor volcano. Therefore, Rb/Sr and $(^{87}Sr/^{86}Sr)_0$ ratios in the acid volcanics studied were gradually increasing in time. Field V takes up the extreme left position in the figure, standing out in low values of Rb/Sr = 0.07 and $^{87}Sr/^{86}Sr$ = 0.70449–0.70432. It corresponds to the BAD series dacites of Aragats volcano that represent an independent Rb–Sr system.

The evolution of isotopic composition of acid volcanics is reflected in Fig. 20. The results point to the two clearly distinct levels of $(^{87}Sr/^{86}Sr)_0$ ratios that branch off at the value of 0.7048 and some independent trends each with a different rate of $(^{87}Sr/^{86}Sr)_0$ ratio increasing as Sr concentrations decreased. At the same time, a decline in Sr has certain age specificity, and hence Phase 1 and 2 volcanics (trend 1) are enriched in Sr to a greater

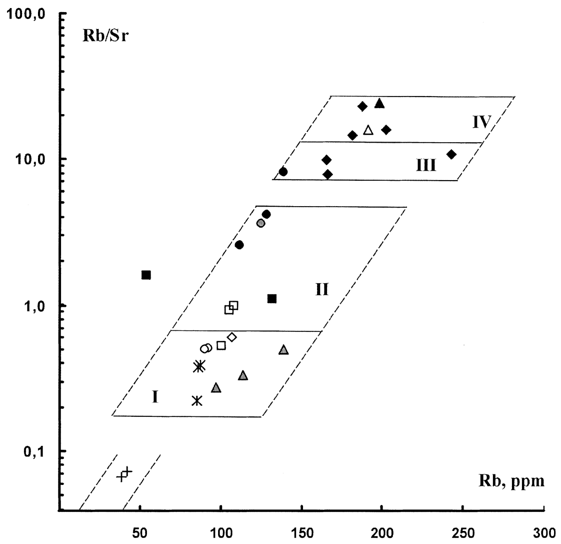

Fig. 19. Relationship between Rb/Sr and Rb(ppm) for Plio-Pleistocene acid rocks of Armenia. Data sources see in Table 5. See symbols in Fig. 12. Explanations are in the text.

extent than Phase 3 volcanics from the western zone and Hrazdan structure that immediately follow them (trend 2). The peculiarity of trends 1 and 2 is their gentle character determined by the leading role of crystallization of Ca-plagioclase (and alkaline feldspar). The group of samples from Mets Arteni (trend 3) contrasts with the compositions of the western zone volcanics by a sharp increase of $(^{87}Sr/^{86}Sr)_0$ along with a slow decline of Sr. The appearance of this independent trend marks the disturbance of isotopic balance connected with the accumulation of radiogenic Sr in the melt. The youngest Phase 3 rhyolites of the eastern zone (sub-vertical trend 4) are characterized by minimum concentrations of Sr and a narrow variation range against the background of a steep rise of $(^{87}Sr/^{86}Sr)_0$ ratio. This can be explained by the appearance of an independent Rb–Sr source, which is probably formed through accumulation of some amount of sedimentary-metamorphic material, and an increasing role of a volatile phase in the initial melt with a supplementary influx of K–Rb fluids from deeper horizons. With maximum Sr concentrations and $(^{87}Sr/^{86}Sr)$ ratios close to those in the mantle, Aragats volcano dacites of the BAD series take a separate position in this figure.

As an attempt to understand petrogenetic relationships between the magmatic sources of recent acid volcanics and underlying Pre-Cambrian granite-metamorphic rocks, a summary of the geochronology and isotopic geochemistry data for the crystalline basement of the Tsakhkuniats outcrop of underlying and intruded granitoid massifs is given in Table 7

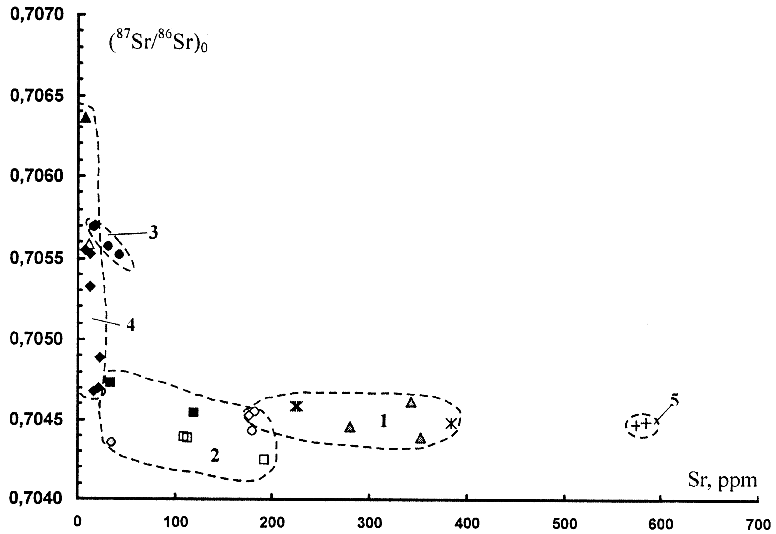

Fig. 20. $(^{87}Sr/^{86}Sr)_o$ versus Sr (ppm) for Plio-Pleistocene acid rocks of Armenia, illustrating Sr abundance decreasing in time and AFC model for the evolution of crustal acidic magmas. Data sources see in Table 5. See symbols in Fig. 12. Explanations are in the text.

Table 7
Isotopic–geochemical composition of granite-metamorphic substrate in the Tsakhkuniats basement outcrop

Formation	*n*	Rb/Sr	$^{87}Sr/^{86}Sr$	Age (Ma)
Trondhjemitic	7	0.05	0.7038	685 ± 77
Phyllitic	8	0.87	0.7222	
Albite-Plagiogranitic	12	0.12	0.7122	647 ± 137
Plagiogranite-migmatitic	5	0.46	0.7154	610
Granite-migmathitic	23	0.68	0.7216	615 + 36
Hankavan-Takarly massif	6	0.91	0.7086	135 + 3
Agveran massif	10	0.14	0.7050	128 ± 11

(Agamalian et al., 1997; Bagdasarian and Ghukasian, 1985; Meliksetian et al., 1993, 1998).

Comparison of these data shows that the underlying crystalline rocks formed over a long age interval, and, having undergone several stages of granitization, differ in low values of Rb/Sr and high crust ratios of Sr isotopes, except for the trondhjemites with mantle values of the latter. Low Rb/Sr and high $(^{87}Sr/^{86}Sr)_0$ ratios mark the departure of alkaline elements from the basement rocks during the recurrent stages of metamorphism (Balashov, 1985).

At least three conclusions are drawn from the comparison of isotopic parameters of the Tsakhkuniats type granite-metamorphic basement to the ones of recent acid rhyolites. (1) Magmatic sources of acid volcanics do not directly inherit the Rb/Sr ratios of the crystalline basement. (2) The initial substrates melted in a system with quite mobile elements. Since the influx of these elements was almost contemporary with the melting, there was no time left for ^{87}Sr accumulation. (3) The considerable rate of Rb/Sr growth in recent acid volcanics is determined by the maximum difference of their age and the one of the underlying rocks.

Therefore, the accelerated growth of Rb/Sr values as compared to the old granite-metamorphic basement allows attributing the acid melts to an anatectic group, formation of which was determined by the young age of the isotopic source and the influence of deep material introducing the most mobile K, Rb, Ba, Th and U elements (Balashov, 1985; Kovalenko, 1987).

Comparison of these isotopic characteristics confirms the earlier assumption that deep zones of continental crust, at the level of basite–granulite metamorphic facies, are an initial substrate for the formation of magmatic sources of the newest acid volcanites (Meliksetian and Karapetian, 1981). Metamorphosed basic effusives and intrusives with low Rb/Sr ratios, or low-pressure mafic granulites, could be an initial substrate for the most primitive volcanics of the earlier phases. The consequent clear increase of Rb/Sr values and radiogenic Sr concentrations in rhyolites and dacites of the final phase was probably determined by the new stage of low-crust substrate metamorphism during the next period of heat front rising. In this age group, the initial substrate corresponded to the rocks of medium-pressure granulite facies, i.e. melting sources deepened. In the basement of the western volcanic zone and Hrazdan structure, granulite sub-facies with anhydrous plagioclase–pyroxene paragenesis could be the source. With temperature increase in individual sources, the restite phases were melting, including garnet, allanite (Pokr Arteni), zircon, ilmenite, apatite (Gutansar, Atis), tantaloniobates (Spitaksar, Geghasar) and other accessories. In the basement of the eastern zone, the initial substrates were probably the deeper sub-facies of hydrous plagioclase–amphibole granulites involving the restite phases of titanite. However, genetic differences between the recent acid volcanics of individual zones (sub-zones and groups) are not solely related to the different volumes of sedimentary-metamorphic material melted, but mainly to the contribution of 'surplus' intratelluric K–Rb fluids that disturb the isotopic equilibrium of magmatic systems (Puzankov et al., 1990). The greatest contribution of this source is implied for the rhyolitic chambers of the Gegham Ridge and, further, for the entire eastern zone. In the western zone, participation of the K–Rb fluids is revealed in separate long-term activity chambers, which form complicated volcanic complexes corresponding to different stages of evolution (Arteni complex).

7. Discussion

The age and geological-tectonic position of acid volcanism in the eastern part of the Armenian Highland is determined by its association with the late-collision stage of the blockwave rising of the region in the geodynamic setting of convergence of the Eurasian and Afro-Arabian lithosphere plates. According to the two-stage model of continental collision, the

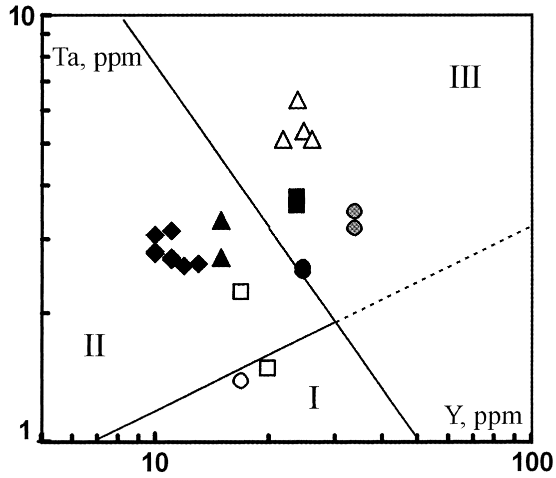

Fig. 21. Ta–Y diagram for obsidians of Phase 3 acidic volcanism of Armenia Data sources are Keller et al. (1994). See symbols in Fig. 14. Fields for different tectonic settings by Pearce et al. (1984): I — volcanic arc; II — syncollision; III — within-plate.

recent acid volcanism of the region can be characterized as a process evolving in the crust layer of the geodynamic system and connected with tectonic stratification of the lithosphere (Khain and Lobkovsky, 1990). At the stage of continental collision and orogene rising, the upper 'fragile' crust layer broke into micro-plates (geo-blocks) capable of moving autonomously on the plastic lower layer. The following comparisons are based on a number of geological, geophysical and petrological data. (1) Close association of the recent acid volcanism with the basalt and basaltic andesite mantle volcanism in time and space points to the constancy of high heat flow (Abramowich and Klushin, 1987; Aslanian et al., 1980). (2) The intensification of the lithosphere under-crust layer overgrowth process during the long thermal preparation contributes to the generation of acid crust melts (Aslanian et al., 1980; Popov et al., 1987; Khain and Lobkovsky, 1990). (3) Acid volcanoes are spatially isolated, and belong to separate sub-zones and structures, and the multivental type of volcanism within their limits is controlled by shallow-crust fractures. (4) Strict lateral NW–SE variation of isotopic geochemistry parameters reflects heterogeneity of initial substrates and increasing depths of their deposition. (5) The eutectic character and near-surface levels of melt formation in local anatexis conditions correspond to the plagioclase stability zone (9–10 kbar).

The geochemical peculiarities of the acid volcanics studied are reflected in tectono-magmatic discrimination diagrams of Ta–Yb (Fig. 21) and Rb–Yb + Ta (Fig. 22). The first of them shows independent trends on different levels within the field of syncollision granites and exact transferring to the intra-plate field. The second one shows clear diversity of compositions and passage from the field of island arc granites to the within-plate granite field. Comparison of both graphs clearly points to the special position of points corresponding to Pokr Arteni and Gegham Ridge, since they fall within the field of within-plate acid volcanics. In the Rb/30-Hf–Ta × 3 diagram (Fig. 23), acid volcanics fall strictly within the field of late-post-collision granites and rhyolites. Plotted compositions of Gegham ridge rhyolites are shifted to the boundary of within-plate rocks due to high concentrations of Ta. The acid volcanics of the Hrazdan structure are distributed along the same boundary, but due to a shift to the Hf (Zr) corner of this diagram.

For reference, compositions of calc-alkaline and peralkaline obsidians of Anatolia are also plotted on this diagram. The major part of the calc-alkaline obsidian group is projected on the field of late post-collision granites and rhyolites. At the same time, a wide scatter of compositions is noted in this group. For instance, data plotted for the obsidians from Orta-dome and Acigol fall within the field of syncollision rhyolites, and shift to the Rb corner of the diagram. The plotted compositions of the Pasinler and Erzincan volcanoes, along with the peralkaline diversities from Nemrut and Bingol-B volcanoes, spread across the field of intra-plate rhyolites due to the abundance of Ta and Hf (Zr). These trends can be interpreted as related to the different character of magmatic source enrichment. As shown by Keskin et al. (1998), two magma sources are accepted for the newest volcanic series of eastern Anatolia (Erzurum–Kars Plateau) — one enriched by subduction components (or crust contaminant) and the other enriched by the within-plate component. The evidence presented shows that the composition of the acid volcanics generally inherits the primary geochemical specialization of the deep substrates.

The late-collision nature of recent rhyolites of Armenia is demonstrated by the values of discriminating ratios: Th × 100/Zr = 4.4–19.8, Nb × 100/Zr = 14–114, Th/Yb = 4–30, Ta/Yb = 0.8–3.1, and

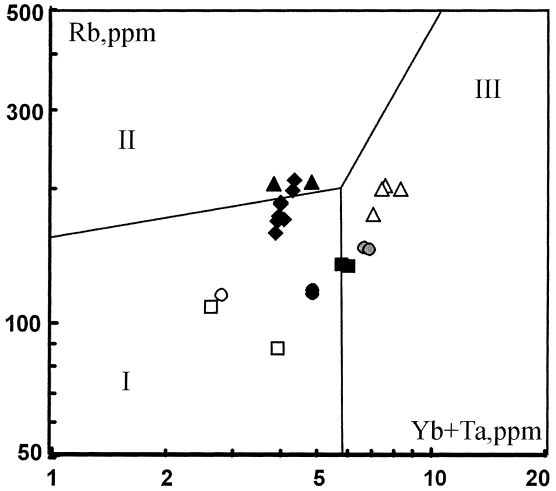

Fig. 22. Rb–Yb + Ta diagram for obsidians of Phase 3 acidic volcanism of Armenia. Data sources are Keller et al. (1994). See symbols in Fig. 14. Acid magmatic rock fields are the same as in Fig. 21.

Nb/U = 2.2–5.1. The ratios presented display a clear NW–SE increase in the transition from the western zone to the eastern zone, indicating the decreased melting degree and more intense contribution of water-containing restite phases. On a whole, these values are 2–5 times as great as the respective values of these elements in acid volcanics of island arcs and correspond to the parameters of continental-rift zones (Puzankov et al., 1990; Kovalenko, 1987; Rottura et al., 1997).

The petrological, geochemical and isotopic evidence presented shows that late-collision rhyolithic volcanism as a genetically independent phenomenon is associated with eutectic crust melts of constant Q–Ab–Or composition. However, in spite of the eutectic nature of these melts, clear differences are revealed in the composition of trace elements inherited from the initial melting substrates. Petrogenetically, the rhyolites studied can be divided into two groups connected with different evolution trends. The first of them corresponds to more evolved rhyolite–dacite melts, generating a Ba-rich geochemical type of acidic volcanics common for the western zone and Hrazdan structure. This group exhibits: (1) both high (up to 30%) and low (up to 20–25%) degrees of melting of the anhydrous mineral assemblage of low-medium granulite facies; (2) involvement of refractory accessory phases in the melting process; (3) significantly low LREE, high HREE

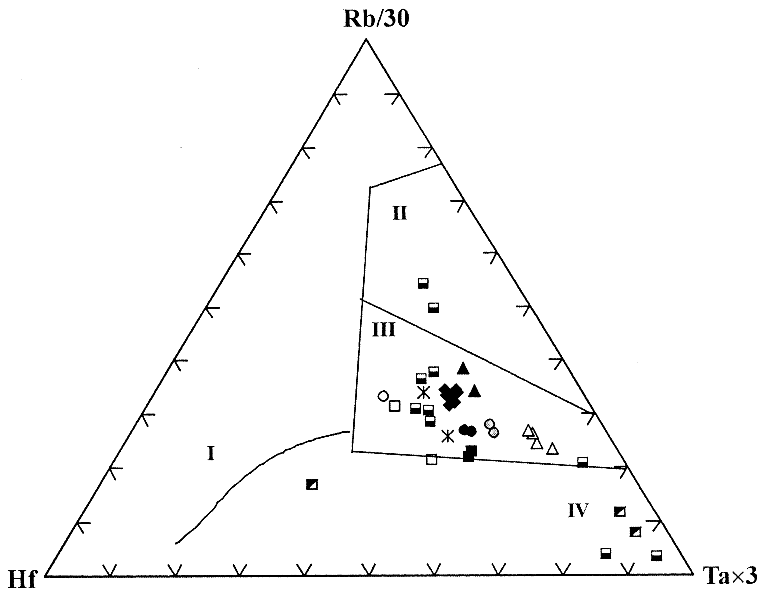

Fig. 23. Rb/30-Hf–Ta × 3 triangular diagram for obsidians of Phase 3 acidic volcanism of Armenia Data sources are Keller et al. (1994). See symbols in Fig. 14. Acid magmatic rock fields for different tectonic settings by Harris et al., 1987: I — volcanic arc; II — syncollision; III — late-post-collision; IV — within-plate.

and Zr, Ta, Nb, and Y contents; (4) a narrow variation range and slightly increasing $^{87}Sr/^{86}Sr$ ratios; and (5) the dominant role of the fractional crystallization evolution mechanism.

The second group belongs to primitive rhyolitic melts, conforming to the Rb-rich geochemical type common for the eastern zone. It is characterized by: (1) only the lower degree of melting under the high-activity volatile phase; (2) a hydrous assemblage of deeper granulite facies as a melting substrate; (3) significantly high LREE and low HREE, and the highest contents of Cs, Th, and U; (4) the sudden leap in $^{87}Sr/^{86}Sr$ ratio increase and high contents of radiogenic Sr related to the increase of the sedimentary-metamorphic rock portion in the initial substrates; and (5) the influx of K–Rb-fluids into the melting source as a dominant mechanism of evolution.

8. Conclusion

The Pliocene–Quaternary stage of continental collision of the Afro-Arabian and Eurasian plates was coincident with the tectonic and thermal activity of mantle sources. During a rapid tectonic uplift under an extensional geotectonic regime, the rising of geotherms led to local crustal anatexis initiating acidic volcanism which developed over a long time interval (17.5–0.10 Ma). The persistence of extensive stresses resulted in the development of the W–NW to SE strike-slip fault system controlling the distribution of the acidic volcanic centers. The variation of geochemical and isotope parameters is explained by the existence of several shallow-depth magma chambers at the level of the plagioclase stability zone. Owing to the high-temperature character, the rhyolitic magma rapidly ascended to the surface through the faults without noticeable crystallization in the transient chambers. The overall trend of rhyolitic magma evolution in time shows the consequent enrichment by Rb and radiogenic Sr components.

The peculiarities of geological position and geochemical composition of acidic volcanism in Armenia contain useful information about the tectonic evolution of the NE part of the Armenian Highland and may be valuable for the analysis of collision-related volcanism of the adjacent Eastern Anatolia region and Mediterranean belt.

Acknowledgements

This work was supported by Grant ref. no. 96-118 of the National Academy of Sciences of the Republic of Armenia. We are grateful to our reviewers—Dr S. Mertzman and Dr M. Norman—for their critical reviews, which significantly improved the manuscript. We also wish to thank Prof. L. Wilson for his useful suggestions.

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