Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Journal of Volcanology and Geothermal Research 126 (2003) 31–62
Journal of volcanology and geothermal research
www.elsevier.com/locate/jvolgeores

Volcanic hazards in the region of the Armenian Nuclear Power Plant

A. Karakhanian[a,*], R. Jrbashyan[b], V. Trifonov[c], H. Philip[d], S. Arakelian[a], A. Avagyan[a], H. Baghdassaryan[a], V. Davtian[a], Yu. Ghoukassyan[b]

[a] *GEORISK Scientific Research Company, Yerevan, Armenia*
[b] *Institute of Geological Sciences, National Academy of Sciences of Armenia, Yerevan, Armenia*
[c] *Geological Institute, Russian Academy of Sciences, Moscow, Russia*
[d] *Montpellier-II University, Montpellier, France*

Received 1 February 2003; accepted 16 March 2003

Abstract

We address volcanic hazards in the region of the Armenian Nuclear Power Plant and discuss the assessment of these hazards conducted in the framework of the International Atomic Energy Agency (IAEA) programs in 1994–1995. An important problem of volcanic hazard assessment is posed by assumptions that the apparent absence of recent volcanic activity in Armenia means that future eruptions in the vicinity of the site are impossible. We present new historical, archaeological, and field data, as well as records of the volcanic activity based on radiocarbon, fission-track, K/Ar and plateau-age determinations. This new evidence attests to volcanism in Armenia and adjacent areas during Holocene and historical time. Volcanic activity is demonstrated for Tskhouk-Karckar, Porak, Vaiyots-Sar, Smbatassar, Gegham Ridge and Ararat volcanoes. Volcanic eruptions occurred on Ararat at distances of 27 and 52 km from the plant site in 2500–2400 BC and in 1840 AD, respectively. New information permits a re-assessment of the volcanic hazards at a level higher than in the 1994–1995 studies.

Keywords: volcanic hazard; Armenian Nuclear Power Plant; Armenia

1. Introduction

Armenia and adjacent parts of Turkey and Iran are situated near the center of the zone of continental collision of the Arabian and Eurasian lithospheric plates and have been subjected to N–S shortening and E–W extension accompanied by faulting, earthquakes and volcanism (Jackson and McKenzie, 1988; Dewey et al., 1986; Taymaz et al., 1991). As a result of the convergence of these plates, the Anatolian block was forced toward the west and the Iranian block toward the east. Recent GPS data have imposed bounds of 10 ± 2 mm/yr on the crustal shortening rates across this region. These are the upper limits for the elastic strain accumulation rates, as they make no allowance for aseismic slip, or possible permanent deformation of the fault-bounding blocks

* Corresponding author. Fax: +374-1-565-625.
E-mail address: georisk@sci.am (A. Karakhanian).

0377-0273/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0377-0273(03)00115-X

(Reilinger and Barka, 1997; McClusky et al., 2000).

The most important active fault zones of Anatolia and Iran terminate within this region, but the contrasting and complex manifestations of geodynamic, seismic, and volcanic activity in the region have not been adequately studied.

The latest manifestations of regional seismic activity include the earthquakes of: 1976 (M = 7.1) Chaldiran; 1983 (M = 6.8) Norman; 1988 (M = 6.9) Spitak; and 1990 (M = 7.3) Roudbar-Mandjil.

Armenia and adjacent regions of east Turkey and northwest Iran are areas of widespread Quaternary volcanism. In Armenia, Quaternary volcanism can be characterized by fissure, central-vent, and areal eruptions.

The fissure volcanism has a rift-related origin and produced large volumes of almost undifferentiated calc-alkaline and sub-alkaline basalts on the Javakhet, Lory, and Kotayk plateaus, and lengthy flows stretching through the river gorges of Akhourian, Debed, and Hrazdan.

The central-vent volcanism has formed large stratovolcanoes (Aragats, Ishkhan-sar, Arailer, and others) that have had prolonged activity (up to 1.5 Ma) and formed many flows of calc-alkaline, and sub-alkaline basalts, andesites, and dacite. Some of these products form widespread ignimbrite fields.

The areal volcanism is represented by many volcanoes spread across the ridges of Ghegam, Vardenis, and Sunik, and parasitic volcanic structures on the slopes of stratovolcanoes. They are composed of calc-alkaline lavas and tephra.

Siliceous volcanism in Armenia is represented by rhyolites, dacites, perlites, and obsidians.

Recent volcanic activity in the region is limited to fumarole emissions of Nemrout and Tendourek volcanoes (east Turkey) and Sabalan Volcano (northwest Iran).

The Armenian Nuclear Power Plant (ANPP) is situated in the northwestern part of the Ararat depression, near the settlement of Metsamor, and 28 km west of Yerevan, the capital of Armenia (Fig. 1). The plant has two power-generating units of VVER-440/Model 230. The first unit was started in 1976 and the second in 1978.

The plant is near the southern foothills of Aragats, the largest polygenetic volcano in Armenia. Ararat, another large polygenetic volcano, is 55 km south of the site. The plant is on the Shamiram Volcanic Plateau. Within a distance of 1.3–6 km north from the site, there are four groups of small volcanoes, the total number of which is 38 (Figs. 1–3 and 6).

From the time the ANPP was designed (1969) until today, assessment of the geological stability of the NPP site, probability of faults close to the site, assessment of seismic and volcanic hazards, and a series of other environmental considerations have been subjects of constant attention. The original seismic design of the nuclear plant was based on an estimated seismic intensity 7 on the MSK-64 scale, and peak ground acceleration was estimated at about 0.1g (IAEA/RU-5270, 1995 Final Report). In 1977, after the Vrancea earthquake in Romania, the seismic safety criterion for some of the ANPP structures was upgraded to intensity 8 (0.2g), and the most critical structures were upgraded to intensity 9 (0.4g).

After the 1988 Spitak earthquake in northern Armenia (M = 6.9), both units of the plant were shut down. Maximum ground displacement at the plant area during the 1988 earthquake was 2.7 mm, and the acceleration was 0.031g (Arakelian et al., 1989). Although that earthquake caused no damage to the ANPP, the plant's location in the area of increased seismic activity raised concern.

In 1993, considering the extremely difficult situation with energy supplies, the Government of the Republic of Armenia decided to resume operation at the second ANPP unit. In 1994 and 1995, Armenian institutions investigated the geological stability and seismic and volcanic hazards in the area of the plant. The studies were conducted with the technical assistance of the IAEA in the framework of the ARM/9/002 Project. The results of work approved by the IAEA experts excluded the likelihood of surface faulting within the plant site, and provided the 0.35g PGA estimate for the seismic hazard level at the site. Volcanic hazards were assigned a quite low probability (IAEA/RU-5270, 1995 Final Report).

The IAEA recommended continuation of the

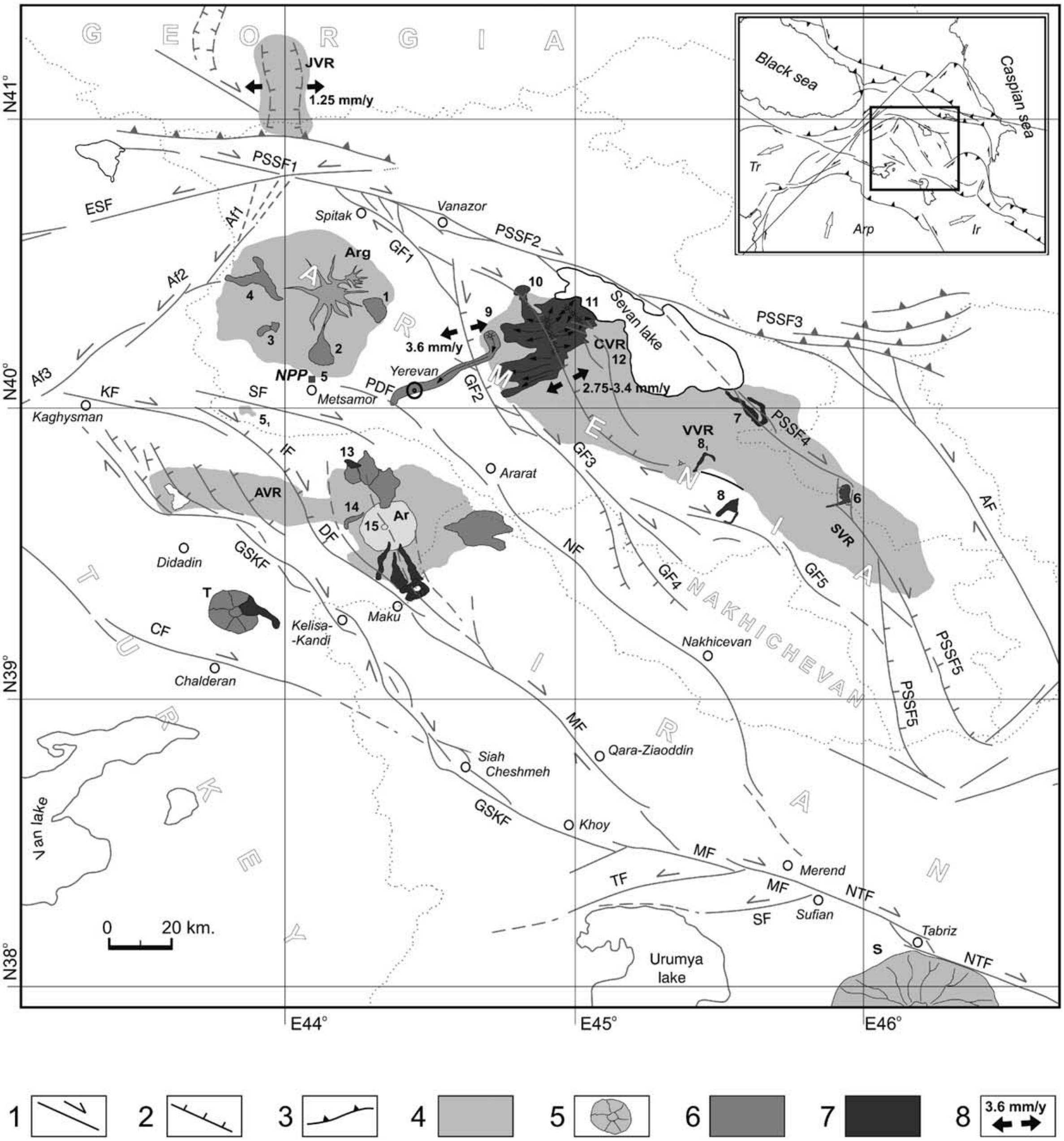


Fig. 1. Young volcanism and active faults in Armenia and adjacent areas. 1, Strike-slip faults; 2, reverse faults and thrusts; 3, normal faults; 4, volcanic areas; 5, large volcanoes; 6, Late Quaternary lava; 7, Holocene–historical lava flows; 8, GPS monitoring data (Doerflinger et al., 1999, 2003). Numbers in the figure: 1, Ashtarak flow, Aragats; 2, Tirinkatar flow, Aragats; 3, Irind flow, Aragats; 4, Pokr Bogoutlu flow, Aratgats; 5, Shamiram Plateau volcanoes, including Shamiram, Karmratar, Blrashark, Dashtakar, and Atomakhoumb; 6, Tskhouck-Karckar group volcanoes; 7, Porak group volcanoes; 8, Vaiyots-sar; 9, western cluster, Ghegam Ridge; 10, central cluster, Ghegam Ridge; 11,12, eastern cluster, Ghegam Ridge; 13–15, Ararat. Volcanic areas: JVR, Javakh volcanic ridge; GVR, Ghegham volcanic ridge; VVR, Vardeniss volcanic ridge; SVR, Sunik volcanic ridge; AVR, Agri-Dagh volcanic ridge; Arg, Aragats stratovolcano; Ar, Ararat stratovolcano, Tr, Tendourek Volcano. Active faults: PSSF, Pambak–Sevan–Siunik Fault; AF, Akery Fault; Af, Akhourian Fault; ESF, Zheltorechensk–Sarykamis Fault; GF, Garni Fault; SF, Sardarapat Fault; MF, Maku Fault; CF, Caldyran Fault; and GSKF, Gailatu–Siah Cheshmeh–Khoy Fault. Arp, Arabian lithosphere plate; Tr, Turkish microplate; Ir, Iranian microplate.

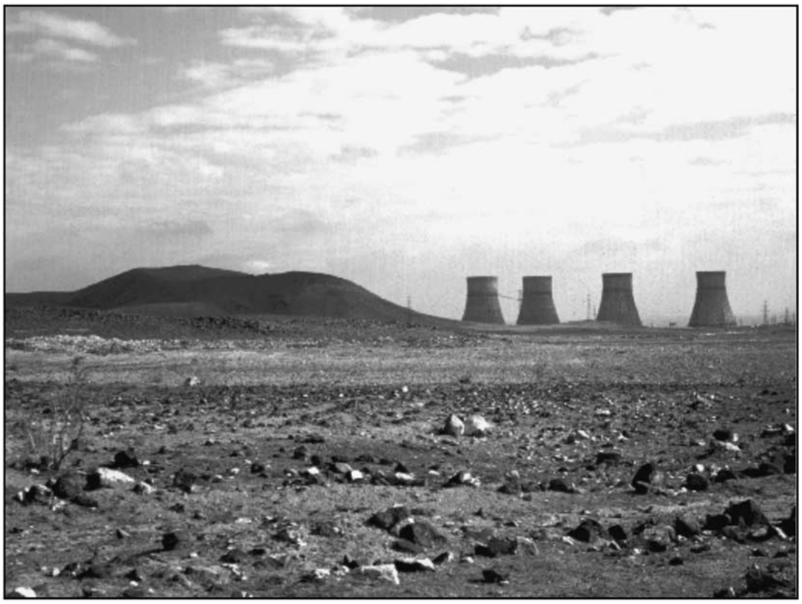


Fig. 2. Volcano of the Dashtakar group near the ANPP viewed from the northwest (photo of Dr. Charles Connor).

studies of tectonics, surface faulting, seismic, and, particularly, volcanic hazards, since the database was not considered adequate (IAEA/RU-5270, 1995 Final Report).

In 1995, the second unit of the ANPP was recommissioned and is operating today. Our goal is to consider the present knowledge about the volcanic hazard in the region.

2. Assessment of volcanic hazards at the nuclear plant site based on the studies of 1994 and 1995, and 2000–2002

Volcanic hazards were studied for the first time in 1994 and 1995 by the Institute of Geological Sciences (Armenian National Academy of Sciences) with the technical assistance of the IAEA (Project ARM/9/002). The studies were of limited duration (4 months) and were undertaken with limited financial, technical, and organizational resources. They included field and laboratory work, as well as reviews of relevant publications. With the support of the IAEA, the isotopic geochronology laboratory in Bern (Switzerland) performed K/Ar age determinations for five samples of volcanic rocks from the area around the plant site. Sampling locations are shown in Fig. 2, and the dating results are presented in Table 1. The limited scope of this investigation is conspicuous when it is compared to the assessment of volcanic hazards for nuclear facilities undertaken in even less active geological zones, such as Yucca Mountain (Nevada, USA).

In 2000 and 2002, we re-assessed the volcanic hazard for the region of the ANPP and used new results of brief field studies, as well as remote-sensing analysis, and radiometric age determinations (Chernishev et al., 2002), and geological data from the works of Lichkov (1931), Lebedev (1931), Aslanian and Asatrian (1950), Paffenholtz (1948, 1952), Milanovsky (1953, 1968), Amarian (1970), and Karapetian (1985).

2.1. Aragats Volcano

Aragats Volcano is 4095 m high and its base has a radius of 140 km (Figs. 1 and 6). Its activity came in four stages, each beginning with an eruption of basic magma and ending with a more siliceous magma (Ghukasyan, 1985; Jrbashyan et al., 1995). The first stage was during the Late Pliocene and was concentrated in the main crater and fissures on its flanks. During the second stage (Early Quaternary), there were eruptions from the main crater, parasitic cones and fissures on the slopes. The third stage broke out during the middle of the Quaternary epoch with eruptions from monogenetic cones on the northern and western slopes of Aragats, from the main crater, and from fissures on the slopes. Ghukasyan (1985, 2003) and Jrbashyan et al. (1995) attribute the fourth and last stage to the Late Quaternary period, when four monogenetic volcanoes were produced: Tirinkatar 1 and 2 on the southern, and Ashtarak 1 and 2 on the eastern slopes of Aragats.

Remote-sensing analysis of 2000–2001 and our brief field studies in 2000 and 2002 enabled us to identify several lava flows on Aragats Volcano that overlie all other volcanic formations (Figs. 1 and 6). The flows are named Ashtarak, Tirinkatar, Irind, and a flow of Pokr Boghoutlu Volcano (1, 2, 3, 4 in Figs. 1 and 6 and Table 2).

Jrbashyan et al. (1995) reported a Late Anthropogene age for the Ashtarak flow. The stratigraphic column of the Aragats volcanic complex presented in the same work assigns the Ashtarak flow to the Late Quaternary, while the map of the Aragats area in the same publication shows that the flow covers alluvial and deluvial deposits dated as Holocene.

Paffenholtz (1948) and Amarian (1970) assign the Ashtarack flow to the Late Quaternary, and Paffenholtz (1948) mentions that Ashtarak lava covers the lower pebble terrace of the Kasakh River. Milanovsky (1953, 1968) dates the lava as Holocene. Lichkov (1931) reports that lava of the Ashtarak flow covers all terraces of the Kasakh River in the section north of Ashtarak near the village of Artashavan. Satellite images and air photos clearly show that the Ashtarak flow rests on the erosional surfaces on the eastern slope of Aragats (Fig. 7).

The radiometric dating of 11 samples from Aragats Volcano and a sample from the Shamiram Plateau was made in 2000 and 2001 by the K/Ar method at the Institute of Geology, Ore Deposits, Petrography and Geochemistry of the Russian Academy of Sciences. A version of the K/Ar method designed for young volcanic rocks was used (Chernishev et al., 2002). Only four of the tested samples can be assigned to relatively young volcanic formations. The radiometric dating of one sample from the Ashtarak flow gave an age of 0.53 ± 0.07 Ma (Chernishev et al., 2002).

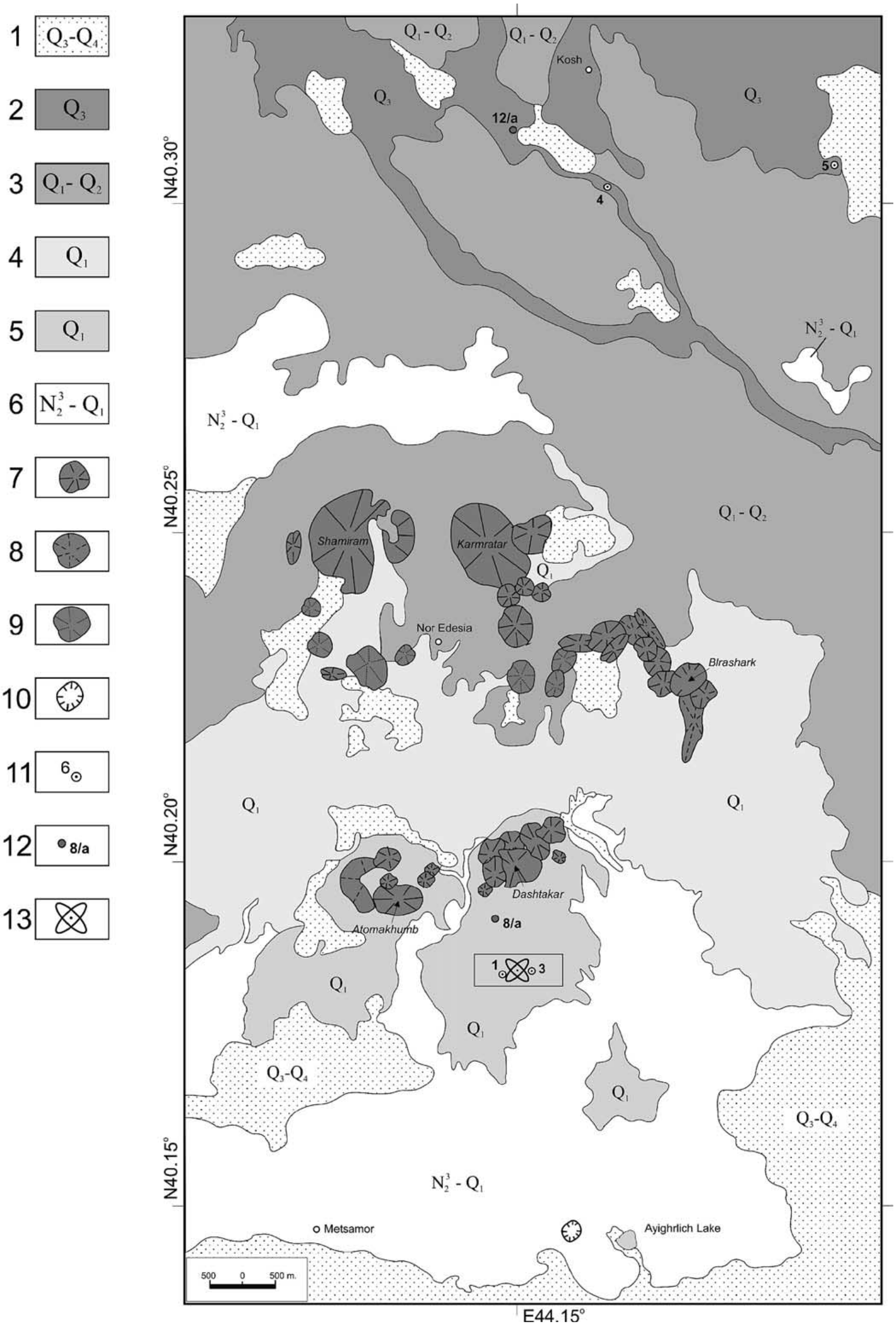
Although Jrbashyan et al. (1995) date the Tirinkatar flow as Late Quaternary, the text and the map they provide indicate that the Tirinkatar lava overlies fluvioglacial deposits near the village of Dzorap, and a Holocene age is shown for these deposits on the map. Paffenholtz (1948, 1952) believes that the lava belongs to the Middle Quaternary period, while Milanovsky (1953, 1968) dates it as Holocene.

Radiometric K/Ar dating of four samples from the Tirinkatar flow at the Swiss University in Bern in 1994 and 1995 established ages of 0.91 Ma and 0.87 Ma, Middle Pleistocene (Fig. 3 and Table 1). Radiometric dating of one sample from the Tirinkatar flow made in 2000 and 2001 by the K/Ar method at the Institute of Geology, Ore Deposits, Petrography and Geochemistry of

Table 1
K/Ar age determinations conducted in 1994–1995 by the Swiss University in Bern

Sample	Mineral	K[a] (%)	$^{40}Ar_{tot}$[b]	$^{40}Ar_{rad}$	Y (%)	$T \pm 1\sigma$ (Ma)	Rely
1	pl	0.622	0.369	0.018	4.9	0.76 ± 0.02	R/A
2	pl	0.280	0.139	0.0039	2.8	0.36 ± 0.02	A
2a	gm	1.99	0.453	0.076	16.9	0.99 ± 0.03	R
3	gm	2.01	0.409	0.071	17.4	0.90 ± 0.03	R
4	gm	1.91	0.479	0.068	14.2	0.91 ± 0.03	R
5	gm	2.89	0.456	0.098	21.5	0.87 ± 0.03	R

[a] K concentrations were determined by solid-source mass spectrometry.
[b] Ar concentrations were determined on ≈100 mg samples by rare-gas mass spectrometry using a spike calibrated against US Geological Survey age monitor FCT-biotite.



1 Q3-Q4
2 Q3
3 Q1- Q2
4 Q1
5 Q1
6 N2 3 - Q1
7
8
9
10
11 6
12 8/a
13
Q1 - Q2
Q1 - Q2
Kosh
Q3
Q3
12/a
5
4
N40.30°
N2 3 - Q1
N2 3 - Q1
N40.25°
Q1 - Q2
Shamiram
Karmratar
Q1
Nor Edesia
Blrashark
N40.20°
Q1
Q1
Dashtakar
Atomakhumb
8/a
1 3
Q1
Q1
Q3-Q4
Q1
Q3-Q4
N40.15°
N2 3 - Q1
Metsamor
Ayighrlich Lake
500 0 500 m.
E44.15°

the Russian Academy of Sciences gave an age of 0.35 ± 0.05 Ma and 0.45 ± 0.07 Ma (Fig. 3) (Chernishev et al., 2002).

There is wide scatter in the ages provided by the geological dating of flows from the Irind and Pokr Boghoutlu volcanoes. They range from the Middle Quaternary (Pokr Boghoutlu) to Early Quaternary (Irind) estimates of Jrbashyan et al. (1995) to the Holocene age for both volcanoes as estimated by Milanovsky (1953, 1968). Radiometric dating of these flows was never conducted.

Dacite lava from Irind Volcano looks young (Fig. 8) and overlies tuff deposits of the Shamiram type (1 in Fig. 8). Several younger volcanoes are located on the surface of dacite lava of the Irind (Ashnak) flow (2 in Fig. 8.)

The field studies conducted during the summer of 2002 show that dacitic lava of Pokr Boghoutlu volcanoes overlies not only tuffs of the Shamiram type, but also glacial deposits of a Würm age that *rest* on the tuffs. Therefore, the flows from Pokr Boghoutlu volcanoes can be dated back to the end of the Late Pleistocene. The dacite flows from Irind Volcano, and particularly the young volcanoes on it, may also have a Late Pleistocene age.

Many archaeological monuments dating back to the Middle–Late Bronze Age (the 3rd–2nd millennia BC) have been found on the flows from Irind and Pokr Boghoutlu volcanoes. Therefore, the lower and upper limits for the age of the flows from Pokr Boghoutlu and Irind volcanoes can be estimated as the end of the Late Pleistocene, and 3rd–2nd millennia BC, respectively.

Remote-sensing analysis of the Aragats summit reveals a 13 km long line of craters and tephra cones stretching in a west-southwesterly direction. This chain appears to cut through the glacial deposits and the northern rim of the Aragats crater. Many of the craters and cones are opened toward the north and east. Down-slope of some craters, 10 km long tongue-like flows of mud and rock are distinguished (Figs. 6 and 9). These flows may include glacial deposits, as well as lahars. The latter are quite characteristic of Holocene summit eruptions.

Milanovsky (1968) points out that eruptions of moderately siliceous andesite–dacite and dacite lavas on Aragats continued in the Pleistocene and Holocene, and attributes all of these flows and several more to the Holocene on his 1955 map. Shirinian (1970) mentions that there were repeated eruptions of basaltic andesite lava on the Aragats volcanic massif from the Upper Pliocene to the Holocene. Simkin et al. (1981) also propose a Holocene age for lava on the summit of Aragats.

2.2. Volcanoes on the Shamiram Plateau

The Shamiram Volcanic Plateau, on which the ANPP is located, has an area of more than 200 km^2 and is inclined toward the south-southwest with a drop in elevation from 1200 to 900 m. The basement under the Shamiram Plateau consists of up to 450 m of basaltic andesite lavas and pyroclastic material. Four principal stratigraphic units have been recognized in the basaltic andesites. The lowermost has been dated as Late Pliocene. This is overlain by an upper layer composed of Early Quaternary basaltic andesite, Mid Quaternary tuffs of the Shamiram–Biurakan type, and Late Quaternary basaltic andesite lava on the southern slope of Aragats (Jrbashyan et al., 1995). Age estimates are based mainly on geological and morphological criteria.

Fig. 3. Map of geology and volcanology of the Shamiram Plateau near the Armenian nuclear plant. 1, Late Quaternary–recent alluvial and proluvial, talus, and eluvial deposits; 2, Late Quaternary andesites and basaltic andesites of the southern slope of Aragats; 3, Early–Middle Quaternary ignimbrite tuffs of the Biurakan–Shamiram type; 4, Early Quaternary andesites and basaltic andesites of volcanoes of the Shamiram, Karmratar, and Blrashark groups; 5, Early Quaternary andesites and basaltic andesites of volcanoes of the Atomakhoumb and Dashtakar groups; 6, Late Pliocene–Early Quaternary basaltic andesites and andesites of the Shamiram Plateau basement; 7, cinder cones; 8, lava volcanoes; 9, mixed cinder–lava volcanoes; 10, phreatic crater; 11, sampling locations of the radiometric age dating conducted by the Swiss University; 12, sampling locations for radiometric estimation of age conducted by the Institute of Geology, Ore Deposits, Petrography and Geochemistry of the Russian Academy of Sciences; 13, the ANPP.

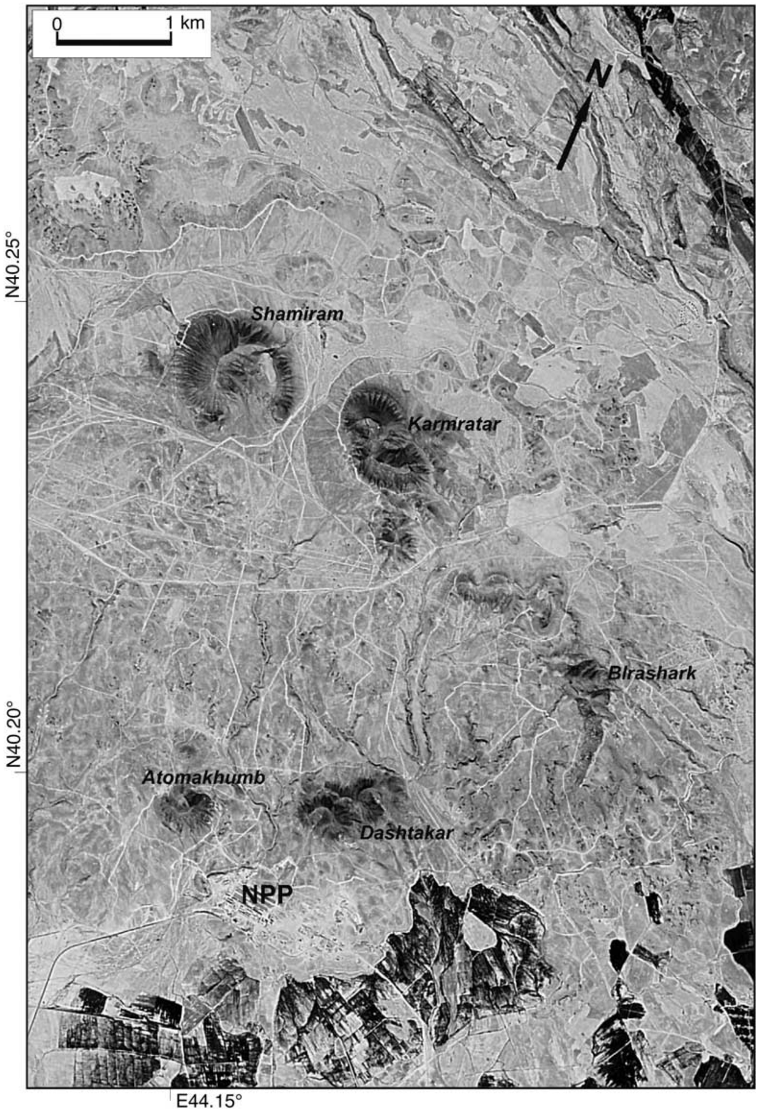


Fig. 4. Corona satellite image (1968) of volcanoes in the Shamiram, Karmratar, Blrashark, Atomakhoumb, and Dashtakar groups.

The monogenetic volcanoes on the Shamiram Plateau form clusters. One of the two largest clusters is near the ANPP (5 in Fig. 1) and the other is 27–32 km west of it (5_1 in Fig. 1). The cluster near the ANPP includes five individual groups: Shamiram, Karmratar, Blrashark, Atomakhoumb, and Dashtakar (Figs. 2–4 and 6).

The Shamiram group is 6 km north of the plant site. It consists of five small cones and one relatively large volcano that is 200 m high and has a base with a radius of 700 m. The volcanoes are composed of oxidized scoria, lapilli, andesitic lava, and agglutinates of basaltic andesite and andesite. The summit of the volcano and its northern foot are covered by tuffs that are 2–3 m thick (Jrbashyan et al., 1995).

The Karmratar group is 5 km to the north of the nuclear plant and also consists of one large (187 m high) and five smaller volcanoes (25–30 m high). The rocks include oxidized scoria, and ba-

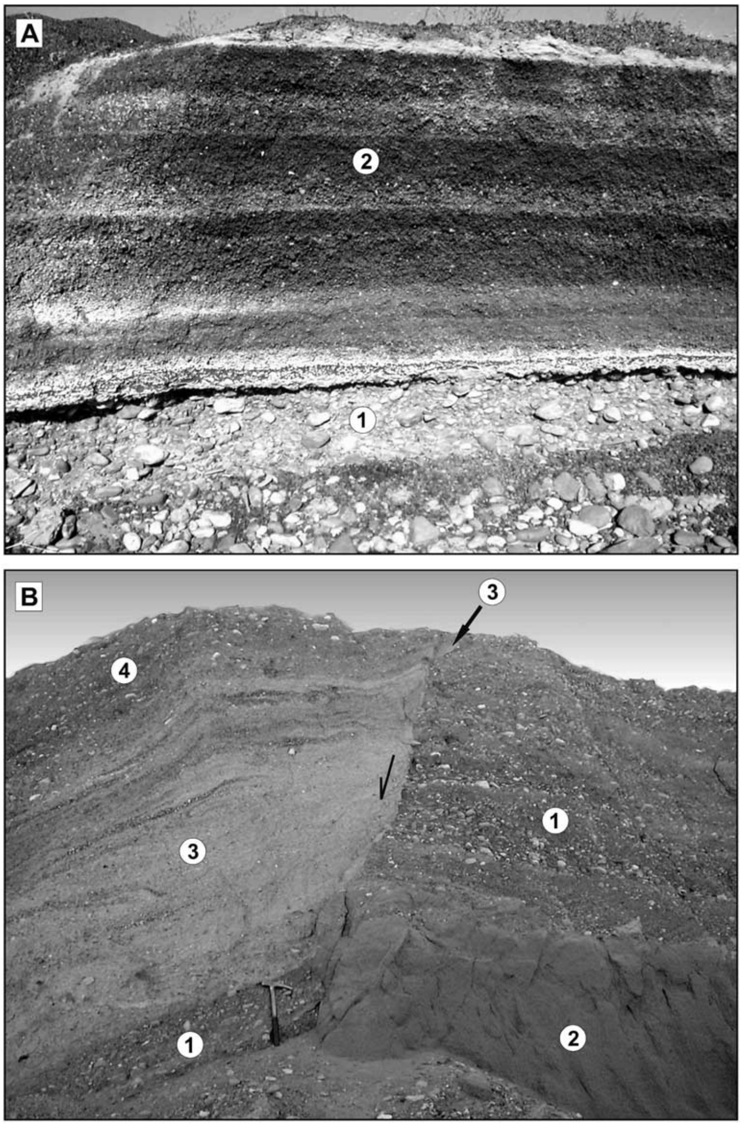


Fig. 5. (A) Scoria from volcanoes of the Karmrassar group that cover the Arax River terrace in the region of Vanand Village: 1, river deposits; 2, scoria. (B) N–S-striking normal fault that cuts through the Arax River terrace, scoria occurring above, and more recent river deposits: 1, older river deposits related to the fourth terrace of the Arax River; 2, lake deposits; 3, scoria; 4, younger river deposits of Arax.

saltic andesite lava covered by tuffs and ignimbrites.

The Blrashark group is 5 km northeast of the nuclear plant and includes 13 small volcanoes, 80–150 m high and elongated in a northerly direction. Most of them are cinder cones, and four volcanoes are andesitic.

The Dashtakar group is 1.8 km north of the nuclear plant and consists of eight volcanoes, four of which are aligned ENE. The nuclear plant rests on an andesitic lava flow from the summit of the westernmost cone. Other volcanoes of this group consist predominantly of scoria–agglutinate material and a multitude of volcanic bombs.

Table 2
Data on location and age of the most recent volcanic activity in the region of the ANPP and adjacent areas

No.	Volcanoes	λ, E	φ, N	Geologic age determination	Radiometric age determination (Ma BP)	Age determinations by ^{14}C (BP) Pre-date	Post-date	Archaeological and historical age determinations (BP) Pre-date	Post-date	Character of volcanic activity	Distance to the ANNP[a] (km)
Aragats											
1	Ashtarak flow	44.29	40.45	Q_3 [b,c,d], Q_4 [e]	0.53, K/Ar [g]	–	–	–	4000 [l]	Eruption of basaltic andesite lava	32/24
2	Tirinkatar flow	44.14	40.44	Q_2 [c]	0.91–0.87, K/Ar [f]	–	–	–	4000 [l]	Eruption of basaltic andesite lava	26/10
3	Irind flow	44.00	40.37	Q_1 [b], Q_4 [e], Q_3–Q_4 [l]	–	–	–	–	5000–4000 [l]	Eruption of dacite lava	23/20
4	Pokr Boghoutlu flow	43.93	40.48	Q_2 [b], Q_4 [e], Q_3–Q_4 [l]	–	–	–	–	5000–4000 [l]	Eruption of dacite lava	23/20
Shamiram Plateau volcanoes											
5	Shamiram	44.12	40.24	Q_{1-2} [b], Q_4 [c,d,e]	0.76, K/Ar [f], 0.90, K/Ar [f], 0.96, K/Ar [g]	–	–	–	5000–4000 [l]	Basaltic andesites, ignimbrites	6
	Karmratar	44.15	40.24								5
	Blrashark	44.17	40.22								5
	Atomakhoumb	44.13	40.19								1.8
	Dashtakar	44.15	40.19								1.3
5_1	Karmrassar	43.78	40.09	Q_3 [l], Q_4 [c,d,e]	–	–	–	–	5000–4000 [l]	Basaltic andesites, ignimbrites	32
	Menakblour	43.79	40.10								30
	Mets Sevblour	43.82	40.12								27
6	Tskhouk-Karckar volcanoes, NE Armenia, Sunik Ridge	45.99	39.75	Q_4 [k]	–	–	4720 [k]	5200 [k]	4800 [k]	Eruption of basaltic andesite lava	160
7	Porak Volcano, NE Armenia, Sunik Ridge	45.72	40.02	Q_4 [k]	–	6640 [k]	6270 [k]	6000 [k]	5000 [k]	Eruption of basaltic andesite lava	135
				Q_4 [k]	–	–	–	2783 [k]	2773 [k]	Eruption of basaltic andesite lava	
8	Vaiyots-sar Volcano, Southern Armenia	45.50	39.79	Q_4 [i]	–	–	–	5000–4000 [l]	2100 [l]	Eruption of basaltic andesite lava	122
Ghegam Ridge											
9	Western cluster	44.75	40.35	Q_3–Q_4 [c,e,i]	$\ll$0.25–0.19 by fission tracks [h]	–	–	Post-Acheullian [i]	Pre-Mousterian [i]	Eruption of basaltic andesite lava	52/25

Table 2 (*Continued*).

No.	Volcanoes	λ, E	φ, N	Geologic age determination	Radiometric age determination (Ma BP)	Age determinations by ^{14}C (BP) Pre-date	Post-date	Archaeological and historical age determinations (BP) Pre-date	Post-date	Character of volcanic activity	Distance to the ANNP[a] (km)
10	Central cluster	44.91	40.35	Q_4 [i]	≪0.042–0.038 by fission tracks [h]	≪30 080 [k]	–	Post-Mousterian [i]	3500–3300 [l]	Eruption of basaltic andesite lava	65/45
11	Eastern cluster	45.05	40.46	Q_3–Q_4 [c,e,i]	–	6270 [l]	2090 [l]	4500 [l]	3000–3500 [l]	Eruption of basaltic andesite lava	78/74
12		45.09	40.31	Q_3–Q_4 [c,e,i]	–	30 080 [k]	3000–3500 [l]	Post-Mousterian [i]	3500–3300 [l]	Eruption of basaltic andesite lava	
Northern Slope of Aragats											
13	Malakliu	44.26	39.74	Q_4 [j]	0.02, K/Ar [j]	–	–	4500 [k]	4400 [k]	Eruption of pyroclastic tuff	27/25
14	Northern slope crater	44.26	39.74	Q_4 [j]	0.02, K/Ar [j]	–	–	2600 [l]	2500 [l]	Eruption of basaltic andesite lava	50/45
15	Akory Canyon	44.31	39.74	Q_4 [j]	0.02, K/Ar [j]	–	–	160 (2/07 1840 AD) [k]		Bandai type eruption, lahar, eruptive cloud	52

The numbering of volcanoes corresponds to their numbering in Fig. 1.

[a] The first and second numbers provided as distance to the ANNP represent distance to the volcano, and distance to the edge of lava flow, respectively.

[b] Jrbashyan et al. (1995).

[c] Paffenholtz (1948).

[d] Lichkov (1931), Aslanian and Asatrian (1950).

[e] Milanovsky (1953, 1968)..

[f] Swiss University (Bern, 1994–1995).

[g] Chernishev et al. (2002).

[h] Badalian et al. (2000), Jrbashyan et al. (2000).

[i] Karapetian (1983, 1960).

[j] Yilmaz et al. (1998).

[k] Karakhanian et al. (2002, 2003).

[l] New determinations made in this article.

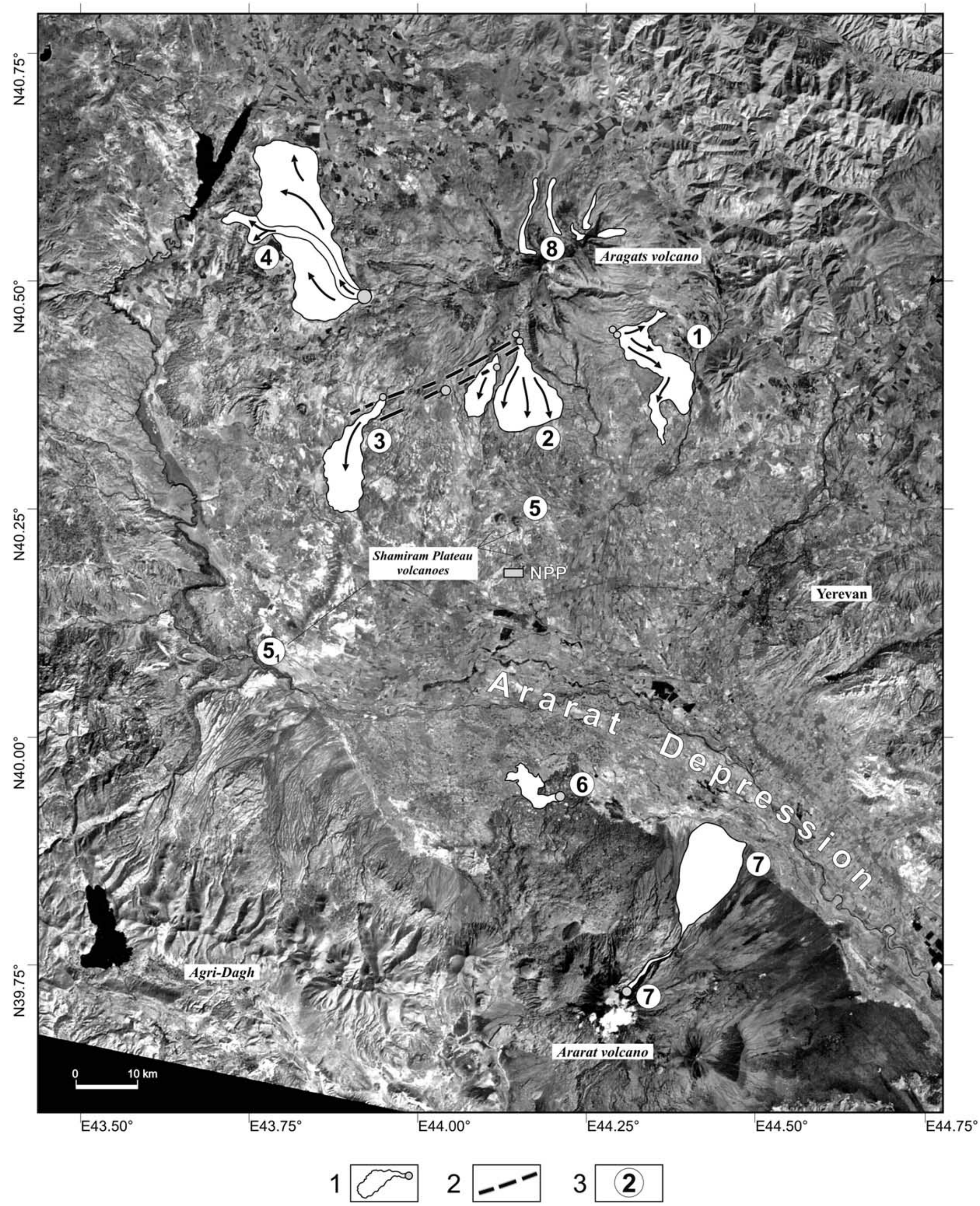


Fig. 6. Landsat-7ETM+ satellite image of the Ararat depression, Aragats, Ararat, and Shamiram Plateau volcanoes. 1, Young lava, mud-and-stone flows and their centers; 2, faults, controlling locations of volcanoes; 3, locations numbered and discussed in the text.

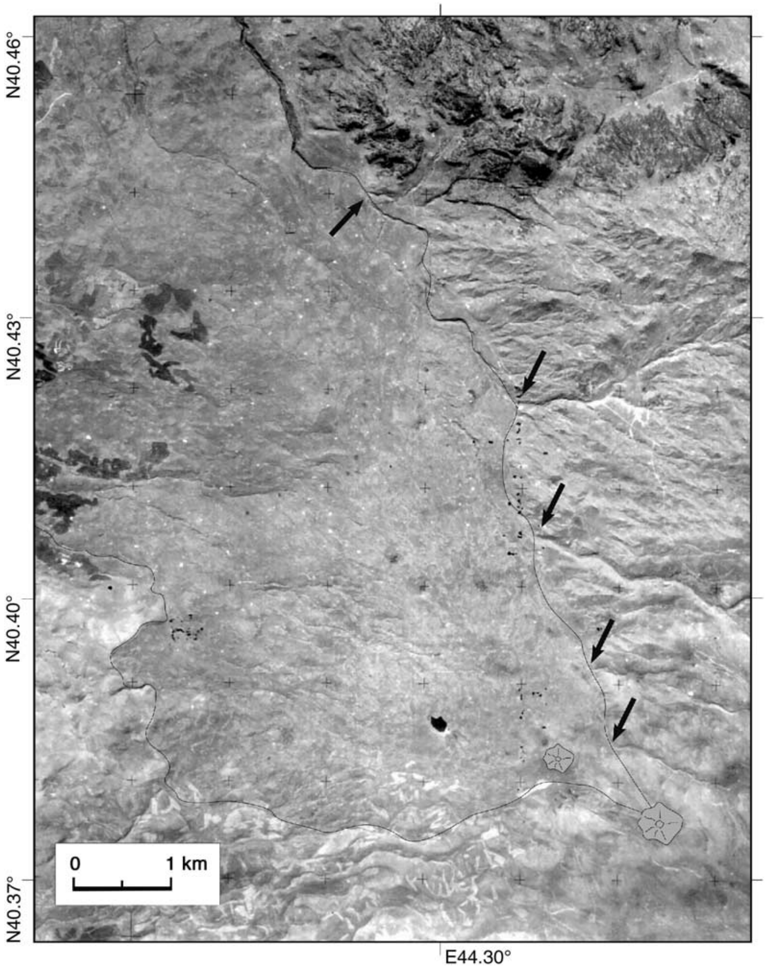


Fig. 7. Air photo of the Ashtarak lava flow from the eastern slope of the Aragats Volcano: arrows indicate where the Ashtarak flow overlies the river valleys.

The Atomakhoumb group is 1.3 km to the north of the nuclear plant and consists of six monogenetic cinder cones and lava volcanoes that range from 100 to 35 m high. The group is surrounded by a lava flow overlaid by younger ignimbrites on its northern slopes.

Data of Jrbashyan et al. (1995) assign the volcanic activity of these groups to the Early Quaternary. The short-lived activity was characterized by Strombolian eruptions concurrent with the beginning of the second stage of activity at Aragats. The age of ignimbrite tuffs forming a continuous cover on the Shamiram Plateau volcanoes is estimated as Early–Middle Quaternary (Jrbashyan et al., 1995).

Ages determined for the Shamiram Plateau volcanoes by geological and radiometric methods, including the volcano groups of Shamiram, Karmratar, Blrashark, Atomakhoumb, and Dashtakar, are also scattered widely from the Early Quaternary to the Holocene.

In their publications of 1994 and 1995, Jrbashyan et al. (1995) establish a Pliocene age for basaltic andesites in the base of the Shamiram Plateau and the Early Quaternary age for volcanoes in the Shamiram, Karmratar, Blrashark,

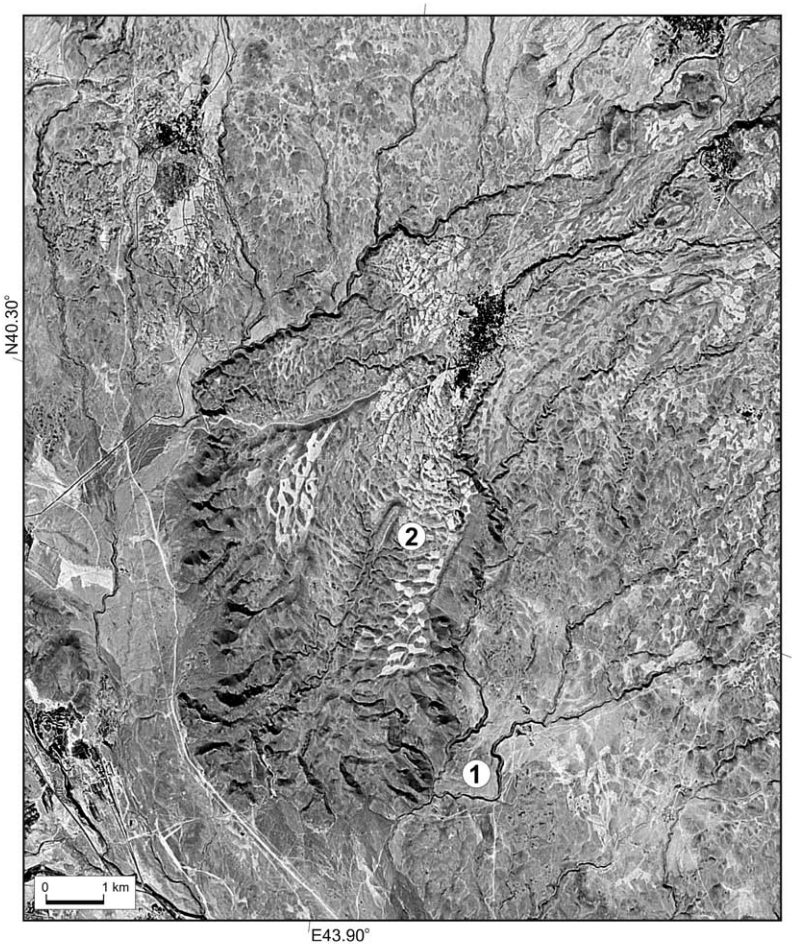


Fig. 8. Corona satellite image of the Irind flow: 1, lava overlying tuff horizon; 2, a young volcano.

Atomakhoumb, and Dashtakar groups. An Early–Middle Quaternary age is estimated for the ignimbrite tuff cover on these volcanoes, while basaltic andesite lava of the Tirinkatar flow lying on the tuff is dated as of Late Quaternary age.

Lichkov (1931) estimated the age of the Shamiram, Karmratar, Blrashark, Atomakhoumb and Dashtakar volcano groups from the fact that all of them consistently cover the third terrace of Arax, i.e. they are younger than the terrace. This conclusion is based on the observation that all the volcanoes rise over the terrace surface, bear no traces of denudation, and have no erosional debris on their surface nor on the surface of their deposits, while the volcanic deposits themselves overlie the terrace. Although Lichkov did not establish the age of the third terrace, he attributed the older (fourth) terrace to post-Würm, i.e. post-Late Pleistocene. Lebedev (1931) reached the same conclusion from an analysis of the geological position and petrographic composition of the volcanic rocks and the terraces. Aslanian and Asatrian (1950) also indicate that basaltic andesite lavas of the Shamiram Plateau volcanoes overlie the fourth terrace (27 m) of the Arax River, which has a Late Würm age, and date the latest activity of the volcanoes to the post-Würm period.

Paffenholtz (1948, 1952) dates the terrace on which the Shamiram Plateau volcanoes rest as post-Würm age and indicates a Holocene age for the latest stage of the volcanic activity. A Holocene age for the Shamiram Plateau volcanoes is also mentioned by Milanovsky (1953), and Amarian (1970) assigned a Late-Quaternary age to these volcanoes.

Our field studies in 2001 and 2002 revealed that scoria and lava of Karmrassar, Menakblour and Mets Sevblour volcanoes (5_1 in Figs. 1 and 6) overlie two generations of the Arax River terraces. In an area west of the village of Vanand ($\varphi = 40.11$, $\lambda = 43.81$), scoria from volcanoes of the Karmrassar group overlies the fourth terrace of the Arax River (Fig. 5A). A N–S-striking normal fault cuts this terrace of Arax, volcanic scoria that occurs above, and younger river deposits (Fig. 5B). To the southwest of Vanand, in the gorge of Elandereh ($\varphi = 40.09$, $\lambda = 43.78$) and a gorge near to it ($\varphi = 40.10$, $\lambda = 43.76$), andesitic lava overlies a younger, third terrace of Arax. It is difficult to establish the exact age of the terraces. Most probably, they can be dated back to the middle of the Late Pleistocene (Vanand) and the end of the Late Pleistocene (Elandereh and the neighboring gorge.) Volcanoes Karmrassar, Menakblour and Mets Sevblour are 27–32 km west of the ANPP.

The IAEA experts were of the opinion that a crater discovered in the Echmiatsin region 4 km south of the ANPP (in 1994–1995) is of phreatic, or phreato-magnetic origin and judging by its well-preserved morphology, it could be the most recent in the region (Fig. 3).

Samples of lava taken from the Tirinkatar flow were dated radiometrically at the University of Bern, Switzerland (1994–1995). They indicated an age for the last volcanic activity at 0.87 (± 0.09) Ma to 0.91 (± 0.03) Ma (Jrbashyan et al., 1995). These ages were consistent with the geological information collected in 1994–1995, which pointed to a pre-Holocene age of the latest eruptions on Aragats and the Shamiram Plateau (Jrbashyan et al., 1995).

A 4×10^{-6} probability for a new volcanic eruption in the limits of Aragats and the Shamiram Plateau was derived in 1994 and 1995 from the assumed age of the latest activity, and the probability of a new eruption within the plant site itself was estimated at 2×10^{-9} (Jrbashyan et al., 1995). The available data seem to lend little support to these estimates.

In its final report, the IAEA Mission (IAEA/RU-5270, 1995) concluded that the geochronological data could date the last activity within 25 km of the site at 1 and 0.7 Ma. The IAEA experts considered that the area within a 25 km radius from the site would not be affected in the near future. Judging from the absence of historical records of volcanic activity, as well as consideration of the geochronological and geological data, the possibility of volcanic re-activation in the lifetime of the plant was found to be negligible.

Nevertheless, in view of the small amount of data in support of these conclusions, the IAEA made a number of recommendations to substantiate and complete the volcanic hazard assessment in order to confirm those conclusions. Unfortunately, the studies recommended by the IAEA experts were never realized.

3. More recent studies of Holocene–historical volcanism in the vicinity of the nuclear plant

The most important task in assessing volcanic hazards is that of finding evidence for the most recent eruptive activity. An additional problem in modern Armenia today is that many geologists, engineers, and managers confidently deny the possibility of historical or even recent pre-historical volcanism. No attempt was made in Armenia to assess volcanic hazards until the first steps were taken in this direction during the IAEA projects of 1994 and 1995. Because of this situation, we attach special importance to new historical, archaeological, and field data attesting to the Holocene and historical volcanic activity in Armenia. The new data were compiled by the GEORISK S&R Company during the period of 1996–2002.

Several workers (Paffenholtz, 1948; Milanovsky, 1953, 1968; Balian, 1969; Karapetian and Adamian, 1973; Azizbekian, 1993) have drawn attention to manifestations of Holocene volcanism in Armenia. Fissure eruptions during the Holocene and historical period have been described for the Nemrout, Sipan, Tendourek, and

Ararat volcanoes in eastern Turkey (Feraud, 1994; Yilmaz et al., 1998; Innocenti et al., 1980), and their relationship with neotectonic faults has been demonstrated (Adiyaman et al., 1998; Dewey et al., 1986). According to the historical record, however, volcanic activity in the region has been limited to a single eruption of Nemrout in 1441 (Yilmaz et al., 1998).

New data on Holocene eruptions at the Kazbek, Elbrus, Kel, and Djava volcanic centers in the Greater Caucasus may change the popular view of the reality of volcanic hazards in the region (Bogatikov et al., 2001; Chernishev et al., 1999; Boubnov et al., 2000). The new evidence shows that volcanism could be renewed at any of the volcanic centers of the Greater Caucasus (Boubnov et al., 2000).

Our working plan was based on an analysis of remote-sensing material (SPOT, Russian Systems, Corona, Landsat-TM, Landsat-7ETM+, Aster, ERS, and aerial photography), GPS monitoring data, field mapping, and determination of age by ^{14}C dating, and archaeological methods. Estimates of age by ^{14}C dating were made in the Institute of Geological Sciences of the Russian Academy of Sciences (IGS) and at the Université de Paris Sud, France; the archaeological dating was carried out by the Institute of Archaeology and Ethnography of the Academy of Sciences of Armenia. The GPS monitoring data were obtained in the course of joint studies conducted in 1997–2000 by Montpellier-2 University, GEO-RISK, and the Institute of Geological Sciences of the Academy of Sciences of Armenia. We used newly discovered evidence from Armenian chronicle manuscripts, and other historical and archaeological sources. Historical records in Armenia cover a period of not less than 3000 years, while the archaeological record goes back 10 000–12 000 years (Armenie, 1996). Thus the data encompass the entire Holocene. Digital Elevation Models (DEM) and GIS-format databases were created. These were supported by *Idrisi* and *Carta Linx* software.

The studies of 1996–1999 revealed Holocene and historical eruptions of basaltic andesite lava from the two groups of volcanoes – Tskhouk-Karckar and Porak – located at distances of 160 and 135 km, respectively, to the east of the ANPP (Karakhanian et al., 1997, 1999, 2002).

3.1. The Tskhouk-Karckar group

Volcanoes of the Tskhouk-Karckar group form a line of eight monogenetic cones within a pull-apart basin formed by segments of the Pambak-Sevan active fault (6 in Fig. 1). The Tskhouk-Karckar group of volcanoes had three generations of recent eruptions. Basaltic andesites of the first phase lie on a Late Pleistocene (Würm) moraine and are assigned to the Late Pleistocene–Early Holocene.

Archaeological dating establishes that the lower age limit of lavas of Phases 2 and 3 should be younger than the late 4th or early 3rd millennium BC.

The upper age limit of Phase 3 lava is established by radiometric dating at 4720 ± 140 yr BP, or 3647–3357 (100% = 3657–3348) BC by σ_1 (GIN-9603). Two strong earthquakes that caused surface rupturing along eruption centers of Phase 2 and Phase 3 lava are attributed to the same period. Early in the 3rd millennium, the eruption of lavas of Phase 3 and a strong earthquake drove the Eneolithic archaeoculture out of the region. The Holocene and historical activity of volcanoes of the Tskhouk-Karckar group is presented in detail by Karakhanian et al. (1997, 1999, 2002).

3.2. The Porak group

This group consists of the central Porak Volcano with 10 parasitic cones and fissure eruption centers located inside a pull-apart basin formed by the segments of the Pambak-Sevan fault (7 in Fig. 1). Detailed evidence on the Holocene–historical activity of Porak group volcanoes is presented by Karakhanian et al. (2002) and Philip and Karakhanian (1999). Urartian cuneiform inscriptions, together with archaeological and radiometric estimates of ages assign eruptions of basaltic andesite lava and strong earthquakes to the period between 6640 ($\pm$90) and 6270 ($\pm$110) yr BP (the 5th millennium BC) and between 782 and 773 BC (Philip and Karakhanian, 1999; Karakhanian et al., 2002; Philip et al., 2001).

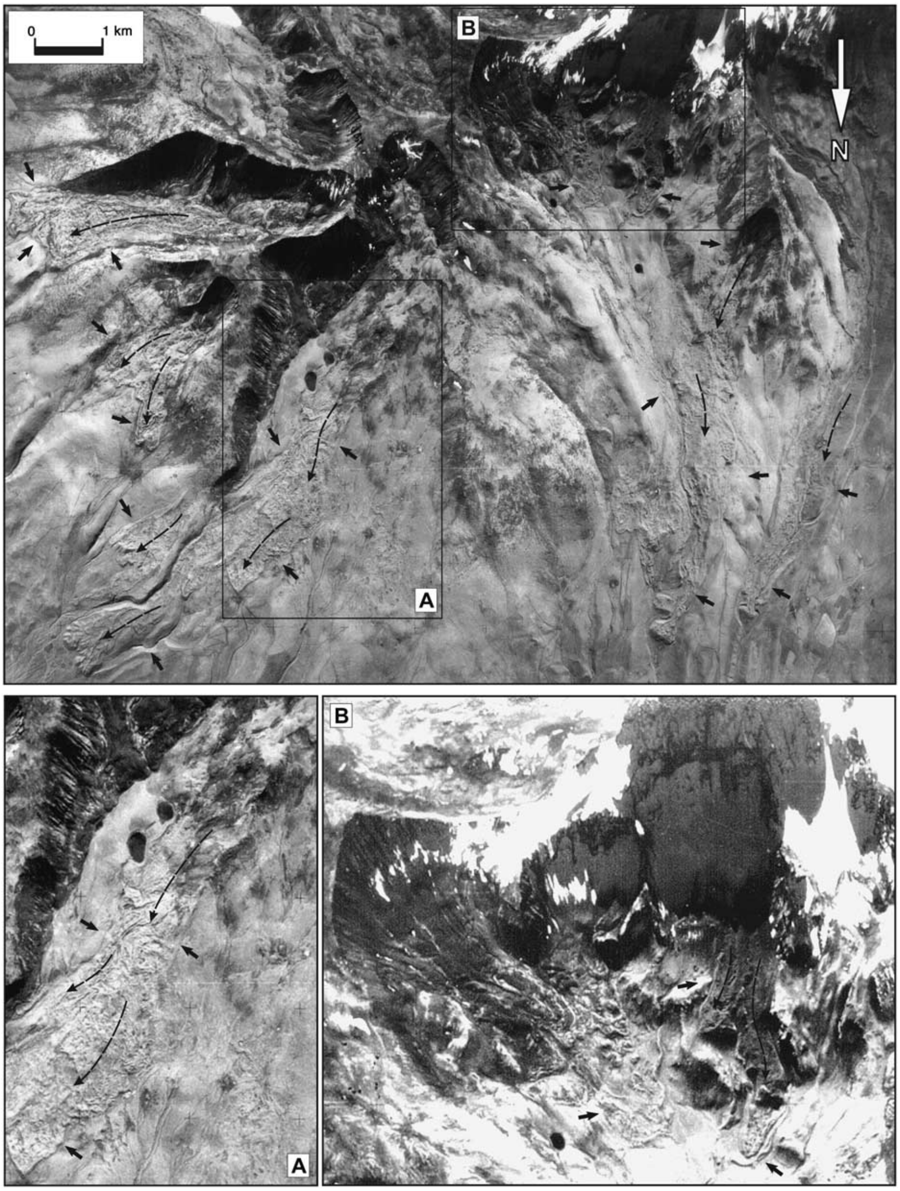


Fig. 9. Air photo of the northern and eastern part of the Aragats Volcano summit with young mud-and-stone and lava flows.

We interpret petroglyphs of the late 5th–early 4th millennia BC found to the southeast of Porak Volcano as depicting a volcanic eruption (Karakhanian et al., 2002).

Vaiyots-sar and Smbatassar volcanoes are 122 and 110 km east of the ANPP, respectively (8 and 8_1 in Fig. 1). Holocene flows of basaltic andesite lava cover Late Pleistocene terraces of the Arpa and Yeheghis rivers (Karapetian, 1960; Karakhanian et al., 2002).

Legends and chronicles of the 10th–13th centuries AD tell of the destruction of the towns of Moz and Yegheghis in 735 AD in the valleys of the Arpah and Yegheghis rivers, respectively. They are said to have been destroyed by a strong earthquake during eruptions of the Vaiyots-sar

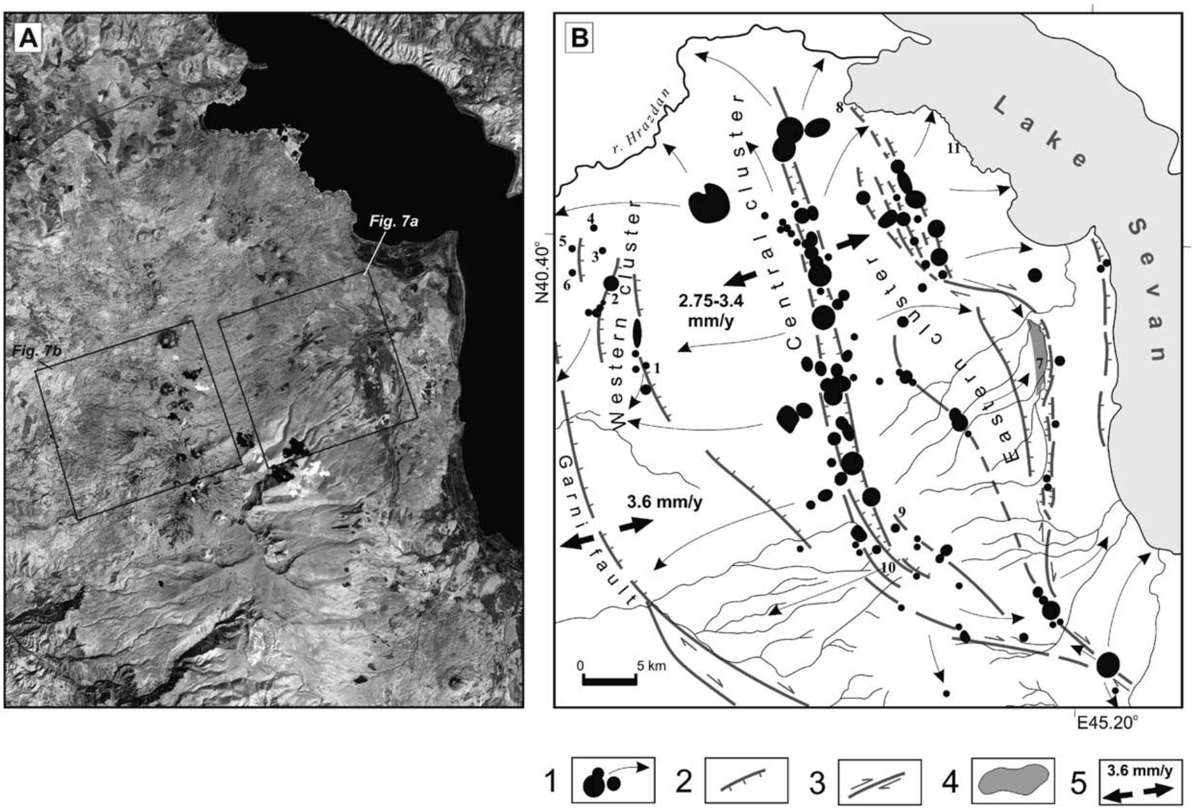


Fig. 10. Ghegam volcanic ridge. (A) Landsat-TM satellite image. (B) Interpretation. 1, volcanoes and directions of basaltic–andesite lava flows; 2, normal faults; 3, strike-slip faults; 4, young depression filled with volcanogenic–lacustrine deposits; 5, GPS monitoring data (Doerflinger, 1999, 2003).

and Smbatassar volcanoes. Chronicles of the 8th century AD recorded outbursts of dust and, possibly, ash fall during the earthquake in 735. The ash falls lasted for 40 days and covered vast areas.

Our field work conducted in 2002 indicated that the town of Moz rested on the surface of a Holocene lava flow, and the structures of the town were built of the fragments of that flow. According to personal communications with Dr. Melkonyan (Institute of Archaeology and Ethnography of the National Academy of Sciences of Armenia), numerous burial places found on the lava flow are dated back to the 11th century BC. In the meantime, this flow covers a field of burial grounds of the 3rd–2nd millennia BC located to the north of the town of Vyke. Therefore, the 3rd–2nd and 1st millennia BC are, respectively, the lower and upper limits constraining the age of eruption of basaltic andesite lava from Vaiyots-sar Volcano.

Consequently, chronicle reports about destruction of Moz by an eruption in 735 AD cannot be taken as factual and are rather echoes of much earlier legends. The fact is that an earthquake destroyed the town of Moz in 735. It is not improbable that the earthquake was accompanied by small volcanic effects, which were later confused with old legends and misrepresented in the chronicles of the 10th–13th centuries AD.

3.3. Ghegam volcanic ridge

Volcanoes of the Ghegam Ridge and Ararat are the closest to the ANPP, for which Holocene–historical activity is established.

The Ghegam volcanic ridge reaches an elevation of 3597 m. It is a 65-km-long and 35-km-wide oval zone with a north-northwesterly elongation. The nearest flank of the ridge is 52 km east-northeast of the nuclear plant (9 in Fig. 1). More than 105 large and middle-size Quaternary volcanoes are located parallel to the axis of the Ghegam Ridge (Karapetian, 1973, 1985).

Remote-sensing analysis and field studies allowed us to identify three distinct alignments of volcanoes. These clusters and associated tensional fractures are controlled by normal faults with a small right-lateral strike-slip component (Fig. 10).

The western (Hrazdan) cluster is 25 km long and consists of 14 volcanoes, the largest of which are Goutansar, Attis, Fontan, Alapars, Avazan, and Giumoush. The long central (axial) cluster stretches for more than 67 km and includes 54 large volcanoes. From northwest to southeast, the largest of these are Bogousar, Mets Tslougloukh, Sevckar, Azhdahak, Armagan, and Spitaksar. Volcanoes of this central cluster are aligned with the *crest* of the Ghegam Ridge within an elevation range of 3200–3500 m (Fig. 10).

The eastern cluster (Uochtepeh–Vaghramassar) is 55 km long, but includes fewer volcanoes (30). From west to east, the largest volcanoes are Uochtepeh (Karapetiana), Jrbashyana, Hambariana, and Vaghramassar. South of Tashats-sar Volcano, the alignment of the eastern cluster branches into western and eastern segments, which join again toward the south, in the region of the Mets Jar-tar (Fig. 10).

The normal faults that control the western, central, and eastern clusters join in a single zone located south of the Ghegam Ridge, near the large Armagan Volcano, and form a large 'horsetail splay' structure (Fig. 10).

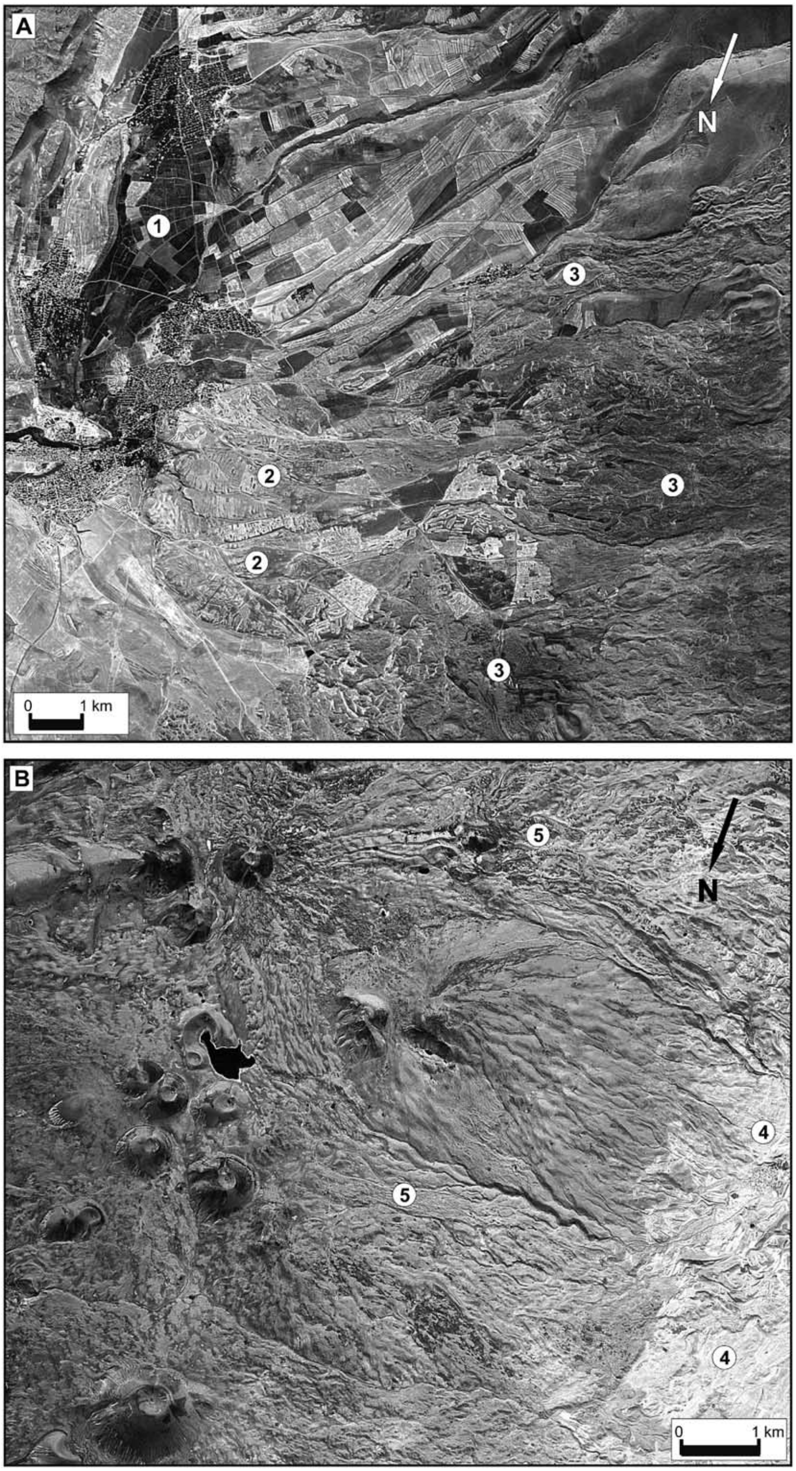
For the Ghegam Ridge, the sequence from earliest to most recent was: 1, explosive pyroclastic tephra; 2, rhyolite–obsidian lava flows; 3, rhyolite–obsidian domes and extrusions; 4, spines and flows of rhyolites and rhyodacites; and 5 (the final stage), lava flows of andesite and basaltic andesite (Jrbashyan et al., 2000.)

Paffenholtz (1948, 1952) and Milanovsky (1953, 1968) pointed out that the basaltic andesite lavas north of the Ghegam Ridge are of Holocene age. New data allow us to confirm their evidence and provide a more accurate age.

For the western, Hrazdan cluster, obsidian samples from the Attis, Goutansar, Fontan, Alapars, Avazan, and Giumoush volcanoes (1, 2, 3, 4, and 5 in Fig. 10) were dated by fission-track and plateau-age methods (Badalian et al., 2000; Jrbashyan et al., 2000). The analyses were performed at the Institute of Geochronology and Isotopic Geochemistry in Pisa (Italy). The results indicate an Upper Pleistocene plateau age of 0.40 ± 0.03 to 0.25 ± 0.03 and fission-track age of 0.30 ± 0.03 to 0.19 ± 0.05 for the third stage of volcanic activity (rhyolite–obsidian domes). These ages confirm the statement that the last (fifth) basaltic andesite stage for the western (Hrazdan) cluster is considerably younger than 0.25–0.19 Ma.

Basaltic andesite lava from the western cluster of volcanoes flowed into the Hrazdan River valley. These lava flows are now southwest of the city of Yerevan (9 in Fig. 1). To determine the age of the valley flows, we observed that they cover the products of the rhyolite–obsidian volcanoes of the western cluster, and obsidian pebbles from those volcanoes are found in the river terrace covered by the flows. The age of the valley flows may therefore be assumed younger than 0.25–0.19 Ma. Paffenholtz (1952) dates these flows back to the post-Würm period, while Kharazian (1993) relates them to the most recent part of the Late Quaternary. Karapetian (1983) uses archaeological age determinations to relate these flows to the pre-Late Acheulian period. One of the valley flows of lava, the Argavand flow, stretches to the west, into the Ararat depression, and terminates 25 km from the ANPP. Yerevan-I and Yerevan-II Mousterian cave sites were found in the base of this flow. The radiometric determination of the age of these sites is 47 000 yr (GrN 7665). Karapetian (1983) estimates the age of the Argavand flow by the archaeological data as post-Acheulian–pre-Mousterian.

A depression filled with volcanogenic–lacustrine deposits lies between the western and eastern segments of the eastern (Uochtepeh–Vaghramassar) cluster (12 in Fig. 1 and Fig. 10). The depression formed as a result of vertical displacements on the


A
N
1
2
2
3
3
3
0
1 km
B
N
5
5
4
4
0
1 km

Gavaraghet normal fault, which represents the eastern segment of the eastern cluster (Fig. 10). A charcoal sample from the volcanogenic–lacustrine deposits taken at a depth of 2 m below the surface in the center of the depression (7 in Fig. 10, to the south of the town of Gavar) provided a radiocarbon age estimated by the Paris Sud University (UPS) as 30 080 ± 500 yr BP.

Since the andesite–dacite lava of the eastern cluster overlies the volcanogenic–lacustrine deposits in the depression (1, 2 in Fig. 11A), the date of 30 080 yr BP is a lower limit (pre-date) for the lava eruption. This pre-date is supported by a Mousterian age estimated for obsidian tools found under the volcanic rocks of the eastern cluster (Karapetian, 1983). Many old structures and markers composed by basaltic andesite boulders have been found on the flows of andesite–dacite lava from the Uochtepeh (Karapetiana), Toumb, and Bogousar volcanoes on the northern flank of the eastern cluster (8 in Fig. 10). Archaeological and radiocarbon dating of the basaltic andesites point to an age of 3500–2300 yr BP, which is the upper age limit of the basaltic andesite eruption from the eastern cluster.

On the northwestern shore of Lake Sevan, near the village of Norashen (11 in Figs. 1 and 10), a fissure eruption on the eastern cluster produced a basaltic andesite flow that entered the lake on a large front. The front of the lava flow has been strongly eroded and transformed into lava clasts. The latter include fragments of basaltic andesite of angular shape, with sizes ranging from 2–3 cm to 50–60 cm. These fragments are chaotically arranged and cemented with a carbonate mortar of lake bottom sediments. Apart from remains of *Gastropoda* and *Ostracoda* shells, the material cementing the lava clasts contains a large amount of bones, ceramics, and other artifacts related to the Early Bronze Age (Koura–Arax culture of 4500–4400 yr BP). Later, the lava flow was overlain with deposits from Lake Sevan, on which the remains of old structures were found. The age of ostracods in the lava clast cement determined by radiocarbon dating is 6270 ± 110 yr BP (MSU-215), while the age of ostracods from the lake deposits overlying the lava is estimated at 2090 ± 70 yr BP (MSU-244) (Sayadian et al., 1977).

We can therefore establish that the eruption in the eastern cluster of the Ghegam Ridge occurred between 4500–4400 and 2090 ± 70 yr BP.

The central (axial) cluster is the area of most intense volcanic activity on the Ghegam Ridge. The southern part of the central cluster is covered by the Riss and Würmian glacial deposits, and has deep river valleys (Fig. 10). River valleys are found only in the southern part of the Ghegam Ridge. The northern part of the central cluster is covered by lava flows of basaltic andesite and has no traces of Riss or Würmian glaciation (Karapetian, 1973). There are no traces of erosion, and the surface of the basaltic andesite is devoid of soils and vegetation (Figs. 10 and 11).

In the southern part of the central cluster, ages were determined for the rhyolite–obsidian of Spitaksar and Geghassar volcanoes (9 and 10 in Fig. 10). Analyses performed in the Institute of Geochronology and Isotopic Geochemistry in Pisa (Italy) indicate a Late Pleistocene plateau age of 0.12 ± 0.01 to 0.042 ± 0.004 and a fission-track age of 0.094 ± 0.009 to 0.038 ± 0.005 for the third stage of volcanic activity (rhyolite–obsidian domes) (Badalian et al., 2000; Jrbashyan et al., 2000).

In the south, basaltic andesites cover ejecta from the rhyolite–obsidian domes of Spitaksar and Gheghassar. We conclude therefore that these rocks are younger than 0.042–0.038 Ma.

Basaltic andesite lava in the northern part of the central cluster overlies lava of the same composition in the southern portion of the cluster, as

Fig. 11. Corona satellite images of the Ghegam Ridge. (A) Eastern part of the Ghegam Ridge: 1, young depression filled by volcanogenic lacustrine deposits; 2, lava flows of basaltic andesite from the eastern cluster covering the depression deposits; 3, basaltic–andesite lava flows of the central cluster overlying the eastern cluster lava. (B) The western part of the Ghegam Ridge: 4, basaltic–andesite lava flows in the western cluster; 5, basaltic–andesite lava flows of the central cluster overlying the western cluster lava.

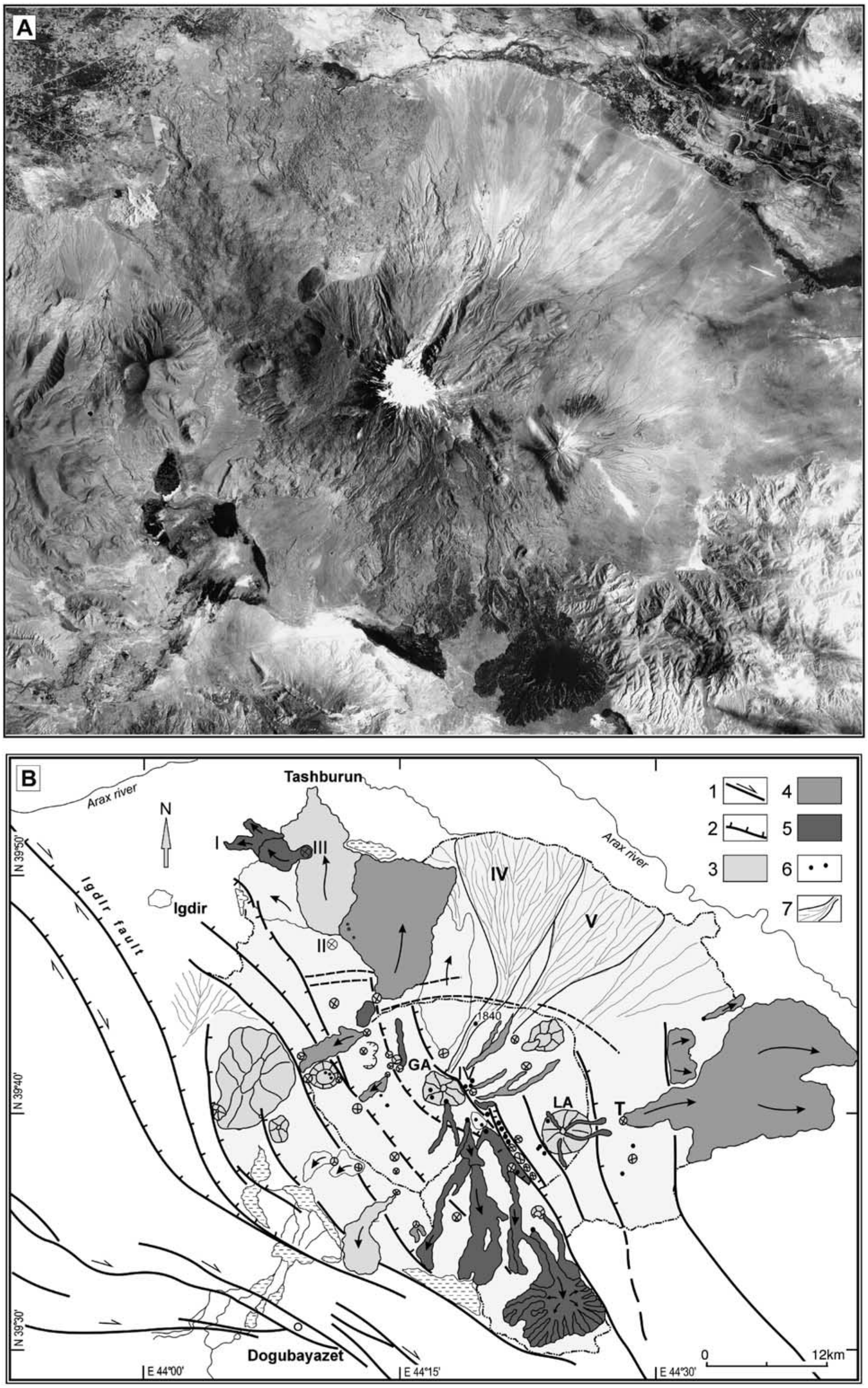


Fig. 12. The Greater and Lesser Ararat volcanoes. (A) Soviet system satellite image. (B) Interpretation (by Karakhanian et al., 2002). 1, Active strike-slip faults; 2, active normal faults; 3, young lava of Phase 1; 4, young lavas of Phase 2; 5, inferred Holocene lavas; 6, parasitic cones; and 7, mud layer deposits. GA, the Greater Ararat; LA, the Lesser Ararat; T, Mount Touzhik.

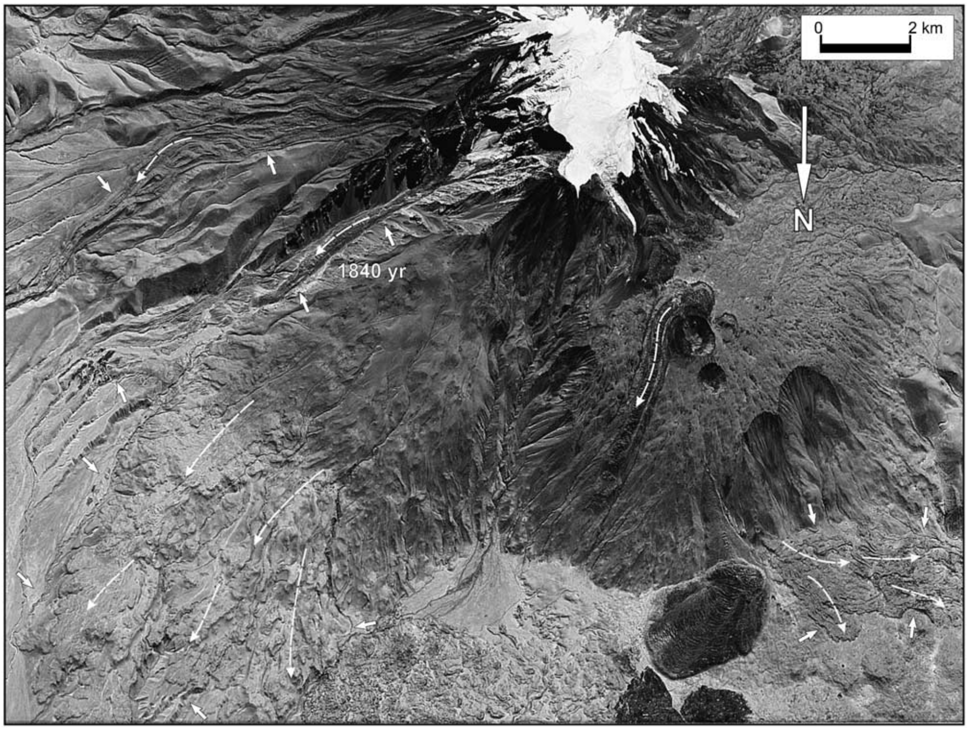


Fig. 13. Corona satellite image of the western and northern slope of Ararat Volcano with young mud and lava.

well as part of lava flows of the western cluster and volcanogenic–lacustrine deposits in the eastern cluster depression (1, 2, 3, 4, and 5 in Fig. 11A,B).

Therefore, the lower age limit of the basaltic andesite lava in the central cluster may be considerably younger than 0.038 Ma, i.e. it may belong to the Holocene. Holocene volcanism in the central cluster of the Ghegam Ridge is indicated indirectly by the widespread petroglyphs on the surface of basaltic andesites in its southern part. This is in contrast to the absence or scarcity of petroglyphs in the northern part of the cluster. According to Karapetian (1983), lava flows of the Sevkar Volcano, located in the middle part of the central cluster, overlie the Kapoutan site of a Mousterian age, while the tools found on the lava belong to the Mesolithic–Neolithic period.

Thus the Ghegam Ridge volcanoes, and the central and eastern clusters in particular, are vast areas of large-scale Holocene and historical volcanic eruptions. They are 50 km from Yerevan, a city with a population of 1 million, and rise 2500 m above the surface of Ararat depression. Data of GPS monitoring conducted in Armenia jointly by the Montpellier-2 University, GEO-RISK, and Institute of Geological Sciences (Doerflinger et al., 1999, 2003) have provided some preliminary results indicating extension at rates of 2.75–3.4 and 3.6 mm/yr in the central cluster of the Ghegam Ridge and along the Garni Fault of the neighboring eastern cluster, respectively (Fig. 10). Together with Ararat Volcano, the Ghegam Ridge volcanoes may pose the greatest volcanic hazards for the central part of Armenia and for the ANPP.

3.4. Ararat Volcano

Ararat Volcano is a calc-alkaline, compound stratovolcano (Yilmaz et al., 1998) in Turkey, 55 km south of the ANPP. It rises to an elevation of 5165 m, 4 km above the Ararat valley (15 in Fig. 1). Radiometeric dating established an age of

20 000 yr for the most recent eruptions. West of the Ararat group of volcanoes, there is an east–west elongated volcanic area on the Agri-Dagh Ridge. Remote-sensing analyses point to numerous young lava flows on the slopes of Ararat Volcano. Many of these flows may belong to the Holocene–historical period (Figs. 6, 12 and 13).

The Ararat depression is a large pull-apart basin formed by active fault segments (Dewey et al., 1986; Yilmaz et al., 1998; Karakhanian et al., 2002, 2003). The position and linear trend of volcanic centers of Ararat are controlled by the 'horsetail splay' structure on the NW flank of the right strike-slip Maku and Dogoubayazit faults (Karakhanian et al., 2002, 2003).

Analyses of archives, chronicles, and archaeological sources revealed a long record of the historical volcanic activity of Ararat (Karakhanian et al., 2002). Kouftin (1944) mentions the results of excavations at the foot of Ararat by P.F. Petrov, a Russian mining engineer, which were conducted in 1914. The excavations were 8.5 km from the town of Igdir (near the village of Malakliu) (1 in Fig. 12, 6 in Fig. 6). The site is at the limit of pyroclastic deposits from Ararat, which cover alluvial and lacustrine deposits of the Ararat valley. The pyroclastic deposits overlie a thick archaeological layer of ancient settlement dated back to the period of the Koura–Arax culture (2500–2400 BC) (Karakhanian et al., 2002). In the upper part of the pyroclastic deposits, Petrov found numerous graves. Artifacts found in the graves are dated back to 700–500 BC (Karakhanian et al., 2002).

This constrains the eruption of the pyroclastic flows from Ararat Volcano to between 2500–2400 BC (the lower date) and 700–500 BC (the upper date). The large number of household utensils, carbonized timber particles, and human and animal bones indicate that the volcanic eruption was within the period when the Koura–Arax settlement was populated and ended with a catastrophe. Thus, the volcanic event may date back to 2500–2400 BC (Karakhanian et al., 2002).

The most probable sources of the pyroclastic flows include eruptive centers on the northern slope of Greater Ararat, or those between the summits of Kariyarikh (1475 m) and Shouper (1222 m). Another possible source is 4 km to the south of the village of Tashbouroun (II and III in Fig. 12, 6 in Fig. 6). The latest significant volcanic activity on Ararat was probably in 1840. A disastrous $M = 7.4$ Ararat earthquake occurred on July 2, 1840 (Ambraseys and Melville, 1982). Many villages in the area around Ararat Volcano and the towns of Dogubayazet, Maku, and Ordoubad were completely destroyed. Up to 10 000 persons were killed. The earthquake produced a 72 km long surface rupture and a landslide from the summit of Ararat (Stepanian, 1964; Ambraseys and Melville, 1982). Historical data and clerical archives of the Ararat Diocese of the Armenian Apostolic Church contain eyewitness accounts of the earthquake and the landslide (Karakhanian et al., 2002).

Analysis of these accounts suggests that the earthquake was accompanied by an explosive Bandai-type phreatic eruption from the northern slope of Ararat close to the summit (IV in Fig. 12, 7 in Fig. 6). The eruption produced ballistic ejecta, an eruptive cloud rising from the summit, and a pyroclastic flow that swept down the slope and destroyed the village of Akory. Sapper (1927), Rittman (1964) and Feraud (1994) also mention an explosive gas eruption on Ararat in 1840 and the close similarity of the eruption to that of Bandai Volcano in 1888.

The 1840 eruption was accompanied by secondary volcanic effects. There were accounts of rain in the Ararat valley in the evening of July 2, a layer of harsh-smelling blue mud and vitriol-blue pools of water left by the eruptive rain.

The debris flow (lahar) from near the summit of Ararat and through Akory canyon appears to have been another secondary phenomenon accompanying the 1840 eruption. By our estimates, the volume of the 1840 Ararat debris flow was 3×10^8 m^3, and the speed was about 175 m/s. Descriptions of the debris flow provided by the eyewitnesses suggest that the synchronous impacts of the explosive eruption and the earthquake destabilized and destroyed the upper slopes of Ararat. The detached part of the slope swept through Akory canyon as it broke into pieces and gathered speed. Satellite images of the north slope of Ararat show clear traces of this flow as well as earlier ones (IV and V in Fig. 12, Fig. 13).

Movses Khorenatsi, an Armenian historian of the 5th century, tells about a large landslide/landfall from the summit of Ararat during a strong earthquake in 550 BC (Movses Khorenatsi, 1990). We believe that some ancient Armenian legends (birth of Vahagn, Azhdahak's dream, or Artavazd's captivity, collected by Movses Khorenatsi, 1990) provide poetically narrated indications of a possible volcanic eruption, earthquake and landslide from Ararat during the conflict between Armenian king Tigran the First and Median king Astiag (Azhdahak) in the first half of the 6th century BC (about 550 BC).

There is evidence from Ptolemeus Claudius for a large natural disaster on Ararat at the time of a strong earthquake in the first half of the 2nd century AD (Movses Khorenatsi, 1990). Volcanic activity on Ararat may also have occurred in the late 3rd–early 4th centuries AD, in 1450 AD and in 1783 AD. Holocene lava flows have been identified in satellite images of Ararat and part of them could have been produced by Holocene or historical volcanic eruptions that have not yet been described.

Archaeological and historical evidence indicates volcanic eruptions between 2500 and 2400 BC, and in 1840 AD from the centers on the northern slopes of Ararat. Deposits of pyroclastic flows associated with the eruption in 2500–2400 BC are 27 km south of the ANPP, and the 1840 phreatic eruption occurred at a distance of 52 km from the plant site. The debris flow deposits of 1840 closest to the ANPP are located 30 km to the east of the power plant.

4. Structural control of the centers of the Holocene and historical volcanism

Structural and geodynamic conditions of the recent volcanic activity constitute another important issue of volcanic hazard assessment for the Armenian region. Many centers of Holocene and historical volcanic activity in Armenia (Tskhouk-Karckar, Porak, and Ghegam Highland) and other zones of the Arabian lithosphere plate collision (Erdijas, Hassan-Dagh, Nemrout, and Tendourek) are controlled by active faults and located in young tectonic depressions of pull-apart basin type, or in 'horsetail splay' structures (Karakhanian et al., 1997, 1999, 2002, 2003; Adiyaman et al., 1998, Tekin Yurur and Chrowicz, 1998, Toprak 1998).

The ANPP is on the northern side of the large Ararat depression situated at the junction of the borders of Armenia, Turkey, Iran, and Azerbaijan. The depression strikes for 140 km NW–SE and has a width of 20–35 km (Figs. 1 and 6).

The Ararat depression is a large pull-apart basin (Dewey et al., 1986; Yilmaz et al., 1998; Karakhanian et al., 2002, 2003) developed in a young extensional zone between en-echelon strike-slip faults. Aragats and Shamiram Plateau volcanoes are on the northern side of the Ararat depression, and on its southern side is the large polygenetic volcano of Ararat and the Agri-Dagh volcanic ridge.

On the northern flank of the Ararat depression, 15 km SW of the ANPP, the Sardarapat fault zone stretches along the longer axis of the Ararat depression (Fig. 1; Karakhanian et al., 2003). The Sardarapat fault zone consists of a system of uplifts and swells composed of Quaternary basalts, and alluvial and talus deposits (Karakhanian et al., 2003). The radiometric ages of these basalts, which were established by the K/Ar method at the Swiss University in 1994–1995, are 0.36 and 0.99 Ma, and the IGEM Moscow Institute provided an age of 0.92 Ma in 2000. North of the Sardarapat swell, Griako, Davtiblour (Armavir) and other volcanoes are aligned with a similar fault.

Volcanoes in the Shamiram, Karmratar, and Blrashark groups are aligned WNW and may be controlled by a fault zone (Figs. 3 and 4). Parasitic volcanic centers of the Kabakhsar, Katnakhpiur, Irind, Bazmaberd, Baisyz, Tirinkatar, and possibly of the Ashtarak flows on the Aragats slope may also be controlled by an ENE-striking fault zone (Fig. 6). This zone has been active recently; there have been minor earthquakes and several larger events of $M = 4.0$–4.5 in this zone.

The presence of the large polygenic volcanoes of Aragats and Ararat, Shamiram Plateau volcanoes, Sardarapat swell, and Agri-Dagh Ridge on both sides of the Ararat depression may be associated with the extension developing inside it, between the en-echelon strike-slip fault segments. There is evidence of Holocene–historical tectonic and seismic activity for the Ararat depression faults (Ambraseys and Melville, 1982; Barka and Kadinsky-Cade, 1988; Berberian, 1976, 1997; Karakhanian et al., 2002, 2003).

The eastern, central and western volcanic clusters of the Ghegam Ridge are arranged in a pull-apart flanked by the Garni and Pambak–Sunik–Sevan active strike-slip faults on the southwestern and northeastern sides, respectively (Figs. 1 and 10). GPS measurements indicate extension at a rate of 3.6 mm/yr along the GF2 segment of the Garni Fault, which has a predominantly normal component (Doerflinger et al., 1999, 2003) (Figs. 1 and 10). The same data indicate that extension along a normal fault of the central cluster of the Ghegam Ridge ranges from 2.75 to 3.6 mm/yr. Therefore, the total rate of extension for the Ghegam pull-apart is 6.35–7 mm/yr. Eruptions of basaltic andesite lava in Holocene and historical times were recorded for the eastern and central clusters of the Ghegam Ridge.

In the northern part of Armenia, the GPS measurements have recently recorded extension at a rate of 1.25 mm/yr across the zone of the Javakh Ridge, which is characterized by intense Quaternary volcanism (Doerflinger et al., 1999, 2003) (Fig. 1). According to the GPS data, slip rates for oblique faults are 3.07 mm/yr, and the rates of shortening along latitudinal thrusts correspond to 2.53 mm/yr (Doerflinger et al., 1999, 2003).

Therefore, the rate of extension in Armenia can approach, or exceed, the rates of compression and shortening, which is important for the structural control of Holocene–historical volcanic centers and volcanic hazards assessment. Although tectonic and volcanic activity are usually linked, specific aspects of the complex structure and chronology of this link in the Arabian continental collision zone require more studies.

Historical and recent eruptions were recorded for many volcanic centers in the zone of the Arabian plate collision. (Mellaart, 1967; Tiedeman, 1991; Berberian, 1994; Trifonov and El-Khair, 1988, Goushenko, 1979; Chernishev et al., 1999; Boubnov et al., 2000; Karakhanian et al., 2002). The recent studies of Feraud (1994), Karakhanian et al., (1997, 1999, 2002) and Haroutiunian (2001) provide indications of many historical volcanic eruptions in Armenia and adjacent areas of eastern Turkey taking up the central part of the Arabian collision zone.

A possible association of volcanic and seismic activity may pose an additional hazard. In many cases, volcanic activity in Armenia and Turkey has coincided with strong earthquakes (Feraud, 1994; Karakhanian et al., 1997, 1999, 2002, 2003; Philip and Karakhanian, 1999; Philip et al., 2001). A number of publications have illustrated the possibility of such a relationship (Doumas, 1990; Hill et al., 1993; Guidoboni et al., 1994; Karakhanian et al., 1997, 2003). Throughout the studied regions, some volcanoes are associated with pull-apart basins and controlled by active faults. Tectonic stresses accumulating in these basins may be released as strong earthquakes producing large seismogenic surface ruptures. Where these ruptures penetrate intermediate magma sources, they can trigger volcanic eruptions (Karakhanian et al., 1997, 2003).

5. Discussion

These studies provide evidence of many instances of historical volcanic activity in Armenia and adjacent areas. The details can be found in the work of Karakhanian et al. (2002). Identification and dating of the latest volcanic activity, particularly in the Holocene, remain the most important issue of volcanic hazard assessment for the area of the ANPP.

The volcanic hazard studies of 1994 and 1995 focused only on the Aragats and Shamiram Plateau volcanoes, which are in the immediate vicinity of the site. It is also important to note, however, that the nuclear plant is 55 km from the summit of the large volcano of Ararat, for which we have found records of many historical volcanic events. The centers of that activity are found at distances of 52–27 km from the plant (Fig. 6).

Field studies indicate that the age of the latest volcanic activity on Aragats and Shamiram Plateau volcanoes can be related to the Late Pleistocene. This was not reported in the studies of 1994 and 1995 (Table 2).

The ages of the Tirinkatar and Ashtarak lava flows on Aragats determined by geologic and radiometric methods range from the Middle to Early Quaternary (Jrbashyan et al., 1995, Chernishev et al., 2002) to the Holocene (Milanovsky, 1953, 1968). Remote-sensing and field studies indicate that the age of lava flows on Pokr Boghoutlu volcanoes and the Irind flow on Aragats can be estimated as the end of the Late Pleistocene. Flows of mud and stones on the northern and eastern parts of the Aragats Volcano summit have much in common with the Holocene age formations and resemble the lahars on Ararat, including the 1840 eruption deposits (Fig. 13).

Geological studies by Lichkov (1931), Lebedev (1931), Aslanian and Asatrian (1950), Paffenholtz (1948, 1952), Milanovsky (1953), and Amarian (1970) estimate a Late Pleistocene–Holocene age for the Shamiram Plateau volcanoes. Geologic determinations of Jrbashyan et al. (1995) and Ghukasian (1985) result in an Early Quaternary age estimate for the same volcanoes (Table 2).

In 1994–1995, the Swiss University performed K/Ar radiometric age measurements of samples taken from the Atomakhoumb and Dashtakar groups of volcanoes closest to the ANPP and a lava flow from Blrashark Volcano. As noted in the conclusions of the Swiss University Laboratory, some of the measured ages are geologically unacceptable as eruption dates since they may reflect contamination with excess Ar. However, the laboratory conclusions indicate that five of the groundmass age estimates (sample nos. 1–5, Table 1) can be interpreted geologically, since they all fall in the range of 0.87 ± 0.03 to 0.99 ± 0.02 Ma. This is evidence of a geochemically and thermally undisturbed history. The IAEA group of experts arrived at the same conclusion.

However, the acceptability of K/Ar analyses of groundmass and phenocrysts for age determinations of recent volcanism is doubted (Chernishev et al., 2000; Boubnov et al., 2000).

In 2000–2001, ages of two samples from the Shamiram Plateau were measured at the Institute of Geology, Ore Deposits, Petrography and Geochemistry of the Russian Academy of Sciences (Chernishev et al., 2002). One of the samples (no. 8/a) was taken from the upper cover of basaltic andesites of the Shamiram Plateau near the volcanoes of the Dashtakar group, and the second (no. 12/a) was from basaltic andesites at the southern foothills of Aragats (Fig. 3 and Table 2). The age of samples was estimated by the new version of the K/Ar method that considerably reduces distortion due to the presence of excess radiogenic ^{40}Ar in phenocrysts (Chernishev et al., 1999, 2000). The dating of sample no. 8/a from the upper cover of basaltic andesites of the Shamiram Plateu gave an age of 0.96 ± 0.10 Ma, while samples of basaltic andesite from the southern foothills of Aragats gave ages of 0.56 ± 0.07 Ma (12/a), 0.45 ± 0.07 and 0.35 ± 0.05 Ma (Table 2) (Chernishev et al., 2002).

The measurements are consistent with the ages given by radiometric analysis of several samples at the Swiss University (0.90 and 0.76 Ma) and are not in conflict with the geological estimates of age provided by Jrbashyan et al. (1995). They are, however, markedly different from the geological estimates of a Late Pleistocene–Holocene age for the Shamiram Plateau volcanoes presented in the studies of Lichkov (1931), Lebedev (1931), Aslanian and Asatrian (1950), Paffenholtz (1948, 1952), Milanovsky (1953), and Amarian (1970) (Table 2). Different researchers using geological and radiometric methods have therefore arrived at conflicting age estimates for the Shamiram Plateau volcanoes. Their age determinations range from 0.96 Ma (Middle Pleistocene) to Late Pleistocene–Holocene (Table 2).

Only two ages of 0.76 Ma (sample 1, Table 1) and 0.90 Ma (sample 3) from the dating conducted by the Swiss University can be considered acceptable for geological interpretation of the Shamiram Plateau volcanoes close to the nuclear plant. The IAEA mission also mentioned this fact (IAEA/RU-5270, 1995 Final Report). However, we must bear in mind that both dates were obtained on samples from depths of 44 and 45 m in a borehole, i.e. from the upper or lower covers of basaltic andesite of the Shamiram Plateau identified by Jrbashyan et al. (1995). The geologically interpretable estimates in the range of 0.87 ± 0.03 and 0.99 ± 0.03 Ma are not directly related to the

Shamiram Plateau volcanoes, but refer rather to Dzorap-type lava from the Aragats Volcano (sample 5, Table 1) and the Sardarapat flow lava (sample 2, Table 1) located 14–18 km from the nuclear plant.

The two radiometric estimates of age produced in 2000–2001 by the Institute of Geology, Ore Deposits, Petrography and Geochemistry of the Russian Academy of Sciences were based on a special method for young volcanic rocks that proved to be efficient in the dating of Holocene eruptions on Kazbek and Elbrous volcanoes (Chernishev et al., 1999; Boubnov et al., 2000). In line with similar estimates of 0.90 and 0.76 Ma obtained at the Swiss University, this indicates that an age of 0.96 ± 0.10 Ma is acceptable for estimating the age of the upper basaltic andesite cover of the Shamiram Plateau.

The upper cover of the Shamiram Plateau is overlain, sequentially, by ignimbrites and flows of basaltic andesite from the southern slope of Aragats. The radiometric dating of this basaltic andesite lava conducted by the Swiss University gave ages of 0.91 and 0.87 Ma, while the Institute of Geology, Ore Deposits, Petrography and Geochemistry of the Russian Academy of Sciences dated the age as 0.56, 0.45 and 0.35 Ma (Chernishev et al., 2002). Therefore, the age of ignimbrites and basaltic andesites overlying the Shamiram Plateau near the ANPP can be estimated as ranging from 0.96 (pre-date) to 0.35 Ma (post-date).

However, these results cannot be used to derive an age of latest activity on Shamiram Plateau volcanoes west of the ANNP.

Lava flows and scoria from Mets Sevblour and Menakblour volcanoes, and volcanoes of the Karmrassar group (Shamiram Plateau) 27–32 km west of the ANPP, cover Late Pleistocene terraces of the Arax River and have a younger age estimated as Late Würm and Holocene by Lichkov (1931), Lebedev (1931), Aslanian and Asatrian (1950), Paffenholtz (1948, 1952) and Milanovsky (1953).

Jrbashyan et al. (1995) mention that the Tirinkatar flow terminates north of the nuclear plant and overlies the Shamiram Plateau ignimbrites, but the analysis of remote-sensing data does not support such a conclusion. High-resolution satellite images and air photos show that the youngest flow of the Tirinkatar Volcano did not reach the Shamiram Plateau (Fig. 6). The flow of basaltic andesites identified on the Shamiram Plateau north of the nuclear plant, for which the age estimated by radiometric dating ranges within 0.91–0.35 Ma, is an older generation of lava on Tirinkatar Volcano and cannot be used to estimate the date of its latest activity.

A crater of supposedly phreatic origin located 4 km south of the plant site in the Echmiatsin region may be a recent feature. Lake Aigerlich 5 km south of the nuclear plant may have a similar form and youthful age, and most probably this lake is a crater filled with water. Larger craters of this type are found near the southern foot of Ararat Volcano.

Jrbashyan et al. (1995) determined the upper age limit (post-date) of the Shamiram Plateau volcanoes from artifacts and ancient structures found on the Karmratar, Armavir, and Oshakan volcanoes and dated as Bronze Age (4000 yr BP).

These age relations suggest that the latest manifestations of volcanic activity in the region of the ANPP could, possibly, have taken place on Aragats Volcano and the Shamiram Plateau in the period from the end of the Late Pleistocene (the lower date) to 4000 yr BP (the upper date), and on Ararat Volcano the latest activity can be related to the interval between 4500–4400 yr BP (the lower date) and 2700–2500 BC (the upper date), as well as to 1840 AD (Table 2).

6. Conclusions

The data presented here point to many cases of historical volcanic activity in Armenia and adjacent areas of the Arabian plate collision. The new evidence accumulated for the Sunik, Vardenis, and Ghegam ridges implies high levels of volcanic hazards in these areas. The main concern is Ghegam Ridge and Ararat, which have the highest potential of volcanic hazard in Armenia.

Holocene volcanoes of the Ghegam Ridge are 52 km from the ANPP, and their Late Pleistocene valley flow terminates 25 km east of the plant site.

The last volcanic eruptions on the Ghegam Ridge occurred between 4500–4400 and 2090 ± 70 yr BP.

Volcanic eruptions on Ararat took place at distances of 27 and 54 km from the nuclear plant in 4500–4400 yr BP, and 1840 AD, respectively.

The most recent activity of Aragats Volcano and volcanoes of the Shamiram Plateau probably occurred in the Late Pleistocene. However, data available on this problem are controversial and incomplete, and final determination of the age of the latest volcanic activity will need additional studies.

Structural control of the volcanism in the region and the interplay between tectonics and volcanism are important issues requiring further investigation. The events during the 1840 earthquake, like many others in Armenia and Turkey, emphasize the possibility of diverse natural hazards (volcanic eruptions, debris flows, river migrations and floods) during strong earthquakes. Alone, each of the listed hazards may not reach an extremely hazardous level for the population, but taken together they can cause disaster.

According to the GPS observations, total rates of recent extension along normal faults controlling the Holocene–historical volcanism in the Ghegam Ridge range from 6.35 to 7 mm/yr. In the Javakh volcanic ridge, extension rates of 1.25 mm/yr were estimated from GPS measurements. These data also suggest a high level of volcanic and seismic hazards for the entire region.

An assessment of the probability of volcanic hazards in the region of the ANPP was conducted during 4 months in 1994 and 1995 with limited resources and was based mainly on the five age estimates by K/Ar method for a few lava flows on Aragats and Shamiram Plateau volcanoes near the nuclear plant. Therefore, this estimate is not complete and a more precise definition should be pursued. New evidence requires revision of the volcanic hazard probability to a higher value than the one established in the study of 1994 and 1995.

Acknowledgements

This research was made possible thanks to the funding under PICS-417, NATO EST.CLG-977044, and INTAS-0840 grants. The authors are grateful to Dr. J. L. Michelot (Laboratory of Hydrology and Isotopic Geochemistry, Paris Sud University) and Dr. L. D. Soulerzhitsky (Geological Institute, Russian Academy of Sciences) for radiocarbon dating of samples. We are also indebted to Dr. Alexander McBirney for his helpful comments and for editing the text of the manuscript, to Dr. Charles Connor (University of South Florida, USA), Dr. Christine Chataigner (Maison de I'Orient Mediterranien, Lyon, France), and Dr. Ruben Badalyan and Dr. Pavel Avetissyan from the Institute of Archaeology and Ethnography of National Academy of Sciences, Yerevan, Armenia, for their inestimable help and contributions to the implementation of this work.

References

Adiyaman, Ö., Chorowisz, J., Köse, O., 1998. Relationships between volcanic patterns and neotectonics in Eastern Anatolia from analysis of satellite images and DEM. J. Volcanol. Geotherm. Res. 85, 18–32.

Amarian, V.M., 1970. Volcanic formations. In: Geology of the Armenian SSR (geologic description), vol. XLIII USSR Geology. The USSR Ministry of Geology, Nedra Publishing House, Moscow, pp. 210–220 (in Russian).

Ambraseys, N.N., Melville, C.P, 1982. A History of Persian Earthquakes. Cambridge Univ. Press, New York, 219 pp.

Arakelian, F.O., Darbinian, S.S., Hakopian, N.A., Mnatsakanian, V.L., Mikaelian, A.N., Poghossian, O.K., 1989. Macroseismic investigation of power plants and instrumental records of the Spitak-88 earthquake. Proceedings of the International Seminar on Spitak-88 Earthquake, Yerevan, May 23–26, pp. 447–451.

Armenie, Tresors de l'Armenie Ancienne (des Origines au IVe Siecle), 1996. Sous la direcion de Jacques Santrot, Paris, 288 pp.

Aslanian, A., Asatrian, A., 1950. Stratigraphy and tectonics of the western part of the Hoktemberian Region, Armenian SSR. Institute of Geological Sciences of the Armenian SSR Academy of Sciences, Yerevan, p. 37 (in Russian).

Azizbekian, O.G., 1993. Study and analysis of data on the geological structure, newest volcanism and tectonics of the Vorotan River basin, Special report of the Geological Survey of Armenia, 83 pp. (in Russian).

Badalian, R., Bigazzi, G., Cauvin, M.-C., Chataigner, C., Jrbashyan, R., Karapetyan, S., Oddone, M., Poidevin, J.-L., 2000. An international research project on Armenian archaeological sites: fission-track dating of obsidians. Radiation Measurements, vol. 34. Elsevier Science, pp. 373–378.

Balian, S.P., 1969. Structural Geomorphology of the Armenian Upland and Surrounding Areas. Publishing House of the Yerevan University, Yerevan, 389 pp. (in Russian).

Barka, A., Kadinsky-Cade, K., 1988. Strike-slip fault geometry in Turkey and its influence on earthquake activity. Tectonics, 3, 663–684.

Berberian, M., 1976. Contribution to the seismotectonics of Iran. Part II, GSI, Rep. 39, 516 p.

Berberian, M., 1994. Natural hazards and the first catalogue of Iran. Historical hazards in Iran prior to 1900. International Institute of Earthquake Engineering and Seismology, 1, 603 pp.

Berberian, M., 1997. Seismic sources of the Transcaucasian historical earthquakes. In: Historical and Prehistorical Earthquakes in the Caucasus. Kluwer Acad. Publ., pp. 233–311.

Boubnov, S., Chernishev, I., Lebedev, V., Arakeliants, M., Holtzman, Yu., 2000. The K-Ar geochronology of the most recent volcanic centers of the Greater Caucasus. In: Isotope Dating of Geologic Processes: New Methods and Results, Proc. of the 1st Russian Conference on Isotope Geochronology, November 2000. GEOS, Moscow, pp. 76–78 (in Russian).

Bogatikov, O., Melekestsev, I., Gourbanov, A., Soulerzhitsky, L., 2001. Catastrophic Pleistocene and Holocene activity of the Elbrous volcanic center, Northern Caucasus, Russia: events and chronology by ^{14}C, EPR and K-Ar dating. Volcanol. Seismol. 2, 15–23.

Chernishev, I., Lebedev, V., Arakeliants, M., Doudaoury, O., Vashakidze, G., 2000. Development of a standard Late Quaternary age sample for K/Ar dating. In: Isotope Dating of Geologic Processes: New Methods and Results, Proc. of the 1st Russian Conference on Isotope Geochronology, November 2000. GEOS, Moscow, pp. 384–386 (in Russian).

Chernishev, I.V., Arakeliants, M.M., Lebedev, V.Y., Boubnov, S.N., Holtsman, Yu.V., 1999. Geochronology of Quaternary volcano eruptions in the Kazbek area of the Greater Caucasus (K-Ar dating data). In: Problems of Geology and Petrology. Publishing House of the Geology Institute of the Georgian Academy of Sciences, Tbilisi, pp. 81–91 (in Russian).

Chernishev, I.V., Lebedev, V.A., Arakeliants, M.M., Jrbashyan, R.T. and Goukassian, Yu.G., 2002. Dokladi Akademii Nauk, Nauka Publishing House, Moscow, 384, 1, pp. 95–102 (in Russian).

Dewey, J.F., Hempton, M.R., Kidd, W.S.F., Saroglu, F., Sengor, A.M.C., 1986. Shortening of continental lithosphere: the neotectonics of Eastern Anatolia - a young collision zone. In: Coward, M.P., Riea, A.C. (Eds.), Collision Tectonics. Geol. Soc. London Spec. Publ. 19, pp. 3–36.

Doerflinger, E., Masson, F., Bayer, R., Avagyan, A., Philip, H., Ritz, J.-F., Daignieres, R., Calais, E., 1999. The present strain-field in the Lesser Caucasus: Setting of a GPS Network in Armenia. Abstracts of the European Union of Geosciences (EUG 99), Strasbourg.

Doerflinger, E., Karakhanian, A., Philip, H., Avagyan, A., Masson, F., Aslanian, R., Bayer, R., Jrbashyan, R., Vernant, P., Davtyan, V., Champollion, C., Hamard, E., Ritz, J.-F., Daignieriers, R., Gerbault, M., Peyret, M., Collar, P., 2003 (in preparation). Fault activity constrained by GPS data in Armenia: the first results.

Doumas, C., 1990. Archaeological observations at Akrotiri related to the volcanic destruction, Thera and the Aegean World III, 3, Chronology. Proc. of the 3rd International Congress, Santorini, Greece. The Thera Foundation, London, pp. 48–50.

Feraud, J., 1994. Les volcans actifs de Turquie: Guide geologique et itineraries d'excursions. Memoire de l'Association Volcanologique Europeenne, ISSN 0982–9601, 2: 140 pp. (in French).

Ghukasyan, Yu.G., 1985. Petrography, mineralogical and geochemical features and history of the formation of the Aragats volcanic complex. Ph.D. Dissertation Abstract, Tbilissi, p. 25.

Ghukasyan, Yu.G., 2003. The Polygenic Volcano of Aragats (Armenia). J. Volcanol. Geotherm. Res. (submitted).

Goushenko, I., 1979. Volcano eruptions in the world: a catalogue. Nauka Publishing House, Moscow, 474 p. (in Russian).

Guidoboni, E., Comastri, A., Triana, G., 1994. Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century. Istituto Nazionale di Geofisica, Rome, 504 pp.

Haroutiunian, R., 2001. About active volcanism and volcanic hazard in Armenia. Abstracts of the Conference in the memory of Simon Achigezyan. Yerevan, 2001, pp. 11–13.

Hill, D.P., Reasenberg, P.A., Michael, A., Arabaz, W.J., Beroza, G., Brumbaugh, D., Brune, J.N., Castro, R., Davis, S., de Polo, D., Ellsworth, W.L., Gomberg, J., Harmsen, S., House, L., Jackson, S.M., Johnston, M.J.S., Jones, L., Keller, R., Malone, S., Munguia, L., Nava, S., Pechmann, J.C., Sanford, A., Simpson, R.W., Smith, R.B., Stark, M., Stickney, M., Vidal, A., Walter, S., Wong, V. and Zollweg, J., 1993. Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake. Science, vol. 260, June 11, 1617–1623.

IAEA/RU-5270, 1995. Review mission to Armenia: Seismic safety (site investigations) of the Armenian NPP (4th follow-up SSRM), Report to the Government of Armenia of May 28-June 2, 1995, under the TC Project ARM/9/002.

Innocenti, F., Mazzuoli, R., Pasquare, G., Serri, C., Villari, L., 1980. Geology of the volcanic area north of Lake Van (Turkey). Geol. Rundsch. 69, 292–322.

Jackson, J., McKenzie, D.P., 1988. The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East. Geophys. J. 93, 45–73.

Jrbashyan, R.T., Ghukasyan, Yu.G., Shirinian, K.G., Sayadian, Yu.V., 1995. Special volcanological investigations in the region of the Armenian NPP. Institute of Geological Sciences of the Armenian National Academy of Sciences, Yerevan, 83 pp. (in Russian).

Jrbashyan, R., Karapetian, S., Bigazzi, G., 2000. New data on the geochronology and geochemistry of the late-collision rhyolite-obsidian dome-shaped volcanoes in Armenia. In: Isotope Dating of Geological Processes: New Methods and Results, Proc. of the 1st Russian Conference on Isotope Geochemistry, Moscow, November 2000. GEOS, Moscow, pp. 128–130 (in Russian).

Karakhanian, A., Trifonov, V.G., Azizbekian, O.G., Hondkarian, D.G., 1997. Relationship of the late Quaternary tectonics and volcanism in the Khonarasar active fault zone, the Armenian Upland. Terra Nova 9, 131–134.

Karakhanian, A.S., Trifonov, G.V., Azizbekyan, O.G., Khondkarian, D.G., 1999. Relationship of Late Quaternary tectonics and volcanism in the Khonarassar zone of active faults (the Armenian Upland). Theoretical and Regional Problems of Geodynamics, issue 515. Nauka, Moscow, pp. 136–152 (in Russian).

Karakhanian, A., Djrbashian, R., Trifonov, V., Philip, H., Arakelian, S., Avagian, A., 2002. Holocene-historical volcanism and active faults as natural risk factor for Armenia and adjacent countries. J. Volcanol. Geotherm. Res. 113, pp. 319–344.

Karakhanian, A., Trifonov, V., Philip, H., Avagyan, A., Hessami, K., Jamali, F., Bayraktutan, S., Bagdassarian, H., Arakelian, S., Davtian, V., 2003. Active faulting and natural hazards in Armenia, eastern Turkey and north-western Iran. Tectonophysics (submitted).

Karapetian, K.I., 1960. Smbatassar Volcano. Izv. Acad. Sci. ArmSSR 13, no. 3-4, 33–45 (in Russian).

Karapetian, K.I., 1973. Volcanoes of the Ghegam Highland. In: Karapetian, K.I., Adamian, A.A. (Eds.), The Most Recent Volcanism in Some Regions of the Armenian SSR. Publishing House of the Armenian SSR Academy of Sciences, Yerevan, pp. 5–62 (in Russian).

Karapetian, K.I., 1983. On the use of archaeological data in stratigraphical description of Quaternary volcanic rocks in the Armenian SSR. In: The Issues of Quaternary Period Geology in Armenia. Publishing House of the Armenian SSR Academy of Sciences, Yerevan, pp. 85–94 (in Russian).

Karapetian, K.I., 1985. Areal volcanism in the Armenian SSR. Final Report of the Institute of Geological Sciences of the Armenian SSR Academy of Sciences, Yerevan, 319 pp. (in Russian).

Karapetian, K.I., Adamian, A.A., 1973. The Most Recent Volcanism of Some Regions of the Armenian SSR. Publishing House of the ArmSSR Academy of Sciences, Yerevan, 162 pp. (in Russian).

Kharazian, E.Kh., 1993. Geologic map of the near-Yerevan region at the scale of 1:25000. Geology Survey of the Republic of Armenia.

Kouftin, B.A., 1944. Urartian columbarium at the foot of Ararat and the Eneolithic of Koura-Arax. Academy of Sciences of the Georgian SSR, Bull. State Museum of Georgia vol. 13-B, Tbilisi, p. 83 (in Russian).

Lebedev, P.I., 1931. The Alaghez Volcano and its lava. In: Alaghez, an Extinct Volcano in the Armenian Upland. Publishing House of the USSR Academy of Sciences, Leningrad, pp. 115–343 (in Russian).

Lichkov, B.V., 1931. On the characteristics of geomorphology and stratigraphy of Alaghez. In: Alaghez, an Extinct Volcano in the Armenian Upland. Publishing House of the USSR Academy of Sciences, Leningrad, pp. 1–115 (in Russian).

McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, K., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoid, S., Mishin, A., Nadaria, M., Ouzounis, A., Paradissis, D., Petetr, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksoz, M.N. and Veis, G., 2000. Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. Journal of Geophysical Research, vol. 105, no. B3, pp. 5695–5719.

Mellaart, James, 1967. Catal Huyuk, a Neolihic Town in Anatolia, Thames & Hudson, London, 176 pp.

Milanovsky, E.E., 1953. Geologic structure and history of formation of the Sevan depression. Thesis. Moscow State University, Moscow 1, 2, 786 pp. (in Russian).

Milanovsky, E.E., 1968. The Most Recent Tectonics of the Caucasus. Nedra Publishing House, Moscow, 480 pp. (in Russian).

Movses Khorenatsi, 1990. History of Armenia, translation from old Armenian and comments by G. Sarkissian. Publishing House Hayastan, Yerevan, 291 pp. (in Armenian).

Paffenholtz, K.N., 1948. Geology of Armenia. State Publishing House of Geologic Literature, the USSR Ministry of Geology, Moscow and Leningrad, 895 pp. (in Russian).

Paffenholtz, K.N., 1952. 1:200000 Scale Geologic Map of the Armenian SSR and Adjacent Areas of the Lesser Caucasus. The USSR Ministry of Geology. Sheet K-38-XXXIII, Sheet K-38-XXXII.

Philip, H., Karakhanian, A., 1999. Tremblements de terre et archeologie. Pour la Science (Scientific American) 261, pp. 36–40 (in French).

Philip, H., Avagyan, A., Karakhanian, A., Ritz, J.-F., Rebai, S., 2001. Estimating slip-rates and recurrence intervals of strong earthquakes along an intra-continental fault: the Pambak-Sevan-Sunik Fault (Armenia). Tectonophysics 343, 205–232.

Reilinger, R., Barka, A., 1997. GPS constraints on fault slip rates in the Arabia-Africa-Eurasia plate collision zone: implications for earthquake recurrence times. In: Giardini, D., Balassanian, S. (Eds.), Historical and Prehistorical Earthquakes in the Caucasus, ILP publication 333, NATO ASI Series 28. Kluwer Academic, Dordrecht, pp. 91–108.

Rittman, A., 1964. Volcanoes and Their Activity. Publishing House Mir, Moscow, 436 pp. (in Russian).

Sapper, K., 1927. Vulkankunde. Verlag J. Engelhorns Nachf., Stuttgart (in German).

Sayadian, Yu.V., Aleshinskaya, Z.V., Khanzadian E.V., 1977. Post-glacial deposits and archaeology of the Lake Sevan coast. In: Geology of the Quaternary Period (Pleistocene), for the 10th INQUA Congress. Publishing House of the

ArmSSR Academy of Sciences, Yerevan, pp. 91–109 (in Russian).
Shirinian, K., 1970. Basaltic andesites and andesites of the Aragats volcanic highland. In: Geology of the Armenian SSR, vol. IV: Petrography and Volcanic Rocks. Publishing House of the Armenian SSR Academy of Sciences, Yerevan, pp. 516–525 (in Russian).
Simkin, T., Siebert, L., Mc Clelland, L., Bridge, D., Newhall, C., Latter, J.H., 1981. Volcanoes of the World. Hutchinson and Ross.
Stepanian, V., 1964. Earthquakes in the Armenian Upland and Adjacent Areas. Publishing House Hayastan, Yerevan, 247 pp. (in Russian).
Taymaz, T., Eyidogan, H., Jackson, J., 1991. Source parameters of large earthquakes in the East-Anatolian fault zone (Turkey). Geophys. J. Int. 106, 537–550.
Tekin Yurur, M. and Chrowicz, J., 1998. Recent volcanism, tectonics and plate kinematics near the junction of the African, Arabian and Anatolian plates in the eastern Mediterranean. Journal of Volcanology and Geothermal Research, 85, 1–4, pp. 10–15.
Tiedeman, H., 1991. Catalogue of Earthquakes and Volcanic Eruptions. Swiss Re, Zurich, 94 pp.
Toprak, V., 1998. Vent distribution and its relation to regional tectonics. Cappadocian Volcanics, Turkey. Journal of Volcanology and Geothermal Research, 85, 1–4, pp. 55–67.
Trifonov, V. and El-Khair, Yu., 1988. A biblical legend through the eyes of geologists. Priroda, 8, Nauka, Moscow, pp. 34–45 (in Russian).
Yilmaz, V., Güner, Y., Saroglu, F., 1998. Geology of the Quaternary volcanic centers of the East Anatolia. J. Volcanol. Geotherm. Res. 85, 173–210.