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Quaternary geology and origin of the Shirak Basin, NW Armenia

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1. Introduction

The area under study belongs to the Armenian part of the Armenian volcanic Highland. Previous investigations (Milanovsky, 1968; Trifonov et al., 2014, 2016; Trifonov, 2016) revealed that mountain systems of the Arabia-Caucasus region as well as other segments of the Alpine-Himalayan Belt rose significantly and rapidly during the Late Miocene and particularly the Pliocene and Quaternary. Intermountain and surrounding basins were partly involved into the uplift and partly subsided within a short period of time (Trifonov et al., 2012a; Trifonov, 2016). The origin of many of these basins was related to the Late Cenozoic fault motions and other manifestations of the collisional plate interaction (Trifonov et al., 2017). At the same time, some basins of the Armenian volcanic Highland do not demonstrate apparent relations to the collisional faulting. Milanovsky (1968) attributed their origin to transformations in deep layers of the lithosphere expressed in volcanism. The present paper is devoted to examination of this hypothesis through the example of the Shirak Basin in NW Armenia. New data on stratigraphy and age of the Shirak Basin Quaternary cover as well as its tectonic deformation and correlation with surrounding volcanism are represented. The origin of the basin is discussed with account of new data.

In the paper we use the stratigraphic division of the Neogene and Quaternary confirmed at the 33rd IGC and the following abbreviations: N_1^3 – Late Miocene, N_2^1 – Early Pliocene, N_2^2 – Late Pliocene, Q_1^1 – Gelasian, Q_1^{1-2}ol – Oldovai subchron, Q_1^2 – Calabrian, Q_2^1 – earliest Middle Pleistocene (≥0.5 Ma), Q_4 – Holocene, a.s.l. – above sea level, DEM – Digital Elevation Model, GPa – gigapascal, H – altitude a.s.l., km – kilometre, IGRF - International Geomagnetic Reference Field, L – layer, Ma – million years, m – metre, mT – millitesla, N – normal magnetic polarity, PC – pollen complex, R – reverse magnetic polarity, SRTM – the Shuttle Radar Topography Mission, s – site, t – temperature. Names of geographic objects used in Armenia before the 1990s are given in square brackets.

2. Regional setting

The Shirak Basin is situated at altitudes between 1500 and 1700 m a.s.l. Most of the basin infill consists of Quaternary terrigenous sediments and volcanic rocks. From north to south the basin is drained by the Akhuryan River which incises into the basin flat surface up to several tens of meters. The average height of the adjacent ridges varies within 2000–2500 m (Figs. 1 and 2). The northern part of the basin is bounded by the western chain of the Bazum Ridge and its southern branch, the Shirak Ridge. These ridges are composed of Paleogene, Cretaceous and Jurassic rocks with fragments of the Meso-Tethys suture, which is considered to be a western continuation of the Sevan-Hakari ophiolite zone (Rolland et al., 2009; Sosson et al., 2010; Adamia et al., 2011). The eastern part of the basin is bounded by the Pambak Ridge, which separates it from the Sevan Basin. The eastern and central parts of the ridge are composed mainly of the Eocene rocks with a large portion of lavas and volcanoclastic sediments (Gabrielyan, 1964; Djrbashyan, 1990). In the vicinity of the town of Spitak and near the Shirak Basin, Cretaceous rocks in southern Tethys facies (Aslanyan, 1958) and Late Cenozoic andesites and basalts are exposed. The southern side of the Shirak Basin does not have a prominent structural

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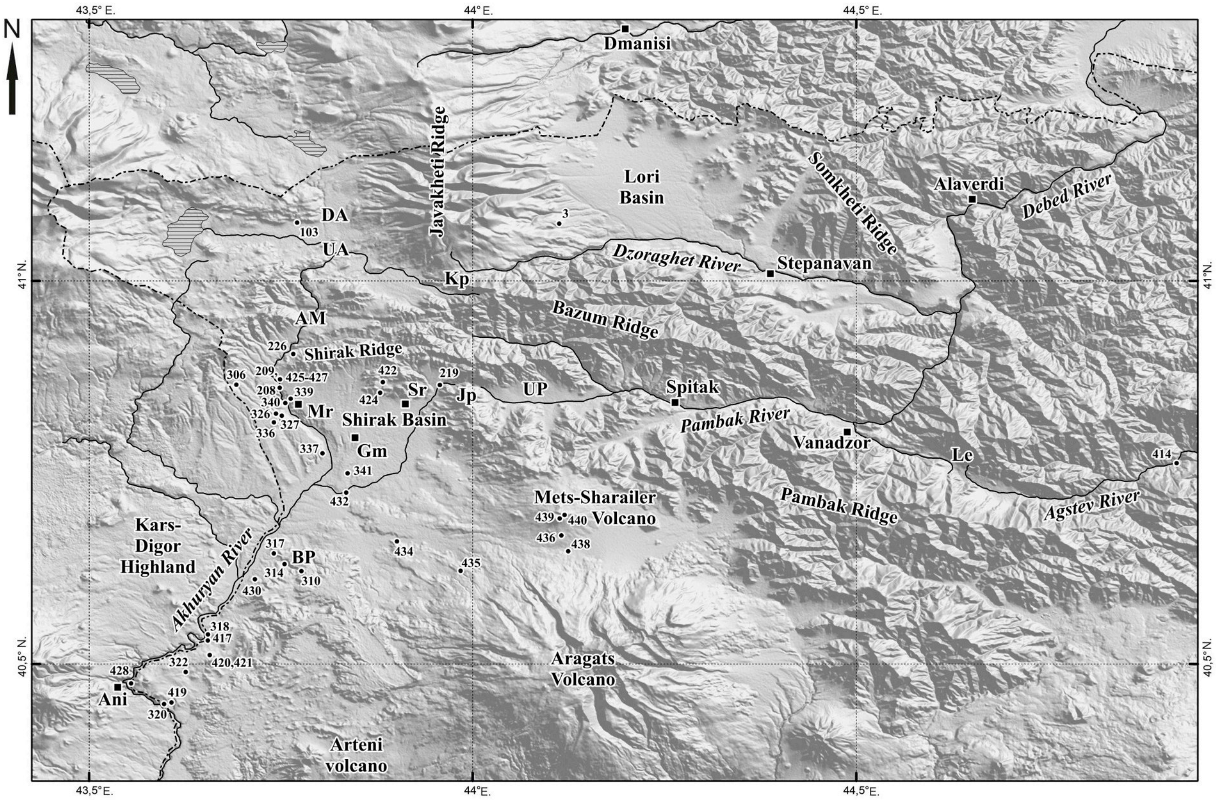

Fig. 1. Topography and drainage system in NW Armenia with sites of observation.
(AL) Arailer Volcano, (AM) Amasya Basin, (BP) Bartsrashen Plateau, (DA) depression of Mada Lake and Dalichay River, (Jp) Jajur Pass, (Kp) Karakhach Pass, (Le) Lermontov Sowneck, (Mr) village of Marmashen, (Sr) village of Shirak, (UA) Upper Akhurian Basin, (UP) Upper Pambak Basin.

boundary. However, it can be marked by the Aragats volcanic center which was active nearly since 1.0 to 0.45 Ma (Chernyshev et al., 2002) and by relics of the older rhyolite-dacite Arteni volcano (Lebedev et al., 2011). The southernmost point of the basin is found near the village of Haykadzor and the medieval city of Ani. Its south-western border is formed by the Upper Miocene and Pliocene volcanic rocks of the Ani area. In the west the basin is bounded by the volcanic Kars-Digor Highland, consisting of the Late Miocene to Pleistocene lavas and tuffs of different composition.

The region underwent intense folding and faulting during the second part of the Eocene and Oligocene. The Lower and Middle Miocene geological formations are almost not exposed in the area, although the Lower Miocene alkaline basalts at the Jajur Pass and the uppermost Oligocene basaltic andesites in the south of the basin are found. We determined their age by K—Ar dating (samples 2014–220, 2016–431/2, 2016–431/3, 2016–431/4 in tables B.1, B.2, and B.3 and s 220 and s 310 in Figs. 1 and 2). Volcanic rocks of the same age are also found on the adjacent Kars-Digor Highland.

3. Methods

A suite of methods was used to study the geology of the Shirak Basin. They are as follows: description of sedimentary sections, geomorphological study, analysis of remanent magnetic polarity, lithological and petrochemical correlation of rocks, K—Ar dating of tuffs and lavas and palaeontological studies.

Geomorphological study included recognition of different topographical levels and definition of their relationships with lithological units, construction of altitudinal profiles across the basin and the adjacent territory, calculation of the fluvial gradients of the Akhuryan river channel. We consider all the altitudinal estimates to be better than 5 m. This accuracy was attained by using the GPS data, the 3 arc-seconds DEM provided by SRTM as well as trig points.

Palaeomagnetic samples were taken as hand blocks and oriented using a magnetic compass. The average interval between the samples was 0.3–0.6 m. In total 197 samples from 11 locations were analyzed. Laboratory studies were performed by A. Latyshev. The local magnetic declination was calculated using the IGRF model. The palaeomagnetic procedures were performed in the Palaeomagnetic laboratory of the IPE RAS. All the samples were subjected to the stepwise alternating fields (AF) demagnetization up to 130 mT with the AF-demagnetizer inbuilt in the 2G Enterprises cryogenic magnetometer. The remanent magnetization of samples was measured using the 2G Enterprises cryogenic magnetometer “Khramov”. The isolation of the natural remanent magnetization (NRM) components was performed with Enkin's (Enkin, 1994) palaeomagnetic software package using principal component analysis (Kirschvink, 1980). The quality of palaeomagnetic signal varies from sample to sample. Nevertheless, about 80% of the studied samples were suitable to isolate the palaeomagnetic directions. In other cases the behavior of NRM vector during the demagnetization is irregular.

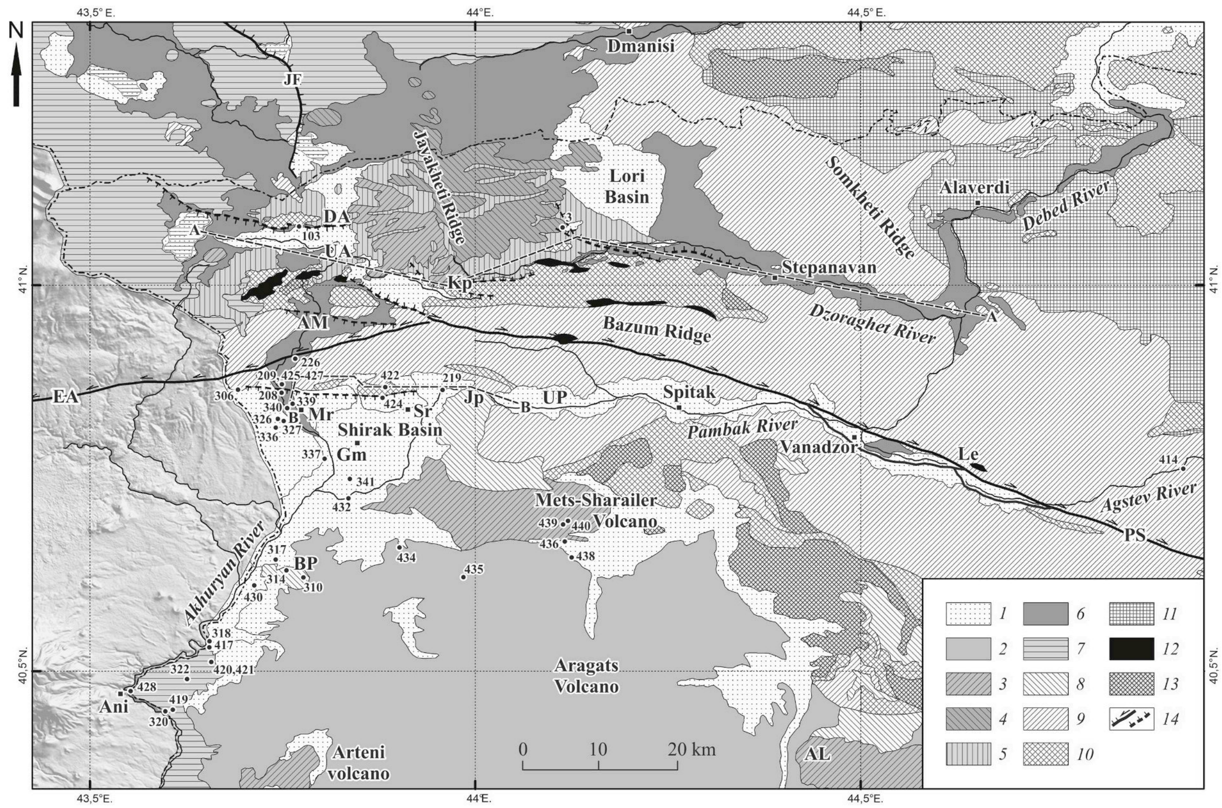

Fig. 2. Geological map of NW Armenia with main sites of observation, after (Nalivkin, 1976; Trifonov et al., 2016) with additions. (1) Quaternary sedimentary deposits; (2) rocks of the Aragats volcano (1.0–0.4 Ma); (3) rocks of the Mets-Sharailer Volcano (~0.9 Ma), the Arailer and Arteni Volcanoes (~1.35–1.0 Ma), and the V unit of andesites and trachiandesites of the Javakheti Ridge (~1.7 Ma); (4) the IV dacite unit of the Javakheti Highland (~1.8–2.0 Ma); (5) the III unit of andesites and trachiandesites of the Javakheti Highland (~1.8–2.0 Ma); (6) basic lavas of the II unit (~2.0–2.5 Ma); (7) the Pliocene I unit of the basic to acid volcanic rocks in the south-western Javakheti Highland and the Messinian and Pliocene volcanic rocks in the Ani area; (8) Upper (probably) Miocene; (9) Paleogene (mainly Eocene); (10) Cretaceous; (11) Jurassic; (12) Mesozoic ophiolits and ultramafic rocks; (13) Paleozoic and Precambrian; (14) faults and flexure-fault zones. (EA) the eastern strand of the East-Anatolian fault zone; (JF) the Javakheti Fault; (PS) the Pambak-Sevan-Syunik fault zone. See other symbols in Fig. 1.

However, in some samples the vectors of NRM are located in the same hemisphere after all demagnetization steps, and we were able to determine the magnetic polarity.

K—Ar dating of 28 samples was performed by V.A. Lebedev in the Isotopic geochemistry and geochronology Laboratory of the IGEM RAS. All the measurements of radiogenic Ar were conducted on the base of MI-1201 IG noble gas mass spectrometer.

Molluscs were found in four sections: Voghji (5 samples), Haykavan (1 sample), Lusaghbyur (3 samples) and Haykadzor (3 samples). In total several thousand shells were collected, most of which were found at Voghji and Haykadzor sections. About 50 shells were collected from both Haykavan and Lusaghbyur sections. In total about 100 kg of sediments were washed and sifted.

The collection of palaeontological material was carried out both by direct selection from the section (large and/or brittle shells and bones were immediately glued at the outcrop and packed to prevent damage during transportation), and by dry sieving and washing through sieves with cell size 0,7 and 0,5 mm. The washed samples were dried up. The remaining concentrate was divided into fractions from which palaeontologically significant material (mollusks, small vertebrate bones, etc.) was selected. Small gastropods were collected by flotation method: after washing the sieve was half-submerged in water, and small, light and undamaged shells floated up. This technique was used to collect material from the Voghji section.

Pollen spectrum was studied from the Voghji and Haykavan sections. In total 26 samples were examined. Samples taken in the Jradzor, Meghrashat, Lusaghbyur and Gyumri Airport outcrops appeared to be with negligible amount of grains or barren. Probe maceration was performed by the method adopted in GIN RAS, which is a modification of the Grischuk's separation method (Grichuk and Zaklinskaya, 1948), namely, the samples were additionally treated by sodium pyrophosphate and hydrofluoric acid. Pollen diagrams were constructed in Tilia 1.5.12 program, which allows to calculate the general spectrum (arborescent pollen + nonarborescent pollen + spores = 100%) and individual components as a portion of the total amount of grains.

Relationships between the basin structure and volcanic activity and the Late Cenozoic fault system caused by the collisional interaction of the lithospheric plates and blocks were studied as well.

Some archaeological finds also contributed to investigation, defining the probable lower time limit on the age of the deposits.

4. Results of the studies

4.1. Geological results

Alluvial and lacustrine sediments as well as volcanic rocks of the Upper Miocene, Pliocene, Gelasian, Calabrian and Middle Pleictocene are recognized within the area under study. The description of the studied sites is given below. K—Ar ages and chemical composition of volcanic rocks is given in Appendix B (Tables B.1, B.2, and B.3). The altitude of the described sections (H) is given for top surfaces.

4.1.1. Upper Miocene, pliocene, and gelasian

The Upper Miocene is represented by the volcanic Goderdzi Formation (~7.5 Ma; Lebedev et al., 2008, 2012) in the western margin of the Javakheti Highland. The Upper Miocene lavas were described also to the east of the Shirak Basin (Karapetian et al., 2001). Several tens of meters thick volcanic-terrigenous breccia is exposed near/on the southern border of the Shirak Basin (s 310). The same rocks of several hundred meters thick were drilled within the basin. The breccia is considered to be an analog of the Voghchaberd Unit with a probable Messinian age (Sayadyan, 2009). Our studies of the breccia in s 310 revealed that its matrix is tuffaceous and hydrothermally reworked. Four K—Ar dates were obtained for the breccia (see table B.1, № 2016–431/1, 431/2, 431/3, 431/4). On account of a large portion of atmospheric ^{40}Ar in the sample 2016–431/1, the obtained age of 1.6 ± 0.7 Ma should be used with caution. The ages of the andesitic fragments (24.4 ± 0.6 Ma – 24.8 ± 0.7 Ma) can be recognized as the lower limit on the age of the breccia.

We subdivide the volcanic sequence near the medieval town of Ani into three parts: the "upper basalt" (UB in Fig. 3), tuff unit, and the "lower basalt" – several flows of weakly alkaline basaltic andesite (LB in Fig. 3). The upper layer of the LB has the K—Ar age of 5.8 ± 0.2 Ma (2016–429/1 in table B.1). Southward of the village of Haykadzor the same basaltic andesites compose a small cone of the Qurtblur [Kurt-tepe] volcano with K—Ar ages of 5.60 ± 0.15 Ma in the cone and at the base (2016–420/1 and 2016–421 in table B.1). In the southern part of the Haykadzor village (s 417) the upper layer of the LB has the age of 4.26 ± 0.12 Ma. Thus, according to K—Ar dating the age of LB varies within 5.8 ± 0.2 Ma – 4.26 ± 0.12 Ma, however, the lower portion of the lavas may be older. According to Chernyshev et al. (2002) the K—Ar age of the UB in the Ani section is 2.5 ± 0.2 Ma. Averaging a series of a repeated K—Ar measurements of the same sample 1/A, V.A. Lebedev obtained more precise age of 2.64 ± 0.10 Ma. The tuff unit between the UB and LB is composed of rhyolitic lithic tuffs and pumice and spreads within the territory of the medieval Ani, Anipemza village, and Ani station (for K—Ar ages and chemical composition see tables B.1, B.2, and B.3).

Sayadyan (2009) represented the drilling data on the fine-grained lacustrine Akchagyl deposits (Upper Pliocene and Gelasian) up to 550 m thick in the northern part of the Shirak Basin and grounded this age on the finds of the Lower Akchagyl fresh water molluscs in the lower part of the unit. This unit is considered to be the earliest evidence of the basin subsidence.

The oldest exposed formation of the northern part of the basin consists of basaltic trachiandesite in the Akhuryan River valley. The lava flows spread to the northern part of the Shirak Basin from the southern slopes of the Javakheti Highland or the Upper Akhuryan Basin. ^{40}Ar/^{39}Ar date from the Amasia Basin (2.09 ± 0.05 Ma; Ritz et al., 2016) and our K—Ar dates from s 208 and s 340 (2.3–2.0 Ma, table B.1) confirm the Gelasian age of lavas. Their thickness reaches 90 m in the Gyumri [Leninakan] borehole (Sayadyan, 2009).

4.1.2. Calabrian and Middle Pleistocene sedimentary sections

The stratigraphically higher part of the Shirak Basin section is composed of terrigenous and tuffaceous deposits. Sayadyan (1972, 2009) described a coarse-grained formation along the northern border of the basin and supposed that it could belong to the Calabrian. Within

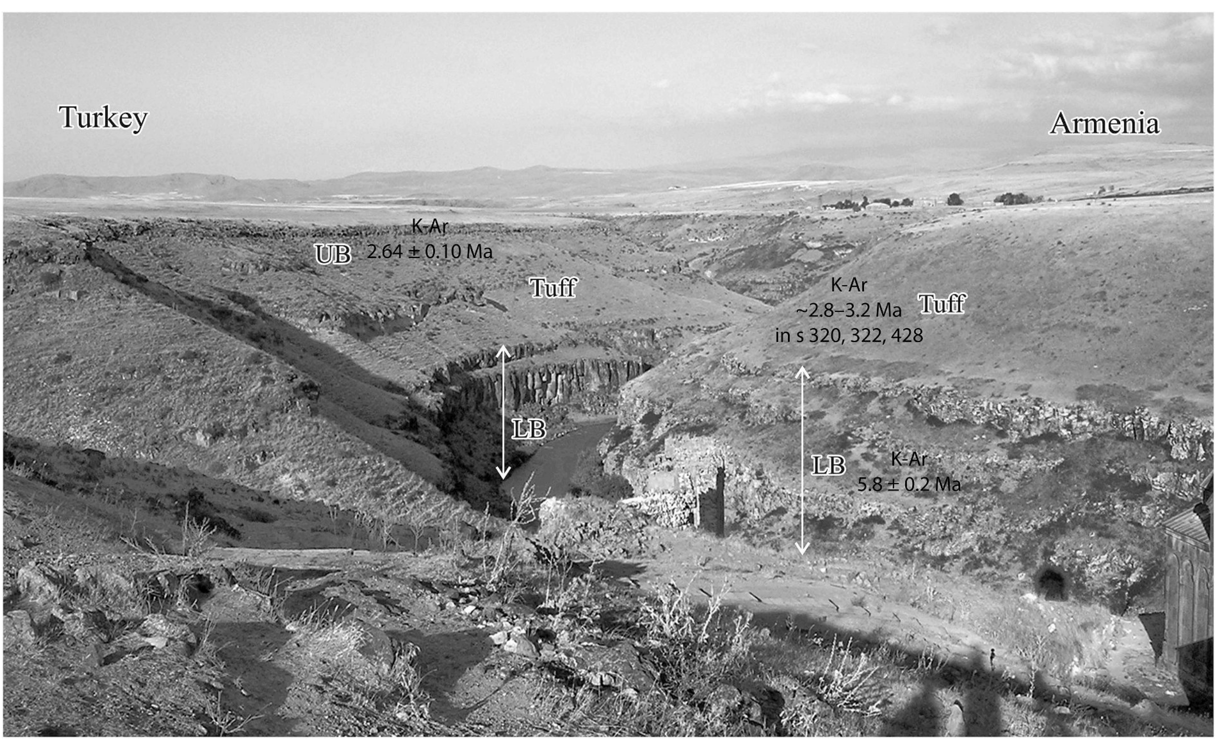

Fig. 3. Akhuryan River valley near the medieval town of Ani. Thickness of the acid tuff layer between the Upper basaltic trachandesite (UB) and the Lower basic lavas (LB) increases to the east in the Armenian territory. Photo by V.A. Lebedev.

the lacustrine formation he distinguished the lower and the upper units and named them Ani and Arapi, respectively. Basing on palaeontological finds, Sayadyan dated the Ani unit as of the lower Middle Pleistocene and the Arapi unit as of the middle Middle Pleistocene. He correlated the Leninakan assemblage of large mammals found in the Arapi unit with the Singil fauna of the Lower Volga River region. We subdivide the Calabrian and Middle Pleistocene deposits of the Shirak Basin into the Karakhach, Ani and Arapi units. All the outcrops are described from top downwards (for a better comparison with drill core descriptions). Altitudes are given for the section top surfaces. GPS coordinates for the sites are given in Appendix B (Table B.4).

4.1.2.1. Karakhach unit. The Karakhach unit is exposed only within the northern rim of the basin. The most complete outcrop was found to the south of the village of Jradzor (Fig. 1, s 226, 227; Fig. 4, s 226). Another outcrop was studied to the north-east of the village of Meghrashat

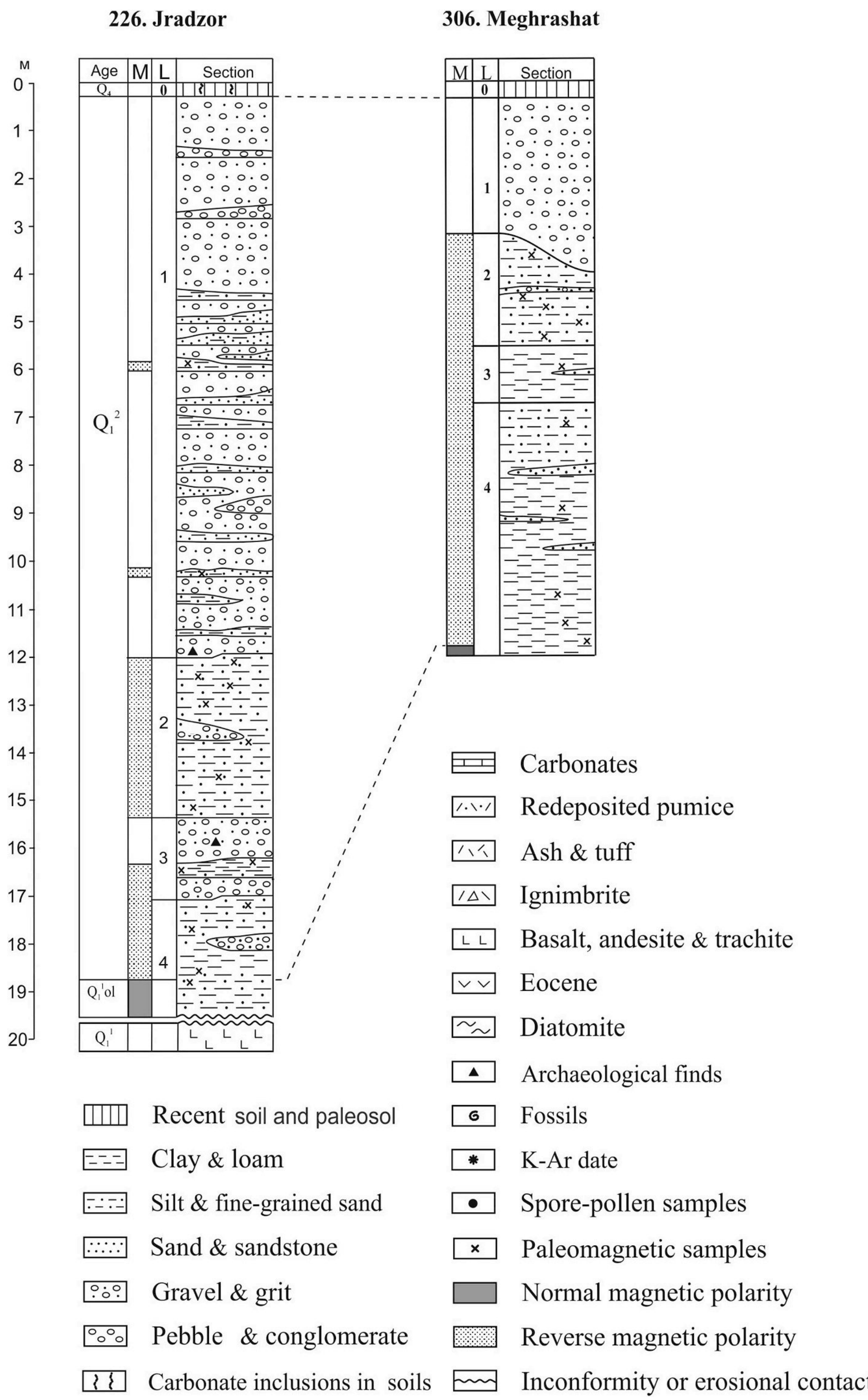

Fig. 4. Stratigraphic sections of the Karakhach unit. Position of the sections is shown in Fig. 1 and 2. (L) number of layer, (M) magnetic polarity.

(Fig. 4, s 306).

In *s 226* (H = 1770 m), 1-m trachyte welded tuff (ignimbrite), the so-called Leninakan tuff, with N polarity covers fluvial conglomerates of 11–12 m thick with lenses of sand and silt with R polarity. Most of the underlying silts (L 2–4) also demonstrated R polarity, whereas sediments at the base of the outcrop showed N polarity (in total 14 samples were taken).

Sediments in s 226 and s 227 dip with a few degrees to the west. Gelasian basaltic trachiandesites are exposed 10–15 m below the Karakhach unit in s 226.

The *s 306* section (H = 1750 m) is represented by the alluvial coarse-grained sediments in the upper part. Small pebbles consist primarily of basalts and andesites as well as rhyolites, jasper, and radiolarites in minor amounts. Underlying lacustrine sediments (L 2–4) with horizontal bedding are constituted by silt and fine-grained sand in the upper part, and clay and loam in the lower part. Except the lowermost portion with N polarity practically all the sediments have R polarity (in total 11 samples were taken).

The thickness of the Karakhach unit is estimated up to 20 m.

4.1.2.2. Ani unit. The stratotype of the Ani unit was described in the borehole 6 near the village of Marmashen (Zaikina et al., 1969a) (Fig. 5). The top of the borehole was at 1630–1640 m a.s.l., the bottom – at 1480–1490 m a.s.l. For the purpose of our study the most essential is that the alluvial layer 8 can possibly belong to the Karakhach unit. At *s 340 (*Fig. 1; H = 1514 m), sediments similar to borehole layers 4 and 7 are exposed. They rest above basaltic trachyandesite in the Akhuryan River channel with K—Ar age of 2.25 ± 0.10 Ma (table B.1, 2015–340). Alluvial layer 8 of the borehole 6 is hypsometrically lower than basaltic trachiandesites of *s 340,* at 1480–1490 m a.s.l. against 1515 m a.s.l. Thus, the alluvium possibly belongs to the buried valley incised into the lava surface.

We have described several new outcrops with layers correlatable with those of the borehole 6 and thus traced them over the area under study (Fig. 5).

The *s 209* section (H = ~1700 m) near the village of Kaps is the smallest outcrop described for the Ani unit. The Leninakan tuff (4 m) covers the 5.4–5.6 m thick alluvial sediments which become finer downwards. The lowermost 0.5 m of the deposits have R polarity and the major part of sediments have N polarity (in total 10 samples were taken). The deposits are underlain by basaltic trachiandesites with K—Ar date 2.1 ± 0.2 Ma (2014–208 in table B.1). Basaltic trachyandesites cover the Eocene porphyrites and deformed fine-grained sandstones.

The thickness of the Ani unit increases to the south within a short distance and reaches 15–20 m near the Leninakan hydro-electric power plant (HPP, s 208; H = 1665 m).

Rocks and sediments of *s 339* (H = 1634 m) constitute a scarp near the Marmashen monastery. They differ from borehole 6 by the increased thickness of the Leninakan tuff (20–25 m) and the presence of redeposited pumice (25–30 m) of sand and gravel size under it (the same pumice forms a landslide on the opposite bank of the Akhurian River). Olive-coloured clays are similar to borehole layers 4, 5, 7 but their thickness is nearly twice lower than in the borehole, 65 m against 114 m. The lowest part of the scarp is covered with talus and monastery cultural sediments and thus has no access. The Gelasian basaltic trachyandesites up to 2 m thick are exposed in the Akhuryan River channel directly below the monastery.

Like previous sites, the *s 326* section (H = 1610 m) near the Voghji [Okhchogli] village starts from the dark-grey Leninakan tuff (L 1). Below the tuff, alluvial coarse-to fine-grained sediments are exposed with intrastratal deformations, possibly seismites, at the middle part of the layer. Sands are enriched with shell fragments (L 2). The rest 47 m are represented by massive clays brown-grey or olive-green with a 4 m interbed of diatomite (L 6) or thinner interbeds of diatomic clays (L 3, 5, 8, 9) and rare interbeds of fine-grained tuffaceous sandstone. Some interbeds are enriched with freshwater shell fragments (L 3, 4, 5, 8) or well-preserved mollusc shells (L 6). Diatomite of L 6 has intense intrastratal deformations (seismites) (Fig. 6). Regarding the results of palaeomagnetic sampling of clays 4 alternating intervals of N and R polarity are clearly distinguished (in total 52 samples were taken).

The *s 336* section (H = ~1600 m) near the Haykavan village has the following structure. The dark-grey Leninakan tuff covers a sequence of alluvial sediments with lacustrine sediments at the base of the outcrop. Alluvial sediments in L 2–5 are represented by alternating layers of loam, sandy loam or silts (probably flood plain deposits) and pebble or gravel beds. The upper parts of the fine-grained sediments are altered by the processes of pedogenesis. Shell fragments are found in sand lenses of L 5. L 6 and L 7 are represented by clays brown or olive-green and are subdivided on the basis of different polarity – primarily R polarity for L 6, N polarity for L 7. An interbed of volcanic ash (5–7 cm) is found in L 7. L 8–10 are represented by pebble, gravel, and sands (the material becomes finer downwards) with horizontal or cross bedding. At the very bottom lacustrine clays of light-brown, bluish-grey, olive-green, brownish-grey colours with a thin interbed of volcanic ash are found. Shell fragments are concentrated in lenses and interbeds up to 5 cm thick. Rare and very-well preserved bone fragments of large mammals are found. In total 38 samples for palaeomagnetic studies were taken in the fine-grained sediments.

Like the Karakhach unit sites, all the Ani unit sites demonstrate the presence of the alluvial sediments in the upper parts and lacustrine sediments below the alluvium. The key issue is that these sites differ in proportions between alluvial and lacustrine sediments and, thus, may represent different parts of the same lake, which once existed in the area.

4.1.2.3. Arapi unit. The type section of the Arapi unit is exposed near the village of Arapi above the Akhuryan River (40º46.443′N, 43º48.369′E). The unit composes a terrace with top surface at 1550 m a.s.l. The water edge below the village is 1475 m a.s.l. Thus, the total apparent thickness of the unit is not more than 75 m. Agadjanyan and Melik-Adamyan (1985) described the unit as shown on Fig. 7, s 337. We described several new sections of the unit (Fig. 7).

The *s 336a* section near the village of Haykavan is represented primarily by sediments of lacustrine origin, namely, alternating brownish-grey silts and fine-grained well-sorted sands with seismits in L 3, and silt and brown loam with a volcanic ash interbed (L 4) at the base of the outcrop. Most of the palaeomganetic samples showed N polarity (in total 15 samples were taken).

The *s 341* section (H = 1516 m) described in a quarry near the Gyumri Airport is composed of alluvial sediments solely and is covered with the Leninakan tuff and some loam and recent soil at the top. It is represented by an alternation of layers of coarse-grained cross-bedded and fine-grained sediments with nearly equal thicknesses. The upper parts of fine-grained sediments are altered by the processes of pedogenesis. Seismites in the upper part of L 6 are clearly distinguished (Fig. 6). The origin of the greenish-grey clays at the base is not clear as only a top part of the layer is exposed. It could be either lacustrine or alluvial (flood plain). Most of the palaeomagnetic samples showed N polarity (in total 7 samples were taken).

Another quarry was studied by Melik-Adamyan (1994) near the Gyumri Airport, 2.5 km to the south-east of the city center (H = 1520 m). Its lithology is similar to s 341 as well as similar rodent fauna was found in sands 1–1.5 m above and beneath the tuff. Identical rodent fauna was found in the southern part of Gyumri (Kazachiy Post section) at the depth of 8 m below the surface (Agadjanyan and Melik-Adamyan, 1985). The fauna was buried within a 4.5 m thick clay layer covered with gravels and sands (4–5 m) and the Leninakan tuff.

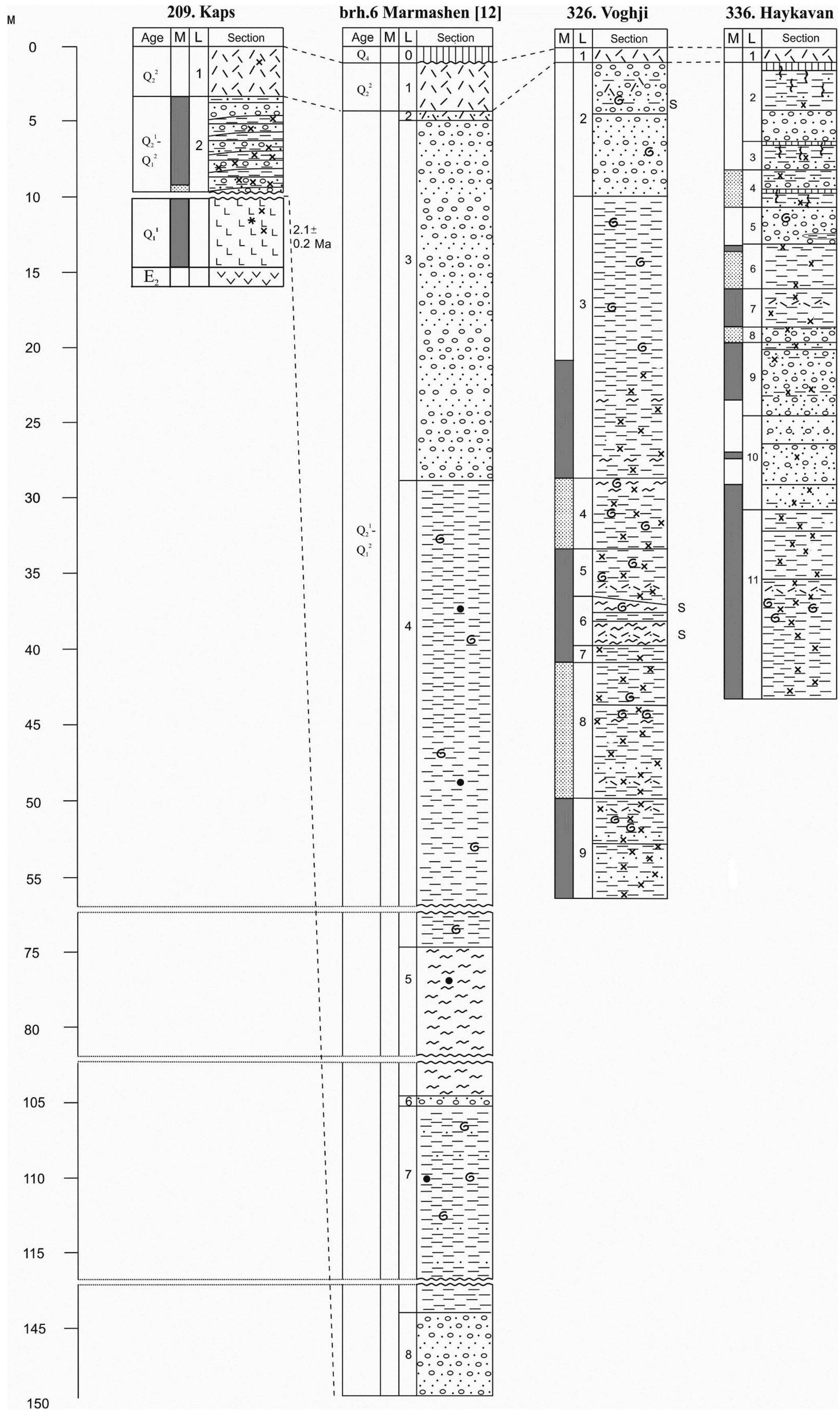

Fig. 5. Stratigraphic sections of the Ani unit. See Fig. 4 for symbols. Position of sections is shown in Fig. 1 and 2.

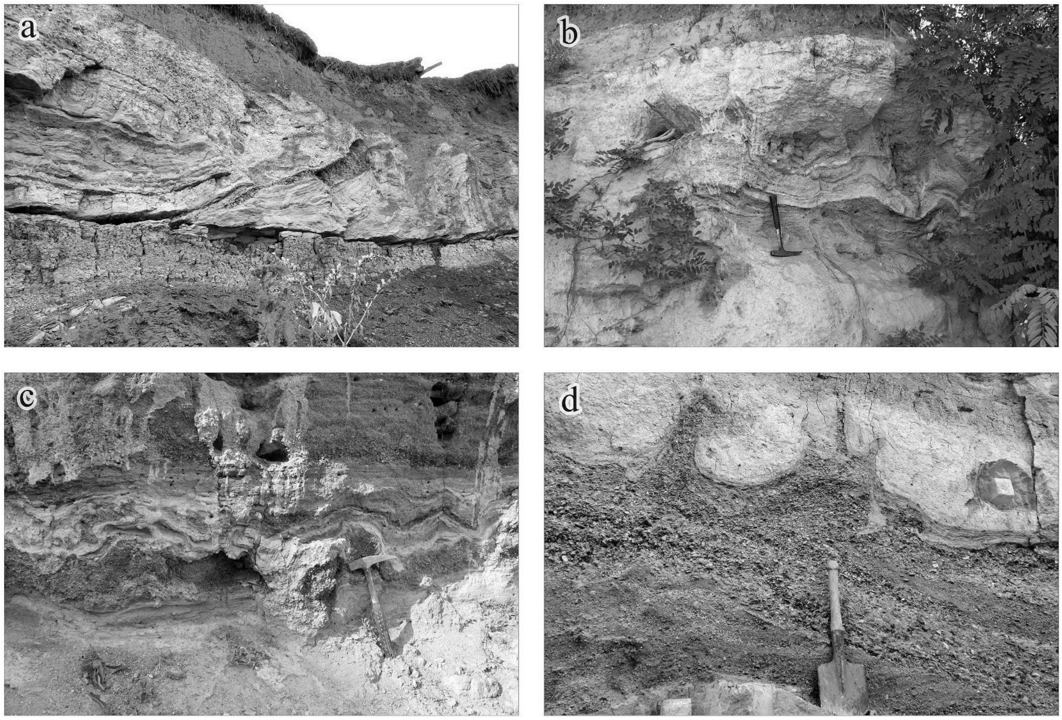

Fig. 6. Intrastratal deformation probably of seismic origin (seismites): (a) site 326, layer 6 (upper); (b) site 326, layer 6 (lower); (c) site 336; (d) site 341. Position of sites is given in Fig. 1 and 2. Photos by E.A. Shalaeva and V.G. Trifonov.

The *s 219* section (H = 1706 m), the second terrace of the Jajur River near the eponymous village is composed of 2.5 m thick gravels and sands with a carbonated paleosol horizon in the upper part and more than 8 m of loam and silts with horizontal bedding and N magnetic polarity in the lower part.

The *s 438* section (H = 2042 m) in front of the northern slope of the Aragats volcano near the village of Hnaberd is composed primarily of alternating horizontally bedded sands, gravel and poorly to well-rounded pebbles with thin interbeds of ash and caliche beneath recent soil. Pebbles consist mostly of andesite and dacite.

The *s 317* (H = 1513 m) Lusaghbyur section exhibits lacustrine sediments covered with the Leninakan tuff with the K–Ar age of 0.70 ± 0.03 Ma (2015–317/u in table B.1). Light-brown-grey clay, light-brown diatomite and greenish-grey clayish diatomite with admixture of volcanic glass (ash) and an interbed of volcanic ash alternate successively from top down. 16 samples for palaeomagnetic study were taken.

The *s 314* section (H = 1495 m) on the terrace of the Magaridzor stream, 2 m thick boulder and pebble layer covers a 4 m light-brownish-grey lacustrine fine-grained sand and clayish silt layer. They are carbonated in the upper part and form sandy travertine. The section covers probably the carbonated weathered surface of the Voghchaberd unit exposed further east (s 310).

The *s 318* (H = 1489 m) Haykadzor outcrop on the left bank of the Akhuryan River is composed of lacustrine sediments and is likely to be the richest in shell fragments and remains of small mammals among all other sites of the unit. Lithologically from top down it is composed of travertine, fine-grained well-sorted sands, silts and clayish diatomites. The section bottom is nearly 5 m higher than the Lower Pliocene basaltic trachiandesite surface. 20 samples for palaeomganetic study were taken.

Palaeomagnetic samples of all the sites showed the predominance of N polarity (see Fig. 7).

The above set of observations let us to deduce that the thicker lower part of the Arapi sections has lacustrine origin and the upper part is alluvial in the northern part of the Shirak Basin. The Lusaghbyur and Haykadzor sections in the southern part of the basin are composed only of lacustrine sediments. The alluvial deposits constituting the upper part of the s 314 section represent the south-eastern margin of the sedimentary basin.

4.1.3. Geomorphological features and tectonic deformation

The area of distribution of the Quaternary units described above corresponds to different topographical levels, which form terraces of the Akhuryan River and its tributaries (Fig. 8). These levels decrease in their altitude from north to south. The highest and the northernmost one corresponds to the Karakhach unit surface (s 226, s 227 and s 306) and shows the altitudes of 1770–1750 m. The intermediate level corresponds to the Arapi unit. Its altitude is about 1700 m near the Kaps village (s 209) and drops sharply to 1665 m near the Leninakan hydropower plant (HPP, s 208). The thickness of the unit changes from 5–6 m to 15–20 m respectively. Like topography the altitude of the Akhuryan River channel decreases by 100 m within the Jradzor - HPP segment. The greatest thickness of the unit according to the borehole drilling achieves 137–138 m (Marmashen brh. 6). The lower part of the unit is composed of lacustrine sediments and may probably cover coarse Karakach alluvium at the very bottom. If this is the case, the total vertical offset of the Karakhach unit between the villages of Jradzor and Marmashen reaches 260 m. The lowest and the southernmost level corresponds to the Ani unit surface. It is situated at altitudes of about 1550 m near the villages of Haykavan and Arapi, 1520–1500 m in the area of the Gumri city (s 308, s 309 and s 341), 1510–1500 m near the village of Lusaghbyur (s 316, s 317), and 1490 m in Haykadzor (s 318).

The longitudinal profile along the Akhuryan River channel indicates that sediment accumulation and deformation of the Shirak Basin were simultaneous processes.

The fluvial gradient of the Akhuryan River channel within the Jradzor (s 227) - Marmashen Monastery (s 340) segment reaches

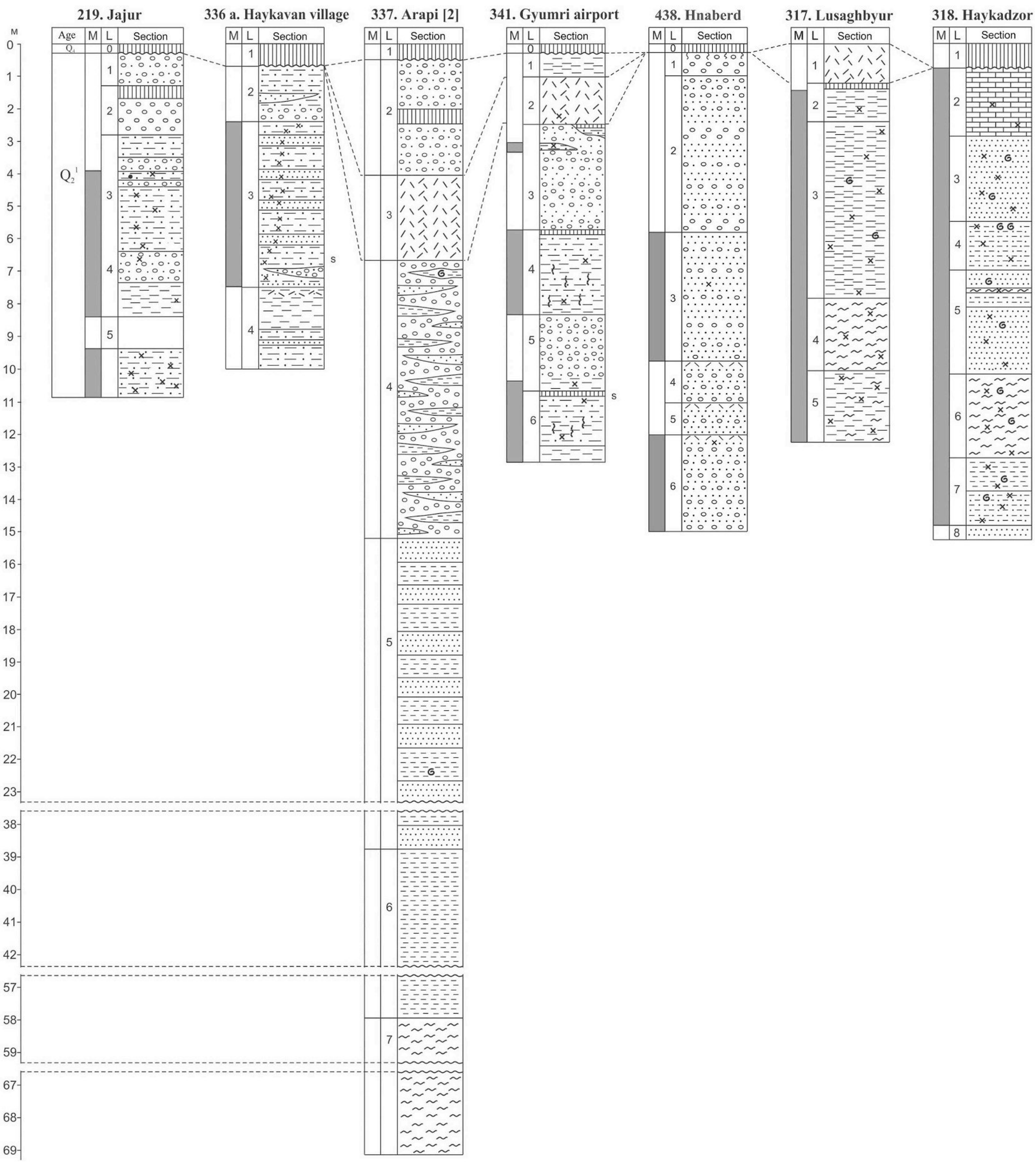

Fig. 7. Stratigraphic sections of the Arapi unit. See Fig. 4 for the symbols. Position of the sections is shown in Fig. 1 and 2.

20.3 m/km. The gradient is particularly high near the Leninakan HPP as the area rests on an intersection of the Akhuryan River channel and the WE trending Late Cenozoic Kaps flexure that stretches along the southern slope of the Shirak Ridge. The flexure probably corresponds to the fault in the underlying rocks and is believed to have been developing at least since the Ani accumulation started. The gradient within a 10 km Marmashen (s 340) - Arapi (s 338) segment equals to 3.9 m/km. It decreases southwards to 3.7 m/km within a 3 km segment and to 1.8 m/km within the next 45 km in the central part of the basin. Within a 9 km segment to the south of the western termination of the Bartsrashen Upland composed of the Voghchaberd unit the gradient increases to 5.3 m/km and then again decreases to 3.9 m/km.

Fig. 8 demonstrates that the surface of the Pliocene – Early Quaternary basaltic trachyandesites also decreases in the north-to-south direction from 1735 to 1740 m within the Jradsor section (north to s 226) and ~1690 m within the Kaps section (s 209) to 1620 m near the Leninakan HPP and 1515 m near the Marmashen Monastery (s 340). Further south the volcanics are not exposed and the Arapi unit constitutes the Akhuryan River banks. To the east of the village of Lusaghbyur, the Arapi unit covers the Voghchaberd unit at the altitude of ~1500 m. The Messinian and Pliocene basaltic trachyandesites spread over the Akhuryan river banks within a 4 km distance to the north of the village of Haykadzor and their surface is situated at ~1470 m in s 318. To the south, near the medieval Ani town, the exposed thickness of lavas reaches several tens of meters. One of the source-volcanoes for the lavas is a Qurtblur volcano (s 421). A layer of the Upper Pliocene rhyolitic tuffs is situated between the uppermost Pliocene and Messinian – Lower Pliocene lavas. The thickness of the tuff increases to the

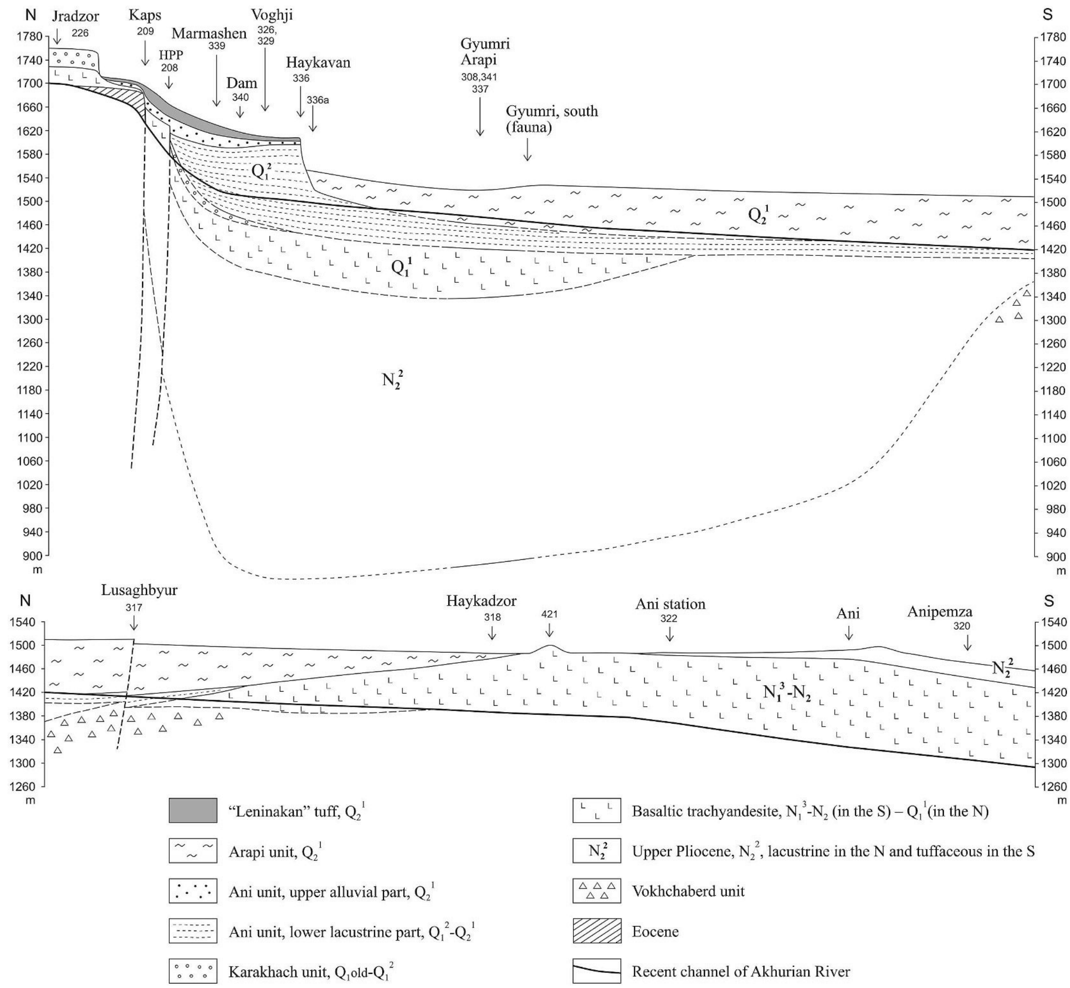

Fig. 8. Longitudinal geological-geomorphological profile along the Akhurian River (the lower section continues the upper to the south).

east and south-east of the medieval Ani town and one of the centers of the tuff eruption is identified to the east of s 428.

The Arapi unit is ruptured in the Lusaghbyur (s 317) outcrop by a thrust tilted ~50° to the north. A clay micro-diapir intrudes along the fault zone and exposes molluscs of the Ani unit composing the buried part of the section.

The altitudinal profile along the southern slope of the Shirak Ridge from the Akhuryan valley in the west to the Upper Pambak Basin in the east demonstrates large zone of deformation (Fig. 9; B—B in Fig. 2). As it is written above the top surface of the Karakhach unit is situated at altitudes between 1750 and 1770 m a.s.l. (s 306, s 226 and 227) and the top surface of the Gelasian lavas is at altitudes between 1735 and 1740 m a.s.l. (s 226). This geomorphological level maintains approximately the same elevation along the southern slope of the Shirak Ridge and sharply increases at the Jajur Pass, where the top surface of the well-rounded pebbles has the altitude of 1955 m. The level sharply decreases to the east, to the Pambak riverhead (UP in Fig. 2), where the surface of the alluvium is not higher than 1730 m and it keeps decreasing further along the Pambak River. The base of the pebble alluvium is not exposed.

Slightly eastwards, pebbles cover Cretaceous deposits and lean against the Early Miocene alkaline basalt, which composes the pass (Jp in Figs. 1, 2 and 220 in tables B.1, B.2, and B.3). Milanovsky (1962) interpreted the presence of the pebbles as deposits of a paleo-valley, which connected the northern part of the Shirak Basin and the Pambak paleo-valley. We consider the pebbles belong to the Karakhach unit. This alluvium proves the uplift of the Jajur Pass by ~200 m relative to the northern border of the Shirak Basin that happened after accumulation of the Karakhach unit.

The similar uplift of the Karakhach Pass (Kp in Figs. 1 and 2) between the Lori Basin in the east and the Upper Akhuryan Basin in the west (A–A in Fig. 2) is recognized (Trifonov et al., 2016). The zone of deformation between the Jajur and Karakhach passes is expressed in sharp lowering of the Bazum Ridge from the west to the east. The chain of the Early Pleistocene volcanoes stretches along the uplifted Javakheti Ridge. Milanovsky (1968) named this NS trending zone of deformation and volcanism as the Trans-Caucasus transverse uplift. Mets-Sharailer and Aragats volcanos belong to its southern continuation. The Aragats volcano is considered to be active since ~1 Ma to ~0.45 Ma (Chernyshev et al., 2002; Meliksetian, 2012). Basaltic andesite lavas are spread to the west, their western front is exposed 10 km to the south of the Gyumri city. K—Ar ages of tephra from the cone, basaltic andesites from the northeastern part of the caldera and lava flow (s 439, 440, and 432 in Figs. 1 and 2 and tables B.1, B.2, and B.3) are about 0.9 Ma. The basement of this volcanic formation is represented by an andesite with the K—Ar age of 5.2 ± 0.2 Ma.

4.2. Palaeontological results

Detailed data on mollusc, fish, and rodent fauna from the Ani and Arapi units of the Shirak Basin will be published in a separate paper by A. Tesakov, P. Frolov et al. In this paper, we sum up the main

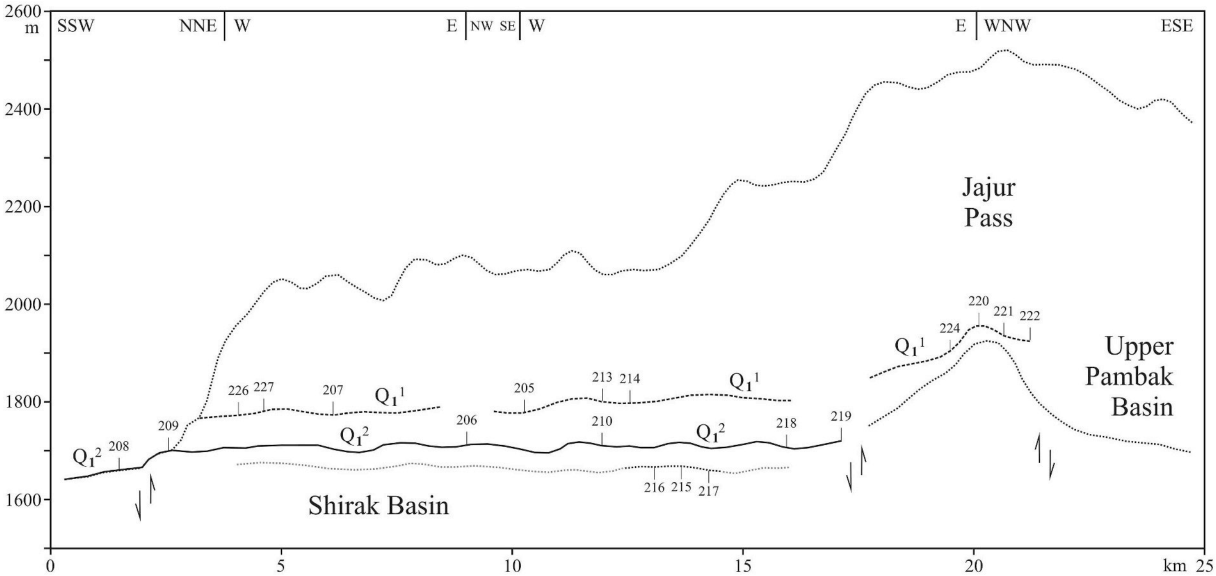

Fig. 9. WE trending geomorphological profile along the southern slope of the Shirak Ridge from the Akhuryan River valley up to the Upper Pambak Basin (line B–B in Fig. 2).

conclusions related to the age and environment of accumulation of these units.

4.2.1. Malacofauna, ichthyofauna, small mammal fauna

The freshwater *gastropods and bivalve molluscs* were found in the Ani and Arapi units. The Ani unit is characterized by numerous molluscs from different layers of the sections 326 (Voghji) and 336 (Haykavan). Records of the Ani assemblage in the clay diapir of s 317 (Lusaghbyur) prove the presence of the Ani deposits below the Arapi sediments in the section of Lusaghbyur. The Arapi unit is characterized by numerous molluscs from different layers of the section 318 (Haykadzor) and few finds in layer 3 of s 317. The malacofauna from the Arapi unit is represented only by recent lacustrine species and can hardly be older than the Middle Pleistocene. The association of malacofauna from the Voghji section, which has similar features with molluscs of the other sections of the Ani unit, is represented mainly by extinct freshwater species. Only *Valvata* cf. *piscinalis* (Müller, 1774) and some species of bivalve molluscs of the Euglesidae family are still present. This points to an older age of the Voghji fauna which perhaps ranges from the Calabrian through the lowest Middle Pleistocene.

Fish remains were found in s 317 (Lusaghbyur, layers 2 and 3) and s 318 (Haykadzor, layer 4) sections. This assemblage contains lacustrine-fluvial association of Cypriniformes with dominant remains of *Capoeta* and representatives of the subfamily Leuciscinae (*Leuciscus*, *Alburnus*).

Numerous *small mammal* remains (mostly teeth of arvicoline rodents) were found in layer 4 of s 318 (Haykadzor). This fauna is dated to the time interval between 0.78 and 0.6 Ma based on stage of evolution of the water vole *Mimomys intermedius* (Newton, 1889) and the presence of primitive *Microtus* (*Terricola*) sp. The fauna cannot be younger than 0.6 Ma, the time, when *M. intermedius* is replaced in Europe and western Asia by its evolutionary successor, the water vole *Arvicola*.

Melik-Adamyan (1994, 2004; Agadjanyan and Melik-Adamyan, 1985) gave a similar age estimation based on small mammal fauna of Arapi 1 and 2, Kazachii post in the Gyumri city, Gyumri airport, and Bayandur (11 km to the south of Gyumri.) He correlated the found rodent fauna with the Tiraspol faunal complex of the East European biochronological system and dated the studied assemblages to the early Middle Pleistocene. Melik-Adamyan (2004) revised the older identifications based on the large mammal fauna from the upper Arapi unit in the Gyumri city (Avakyan, 1959; Avakyan and Alekseeva, 1966; Alekseeva, 1977; Vangengeim, 1980) and concluded that they did not contradict to the Arapi unit age estimates based on small mammals.

This conclusion conforms to the observations in the Arapi unit section (s 430) southward of the village of Lusaghbyur, where loess-like loam and fine-grained sands (3 m), and thin-bedded silts and fine-grained sands with lenses of coarse sand, gravel and well-rounded pebbles (4 m) below are exposed. The lower layer contains obsidian pebbles. In talus just near the lower layer, a lower tooth of *Equus* sp. was found. According to the opinion of I.V. Foronova from the Institute of Geology and Mineralogy of the Siberian Branch of the Russian Academy of Sciences in Novosibirsk (personal communication), the morphology of the tooth shows that the horse belongs to the late forms of the stenonid lineage and its age can correspond to the late Calabrian through early Middle Pleistocene.

4.2.2. Palynological data

In total 26 samples from the Voghji (s 326) and Haykavan (s 336) sections of the Ani unit were examined by A.N. Simakova. Pollen diagrams are given in Appendix A (Fig. A.1 and A.2). The spectra of Voghji (s 326) and Haykavan (s 336) sections of the Ani unit falls into several pollen complexes.

Four PC were identified in the Voghji section (Fig. A.1). PC-1 from layer 9 and PC-2 from layer 8 characterize the lower clay part of the section. The spectra contain up to 70% of herb pollen. Trees are represented in PC-1 by the pollen of *Pinus, Picea, Tsuga canadensis*, and single grains of *Pterocarya* and *Betula*. The pollen of Chenopodiaceae, Poaceae, and Asteraceae dominate in the herb group. Such spectra indicate the predominance of forest-steppe coenoses and relatively cool and dry climate.

Pollen of Chenopodiaceae, Asteraceae, and *Ephedra* is present in greater amount in PC-2 spectra. There is pollen of different conifers: *Taxodium, Podocarpus, Tsuga canadensis, T. sieboldii, T. aculeata, T. diversifolia, Abies, Picea, Pinus*, and broad-leaved trees: *Acer, Castenea, Carya,* Juglandaceae, Moraceae, *Carpinus,* Fagaceae, *Tilia, Ulmus, Liquidambar, Myrica,* and *Quercus.* Grasses are represented mostly by the pollen of Chenopodiaceae, Asteraceae, and *Ephedra.* This indicates the predominance of forest-steppe vegetation and relatively warm temperate climate. Probably, vertical zonation already existed at that time. *Sciadopites, Podocarpus, Cedrus, Tsuga, Picea* and *Abies* occupied

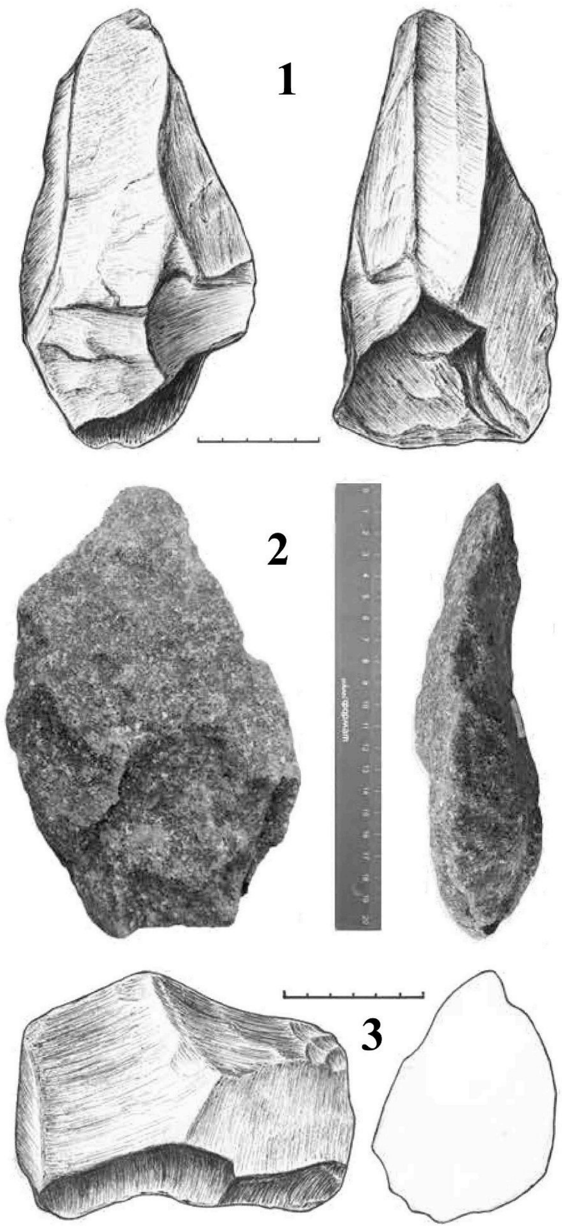

Fig. 10. Lithics from the Karakhach unit (s 226 and s 227) in the Shirak Basin, NW Armenia: (1) pick, (2) primitive handaxe, and (3) chopper. Photos and pictures by E.V. Belyaeva.

highlands. Mixed forests with *Pinus, Acer*, Juglandaceae, *Castanea, Liquidambar*, *Quercus, Carpinus,* and *Ulmus* dominated lower altitudinal belts. Lowlands were covered by meadow-steppe vegetation.

PC-3 and PC-4 belong to layer 3. The pollen of *Pinus* is more numerous and the pollen of *Carya, Pterocarya,* and *Liquidambar* are absent in PC-3. The trees are represented by the pollen of *Castanea, Betula, Ulmus,* and *Quercus.* The quantity of the pollen of Chenopodiaceae and *Ephedra* decreases. It was a time of widening of areas of conifer (*Pinus* and *Picea-Tsuga*) forests and more humid and cool climate than at PC-2 time. PC-4 spectrum is characterized by the increase of content of the herb pollen of Chenopodiaceae and Asteraceae that proves the aridization of climate.

Two PC were distinguished by analyzing samples from the layer 11 of the Haykavan (s 336) section (Fig. A2). PC-1A characterizes the lower olive-green clays and the lower part of middle bluish-grey clays. PC-2A characterizes the upper part of the middle clays and the upper light-brown clays. The upper part of the Haykavan section contains only single grains of herb plants.

The spectra of PC-1A contain 20–50% of the pollen of trees: *Tsuga canadensis, T. sieboldii, T. diversifolia, T. minima, Pinus, Picea,* and single grains of A*bies, Cedrus, Carya, Liquidambar, Carpinus, Tilia,* and *Betula*. The pollen of Chenopodiaceae, Poaceae, and Asteraceae dominate in the herb group. Spores represent *Sphagnum*, Polypodiaceae and *Riccia*. The spectra evidence the predominance of forest-steppe coenoses under temperate climate. The PC-1A is similar with the PC-1 of the Voghji section.

The amount of herb and small-shrub pollen of Chenopodiaceae, Asteraceae and *Ephedra* increases in PC-2A. The amount of *Picea* and *Pinus* as well as species of *Tsuga* decreases. *Cedrus, Abies, Podocarpus* and *Carya* disappeared. The trees are represented by grains of *Ilex*, *Acer*, Moraceae, Fagaceae, *Lonicera, Salix,* and *Quercus.* The spores of freshwater algae *Cosmarium* and *Sphagnum* indicate the presence of marshy areas, which could be formed because of the shallowing of the Shirak lake as a result of aridization or tectonics. The steppe vegetation expanded. The PC-2A spectra are similar to the spectra of PC-2 and PC-4 of the Voghji section and the spectra of Ani unit in the Marmashen borehole at the depths of 30–50 m (Zaikina et al., 1969a,b).

4.2.3. Diatoms

The samples for studies of diatoms were collected from layers 6 and 7 of the Haykadzor section of the Arapi unit (samples 318/1–4) and from diatomaceous clay interbeds of the lower part of the Haykavan section of the Ani unit (samples 336/5 and 336/6). The diatoms were identified by G.V. Kovaleva.

Epithemia sp.*, Cocconeis* sp.*, Navicula* sp.*, Rhopalodia* sp., and *Cymbella* sp. are present in all samples from the Haykadzor (s 318) section. *Cymatopleura solea*, *C. elliptica*, and *Gomphonema* sp. were found in samples from the lower and middle parts of the section, where *Cyclostephanos* sp. and rarely *Cocconeis placentula*, *Melosira* sp., *Pinnularia* sp., and *Hantzschia* sp. are present. *Nitzscha* sp.*, Opephora* sp.*, Diploneis* sp.*, Amphora* sp., and *Cyclotella* sp. were found in the samples from the middle and upper parts. The brackish water forms *Thalassiosira* sp. as well as *Gyrosigma* sp. and *Campylodiscus* sp. were determined in the upper sample as well. The diatoms from the upper parts are less well preserved. Taking into account that the majority of diatoms are fresh water, and that brackish water forms were found together with fresh water forms and only in the upper samples, we can deduce that in general the forms characterize freshwater conditions. Diatoms occurred in near coastal shallow areas overgrown with macrophytes. Both benthic and epiphytic forms are present. They indicate conditions of temporary lake with a variable position of a coastline.

The lower sample 336/5 from the Haykavan (s 336) section contains large diatoms in abundance. *Epithemia* sp., *Cyclotella* sp. aff., *Amphora* sp.*, Cocconeis* sp.*, Surirella* sp. are found. *Cyclotella scrobiculus* Alesch. et Pirum, which were described earlier in the Pleistocene deposits of Armenia, are rare in occurrence. *Cyclostephanos aff. dubius* dominates and *Diploneis* sp. and *Amphora* sp. are less frequent in the upper sample 336/2. The finds indicate a nearshore part of the basin, which was deeper and less overgrown with macrophytes than the Haykadzor lake.

4.3. Archaeological results

Early Palaeolithic artifacts were found in the lower and middle parts of the Jradzor section in L 1 and 3 (Fig. 4, s 226; Fig. 1, s 277). E.V. Belyaeva collected seven pieces, among which are a scraper, chopper, large flake, three picks, and a primitive handaxe (Fig. 10) made mostly of the Eocene dacites. Tool types and their technological and morphological features are analogous to those in the Early Acheulian industry found earlier by Lyubin and Belyaeva (2011) in the Lori Basin, in the lower part of the Karakhach quarry section (41°04.427′N, 44°07.2375′E; H = 1800 m), after which the Karakhach unit was named. Several similar lithics were collected by D.V. Ozherelyev in the

Agvorik [Yeni-yol] section of the unit (s 103; 41°04.540′N, 43°46.312′E; H = 2033 m) in the Upper Akhurian Basin (Trifonov et al., 2016).

5. Discussion

5.1. Dating of sedimentary units

The successive overlapping of the three units within the Shirak Basin proves that the Karakhach unit is older than the Ani unit, and the Ani unit is older than the Arapi unit. All three units cover the Gelasian basaltic trachyandesites in the northern part of the Shirak Basin with the age of 2.3–2.0 Ma (2014–208 and 2015–340 in table B.1) and underlie the Leninakan trachytic tuff with an average K–Ar age of ~0.68 ± 0.05 Ma (2014–254/2, 2014–254/3, and 2015–317/u in table B.1). Our age estimates of the tuff are similar to ^{39}Ar-^{40}Ar date of 0.65 ± 0.04 Ma obtained by C. Connor et al. during the studies for volcanic hazard assessment of the Armenian Nuclear Power Plant (Meliksetian, 2012).

Stone implements found in the lower and middle parts of the Jradzor sections of the Karakhach unit (s 226 and s 227) are dated to the Early Palaeolithic on the basis of their micromorphology. Similar implements were found in the Karakhach quarry (the type section of the Karakhach unit). The sediments of the quarry were dated by SIMS ^{238}U–^{206}Pb and K–Ar techniques and have the age of 1.9–1.75 Ma (Presnyakov et al., 2012; Trifonov et al., 2016). They are characterized by N polarity in the lower part and R polarity in the upper part. Like Karakhach sections, the Jradzor (s 226) and Meghrashat (s 306) sections have N polarity at the bottom and R polarity in the most part of the overlying sequence. The Karakhach unit is older than the Ani and Arapi units, thus, N polarity at its bottom can belong neither to Cobb Mt. nor to Jaramillo. At the same time, it cannot belong to Gauss Chron or Reunion subchron as the presence of archaeological artifacts in the sediments of such an age is problematic. Thus, it is very likely that the Karakhach unit of the Shirak Basin corresponds to the Olduvai subchron and the lower Calabrian. Its base is dated to 1.9–1.77 Ma and its top is younger than 1.77 Ma.

The malacofauna of the Voghji section (s 326) of the Ani unit is represented mainly by extinct forms and can be dated to the late Calabrian and the earliest Middle Pleistocene.

The presence of many exotic forms (*Tsuga, Podocarpus, Cedrus, Abies alba, Taxus, Liquidambar, Altingia, Castenea*, and *Carya*) indicates a relatively old age of the lacustrine deposits of the Voghji and Haykavan sections. The obtained spectra are similar to spectra from the Apsheronian (Calabrian) deposits in the Caspian region (Filippova, 1997) and Gurian – Early Chauda (upper Calabrian – lowermost Middle Pleistocene) layers in Georgia (Shatilova, 1974; Shatilova et al., 2011). Thus, the spectra of the Voghji and Haykavan sections fit to the geological age assessed for these deposits. The forest-steppe and steppe landscapes dominated at that time in the Shirak Basin. The climate experienced some fluctuations at that time. Palynological data on the Voghji section demonstrate changes from cool and dry (PC-1) to warm and dry (PC-2), cool and humid (PC-3), and cool and dry (PC-4) climate. PC-2 vegetation may correspond to the warm epoch of the late Apsheronian – Gurian, i.e., to the final Calabrian.

Thick clayish part of the Voghji and Haykavan sections is characterized by R magnetic polarity with two intervals of N polarity. These intervals may probably correspond to the Jaramillo and Cobb Mountain (1.24–1.22 Ma) subchrons. The base of the unit is probably older. The upper part of the Voghji section has N polarity and belongs to the Brunhes Chron, i.e., the Middle Pleistocene. Thus, the Ani unit is dated to the time interval of ~1.3–0.75 Ma.

All the examined sections of the Arapi unit have N magnetic polarity, i.e., belong to the Brunhes Chron. The analysis of small mammal fauna shows that the unit is dated to the earliest Middle Pleistocene and is not younger than 0.6 Ma. The data on the malacofauna confirm this conclusion. The leninakan tuff covers most of the Arapi sections. Only in the section near the Gyunri Airport, Melik-Adamyan (1994) reported similar rodent fauna below and above the tuff. Thus, the Arapi unit is dated to the range of 0.78–0.6 Ma.

5.2. History of the Shirak Basin formation

The Shirak Basin was formed on the heterogeneous basement, which is mainly composed of the deformed volcanic-sedimentary Eocene and probably Mesozoic rocks with a few Paleozoic blocks. The latest Early Cenozoic volcanic events occurred along the southern and north-eastern borders of the basin at the end of the Oligocene (24–25 Ma) and Early Miocene (22–23 Ma). It is not evident whether the basin already existed as a depression during accumulation of the Voghchaberd unit. According to a borehole drilled 8 km to the south-west of Gyumri (Sayadyan, 2009), the thickness of the Voghchaberd unit within the basin reaches 840–920 m. A thick section of the unit is exposed also within the southern border of the basin (s 310). Taking into account the results of K–Ar dating the interpretation of the Voghchaberd unit age may be twofold. On the one hand, the age of the unit may correspond to the age of the included volcanic blocks, i.e., 24–25 Ma. On the other hand, the age of the tuffaceous matrix of 1.6 ± 07 Ma may approximately correspond to the age of the Voghchaberd breccia. However, the latter figure should be used with caution. Such a young age may be the result of its hydrothermal reworking. Anyway, the breccia was formed before the accumulation of the Ani unit due to explosions that manifested the beginning of volcanic activity in the Arteni-Aragats area.

The Messinian and Early Pliocene (5.8 ± 0.2 Ma to 4.26 ± 0.12 Ma) eruptions of basic lavas in the Ani area dammed the Akhurian River. This damming and subsidence of the Shirak Basin led to the formation of a lake, which was filled with the Upper Pliocene and lower Gelasian fine-grained lacustrine deposits (Sayadyan, 2009). In the Late Pliocene the subaerial rhyolitic tuff explosions occurred in the Ani area. If the northern part of the Shirak Basin remained as a depression later, it could be filled with the Gelasian basaltic trachiandesites (2.3–2.0 Ma).

At the “Karakhach” time (about 1.9–1.7 Ma), the alluvial sedimentation took place within the northern border of the Shirak Basin (s 226, s 227, s 306, and probably Marmashen borehole 6). Fine-grained deposits of the lower part of the unit were accumulated by stagnant waters, partly (s 306) in lacustrine conditions. The analogous sediments are absent near the Marmashen Monastery (s 339 and s 340) and in the more southern sections of the basin (s 314 and s 318), where the age of the Quaternary deposits covering the Miocene or Pliocene formations is younger. The “Karakhach” time drainage system of the northern part of the Shirak Basin accumulated local terrigenous material and transported it to the Pambak River paleo-valley. This system was isolated from the Akhuryan riverhead because of the uplift of the western termination of the Bazum Ridge, which took place about 2 Ma ago (Ritz et al., 2016). The Akhuryan riverhead of the “Karakhach” time found its way via the Karakhach Pass to the Dzoraghet-Debed valley (Trifonov et al., 2016).

In the Calabrian, the Shirak Basin subsided along the Kaps flexure-fault zone and the paleo-valley of the “Karakhach” time remained in its relatively uplifted side. At the same time, the uplift of the Trans-Caucasus transverse zone isolated the Shirak part of the paleo-valley from the Pambak River basin. The lacustrine sedimentation represented by the Ani and Arapi units began in the Shirak Basin not later than 1.25 Ma ago. Each of these units corresponds to a separate cycle of sedimentation, which started with lacustrine accumulation and ended with alluvium accumulation. Lacustrine deposits sometimes have interbeds of permanent and temporary stream sediments like, for example, at the Haykavan section (s 336).

The alluvium of the upper Ani unit (the end of the “Ani” cycle) indicates the probable intensification of water erosion that resulted in the level drop of the “Ani” lake in the Akhuryan valley in the south of the basin during the earliest Middle Pleistocene. This could be due to the relative uplift of the northern part of the Shirak Basin. The younger sediments of the "Arapi" lake basin (the early Middle Pleistocene) were incised into the Ani deposits by 50–100 m. Within the southern part of the Shirak Basin, the Arapi lacustrine deposits covered the Ani unit (s 317) and spread further to the south and to the east (s 314 and s 318), i.e., outside the area of the Ani sedimentation. Thus, the successive migration of the area of sedimentation to the southern part of the Shirak Basin occurred due to the uplift of its northern part.

Lacustrine sedimentation gave place to accumulation of alluvium in the central part of the Shirak Basin at the end of the "Arapi" cycle (0.7–0.6 Ma). The intensification of water erosion and/or volcanic activity of the Araghats volcano (eruption of the Leninakan tuff) resulted in the level drop of the residual "Arapi" lake in the south of the basin. After 0.6 Ma, the basin was drawn into the tectonic uplift of the Lesser Caucasus. Nowadays the Akhuryan River incises intensively and controls water transit from the Upper Akhuryan and Shirak Basins to the south.

Seismites within the Ani and Arapi units may serve as an evidence for strong palaeoearthquakes (Fig. 6). A micro-graben in the Arapi unit in s 316 (Lusaghbyur) and the landslide in s 327 (Voghji), which is deformed by ruptures without any regularity in their orientation, could be caused by palaeoseismic events as well.

5.3. Origin of the Shirak Basin

The configuration and observed Quaternary structure of the Shirak Basin do not demonstrate significant influence of the major Late Cenozoic faults caused by collision in the Arabia-Caucasus segment of the Alpine-Himalayan Belt (Trifonov et al., 1994, 2017). At the same time, subsidence of the basin was accompanied by volcanism in the surrounding area during the whole period of the basin development. Those were eruptions in the Late Oligocene along the southern side of the basin that resulted in formation of the Voghchaberd unit, in the Early Miocene in the north-eastern border (Jajur Pass), and in the Late Miocene in the eastern surroundings of the basin (Tsaghkunyats and Teghekunyats Ridges). In the Messinian and Early Pliocene, they gave place to eruptions of the basaltic andesites within the southern surrounding of the Shirak Basin (the Ani area) that were continued by explosions of the rhyolithic tuffs in the Late Pliocene. Andesites erupted in the Messinian – Early Pliocene in the eastern boundary of the basin, which is a part of the Trans-Caucasus transverse zone (s 432). According to the V.A. Lebedev's data, eruptions lasted during the whole Pliocene on the Kars-Digor Highland.

Basic lavas were erupted in the southern part of the Javakheti Highland and Upper Akhuryan Basin in the Gelasian (Trifonov et al., 2016). As a result, lavas filled the Akhurian paleo-valley and spread to the northern part of the Shirak Basin (Lebedev et al., 2008, 2015). In the Calabrian and Middle Pleistocene, the volcanic activity renewed in the southern surrounding of the Shirak Basin, that is, the basalts near the Digor town in Turkey have the age of ~1.6–1.3 Ma (Innocenti et al., 1982). The Arteni and Arailer volcanoes as well as the Aragats volcanic center began to act successively. The Arailer volcano lavas are dated to 1.37 ± 0.04 Ma to 1.28 ± 0.04 Ma and the Arteni volcano acid products are dated to 1.26 ± 0.05 Ma (Lebedev et al., 2011). According to K—Ar dating the Aragats volcano was active within the period of 0.97 ± 0.09 Ma to 0.45 ± 0.07 Ma (Chernyshev et al., 2002). Its lavas filled the south-eastern part of the Shirak basin (s 434). The Mets-Sharailer volcano was active nearly 0.9 ± 0.1 Ma (s 439 and s 440) and its andesite lavas cover the eastern part of Shirak Basin (s 432). On the basis of K—Ar dating and chemical composition the Leninakan tuff is attributed to the late stage of the III phase of the Araghats volcano activity, the age of which was determined by Chernyshev et al. (2002) as 0.72 ± 0.07 Ma and 0.68 ± 0.07 Ma. The Araghats trachyte-dacite cone was formed in that phase and was partly destroyed after an explosive event that produced the Leninakan tuff.

Thermodynamic calculations and their correlations with the results of geochemical and petrological studies showed that the Late Cenozoic magmas were generated in the northern part of the Armenian Highland (including the region under study) under P = 0.95–1.05 GPa and T = 850–1100 °C, characteristic for the depths of 35–40 km, i.e., the lowest Earth's crust (Koronovsky and Demina, 1999, 2007). According to the quoted authors' opinion, the magmatic sources near the crust-mantle boundary was formed by the heat-mass transfer from the deeper horizons of the mantle. Synchronism of the Shirak basin subsidence and volcanism in its surrounding area supports the idea of the interrelation of the subsidence and the sub-lithosphere movements and transformations of matter manifested in volcanism. Sokolov and Trifonov (2012) analyzed possible mechanisms of such links. This conclusion is supported by the successive migration of the area of subsidence and sediment accumulation in the Shirak Basin to the south simultaneously with the increasing volcanic activity within the southern border of the basin. Similar interrelations could influence the formation of the Van Lake depression as well as the Ararat and Major Sevan Basins, although the origin of the two latter basins is also controlled by major fault zone, forming the Late Cenozoic structural pattern of the Armenian Highland.

6. Conclusions

1. Numerical ages for of the Quaternary units were determined: 1.9– < 1.7 Ma – the Karakhach unit, 1.3–0.75 Ma – the Ani unit, 0.75–0.6 Ma – the Arapi unit.
2. During the "Karakhach" time the river flow from the northern part of the Shirak Basin was directed mainly towards the Pambak River paleo-valley, i.e. it was roughly EW trending. Later the flow acquired NS direction. It happened for two reasons: the uplift of a segment of the Trans-Caucasus transverse flexure-fault zone along the eastern side of the basin and the development of the Kaps flexure-fault zone along the northern side of the basin.
3. During the "Ani" and "Arapi" time the Shirak Basin became the area of predominantly lacustrine sedimentation. It is quite possible that the lake, which corresponds to the "Ani" clays ("Leninakan" lake") appeared due to lava damming on the southern rim of the basin. Lacustrine sedimentation migrated from the north to the south of the basin due to the tectonic uplift of its northern part.
4. It is not likely that the flexure-fault zones along the Shirak Basin boundaries have any relation to the major faults caused by the collisional shortening. Besides, during the whole epoch of the basin subsidence, the latter was accompanied by volcanism in the surrounding areas. These two facts allow to suppose the dependence of the basin subsidence on movements and transformations of mantle matter.

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Appendices

Appendix A

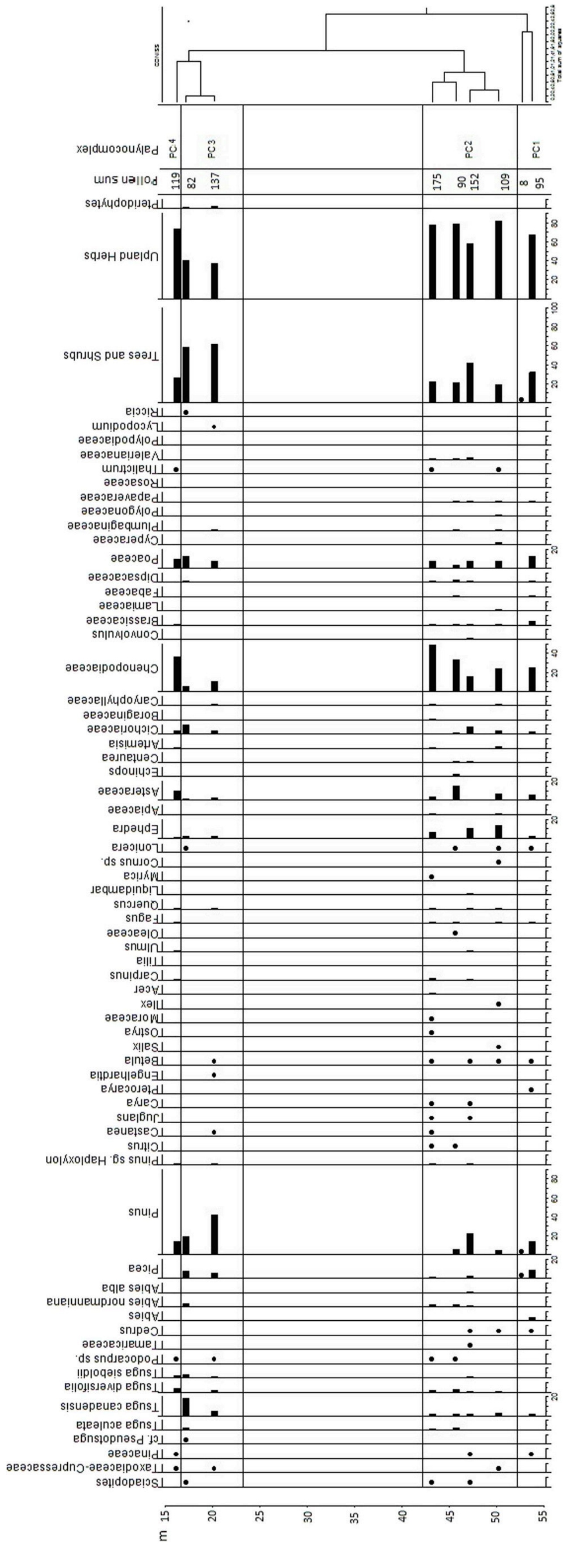

Fig. A.1. Pollen diagram from the Voghji section (s 326).

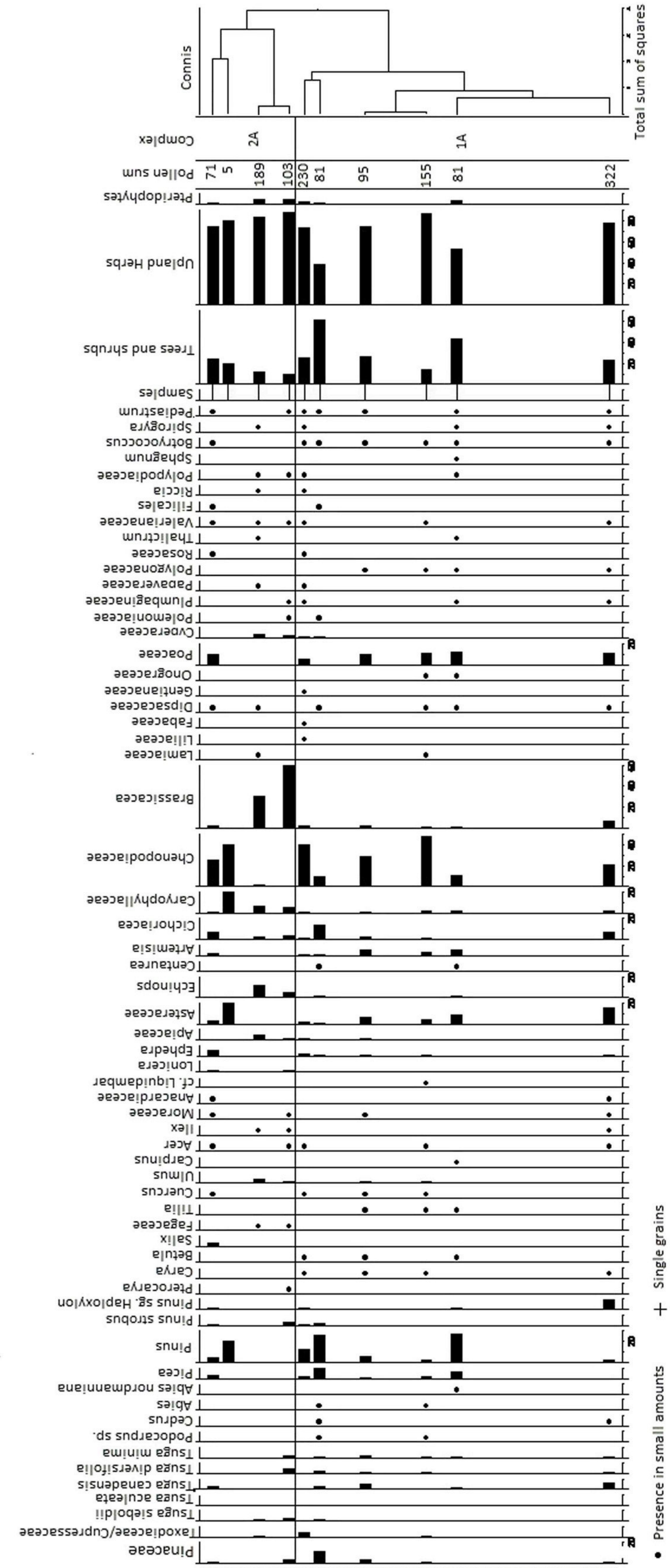

Fig. A.2. Pollen diagram from the Haykavan section (s 336).2

Appendix B

Table B.1
Ages of the volcanic rocks determined by K-Ar method, NW Armenia (performed by V.A. Lebedev).

No	Year-sample No	Location	Coordinates	Rock	Material	K, % ± σ	$^{40}Ar_{rad}$ (ng/g) ± σ	$^{40}Ar_{atm}$,% (in sample)	Age, Ma ± 2σ
Lower Miocene volcanic rocks									
1	2014-220	Jajur Pass, s 220, H = 1958 m	40°51.884´N 44°00.016´E	Alkaline basalt	Ground-mass	1.50 ± 0.02	2.336 ± 0.013	22.9	**22.5 ± 0.6**
Voghchaberd unit									
2	2016-431/1	Southern Shirak Basin. Magaridzor canyon, s 431 = s 310, H = 1583 m	40°37.261´N 43°46.658´E	Andesitic breccia, matrix hydrothermally reworked	Ground-mass	1.69 ± 0.02	0.19 ± 0.05	96.0	**1.6 ± 0.7***
3	2016-431/2	Southern Shirak Basin. Magaridzor canyon, s 431 = s 310, H = 1583 m	40°37.261´N 43°46.658´E	Andesite of big lava block within breccia	"	2.41 ± 0.03	4.117 ± 0.015	20.7	**24.5 ± 0.6**
4	2016-431/3	Southern Shirak Basin. Magaridzor canyon, s 431 = s 310, H = 1583 m	40°37.261´N 43°46.658´E	Andesitic fragment within breccia	"	2.39 ± 0.03	4.066 ± 0.016	20.1	**24.4 ± 0.6**
5	2016-431/4	Southern Shirak Basin. Magaridzor canyon, s 431 = s 310, H=1583 m	40°37.261´N 43°46.658´E	Andesitic fragment within breccia	"	2.09 ± 0.03	3.625 ± 0.019	59.7	**24.8 ± 0.7**
Ani, lower lavas, Messinian to Lower Pliocene									
6	2016-429/1	Southern surrounding of Shirak Basin, Ani, s 429, H = 1428 m	40°30.202´N 43°34.910´E	Lower basaltic andesite	Ground-mass	1.42 ± 0.02	0.57 ± 0.006	79.4	**5.8 ± 0.2**
7	2016-420/1	Southern Shirak Basin, v. Haykadzor, s 420, H = 1549 m	40°30.707´N 43°39.317´E	Andesite. Southern foot of Qurtblur cone	"	1.72 ± 0.02	0.671 ± 0.004	59.4	**5.60 ± 0.15**
8	2016-421	Southern Shirak Basin, v. Haykadzor, s 421, H = 1613 m	40°30.698´N 43°39.543´E	Andesite. Southern slope of Qurtblur cone	"	1.68 ± 0.02	0.649 ± 0.009	84.5	**5.6 ± 0.2**
9	2016-417	Southern Shirak Basin, v. Haykadzor, s 417, H = 1449 m	40°31.841´N 43°39.305´E	Upper basaltic andesite, N_2^1	"	1.69 ± 0.02	0.500 ± 0.003	69.8	**4.26 ± 0.12**
Basaltic andesite lavas between the Sharailer and Aragats volcanoes									
10	2016-436	Eastern Shirak Basin, v. Geghadyr, s 436, H = 2067 m	40°39.227´N 44°06.967´E	Basaltic andesite southern foot of Sharailer	Ground-mass	1.60 ± 0.02	0.578 ± 0.006	78.8	**5.2 ± 0.2**
Ani, Anipemza, and Ani station, rhyolitic tuffs and ignimbrites, Upper Pliocene									
11	2016-429/2	Southern surrounding of Shirak Basin, Ani, s 429, H = 1428	40°30.202´N 43°34.910´E	Rhyolitic ignimbrite	Matrix of tuff	3.52 ± 0.04	0.81 ± 0.06	96.0	**3.3 ± 0.5**
12	2015-322/2	Southern surrounding of Shirak Basin, Ani station, quarry, s 322, H = 1497 m	40°29.385´N 43°37.609´E	Rhyolitic pumice	Glass	3.36 ± 0.04	0.732 ± 0.008	79.3	**3.14 ± 0.10**
13	2016-418	Ani station, quarry, s 418 = s 322, H = 1497 m	40°29.385´N 43°37.609´E	Upper rhyolitic ignimbrite	Matrix of tuff	3.39 ± 0.04	0.71 ± 0.06	96.5	**3.0 ± 0.5**
14	2015-320	Southern surrounding of Shirak Basin, Anipemza quarry, s 320, H = 1438 m	40°26.856´N 43°35.892´E	Rhyolitic tuff	Glass	3.65 ± 0.04	0.76 ± 0.03	94.4	**3.0 ± 0.3**
15	2016-419	Southern surrounding of Shirak Basin, Anipemza, s 419, H = 1449 m	40°26.968´N 43°36.447´E	Upper rhyolitic ignimbrite	"	3.48 ± 0.04	0.715 ± 0.022	92.4	**3.0 ± 0.2**
16	2016-428	Southern surrounding of Shirak Basin, Ani, s 428, H = 1499 m	40°29.962´N 43°34.582´E	Rhyolitic ignimbrite	"	3.90 ± 0.04	0.759 ± 0.011	85.1	**2.80 ± 0.15**
Unit II of the southern Javakheti Highland, northern Shirak basin, Gelasian									
17	2015-340	Shirak Basin, Marmashen Monastery, s 340, H = 1514 m	40°50.443´N 43°45.500´E	Basaltic trachyandesite	Ground-mass	1.06 ± 0.02	0.1662 ± 0.0014	72.6	**2.25 ± 0.10**

(*continued on next page*)

Table B.1 (*continued*)

No	Year-sample No	Location	Coordinates	Rock	Material	K, % ± σ	$^{40}Ar_{rad}$ (ng/g) ± σ	$^{40}Ar_{atm}$,% (in sample)	Age, Ma ± 2σ
18	2014-208	NW Shirak Basin, s 208, H = 1620 m	40°51.610´N 43°44.954´E	Basaltic trachyandesite	"	1.15 ± 0.02	0.171 ± 0.010	65.5	**2.1 ± 0.2**
Lavas of Sharailer volcano, uppermost Calabrian									
19	2016-439	Eastern Shirak Basin, Mets-Sharailer cone, s 439, H = 2304 m	40°41.371´N 44°06.836´E	Basaltic trachyandesite, tephra	Matrix of tephra	2.28 ± 0.03	0.181 ± 0.010	95.6	**1.1 ± 0.2**
20	2016-432	Shirak Basin, SSE of Gyumri, s 432, H = 1505 m	40°43.403´N 43°50.114´E	Basaltic andesite	Ground-mass	2.06 ± 0.03	0.131 ± 0.003	65.3	**0.92 ± 0.04**
21	2016-440	Eastern Shirak Basin, wall of Mets-Sharailer caldera, s 440, H = 2294 m	40°41.601´N 44°07.194´E	Basaltic andesite	"	1.52 ± 0.02	0.093 ± 0.006	86.1	**0.89 ± 0.11**
Lavas of the northern slope of Aragats, uppermost Calabrian									
22	2016-434	Shirak Basin, northern slope of Araghats, Orom village, s 434, H = 1608 m	40°39.572´N 43°54.092´E	Trachyandesite	Ground-mass	3.24 ± 0.04	0.206 ± 0.02	39.3	**0.92 ± 0.03**
Leninakan tuffs and ignimbrites									
23	2015-227	Shirak Ridge, s 227,H = 1760 m	40°54.494´N 43°46.310´E	Trachitic ignimbrite	Glass	3.88 ± 0.04	0.226 ± 0.008	93.0	**0.84 ± 0.07**
24	2015-317/l	Southern Shirak Basin, s 217, H = 1513 m, below thrust	40°38.637´N 43°44.507´E	Trachitic ignimbrite	"	3.96 ± 0.04	0.225 ± 0.005	90.3	**0.82 ± 0.05**
25	2016-435	Shirak Basin, Artik, s 435, H = 1864 m	40°37.277´N 43°59.079´E	Trachitic ignimbrite	Matrix of tuff	3.75 ± 0.04	0.191 ± 0.002	95.4	**0.74 ± 0.05**
26	2015-317/u	Southern Shirak Basin, s 317, H = 1513 m, above thrust	40°38.637´N 43°44.507´E	Trachitic ignimbrite	Glass	3.96 ± 0.04	0.193 ± 0.003	87.1	**0.70 ± 0.03**
27	2014-254/2	Pambak River, Saraghart s 254, H = 1649 m, lower part of the layer	40°51.702´N 44°13.188´E	Upper trachitic ignimbrite	"	3.98 ± 0.04	0.187 ± 0.016	85.1	**0.68 ± 0.10**
28	2014-254/3	Pambak River, Saraghart s 254, H = 1649 m, upper part of the layer	40°51.702´N 44°13.188´E	Upper trachitic ignimbrite	"	3.79 ± 0.04	0.171 ± 0.008	82.9	**0.65 ± 0.06**
Lavas of the Aragats volcano, correlated to the Leninakan tuff									
29	Ch-2002-7A**	Summit of Aragats		Trachyte	Ground-mass	3.47 ± 0.04	0.164 ± 0.012	71.5	**0.68 ± 0.07**
30	Ch-2002-11A	Summit of Aragats		Trachyte	"	2.64 ± 0.03	0.131 ± 0.011	50.4	**0.72 ± 0.07**

* Because of high portion of atmospheric Ar the figure seems to be doubtful
** Ch-2002 – (Chernyshev et al., 2002)

Table B.2
Chemical composition of volcanic rocks dated by the K-Ar method, NW Armenia. Major oxides.

No.	Year-sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	K_2O	Na_2O	P_2O_5	LOI	Sum
Lower Miocene volcanic rocks													
1	2014-220	44.10	1.87	18.14	9.80	0.14	5.61	11.49	1.75	3.44	0.68	2.34	99.37
Voghchaberd unit													
2	2016-431/1	57.64	1.10	16.88	6.11	0.04	1.73	5.56	2.22	2.45	0.32	5.94	100.01
3	2016-431/2	53.41	0.88	15.87	10.24	0.09	2.18	8.42	2.52	3.56	0.38	2.45	100.00
4	2016-431/3	57.32	0.93	16.70	7.74	0.09	2.23	6.53	2.65	3.27	0.28	2.26	100.00
5	2016-431/4	55.28	1.08	16.67	8.43	0.05	2.11	7.53	2.40	4.00	0.54	1.91	99.99
Ani, lower basaltic andesite – andesite lavas, Messinian to Lower Pliocene													
6	2016-429/1	54.56	1.00	16.69	10.46	0.15	3.11	8.01	1.73	3.95	0.24	0.10	100.00
7	2016-420/1	56.42	0.76	15.73	8.65	0.12	2.82	8.10	2.03	3.74	0.20	1.45	100.01
8	2016-421	58.79	0.78	16.44	7.20	0.11	2.89	6.91	2.08	4.03	0.21	0.56	100.00
9	2016-417	57.73	0.76	15.80	10.23	0.11	2.50	6.61	1.99	3.91	0.26	0.10	100.00
Basaltic andesite lavas between the Sharailer and Aragats volcanoes													
10	2016-436	53.61	1.05	16.92	9.00	0.14	4.36	8.25	1.94	4.12	0.49	0.12	99.99
Ani, Anipemza, and Ani station, rhyolitic tuffs and ignimbrites, Upper Pliocene													
11	2016-429/2	69.84	0.36	13.76	2.35	0.07	0.51	1.49	4.48	3.35	0.06	3.74	100.00
12	2015-320	69.49	0.39	14.71	2.42	0.06	0.74	1.49	3.70	3.83	0.07	3.05	99.96
13	2016-419	69.32	0.37	13.93	2.41	0.07	0.70	1.60	4.20	3.59	0.05	3.76	100.00
14	2015-322/2	68.56	0.34	14.77	2.25	0.06	0.51	1.42	3.51	3.76	0.05	4.68	99.90
15	2016-418	67.80	0.51	14.36	3.20	0.08	0.77	2.18	4.00	4.00	0.09	3.02	100.01
Unit II of the southern Javakheti Highland, basaltic trachyandesites, northern Shirak Basin, Gelasian													
16	2015-340	52.67	1.76	17.79	9.11	0.13	2.74	8.35	1.48	4.57	0.40	0.55	99.57
17	2014-208	50.68	1.53	19.88	8.35	0.14	2.31	8.90	1.49	5.75	0.50	0.18	99.70
Basaltic andesite lavas of Sharailer volcano, uppermost Calabrian													
18	2016-432	53.75	1.38	16.90	9.35	0.15	3.27	7.45	2.39	4.75	0.52	0.10	100.00
19	2016-440	53.22	0.98	16.35	10.47	0.14	5.07	7.79	1.72	3.86	0.31	0.10	100.00
20	2016-439	51.03	1.16	14.38	8.15	0.13	4.89	7.79	2.41	1.97	0.47	7.63	100.01
Trachyandesite lavas of the northern slope of Aragats, uppermost Calabrian													
21	2016-434	59.98	0.99	14.68	5.27	0.09	1.24	3.47	3.19	4.78	0.29	6.01	99.99
Leninakan trachytic tuffs and ignimbrites, Shirak Basin and the Pambak River upper reaches													
22	2014-254/2	63.71	0.96	16.01	3.11	0.077	0.54	2.74	4.01	5.40	0.22	2.52	99.28
23	2014-254/3	64.90	0.93	15.91	2.88	0.073	0.51	2.22	3.91	5.53	0.20	2.44	99.50
24	2015-227	64.08	0.86	16.59	3.38	0.08	1.46	2.16	3.93	3.93	0.16	3.30	99.92
25	2015-317/u	64.91	0.83	15.81	3.38	0.08	1.18	2.27	4.05	4.53	0.17	2.62	99.98
26	2015-317/l	64.26	0.87	16.05	3.76	0.08	1.07	2.55	4.22	4.47	0.18	2.39	99.91
27	2016-435	66.89	0.86	15.23	3.71	0.08	0.78	2.13	4.68	5.07	0.18	0.4	100.01
28	2016-422?	63.82	1.02	15.15	4.61	0.09	1.18	2.67	4.31	4.45	0.21	2.48	100.00
Trachytic lavas of the Aragats volcano, correlated to the Leninakan tuff													
29	2002-7A	65.15	0.84	15.84	4.87	0.09	1.04	2.98	3.83	5.06	0.21	0.10	100.01
30	2002-11A	64.00	0.79	15.81	5.44	0.10	1.55	4.53	3.08	4.39	0.21	0.10	100.00

Samples 2002-7A and 2002-11A are represented by I.V. Chernyshev and V.A. Lebedev

Table B.3
Chemical composition of volcanic rocks dated by the K-Ar method, NW Armenia. Microelements and some rare earth elements (ppm).

№	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Y	Zr	Nb	Mo	Ba	Pb	Th	U
Lower Miocene volcanic rocks																			
1	28	170	190	41	12	67	97	17	18	43	2300	21	180	33	<1	720	9.2	4	<2
Voghchaberd unit, Miocene																			
2	21	167	74	25	64	56	57	19	3.5	51	905	18	163	14	<2.0	670	7.0	11	<2.0
3	25	207	112	27	145	66	71	16	5.0	52	992	20	135	12	<2.0	869	7.7	12	<2.0
4	<5.0	169	77	18	41	56	63	16	3.7	61	894	15	142	12	<2.0	79	8.7	9.2	3.3
5	21	260	192	24	83	57	60	18	6.8	48	1288	15	151	13	3.5	907	10	12	3.2
Ani, lower basaltic andesite – andesite lavas, Messinian to Lower Pliocene																			
6	18	139	210	27	91	66	112	16	2.1	31	484	21	150	12	<2.0	488	9.0	7.4	<2.0
7	22	126	114	22	51	41	89	15	<2.0	41	460	19	165	13	2.6	542	10	8.0	3.5
8	20	107	92	21	44	35	79	17	<2.0	40	451	21	187	15	3.2	528	12	10	<2.0
9	17	126	134	18	55	47	74	16	<2.0	41	482	20	161	13	2.9	588	10	9.2	2.4

(*continued on next page*)

Table B.3 (*continued*)

№	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	As	Rb	Sr	Y	Zr	Nb	Mo	Ba	Pb	Th	U
Basaltic andesite lavas between the Mets-Sharailer and Aragats volcanoes																			
10	22	168	197	30	129	57	99	15	<2.0	28	924	18	151	14	<2.0	674	9.2	5.3	<2.0
Ani, Anipemza, and Ani station, rhyolitic tuffs and ignimbrites, Upper Pliocene																			
11	<5.0	20	19	<5.0	11	13	41	15	6.5	110	162	21	265	25	3.4	782	17	24	5.7
12	<5.0	18	8.5	5.8	13	12	45	13	7.1	107	187	19	257	21	4.9	726	20	15	4.2
13	<5.0	19	24	<5.0	16	18	40	14	6.4	110	167	20	269	25	5.7	791	17	22	6.1
14	<5.0	11	7.5	<5.0	10	14	41	13	7.6	106	200	18	250	19	6.4	729	19	18	3.5
15	5.6	31	13	<5.0	11	16	52	16	2.2	98	218	23	256	23	4.2	786	16	18	4.8
Unit II of the southern Javakheti Highland, basaltic trachyandesites, northern Shirak Basin, Gelasian																			
16	20	173	105	30	48	42	77	18	<5.0	21	535	31	201	14	<3.0	343	6.1	<2.0	<2.0
17	23	130	62	32	57	56	84	18	4	22	670	28	200	23	<1.0	480	11	4	<2.0
Basaltic andesite of the Mets-Sharailer volcano, uppermost Calabrian																			
18	17	173	114	26	73	40	88	15	<2.0	40	854	28	230	20	2.7	746	11	7.3	2.5
19	24	152	263	31	180	66	86	15	<2.0	26	715	20	143	12	<2.0	593	8.0	4.7	<2.0
20	24	121	149	22	118	65	85	16	<2.0	32	882	19	168	17	<2.0	589	7.5	5.0	<2.0
Trachyandesite of the northern slope of Aragats, uppermost Calabrian																			
21	6.5	101	34	5.8	14	25	57	16	2.9	71	402	35	351	25	<2.0	778	13	14	3.8
Leninakan trachytic tuffs and ignimbrites, Shirak Basin and the Pambak River upper reaches																			
22	15	31	13	13	<10	13	64	18	7	110	430	39	480	45	4	880	19	19	8
23	12	34	16	15	<10	21	61	17	<3.0	100	410	38	430	42	4	880	24	24	11
24	7.2	47	15	5.5	17	58	61	16	<5.0	97	313	35	469	31	4.2	881	18	14	3.2
25	10	55	19	7.2	14	18	53	16	<5.0	100	303	33	456	30	5.3	819	19	14	2.7
26	8.1	56	16	7.3	14	24	61	17	5.3	91	375	31	416	28	4.3	811	18	13	2.8
27	<5.0	55	21	<5.0	10	18	62	17	4.1	104	244	37	463	36	3.9	927	14	18	5.2
28	8.3	69	35	<5.0	17	20	61	16	5.7	97	303	36	433	35	5.5	912	16	16	5.0
Trachytic lavas of the Aragats volcano, correlated to the Leninakan tuff																			
29	7.0	81	35	5.7	14	24	55	17	3.6	81	400	36	342	26	4.7	906	13	16	4.1
30	12	91	47	11	30	28	63	17	<2.0	64	453	25	256	20	4.1	754	12	9.8	<2.0

Table B.4
List of GPS coordinates for the main sites of the described units.

Age	Unit	Site №	GPS coordinates	Nearest village
Q_2^1	*Arapi unit*	s 219	40°51.831′N 43°57.468′E	Jajur
		s 314	40°37.814′N 43°45.336′E	Lusaghbyur (Magaridzor gulley)
		s 317	40°38.637′N 43°44.507′E	Lusaghbyur
		s 318	40°32.267′N 43°39.335′E	Haykadzor
		s 336a	40°48.604′N 43°45.145′E	Haykavan
		s 341	40°44.939′N 43°50.282′E	Gyumri
		s 438	40°38.833′N 44°07.490′E	Hnaberd
$Q_1^2 – Q_2^1$	*Ani unit*	s 208	40°51.610′N 43°44.954′E	Vaghramberd (Leninakan HPP)
		s 209	40°52.372′N 43°45.036′E	Kaps
		s 326	40°49.604′N 43°44.736′E	Voghji
		s 336	40°48.845′N 43°44.808′E	Haykavan
		s 339	40°50.726′N 43°45.790′E	Marmashen
		s 340	40°50.443′N 43°45.500′E	Marmashen
Q_{1ol}^1 - Q_1^2	*Karakhach unit*	s 226	40°54.313′N 43°46.081′E	Jradzor

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.quaint.2018.09.017.

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