Tatyana V. Sapelko[1*], Vladimir R. Boynagryan[2], Mikhail A. Naumenko[1], Dmitry V. Sevastyanov[3], Ivan G. Gabrielyan[4], Artak S. Piloyan[2], Liana A. Margaryan[2], Mikhail Yu Aleksandrin[5], Anton V. Terekhov[1]
[1]Institute of Limnology RAS, St. Petersburg, Russia,
[2]Yerevan State University, Yerevan, Armenia
[3]St. Petersburg State University, St. Petersburg, Russia
[4]Institute of Botany of NAS RA, Yerevan, Armenia
[5]Institute of Geography RAS, Moscow, Russia
*** Corresponding author:** tsapelko@mail.ru

FIRST MULTY-PROXY STUDIES OF HIGH-MOUNTAIN LAKES IN ARMENIA: PRELIMINARY RESULTS

ABSTRACT. Within the framework of the Russian-Armenian project "The Paleolimnological Aspect of Studying the Evolution of Ecosystems of High-Mountain Lakes of Russia and Armenia" in July-August 2018, we investigated four high-mountain lakes of Armenia. The research focuses on the lakes Kari, Umroi, Akna and Sev. All investigated lakes are located at the altitudes about 3000 m above sea level. We first time these lakes were investigated using a multi-proxy method that includes paleolimnological, geomorphological, hydrological, geochemical and biogeographic studies. The research offers the first statistical characteristics of lake depth distribution, water volume and other morphometrics. Lake sediments sequences and radiocarbon dates were received and analyzed for Armenian small lakes for the first time. We determined that all the studied lakes were formed during the Holocene. Sediments of Lake Kari were deposited in the last 4000 years, sediments of Lake Umroi – within the last 8000 years, while maximum thickness of sediments is around 1 m in both lakes. Hence, we assume low deposition rate in Armenian high-mountain lakes, however, it varied significantly in different periods of lake history.

KEY WORDS: mountain lakes, Armenian plateau, geomorphology, paleolimnology, Holocene

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INTRODUCTION

Almost all the data concerning the history of Armenian lakes are associated with the studies of Lake Sevan. Evolution of this lake, the largest in Armenia, was reconstructed based on small outcrops of buried peat and archeological sites (Sayadyan 2000; Ollivier et al. 2010; 2011; Joannin et al. 2014). Reported Holocene radiocarbon ages were obtained either from Lake Sevan or on its watershed. Analysis of peat located on the shore of Lake Sevan, near Vanevan village (Leroyer et al. 2016), shows that the climate of the Early Holocene was dry (precipitation rate was below 180 mm per year), and steppe landscapes prevailed. In the Mid Holocene (between 7800 and 5100 cal BP) precipitation became higher by 28%, climate got to be milder, the water level in Lake Sevan rose and the forest vegetation spread over lake watershed. Around 5700 cal BP climate started to turn drier and after 5100 cal BP arid conditions are dominating.

First research of high-mountain lakes situated on Armenian plateau was reported by L. Arnoldi (1931) in the beginning of the XX century. The research covered hydrological, hydrochemical, biogeographical studies of lake sediments of Lake Akna (western slope of Gegham mountains). In 1930s, the first data on chemical composition of Lake Kari lake water (southern slope of Mount Aragats massif), its sediments and phytoplankton (Kireeva 1933) were published. The other high-mountain lakes located in Armenia were hardly studied (Boynagryan et al. 2018). Paleolimnological investigations are carried out for the first time. The main purpose of this research is to study the history of lakes in different spatial and temporal scales, which allows discovering the main patterns of the variations of environmental conditions (Sevastyanov et al. 2014; Subetto et al 2017).

STUDY AREA

The Caucasus is part of the Alpine-Himalayan mountainous belt that was created by the collision of the Arabian and Eurasian continental plates during the Neogene (Sayadian et al. 1983). This tectonic activity resulted in the formation the Lesser Caucasus ranges.

The research was carried out in the reference points of the lakes Kari, Umroi, Akna and Sev in July-August 2018 (Fig. 1). Studied lakes are situated in different parts of Armenian Highlands at elevations around 3000 m above sea level (m a.s.l.). Aragats is a volcano massif, the most elevated part of Armenian plateau. Slopes of Aragats show the traces of ancient glaciations like cirques and moraine fields with water-filled depressions. Southern slopes of Aragats are made of andesite-basalt lava outflows during mid- and late Oligocene and possess a typical block surface topography. South-western and south-eastern slopes are made of andesite-basalt lava flows. Northern slopes consist of pyroxene-andesites, which create here knob topography. From north-east Aragats is surrounded by block lavas, descending towards river Kasakh valley. These lavas superimpose fluvio-glacial and lake sediments of Riss glaciation age. At the contact of these geological formations, springs are outflowing. Lava-made surfaces are rugged, knobs and hills covered with blocks, are interleaved by depressions, filled with small seasonal lakes and bogs. Western slopes of Aragats are similar to south-eastern ones. Their surface is shaped by tuffs and lavas, significantly changing their thickness due to ruggedness of underlying rocks. Here most widespread is the landscape of plateau, hills and ridges (Balian 1969). Blister volcanic cones are presented at the western and south-western slopes. Lots of small lakes are situated on Aragats, mostly between 2900 and 3500 meters. Lakes are situated inside depressions of glacial relief, being moraine-dammed or cirque-situated. Only several lakes are located near north-eastern foot of Aragats, in the pits inside lava-made surface, and they could be considered as volcanic. The largest lakes among high-mountain ones are moraine-dammed Kari (3187 m, southern slope) and Umroi (3050 m).

Lake Kari is located at the southern macroslope of Mount Aragats at 3200 m a.s.l. Kari catchment presents a glacial knob-and-basin topography on volcanic rocks having the traces of the mountain glaciation. Lake itself is moraine-dammed. Trench-shaped lake Umroi lies in an intermorainal depression at the eastern macroslope of Mount Aragats at 3050 ma.s.l. The topography of its watershed territory is mountainous and glacial.

Large number of lakes is possessed by high-mountain lanscapes of Gegham massif. The largest lake – Akna, is located 122 meters below the water divide at 3031 m a.s.l. It is surrounded by ancient volcanic cones, which consists of tuff and slags. The outflow is controlled by a human-made dam.

Lots of lakes are situated in the tundra belt of Syunik volcanic plateau, being originated inside depressions of volcanic and glacial relief. Enclosed lake Sev is situated at the southeastern slope of Ishkhansar Mountain, Syunik highlands, at 2660 m a.s.l. in a trough valley with volcanic cones besides it. From north and south lake is surrounded by steep slopes, other slopes are relatively shallow. On the steep slopes the numerous stone fields are located, moving downwards up to 4-8 cm per year (Boynagryan 2007). According to weather station located near Lake Kari, mean annual temperature in the region is around 6.7°C while mean annual precipitation is 560.7 mm. Watersheds of lakes Kari, Umroi and Akna are covered with alpine meadows, and also with mountain meadows for Lake Sev.

Present-day vegetation of lakes and their watersheds was described by S. Baloyan (2005) as well as during our studies (Gabrielyan and Sapelko 2018). A detailed investigation of the flora around the studied four lakes revealed the presence of 323 species of higher vascular plants. Aquatic plants of ***Lake Kari*** are mainly presented by rare species of Characeae. In the surroundings *Anthriscus nemorosa* (Bieb.) *Spreng., Bupleurum polyphyllum Ledeb., Chamaesciadium acaule* (Bieb.) Boiss., *Aster alpinus L., Jurinea moschus* (Habl.) *Bobr., Chamaenerion angustifolium* (L.) Scop., *Draba bruniifolia Stev., Campanula tridentata Schreb., Cerastium cerastoides* (L.) Britt. and other species are found.

Rare species of Characeae exist in ***Lake Umroi*** as well. In the surroundings *Allium szovitsii* Regel, *Carum caucasicum* (Bieb.) Boiss., *Bupleurum persicum* Boiss., *Chamaesciadium acaule* (Bieb.) Boiss., *Erigeron caucasicus Stev., Jurinea moschus* (Habl.) Bobr., *Taraxacum bessarabicum* (Hornem.) Hand., *Campanula aucheri* A. DC., *Silene ruprechtii Schischk*. and other species are widespread.

During underwater survey in ***Lake Akna***, we discovered a dense thicket species from Characeae family. Around the lake *Allium schoenoprasum* L. var *alpinum* Lam., *Allium szovitsii* Regel, *Bupleurum persicum* Boiss., *Chamaesciadium acaule* (Bieb.) Boiss., *Aster alpinus* L., *Jurinea moschus* (Habl.) Bobr., *Coluteocarpus vesicaria* (L.) Holmboe, *Vavilovia formosa* (Steven) Fed., *Draba bruniifolia* Stev., *Campanula tridentata* Schreb., Cerastium cerastoides (L.) Britt. and other species could be found.

On the date of our fieldwork, the water of ***Lake Sev*** was muddy green due to the presence of microbial algae communities. *Persicaria amphibia* (L.) Delarbre, *Carex caucasica* Stev., *Carex huetiana* Boiss. and other *Carex* grow inside the lake and on its shores. Alpine meadows and mountain meadows around Sev consist of: *Allium szovitsii* Regel, *Carum caucasicum* (Bieb.) Boiss., *Chamaesciadium acaule* (Bieb.) Boiss., *Dryopteris oreades* Fomin, *Aster alpinus* L., *Erigeron caucasicus* Stev., *Tanacetum chiliophyllum* (Fisch. et C.A. Mey. ex DC.) Sch. Bip., *Taraxacum bessarabicum* (Hornem.) Hand., *Hordeum violaceum* Boiss. et Huet, *Chamaenerion angustifolium* (L.) Scop., *Draba bruniifolia* Stev., *Urtica dioica* L., *Polygonum hydropiper* L., *Rumex crispus* L., *Papaver orientale* L., *Campanula aucheri* A. DC., *Silene ruprechtii Schischk*. and of other species. Unlike the other lakes, the coastal zone of Sev is covered with bushes of Rosa spinosissima L. Nearby Lake Sev, within the distance of 270-300 m, a small and shallow nameless lake is situated at 2667 m a.s.l. In contrast to Lake Sev, aquatic vegetation here is more widespread and presented by *Potamogeton gramineus* L. and other species. The shore is covered with *Sparganium neglectum Beeby*., etc.

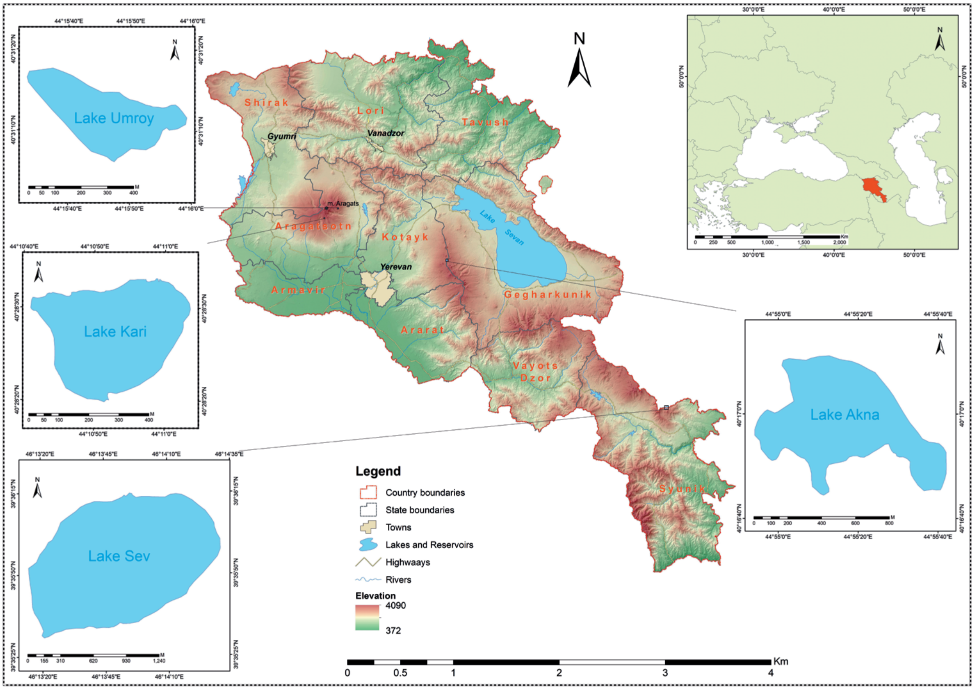

Fig. 1. Map of Armenia with studied lakes

METHODS

Multi-proxy investigations of four mentioned lakes included paleolimnological, geomorphological, hydrological, hydrochemical and biogeographical studies. Sediments of all the lakes were sampled for paleobotanical, carpological, diatom, geochemical and radiocarbon analyses. Bathymetric surveys allowed to obtain depth maps and 3D models of Lake Floor. We have also compiled geomorphological maps for watershed territories. Reconstruction of lake history is conducted in different spatial and temporal scales based on bottom relief and sediments, which allows discovering the main patterns of environmental conditions change.

Depth measurements were made with 0.1 m accuracy using echo-sounding device «Lowrance», equipped with a GPS receiver, for digital bathymetric elevation model creation. Total number of measured points is over 60000. A horizontal spatial resolution of derived DEM is 10 m.

Water samples were collected from at depth of 0.5m, near shore. Water sampling was done according to ISO 5667 and the requirements of the developed protocols and forms (ISO 5567-1:2006). Water temperature, dissolved oxygen, turbidity and pH were measured in-situ by advanced test kits (Hanna pH-meter, WTW 320i multi parameter device).

The collected water samples were labeled and transported to the laboratory in the special cooler box (under the <6°C) for the further test. In the laboratory, water samples were stored in the refrigerator for no more than a day.

In all sampling points we performed hydrochemical measures of the lakes for general ions, mineralization, conductivity, total hardness, BOD_5, COD, nutrients and 20 metals (Manual 1977; Standard methods for the examination of water and wastewater 1998). The mineralization of lake water was assessed as the sum of general ions (calcium, manganese, potassium, sodium, sulphate, chloride, bicarbonate) (Guidance… 1977; Standard methods for the examination of water and wastewater 1998). Total hardness of water was assessed as the sum of calcium and manganese equivalents amount. Concentrations of calcium, manganese, potassium, sodium, total phosphorus, as well as 20 metals (Li, Al, Ti, V, Cr, Fe, Mn, Co, Ni, Cu, Zn, As, Se, Sr, Mo, Cd, Sn, Sb, Ba, Pb) were determined by ICP-mass spectrometric methods on ISO 17294-2:2005 via Elan 9000 device. Concentrations of sulphate, chloride and nitrate were determined by ion-chromatography method on ISO 10304-1:2007 via Dionex 1000 device. Concentrations of bicarbonate in water samples were measured by Turbidimetric method on GOST 20806-228:069 (02)-77.

Lake sediments were sampled using Russian corer with 5 cm chamber diameter from a platform mounted on a catamaran. The corers consist of single 1 m length corers, sampled with overlapping to provide a continuous sediment sequence. Radiocarbon dating (AMS) was performed by Institute of Geography, Russian Academy of Sciences. The calibrated age ranges were calculated using CALIB REV7.1.0 and the Intcal 13 dataset (Stuiver et al. 2019; Reimer et al. 2013). The range represents the 2-sigma values, and the median ages are in parentheses (Table 1). We performed preliminary lithological description and photography during the fieldwork. Then, in the laboratory, in the process of core splitting, we refined the borders between stratigraphic units, as well as their lithological composition. Further correlation of overlapping cores was made based on lithostratigraphy.

RESULTS

Lithostratigrsphy and chronology

Lake sediment thickness for all the studied lakes is relatively low and cored successions length does not exceed 2 m. Cores mainly consist of loam, sand, gyttja and, in some of the lakes, peat (Fig. 2). Seven cores were retrieved from different parts of Lake ***Kari***. Cores 1-3 were retrieved at the sampling point 1 (40°17'6" N; 44º6'26"E), cores 4-7 – at the sampling point 2 (40°17'1" N; 44º6'35"E). Cores 3 (water depth 2.28 m), 5 (water depth 1.2 m) and 7 (water depth 1.9 m) were split for carpological analysis soon after coring. The longest ones are the cores 2, 4 and 6, they are about 50-55 cm long. Apparently

Table 1. Radiocarbon ages (AMS) for sediments of Kari and Umroi lakes

Lake, core number	Depth, m	Lab Number	Material Dated	Radiocarbon Age, ^{14}C yr BP	Calibrated Age, cal yr BP (2σ range, median)
Kari-6	2.43	IGAN-6540	plant macrofossils	3730±30	3981–4154 (4080)
Kari-6	2.19-2.21	IGAN-6541	plant macrofossils	1430±35	1291–1382 (1329)
Kari-6	2.07-2.09	IGAN-6542	plant macrofossils	1055±30	926–1051 (960)
Kari-6	2.00-2.01	IGAN-6543	plant macrofossils	585±30	535–651 (604)
Kari-6	1.96-1.97	IGAN-6544	TOC	680±35	559–683 (648)
Umroi-4	4.42-4.44	IGAN-6545	TOC	6285±40	7156–7313 (7216)
Umroi-4	4.15-4.17	IGAN-6546	TOC	2915±40	2945–3179 (3057)
Umroi-4	4.03-4.05	IGAN-6547	TOC	2925±30	2973–3163 (3072)
Umroi-4	3.84-3.86	IGAN-6548	TOC	2415±20	2348–2700 (2455)
Umroi-4	3.40-3.42	IGAN-6549	TOC	650±20	560–666 (591)

these sediment sequences represent all the history of the lake. According to AMS-dating, these sediments have been accumulated within 4000 cal years BP. Underlying formation is a dense sandy loam. Cores number 1, 3, 5 and 7 are 22-39 cm long.

Sediment sequences of Lake *Umroi* were sampled at one point (40°18'46"N; 44º9'21"E) with water depth 3.35 m, six cores were retrieved (Fig. 2). Maximum sediment thickness is 1.17 m. Lithostratigraphical analysis and radiocarbon dating were performed. Lithological unit borders are the same in primary and secondary sediment sequences, except well-distinguished layer of coarse sand located at 4.05-4.06 depth in the primary sediment sequence and not presented in the secondary. Laminated loam thickness is significant in the bottom part of sediment sequences. Thickness of organic sediments is low. According to radiocarbon dating, sediments of Lake Umroi were formed within 8000 cal years BP (Table 1).

At the Lake *Akna*, four sediment sequences were retrieved at one sampling point (40°16'47" N; 44°55'38" E). All four successions are duplicative for different analyses (Fig. 2). Maximum sediment thickness is 0.92 m. Bottom part of the sediment sequences contains gravel or pebbles. Above the interbedding of dark and lighter interlayer of the clay gyttja begins. Then gyttja becomes more organic and liquid. Upper parts contain a significant number of non-decomposed organic remains. Sediments from all the lithological units were sampled for radiocarbon dating.

At Lake *Sev*, 3 sediment sequences were retrieved, each composed of 3 single cores, from one sampling point (39°35'47" N 46°13'25" E). Maximum sediment thickness is 2.52 m (from cores 1, 2 and 3). Other cores are duplicative. Bottom part of sediment sequences consists of densely laminated loam with presence of seeds, loam is gradually becoming homogenous. Above there is the clayey gyttja, which is periodically substituted by peat gyttja with

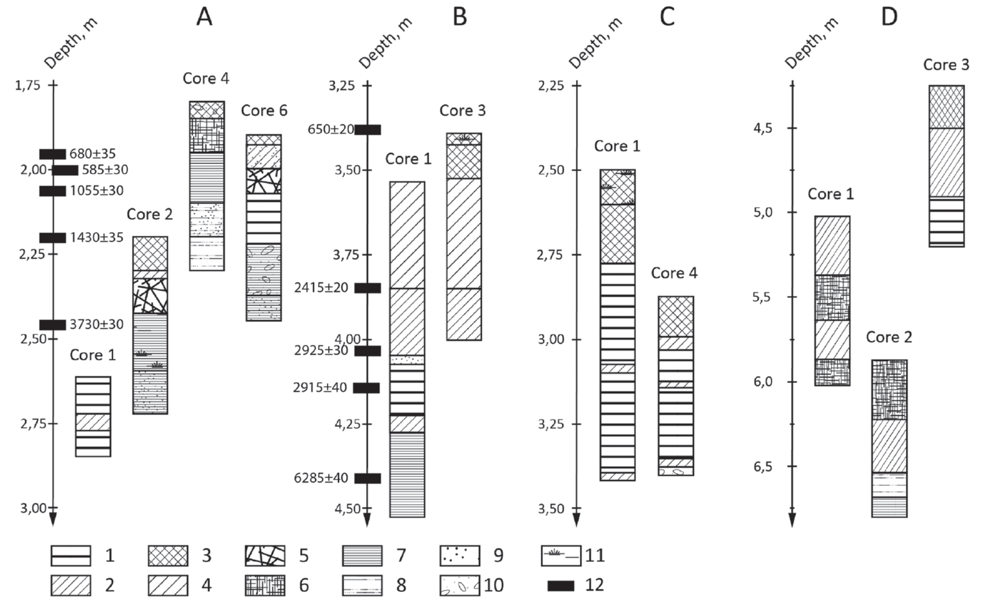

Fig. 2. Lithostratigraphy of lake sediments: A – Lake Kari, B – Lake Umroi, C – Lake Akna, D – Lake Sev. Legend: 1 – brown and dark-brown clayey laminated gyttja; 2 – brown and dark-brown clayey homogenous gyttja; 3 – liquid organic gyttja; 4 – light-brown homogenous gyttja; 5 – peat with organic remains; 6 – black peat gyttja with organic remains; 7 – laminated loam; 8 – homogenous loam; 9 – sand; 10 – gravel and/or pebble; 11 – organic remains; 12 - Radiocarbon Age, 14C yr BP.

a significant number of non-decomposed organic remains. Upper part of sediment sequences is liquid organic gyttja without visible remains, some ruptures present. Samples for radiocarbon analysis were collected from all lithological units, mostly near unit borders.

According to radiocarbon ages age-depth models for Kari and Umroi lakes were constructed (Fig. 3). As it is shown, sedimentation rates varied in time during the Holocene. It is intended to refine these models based on pollen analysis results in the future.

Geomophology and the lakes morphometry

Geomorphological data were obtained for the four studied lake basins and their watersheds. Relief of lake basins was investigated on the base of created digital models (Naumenko et al. 2014). Digital models of underwater relief allowed studying basins carefully and therefore to obtain morphometric values for Kari, Umroi, Akna and Sev lakes (Fig. 4). Direct depth measurements were made by echo-sounding device with GPS positioning which allowed to create digital morphometric models. It should be noted that values of a lake water volume and coastline length depend on water level and they are determined by seasonal dynamics of water balance components: precipitation, evaporation and snow amount on watershed territory.

Prior to our research, only topographic maps (Boynagryan 2007) and direct measurements (Arnoldi 1931) supplied morphometric values of the lakes. In this study, for the first time we created a digital model with 10 × 10 m spatial resolution offering statistical characteristics for depth distribution, water volume and other parameters. The model allowed to refine lake surface areas and maximum depths reported before (Table 2).

Lake Umroi lies in an intermorainal depression, is oviform and oriented along NW-SE direction. There is a shallow bay in the south-east part of the lake, which is separated from the main basin by rock ridge during low water level. Lake Basin is trench-shaped with hogbacked bottom and large boulders. Maximum depths are situated in the north-western part of the lake and exceed 10 m according to our measurements (Fig. 4). Coast is mainly steep, consist of coarse colluvial material. Swampy sites exist near the three inlets flowing from north-west, north and east. Lake Umroi is fed primarily by snow and snowfields melt. Relief of watershed territory is mountain and glacial. In the south and in the north-west, the lake is surrounded by steep slopes of a cirque-shaped rock fold, exposed in a north-eastern direction. Altitudes of its ridge are 3283-3372 m. A thick moraine field lies between the lake and a wide corrie in a rock ridge to the North. Three terminal moraines are well-distinguished here. Smaller lakes are situated in the lows between these moraine ridges according

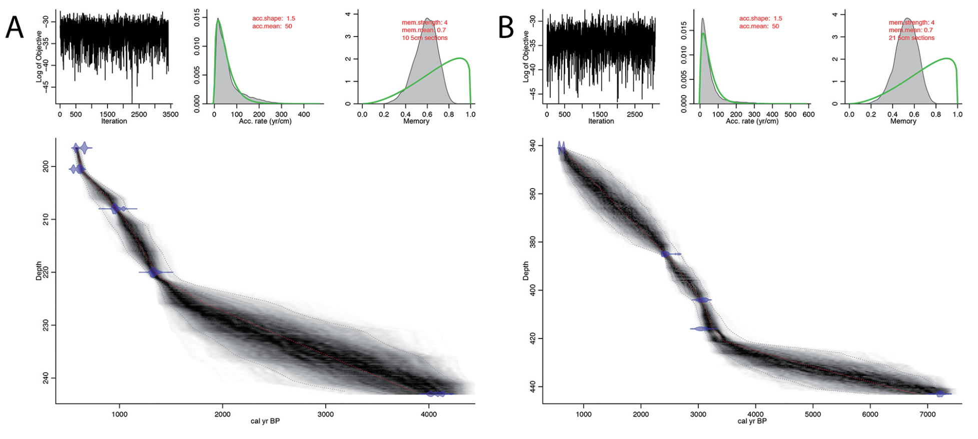

Fig. 3. Age-depth models for Kari (left) and Umroi lakes (right)

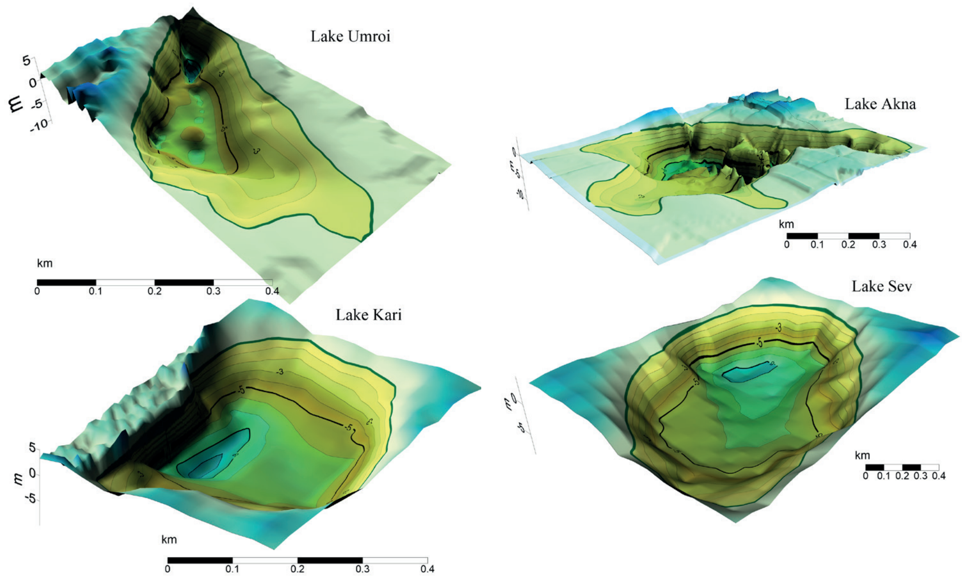

Fig. 4. 3D-view of studied lakes floor from Lake Umroi, Lake Kari, Lake Akna and Lake Sev

to topographic maps. It could be assumed that these moraines correspond to stationary termini positions of a retreating glacier in the Holocene during the last phase of Caucasus glaciation decline (Shnitnikov 1985). Retreat of the glacier to the North probably led to a formation of moraine-dammed Lake Umroi.

Coastline of Lake ***Kari*** is not indented. Watershed territory is made up of volcanic rocks and possesses a knob-and-basin topography, having traces of last glaciations, which existed on the Armenian plateau in the Late Pleistocene and Holocene. Altitudinal range of a relief is 50-250 m. Lake basin is dammed by ancient moraine remains, significantly eroded. Lake is fed mainly by snow and snowfields melt, and groundwater inflow. North-eastern bank is swampy, spring-water outflows are observed. Present-day water level is controlled by human-made dam with a spillway. Outflow takes place in spring and in summer, during ablation season. Coastline is rocky, made of colluvial boulders and pebble, partly swampy with light-grey sand and silt. Bottom is flat, saucer-shaped (Fig. 4). Maximum depth 9.8 m was discovered in the central part of Lake Basin, closer to the northern side of the shore, which adjoins the steepest mountain slope.

Lake ***Akna*** basin is made up of volcanic rocks and lies in a depression surrounded by ancient volcanic cones, consisting of tuff and slags, elevated for 50-450 m above the lake. Coastline is indented with small bays and gulfs. According to the studies of the 30s of XX century (Arnoldi 1931), interannual water level change is more than 2 m. Thus, lake surface area and depth vary significantly. The highest water level is observed in summer, while the lowest – in February and March. During our fieldworks in August 2018, water level was 0.3-0.5 m below maximum judging by coastal terraces. Several smaller shallow lakes were isolated from the south-eastern gulf of the Lake Akna, as the bathymetric map created by Arnoldi (Arnoldi 1931) shows. Lake Akna is mainly fed by snow melt. Snowfields of the surrounding slopes ensure the level rise of the several temporal watercourses in the warm season. Outflow from the lake takes place by a canal in the north-western part of a basin, controlled by a human-made dam and used for pasture irrigation. Relief of lake bottom is complex: bathymetric survey revealed two depressions separated by a slight ridge (Fig. 4). Lake sediments vary in grain size and in material and depend on depth. Nearby lake shore, in the East and the South, coarse sediments, consisting of andesite-basalt and rusty-brown tuff,

Table 2. Morphometric values from digital lake floor models

Morphometric value	Lake			
	Umroi	Kari	Akna	Sev
Number of pixels	1152	1465	3790	12105
Area, km^2	0.117	0.146	0.496	1.747
Volume, m^3	$365.1.10^3$	$661.9.10^3$	$1843.1.10^3$	$7791.3.10^3$
Average depth, h_{mean}, m	3.2	4.5	3.7	4.5
Median, m	2.6	5.0	3.2	5.0
25% quartile, m	1.0	2.4	1.6	2.5
75% quartile, m	5.5	6.5	5.3	6.3
Max. depth, h_{max}, m	10.9	9.8	12.4	8.5
Standard deviation, δ_h, m	2.46	2.40	2.75	2.31
Coefficient of variation, δ_h / h_{mean}	0.77	0.53	0.74	0.52
h_{mean} / h_{max} ratio	0.29	0.46	0.30	0.53
Perimeter, km	1.55	1.52	3.86	5.01
Shoreline development	1.28	1.12	1.55	1.07

dominate. In the shallow parts fine sand and light-grey or yellow silt are widespread.

The basin of Lake ***Sev*** is situated in a trough valley with volcanic cones besides; elevated from 3073 to 3550 m. Lake is oviform and elongated from South-West to North-East. According to our measurements, lake surface area is 1.77 sq km and maximum depth is 8 m (Fig. 4). Lake is fed primarily by liquid precipitation and snowfields located on volcanic slopes. High water surface temperature (18-20°C) observed at the moment of fieldwork (August 2018) could be explained by relative shallowness of the lake, intensive water overturn and water warm-up. It is notable that the water is turbid and green due to presence of algae. No outflows were discovered. Bottom sediments are presented by light-grey silt and sand. The steepest northern bank is made up of coarse colluvial material.

Hydrochemistry

The hydrochemical study results showed that the water of lakes Kari, Umroi, Akna and Sev has hydrocarbonate-calcium-sulphate nature with low mineralization and hardness. Water in lakes Umroi, Akna and Sev has light alkalinity pH, whereas water in Lake Kari has neutral environment. The oxygen regime in lakes Umroi and Akna was normal for the functioning of the lake's biodiversity, compared to the other two lakes where dissolved oxygen was dissatisfied. These two lakes Kari and Sev were also distinguished by comparatively high turbidity. The concentrations of V, Cr, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sn, Sb, Pb were below 5×10-5 mg/l. Despite some similarities, all the four observed lakes differed in their unique hydrochemical regimes, which did not correspond to each other.

DISCUSSION

Depth distributions for the three lakes (Kari, Umroi and Sev) are relatively simple, as well as the shapes of their basins. In each basin only one depression with a maximum depth exists. Maximum depths are located not exactly in the center, but closer to the shore. Mean depth to the maximum depth rate varies from 0.29 (Lake Umroi) to 0.52 (Lake Sev). Lake Akna is the deepest of the studied lakes and possesses a highly dissected bottom relief and an indented shoreline.

Lake Kari: the water of lake distinguished by the lowest mineralization and concentration of main ions, low content of organic pollutants, as well as low content of nutrients (nitrate, phosphate and ammonium ions). However, the lake had relatively high turbidity, water temperature and low oxygen content, which might be a result of the source of the lake feed (mainly surface flows, melting waters) and water depth. Sediment thickness is the lowest among the studied lakes. The longest core retrieved is 0.55 m. However, large amount of described lithostratigraphic units indicates significant changes of sedimentary conditions during the 4000-year period of Lake Kari existence. Low sediment thickness may be determined by severe environmental conditions: according to our botanical descriptions, the vegetation cover on Lake Kari catchment is the sparsest and poor as compared to the three other lakes.

Lake Umroi: the water of the lake distinguished by the highest concentration of sulphate and nitrate ions. The limiting nutrient is phosphorus. This may be the result of the presence of an underground water flow at the bottom of the lake. The lake was formed 3000 years earlier than Lake Kari and the sediment thickness here is higher. The longest succession sampled is 1.17 m. Maximum depth is relatively large – 10.9 m, this promotes more inorganic sedimentation as compared with the other lakes. Here, the thickest mineral sediments were found, while organic gyttja layer is the thinnest. However, according to heterogeneity of

Table 3. Hydrochemical characteristics for the studied lakes

	Lake			
	Kari	Umroi	Akna	Sev
pH	7.72	8.02	8.96	8.67
Cond. µS/cm	22	27	24	116
Ca µeq/l	135.90	187.31	183.81	961.72
Mg µeq/l	31.76	39.53	44.93	197.52
Na µeq/l	29.83	21.12	15.70	71.70
K µeq/l	15.28	28.80	16.71	107.25
HCO_{3-} µeq/l	250.08	300.10	350.11	1200.39
SO_4^{2-} µeq/l	41.08	51.57	36.21	45.55
Cl- µeq/l	27.01	28.09	24.61	67.35
NO_{3-} µgN/l	1.76	3.28	0.64	0.27
NH_{4+} µgN/l	1.98	0.99	2.97	0.74
TP µg/l	0.1–1ppb	0.1–1ppb	13.24	92.25

lithostratigraphy, during the last 7000 years lake sediments were forming under changing environmental conditions.

Lake Akna: the water of the lake distinguished by a relatively high level of BOD and COD, which indicates the existence of the high level of organic compounds. However, the dissolved oxygen was 7 mg/l, which is favorable for aquatic biodiversity. Lake Akna revealed the most intensive Charophyceae bloom. The normal oxygen regime can be caused by the periodic flow of surface water into the lake. Lake Akna is the deepest among the studied lakes; maximum depth measured is 12.4 m. Sediment thickness does not exceed 1 m. Basing on lithology, it could be assumed that deposition environment was the most stable. Transition to the organic gyttja in the upper part of the sediment cores is the clearest.

Lake Sev: the lake has a completely different hydrochemical regime compared to the three other lakes. The lake is characterized by the highest concentrations of the hydrocarbonate, chloride, phosphate, sodium, magnesium, potassium and calcium ions, as well as iron, strontium and barium. The Lake distinguished by the high content of phosphorus except for the nitrogen, which was a limited nutrient for the lake. In addition to the content of nutrients, the lake water also showed the high content of organic compounds and turbidity. These indicate the existence of the active eutrophication processes in the lakes. Lake Sev is located at a lower altitude than the other lakes and hence the vegetation of its catchment is the most diverse. It is covered with alpine and mountain meadows, the latter are not present within the catchments of the other three lakes. Lake is the shallowest (maximum depth around 8.5 m), while sediment thickness (2.52 m) is the highest. Basing on lithology, we assume that depositional settings had changed drastically: there are thick layers of peat gyttja indicating sudden water level decrease.

CONCLUSION

The results of the multi-proxy research allowed to obtain data on poorly studied high-mountain Armenian lakes. The research provided the first-time statistical characteristics of depth distribution, water volume and other morphometric values. The deepest lake among the studied is Lake Akna, the shallowest and the largest is Lake Sev. The hydrochemical results are important for further paleolimnological reconstructions. All the samples were collected while the fieldwork with the time of sampling. So, the hydrochemical results can be intercompared. The first time, the hydrochemical regime was studied for 41 parameters for four target lakes. The hydrochemical study results showed that the water of the Umroy, Kari, Akna and Sev Lakes has hydrocarbonate-calcium-sulphate nature with low mineralization and hardness. Water in the lakes Umroy, Akna and Sev has light alkalinity pH, as well as water in Kari Lake has neutral environment. The oxygen regime in the lakes Umroy and Akna was normal for the functioning of the lake's biodiversity, compared to the other two lakes where dissolved oxygen was dissatisfied. These two lakes (Kari and Sev) were also distinguished by comparatively high turbidity. The concentrations of V, Cr, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sn, Sb, Pb were low of the 5*10-5 mg/l. Despite some similarities, all four observed lakes differed in their unique hydrochemical regimes, which did not correspond to each other. According to hydrochemical analysis, Lake Sev has the most eutrophic water. The smallest surface area belongs to Lake Umroi, though its depth is relatively high exceeding 10 m. Kari lies at the highest altitudes, and therefore the water and coastal vegetation of lake is poor. 1. Lake sediments sequence and radiocarbon dates were sampled and analyzed for the first time, none of small Armenian lakes were sampled for radiocarbon dating before the described ones. According to our results, all the studied lakes were formed during the Holocene. Sediments of Lake Kari were deposited in the last 4000 years, of Lake Umroi – within the last 7000 years, while maximum thickness of sediments is around 1 m in both lakes. We assume low deposition rate in Armenian high-mountain lakes, however it varied significantly in different periods of lake history.

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