Tectonic impact on the Lake Sevan environment (Armenia)

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Abstract The geology of Lake Sevan is characterized by the structure of a pull-apart basin. Methane emission from the lake surface correlates with evidence of physical and chemical water properties, remote sensing, etc., and suggests its possible emission from active fault zones at the lake bottom, as well as emission of biogenic methane from the fermentation of bottom organic remains. Correlation with anomalies in the lake bottom geochemistry suggests a high permeability of active fault zones and suggests that geodynamic, seismic and geochemical activity across the fault zones during the buildup to the M = 7.1 Spitak earthquake led to plankton depression, which resulted in a large number of fish dying in 1984, and ended with a seismic disaster in 1988.

Keywords Active faults · Lake Sevan environment · Methane emission · Pull-apart basin

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Introduction

Lake Sevan (33.4 km^3 volume and 1,241 km^2 water surface area) is in the northern part of the Armenian Upland at an altitude of 1,897 m above sea level (Fig. 1). It has a great impact on the climate, environment and economy of Armenia and its neighboring states. In 1933, artificial withdrawal of water and lowering of the water level took place for energy and agriculture needs. Between 1937 and 1996, the water-table level dropped 19.3 m, the water surface area decreased by 175 km^2, and the volume of lake water was reduced by 25 km^3 (Manukyan 1996). The lake passed from oligotrophy to eutrophy, accompanied by the formation of enormous plankton masses, and changes in flora and fauna.
Recognizing that Lake Sevan basin is one of the principal agricultural regions in Armenia, and that water resources of the lake present the sole fresh water source for the region, the RA Government has made efforts to minimize the consequences of this environmental catastrophe (Kirakosyan 1996; Ohanyan 1996).
This paper addresses the complex issues of anthropogenic and endogenous environmental changes in Lake Sevan basin and relates them to geological activity and other environmental processes based on monitoring of the plankton population between 1979 and 1997, and the rapid decline in fish population in 1984.

Geological structure and origin of Lake Sevan

Lake Sevan is triangular-shaped (Fig. 2). The NE coast is a large Upper-Cretaceous ophiolitic structure, whereas western and southern lake margins are formed by linear volcanic ridges that are noted for their Quaternary volcanic activity.
The geology of the lake basin has been investigated (Milanovski 1980; Knipper 1983; Satian 1984, 1990); however, few researchers have addressed the issue of the origins of Lake Sevan. Previous studies have speculated that the lake formed as a result of a volcanic dam at its NW flank (Vardaniants 1948; Aslanian 1979; Milanovski 1980). Structure and geology of the lake bottom have not been studied.

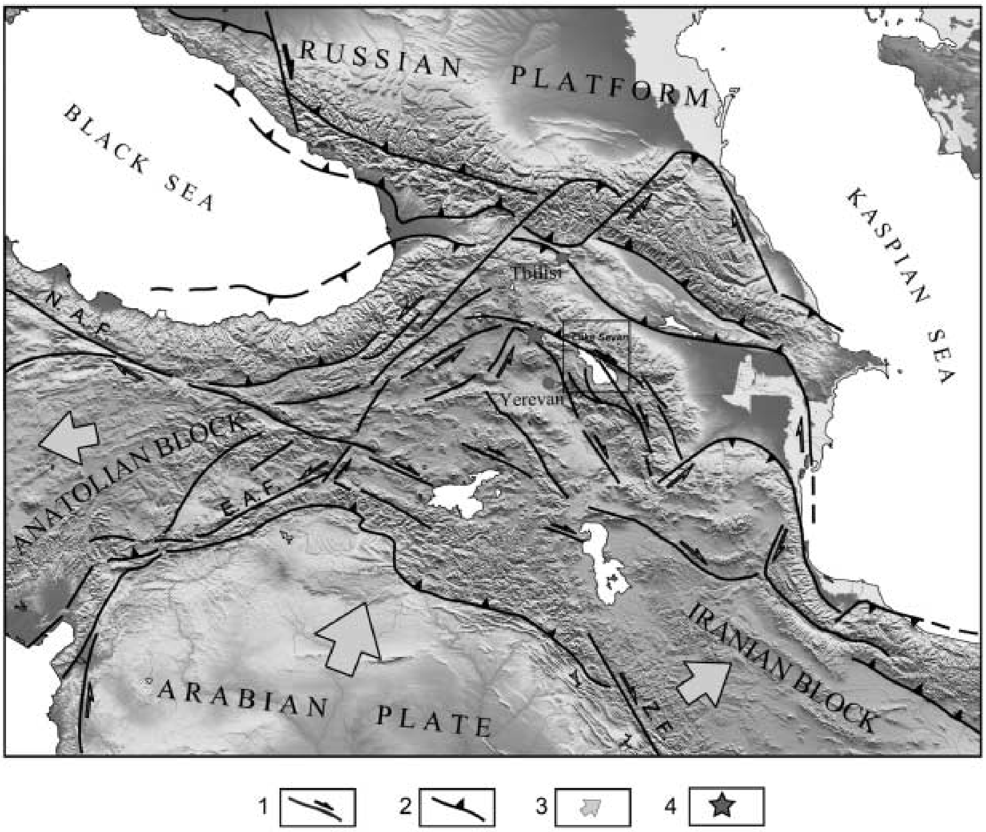


Fig. 1
Geodynamic Scheme of the Armenian Upland territory. *1* Active strike-slip faults; *2* active thrust faults; *3* displacement directions for lithosphere plates and blocks; *3* epicenter of the 7.12.1988 Spitak earthquake

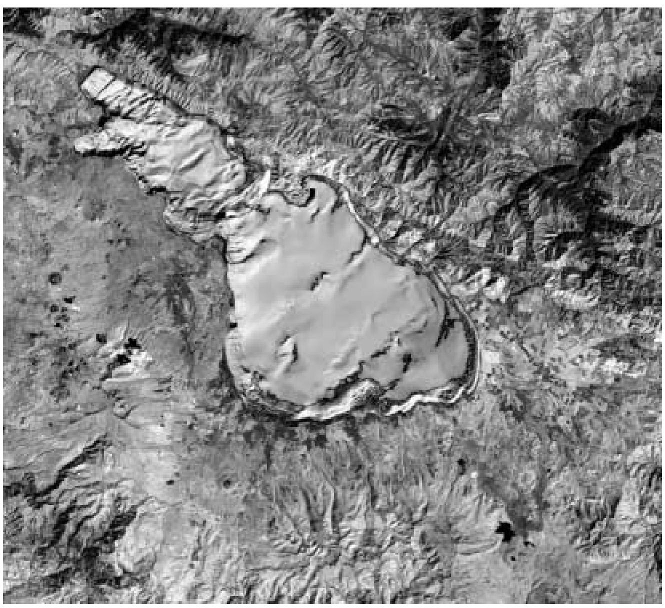


Fig. 2
Landsat-TM space image of the Lake Sevan bottom with inserted digital model (DEM)

Recent studies have included active tectonics, geodynamics, and seismic and volcanic activity in the Lake Sevan basin and adjacent areas (Philip and Karakhanian 1999; Philip and others 2000). A hydrogeology model for the Lake Sevan basin has been suggested (Grillot and Bodoyan 1997). Spot and Landsat-Thematic Mapping space images, along with detailed air photography, have been used in the research. Fieldwork has assessed tectonics, paleoseismicity, volcanism and geochemistry.

To study the relief and structure of the lake, a digital model (DEM) of the bottom has been produced from bathymetry mapping (Fig. 2).

Two large W–NW-striking active faults border Lake Sevan to the north and south (Fig. 3). Both faults are right strike slips with a combination of reverse components on their northern and southern sides. Shorter systems of oblique active faults occur on the lake flanks to the west and to the east. These systems are a combination of strike slips and normal faults. The faults form grabens. The digital model for the lake bottom (DEM) suggests the presence of a system of NE normal faults arranged in stepped grabens (Figs. 2 and 3).

Lake Sevan is a large pull-apart basin formed by two large NW strike-slip faults and a system of oblique extension faults (Fig. 3). Right strike-slip motions along the faults cause intense extension at the sites of “en echelon” fault overstepping. The extension, in turn, forms large tectonic basins containing inner systems of normal faults and grabens (Burchfiel and Stewart 1966; Rahe and others 1997). This supports the concept of a large pull-apart basin as the most probable geodynamic origination model for Lake Sevan (Fig. 3). The lake is in the central part of the pull-apart basin, and is flanked by a system of obli-

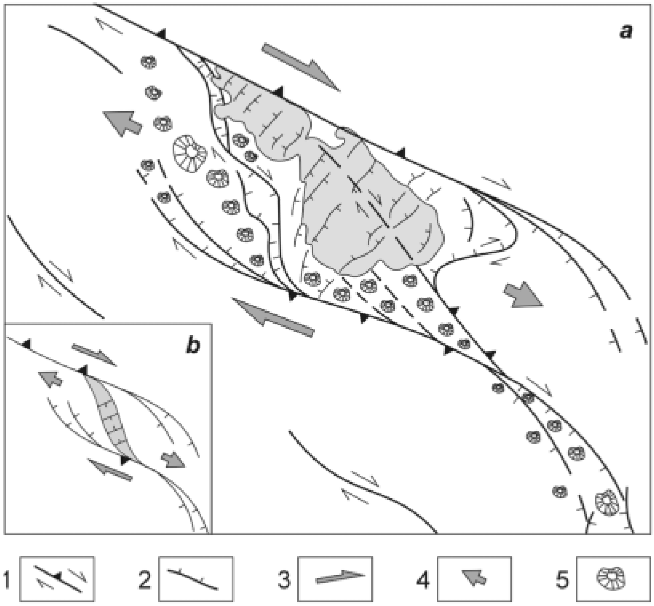


Fig. 3
Sevan pull-apart basin. **a** Geodynamic scheme of the Sevan pull-apart basin. **b** Principal formation model for the Sevan pull-apart. *1* Active strike-slip faults; *2* active normal faults; *3* main fault displacement directions; *4* stress field directions; *5* volcanoes

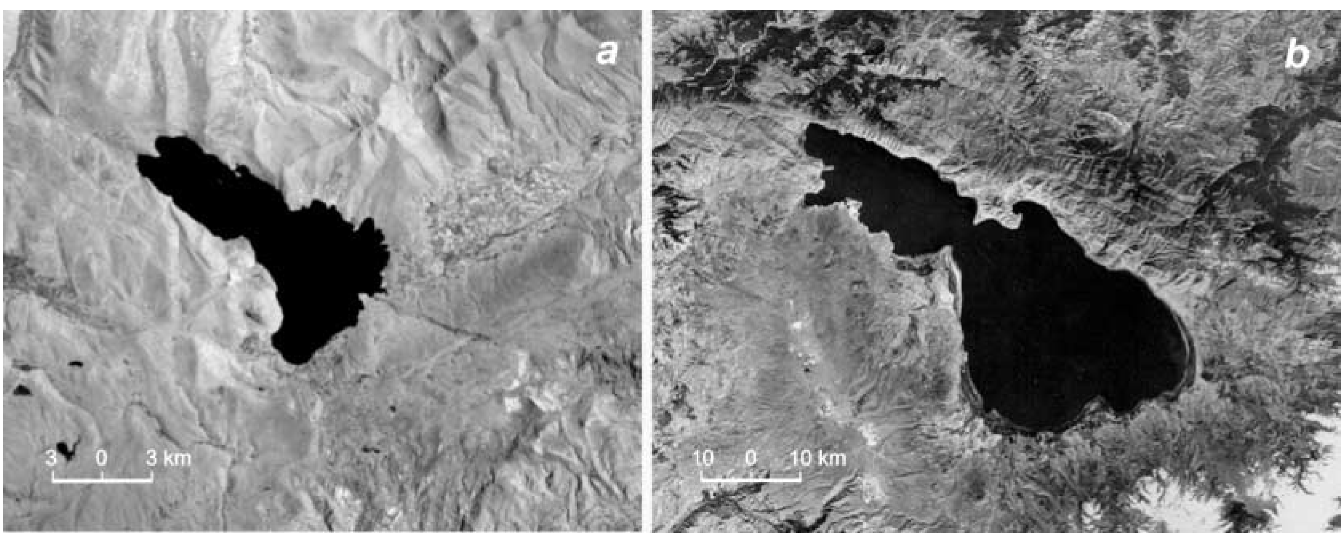
que grabens and young volcanism zones. Formation of the Sevan basin took place throughout the Holocene and continues at present as evidenced by numerous landscape deformations, seismic activity and volcanism of Holocene and recent historical age (Karakhanian and others 1997; Philip and Karakhanian 1999; Philip and others 2000).

Fig. 4
Space images of **a** Balik-Goël Lake (NE Turkey) and **b** Lake Sevan. Both lakes were formed within the limits of pull-apart basin structures

Formation of large water reservoirs inside active structures of pull-apart basins is quite common elsewhere (Sharp 1975; Rodgers 1980; Aydin and Page 1984; Barka and Kandinsky-Cade 1988). The geometry of lakes and pull-apart basins is quite similar (Fig. 4a, b).

Methane emission from the lake surface and geochemistry of its bottom

Objectives included in this study included estimation of methane emission rates at different sites across the surface of Lake Sevan, assessment of anthropogenic constituents resulting from the fermentation of accumulated eutrophication biomass (Evans 1996), and assessment of endogenous sources contributed by gas emission from lithosphere fault zones (Holbrook and others 1996; Moretti 1998).
To measure methane emission, four sites were selected within the lake system (Fig. 5) in terms of maximum possible (site 3) and least probable (sites 1, 2 and 3) accumulation of organic material on the lake bottom. The observation period included autumn 1997 and summer–autumn 1998. Methane emission was measured using a device designed for gas emission measurements at water surfaces (Melconyan and others 1999). Emission rate was estimated from the slope of methane accumulation curve over time. Methane content in air samples from the chamber was measured in situ by a portable chromatograph with a flame ionization detector. In parallel, physical and chemical parameters were measured in the lake water sampled from different depths. Water sampling was made with a SEBA 105/5C2 bathometer at 5- to 10-m-depth intervals. Water temperature, pH, Eh, and dissolved oxygen content were measured with a WTW-320 pH-meter and WTW OXI-96 oxymeter. Measurement results for August–November 1998 (Fig. 6) are of the



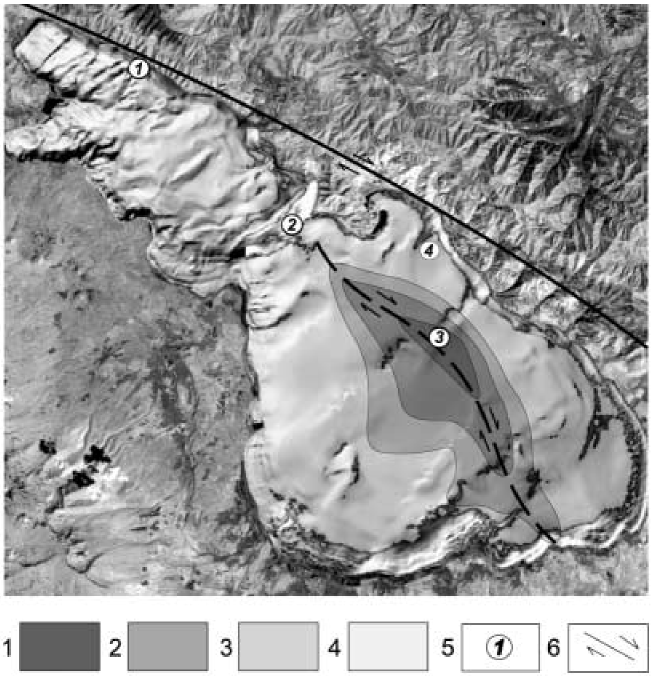


Fig. 5
Geochemical anomalies of the Lake Sevan bottom and sites of methane emission measurement from the aquatic surface. *1* Cl^- >100 mg/100 g; *2* Cl^- 50–100 mg/100 g; *3* Cl^- 30–50 mg/100 g; *4* Cl^- <30 mg/100 g; *5* methane emission measurement sites; *6* active faults

greatest interest for the analysis of methane emission and its dynamics. Methane emission rate was constant at sites 1 and 2 throughout the measurement period (Fig. 6). No methane emission was recorded for site 4. The site 3 record showed a high emission rate in August–September – a period characterized by higher water temperature and boosted plankton proliferation – and a drop in rate in November (Fig. 6).
Physical and chemical water characteristics at the measurement sites are of interest for the analysis of methane emission results. Figures 7 and 8 provide Eh and oxygen content measurement data for sites 1, 2 and 3. At site 3, Eh levels at a depth of 20 m dropped sharply to values of <minus 100 to minus 150 mV in September–October. The original level was regained in November. Similar phenomena were not observed at sites 1 and 2 (Fig. 7a). Site 1 did not show a significant Eh decrease along the full depth (Fig. 7b), whereas at site 3, Eh values were considerably lower starting from 10–15 m depth (Fig. 7c). Dissolved oxygen data were consistent with the Eh data. In September–October, there was a considerable reduction in oxygen content at 20-m depth at site 3, however, this was not the case for sites 1 and 2 (Fig. 8a). Likewise, for Eh, oxygen content did not decrease considerably with depth at site 1 (Fig. 8b), but in September–October a sharp reduction in oxygen content was noted at site 3 from a depth of 10 m (Fig. 8c). In August–September, the pH value dropped from 9.06 to 8.24 at a depth of 20 m (site 3), which could be correlated with the presence of hydrogen sulfide found at this depth. At sites 1 and 2, pH value did not fall below 8.64, and hydrogen sulfide was not observed.

Discussion

Measurement of greenhouse gas emission (for instance, methane and carbon dioxide) has been increasingly emphasized during recent years in view of global climate warming (Graedel and McRae 1980; Khalil and Rasmussen 1989; Houghton 1997).
In the search for mitigating factors it is important to identify man-made sources of greenhouse gas. The results obtained for methane emission from the lake surface can by classified into the three groups:

1. Emission without significant seasonal fluctuation within the entire period of observation (sites 1 and 2). At these sites, physical and chemical water parameters point to the absence of methane fermentation (no plankton accumulated, anaerobic conditions, high Eh rate, etc.);
2. Emission throughout the entire period of observation with peak values in September–October (site 3). This is the time of the most intense plankton bloom and methane fermentation conditions in the lake (i.e., considerably lower Eh value and dissolved oxygen content, accumulation of plankton). Presence of hydrogen

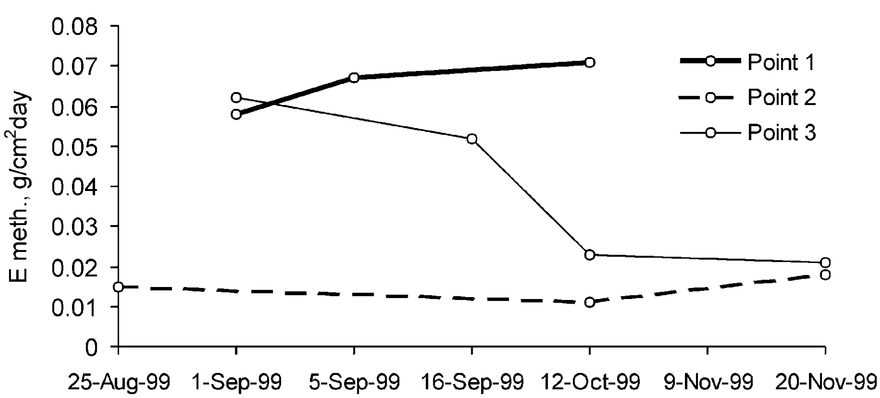


Fig. 6
Dynamics of changes in methane emission rate from the lake surface at sites 1, 2, and 3

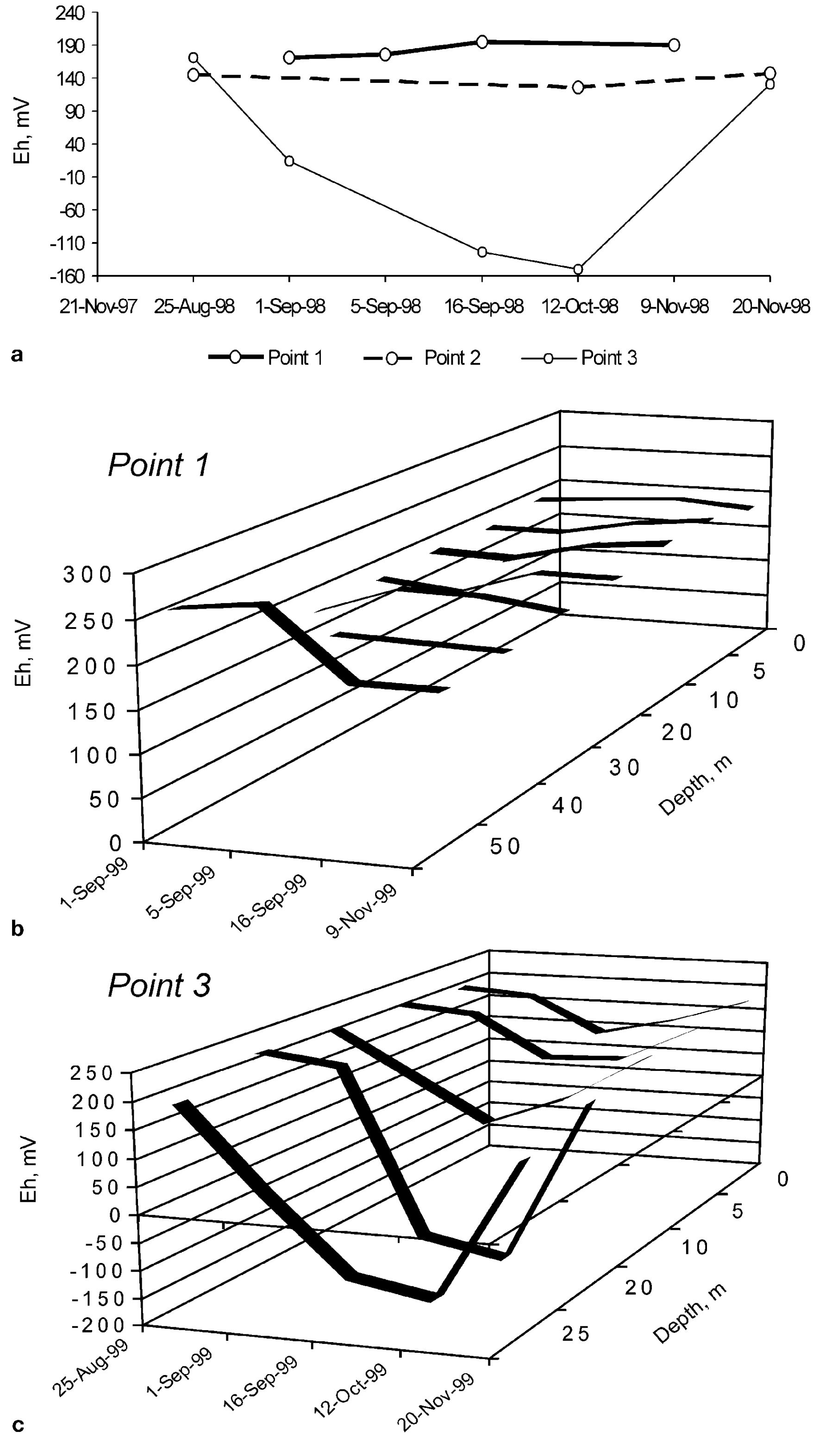


Fig. 7
Dynamics of Eh changes in the water of three sites tested in Lake Sevan: **a** dynamics of Eh changes for the three sites at a depth of 20 m; **b** dynamics of Eh changes for site 1 at different depths; **c** dynamics of Eh changes for site 3 at different depths

sulfide at a depth of 15 m (site 3) may be an additional indicator of possible methane fermentation during this period.

3. Absence of methane emission (site 4).

This suggests the endogenous nature of methane emission at sites 1 and 2 and its association with active fault zones. The higher rate of methane emission at site 1 might be explained by its location in the zone of the main Pambak–Sevan active fault. Similarly, site 2 is in the inner zone of the Sevan pull-apart faults.

Most probably, emission at site 3 stems from two phenomena: the active fault in the zone; and in August–Sep-

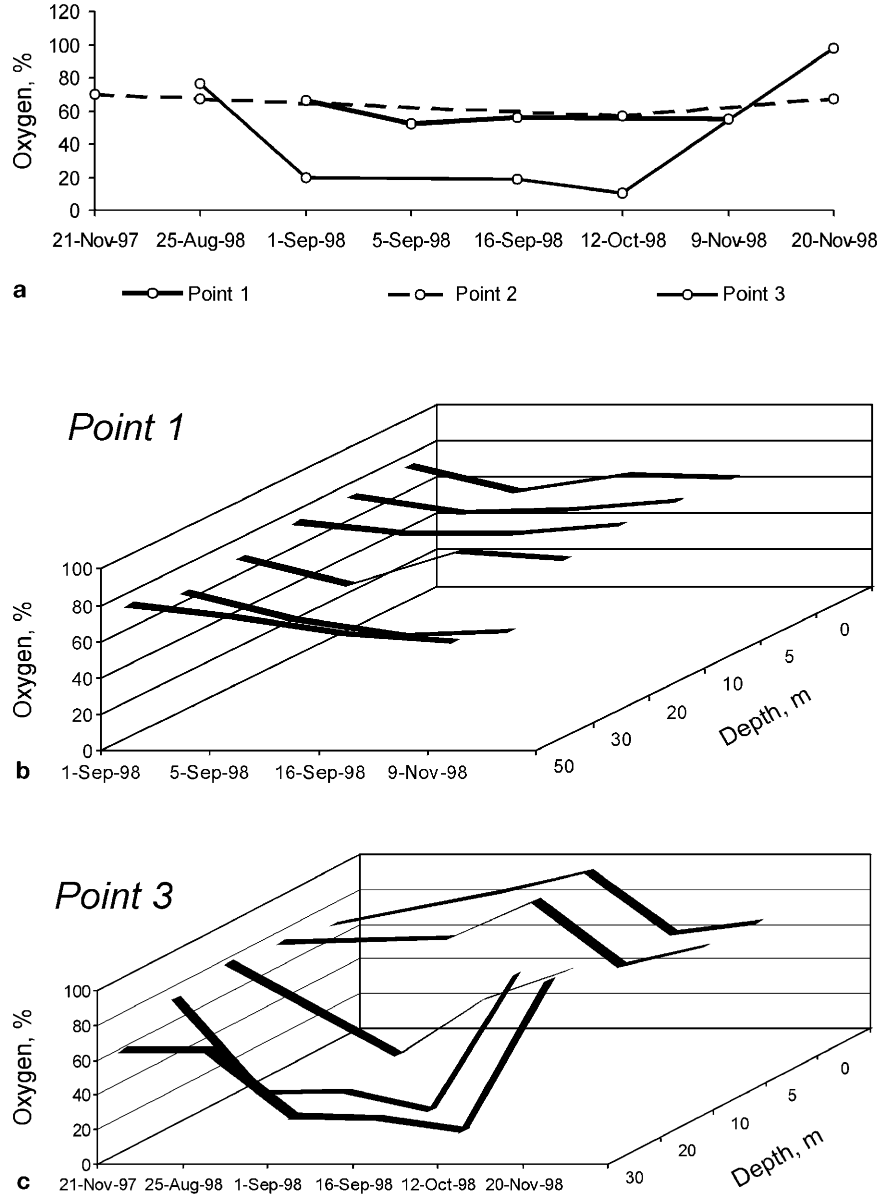


Fig. 8
Dynamics of oxygen content changes at the three sites tested in Lake Sevan. **a** Dynamics of O_2 content changes for the three sites at a depth of 20 m; **b** dynamics of O_2 content changes for site 1 at different depths; **c** dynamics of O_2 content changes for site 3 at different depths

tember, the emission value is supplemented by methane fermentation of organic remains from the lake bottom. Bottom relief (central part of the stepped graben) and currents could cause high accumulation of organic residues at site 3 (Fig. 9).

At site 4, there are no methane fermentation conditions or active faults.

Bottom sediments from Sevan were studied in 1960–1962 (Jamgortzian and Chitchian 1962). Silt sediments from the lake bottom were sampled to a depth of 4.5 m through vibration boring. The samples were analyzed for content of Mo, Zn, Pb, Mn, Cr, Ni, and Mg, and many other microelements. The results were plotted on geochemistry maps for the SE lake bottom (Satian 1990). The data are of interest because clear geochemistry anomalies of higher contents of Zn, Pb, Cr, Mg, and Mo are confined to the inner faults of the Sevan pull-apart basin area. In spatial distribution, anomalous mean content values for SO_4^{2-} and Cl^- are best correlated with the active fault zones (Fig. 6).

For many of the elements, mean values increase downwards with the thickness of bottom sediments and exceed the background values by as much as 5- to 25-fold (Satian 1990). The explanation for this is the geochemical permeability in the active fault zones that form the structure of Lake Sevan bottom.

The faults in Lake Sevan display high seismic activity manifested in strong earthquakes ($M \geq 7.3$) and numerous smaller events (Philip and others 2000). Zones of intense Quaternary volcanism are responsible for three-quarters of the geological formations. Volcanic activities occurred during the Holocene (Philip and Karakhanian 1999). Geodynamic activation of faults, strong earthquakes, volcanic eruptions, as well as regressions and

Fig. 9
Space image of Lake Sevan made in 1978 showing maximum spread of plankton (white color on the photo)

transgressions of the lake took place in the Holocene period and within recent historical time periods. The consequences were considerable and affected both the environment and the population (Karakhanian and others 1996; Philip and Karakhanian 1999; Philip and others 2000). Similar "pulsed" strokes of natural hazards will continue affecting Sevan in the future. In this study, however, the slow and continuous environmental influence of active geological processes is the main concern. Recent publications provide examples of biological, environmental and health aspects of such influences (Bargagli and others 1989; Capocaccia and others 1995; Quemsiyeh and others 1997; Djrbashian and others 1998; Grasso and others 1999). There are observation data for Lake Sevan as well. A fish species, *Coregonis* sp., was introduced into Sevan from Ladoga and Choudskoye lakes (Russia) in 1920. The fish rapidly proliferated, but became almost halved in size. In contrast, fish of an endemic variety of *Salmo ischan* (Sevan trout sp.) introduced into Hissik-Koul (a lake in Kirgizia) grew to more than twice in size. These changes are attributed to higher Mg content in Sevan, which depresses growth and the size of living organisms. This higher Mg content in the water is explained by the presence of ophiolitic rocks along the NE coast of Sevan Lake (Satian 1997).

This is evidence for the constant and long-term environmental effects of geology factors. There may be other examples. Figure 10 shows that eutrophication in the lake below 19 m caused plankton growth, and increased its mass by many orders of magnitude (see data for 1959 and 1976–1978). Such explanations seemed to be quite acceptable. However, plankton mass started decreasing sharply from 1979 and became almost halved. Other principal parameters contributing to eutrophication and plankton proliferation (water level, temperature, etc.) remained almost unchanged. Plankton mass reduction was observed until 1992. From that point onwards, plankton mass has proliferated and is nearly restored its original level. The phenomenon has not been studied and still remains unexplained.

Legovich (1979) analyzed the ecosystem dynamics in 1964–1972 and concluded that biological processes in the lake depended on the speed of drop in water-table level. In this study, the qualitative effect of the dynamics of table drop (Fig. 11, plot F) on the changes in primary plankton productivity (Fig. 11, plot G) and terms of reproduction of plankton population (Fig. 11, plot H) have been analyzed.

To do this, the following yearly data have been used:

W volume of water table drop from the lake (km^3/year);
S area of the lake water table (km^2);
P mean annual value of primary plankton productivity (g C/m^{2}per day, C = carbon).

The following parameters are calculated for each year:

$h=(W/S)$ height of water layer table drop from the lake (m);
$M=P\times S$ annual plankton mass production (g).

The following plots have been constructed (i is year number):

$Fi=(h_{i+1}-h_i)$ water table drop dynamics;
$G_i=(P_{i+1}-P_i)/F_i$ primary productivity dynamics vs dynamics of water table drop;
$H_i=M_{i+1}/M_i$ reproduction of plankton mass.

Analysis of corresponding plots in Fig. 11 does not prove any considerable influence of annual table drop (Fig. 11, plot F) on the biological processes in the lake today. A sharply increased rate of table drop in 1990 appeared to be the event that triggered the increase in plankton population (Fig. 11, plot H). The growth ceased after table drop decreased in 1992–1993. In 1994–1997, table drop was abruptly slowed again, however, this did not change the rate of eutrophication in the reservoir (trend in Fig. 11, plot H).

Possible influencing factors perturbing the reproduction conditions and primary plankton population dynamics may be suggested for the period 1978–1986 (Fig. 11, plot G). Primary plankton productivity dropped sharply in 1985 (following a seismicity peak in 1984) and stabilized in 1986–1997 (trend in Fig. 11, plot G).

In the summer of 1984, Sevan suffered an ecological disaster: various species of fish inhabiting the lake died en masse and more than half of the fish population was exterminated. The "pestilence" continued from early spring until November–December 1984. Then, it attenuated gradually.

Some explanations of the phenomenon were related to the abrupt reduction in plankton, which was the main food stock for the fish, and possible deterioration of water quality induced by some technogenic impact.

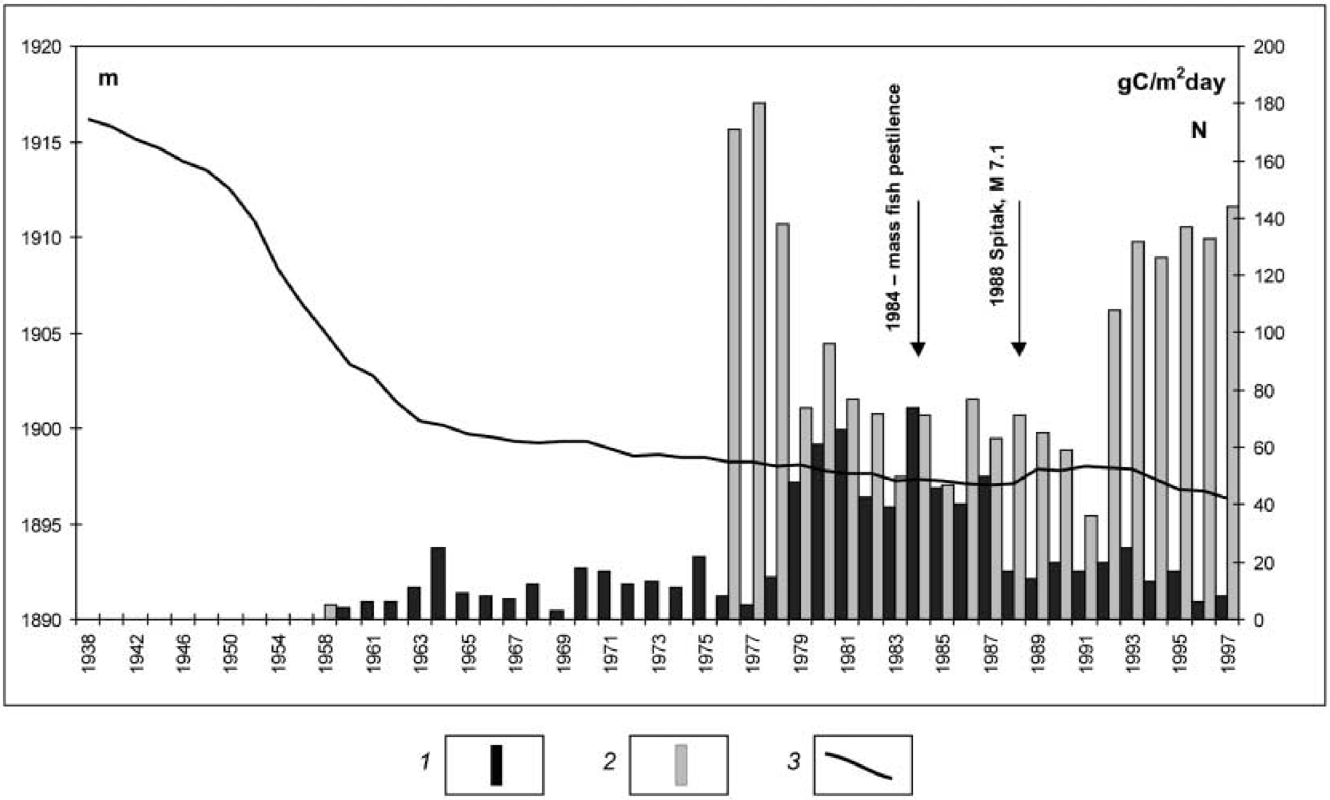


Fig. 10
Dynamics of water-table level in Lake Sevan, plankton content and number of earthquakes that have occurred in the lake basin. *1* Number of earthquakes; *2* plankton content; *3* water-table level in the lake

Plankton mass was reduced abruptly in 1979 (Fig. 10), i.e., 5 years before the wholesale death of fish. Thus, food shortage could hardly cause the disaster, and it should be noted that certain species of fish do not depend on plankton as a food source.

As evidenced by Hovhannissian and Hovsepian (1996) and Simonian and others (1996), contamination of water in Sevan in 1980–1988 did not exceed the background level, and water quality during that period was quite suitable for fish.

Figure 10 shows that the reduction in plankton mass in 1979 paralleled the increase in seismic activity [increased number of earthquakes (*n*)] in the Sevan basin. The seismic energy released did not change (log E). However, the number of small earthquakes exceeded the background level by as much as four- to fivefold (Fig. 10). Maximum seismic activity was recorded for spring–autumn 1984. It

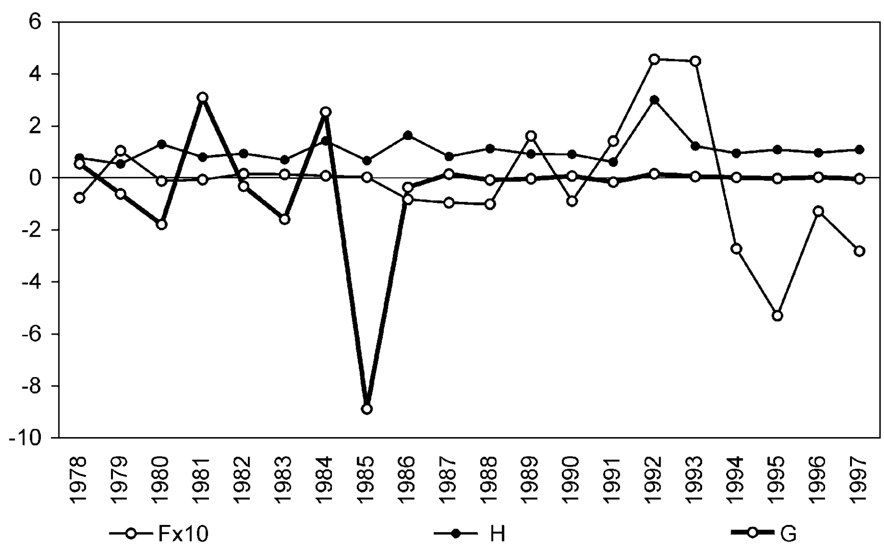


Fig. 11
F Dynamics plots for water outlets; *G* changes in the primary plankton productivity; and *H* plankton population reproduction

continued until mid-1988 and later decreased to background levels. The disastrous Spitak earthquake (M = 7.1) took place in late 1988 at the Pambak–Sevan fault, 60 km to the west of Lake Sevan (Fig. 1). The Pambak–Sevan fault is the main structure forming the northern border of the Sevan pull-apart area.

About the time of the Spitak earthquake, the number of small earthquakes in the pull-apart area increased sharply (three to five times) until autumn 1988. Short-term seismic quiescence ended with the main shock of 7 December 1988.

Abrupt buildup of a number of small earthquakes is related to intense creep along active faults in the pull-apart area prior to the main shock of 7 December 1988. A peak frequency of small earthquakes (i.e., six times as many as the background number) was recorded in 1984, i.e., at the time of mass mortality of fish in the lake.

The intense creep on active extension faults of the lake bottom was accompanied by an increased number of small earthquakes, and resulted in a greater permeability of submerged fault zones and volcanic activity sources. Emission of various chemical components from such zones may be considered a consequence. Stronger chemical emanations from the creeping active fault zones could have depressed plankton growth and reduced its mass in 1979, and when it reached its maximum value in 1984, it caused the mass death of fish. After the 1988 Spitak earthquake, creep-like, seismic, and geochemical activities in the fault zones ended and plankton mass had almost reverted to its original level by 1992.

Therefore, the suggestion is that geodynamic and seismic activity changed the geochemistry in the Sevan pull-apart fault zones during the preparation of the M = 7.1 Spitak earthquake and led to plankton depression, and the environmental disaster of fish death in 1984, which ended with the seismic catastrophe of 1988.

It is suggested that there might be a close correlation between the 1984 environmental disaster and the seismic event of 1988.

Conclusion

Structurally, the bottom and basin of Lake Sevan form a large pull-apart area formed by two right-lateral strike-slip faults. Inside the Sevan pull-apart area there are extension zones of linear and stepped grabens, and young volcanism zones. Intense seismic and volcanic activity in these zones has been observed in the past and is still being recorded.

The studies show methane emission from the lake surface. Compared with other data (physical and chemical water properties, space images, etc.), this suggests the emissions originate from active fault zones at the lake bottom, and from biogenic methane produced by the fermentation of organic remains at depth.

A possible mechanisms to explain the tectonic impacts on the lake environment has been suggested. Abrupt creep, and seismic and geochemical activation along the faults at the lake bottom during the buildup to the 1988 (M = 7.1) earthquake could have increased permeability of the fault zones and emission of chemical components from them. This might have resulted in the depression of plankton populations, and mass extermination of fish in the lake in 1984. Environmental repercussions of the geological (tectonic) activity for Lake Sevan are important factors that require in-depth study.

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