Spatial variations in sedimentation and inferred climate changes as revealed by new XRF records from Lake Saki

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1 Introduction

Lake Saki is a hypersaline lake is the southwestern part of the Crimean peninsula. It is separated from the Black Sea by a sandbar, which is around 500 m in width. The lake is 5.5 km in length and 1.6 m in width. The average depth is 0.5 m and the maximum depth is 1.2 m. The area of the lake is 8.1 km^2. The waterbody is located in the mouths of two connecting ravines and its bedrock is composed of reddish clays and loams of the middle and upper Pliocene age. At present, the lake is divided into seven basins, which have their own functions in recreation and salt mining. The salinity of the lake mud ranges from 150 to 180‰. Geomorphological setting around the lake is characterised by hilly plains 50–100 m a.s.l. The study site is characterised by temperate climate with uneven distribution of precipitation: the precipitation rates decrease from the shoreline inland. Mean annual temperature is +10…+11°C, mean July temperature is +23…+24°C, and mean January temperature is –1…+1°C. The annual precipitation rate is around 400 mm. The regional vegetation cover is represented by grass steppes and the lake itself is surrounded by thin communities of xerophytic and halophytic plants.

Laminated lake sediments from the Lake Saki basin provide high-resolution records of climatic variability in the Black Sea region, which is especially sensitive to changing climatic conditions. The first XRF analysis of the lake sediments was performed by Veselova (2012) and later by Morozova et al. (2015), which gave basis to establish three periods of distinct depositional processes: (i) shallow basin with a high level of hydrodynamical regime, (ii) deepening of the lake and stable hydrological conditions, and (iii) shallowing of the basin and an increase in hydrodynamical regime. Here we present a correlation of XRF datasets from two cores from the lake and discuss changes in depositional environment and inferred climate variations, as well as human impact on the lake system.

2 Materials and methods

In 2011, two sediment cores were retrieved from the central and eastern parts of the lake by V. Vasenko and I. Pustovoitov. The core from the central part (S-46-12) is 150 cm long; the coring below 150 cm was hindered by a thick salt layer below the lake sediments (see Popov et al., 2015). The core from the eastern part (S-45-12) is 400 cm long. Here we focus on the top part (1.5 m) of S-45-12 core, as well as core S-46-12, to correlate and compare sedimentary changes within the lake basin. XRF scanning was performed in the Department of Geology, Lund University, using Thermo Scientific portable XRF analyser Niton XL3t GOLDD + X-ray fluorescence instrument detecting elements set in the Cu/Zn mining calibration mode. Total elemental contents were determined on 60 dried and homogenized sediment samples, collected at every 5 cm. All analyses were performed by using an 8 mm radius spot size in order to get a representative analysis. The elemental detection depends partly on the duration of the analysis at each point and for this reason the measurement time was set to 4 min. To facilitate interpretation and highlight main changes in elemental composition the elemental profiles were smoothed using a 3-point moving average. The datasets were subdivided into geochemical zones using cluster analysis (UPGMA) and visual interpretation.

3 Results and Interpretation

The sediments of the two cores consist mainly of Ca, S, and Si, with lesser concentrations of Cl, Al, Fe, K, Ti, Sr, Mn, Zr, and Rb (Fig. 1, 2). Most lithogenic elements (Ti, Si, Zr, and Rb) are more abundant in core S-46-12, whereas elements associated with evaporites (Ca, Sr, S) are more dominant in core S-45-12. Aluminium, Fe, and K are characterised by similar concentrations in both cores. Overall, both datasets display similar trends in the changes of elemental concentrations, however the elemental curves in the S-46-12 dataset are characterised by fewer fluctuations than the ones in the S-45-12 dataset, suggesting that depositional environment was more stable in the central part of the lake than in its eastern part, which more frequently experienced lake level lowering as indicated by higher contents of elements associated with evaporites.

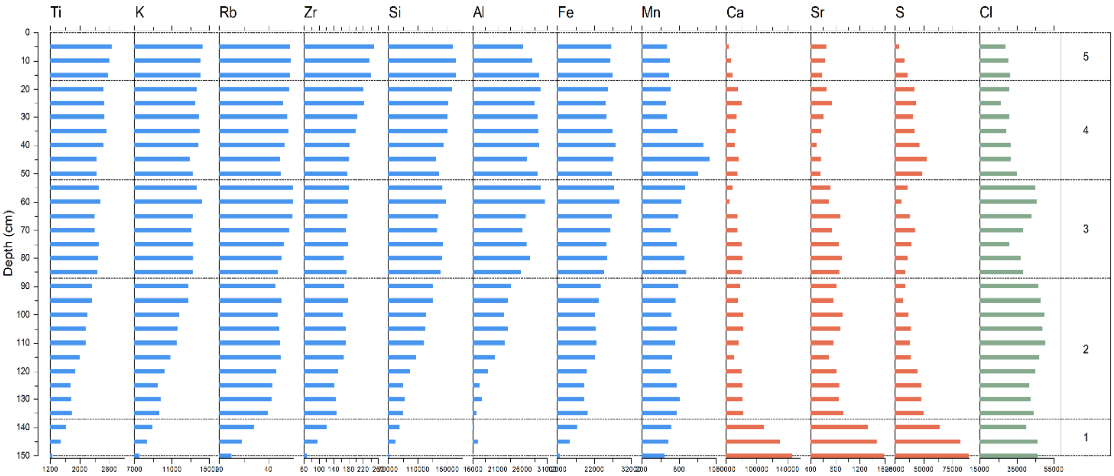

Figure 1 Depth profiles of the selected elements from core S-46-12 (central basin).

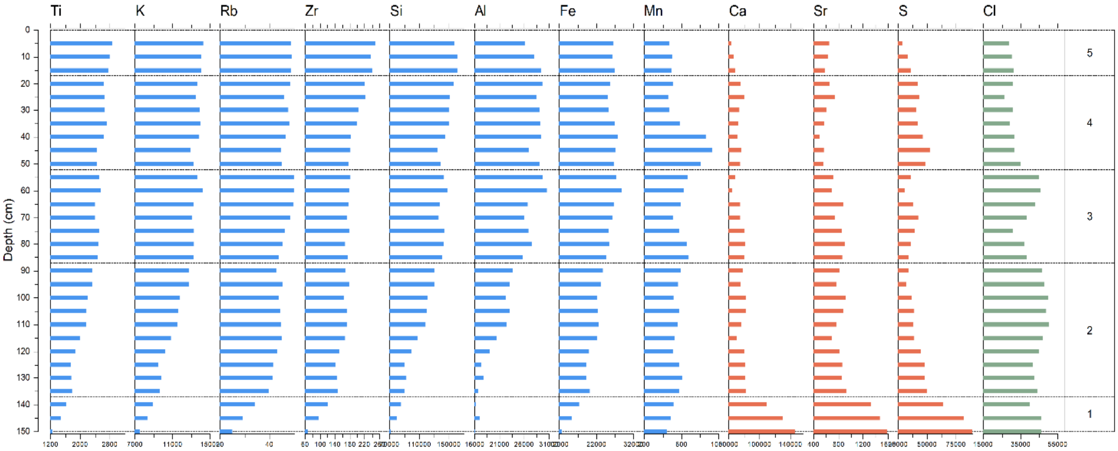

Figure 2 Depth profiles of the selected elements from core S-45-12 (eastern basin).

Principal Component Analysis (PCA) was performed on the geochemical variables of the core samples to reveal the main sedimentary processes induced by environmental and climate changes. In the S-46-12 dataset, PC1 explains 67.5% of the total variance while PC2 – 12.8% (Fig. 3). PC1 is characterised by the positive loadings of Si, Ti, Zr, Rb, K, Fe, Al, and Mn, and the negative loadings of Ca, Sr, S, and Cl. In the S-45-12 dataset, PC1 explains 67.1% of the total variance and PC2 – 12.5%. Similarly, PC1 is tied by the positive loadings of Si, Ti, Zr, Rb, K, Fe, Al, Mn, but also Cl, and by the negative loadings of Ca, Sr, and S. Therefore, PC1 might be interpreted as related to the terrigenous influx into the lake (siliciclastic particles) versus the mineral autochthonous precipitation such as carbonates and sulphates. PC2 of the S-46-12 dataset is tied by the positive loadings of all elements, except for Cl and Rb, whereas the negative loadings of PC2 of the S-45-12 dataset are attributed to Zr and Si. Chlorine may be incorporated in the sediment pore water (Neugebauer et al., 2015) and Rb is abundant in fine-grained, siliciclastic material (Dypvik and Harris, 2001), which together might indicate changes in sediment porosity. On the other hand, Zr and Si are common components of coarser deposits, which might indicate input of coarser sediments into the lake. Therefore, we assume that the sedimentation in the lake was primarily controlled by influx of terrigenous material alternated by precipitation of evaporites. Secondary processes, revealed by PC2, are believed to indicate changes in sediment grain-size.

The chronology of the studied cores is based on pollen correlation of core S-45-12 with the dated core S-13-05 (Gerasimenko, Subetto, 2011; Rohozin, Gerasimenko, in preparation) and further projected on core S-46-12, based on similarities of geochemical composition. The tentative correlation of the cores showed that the basal sediments of both cores were most probably deposited around 2000 yr BP. On the basis of geochemical zones (GZ 1–5) subdivided by cluster analysis and the results of PCA, the following reconstructions can be made.

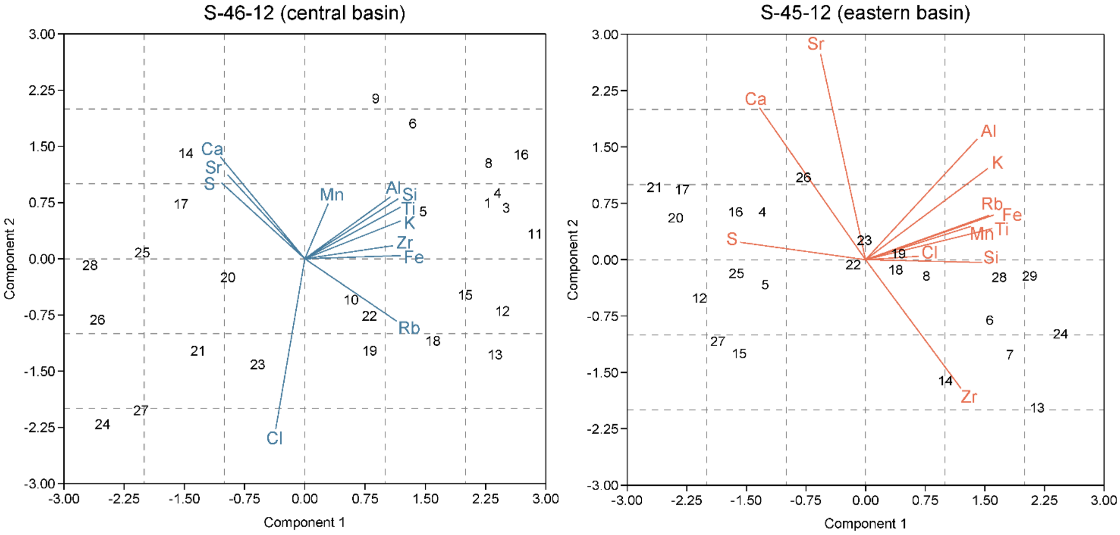

Figure 3 2D-plots of distribution of PCA loadings of geochemical elements and core samples.

The phase between ca. 2000 and 1600 yr BP was characterised by active precipitation of evaporites in the lake. These processes are evidenced by the highest content of Ca, Sr, and S in the core from the central part of the lake. Relatively high concentrations of Ca, Sr, and S are also observed in the eastern core, where the active evaporite precipitation is supported by the occurrence of thick salt layers around 2000 yr BP as observed by I. Pustovoitov (personal communication). Thus, it can be concluded that the level of the whole lake was low, which led to precipitation of salts from the brine. The concentrations of lithogenic elements are the lowest in core S-46-12 and are slightly higher in core S-45-12, which might be explained by primary accumulation of evaporites in the deep part of the lake, while the more marginal eastern basin witnessed enhanced clastic deposition. The later part of the Early Subatlantic (2200–1600 yr BP) was characterised by warm and arid conditions in the Crimea with expansion of xeric steppe vegetation around the lake (Gerasimenko, 2007; Gerasimenko, Subetto, 2011), which is clearly reflected in our XRF record.

The phase after ca. 1600 yr BP was characterised by more humid conditions, which led to the higher rates of erosion in the catchment (indicated by higher content of lithogenic elements). The obtained XRF records display different patterns in elemental profiles for this interval. The elemental curves of core S-45-12 show slight fluctuations during this period, but otherwise remain unchanged, while the elemental profiles of core S-46-12 (in particular, Ti, K, Al, and Si) show a continuous increase throughout this phase. The increase in Ca and S in core S-45-12 suggests that precipitation of evaporites continued in the eastern part of the lake, while terrigenous influx largely prevailed in the central part. Interestingly, both datasets display a short dry event in the middle of this phase, which could be correlated with a dry spell in the SW Crimea between 1400 and 1200 yr BP (Gerasimenko, 2007).

The next phase (ca. 1100–500 yr BP) is notable for the increase in marine productivity as evidenced by the highest concentrations of Ba in both datasets. Sedimentation regimes were probably most contrasting during this phase. While the clastic deposition continued the infilling of the central part of the lake, the eastern basin experienced lowering of the water level and precipitation of evaporites (mainly gypsum), interrupted by a short phase of increased erosion. The marked lowering of the eastern basin at the end of this phase could be a result of a significant aridification after 650 yr BP, revealed by pollen data from Lake Saki (Gerasimenko, 2007).

After 500 yr BP, the accumulation processes in the central basin were stabilised, indicating calmer depositional environment. On the other hand, relatively stable sedimentation conditions, which prevailed before in the eastern basin, were replaced by increasing runoff in the catchment and deposition of thicker annual laminae. The rates of evaporite precipitation in the lake became slower as indicated by decreasing contents of Ca and S. The highest representation of Cl probably suggests the increased sediment porosity, as no salt layers were observed in this interval.

Starting from the mid-XIX century, the detrital deposition became more significant, as indicated by the highest contents of most lithogenic elements in core S-45-12. In core S-46-12 these changes are reflected in the elevated values of Ti, K, Zr, and Si. The rates of evaporite precipitation further decreased, which might indicate an increase in the lake level. This interval also marks the start of human exploitation of the lake, when in 1885 a channel, connecting the Black Sea and the lake, was built to saturate the lake with seawaters (Kurnakov et al., 1936). The relative increase in As, V, Nb, Pb, and Cr values in both datasets also confirms industrial development in the region. In the early XX century, the lake was subdivided with dams and cofferdams for salt extraction.

The obtained XRF records reveal some new insights into the lake sedimentation history during the late Holocene. The PCA analysis suggests that deposition in the lake was controlled by allochthonous input of siliciclastic material alternated by autochthonous precipitation in the lake. The comparison of two XRF datasets shows that while the central part of the lake experienced virtually continuous influx of terrigenous material over the last 2000 years, the eastern basin was more susceptible to climate changes, which led to fluctuations of the lake level and deposition of evaporites.

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