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ORIGINAL PAPER

The evolution of Petrov lake and moraine dam rupture risk (Tien-Shan, Kyrgyzstan)

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Abstract An interdisciplinary study of glacier-related hazards in the Petrov lake region (Ak-Shiirak Range, the Inner Tien-Shan, Kyrgyzstan) has been undertaken to identify potential dangers to the area. A cooperative effort from experts in the fields of hydrology, glaciology, geomorphology and geophysics has been employed in this study. For the hazard assessment, evolution of the Petrov glacier and lake was reconstructed using historical reports, aerial photographs and satellite images. Geomorphological mapping and geophysical soundings was applied to the lake territory and the moraine dam. This has identified potentially hazardous areas of the dam including subsurface drainage zones and cracks that could cause a sudden extremely high discharge. In the past three decades, the Petrov lake has doubled in size, while in recent years, its area has been increasing by more than 92,000 square metres per year. Although there is no evidence for an imminent outburst, the dramatic increase in the lake's size emphasizes the importance of this study.

Keywords Moraine-dammed lake · Rupture risk · Bathymetry · Geophysical measurements · Glacier fluctuations · Petrov glacier · Tien-Shan

Abbreviations

GPR	Ground penetrating radar
GPS	Global positioning system
SP	Spontaneous polarization

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1 Introduction

In the mountainous regions of Kyrgyzstan there are some 1,500 lakes with an area of more than 0.01 km^2 (Yerokhin 2002). Many of the lakes' dams are extremely unstable and various natural processes cause their destruction. The lakes which pose the greatest threat in the area are prone to imminent risk of rupture, and such an event would have far-reaching consequences for both population and property. According to Yerokhin (2002), there are now in Kyrgyzstan 302 perilous lakes, out of which 15 are at risk of rupture. Amongst these, the Petrov lake in the Ak-Shiirak Range (the Inner Tien-Shan, Kyrgyzstan) represents one of the biggest potential flooding dangers.

The Petrov lake belongs to the moraine-dammed glacial lakes which were formed as a result of a valley glacier retreat (Fig. 1). The lake has been developed between Petrov glacier terminus and the terminal moraine, which is ice-cored. The moraine damming of the lake is from the Little Ice Age (LIA) and consists of typical unconsolidated morainic material (Meiners 1997). The constitution of the moraine thus represents an unstable part of the moraine dam complex and corresponds to the outburst potential of the Petrov lake. Accelerating flow into the lake or melting of ice that constitutes the dam can lead directly to dam failure and subsequent rapid release of water from the lake. Glacial lake outburst floods are common in high-mountain areas around the world. They have been reported from the Alps (Haeberli 1983; Huggel et al. 2002), Karakoram (Hewitt 1982), Himalayas (Richardson and Reynolds 2000; Kattelmann 2003), Tien-Shan (Mayer et al. 2008), Coast Mountains (McKillop and Clague 2003), Rocky Mountains (Walder and Driedger 1995; Clague and Evans 2000) and Andes (Clague and Evans 1994; Hubbard et al. 2005; Vilímek et al. 2005; Carey 2008). Whereas inventories in most of these regions contain

Fig. 1 The moraine dam of Petrov lake with superficial outflow (centre)

hundreds of moraine-dammed lakes and a lot of systematic information for hazard assessment, scarce data exist for the Tien-Shan Mountains. As glacial lake outbursts generally represent a serious problem (Kääb et al. 2005), the assessment of outburst hazards in this area is of key importance.

This article is part of an interdisciplinary hazard assessment and study for a gold mine in the Ak-Shiirak Range in the Inner Tien-Shan. This study focusses on glacier-related and structural hazards influencing stability of the moraine dam. This article consists of two main parts: The first part is concerned with the detection and evaluation of glacier-related hazards. In the second part, a geomorphological and geophysical survey is applied to the moraine dam to identify weak zones of the dam prone to failure. In this article, the methods and results of geophysical soundings, geomorphological mapping and hydrological measurements are presented.

2 Study area

The Petrov lake (3,741 m a.s.l.) is located in the foreground of the Petrov glacier which is situated on the north-western slope of Ak-Shiirak massive in central Kyrgyzstan (Fig. 2). The Ak-Shiirak massive belongs to short mountain ranges of inner Tien Shan that are elevated above wide and shallow valleys formed during the Quaternary glaciations.

The region is characterized by a highly continental climate with marked seasonal variation (Fig. 3). In the zone of predominantly west winds, precipitation mainly falls in

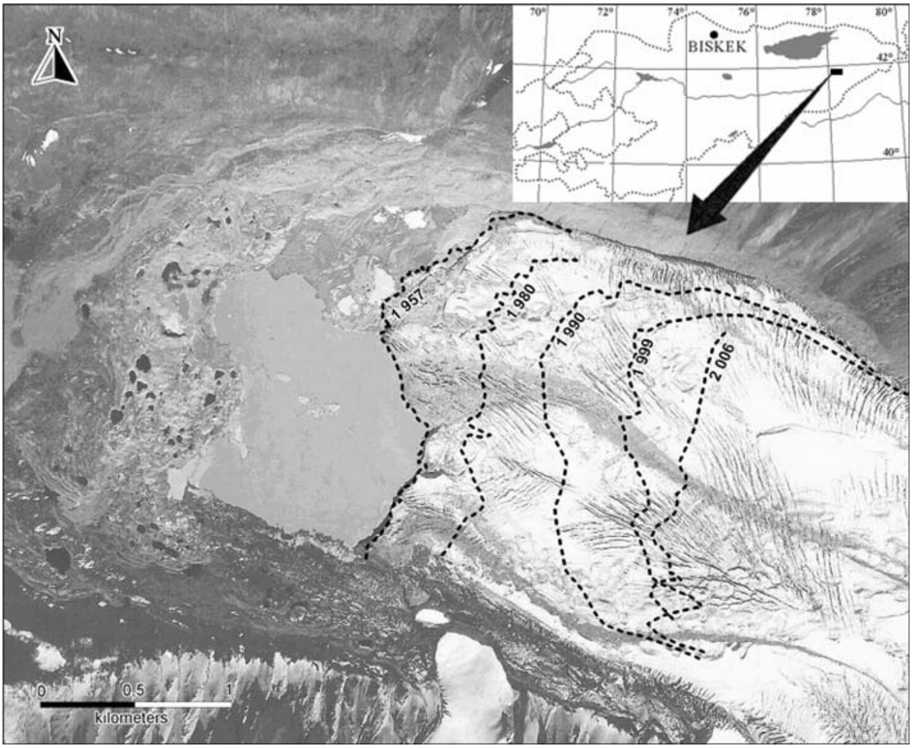

Fig. 2 Fluctuations of the Petrov glacier terminus since 1957

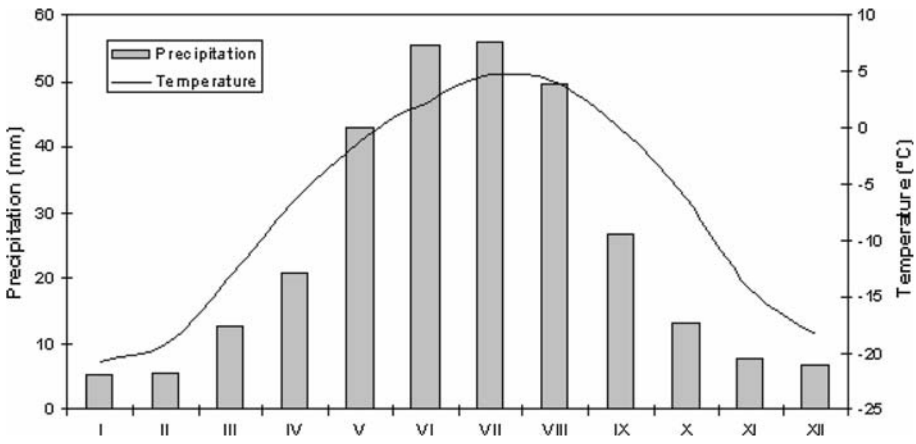

Fig. 3 Average monthly precipitation and temperature (Tien Shan station, 1930–2005)

the spring and summer months while the winters are cold and dry. Mean January, July and annual temperatures are −7.6, −20.8, and 4.6°C, respectively, and the mean annual precipitation is 303 mm. According to meteorological data from the nearby Tian Shan station (3,614 m a.s.l.), an increase in average annual temperature of 0.009°C has occurred during 1930–1989 (Dikih 1997). The snowline is located at 4,230 m a.s.l. (Dyurgerov 1995).

Petrov lake is fed by meltwater from the Petrov glacier and small hanging glaciers in the rock walls and side valleys. The Petrov Glacier is 69.8 km^2 in area and 12.3 km long (Dyurgerov 1995). The terminal moraine complex that dams the lake consists predominantly of granitic material situated in the accumulation area of the glacier. The grain-size distribution (sand/silt/clay: 40/49/11%) is typical for moraine from which the silt and clay fractions have not been completed washed out during the slow melting of the glacier tongue (Meiners 1997).

3 Materials and methods

cThe evolution of the Petrov glacier was determined based on available documentation. The position of the glacier terminus is reconstructed from the end of the Little Ice Age until 2006. The glacial deposits mark the boundaries of the glacier in 1869, whereas aerial photographs from 1957 (~ 1:40,000 scale) and 1980 (~ 1:47,000 scale) archives together with the 1990 and 1999 SPOT panchromatic satellite image (10 m resolution) give data on the deglaciation within the second-half of the 20th century. GPS measurements made in the field augmented by a Quickbird panchromatic satellite image (0.6 m resolution) delimited the boundaries of the glaciers in 2006. Glacier positions from six periods were digitised into the GIS, enabling a tentative analysis of the glacier terminus fluctuations and its dynamic. The studies by different authors show that aerial photography still remains the main source of data for measuring a number of glacier characteristics. In addition, fine-to-moderate spatial resolution satellite sensors also provide useful information that can be used to support the assessment of hazards in high-mountain glacierized terrain (e.g. Quincey et al. 2005).

Geomorphological and hydrological observations deal with the moraine dam and with the Petrov lake area. In 2005 and 2006 a geomorphologic map of the dam was made using GPS measurements and an existing 1:25,000 scale topographic map. Detailed geomorphological mapping of meso- and microforms of the relief in the dam area was realized. Then geodetic survey was applied on shore lines of 35 thermokarstic lakes in the central part of the moraine dam, which is the most threatened part. Systematic measurements of the depths of the thermokarstic lakes were taken and re-evaluated 1 year later. Precise depth measurements of 29 profiles on Petrov lake allow for construction of a detailed bathymetric map of the lake. A variety of geophysical methods were applied at the narrowest part of the moraine dam. The traditional method of geoelectric profiling and sounding in these conditions was used, as well as the methods of dipole electromagnetic profiling (DEMP), spontaneous polarization (SP) and resistivity tomography, ground penetrating radar (GPR) and gravimetry. The measurement was carried out for irregular profile grid, which was laid out at the dam with focus on a weakened dam segment (Fig. 4). This profile grid was composed of seven profiles (survey lines) of varying lengths (the longest reached the length of 400 m) routed along the longitudinal dam axis and of three profiles perpendicular to the dam (Fig. 5). The positionings of the profiles were registered using GPS system and significant profile points altitudes also surveyed.

Geophysical measurements were realized using device for resistivity measurements (SP and geoelectric profiling) manufactured in the Czech Republic and Russia. In addition, Geophex GEM-2 (DEMP method), Scintrex CG-3 M (gravimetry) and GF Instruments ARS-200 (resistivity tomography) were used. The measured data were processed using Golden Software Grapher and Surfer software. Geotomo Software Res2dinv was used for the processing of the resistivity tomography, with combined method having been preferred in inversion. Resulting RMS error at the final (the 3rd through the 6th) iteration ranged between 8 and 24%.

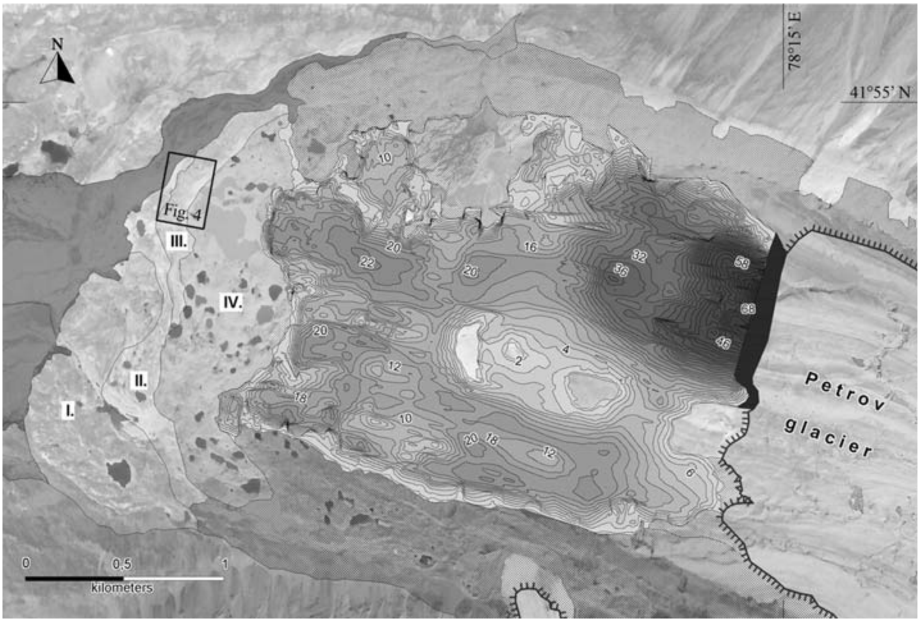

Fig. 4 Morphology of the Petrov lake basin. Explanations: waved lines—glacifluvial plain, parallel lines—dejection cones, dotted areas—moraines, cross-wise lines—icebergs; isobathic lines—2 m

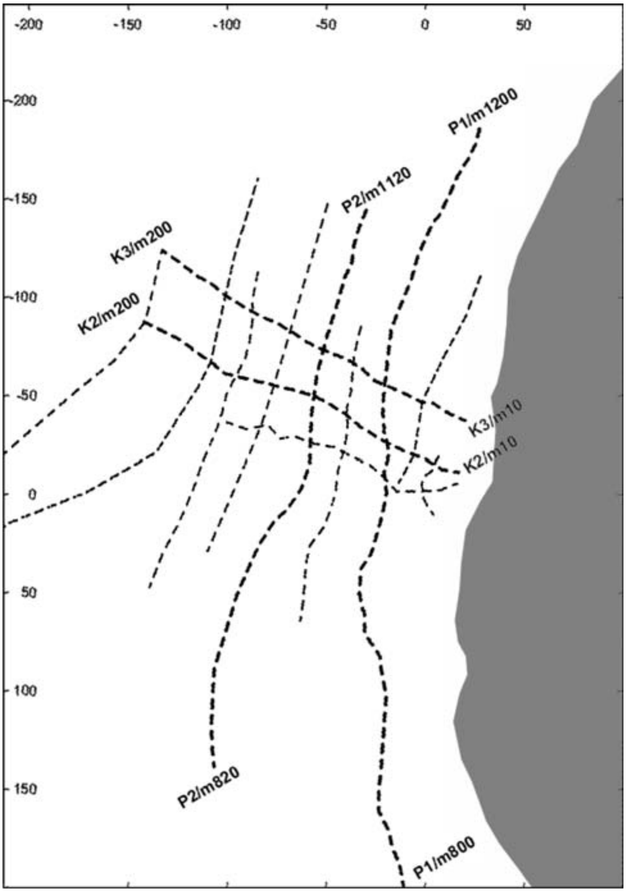

Fig. 5 Localization of geophysical soundings in the narrowest segment of the moraine dam

4 Results

4.1 Evolution of the Petrov lake and fluctuations of the Petrov glacier terminus

The Petrov glacier tongue flows from the central part of the Ak-Shiirak ridge and forms the eastern shore of the Petrov lake. In 1869 the terminal moraine of the Petrov glacier was accumulated at 3,710 m a.s.l. According to the sketch of Kaulbars (1875) a small lake appeared in front of the glacier at that time. During the second half of the 19th century the glacier retreated from this position and the surface of the lake increased to 0.2 or 0.3 km^2 in 1911 (Table 1). Subsequent observations by Davidov (1927) indicate that the glacier terminus probably reached the morainic plain, between the terminal moraine and the western shore of the current Petrov lake. Generic outline of the glacier position does not, however, enable determination of the exact terminus position.

The next survey in 1919 revealed a small re-advance of the glacier, driving the glacier terminus towards the terminal moraine of the Little Ice Age. During the 1920s and 1930s the Petrov glacier had undergone a remarkable retreat after which another period of

Table 1 Increase of the lake area

Year	Area (km^2)	Annual grown (m^2)
1911	0.2–0.3	–
1947	0.80	15,000–18,000
1957	0.96	11,000
1980	1.83	37,600
1995	2.78	63,000
2006	3.80	92,700

Table 2 Terminus fluctuations of Petrov glacier

	Total retreat (m)	Annual retreat (m/y)
1869–1957	1,330	15.1
1957–1980	570	24.8
1980–1990	380	38.0
1990–1999	390	43.3
1999–2006	430	61.4

advance emerged during 1947–1957. The Petrov lake had extended to approximately 0.85 km^2 between 1911 and 1947 which represents a yearly increase in surface area of 0.015 or 0.018 km^2 (Avsiuk 1953). In the next aerial photograph from 1957, Petrov lake takes up as much as 0.96 km^2 whereas the dynamics of the surface enlargement during 1947–1957 decreased to 0.011 km^2 a year (Bondarev 1963). This is apparently related to the growth of Petrov glacier between 1947 and 1957.

Since the end of the 1950s till now, the glacier terminus has retreated continuously (Fig. 2) with an accelerating rate of recession. Table 2 presents the average values for linear retreat of the glacier terminus. Between 1957 and 1980 the surface of the lake increased considerably. It expanded 1.9 times, i.e. a yearly increase of the lake surface area by 0.037 km^2. The expansion of the surface has persisted. Between 1980 and 1995 the lake grew approximately 0.063 km^2 every year to reach a size of 2.78 km^2. The increase in volume was directly related to the decline of the glacier front during this same period. The increase of the lake surface correlates with an increase in volume of the lake basin.

On the basis of depth measurements in 1978 (Sevastianov and Funtikov 1981) and 1995 (materials of the Kumtor mine), bathymetric maps of the lake were drawn. They show that the lake basin contains two longitudinal depressions separated by a shallow water back and four islands. The morphometry of the basin is related to the shaping affects of the Petrov glacier which is made up of two main glacier bodies separated by the middle moraine which continues on the bottom of the lake basin. The deepest parts of the lake are found in front of the Petrov glacier terminus.

In 2006 the Petrov glacier terminus was 1.5 km wide and more than half of it (800 m) was immersed in the lake water. As a result of the hydrostatic forces and oscillation of the water level in the lake there is intensive calving of the glacier terminus which rises up to 25 m. The falling of broken ice into the lake causes waves with the amplitude of up to 2 m, although higher waves cannot be excluded. The accelerating decay of the glacier terminus reflects the generally negative mass balance of glaciers in the Ak-Shiirak reported by Dyurgerov (1995).

4.2 Current processes in the moraine dam

The Petrov lake is enclosed by the terminal moraine and the lateral moraines at the foot of the valley slopes. These form the shore line all the way to the current terminal moraine. While the lateral moraines are of no serious danger to the lake, the eastern and western shores are under continual development. The glacier dam on the western side of the lake is affected by the most destructive processes. It is exposed to lake level oscillations and to degradation processes in the moraine area. Among the potentially hazardous processes influencing the moraine dam through the changes of lake level are the glacier melting and calving. The estimated volumes of largest observed ice break-off exceed 500,000 m^3. Other processes such as rock or ice avalanches from adjacent rock walls and hanging glaciers could be excluded from the assessment of potential risk to the glacier dam, due to the snow and ice masses being too remote from the lake. Therefore, the hazard assessment concentrates on the Petrov glacier and lake behaviour and moraine dam properties.

The deciding factor for the moraine dam development is the presence of buried ice which is the cause of the instability and transient lifetime of the current dam. Forming the major part of the overall moraine content, ice protrudes in many places of the sedimentary cover and represents the most dynamic part of the dam. The degradation of the dead ice is accompanied by relief sinking, thermokarstic lakes emerging, morainic sediment sliding and down-slope falling (e.g. Richardson and Reynolds 2000). Major changes to the sedimentary cover of the dam are caused by the affect of intensive periglacial processes. Many active periglacial landforms are developed in the dam. According to the amount and activity of the dead ice, it is possible to distinguish four zones in the moraine (Fig. 4). Each of these zones affect the processes linked to ice degradation and geomorphological hazards to a different rate (Table 3).

The slope declinations on those shores often exceed the critical value, which is connected with further deepening of the thermokarstic lakes. Narrow strips of dry land between individual lakes are constantly sinking which caused hydrological connecting of lakes. An especially rapid development can be observed in the largest thermokarstic lake of

Table 3 Morphological zones of the moraine dam of Petrov lake

Zone	Morphology	Dead ice
I.	The low elevations and shallow depressions area. The shallow depressions filled up by round lakes. Slopes up to 25° completely filled up by soil and overgrown by grass formations	Non-active or defunct
II.	The area of 1–2 slope steps in outer slope of terminal moraine mound. These steps are strictly separated from the mounds by distinct morphological line, which is highlighted by the presence of the oblong lakes. The surface of the higher step is partly filled up by soil; more than 50% of the lower one is covered by grass formations. The steps consist of rough boulders	Passive
III.	The highest moraine area consists of two parallel ridges, which are concentrated along the central part (IV.) of the moraine. The dead ice protrudes in many places. The 30–35° slopes are composed of rough block accumulations	Active
IV.	The central part of the accumulation, formed by the dead ice depressions, filled with water. Ragged relief of thermokarstic lake depressions and steep ridges of mostly fine grain material. Steep slopes (often more than 39°) bear the stamp of recent activity of the dead ice (ice and sediment sliding, surface subsiding)	Active, considerable display

Table 4 Morphometric characteristics of Petrov lake (fieldwork measurements in 2006)

Area (km^2)	3.90
Perimeter (km)	17.03
Maximum length (km)	2.68
Maximum width (km)	1.88
Maximum depth (m)	69.30
Volume (mil. m^3)	60.30

the moraine complex in the northeastern part of the dam. In comparison with the last mapping from 1995, its surface area has increased to 0.09 km^2, it contains 745,000 m^3 of water, its maximum depth is 21 m and its average depth is 5.1 m. This lake cuts deeply into the body of the dam and dissects it. The fact that this is the place where the dam is most weakened is worthy of attention. The direct distance between the lake shore and the outer slope of the dam on the windward part of the dam is only 63 m at the water level. On the profile across the dam the bottom of the lake is distinct in that it lies about 9 m above the level of the alluvial plain of the Kumtor River below the dam. The depression with the lowest dam level being situated only 11.9 m above the lake level is also noteworthy.

The maximum depth of Petrov lake measured in July 2006 in front of the glacier terminus was 69.3 m (Fig. 4). According to 2006 fieldwork the lake measures 3.9 km^2 and its volume is more than 60.3 million m^3. All measured morphometric data on the Petrov lake basin are presented in Table 4.

4.3 Geophysical analysis

Resistivity cross sections positioned on the basis of the resistivity tomography measurements give information about the conditions in the narrowest part of the dam (Fig. 4). The resistivity values vary between one thousand (bouldery debris, moraine) and hundreds of thousand ohms (ice blocks and rocky debris bonded by ice). The interpretation is based on the theoretical values for individual material types. Resistivity values measured in the uppermost part of the moraine dam point at the presence of buried ice with a thickness of up to 20 m, gradually declining to the depth of ice in the dam. The blocks are overlain by rocky debris showing a thickness of mostly between 2 and 5 m. Ice core is not homogeneous in the entire dam axis. The sections at 1,000 m and 1,050 m of the profile P1 show marked disturbances of the measurements (Fig. 6). We propose that lower resistivity values are related to reduced ice content in these zones. Cross sections also identified an area with very high resistivity in the terminal part of the moraine complex.

The results of resistivity measurements were complemented by DEMP method. Despite this method not generally being used for areas with very high resistivities, it provides an indication of disturbed parts of the moraine ice core (cracks, etc.) or moistened parts around the thawing core. The fact that the major deformations of the dam surface relief correlated with these disturbances cannot be dismissed. The upper section of these disturbed structures runs in the lowermost zone of the dam, an area which appears to be highly unstable. Further anomalies were detected using the SP method which clearly indicated problems in the same weakened site of the dam. The SP results indicate occurrence of water infiltration below the surface of the dam (Fig. 7). Results of the measurements performed in 2006 corresponded to, and refined, the original image of the dam setting and

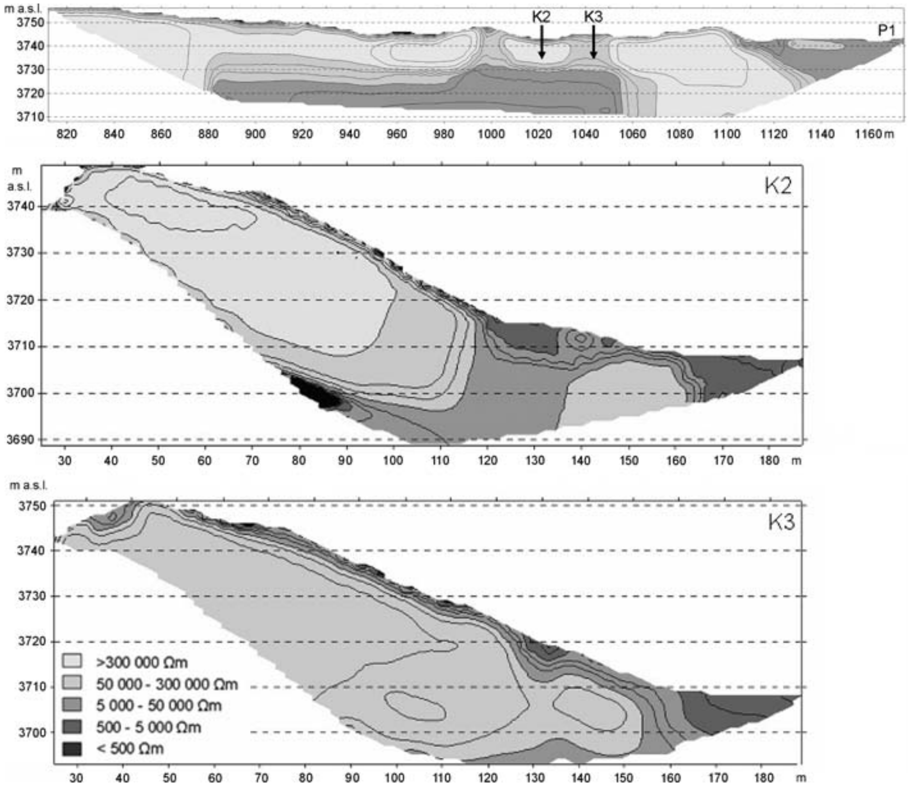

Fig. 6 Resistivity tomography—the longprofile P1 and cross-section profiles K2, K3 (position in Fig. 5, explanations in Fig. 6: profile K3)

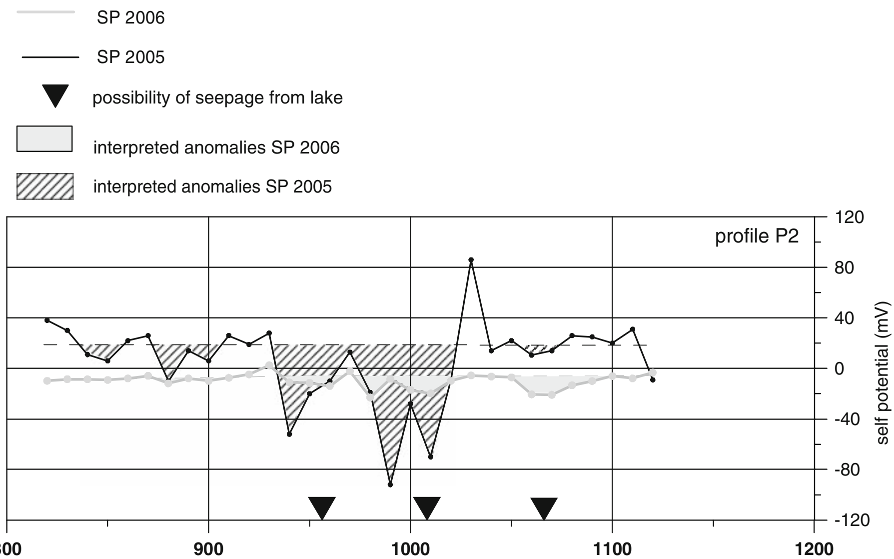

Fig. 7 Spontaneous polarization measurements: profile P2

structure obtained in 2005. As in this case, the most apparent anomalies were detected in the area of the narrowest part of the dam.

Gravimetric survey was used in the majority of the profile grid, covering the dam part of interest. The resulting interpretation was based on residual Bouguer anomaly, which best informs on local density heterogeneities in the dam body (for example, ice blocks, increased thicknesses of debris, etc.). This residual Bouguer anomaly was calculated by deducting the measured values from the regional field. The results show the measured density minimums at the locations of "ice cores" detected by resistivity methods. The hypothesis of ice cores was also confirmed by compilation of density models of transverse gravimetric profiles (Figs. 8 and 9). All models suggest that a marked anomalous body with reduced bulk density occurs in the upper part of the moraine dam. Another similar body corresponding to buried ice occurs in the frontal part of the moraine dam.

According to the results of particular geophysical methods, the ice core of the moraine dam is disturbed in the narrowest part of the dam. These disturbances developed recently as revealed by the repeated year-to-year VES measurements. A comparison of the measurements indicates thawing of the ice core of the dam.

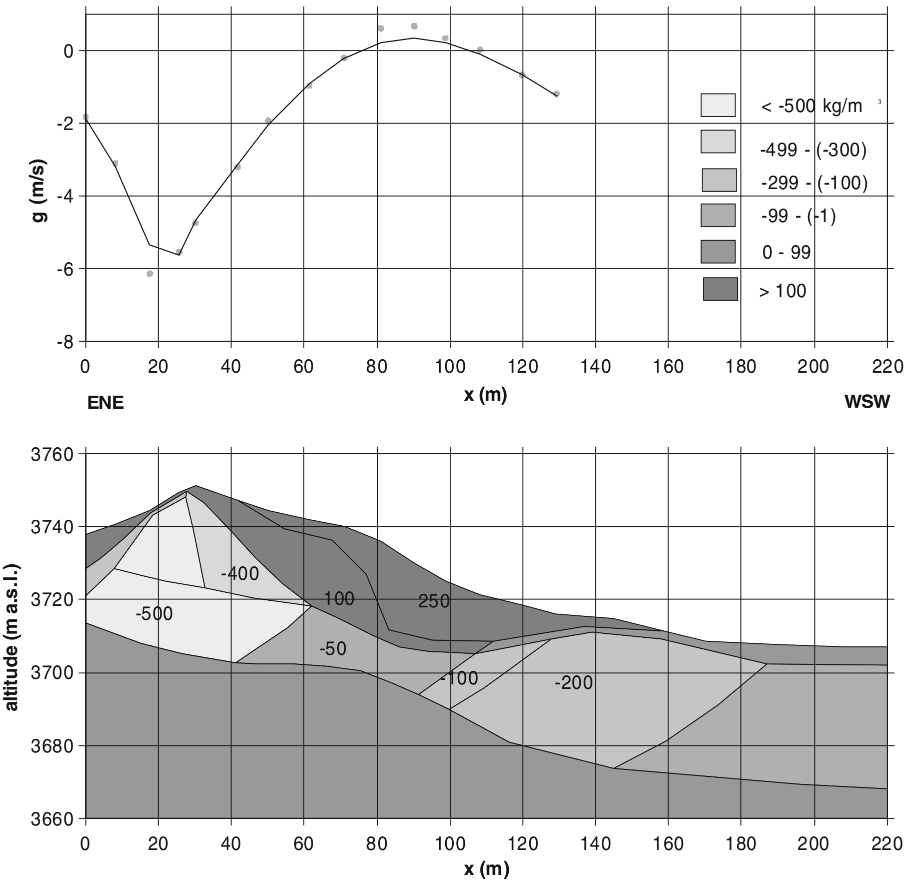

Fig. 8 Gravimetry and density model: profile K2

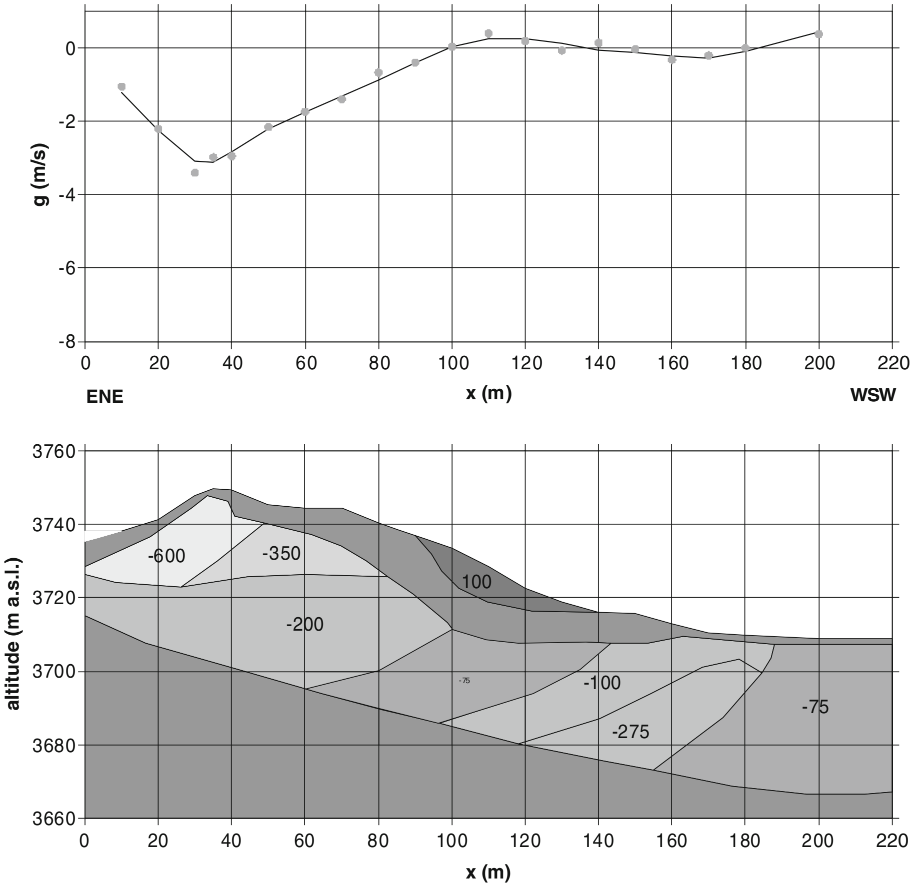

Fig. 9 Gravimetry and density model: profile K3. *GPR*, ground penetrating radar;*GPS*, global positioning system; *SP*, spontaneous polarization

5 Conclusions

Geophysical investigation of the Petrov lake dam has helped answer a number of questions regarding the dam's physical properties. Application of many geophysical methods has demonstrated the advantages and disadvantages of each individual method. The transfer of results of one method and interpretation by another method has made this process markedly easier, allowing conclusions to be drawn in greater detail and complexity. Monitoring the anomalies in the lake is of crucial importance. The results of repeated (monitoring) measurements can be mutually compared; the differences may then lead to assessment of risk levels for particular dam segments.

The retreat of the Petrov glacier has continually been accelerating since 1957. The rate of annual retreat has tripled during the second half of the 20th century and within the past decade it has increased up to 61.4 m per year. The area and volume of the retained water in the Petrov lake has increased considerably. Since 1980 the lake surface area has increased more than twice and since 1995 has grown annually to 92,700 m^2.

The thermokarstic processes caused by melting of the buried ice in the moraine dam of the Petrov lake undergo vigorous development. The number and size of thermokarstic lakes in the area of the lake dam have increased and deepened considerably. On the shores of those lakes new masses of buried glacier material have been denuded constantly.

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