A39

Geophysics in Glacial-hazard Initiation Zones, Russian Caucasus

I. Lecomte* (ICG/NORSAR), F. Köllner (University of Leipzig), D. Petrakov (Moscow State University), S. Chernomorets (UCEGM, Moscow), M. Shakhmina (Moscow State University), S.E. Hamran (University of Oslo), H. Juliussen (University of Svalbard) & A. Kääb (University of Oslo)

SUMMARY

Numerous glacier lakes have formed in recent decades due to worldwide glacier retreat induced by climate change. These lakes, dammed by glaciers and moraine ridges, are hazardous because of potential glacial lake outburst flows (GLOF). The GLOF probability is increasing in the Russian Central Caucasus, like at the Bashkara glacier which has been extensively studied, but detailed information about the ground is missing. A pilot geophysical campaign carried out during summer 2009 tested GPR and resistivity profiling at this site, using towed-systems to facilitate acquisition. The GPR measurements were successful with penetration depth down to 70 m on icy ground, though the acquisition was difficult due to rough ground terrain. The results show that GPR measurements would greatly improve the knowledge of the internal structure of that complex zone, thus helping for hazard assessments, but more field work is needed, including CMP measurements. The resistivity measurements were not that successful, the towed system requiring repeating each profile with increasing offset, the progression on the ground being heavy. Only the very first meters of the ground were retrieved, i.e, not really providing useful information. Results and experience gathered in 2009 are now analysed to plan another campaign summer 2011.

Introduction

Numerous glacier lakes have formed in recent decades due to worldwide glacier retreat induced by climate change, especially increase in summer temperatures. These lakes, dammed by glaciers and moraine ridges, are potential hazardous. If the flotation level of the damming ice is reached (ice dam thinning or lake level increase), a glacial lake outburst flow (GLOF) may start; a GLOF may also start by dam overtopping. GLOFs can travel hundreds of kilometers downstream and pose serious threats to population, infrastructure, and economic development. Critical conditions leading to GLOF formation and triggering mechanisms are yet poorly understood. Accurate predictions of the timing and behaviour of GLOF is also challenging. The GLOF probability is increasing in the Russian Central Caucasus, where more than 70 lakes were inventoried in the early 21st century (Petrakov et al., 2007). Among these sites, the Bashkara glacier lake system located in headwaters of the Adylsu river, Prielbrusie, in the Kabardino-Balkaria Republic of Russia, has been extensively studied by geomorphology, glaciology, hydrology, climatology, and remote sensing, but sub-surface dam and glacier structures had yet to be studied. A pilot Norwegian-Russian project was thus decided.

Knowledge about the composition (ice/rock/till) and structure of the damming media is crucial for the evaluation of dam stability, and a variety of geophysical methods are used for this purpose. The first reported use of geophysics was in the Peruvian Andes in the 1970s, followed by studies in the European Alps since the 1980s, and later in the Himalayas in the 1990s (Reynolds, 2006). A combination of electrical resistivity soundings and Ground-Penetrating Radar (GPR) frequently gives the best results, and are thus recommended in glacial hazard studies (Reynolds, 2006; Lecomte et al., 2008). We here describe the first results of a pilot geophysical campaign done during summer 2009 near the Bashkara glacier mentioned above. The objectives were to i) to measure the glacier thickness in the vicinity of the lakes, to estimate the lower lake growth potential, and ii) to clarify the composition of the upper lake dam. Due to the expected rough terrain conditions, we took towed-systems for both GPR and resistivity measurements to facilitate and speed up acquisition during the 10 days on site.

Study site and GLOF hazard

The Bashkara group of pro-glacial lakes, with a total area of 93000 m^2 and a total volume over 900000 m^3, is located at 43°12´N and 42°46´E on the northern slope of the main Caucasus ridge at 2500–2590 m.a.s.l. and in the headwaters of the Adylsu river at the margin of the Bashkara glacier (Figure 1). The Bashkara glacier is a valley-type temperate glacier with abundant surface debris and well-developed englacial drainage system. Some moulins have a depth of about 100 m (Mavlyudov, pers. comm.). During the Little Ice Age (LIA; from about the 16th to 19th centuries), the Bashkara glacier advanced but was obstructed by a glacier branch from the Ullukara mountain. As a result, the Bashkara glacier created a moraine system in a lateral position of the longer Ullukara branch. The upper lake (lake Bashkara) formed inside this moraine system during 1930s–1940s. GLOFs from the Bashkara lake occurred in 1958, 1959, and 1960, with much lower initial water impulse than a possible outburst would give nowadays (150 m^3/s; Petrakov et al., 2009). A lower lake, named Lapa, formed in 1980-1990s as the Ullukara glacier retreated and is about 90 m below the upper lake.

During 2001-2008 an annual growth of the Bashkara lake level, due to the thinning of the damming Ullukara glacier was observed, in parallel to thermokarst processes. From 2001 to 2006 the volume of the Lapa lake consequently increased by 5 times its initial volume. In August 2007, an ice grotto formed at the glacier margin 30 m away from the Bashkara lake. Overtopping of that lake occurred in July 2008 due to a rapid water level rise. No GLOF was released, but the situation lead to panic in the downstream settlements. Continued ice melting and lake level rise will most probably lead to the recurrence of critical situations in future years. The Bashkara lake is considered the main hazardous lake because a GLOF from this lake would enter the Lapa lake, thereby increasing the magnitude of the GLOF. The geophysical soundings were therefore focused on the area between the two lakes, but closest to the Bashkara lake where an initial yield is most probable. Figure 1 shows the location of all geophysical profiles, i.e, GPR and resistivity, superposed over a detailed DEM acquired by LIDAR.

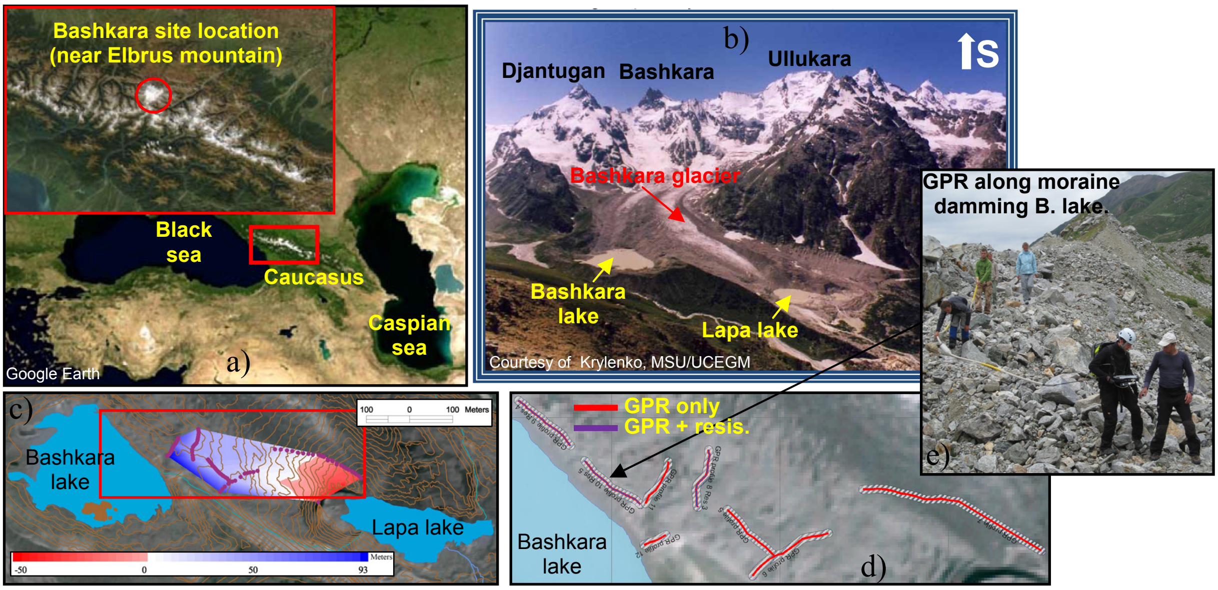

Figure 1: *a) Geographical location, b) Bashkara site, c) Studied zone between the two lakes with superimposed elevation obtained by LIDAR, d) Profile locations, and e) example of GPR acquisition.*

GPR acquisition

Due to the high resistivity of ice, GPR usually reaches good penetration in glaciers, though this also depends on the water content. The high contrasts in dielectric properties between water, rock and ice allow in addition an easier discrimination of the internal ice structures. On moraines, the quality of the results will highly depend on the clay content of the material. We used the Malå RAMAC system with a 50 MHz Rough Terrain Antenna (RTA; 4-m between transmitter and receiver), i.e., an unshielded, in-line towed acquisition system. Though the data may be of less quality than conventional antennas, the use of such towed system in difficult ground conditions is highly recommended for easier and quicker acquisition as tested by Lecomte et al. (2008). The presence of stones and boulders on the Bashkara site would have anyway prevented the use of the long rigid antennas needed for a 50 MHz acquisition. Though the RTA system is light and flexible, using a hip-chain system as distance trigger (a radar trace measured every 20 cm in our case) and usually requiring only 2 persons to operate, the ground in our case was very challenging. Up to 5-6 persons were needed on site to facilitate the progression of the antenna (stopped by rocks and boulders) and avoid damages. The acquisition was therefore much slower than expected and 8 2D profiles (30 to 250 m length) were acquired during the 10 days on site. The data were however of good quality, with a penetration depth up to 70 m (in ice) and down to 10-15 m when on moraine material. Standard processing was applied using the Reflexw software. The depth resolution is about 0.75 m. Profile examples are given in Figure 2.

Resistivity acquisition

Like for the GPR acquisition, we used a towed system so as to test such a system on glacial grounds because supposed to allow faster acquisition than conventional electrode-based DC resistivity systems. The Geometrics OhmMapper system chosen here operates on the base of capacitively-coupled AC induced in the earth at a particular frequency of 16.5 kHz, with receiver(s) and transmitter in a dipole-dipole mode. The capacitive current injection is good to overcome high contact resistance of high-resistivity material at the surface, like on roads or on ice in our case. The same profile is repeated several times, with increasing offset between transmitter and receiver(s), this to increase the penetration depth. The ground at the Bashkara site was however too rough to allow offsets longer than 15 m (very difficult progression) and the penetration depth was unfortunately as low as 4-5 m. Combined with battery problems, the resistivity acquisition was therefore limited to 3 of the GPR profiles and used to discriminate between different materials (ice, soil, rock, water), though the small penetration depth prevented to identify the deeper materials and measure the corresponding resistivities. The post-acquisition processing was performed with Geometrics' DataMap and the inversion with the standard Res2DInv software. The measured resistivity values range from 10^2 to 10^5 Ωm, with a clear contrast between moraine material and ice, as expected.

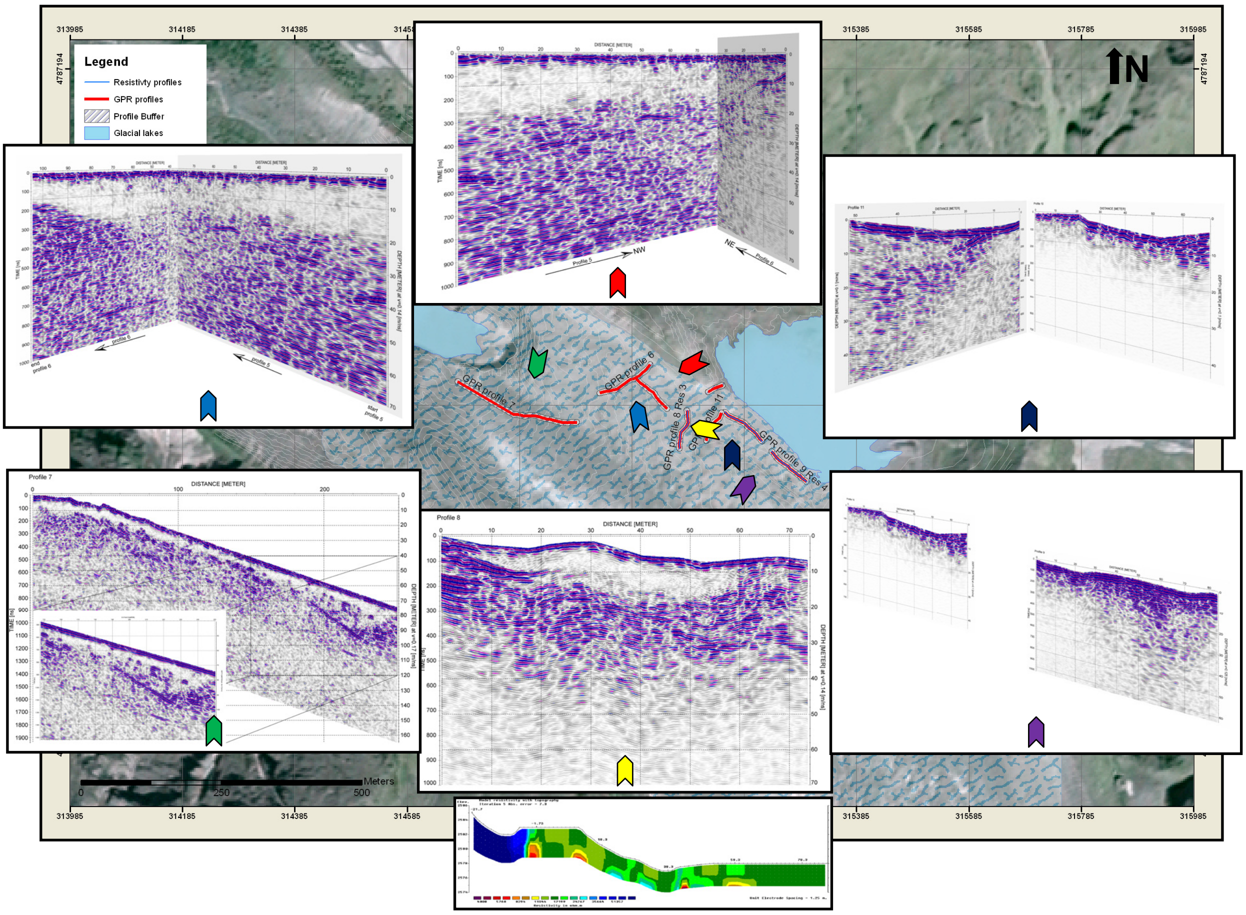

Figure 2: Overview of the GPR profiles. The topography corrections were obtained from the Lidar measurements carried out during the 2009 campaign. The depth axes, using a constant velocity depending on the profile location, are only given as an indication because the velocity model is not constrained by CMPs. The transparent layer and high scattering level is visible on all profiles on icy ground. One resistivity profile is given for the sake of information (only 4 m in depth).

Results

Deep penetration was obtained for GPR (up to 70 m on icy ground) and the resulting sections are of good quality, except along the Bashkara lake where the ice content of the moraine directly damming the lake could not be estimated due to lower penetration depth. In contrary, the resistivity measurements were difficult and time-demanding and could not cover the deep structures, thus only providing information about very shallow depths (4-6 m), though with high resolution. At that depth level, the observed resistivity values are typical of ice or debris-rich temperate ice, and moraine material, depending of the location of the profiles. A systematic observation on the GPR profiles on icy ground is the presence of a thick (5-20 m) and rather continuous transparent unit, which could correspond to a dry, compacted part of the ice. Significant scattering in the GPR data below that transparent layer is probably related to small water channels (no evidence of larger channels, at least in the investigated sites) and temperate ice (water bubbles, etc). The glacier is indeed known to be a rather well drained system as the water is flowing more or less continuously through it. Several strong reflectors at different depths are probably caused by different factors, e.g., the different ice-/rock-/water transitions (e.g., water table from Lapa lake). The deeper reflector, when identified, seems to correspond to the bedrock. Ice thickness estimation may thus be possible from GPR data but we only covered a very small portion of the area. In addition, the depth is only deduced from rather crude estimations of velocities as we did not have CMP acquisition; velocities were estimated by diffraction hyperbola analysis in Reflexw. This was especially possible on glacier parts with nice and deep diffraction hyperbolas and a velocity of 0.16 m/ns was estimated (typical of ice) in such zones. Though more care – and more measurements - is needed to properly assign a depth to the reflector identified as bedrock location, the Bashkara glacier bed seems to be at some locations a few meters below the Lapa lake level. It means that the lake volume could increase in case of further glacier recession, making the Lapa lake more hazardous.

Conclusions

The pilot geophysical acquisition carried out summer 2009 at the Bashkara site, originally planned as a feasibility study for the use of geophysics, provided interesting information, both about the technology to use and about the Bashkara glacier site. More geophysics has however to be done to draw proper hazard assessments in combination with other available information (e.g., glaciology). GPR measurements with a towed system were proven to be feasible, but are still time-demanding and the location of future profiles should be carefully chosen to cover the key zones. GPR should cover the margins of the glacier to better assess the difference between ice and non-ice. It will also be necessary to acquire a few CMPs at key locations to properly constrain the depth to the different structures, especially the bedrock. This will however require the use of conventional antennas, which is challenging on such a site with heavy debris cover. The use of a conventional resistivity system (electrodes in the ground) is highly recommended for a profile along the Bashkara lake as this is the potentially fragile zone. A second profile should go from the damming moraine down to the glacier and a third one along the main path of water between the two lakes. This may be part of a new campaign planned for summer 2011 (NATO Science for Peace and Security Program project).

Acknowledgements

Special thanks go to all Russian students and colleagues supporting our work in the field and Karl Joseph Sandmeier (ReflexW) for the support in the GPR processing. We thank the NATO Science for Peace and Security Program and the Russian Foundation for Basic Research, project 09-05-00934, for their funding. Many thanks go to the University of Oslo for the equipment and to Prof. Andi Kääb for his support. F. Köllner had a grant from the International Centre of Geohazards (ICG).

References

Köllner, F., Lecomte, I., Petrakov, D., Chernomorets, S., Shakhmina, M., S.-E. Hamran, Kaab, A., and Juliussen, H. [2009] Geophysics in glacial-hazard initiation zones: the high mountains of South Russia. *“Glacier Hazards, Permafrost Hazards and GLOFs in Mountain Areas: Processes, Assessment, Prevention, Mitigation” international workshop*, proceedings,Vienna, 10-13 November.

Lecomte, I., Thollet, I., Juliussen, H., and Hamran, S.-E. [2008] Using geophysics on a terminal moraine damming a glacial lake: the Flatbre debris flow case, Western Norway. *Advances in Geosciences*, 14, 301–307, ICG contribution 191.

Petrakov, D.A., Krylenko, I.V, Chernomorets, S.S., Tutubulina, O.V., Krylenko, I.N., Shakhmina, M.S. [2007] Debris flow hazard of glacial lakes in the Central Caucasus. *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*, Chen & Major, 703–714, Millpress.

Petrakov D.A., Aleinikov A.A., Kidyaeva V.M., Krilenko I.N., Norin S.V., Seinova I.B., Tutubalina O.V., Chernomorets S.S., Shahmina M.S. [2009] Recent evolution of proglacial lakes near Mount Elbrus. *Mitigation of natural hazards in mountain areas*. Materials of International Conference, Kyrgyz Republic, Bishkek city, 15-18 September 2009. Bishkek: Salam, 2009, p. 64-69.

Reynolds, J.M. [2006] Role of geophysics in glacial hazard assessment. First Break, 24, 61–66.