

Rapid ASTER Imaging Facilitates Timely Assessment of Glacier Hazards and Disasters

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Glacier- and permafrost-related hazards increasingly threaten human lives, settlements, and infrastructure in high-mountain regions. Present atmospheric warming particularly affects terrestrial systems where surface and sub-surface ice are involved. Changes in glacier and permafrost equilibrium are shifting beyond historical knowledge. Human settlement and activities are extending toward danger zones in the cryospheric system. A number of recent glacier hazards and disasters underscore these trends. Difficult site access and the need for fast data acquisition make satellite remote sensing of crucial importance in high-mountain hazard management and disaster mapping.

Here, rapid imagery from the ASTER (Advanced Spaceborne Thermal Emission and reflection Radiometer) instrument aboard the NASA TERRA satellite is used to support those authorities and scientists responsible for assessing the condition of the 20 September 2002 rock/ice avalanche at Kolka-Karmadon, North Ossetian Caucasus, Russia, and the spring 2002 glacier lake on the Belvedere glacier in the Italian Alps.

Glacier-related Hazards

Glacier- and permafrost-related hazards include glacier lake outbursts, ice avalanches, and destabilization of rock faces due to glacier and permafrost retreat. Glacier lake outbursts are often accompanied by heavy floods and debris flows. Recent increases in retreat rates of glaciers in virtually all mountain ranges of the world have led to the development of numerous new glacier lakes. In spring 2002, for example, the United Nations Environment Programme (UNEP) launched a high-level warning in view of the dramatic growth of gigantic glacier lakes in the Himalayas.

Ice avalanches are able to trigger far-reaching hazards such as enormous snow avalanches, lake outbursts, and mudflows. The 1970 Huascarán (Peru) and 2002 Kolka-Karmadon rock/ice avalanches and mudflows were among the most devastating of all glacier catastrophes. Given the lack of clear statistical evidence, it is difficult to know whether some of these hazards are a normal part of glacier and permafrost behavior, or whether they signal dramatic new threats from a changing cryosphere. A number of recent, high-magnitude rock fall events from glacierized and perennially frozen rock slopes [e.g. Bottino *et al.*, 2002] have also directed attention toward the possible influence of atmospheric warming on high-mountain rock faces.

Glacier Monitoring using ASTER Imagery

High-resolution satellite instruments such as Landsat ETM+ (Enhanced Thematic Mapper Plus; 15-m resolution for panchromatic band), ASTER (15-m for Visible and Near-Infrared—VNIR—bands), and others of their class help in recognizing important details of natural hazards; e.g., avalanche and debris-flow traces, glacier crevasses, and lakes and their changes over time. ASTER proved to be very suitable for assessing glacier hazards [Kääb, 2002; Wessels *et al.*, 2002]. With topography being a crucial parameter for the understanding of high-mountain hazards, DEMs generated from the ASTER along-track stereo band are especially helpful [Kääb, 2002]. Imaging opportunities by ASTER are governed by TERRA's 16-day nadir-track repeat period, and the fact that the ASTER VNIR sensor can be pointed cross-track by up to $\pm 24^\circ$, which allows for repeat imaging as frequently as every second day in response to urgent priorities.

The rapid development of the 3-million-m³ glacier lake on the Belvedere glacier in the Italian Alps during late spring 2002, and the

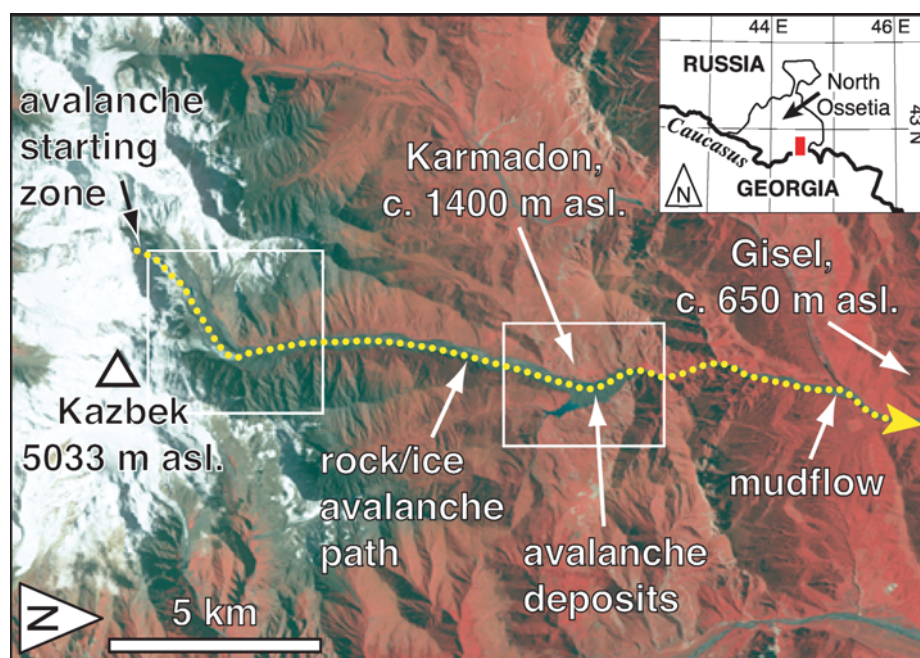


Fig. 1. ASTER false color image of 6 October 2002 showing the trace (yellow dotted line) and deposits from the 20 September 2002 Kolka-Karmadon rock/ice avalanche. North is on the right-hand side of the image. The red area in the inset indicates the location of the satellite image. Image details for the zones in white-outlined rectangles are shown in Figure 2.

devastating rock/ice avalanche from Kolka glacier, Caucasus, were given the highest acquisition priority by the ASTER science team at the NASA Jet Propulsion Laboratory (JPL) and the Japanese Earth Remote Sensing Data Analysis Center (ERSDAC). Both cases are very unusual in that they have no recorded precedent. A sound glaciological investigation of case details is, therefore, urgently required to update the knowledge base of scientists and authorities involved in glacier hazard mitigation. ASTER imagery has been rapidly available on site at the Kolka-Karmadon event, and has helped much with the disaster assessment.

The Rock/Ice Avalanche at Kolka-Karmadon

During the late evening of 20 September 2002, a combined rock/ice avalanche of several million m^3 started from a nearly 1.5-km-wide zone between around 3600 and 4200 m elevation in the perennially frozen north face of the Dzimara-khokh peak in the Kazbek Massif (Figure 1). The unusually large avalanche fell down onto the Kolka glacier tongue located at around 3200 m elevation. The Kolka glacier is known to have surged in the past (e.g., 1969), but no such activity was reported in 2002. Descriptions about two similar avalanche events in 1902 in the same area are available to the authors and are presently being carefully evaluated and compared to the 2002 event.

The impact of the initial rock/ice avalanche sheared off a major part of the Kolka glacier tongue and started a sledge-like rock/ice avalanche of tens of millions m^3 (Figure 2, bottom). Such a total detachment of a rather flat glacier tongue has no known precedent. The Kolka rock/ice avalanche crossed the tongue of the Maili glacier (Figure 2, bottom). It thereby removed and picked up lateral moraines from both glaciers. Even at this time, the speed of the mass must have been around 100 km/h as suggested by the vertical rise of approximately 300 m as the avalanche rose up the valley wall, turning from northeast to north to follow the main valley (Figure 2 bottom, eastward bulge in path). On its devastating journey, the avalanche picked up a large amount of loose sediments in the valley bottom. An avalanche track extracted in three-dimensional from the ASTER stereo data will be used for a thorough reconstruction of the avalanche dynamics.

A few minutes after initiation and 18 km downvalley from the Kolka glacier, the gigantic mass overran the lower parts of the village of Karmadon (Figure 2, top), killing dozens of inhabitants. Shortly beyond this point, the avalanche was abruptly stopped by the narrowing valley flanks of the Karmadon gorge (Figure 2, top) and roughly 80 million m^3 of ice and debris were deposited. Large amounts of mud were suddenly pressed out of the mass. The resulting mudflow, up to 300 m wide, ravaged the valley bottom below Karmadon, traveling for another 15 km down from the gorge (Figure 1). In total, the avalanche and subsequent mudflow killed over 120 people.

No unusually high runoffs were registered at the Gisel bridge some 20 km downvalley of Karmadon, which suggests that the mudflow had a low water content. At present, evidence is missing on whether the water content of

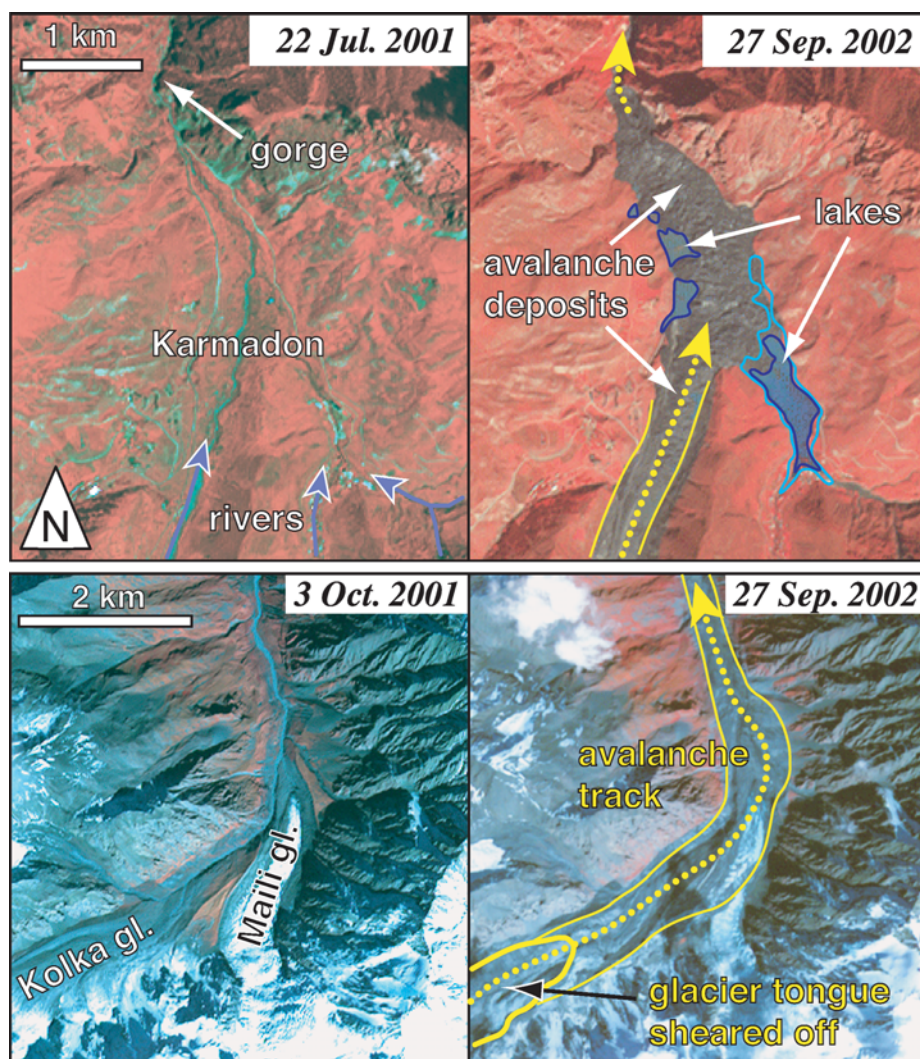


Fig. 2. ASTER false color imagery from before (left) and after (right) the 20 September 2002 Kolka-Karmadon disaster. A large rock/ice avalanche from the north face of the Kazbek massive (cf. Figure 1) sheared off the entire Kolka glacier tongue (bottom, yellow outline). Approximately 80 million m^3 of ice and debris were deposited at the village Karmadon, south of the Karmadon gorge (top). The rivers in the area (blue arrows) were dammed by the avalanche deposits and formed lakes (dark blue line: lake extent as of 27 September 2002; light blue line: lake extent as of 22 October 2002). North is to the top.

the Kolka-Karmadon avalanche was produced largely from ice melt due to friction heating during the avalanche event, or whether the water was already stored in the Kolka glacier, possibly facilitating its disintegration. Most likely, water played an important role in substantially reducing basal friction and allowed the high avalanche speed and reach. Conversion of gravitational potential energy into frictional heating and enthalpy of fusion of ice may have changed as much as 6% of the avalanche mass to liquid water. Unusually low basal friction and small ratios between vertical drop and horizontal runout zone have also been reported for other rock/ice avalanches in glacial environments [e.g., Bottino *et al.*, 2002].

The avalanche deposits at Karmadon soon started to block the rivers entering the gorge (Figure 2 top, blue arrows). Over a period of approximately one month, the dammed river water progressively flooded the populated areas near Karmadon that had not been directly affected by the avalanche. Water stored in the avalanche or produced from its melt might, to

a certain extent, also have contributed to the formation of the lakes. These lakes, estimated from the 22 October 2002 ASTER image to be over 400,000 m^2 in area, and close to 10 million m^3 in volume, posed a dramatic danger of lake outburst and catastrophic flooding of downvalley areas (Figure 2, top). The lake level started to slowly sink after the 22 October 2002, possibly due to the development of channels within or under the ice. A new critical stage is, however, expected in springtime with the onset of snow melt. Due to their high mass and thermal content, the ice avalanche deposits at Karmadon will persist and represent a hazard over many years. Urgent mitigation work and a more thorough documentation are underway.

Rapid Development of a Glacier Lake, Italian Alps

Whereas satellite imagery is often the only available data source for remote high mountain regions, airborne and terrestrial measurements may be applied to regions with comparably easy

access such as the European Alps. However, routinely taken satellite images might still be the only available data source when it comes to reconstructing past developments.

In summer 2001, the Belvedere glacier (Figure 3) underwent a surge-type movement, with speeds of up to 200 m a⁻¹ as opposed to the approximately 30 m a⁻¹ measured for the mid-1980s and 1995–1999 [Haeblerli *et al.*, 2002]. Detailed observations of the Belvedere glacier started in the mid-1980s in connection with a catastrophic outburst and subsequent artificial drainage of the moraine lake Lago delle Locce in 1979. In autumn 2001, a small lake developed at an altitude of approximately 2150 m asl. on the flat Belvedere glacier tongue at the foot of the east face of the Monte Rosa. The lake formation was attributed to enhanced englacial water pressure and/or ice compression from the surge-type movement. Development of a large topographic depression on the glacier surface and the rapid evolution of a supraglacial lake are rare on temperate glaciers, and have not been previously observed in the Alps in this dimension.

It was with great surprise, therefore, that the first control visit in mid-June 2002 encountered an exceptionally large lake of 150,000 m² with a volume of 3 million m³ (the lake area at that time was comparable to that on the 19 July 2002 ASTER image; Figure 3). The lake level was rising at up to 1 m per day and had only a few meters of freeboard left. The Italian Civil Defense Department and the scientists involved initiated emergency actions. This included continuous lake level monitoring, evacuation of certain parts of the village of Macugnaga, an automatic alarm system, the installation of pumps, and detailed scientific investigations. A cold spell in early July 2002 significantly reduced melt water input, and together with pumping and naturally occurring, sub-glacial drainage, helped to stabilize and then lower the lake level. By the end of October 2002, the lake area had decreased to a size comparable to that seen on the 24 August 2001 ASTER image (roughly 2000–3000 m²; Figure 3).

ASTER imagery formed the base for a rapid, first-order assessment of the surge-type glacier dynamics, in that it detected enhanced glacier speed and crevassing. The 30 May 2002 ASTER image, in which an open water surface of roughly 20,000 m² is visible (or roughly 40,000 m² if the snow and ice-covered area in the lake center is included) represents the only data source documenting the development of this supraglacial lake during spring 2002. These findings illustrate the need for continuous monitoring of the area over the winter of 2002–2003 in order to facilitate an early warning if the lake depression should start to refill. This would allow a quick implementation of mitigation measures. Lastly, in view of the Kolka–Karnadon event, special attention will be given to an increasingly active rock and ice fall zone in the permafrost on the Monte Rosa east face, with its steep hanging glaciers (Figure 3, yellow arrow).

The applied rapid ASTER imaging has been performed within the Global Land Ice Measurements from Space (GLIMS) program, one of the science projects connected to the ASTER sensor [Kieffer *et al.*, 2000]. GLIMS is a

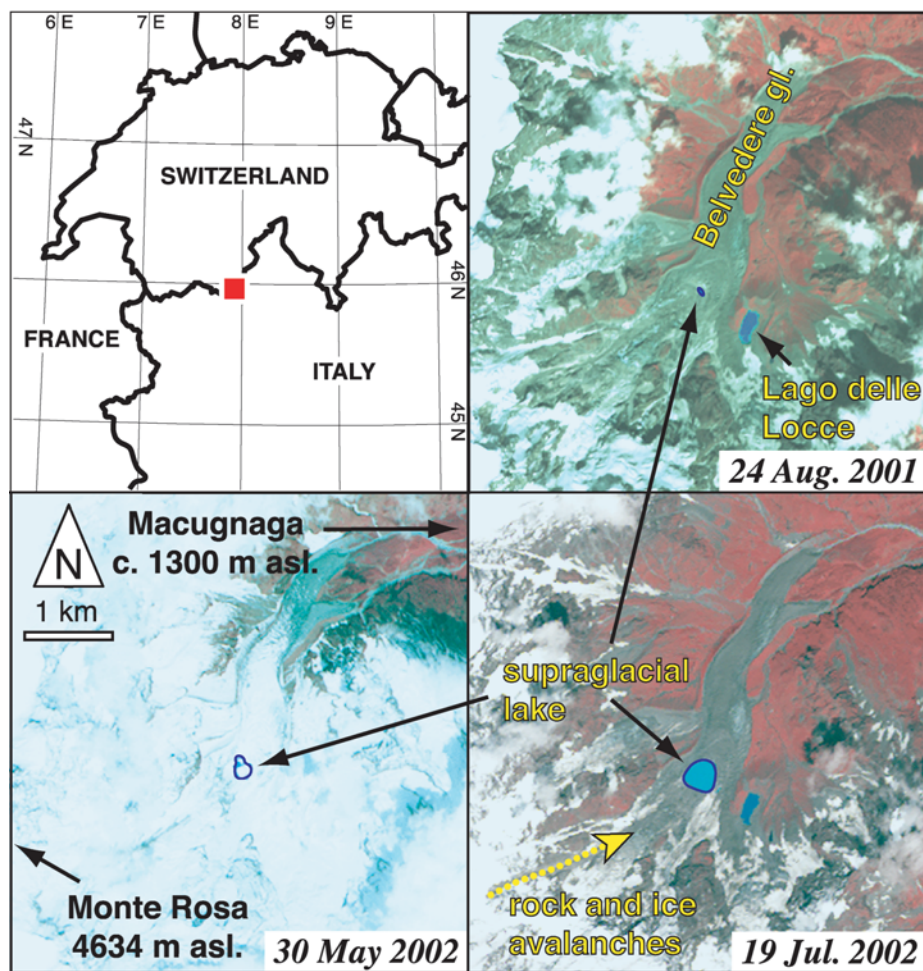


Fig. 3. ASTER false color imagery documenting the fast development of a 3-million-m³ glacier lake on Belvedere glacier, Italian Alps. In spring 2002, the lake provoked a sudden flood risk for the village of Macugnaga. The red area on the map shows the location of the image. Lake boundaries are highlighted by blue lines. The yellow dotted line indicates a zone of presently increasing rock/ice avalanche activity.

global consortium that is working to establish a remote sensing-derived digital baseline inventory of global land-ice extent for climate monitoring purposes. The GLIMS data base will be hosted at the National Snow and Ice Data Center in Boulder, Colorado. The GLIMS coordination center at the U.S. Geological Survey in Flagstaff, Arizona, also provides satellite data acquisition support to help scientists and responsible authorities in dealing with glacier hazards and disasters.

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