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Ground Penetrating Radar Survey for Risk Reduction at Imja Lake, Nepal

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High Mountain Glacial Watershed Program

Ground Penetrating Radar Survey for Risk Reduction at Imja Lake, Nepal

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ACRONYMS AND SPECIAL TERMS

EMR	Electromagnetic Radiation
ERT	Electrical Resistivity Tomography
GLOF	Glacial Lake Outburst Flood
GPR	Ground Penetrating Radar
HMGWP	High Mountain Glacial Watershed Program
IPCC	Intergovernmental Panel on Climate Change
IRG	International Resources Group
PDGL	Potentially Dangerous Glacier Lake
TMI	The Mountain Institute
USAID	United States Agency for International Development
UT	University of Texas at Austin

PROJECT TEAM AND CONTACT INFORMATION

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EXECUTIVE SUMMARY

This study presents observations of the structure of the terminal moraine complex at Imja Lake. Detailed ground penetrating radar (GPR) surveys were conducted at Imja Lake. The lake and the surrounding Imja glacier have been described in the previous section. This paper should contribute to the understanding of the structure of the terminal moraine and the distribution of ice in the core of the moraine.

The formation of glacier lakes in the Nepal Himalaya has been increasing since the early 1960s. Accompanying this increase in the number and size of glacier lakes is an associated number of GLOF events. The Khumbu region of Nepal (which includes the Dudh Koshi basin) is regularly mentioned as an area particularly prone to GLOF events and containing important sites for possible GLOF risk reduction projects (especially in the Imja Khola).

Imja lake in the Khumbu is often mentioned as a potentially dangerous glacier lake (PDGL) and its GLOF risk has been investigated for more than 20 years (Armstrong, 2010). In May and September 2012, the authors visited the lake and observed the rapid rate of change of the terminal moraine complex. They performed ground penetrating radar surveys of most of the terminal moraine complex and mapped the ice core of the moraine.

Imja Lake is currently the focus of several groups in an effort to reduce the risk of a GLOF posed by the increasing lake level. The presence or absence of ice in the core of the terminal moraine complex is of critical importance in designing a risk reduction program for the lake. This work has used Ground Penetrating Radar (GPR) to investigate the internal structure of the moraine complex in order to map out the ice thickness in critical areas.

The results of the GPR survey show that there is extensive ice present in the core of the terminal moraine complex at Imja Lake (see Figure 8). The thickest areas of ice are in the moraine near the western end of the lake on the northern side of the lake outlet. The ice in this region is several tens of meters thick and up to fifty meters thick in some places. Along the northern and southern sides of the lake outlet, the ice is between ten and twenty-five meters thick. In some portions of the moraine on the southern side of the outlet the ice thickness is up to forty meters.

Extensive seepage of water from the terminal moraine was observed in two locations during visits to the lake in September 2011, May 2012, and September 2012. GPR transects above and below the site of seepage show the presence of ice above the seep and much less ice below the seep. Seepage of water through the terminal moraine is an indication of potential weakness in the moraine and a possible site of future moraine failure.

Recent work has been initiated by the United Nations Development Programme to develop an Imja Lake Risk Reduction Program. One of the primary methods suggested for reducing risk associated with the lake is to reinforce and deepen the outlet channel so that it can lower the lake level up to 3 meters below the current level. This project involves making excavations of the outlet channel and the construction of a diversion channel on the southern side of the outlet. The results presented here indicate that there may be ice present in the moraine in the vicinity of the excavations being considered

in this project. Excavation activities that encounter ice in the moraine material may cause weakening of the ice resulting in increased water seepage and erosion of the moraine. Therefore, it is recommended that additional GPR surveys be conducted in this area accompanied with Electrical Resistivity Tomography (ERT) surveys. The ER surveys will be able to more definitively indicate the presence of ice in the moraine as well as the degree of water saturation of the moraine material.

INTRODUCTION

GLACIERS AND CLIMATE CHANGE

According to Orlove et al. (2008) during the last two centuries glaciers have taught us two important lessons: first, the existence of ice ages, and second, the emerging trends of climate change. In the 19th century, around 1820 to 1830, Swiss naturalists studying glaciers established the existence of ice ages and determined that many places where we now find forest, towns or fields were once under huge quantities of ice. Scientists then began to relate the ice ages to the cyclical fluctuations in the earth's orbit, which provided new understanding of the dynamics of the earth. In addition geologists correlated the new ice age date to different geologic discoveries, eventually concluding that the earth was much older than previously thought. Now, in the 21st century, glaciers provide us a second important lesson to better understand climate change. During the 19th century, the perspective of our Earth's climate was that it was dominated by slow processes that occurred over many years due to natural factors. Now, we are beginning to understand a climate paradigm dominated by faster processes, which are induced by the intervention of humans in the environment. According to the Intergovernmental Panel on Climate Change (IPCC) (2001) "Numerous studies worldwide show a widespread, and well documented, retreat of mountain glaciers in non-polar regions of the world during the 20th century." Coudrain et al. (2005), Casassa et al. (2009), and Armstrong (2010) note that mountain glaciers are a good indicator of climate change. When glaciers melt, runoff increases and there is a high risk of flooding in zones adjacent to downstream rivers. These melting processes also lead to the formation of new glacier lakes at or on the terminus of glaciers (Awal et al., 2010) in high elevations in rugged terrain of remote areas (Bajracharya et al., 2008; Chen et al., 2010).

Newly formed glacier lakes are often contained by their glacier moraines, dams of loose boulders and soil, that present a risk of Glacial Lake Outburst Floods (GLOFs) (Bajracharya et al., 2007a; Osti & Egashira, 2009; Sakai et al., 2003; Shrestha et al., 2010). According to several authors (Kattelmann, 2003; and Richardson & Reynolds, 2000) GLOFs represent one of the most significant hazards related to glacier recession and temperature increase due to climate change. GLOFs can affect fragile mountain ecosystems as well as economic activities due to the large magnitude and power of the flood flow comprised of water and debris (Bajracharya et al., 2007b).

A GLOF is a sudden release of a huge amount of water, many orders of magnitude higher than the normal flow, from a glacier lake due to a triggering mechanism (often a breach of the moraine dam) (Carrivick, 2006). According to Awal et al. (2010) it is common to find moraine dammed lakes and GLOFs in different glacierized regions. In addition, Osti & Egashira (2009) point out that even though there is a great urgency to evaluate the impact of GLOFs and validate models that represent such events, this is difficult because of the lack of information. Attention has been primarily focused on past events, and satellite image information, but not on the hydrodynamic characteristics and continuum mechanics of the floods (Osti & Egashira, 2009). According to Horritt & Bates (2002), glaciers have been receding due to climate change; which has caused the formation of more glacier lakes and increased the volume of those lakes, in conjunction with increasing risk of failure of terminal moraines due to the weakening of ice cores combined or due to the increase in trigger mechanisms (e.g., rock and ice avalanches) in such places.

GLACIER LAKES AND GLOFS IN NEPAL

The formation of glacier lakes in the Nepal Himalaya has been increasing since the early 1960s. Accompanying this increase in the number and size of glacier lakes is an associated number of GLOF events. Table 1 lists known GLOF events in Nepal (Ives et al., 2010; Shrestha & Aryal, 2010). Kattelmann (2003) estimates that since 1960, GLOFs occur on average every 3 to 4 years in the eastern Himalaya. The appearance and danger posed by glacier lakes in this region has prompted national and regional groups to assess the increasing GLOF risk to communities downstream of the lakes. Glacial lakes in Nepal that need further investigation due to their GLOF risk include Tsho Rolpa, Lower Barun, Imja, Lumding, West Chamlang, and Thulagi lakes (Ives et al., 2010; Yamada, 1998).

Table 1. GLOF Events in Nepal (Ives et al., 2010; Shrestha & Aryal, 2010; Yamada, 1998)

Date	River basin	Name of lake	Cause
450 years ago	Seti Khola	Machhapuchhare	Moraine collapse
Aug. 1935	Sun Kosi	Taraso	Moraine collapse, seepage
Sept. 1964	Arun	Gelhaipco	Moraine collapse, ice avalanche into lake
1964	Sun Kosi	Zhangzangbo	Moraine collapse, seepage
1964	Trisuli	Longda	
1968	Arun	Ayaco	Lake burst 3 times ('68, '69, '70)
Sept. 1977	Dudh Koshi	Nare	Moraine collapse
1980	Tamur	Punchan	
Jun. 1980	Tamur	Nagmapokhari	Moraine collapse
Jul. 1981	Sun Kosi	Zhangzangbo	Moraine collapse, ice avalanche into lake
Aug. 1982	Arun	Jinco	Moraine collapse, ice avalanche into lake
Aug. 1985	Dudh Koshi	Dig Tsho	Moraine collapse, ice avalanche into lake
Jul. 1991	Tama Koshi	Chubung	Moraine collapse, ice avalanche into lake
May 1995	Kaligandaki		
Sept. 1998	Dudh Koshi	Tama Pokhari	Ice avalanche
Aug. 2003	Madi River	Kabache Lake	Moraine collapse
Aug. 2004	Madi River	Kabache Lake	Moraine collapse

The Khumbu region of Nepal (which includes the Dudh Koshi basin) is regularly mentioned as an area particularly prone to GLOF events and containing important sites for possible GLOF risk reduction projects (especially in the Imja Khola). Much of this attention stems from the fact that it is a famous region (on the Everest Base Camp trekking route) and there would be significant economic costs for the region if a GLOF were to occur, and two previous GLOFs that have occurred there in recent years:

- Nare GLOF (1977): Nare Lake is situated in the Dudh Koshi watershed on the southern slope of Ama Dablam in the Mingbo Valley a tributary of the Imja Khola. The lake was formed by a moraine dam having an ice-core. A GLOF event occurred on 3 September 1977 when a small glacial lake located at a higher elevation discharged into the Nare Lake causing the lake to overtop its damming moraine and creating a GLOF into the Imja Khola and finally the Dudh Koshi below. The discharge was estimated variously to have been between 400,000-500,000 m3 (Fushimi et al., 1985; Buchroither et al., 1982) and reached Pangboche about 45 minutes after the outburst. Several lives were lost in the flood and bridges were destroyed for 35 km downstream (Mool et al., 2001; Ives et al., 2010; Buchroithner et al., 1982; Fushimi et al., 1985; Zimmerman et al., 1986).

- Dig Tsho GLOF (1985): The Dig Tsho glacial lake contacts the Langmoche glacier and drains into the Bhoti Koshi tributary of the Dudh Kosi. The lake burst on 4 August 1985 destroying

the nearly completed Namche Hydropower Plant (11 km downstream), 14 bridges, trails, cultivated land, and caused the loss of several lives. The GLOF was triggered when an ice avalanche fell into the lake, which had little freeboard at that time, resulting in a wave that overtopped the moraine dam and caused a breach in the dam. The GLOF was estimated to have a volume of 6-10 million m3 and drained in about 4 hours. Eyewitnesses reported at least two GLOF surges coming from the lake. The mix of water and debris in the resulting flood wave significantly increased the destructive power of the flood. Since the 1985 GLOF, the lake has not been considered dangerous (Mool et al., 2001; Ives 1986; Vuichard and Zimmerman 1986, 1987; Ives et al., 2010).

Imja lake in the Khumbu is often mentioned as a potentially dangerous glacier lake (PDGL) and its GLOF risk has been investigated for more than 20 years (Armstrong, 2010). This lake has been reported by Fujita et al. (2009) and Watanabe et al. (2009) as a stable lake. However in September 2011, Dr. Watanabe and people from downstream villages agreed that many surface ponds on the terminal moraine were coalescing into bigger pounds and eventually will form part of the main water body, which could weaken the terminal moraine (Goldenberg, 2011). In May and September 2012, the authors visited the lake and observed the rapid rate of change of the terminal moraine complex. They also performed ground penetrating radar surveys of most of the terminal moraine complex and mapped the ice core of the moraine. That work and its implications for reducing the risk posed by an increasing volume of water in Imja Lake are the subject of this paper.

IMJA GLACIER AND LAKE

Imja Lake (or Imja Tsho) is located in the Solokhumbu region of the Nepalese Himalaya (27.898 N, 86.928 E), about 9 km south of Mt. Everest (see Figure 1). The lake has experienced rapid growth in area and volume over the last 50 years, leading to concern over the risk of a catastrophic GLOF event. A GLOF from Imja Lake could affect those villages that are nearby downstream, e.g., Dingboche, 8 km downstream of the lake's terminal moraine. Figure 2 shows the geographic locations of Imja Lake and Dingboche village.

The population in the village areas downstream of Imja Lake is about 96,767 for Imja, and about 5,784 to 7,762 people would likely be affected by a potential GLOF, with up to 501,773 people indirectly affected through infrastructural damage and loss of goods and services (ICIMOD, 2011). Imja Lake lies within one of the top 10 tourist destinations in Nepal, with more than 30,000 tourists visiting the region annually. According to ICIMOD (2011), the human capacity to deal with a GLOF event is poor. Farms are not large enough to provide sufficient food, and incomes are low.

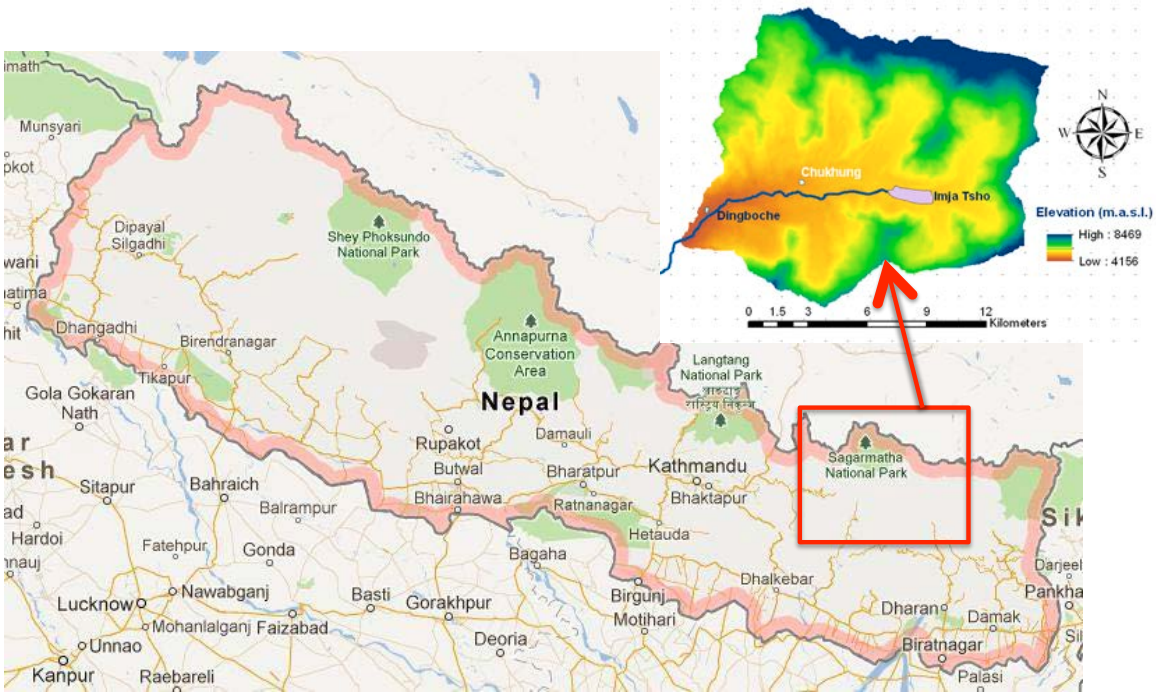


Figure 1. Location of Imja Khola basin within Nepal. (*Source:* Google Earth and the authors)

Imja Lake is bounded on the east by Imja glacier, on the north and south by lateral moraines, and to the west by a terminal moraine. The elevation of the lake in 2006 was 5006 m (Lamsal et al., 2011). Figure 2 shows the lake in an aerial photo from 2009 (Google Earth, 2009). The outlet of the lake is through the terminal moraine incised in the western end of the lake and forms the Imja Khola (river), which is a tributary of the Dudh Khosi. The area of the Imja basin is about 141 km^2 with altitude ranging from 4355 to 8501 m and it is about 38% covered by glaciers (Konz et al., 2005).

Monsoon circulation dominates the climate in the basin, with easterly winds in the summer and westerly winds from October to May. About 70–80% of the annual precipitation of the basin falls during the monsoon period. Runoff in the basin also follows the monsoon with about 64% of the annual discharge occurring between June and September, and winter discharge is about 15% of the annual discharge, with mean discharge from December to April about 1.3 m^3/s (Konz et al., 2005).

The Imja glacier has been extensively studied (e.g., Watanabe et al. 1994; Sakai et al. 2007; Bolch et al. 2008; Hambrey et al. 2008; Lamsal et al., 2011). The development of Imja Lake has been discussed by several authors (Quincey et al. 2007; Bajracharya et al. 2007a; Byers 2007; Yamada 1998; Watanabe et al. 2009; Ives et al. 2010; and Lamsal et al. 2011). Lamsal et al. (2011) provide a general description of the evolution of the Imja glacier and lake since the early 1960s. Imja lake appeared during the 1960s after several small meltwater ponds on the glacier coalesced into an emerging glacier lake. Measurements in 2002 showed the average depth of the lake had grown to 41.6 m with a maximum depth of 90.5 m and a volume of 35.8x10^6 m^3 (Sakai et al. 2003). By 2007 the lake was about 2000 m long, 650 m wide, and an area of about 1.03 km^2 (Watanabe et al. 2009). Recent estimates indicate that the volume of the lake is about 45x10^6 m^3 (Budhathoki et al., 2010). Figure 4 shows an estimated progression of the area from 1956 to 2007 (Watanabe et al., 2009). Although the lake has expanded rapidly in the last 50 years, most of the expansion has occurred through calving of the eastern end of the glacier and not through movement of the terminal moraine (Hambrey et al., 2008). The down-valley expansion has stabilized in recent years while the up-glacier expansion continues unabated (Watanabe et al., 2009).

Figure 2. Location of Imja Lake (*Source:* Google Earth, 2010)

The terminal moraine of the Imja glacier is about 700m wide and 50m high with a dead-ice core (Watanabe et al., 2009). The moraine has sparse vegetation and numerous kettle holes and ponds. The lake level inside the moraine is about 40 m below the lowest point on the crest. Drainage from the lake, and hence the entire glacier, is focused on a single channel that winds its way between the hummocks (Hambrey et al., 2008). The minimum relative height between the lake level and the lateral moraine crest is 47m and increasing (Watanabe et al., 2009). The lateral moraine troughs also act as gutters, trapping debris derived from rockfall, snow avalanches and fluvial transport (Hambrey et al., 2008).

The Imja glacier still covers the area beneath Imja Lake and melting of this ice has caused the lake level to fall in recent decades (Watanabe et al. 1995; Fujita et al. 2009). Lamsal et al. (2011) report the average lowering of the glacier surface for the period 1964 to 2006 in the area west of the lakeshore is 16.9 m. The average lowering in the up-glacier area east of the lakeshore is 47.4 m. Knowledge of the vertical lowering of the Imja glacier and lake as well as the terminal moraine complex is minimal.

Table 2. Imja Lake Area Expansion 1962 to 2009.

Year	Area (km^2)	Source
1962	0.03	Bajracharya. et al. (2007a)
1975	0.30	Bajracharya. et al. (2007a)
1983	0.56	Bajracharya. et al. (2007a)
1989	0.63	Bajracharya. et al. (2007a)
1992	0.64	Yamada and Sharma (1993)
2000	0.77	Bajracharya. et al. (2007a)
2001	0.83	Bajracharya. et al. (2007a)
2002	0.86	Sakai et al. (2003)
2006	0.94	Bajracharya. et al. (2007a)
2007	1.03	Watanabe et al. (2009)
2009	1.01	Watanabe et al. (2009)

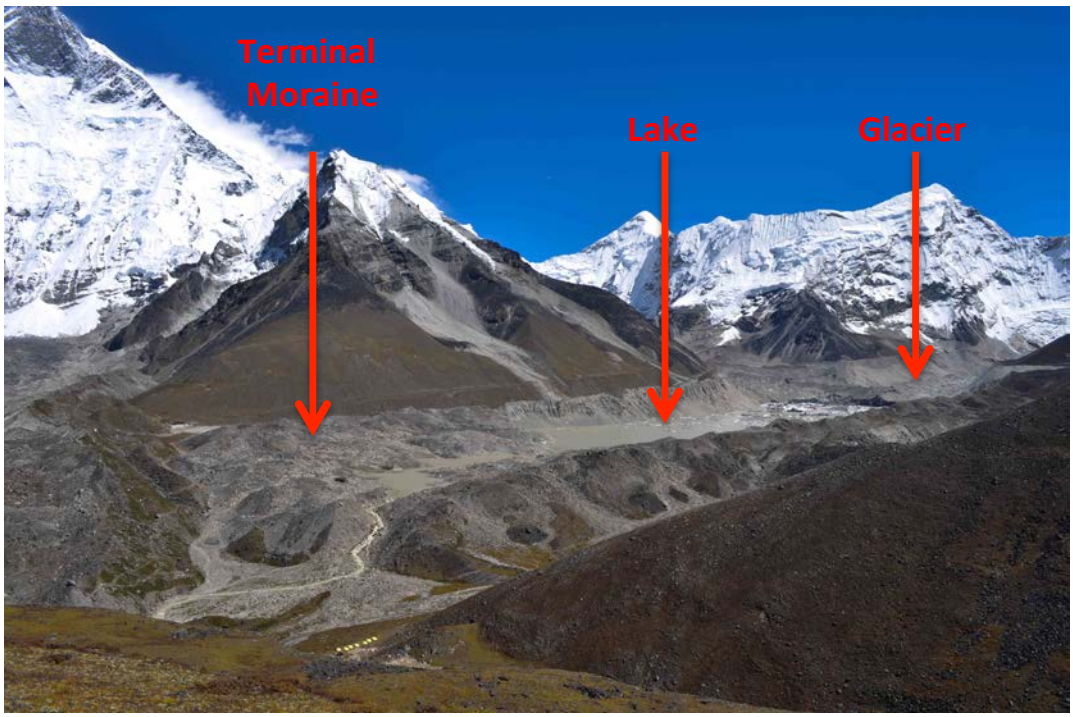


Figure 3. Photo of Imja Lake, September 2012 (*Photograph:* Daene McKinney)

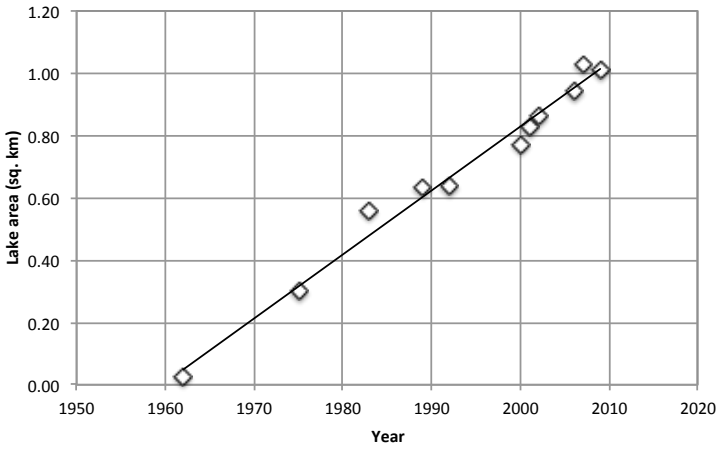


Figure 4. Imja Lake Expansion 1962-2009.

The potential GLOF hazard posed by Ijma Lake has been discussed by Bajracharya et al. (2007b) and ICIMOD (2011). Bajracharya, et al. (2007b) and Watanabe et al. (1994, 1995) reported rapid melt of the debris-covered ice and significant changes in the outlet position of Imja Lake. Enlargement and merger of intermediate ponds in the outlet course may cause outward migration of the lake shoreline, reducing the width of the dam considerably and potentially leading to an outburst of the lake.

METHODS

This study presents observations of the structure of the terminal moraine complex at Imja Lake. Detailed ground penetrating radar (GPR) surveys were conducted at Imja Lake. The lake and the surrounding Imja glacier have been described in the previous section. This paper should contribute to the understanding of the structure of the terminal moraine and the distribution of ice in the core of the moraine.

Ground-penetrating radar (GPR) is a geophysical technique developed for the non-invasive investigation of subsurface features (Davis and Annan, 1989). GPR techniques were first developed in the 1950's to determine ice sheet thickness in Greenland and Antarctica. Applications grew rapidly through the 1970's to portable GPR systems for glaciological research in the 1980's (Woodward and Burke, 2007). Using GPR, transmitted energy is reflected at the interface of different materials and the reflection is picked up by a receiver and displayed as a plot of signal amplitude against two-way travel time (Woodward and Burke, 2007; Davis and Annan, 1989).

The electromagnetic radiation (EMR) wavelengths used in GPR are in the microwave range (5 – 100 MHz). Substances through which EMR moves are characterized by their permittivity (the degree to which the material modifies the electric field of the EMR). The interface between materials of different permittivity causes reflection of EMR, and a high permittivity differences between materials results in more reflection. Identification of subsurface structures with GPR involves transmitting EMR pulses into the ground and measuring the time elapsed between transmission, reflection off a subsurface discontinuity, and reception back to a surface receiving antenna. GPR transmitters generate very short, high-voltage pulses and transmit them into the antenna, which emits it at the specified frequency into the surrounding area.

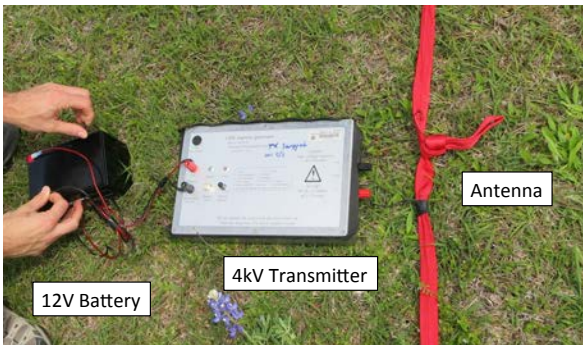
There is a delay between the time that the GPR transmitter emits its signal and the time at which any echoes return back to the GPR receiver (Annan 2001). This delay is determined by the distance to and from the target divided by the speed with which the waves propagate through the host material; the longer the delay the greater the distance to the target, assuming uniform velocity conditions. Velocities can range from $33x10^6$ m/s in fresh water, to $60x10^6$ m/s for saturated sand, to $110x10^6$ m/s for loose debris and frozen sediments, to $160x10^6$ m/s for ice, and $300x10^6$ m/s in air (Davis and Annan, 1989; Neal, 2004; Sass 2007).

Imaging of the subsurface is possible due to the large contrast between the electromagnetic properties of rock, ice, water, and sediments (Annan and Davis, 1976). GPR pulses can penetrate 50 – 1000 m in depth (depending on the antenna used). The GPR surveys described here were carried out using a custom built, low-frequency, short-pulse, ground-based radar system (Catania et al., 2010) refitted from sled to back-pack deployment with one person carrying the transmitter and one person carrying the receiver. In addition, one person moves in the lead of each antenna (Figure 5). The GPR transmitter used was a Kentech Instruments Ltd. GPR pulser outputting 4kV signals with a 12v power source (Figures 5 and 6). The antennas for the system are The receiving antenna is connected to an amplifier and a National Instruments USB-5133 Digitizer. The digitizer is run through a National Instruments LabView program for immediate processing in the field. GPS signals are correlated with the GPR signals in the LabView application. The structure of the subsurface is surveyed using the GPR with pulses at 4KV and weighted dipole antennae threaded insude climbing webbing (Gaddes et al., 2000) oriented in-line and operating at 5 MHz (10 m half-length), 10 MHz (5 m half-length), 20 (2.5 m half-

length) MHz and 20 MHz (1 m half-length), depending on which antenna provides the best resolution for the depth of the moraine and ice (Table A.1, Appendix 1). Both GPR and GPS signals are post-processed using MatLab programs.

In terms of propagating GPR waves, the dielectric constant (permittivity) of the medium has a direct effect on the capacity of a transmitting material to store electrical potential energy under the influence of an electric field (Reynolds, 1997, cited in Degenhardt, 2009). Estimating the velocity of propagation of the GPR signal in the subsurface is critical to calculating the depth of various objects and layers. Moorman and Michel (2000) used GPR to characterize the hydrologic system of an Arctic glacier. They determined the depth to subsurface objects using a Common-Mid Point (CMP) velocity survey, where the velocity is calculated from reflections off horizontal interfaces of known depth. They report velocities of $170x10^6$ m/s in ice and $130 - 170x10^6$ m/s in gravel and frozen till. We have consistently used a propagation velocity of $110x10^6$ m/s in this work since there is a mix of ice and debris in most locations and no CMP or other methods were used to calibrate the velocity. These measurements will be made in September 2012 on a return visit to Imja Lake to take more GPR data.

Figure 5. Backpack mounted GPR system deployed in the field at Imja Lake. (*Photograph:* Alton Byers)



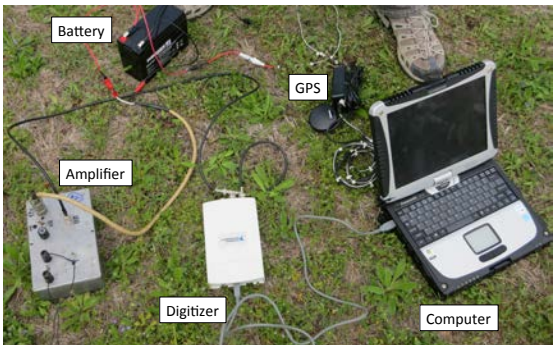


Figure 6. GPR transmitter (left) and GPR receiver (right) (*Photographs:* Daene McKinney)

Gades et al. (2000) used a similar GPR system to measure ice thickness on the Khumbu glacier of Nepal, but it was not configured for moving transects. Ice thickness measurements were made using the highest frequency that allowed bed reflection detection; the lowest used was 5 MHz. Longer wavelength (lower frequency) increases the amount of energy that passes through the surface debris layer and decreases the amount of energy scattered from within the ice; however, it also decreases the resolution. Gades et al. (2000) noted errors in their GPR measurements arising from three main sources: migration, inability to select the precise bed reflection location from the migrated records, and uncertainty in the GPR wave velocity within the glacier.

RESULTS

The overall purpose of the GPR survey of Imja Lakes described here is to provide additional information to characterize the lake in terms of GLOF potential, vulnerability of downstream communities, and the risk posed to local inhabitants or visitors. The potential impact on the communities downstream of glacial lakes in the Nepal Khumbu region are being studied, including the Imja Khola subbasin below Imja Lake.

In order to meet this aim the following activities the terminal moraine complex of Imja Lake was surveyed using GPR. Survey transects were taken on both sides of the lake outlet complex, longitudinal surveys on each side of the lake outlet, and surveys near the lateral moraines. The data collected in this survey are compared to the survey lines used by Reynolds in 2001 (RGSL 2003; Hambrey et al., 2008). In addition, the area of groundwater/ice melt seepage from the base of the terminal moraine was surveyed. One of the hypotheses to be considered in this research is that global temperature increase has caused the ice core inside the terminal moraine complex of Imja Lake to melt resulting in a smaller ice core than that observed in the previous survey of Reynolds in 2001. This information will provide a differential signal of the likely progression of the deterioration of the terminal moraine and provide inputs to the Imja Lake community-based glacial lake risk assessment and decision making project.

Table 4 lists the GPR transects conducted at the terminal moraine of Imja Lake and one on the Imja glacier 22-26 May and 21-25 September 2012. Figure 7 shows the layout of GPR transects on an image of the lake.

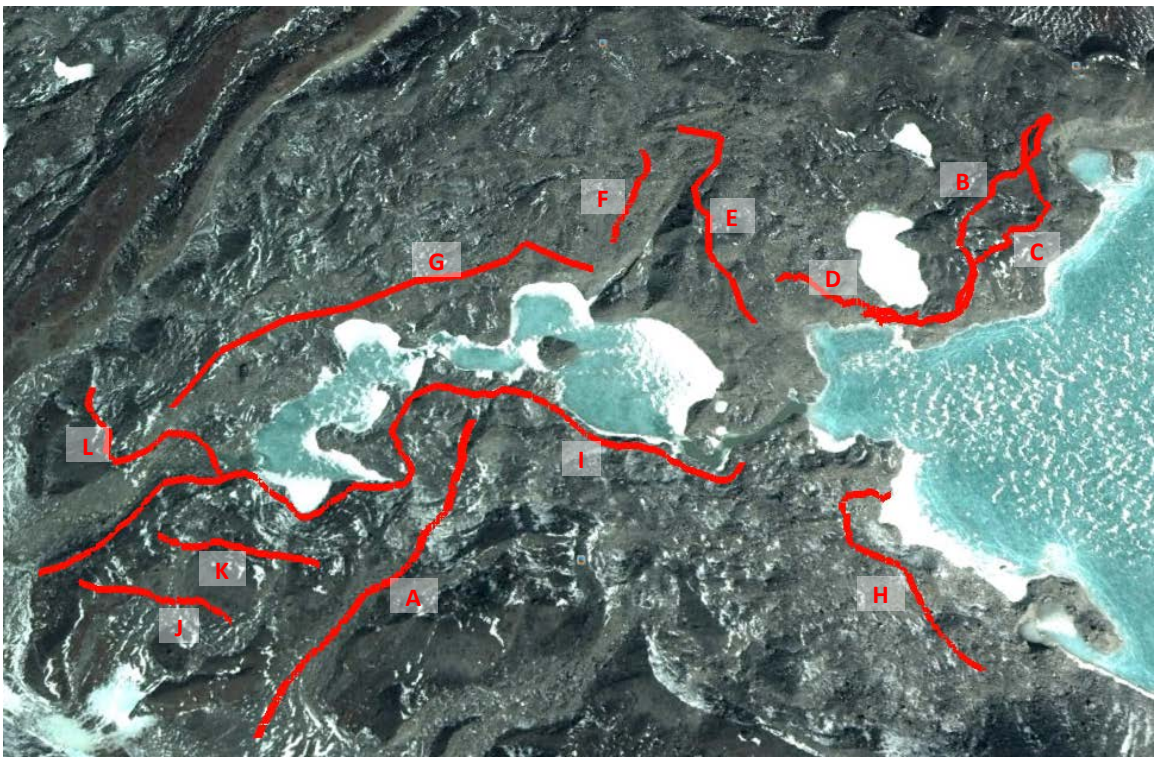


Figure 7. Mapping of GPR transects at the terminal moraine of Imja Lake taken in May 2012. (*Source:* Google Earth, 2010)

Table 4. List of GPR Transects Taken at the Terminal Moraine of Imja Lake in May 2012.

Label	Date	File	Length (m)	Frequency (MHz)
Imja Glacier	25 May 2012	4-3	210	10
A	22 May 2012	1-34	341	10
B	23 May 2012	2-1	389	5
C	23 May 2012	2-2	483	5
D	23 May 2012	2-4	166	10
E	23 May 2012	2-5	257	10
F	23 May 2012	2-6	114	10
G	23 May 2012	2-7	469	10
H	26 May 2012	5-3B	238	10
I	24 May 2012	3-78	762	5
I-2	Sept 25, 2012	Fall12_1-2		10
J	26 May 2012	5-4	146	10
K	26 May 2012	5-5	142	10
L	26 May 2012	5-6	217	10

Surface elevations were measured by GPS during the GPR transects. The GPS data were collected using both a Garmin BU-353 and a handheld Garmin Etrex Vista HCx unit. Figure 8 shows the depth of the bottom of the ice (m) in the Imja Lake terminal moraine interpreted from the GPR transects assuming a velocity of propagation in the subsurface material of $110x10^6$ m/s.

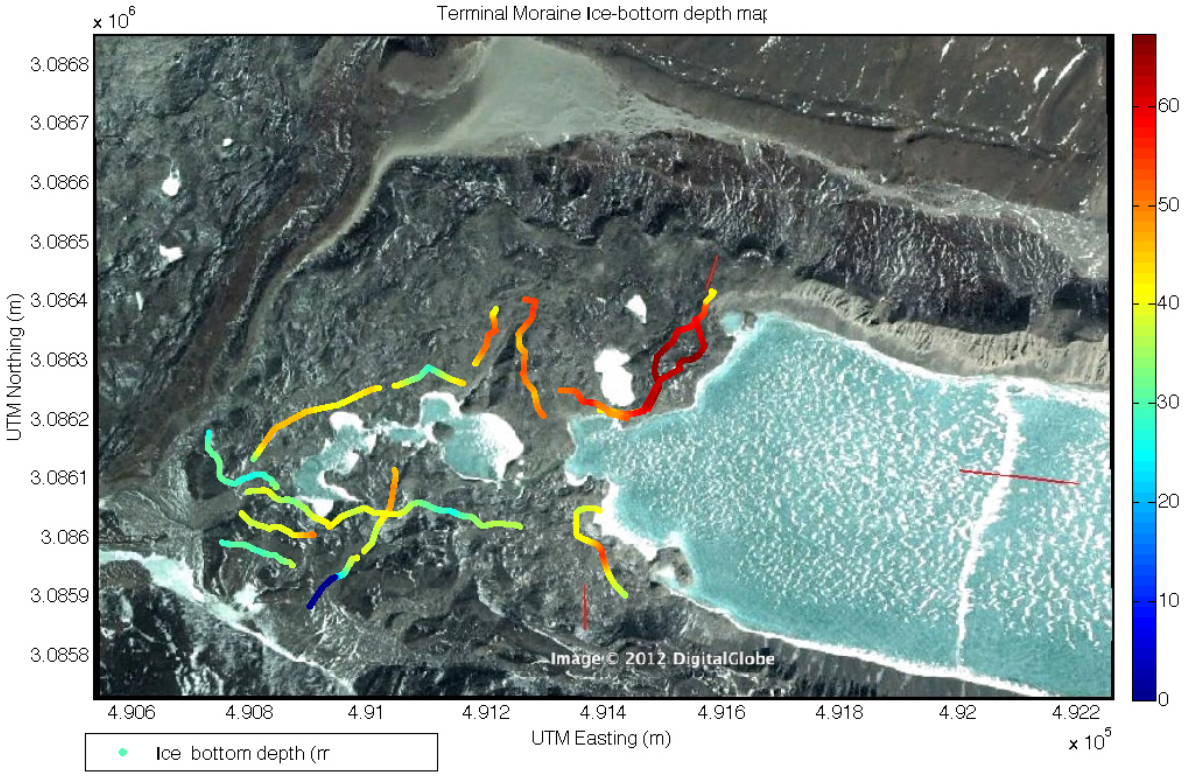


Figure 8. Imja lake ice-bottom depth (m) within the terminal moraine area.

Figure 9 shows the location of the GPR transect taken on the Imja glacier. Figure 10 shows the resulting GPR data from the transect, clearly illustrating the transition from layered ice (upper left) to bedrock (lower right). The GPR data were processed assuming a velocity of propogation through the ice of $167x10^6$ m/s, typical of a debris containing ice. Figure 11 illustrates the nature of the glacier with its thin layer of debris overlying the thick ice formation. The thin layer of debris has contributed to the rapid melting of the Imja glacier since the 1960s.

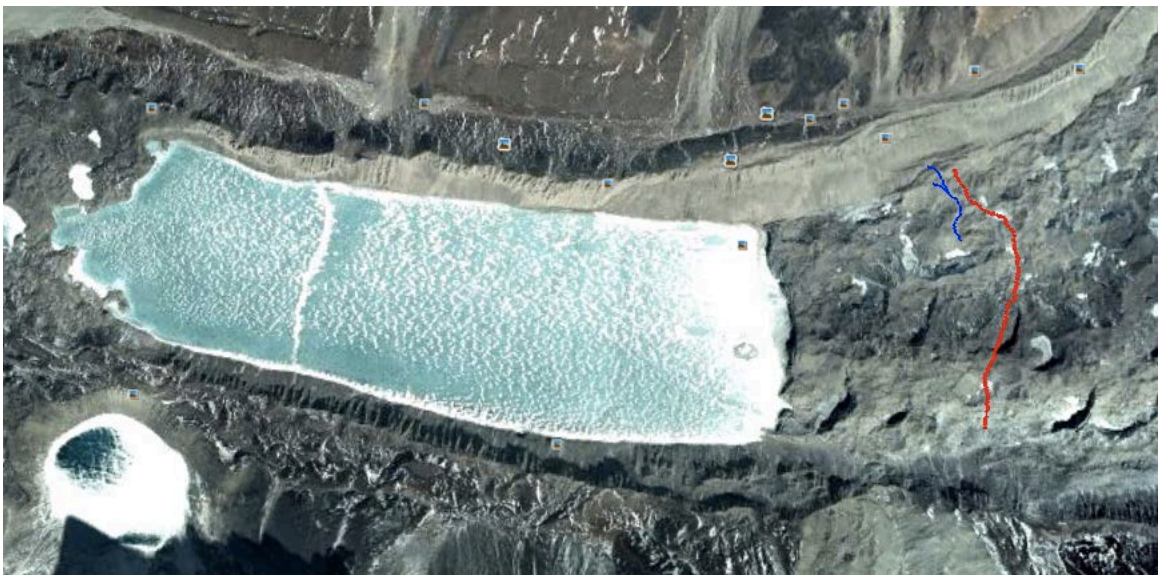


Figure 9. Mapping of GPR transects at Imja glacier taken May 25, 2012 (Blue) and September 25, 2012 (Red). (*Source:* Google Earth, 2010)

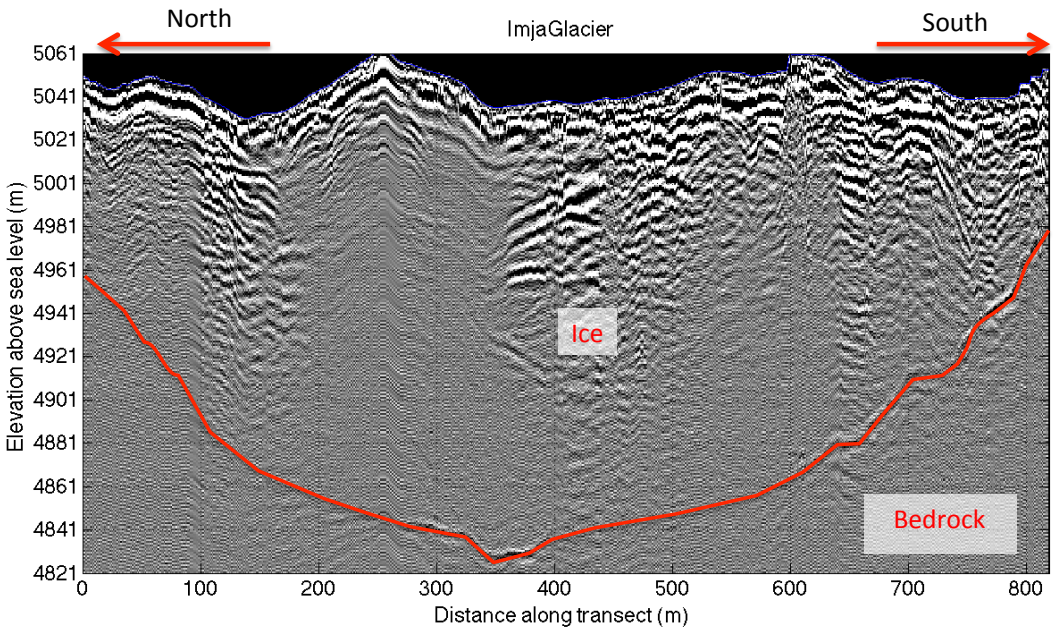


Figure 10. GPR transect at Imja glacier at Imja Lake crossing from north to south on September 25, 2012 using a 10 MHz antenna assuming a velocity in ice of 167×10^6 m/s.

Figure 11. Photo of the Imja glacier showing the thin debris cover and ice structure beneath. (*Photograph:* Daene McKinney)

CMP at Imja Terminal Moraine

The common mid point (CMP) method (Annan 2001) was used to estimate the propagation velocity of the GPR signal in the terminal moraine at Imja Lake. In order to achieve that we took a set of five static GPR measurements on September 25, 2012 at the location of Transect B (see Fig. 7) on the terminal moraine on the north side of the outlet of the lake. The 5 sets of measurements have different distances (20, 25, 30, 35 and 40 m) from the transmitter (Tx) to the receiver (Rx) with a constant (common) midpoint location. From now on the transects are going to be identified by their distance from the Rx to Tx. Figure 12 shows an idealized sketch of the field setting. We have three important variables, the distance from Rx to Tx which is known, the depth of the reflector point (h) which needs to be calculated and the distance traveled by the signal from the reflector to the receiver (r) which also needs to be calculated.

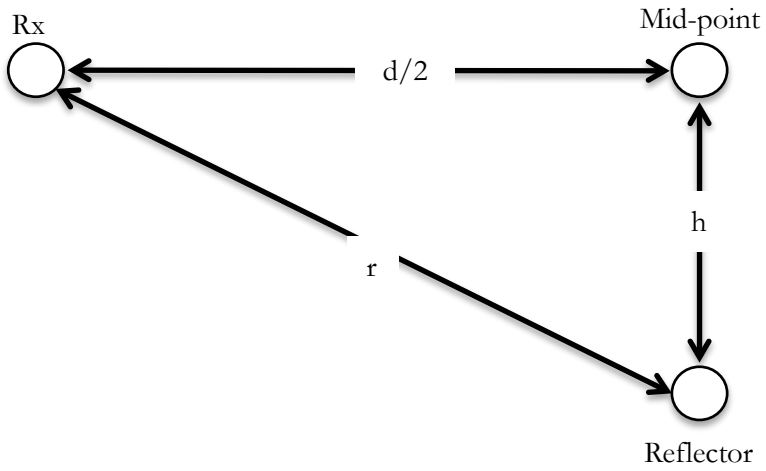


Figure 12. Common Mid-Point (CMP) method setting.

$$r^2 = (h)^2 + \left(\frac{d}{2}\right)^2 \quad (1)$$

where

h = depth to reflecting point (m)
d = distance from Tx to Rx (m)
r = distance from receiver or transmitter to reflecting point (GPR velocity *travel time) (m)
v = group velocity (m/s)
t = one way travel time (s)

or

$$\left(v_{GRP_velocity} * time_{one\ way\ travel}\right)^2 = h^2 + \left(\frac{d}{2}\right)^2 \quad (2)$$

The CMP method is used to calculate the GPR signal velocity from the ground to a reflector point in the moraine. Since the moraine is made from a heterogeneous mixture of materials (rock, ice, water, etc.), the velocity is unknown and less than the speed of the wave in pure ice. For the CMP method, 2 points, P_1 and P_2, are needed with distances d_1 and d_2, respectively from the transmitter to the receiver. The

vertical distance from the surface to the reflector point is constant and we assume that the velocity in the medium is constant as well. Replacing the values for P_1 and P_2 we obtain the next 2 equations:

$$h^2 = (vt_1)^2 - \left(\frac{d_1}{2}\right)^2 \quad (3)$$

$$h^2 = (vt_2)^2 - \left(\frac{d_2}{2}\right)^2 \quad (4)$$

Therefore

$$v = \sqrt{\frac{-\left(\frac{d_2}{2}\right)^2 + \left(\frac{d_1}{2}\right)^2}{t_1^2 - t_2^2}} \quad (5)$$

The data collected at Imja Lake terminal moraine for the CMP calculation is shown in Figure 13 and the results are shown in Table 5. The average earth wave velocity is estimated in 118×10^6 m/s. The average velocity from the reflector is 124×10^6 m/s ± 8.1×10^6 m/s. The vertical distance from the surface to the reflecting point is 16.3 m ± 0.2 m.

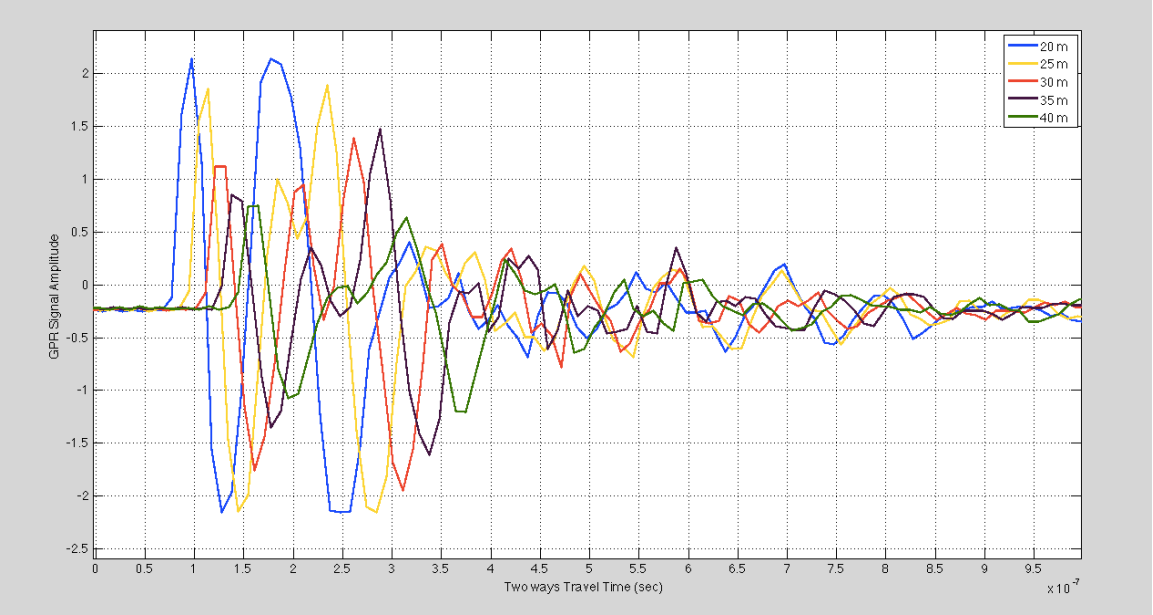


Figure 13. Static data collected at the Imja Lake moraine using a common mid point (CMP) for different distances from the transmitter to the receiver.

Table 5. Calculations of the Ground Wave Velocity (distance/time), Velocity to the Reflector (Equation 5), and the Depth of the Reflector (Equation 3 or 4).

Distance (m)	Time ground wave (10^{-7} s)	Velocity ground wave (10^{6} m/s)	Time to first reflector (10^{-7} s)	Combinations using the distances as indicators	Velocity First Reflector (10^{6} m/s)	Depth to reflector (m)
20	1.76	114	3.05	20-25	108	16.11
25	2.35	106	3.35	25-30	141	16.66
30	2.60	115	3.55	30-35	121	16.19
35	2.78	126	3.85	35-40	125	16.33
40	3.10	129	4.15	20-40	123	16.30
				20-30	123	
				25-35	129	
				30-40	123	
				20-35	122	
				25-40	127	
	Average	**118**			**124.3**	**16.32**
	Standard Deviation	**9.29**			**8.13**	**0.21**

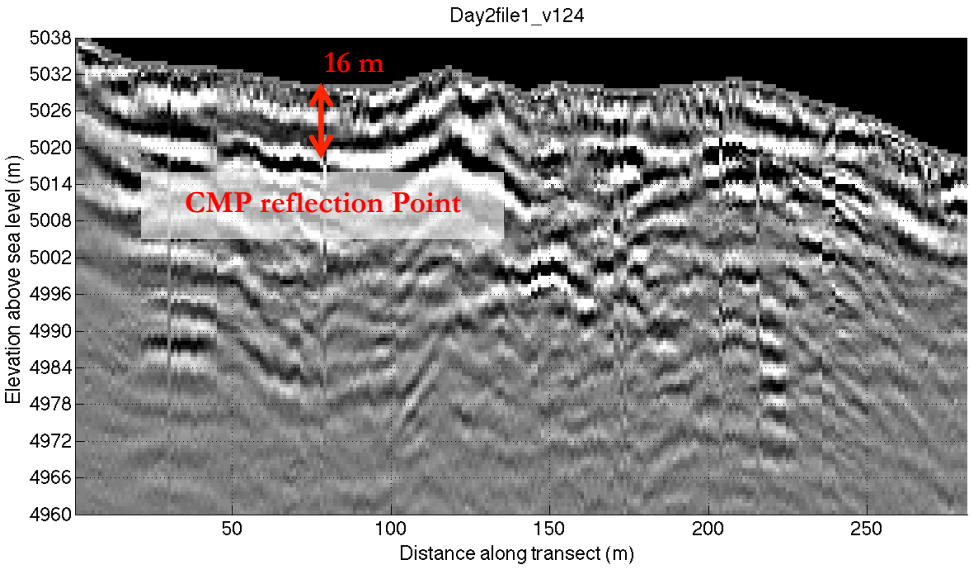


Figure 14. Location of the CMP measurement in Transect B (see Fig. 7). The velocity used in this echogram is 124x10⁶ m/s.

Figure 15 shows the GPR transect at the south lateral moraine crossing from south to north using a 10 MHz antenna (see Fig. 7 for location of Transect A). After 50 m along the transect high reflections indicate ice underneath. Around 75 m, more areas with high reflections are visible with ice thickness from 30 m at the outer side of the moraine to 70-80 m in the inside of the moraine.

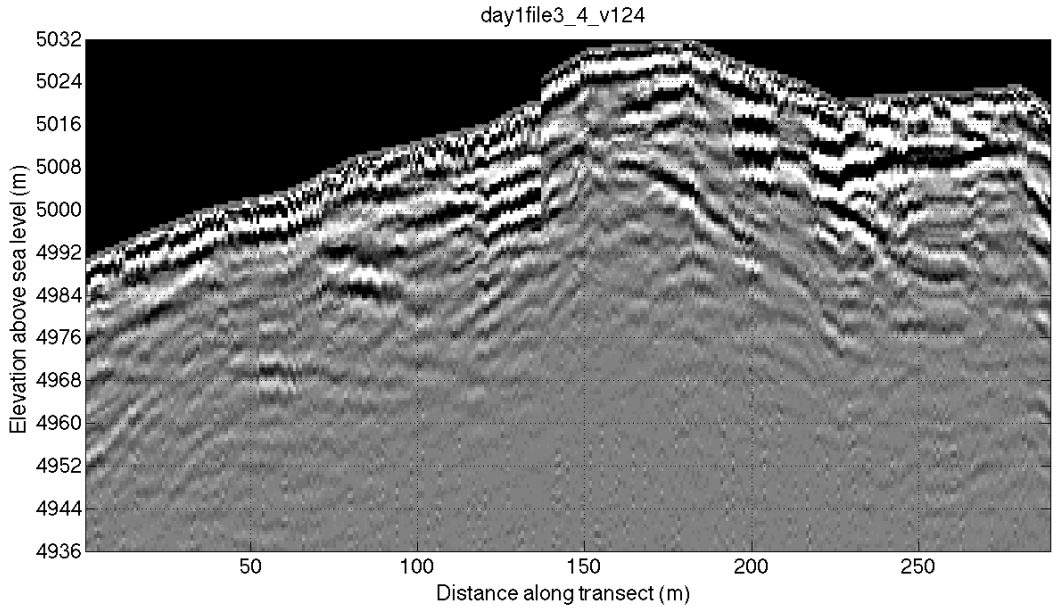


Figure 15. GPR transect A (Day1file3_4) at Imja Lake on the south lateral moraine crossing from south to north using a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 16 shows GPR Transect B (Day2file1) moving from north to south on the terminal moraine above the north-west shore of Imja Lake using a 5 MHz antenna. In the center of the transect (after about 150 m) the depth of the ice is about 60 m. On the face of the moraine, this ice is collapsing into the lake according to observations in the field (see Figure 17).

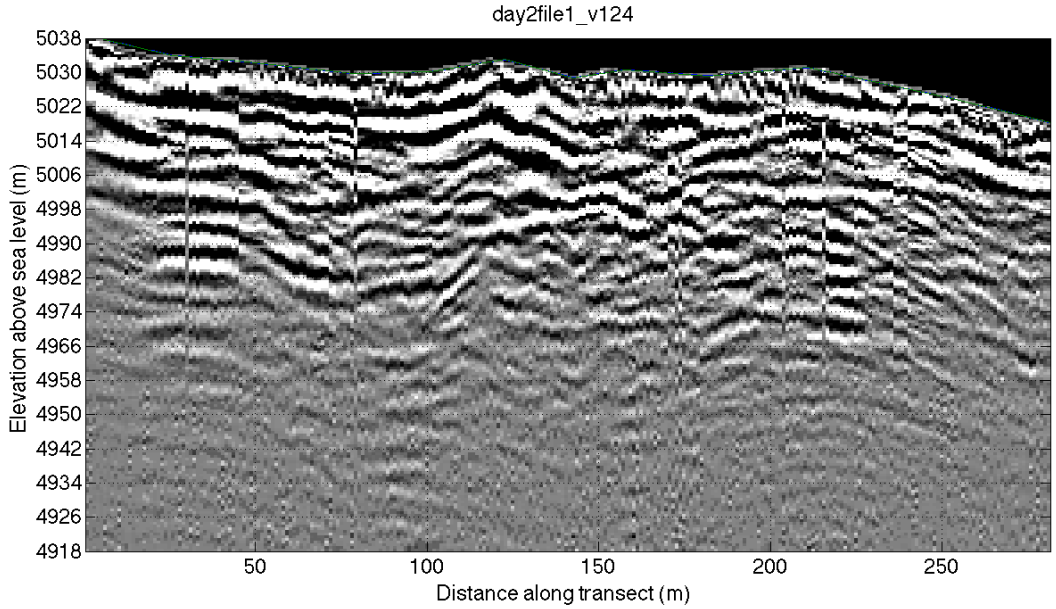


Figure 16. GPR Transect B (Day2file1) at Imja Lake from north to south on the terminal moraine above the north-west shore using a 5 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 17. Ice on the face of moraine on Transect B, May 23, 2012. (*Photograph:* Daene McKinney)

Figure 18 shows GPR Transect C (Day2file2) moving from south to north on the terminal moraine above the north-west shore of Imja Lake with a 5 MHz antenna. In the center of the transect the depth of the ice is about 60 m.

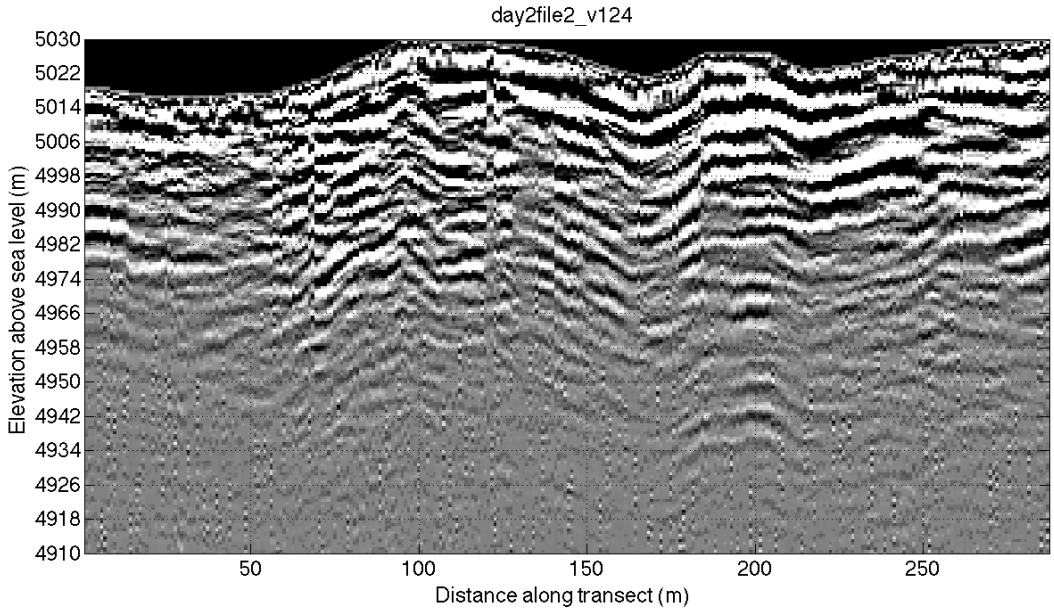


Figure 18. GPR Transect C (Day2file2) at Imja Lake moving from south to north on the terminal moraine above the north-west shore with a 5 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 19 shows GPR Transect D crossing between the blue pond at the north side of the outlet using a 10 MHz antenna. Figure 20 shows the exposed ice face on the side of the moraine above the blue pond.

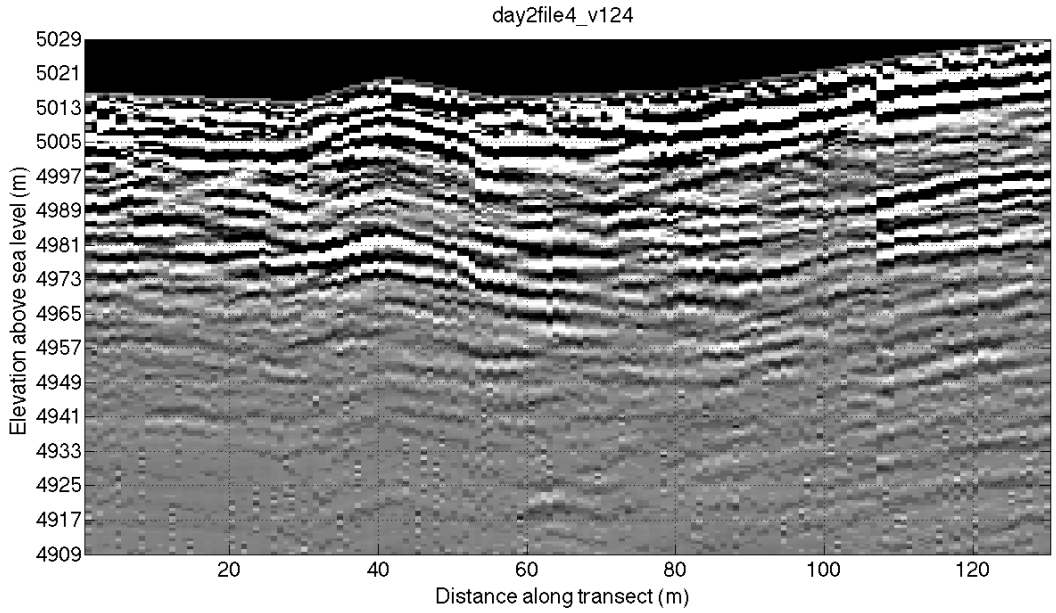


Figure 19. GPR Transect D (Day2file4) at Imja Lake crossing between the blue pond at the north side of the outlet using a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 20 shows GPR Transect E near the middle of the terminal moraine, starting from the outlet and moving in the direction of the northern lateral moraine with a 10 MHz antenna. This transect corresponds to the highest surface elevation points of the moraine. Reynolds Geoscience Ltd. (RGSL 2003; Reynolds 2006; Hambrey et al. 2008) deployed a Sensors and Software PulseEKKO 100 system with an antenna center-frequency of 100 MHz at Imja Lake in 2001 along two profiles across the terminal moraine complex (one transverse from the north lateral moraine to the lake outlet (similar to Transect E reported here) and one longitudinal along the north side of the outlet (similar to Transect G reported below) to determine depths of the debris cover over ice within the moraine complex, and to estimate ice thickness (Hambrey et al. (2008). The results from one transect (near Transect E) show an ice-cored inner zone at the western end of Imja Lake comprised of debris-covered ice tens of meters thick. They note that the presence of ice is clearly indicated, especially by ERT and that the morainic debris is layered. The electrical resistivity measurements reported by Hambrey et al. (2008) are interpreted to show a debris cover about 5 – 20 m thick with 20 – 30 m of ice below that. Their GPR measurements are only reported in terms of two-way-travel time and not converted to depth since the velocity of GPR wave propagation in the subsurface was unknown.

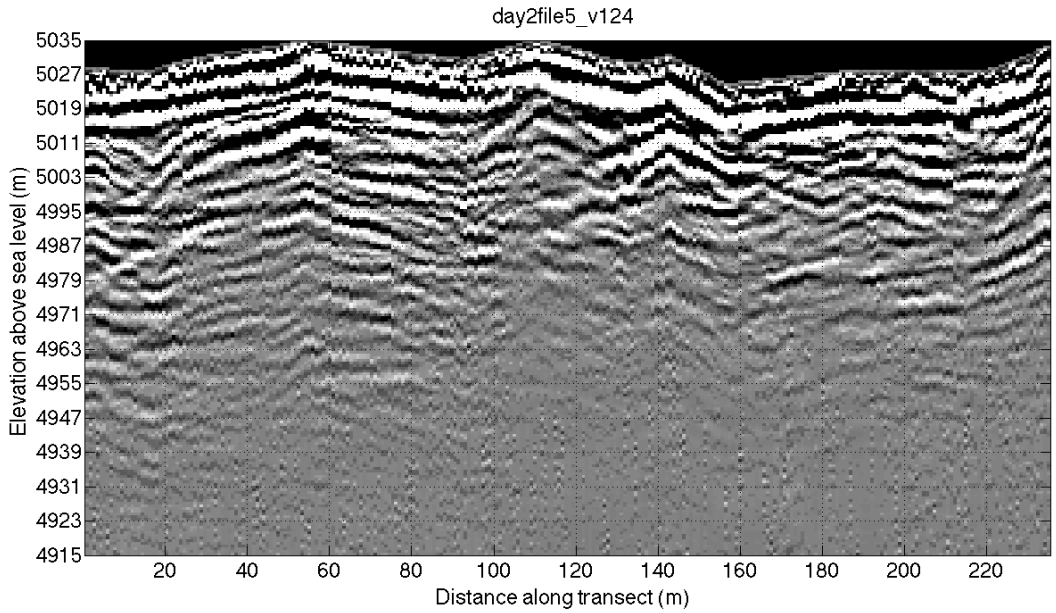


Figure 20. Transect E (Day2file5) at Imja Lake moving in the direction of the northern lateral moraine with a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 21 shows GPR Transect F on the north side of the outlet near the middle of the terminal moraine, starting north of the outlet and moving in the direction of the northern lateral moraine with a 10 MHz antenna. This transect reflects a shallow thickness of ice, especially at the end of the transect.

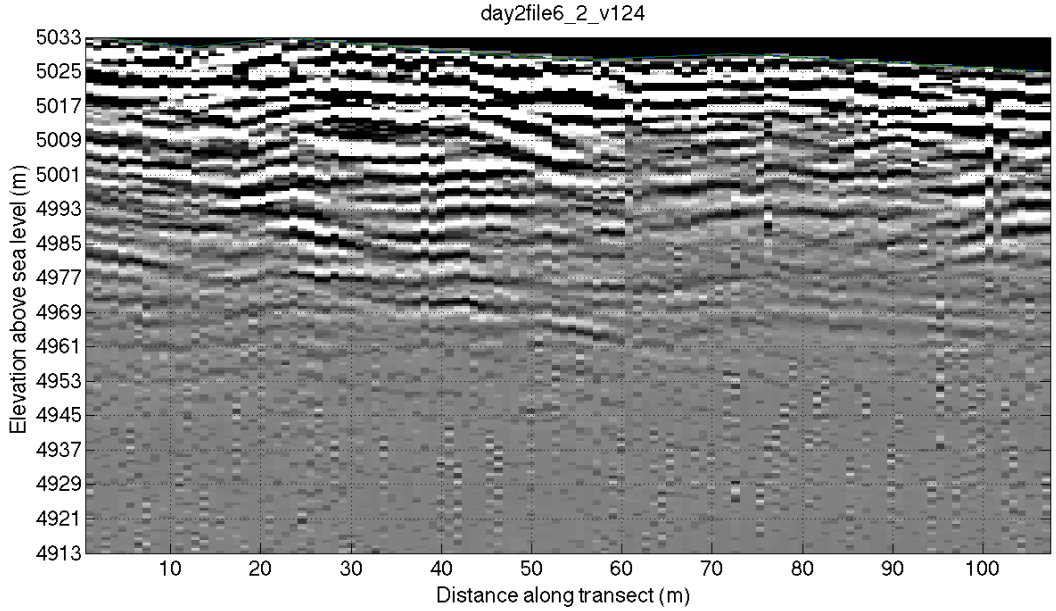


Figure 21. GPR Transect F (Day2file6) at Imja Lake moving in the direction of the northern lateral moraine with a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 22 shows GPR Transect G which is a longitudinal transect on the north side of the outlet using a 10 MHz antenna. This profile illustrates the presence of a debris cover up to 10 m and then ice of 20-30m thick over most of the transect. In the middle of the transect (from 120 to 160 m) the data was lost which explains the vertical fringe without changes in that range. After that it is possible to see some ice

with a thickness of 20-30 m. The results from the second transect of Reynolds (Hambrey et al., 2008) (near Transect G) show a relatively ice-free zone several hundred meters wide forming the outer part of the moraine complex. They report surface debris from 5 to 10m thick overlying an intermediate layer, believed to be water-saturated moraine. This layer, in turn, overlies a basal zone, the top of which is about the same elevation as the outlying floor of the valley. This report shows considerably more ice in this area than Hambrey et al. (2008) show. However, they used a 100 MHz antenna, so the penetration was limited to a few meters and we used a 10 Mhz antenna resulting in much deeper penetration. The depth of penetration for the 100 MHz GPR system used by Hambrey et al. (2008) is unlikely to be greater than 15 – 20 m (Jol, 1995). Hambrey et al. (2008) do not consider the lake to pose a threat in the short term, contrary to Yamada (1998) and Bajracharya et al. (2007).

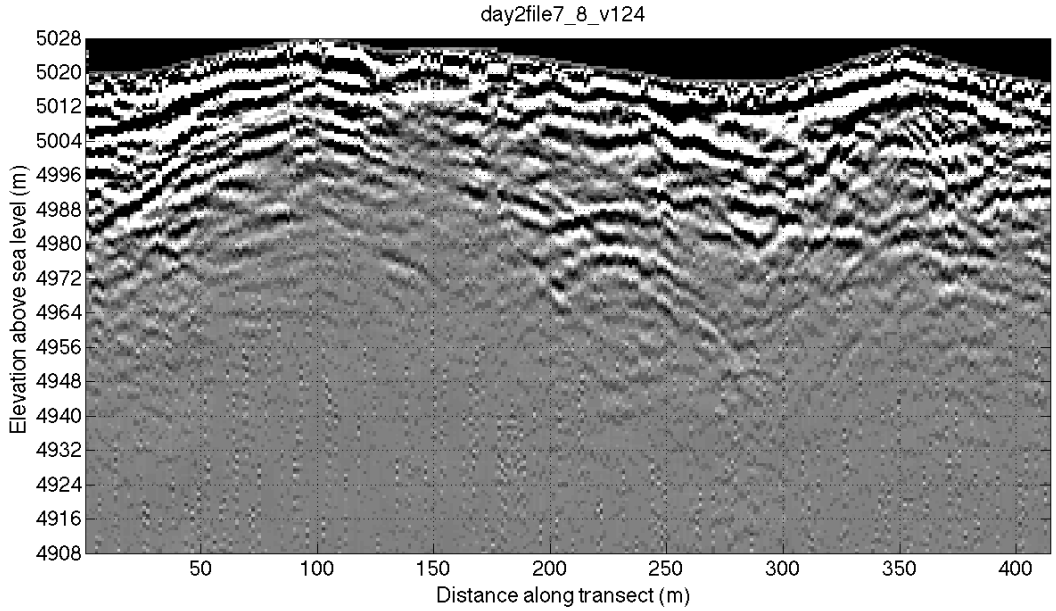


Figure 22. GPR transect G (Day2file7_8) at Imja Lake on the north side of the outlet using a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 23 shows GPR Transect H along the shore of the lake at the south lateral moraine in an area where ice is visible from a small peninsula in the lake (see Figure 24) using a 10 MHz antenna. Since we were able to see the first 20 m depth of this profile from the lake, this transect helped us to interpret the data from other areas. The debris in this area appears to be about 10 m thick with about 20 - 30 m of ice below that.

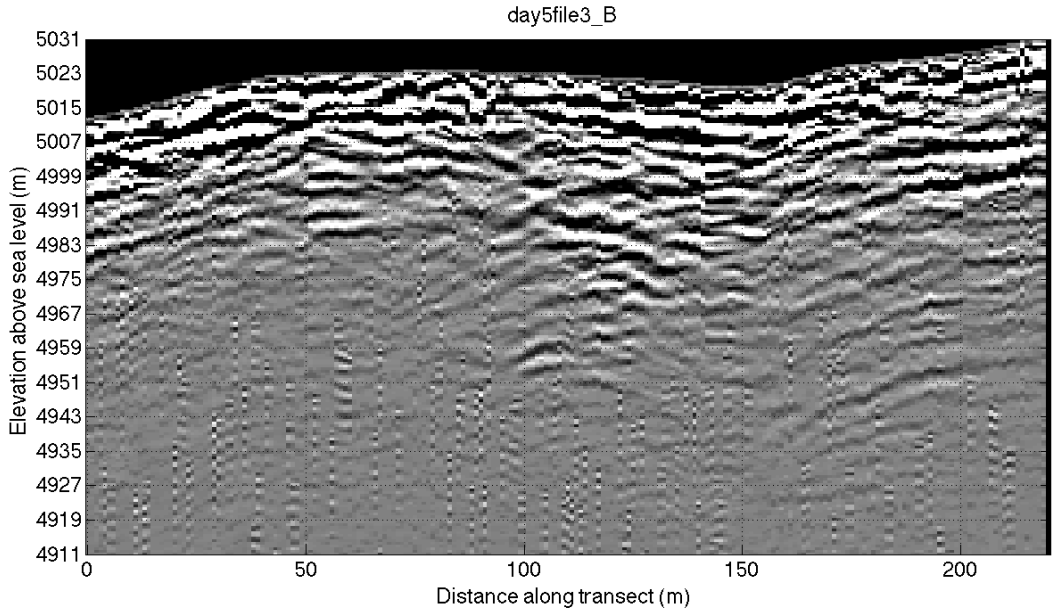


Figure 23. GPR transect H (Day5file3_B) at Imja Lake on the south side of the outlet using a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 24. Ice visible below GPR transect H seen from a small peninsula near the shore of the lake. (*Photograph:* Marcelo Somos-Valenzuela)

Figure 25 shows the long GPR Transect I (from September 21, 2012) along the south side of the outlet from the lake to the bottom of the outer side of the terminal moraine using a 10 MHz antenna. The image shows a debris layer about 10 m thick with ice present under the debris in the first 300 m of the transect and some ice present near the lake outlet.

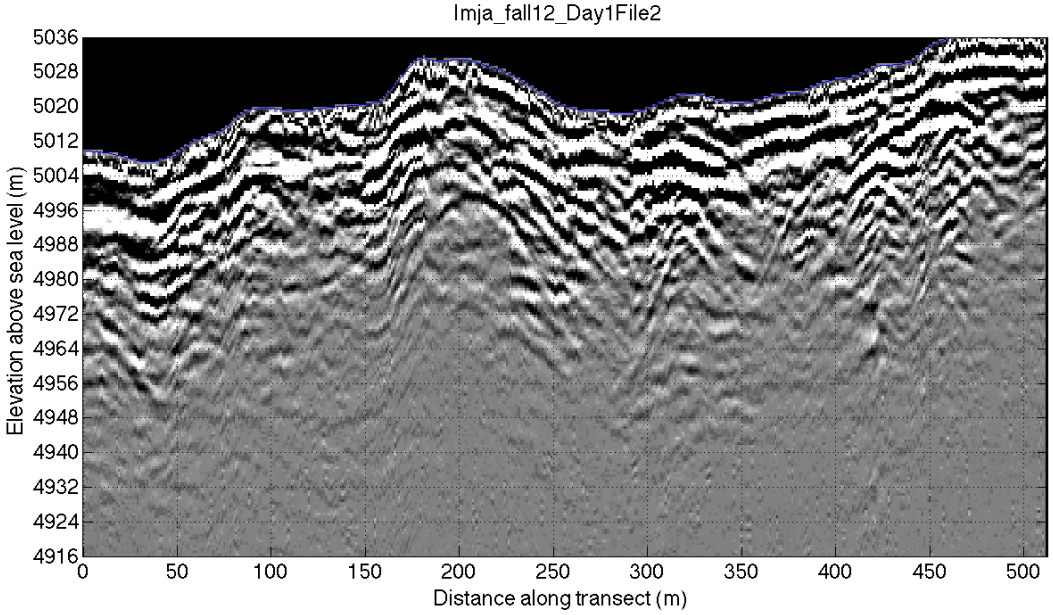


Figure 25. GPR transect I (Fall12_Day1File2) along the south side of the outlet from the lake to the bottom of the outer side of the terminal moraine using a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Extensive seepage from the base of the southern portion of the terminal moraine was observed in September 2011 and May 2012. The location of the seepage was different during these two times (see Figure 26) with the September 2011 observation (see Figure 27, left) being on the western side of the terminal moraine and the May 2012 observation being farther east and on the other side of a small ridge (see Figure 27, right).

Figure 26. Location of seepage observations at the terminal moraine of Imja Lake in September 2011 and May 2012. (*Source:* Google Earth, 2010)

September 2011 **May 2012**

Figure 27. Seepage from the base of the terminal moraine at Imja Lake observed in September 2011 (left) and May 2012 (right). (*Photograph:* Daene McKinney)

Figure 28 shows GPR Transect J at the middle of the outer face of the south lateral moraine above a seepage point using 10 MHz antenna. We observed water running 15 meters below the ridge of the moraine. This transect has the same pattern as an area in which there is ice. The image indicates about 10 m of debris cover with about 10 m of ice below that. We observed water running just above this transect, about 15 meters below the ridge of the moraine (see Fig 27, right). Figure 29 shows GPR Transect K at the middle of the outer face of the south lateral moraine above Transect J and above a major seepage point using a 10 MHz antenna. This transect has the same pattern as Transect J (see Figure 28) except that the ice layer is much thicker, about 20-30 m.

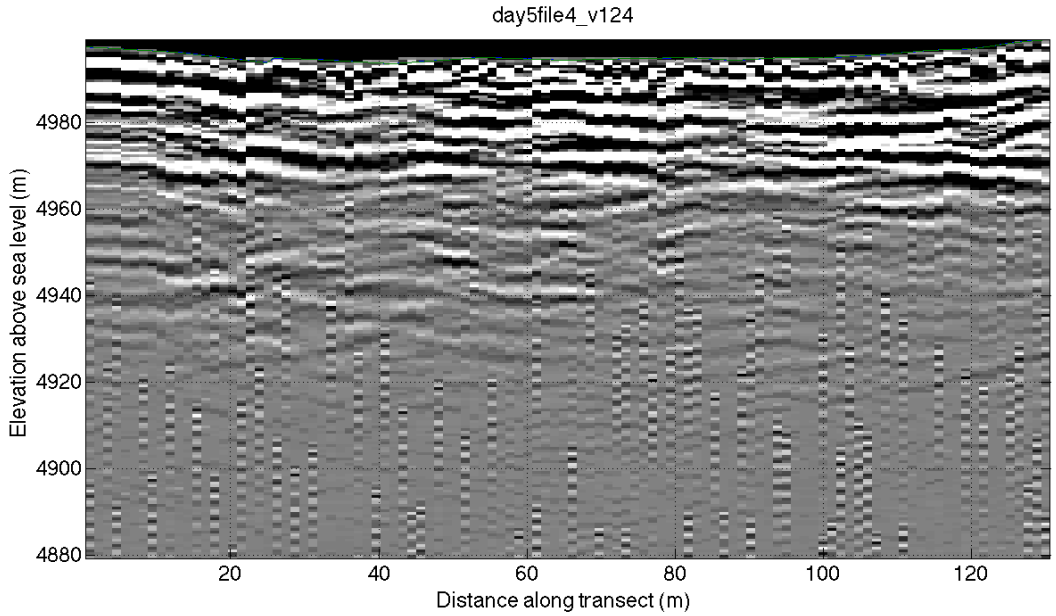


Figure 28. GPR Transect J (Day5file4) at the middle of the outer face of the south lateral moraine below a major seepage point using a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

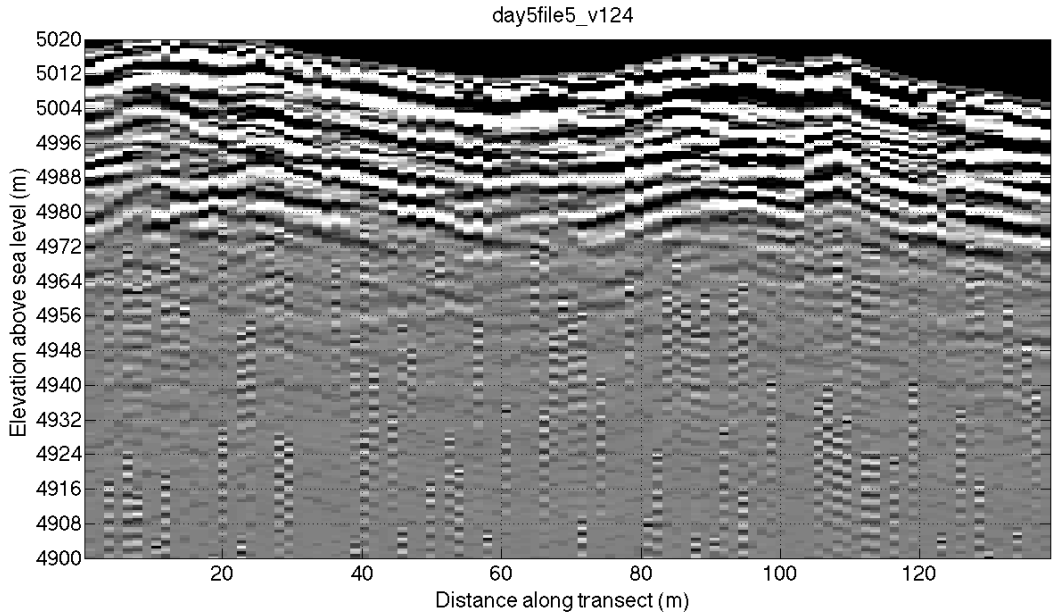


Figure 29. GPR Transect K (Day5file5) at the middle of the outer face of the south lateral moraine above transect J and above a major seepage point using a 10 MHz antenna and assuming a velocity of $124x10^6$ m/s.

Figure 30 shows GPR Transect L crossing the outlet from south to north heading down to the outer face of the terminal moraine using a 10 Mhz antenna. This transect indicates that some ice is present in the end of the terminal moraine at the north side of the outlet, perhaps as much as 20-30 m thickness.

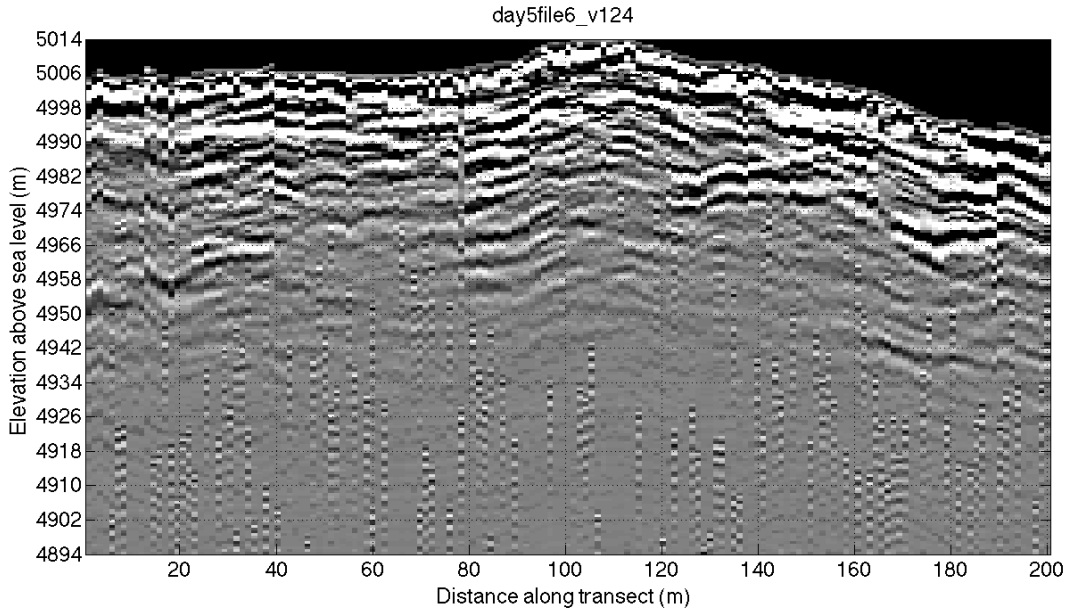


Figure 30. GPR Transect L (Day5file6) crossing the outlet from south to north heading down to the outer face of the terminal moraine using a 10 Mhz antenna and assuming a velocity of $124x10^6$ m/s.

CONCLUSIONS

Imja Lake is currently the focus of several groups in an effort to reduce the risk of a GLOF posed by the increasing lake level. The presence or absence of ice in the core of the terminal moraine complex is of critical importance in designing a risk reduction program for the lake. This work has used Ground Penetrating Radar (GPR) to investigate the internal structure of the moraine complex in order to map out the ice thickness in critical areas.

The results of the GPR survey show that there is extensive ice present in the core of the terminal moraine complex at Imja Lake (see Figure 8). The thickest areas of ice are in the moraine near the western end of the lake on the northern side of the lake outlet. The ice in this region is several tens of meters thick and up to fifty meters thick in some places. Along the northern and southern sides of the lake outlet, the ice is between ten and twenty-five meters thick. In some portions of the moraine on the southern side of the outlet the ice thickness is up to forty meters.

Extensive seepage of water from the terminal moraine was observed in two locations during visits to the lake in September 2011, May 2012, and September 2012. GPR transects above and below the site of seepage show the presence of ice above the seep and much less ice below the seep. Seepage of water through the terminal moraine is an indication of potential weakness in the moraine and a possible site of future moraine failure.

Recent work has been initiated by the United Nations Development Programme to develop an Imja Lake Risk Reduction Program. One of the primary methods suggested for reducing risk associated with the lake is to reinforce and deepen the outlet channel so that it can lower the lake level up to 3 meters below the current level. This project involves making excavations of the outlet channel and the

construction of a diversion channel on the southern side of the outlet. The results presented here indicate that there may be ice present in the moraine in the vicinity of the excavations being considered in this project. Excavation activities that encounter ice in the moraine material may cause weakening of the ice resulting in increased water seepage and erosion of the moraine. Therefore, it is recommended that additional GPR surveys be conducted in this area accompanied with Electrical Resistivity Tomography (ERT) surveys. The ER surveys will be able to more definitively indicate the presence of ice in the moraine as well as the degree of water saturation of the moraine material.

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APPENDIX 1. GPR ANTENNA DESIGN

Table A.1. GPR Antenna Design for 400 Ohm Damping

Frequency	5 MHz		10 MHz		20 MHz		50 MHz	
	Spacing	Resistance	Spacing	Resistance	Spacing	Resistance	Spacing	Resistance
Resistor #	(m)	(W)	(m)	(W)	(m)	(W)	(m)	(W)
1	0.50	42	0.50	89	0.25	89	0.10	89
2	1.00	47	1.00	114	0.50	114	0.20	114
3	1.00	53	1.00	160	0.50	160	0.20	160
4	1.00	62	1.00	267	0.50	267	0.20	267
5	1.00	73	1.00	800	0.50	800	0.20	800
6	1.00	89	0.50		0.25		0.10	
7	1.00	114						
8	1.00	160						
9	1.00	267						
10	1.00	800						
	0.50							
Arm length	**10.0 m**		**5.0 m**		**2.5 m**		**1 m**	