FINAL REPORT

RESEARCH AT HUASCARAN NATIONAL PARK

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1 Background

This activity had several objectives, including:

1.1 Laguna Palcacocha

Improve the quality of a previously developed GLOF model of Laguna Palcacocha (Somos et al. 2011) by performing a GPR survey of the terminal moraine in the vicinity of the 1941 breach in the glacial terminal moraine. In addition, the results of the GLOF model will be presented to a group of interested stakeholders in Huaraz. Through this process, we hope to obtain access to updated information about the lake and potential new GLOF risk reduction system, and develop new relationships with stakeholders including the Office of Civil Defense of the Ancash Department.

1.2 Pastoruri Glacier

Map the thickness of the ice in the Pastoruri glacier using GPR in order to provide needed information to the Huascaran National Park and the Municipality of Catac. The Park and Municipality are in the process of creating an outdoor climate change museum using the popular Pastoruri glacier as the centerpiece. The GPR data, once processed, will be used in interpretive maps of the current extent of glacier ice. Modeling of the glacier hydrology will allow prediction of the future extent of the ice.

1.3 Arteson Glacier

Perform a GPR survey at the Arteson glacier in order to estimate the future evolution of the newly forming glacier lake at the base of the glacier. This lake has been identified as one of the newst risks forming in the Cordillera Blanca and the Glaciology Office is monitoring its mass balance monthly. Measuring the ice thickness with GPR will allow mapping of the ice thickness and the bedrock location, an indicator of the potential for dangerous glacial lake formation.

2 Tasks Performed During the Trip

2.1 Meetings in Lima, Peru

The GPR equipment was retrieved from customs at Lima Airport and we received permission to use the equipment in Peru. There was some difficulty to receive the equipment from the customs officials since they, at first, did not understand that it was for university studies to be carried out in collaboration with the Huascaran National Park.

A meeting was held on Monday, July 2, 2012 Lima, Peru with Professor Wilfried Haeberli of University of Zurich who is directing a Swiss Development Agency project “513 Glaciers” to strengthen the capacity of the Glaciology Unit of ANA. The project is implemented by CARE-Peru with the assistance of the University of Zurich. Prof. Haeberli has developed a GIS-based approach to determining the future formation of glacier lakes and is applying this technique to the glaciers of the Cordillera Blanca. Our GPR surveys may be useful in collaboration with his technique to determine the future extent, volume and risk of glacier lakes that have begun to form or may form in the future. We will be following up on this collaboration in the coming months.

A meeting was held July on Monday 2, 2012, in Lima, Peru at ANA with the Director General. We met with the General Director of ANA and explained the basic purposes of the HMGWP. He was very supportive of our efforts to assist various communities and groups in the high mountain areas develop adaptation methods to deal with climatic change. He attended the following workshop and listened to each presentation with interest.

A presentation was made on Monday, July 2, 2012 in Lima, Peru presenting the High Mountain Glacial Watershed Program at the National Water Authority of Peru. CARE, the University of Zurich, and the Swiss Agency for Development and Cooperation Conference "Effects on Water Reduction by High Mountain Glaciers" organized by Professor Haeberli. The audience consisted of about 150 staff members of ANA including the General Director. Other presentations were by Prof. Haeberli, Jorge Recharte of TMI, Jesus Gomez of the Glaciology Unit, and Wilson Suarez of the ANA Meteorology Department.

2.2 GPR Survey at Laguna Palcacocha

Kate Voss, Marcelo Somos, and Cesar Portocarerro trekked to Laguna Palcacocha to conduct a Ground Penetrating Radar (GPR) survey of the terminal moraine of the lake on Thursday, July 5, 2012. The initiation of a new GLOF risk reduction project were seen in the form of 5 siphons that were being used to lower the lake before beginning a new cut in the moraine to install a new system. Only 1 of 5 siphons was operational and the other 4 were under repair. This lake lowering system is being upgraded due to the inability of the prior system to handle the current melt rates of the glaciers and expansion of the lake. The left Figure 1 below shows the proximity of the dangerous hanging ice to the lake. The right figure shows the GPR image of the material under the breach in the terminal moraine at the lake indicating that there is little moraine material remaining beneath the breach and that it is almost all bedrock.

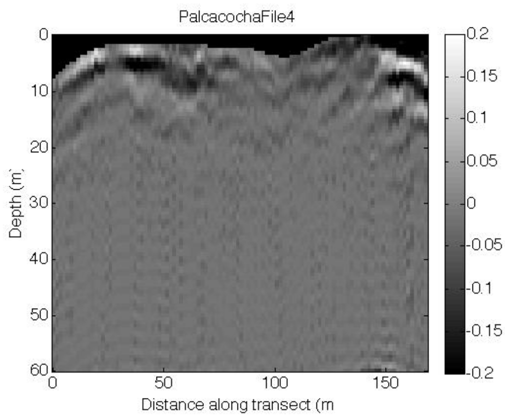

Figure 1. Left: Palcacocha Lake showing siphon pipes leading to the lake. Note the proximity of the hanging ice to the lake. Right: Ground Penetrating Radar (GPR) image of the material under the breach in the terminal moraine at the lake showing that there is Little moraine material remaining beneath the breach and that it is almost all bedrock.

A meeting was held on Monday, July 9, 2012 in Huaraz, Peru with Cesar Portocarrero to discuss the effort of Huascaran National Park and the city of Catac to develop a climate change museum around the glacier recession at Pastoruri glacier. The National Park and the city are interested to have us perform a GPR survey of the glacier to map the thickness of the ice and include this as a display in the museum.

A meeting was held on Tuesday, July 10, 2012 in Huaraz, Peru with Director (Sr. Martin) and Dep. Director of Huascaran National Park in Huaraz to discuss the climate change museum related to the glacier recession at Pastoruri glacier. We agreed that the Director would accompany us on the GPR survey of the glacier along with a representative of the city of Catac.

2.3 GPR survey of the Pastoruri Glacier

A GPR survey of the Pastoruri Glacier in the Cordillera Blanca was conducted on Wednesday, July 11, 2012. Pastoruri is one of the fastest receding glaciers in the Cordillera Blanca and a major tourist site (over 1000 people participated in a ski-snowboard competition on the glacier in June 2012). The municipality of Catac and the Huascaran National Park have received funds to construct an interpretive outdoor museum illustrating the impact of climate change on the glacier and document its recession over the past decades. The impact of climate change on the Pastoruri Glacier is very evident when comparing photographs taken in 2009 with ones taken in 2012 (Figure 2).

Pastoruri glacier lake, snout and main body of the glacier are shown in Figure 4. The transect of the GPR data (approximate route indicated by red line) was taken on a line up to the top of the glacier in the picture in Figure 5. Figure 6 shows the GPR data taken on the ascent up the Pastoruri glacier. The top of the ice is seen as the white and black lines at the top of the image and the bedrock below the ice is seen as the lower strong black and white line about 50-60 m below the ice surface. Figure 7 shows a similar image, but taken on the descent from the top of the glacier.

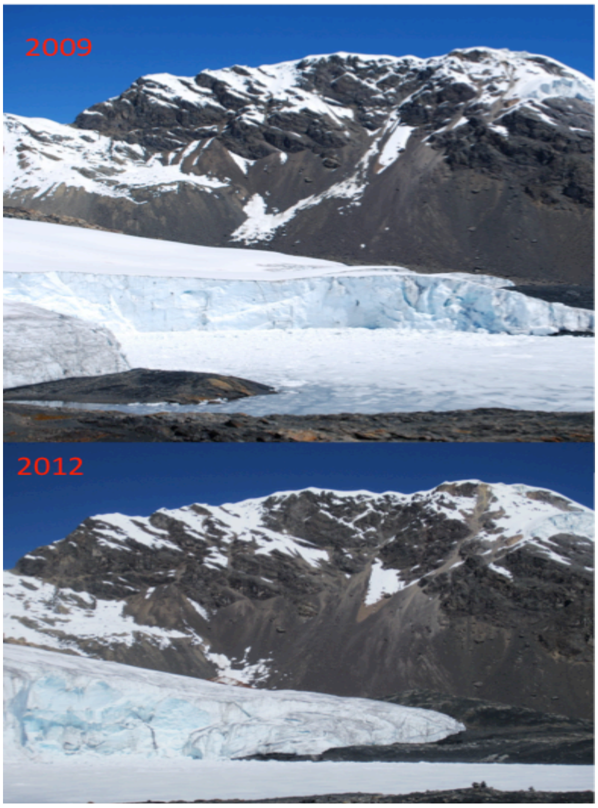

Figure 2. The terminal end of Pastoruri glacier in 2009 (top) and 2012 (bottom), illustrating the recession of the glacier over this period.

Figure 3. Meeting with Huascaran National Park Director (Sr. Martin) and an official from the Catac Municipality (Jesus) at Pastoruri glacier.

Figure 4. Conducting GPR survey on Pastoruri glacier.

Figure 5. Pastoruri glacier lake, snout and main body of the glacier. GPR data (approximate route indicated by red line) was taken on a line up to the top of the glacier in the picture.

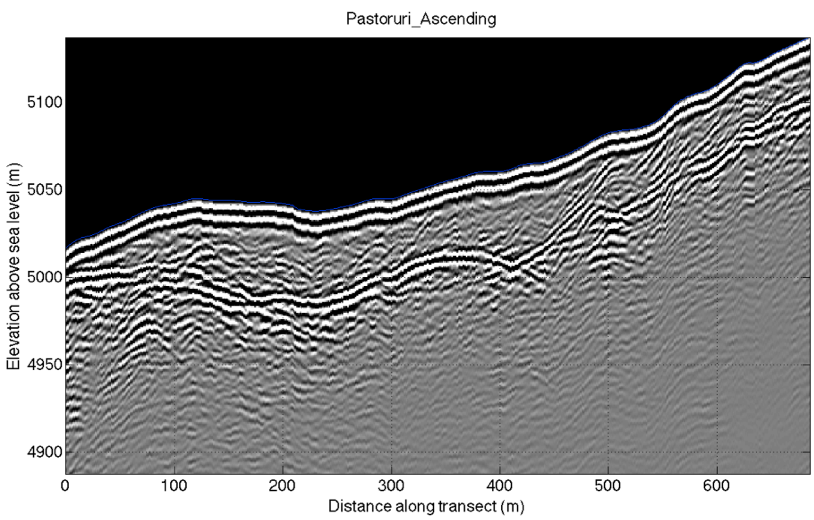

Figure 6. Image of GPR data on the ascent of Pastoruri glacier. The top of the ice is seen as the white and black lines at the top of the image and the bedrock below the ice is seen as the lower strong black and white line about 50-60 m below the ice surface.

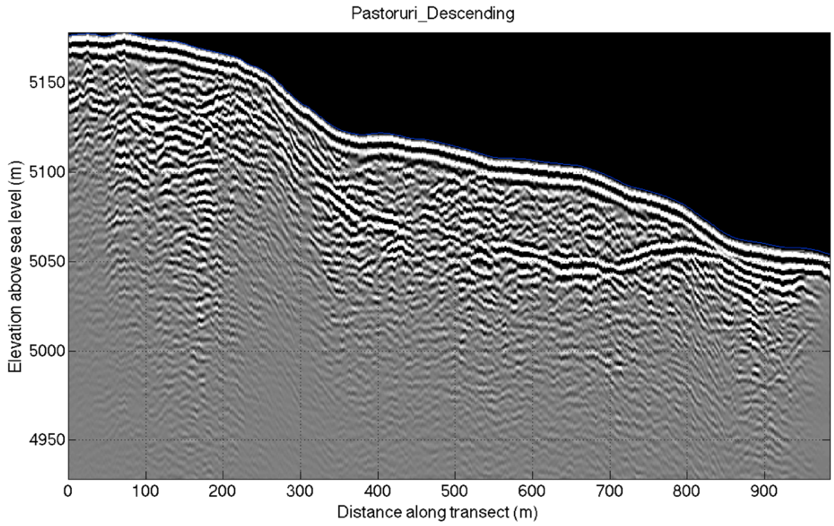

Figure 7. Image of GPR data on the descent of Pastoruri glacier. The top of the ice is seen as the white and black lines at the top of the image and the bedrock below the ice is seen as the lower black and white line about 50-60 m below the ice surface.

2.4 Presentation of Pastoruri Glacier and Laguna Palcacocha Findings in Huaraz

A Presentation of the findings of the HMGWP work at Pastoruri Glacier and Laguna Palcacocha was made on Friday, July 13, 2012 Huaraz, Peru to Huascaran National Park staff and other interested persons (office of Civil Defense and Unit of Glaciology). The Director of Civil Defense for Ancash Department invited us to make presentation to the Ancash Department Governor.

A Meeting was held on Monday, July 16, 2012 Huaraz, Peru with Jesus Gomez at the Glaciology Office to finalize the plan for a GPR survey at the Arteson glacier. We met the temporary head of the Glaciology Unit and they were very interested in using GPR to map the thickness of ice at many of the glaciers in the Cordillera Blanca in order to be prepared for dealing with the problems of newly forming glacier lakes. The Glaciology office has an existing GPR system, but it is very low power and limited to a single frequency (50 MHz which is too high for most glacier ice surveys).

2.5 GPR survey of the Arteson Glacier

A three day trek to perform a GPR survey of the Arteson glacier was begun on Tuesday, July 17, 2012. We received good data from the survey. There is a new glacier lake (Alto Artesoncocha) forming rapidly at the base of the Arteson Glacier. The lake was not present in satellite images prior to 2003 and it has been growing quite rapidly since then. The GPR survey allows us to estimate the ice depth and determine the size of a glacial lake that is likely to form at this site. A dip in the ice at the back of the current tongue (up glacier) indicates that a lake may form there. If not then the melt water will probably run off harmlessly into the lower lake.

Introduction

Tropical glaciers are an essential component of the water resources systems in the mountainous regions where they are located, e.g., the Cordillera Blanca, and a warming climate has resulted in the accelerated retreat of many of these glaciers in recent decades (Rabatel et al, 2012). This work aims to study the flood risk for communities living downstream from new glacial lakes that are forming at the termini of some glaciers. As these lakes continue to grow in area and volume, they pose an increasing risk of glacial lake outburst floods (GLOFs) that can be catastrophic to the communities living in the path of these floods (Carey et al., 2012). Many of these glacial lakes did not exist until 50 or 60 years ago, but they are quickly becoming hazardous to the populations living below. GLOFs can be triggered by a failure in the moraine. However, the most common GLOF triggers are landslides, avalanches, or ice calving into the lake; these events result in a large wave that is propagated across the lake and results in water overtopping the moraine.

The glacial watershed system is influenced by several factors, including a changing climate, glacier hydrology and thermodynamics, glacier lake mass balance, lake dynamics, and slope stability. All of these factors contribute to the risk to downstream communities from GLOFs as illustrated in Figure 8.

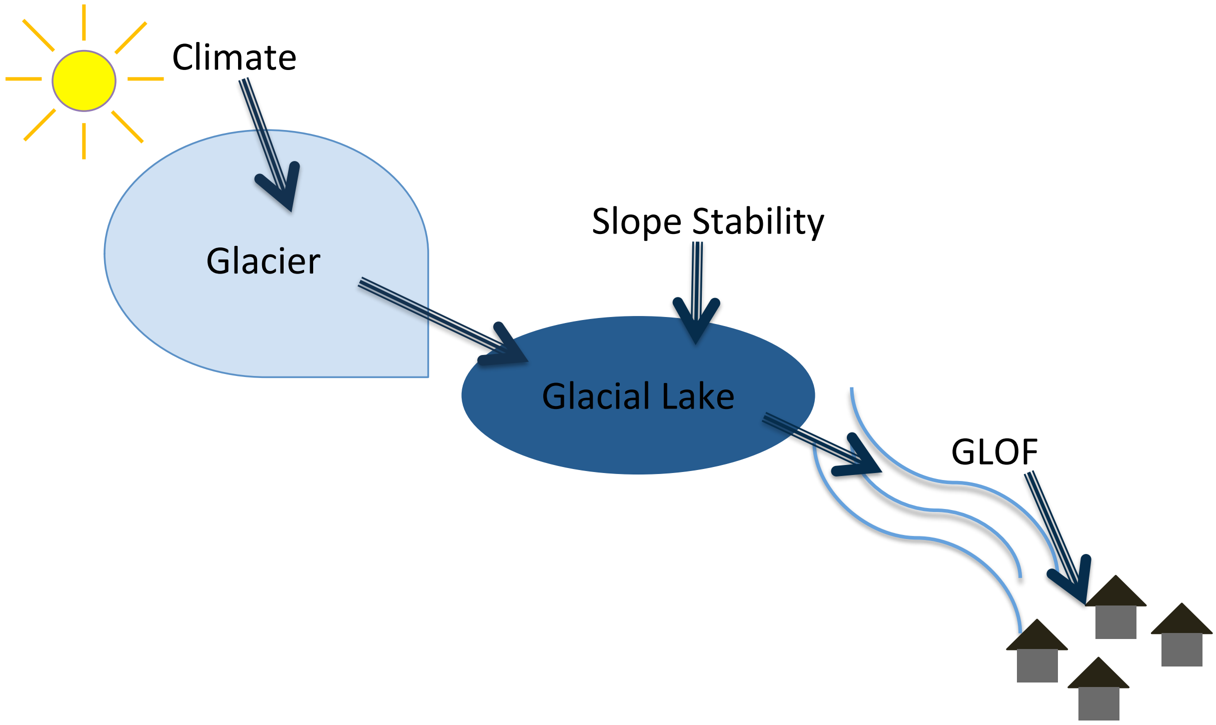

Figure 8. Components of the glacial watershed system

Research Objectives

The goal of this research is to aid in the GLOF risk assessment effort by studying the long-term changes in glacier lake mass balance. The growth of high mountain glacial lakes is generally proportional to the retreat of the nearby glaciers, so knowing the rate of glacier retreat can give us a very good idea of the future size of a glacial lake (Shrestha and Aryal 2010). Actual glacier melt based on local climatic conditions will be calculated using a glacier melt and mass balance model. Due to a lack of data on ice thickness, previous glacier melt models in the tropical Andes have looked only at changes in aerial extent of the glacier. A glacier model informed by ice thickness can give us much better estimates of future growth of glacial lakes due to glacier retreat including improved estimates of the volume of water stored in glacial lakes. The research presented in this poster focuses on the use of ground penetrating radar (GPR) to measure ice thickness.

Current and future research objective are to develop:

- Ice thickness profiles from GPR measurements
- Glacier model incorporating
    - climate variables
    - local mass balance

Glacial lake mass balance model including runoff from glacial melt.

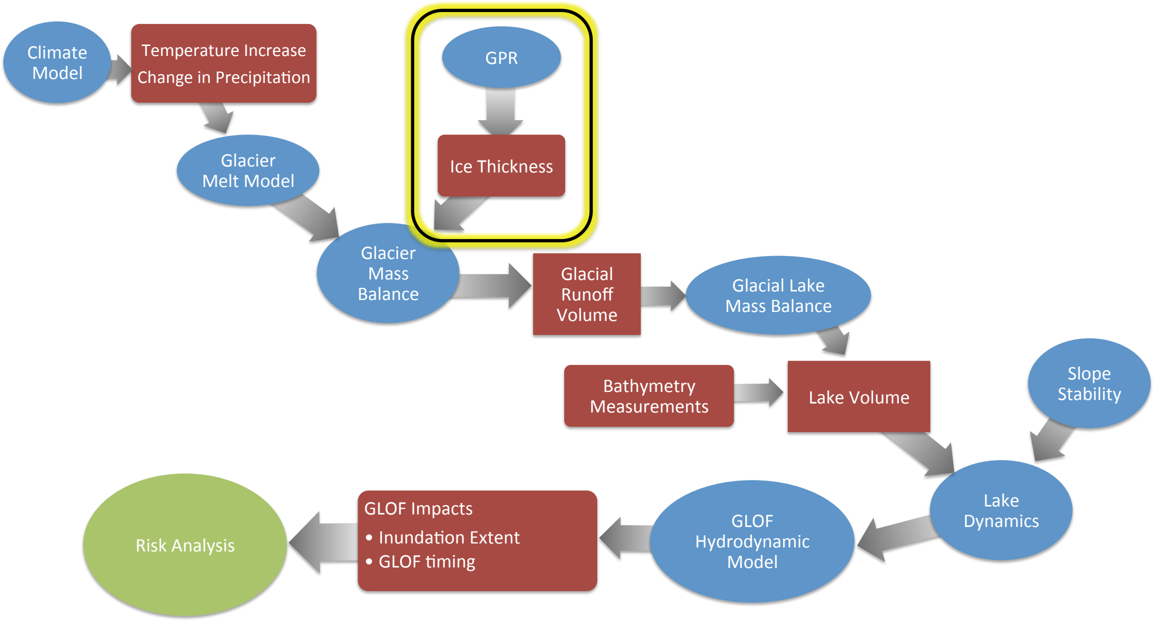

Figure 9. Processes and key data involved in studying flood risk in glacial watershed systems. *Blue circles represent key processes to be studied and red squares represent key data needed to assess GLOF risk. The part highlighted in this poster is the use of GPR to measure ice thickness.*

Study Area

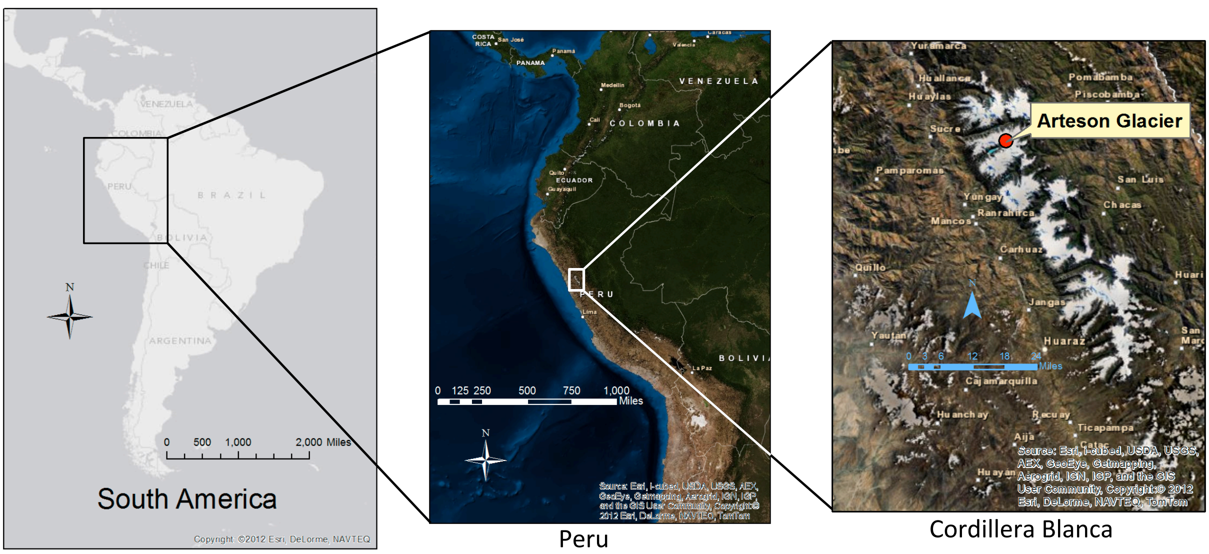

Figure 10. Location of Artesón Glacier in the Cordillera Blanca, Peru

The Artesón Glacier is located in the Cordillera Blanca in Peru (see Figure 10). A small lake began to form at the terminus of Artesón Glacier around 2003 and continues to grow as the glacier retreats. This lake is part of a system of three glacial lakes that includes Laguna Parón, a large lake that has been known to outburst flood in the past (see Figure 11). A drainage system has been installed in Laguna Parón now that controls the lake level to reduce the risk of flooding, but the operation of this drainage system does not take into account any changes that may be happening in the upper lakes as a result of the retreat of Artesón Glacier.

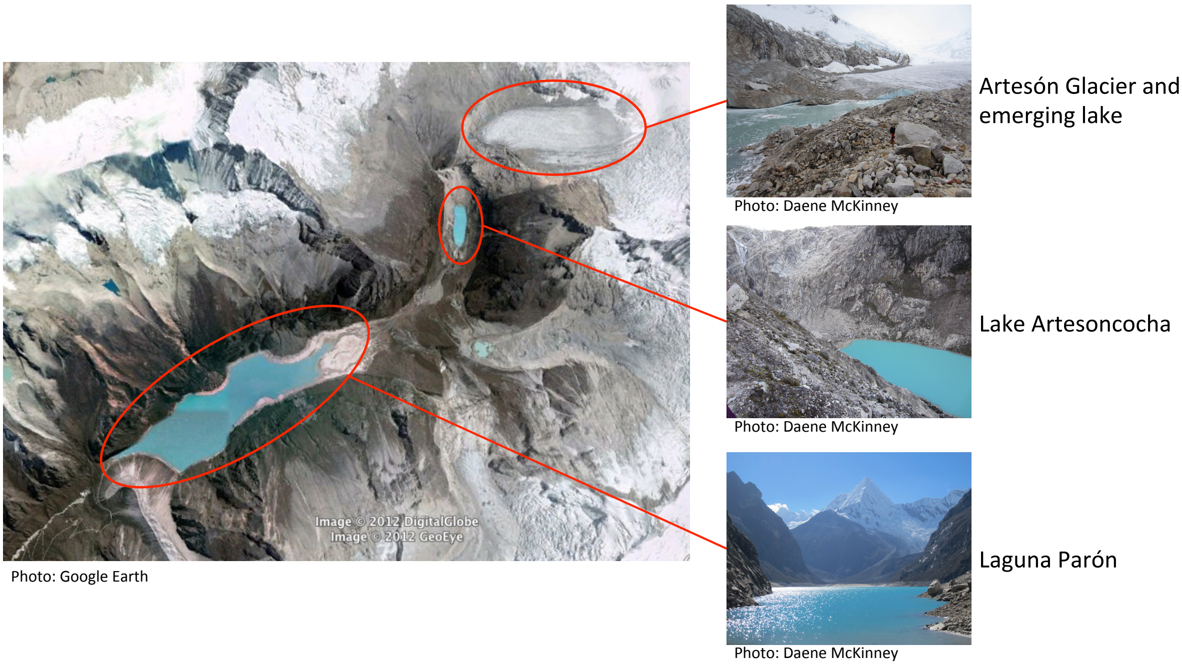

Figure 11. Glacial lake system fed by melt runoff from Artesón Glacier

Background: Artesón Glacier

The Artesón Glacier ranges in elevation from 4684 to 5176 msl and spans an area of approximately 5.4 km^2 (GLIMS 2012). Snow and ice accumulate in the steeply sloped upper portions of the glacier. The tongue of the glacier is less steeply sloped and covers an area of approximately 0.56 km^2. The glacier has a northward facing aspect which means that because of its location in the Southern Hemisphere it receives more direct solar radiation.

In the tropics, the daily temperature fluctuations are higher than the variations in the seasonal average temperatures throughout the year. Artesón Glacier experiences typical tropical weather patterns with most of the accumulation occurring during the rainy months coinciding with austral summertime. Melt is highly influenced by moisture variables in the tropics, and while melt occurs year-round, it is higher during the summer months when accumulation and ablation happen simultaneously. The meltwater and water stored in Laguna Paron is vitally important to the hydroelectric facility located in Canyon del Pato downstream in terms of water regulation of flows during the dry season to meet minimum flows for hydropower generation. This water is also extremely important for irrigation use, both in the local communities directly below Laguna Paron and at the Pacific coast in the large agro-industrial irrigation districts.

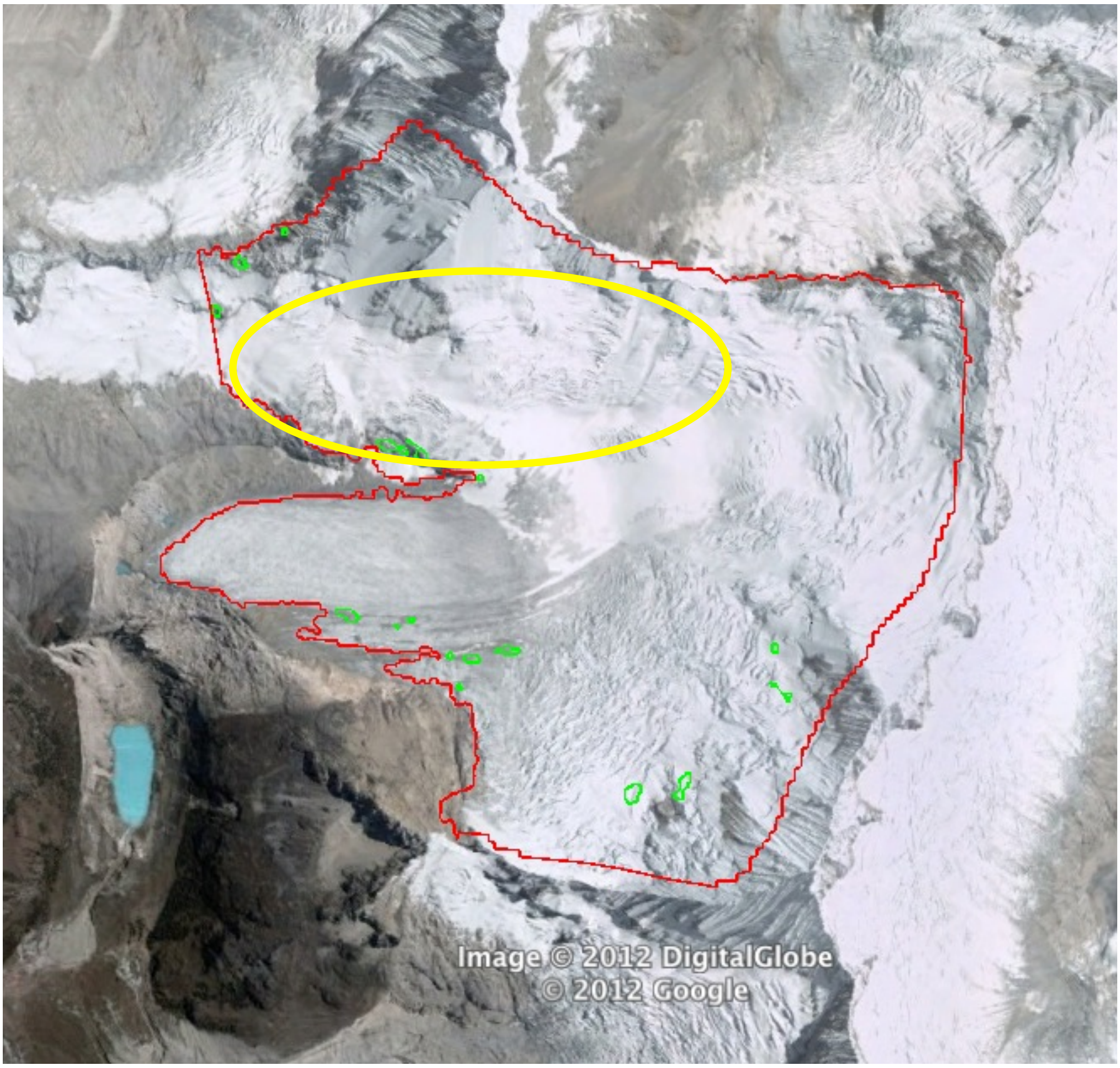

Figure 12: Extent of Artesón Glacier c. 2003. *The glacier outline is taken from Global Land Ice Measurements from Space (GLIMS) database.*[2]

Rough estimates of the lake evolution by Prof. Haeberli (personal communication, Wilfried Haeberli, University of Zurich, July 20, 2012) indicate that: the lake will probably develop at an increasing rate; the depth is likely to reach more than 50 m; the length of the lake is likely to be about 1500 m; and a volume of at least 20 million m^3.

The portable ground penetrating radar (GPR) system that was used to detect the ice thickness and bedrock profile for Artesón Glacier includes a transmitter that emits radar waves at a frequency of 5 MHz and a receiver that detects the signal reflected from the interface between the ice and bedrock. Radar signals were transmitted and detected continuously at regular intervals as operators walked with the GPR system across the surface of the glacier. A constant distance of 40 m was maintained between the transmitter and receiver. The ice thickness was determined based on the two-way travel time (t) between the transmitter and receiver assuming that the signal traveled at velocity (v) of 150 x 10^6 m/s, a typical wave velocity for temperate ice (Woodward Burke 2007).

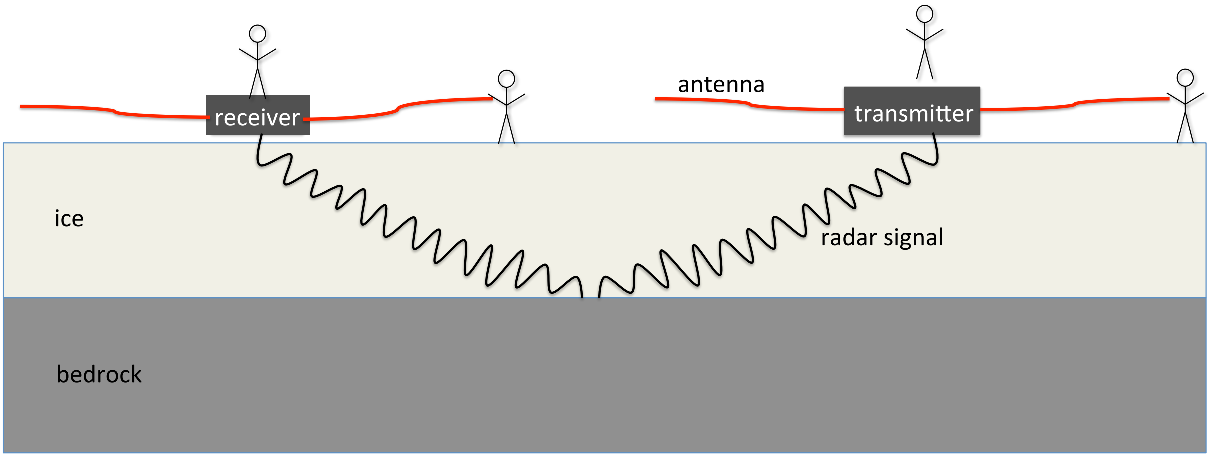

Figure 13. Schematic diagram of portable GPR system


Figure 14. GPR being used in the field to measure ice thickness at Artesón Glacier

Results

Several GPS tracks were taken along the length of the tongue of Artesón Glacier to obtain profiles of the ice thickness and bed rock. The primary reflection occurs at the interface between the ice and bedrock at the base of the glacier. The ice thickness increases moving away from the terminus due to both the positive slope of the glacier surface and the negative bed slope.

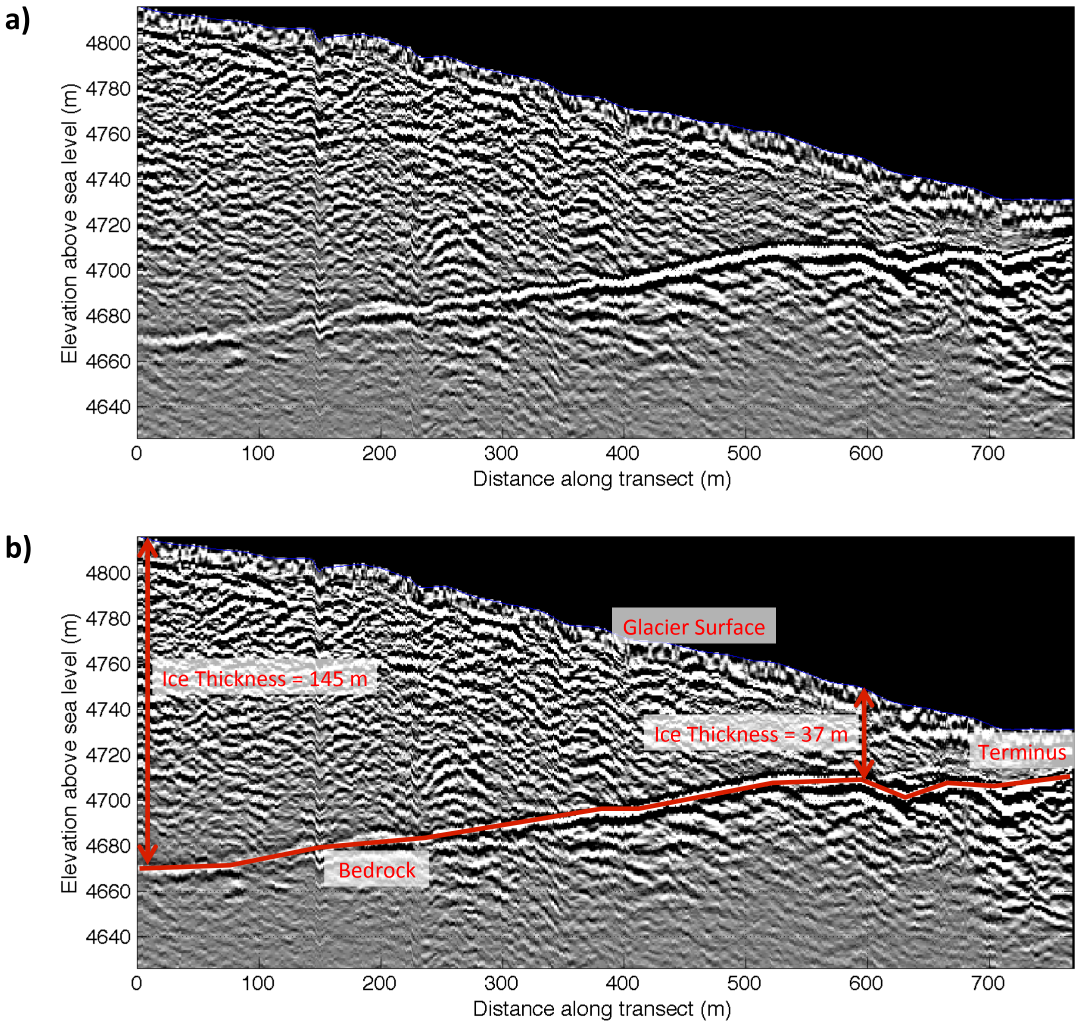

Figure 15: a) Radar profile of Artesón Glacier; b) Annotated radar profile showing the location of the bedrock and terminus and indicating the ice thickness
Wednesday, July 18, 2012 Huaraz, Peru

Ice Thickness

GPR tracks were taken along the lower half of the tongue of Artesón Glacier (see Figure 16). The ice thickness ranged from approximately 167 m a distance of approximately 850 m from the terminus to a thickness of approximately 23 m at the glacier's terminus. Because of the negative bed slope, the ice thickness increases at a rate greater than the surface elevation moving up the glacier away from the terminus.

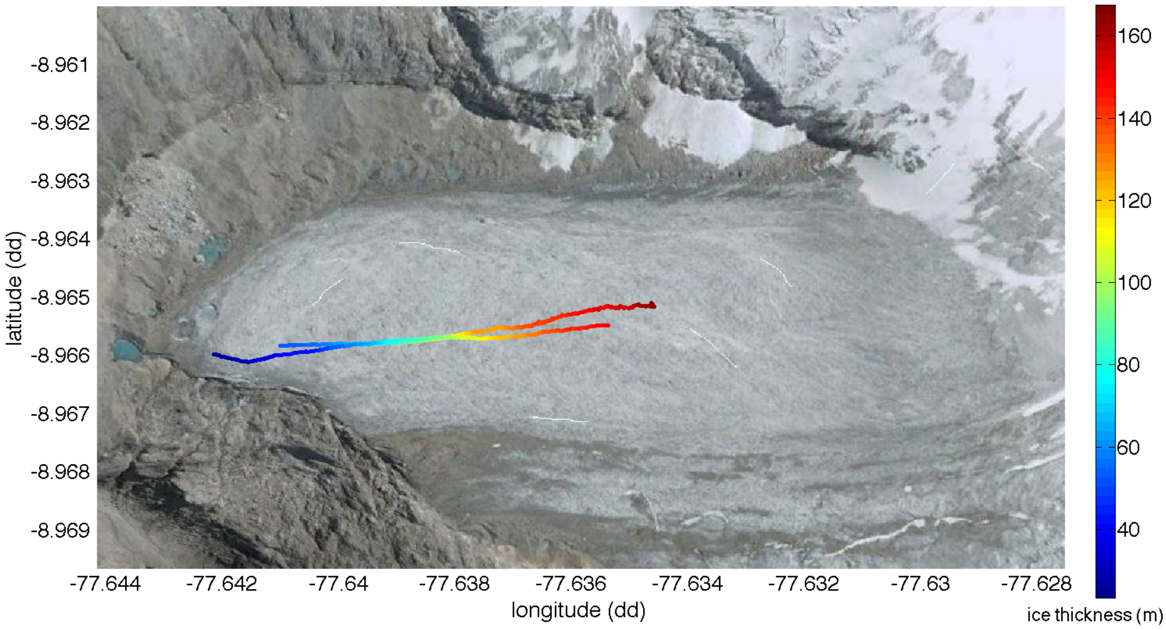

Figure 16: Traces of ice thickness measurements taken at Artesón Glacier

Conclusions

Using the ice thickness data obtained from GPR measurements, a mass balance model of Artesón Glacier will be developed to study how the emerging lake is likely to evolve over time. Due to the negative bed slope, as the glacier retreats, meltwater is likely to accumulate at the base of the glacier rather than draining downhill as surface runoff. This means that the primary variable influencing the growth of the emerging lake at Artesón is the rate of glacial retreat.

Dr. Haeberli estimates that the lake may increase to a maximum water depth of approximately 50 m at a location where the glacier surface elevation is currently approximately 4800 m (with the lake bottom at an elevation of approximately 4650 m). The GPR results at Artesón Glacier are reasonably consistent with this estimate as the bedrock is at approximately 4650 m where the glacier surface is 4800 m.

Ice calving into the lake is one of the key processes that influences the rate of glacier retreat as well as the lake mass balance and dynamics. Because of the presence of overhanging ice at the lake developing at the base of Artesón Glacier, ice calving is likely to have a significant impact on this lake and the flood risk it will pose as the lake grows (a photo of the calving front is shown in Figure 17). An area of future investigation at Artesón Glacier will be the ice calving process. This process is currently not very well understood, but we hope to gain a better understanding of how crevasses form and develop into chunks of ice that break away from the glacier.


Figure 17: Overhanging ice at the glacier's terminus that is likely to calve into the lake below

3 Recommendations

3.1 Refinement of Palcacocha Lake GLOF Model

A hydraulic model of a potential Palcacocha Lake GLOF was created by McKinney and Somos in 2011. This model assumes that the potential GLOF contains only water as it propagates downstream. This is not correct since there will be considerable sediment transported by the GLOF as well. Some of the sediment could come from the moraine of the lake and some will be picked up (and deposited) from the riverbed downstream. It has been shown (Osti and Egashira, 2009) that by not considering the sediment transport of a GLOF, the destructive power of the GLOF is significantly underestimated. Therefore, it is recommended that the existing Palcacocha GLOF model be improved to consider both the sediment transport from the moraine at the lake as well as deposition and scouring of sediment from the stream channel downstream of the lake.

3.2 Vulnerability Analysis of Potential Palcacocha Lake GLOF

Benefits of decreasing the risk of a GLOF from Palcacocha Lake should be calculated. The most appropriate way of calculating these benefits is through a formal vulnerability analysis of the communities and assets downstream of the lake and potentially in the path of a GLOF. Using the Palcacocha Lake GLOF model and the knowledge that we are gaining about the downstream communities, a vulnerability analysis should be performed to determine the potiential losses from a GLOF and what the benefits to the communities might be from a lake risk reduction project.

3.3 Hydrologic Model of Pastoruri Glacier

Pastoruri Glacier has been decreasing in size since the early 1960s and the recession rate of the glacier has increased in recent years. The local municipality of Catac and the Huascaran National Park have initiated a project to develop a Climate Change Exhibit at the glacier to demonstrate the impact of climate change on the region with Pastoruri Glacier and its recession as a centerpiece. The evolution of the volume of ice in the glacier over coming years or even decades can be predicted using a simple hydrologic (or mass balance) model of the glacier. Using the glacier ice depth data obtained on this mission along with various glacier volume estimates made in recent years and available climatic data, a rough estimate of the future size and volume of the glacier can be made. In addition, the GRP survey of the glacier can be repeated next year (2013) during the International Workshop and those results compared with the results obtained on this mission to obtain a more accurate estimate of melt rate.

3.4 Hydrologic Model of Arteson Glacier and GLOF Model of Newly Forming Glacier Lake

Arteson Glacier has been decreasing in size since the early 2000s and the recession rate of the glacier has increased in recent years. The office of Glaciology has become increalingly concerned about a potential GLOF from the newly forming glacier lake at the base of the glacier. The evolution of the volume of ice in the glacier over coming years or even decades can be predicted using a simple hydrologic (or mass balance) model of the glacier. Using the glacier ice depth data obtained on this mission along with various glacier volume estimates made in recent years (available from the Glaciology office) and available climatic data, a rough estimate of the future size and volume of the glacier and melt into the glacier lake can be made. In addition, the GRP survey of the glacier can be repeated next year (2013) during the International Workshop and those results compared with the results obtained on this mission to obtain a more accurate estimate of melt rate.

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