High Andean deglaciation from the Pleistocene into the recent times and its effect on water quality from pyrite contamination.

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Abstract

This study aims to investigate the surface areal extent of a tropical glacier close to Huaraz in the Cordillera Blanca, Peru from 18 000 years before present (BP) to 2011. This was completed by identifying glacial deposits and landforms in satellite images using the programs Google Earth and ArcGIS. The equilibrium line altitude (ELA) for these glaciers were calculated to range from 4500 – 4550m asl during the Pleistocene to 5050 -5100m asl in recent times. The glacier front is currently retreating at a rate of 85 100m^2 (1.5%) per year, while in the Pleistocene it receded at a rate of 4800m^2 (0.01%) per year. This deglaciation implies a significant increase in the ELA.

Deglaciation also exposes more of the underlying bedrock to weathering and erosion. In this area pyrite (FeS_2) is present in the bedrock in the Chicama formation and glacial tills, it is readily oxidised and dissolved into water to form iron hydroxides ($Fe(OH)_3$) and sulphuric acid (H_2SO_4) which are harmful to humans and animals. This is a natural source of contamination for the local river, the Río Negro, so a link between lithology and water quality in sources is also tested here, as the water is used for drinking and agriculture in the Ollieros district, Peru. Glacial tills appear to be related with the cause for high concentrations of dissolved pyrite in the Río Negro.

Content

1. Introduction

The Cordillera Blanca mountain range lies in the Jurassic-Cretaceous Chicama-Goyllarisquizga basin *(Romero, 2008)*, with the oldest rocks dating back to the Mesozoic era around 250 million years ago *(Sevink, 2009)*. At that time there was a large trench between the Nazca and South American tectonic plates. Sediment was collected, largely from eroded material from the South American plate, inside this trench forming limestone and peat. Around 150 million years later the plates changed direction and began to move towards each other, compressing the material in the trench into sedimentary layers and uplifting it with huge folds. In the Eocene epoch (around 55 million years before present (BP)) massive volcanic eruptions covered the folded sedimentary rocks with lava and ignimbrites. Magma also intruded forming granitic batholiths during the mid-Pliocene (around 10-15 million years BP) and the area continued to uplift. Large scale glaciation occurred in the quaternary (around 2 million years BP) leaving an extensive moraine network with fluvio-glacial deposits *(Sevink, 2009)*.

Ignimbrites, volcanic breccia's, batholiths and sedimentary rocks are characteristic features of the region, but pyrite is also contained in the Chicama formation *(Romero, 2008; Sevink, 2009)*. The Chicama formation is a Mesozoic unit from the Middle Upper Jurassic made of sandstones intercalated with shale and mudstone from a deltaic environment, over intrusive batholithic granodiorite. Finely divided carbon and pyrite contained in the rock give it a distinctive dark colour *(Sevink, 2009)*. Pyrite (FeS_2) is a major source of contamination for water as it becomes reactive in the presence of dissolved oxygen or ferric iron (Fe^{3+}). It is weathered by the processes of oxidation and dissolution, producing sulphate (SO^{2-}_4), iron (Fe^{2+}) and hydrogen *(Moses et al., 1986).* As the iron (Fe^{2+}) produced is more reactive, it rapidly oxidises into ferric iron (Fe^{3+}) which can bond with hydrogen to form the more stable and more toxic iron hydroxides ($Fe(OH)_3$) *(Todd et al., 2005; Vuori, 1995)*. Studies have shown that this impairs livelihood of aquatic animals *(Biesinger and Christensen, 1972; Furmanska, 1979; Martin and Holdich, 1986, Maltby et al, 1987 and Gerhardt, 1995),* as it is highly immobile and accumulates on surfaces *(Sevink, 2009)* such as river beds and in the cells walls of organisms *(Vuori, 1995).* The sulphate also reacts with hydrogen in the water and produces sulphuric acid (H_2SO_4) which is also toxic to aquatic life but can be transported in the water and leached out by rain *(Sevink, 2009)*. The amount of contaminants contained in the water will depend on how much contact time it has with the pyrite mineral, determined by the flow path, whether it flows overland or subsurface will also play an important role.

A concept first introduced by James Hutton in the 1780s but summarised by Charles Lyell in 1830, "The present is the key to the past" can be used as the fundamental reason for reconstructing former glaciers in order to better understand the landscape as it is now and to predict how it might behave in the future *(Menzies, 1995).* As a glacier flows it scours and erodes rock in one area, transports it to another place where it is deposited as glacial debris accumulations *(Benn and Evans, 1998).* These accumulations can then be used to reconstruct the extent of former glaciers.

The Cordillera Blancas were once heavily glaciated, covering the pyrite rich Chicama formation in ice. As the glacier retreats more of the environmentally toxic pyrite is exposed therefore available for weathering and contamination in water.

2. Study Area

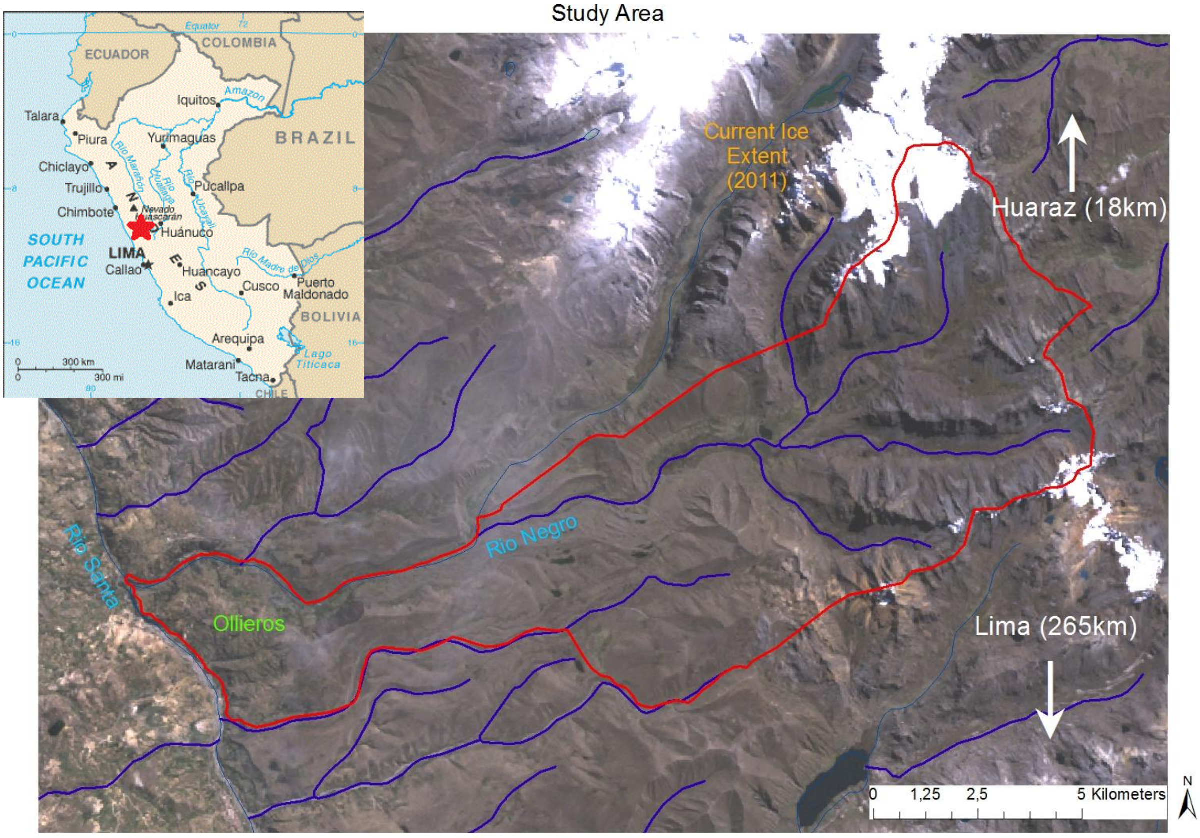

Figure 1: The study area indicated by a red star on map of Peru (inlay) and in closer detail outlined in red (main picture).

The area used in this study is the catchment area for the Río Negro, near the village of Ollieros around 20km South of Huaraz in the Cordillera Blanca, Peru. The river is a tributary of the Rio Santa which is used as a source for drinking water, agricultural activities and hydroelectric power plants (accounting for ten per cent of the whole country's capacity) and ultimately flows into the Pacific Ocean *(Mark et al, 2010)*. Figure 1 outlines the study area, it is around 20km from east-west and 8km north-south (centre coordinates are 9^{o}38'40 S 77^{o}23'12 W). Altitudes range from 3300m asl close to the Río Santa, to over 5600m asl where the glacier currently lies.

The tropical climate of the region is split into two distinct seasons, wet and dry, with high diurnal variation *(Kaser et al., 1990)*. Eighty per cent of annual precipitation occurs in the wet season *(Mark et al., 2010)* between the months of October to April where it falls daily as rain in valleys and snow at higher altitudes, peaking in January to March *(Silverio and Jaquet, 2005)*. River discharge is also highest during the wet months of October to April *(Mark et al., 2010)*.The dry season occurs from May to September, where precipitation is not common in valleys but can fall for periods of 1-2 days at high elevations in rain or snow *(Silverio and Jaquet, 2005)*. The temperatures reach around 20^{o}C at 4000m asl at noon but fall to below freezing at night.

Iron and sulphates have been observed in the Río Negro, implying that there must be a source of pyrite in the region. The geology of the upper part of the study area exists mainly out of the Chicama (see Figure 2: **The geology map in the study area, with the Chicama formation (**. The importance of the Chicama lies in the pyrite content. Pyrite is also present in the morranic deposits that were left by the former glacier and is lying in the upper part of the study area. The pyrite in this glacial till are more exposed to weathering and erosion than the Chicama and can be seen as the largest concentration source of pyrite that is found in water streams in the research area.

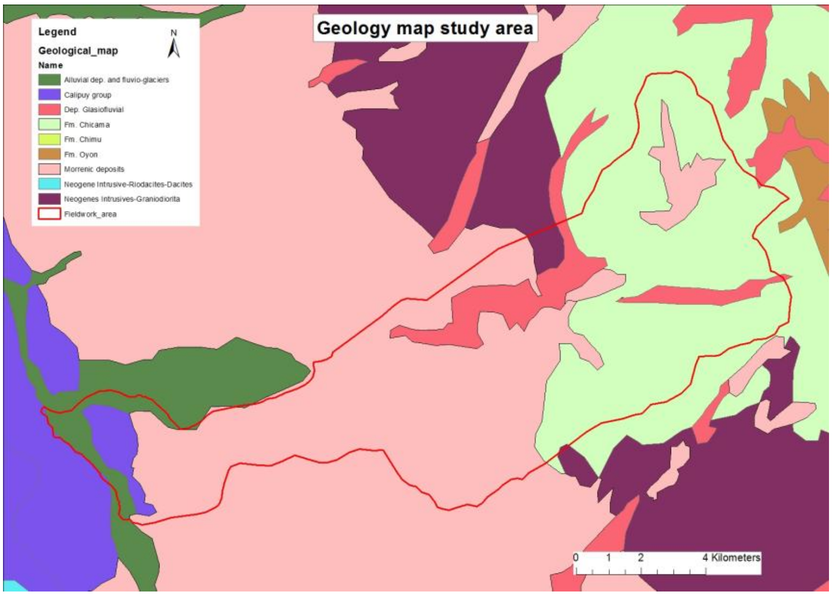

Figure 2: The geology map in the study area, with the Chicama formation (green) & glacial till (pink)

With over 700 glaciers, the Cordillera Blancas are home to 70% of all existing tropical glaciers in the world at the moment *(Chevailler, 2011),* also making it the world's largest concentration of them in any one area *(Mark et al., 2010).* It has also undergone much heavier periods of glaciation in the more recent past than similar periods across Europe (E.g. LGM) and although there is much human activity in the region, the landscape is much more unscathed. This makes it an ideal place to observe glacial features such as cirques, terminal moraines, lateral moraines, eskers, drumlins and glacial lakes, which can all be used to reconstruct a former glacial extent.

3. Aim

Given the fact that the Río Negro has been observed to contain iron and sulphites and local inhabitants are worried as to what might be the cause of this, the decline of the glaciers in the area is going to be investigated to identify if it is this that is causing increased levels of pyrite containing rock to be exposed. Therefore our aim can be summarised as:

Investigate if the retreat of the glacier front is affecting the water quality in a high altitude catchment area in the Andes, Peru.

4. Objectives

- Reconstruction of the former glacier extension in GIS/Google Earth and understanding of the landscape in the research area using a vector layer.
- Calculate rate at which glacier has decreased in surface area and to project this to future change.
- Create hypsometric curves from the former glacial extents in order to calculate former Equilibrium Line Altitudes using the AAR method.
- Use Chicama formation and glacial till as a proxy for pyrite exposure and investigate a link to glacial retreat, produce this in graphs.
- Compare toxicity of water sources from Iron and Sulphate concentrations in relation to pyrite exposure.

5. Research Questions

- Is it possible to reconstruct the formal glacial extent by identifying geomorphological and glacial features from satellite images and field observations?
- How is the extent of the surface area of the glacier changing from the Pleistocene through to recent times?
- Which calculations can be used from a glacial reconstruction in order to predict future conditions?
- Is glacier retreat affecting the water quality of springs in the fieldwork area, from increased exposure to pyrite?

6. Methodology

In order to identify if there is a link between glacial front retreat and iron and sulphate contamination in water, the first step was to reconstruct former stages of glacial extent. This was achieved using the programs Google Earth and ArcGIS. The polygons created in these programs were then used to calculate the former equilibrium line altitude (ELA) of each glacier. The amount of the Chicama formation exposed at each stage of glacial size was calculated. Finally, maps showing the level of contaminants in water sources were projected over a map of possible sources of pyrite, i.e. Chicama formation and glacial till.

6.1. Reconstruction of former glacial extents

The polygon function in Google Earth was used to outline the largest surface area extent of the glacier from visible lateral and terminal moraines, striations and other glaciological features. Image quality in Google Earth allowed for a more superior identification of features than was possible in ArcGIS, see figure 3 for a comparison of this. A new polygon was used for each stage of glacier retreat. In total seven large glacier extents and seven valley glaciers were mapped using this method. For the identification of the age of the large glaciers, radiocarbon dating information in the study area was used from Rodbell (2000). Landsat images (bands 1, 2 and 3) from Global Land Cover Facility (www.landcover.org) were downloaded and used to reconstruct recent glaciers from 1989, 1991, 1999, and 2007. All images have a pixel resolution of 30m and are from the multi-spectral TM (Thematic Mapper) dataset, except for 1999 which is from the ETM+ (Enhanced Thematic Mapper Plus) dataset. The images were exported to ArcMap 10 and the glacial extent in each image was outlined using the polygon feature, using a new shapefile for each year. The glaciers in each image were assigned a number (1-6) for recognition, as shown in Figure 6 (in results). The most recent glacial extent, from 2011, was outlined in Google Earth.

The polygons created in Google Earth were converted from Google Keyhole Mark-up Language (.kml) to an ESRI Shapefile (.shp) for use in ArcMap using the program DNRGPS *(Minnesota Department of Natural Resources, 2012).* Then the polygons could be imported to ArcGIS for the ELA to be calculated.

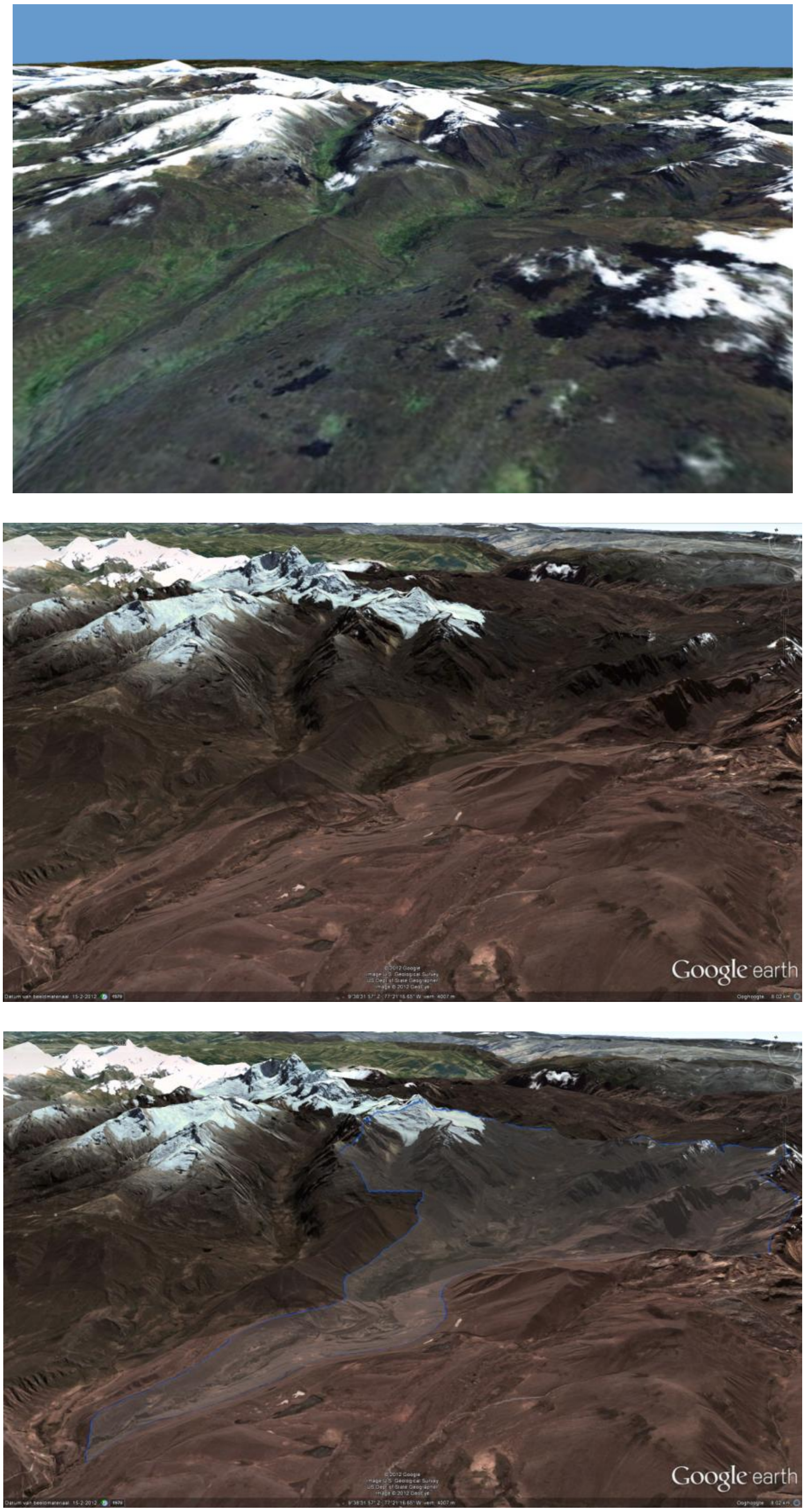

Figure 3a, b and c: 2a (top): View of the landscape in ArcGlobe. 2b (middle): View of the landscape in Google Earth. 2c (bottom): Google Earth view with a polygon constructed showing the outline of a large glacier.

6.2. Calculating and reconstructing former Equilibrium Line Altitudes (ELA)

The method for calculating former ELAs is based on the three-dimensional form of the glacier surface, combined with assumed mass balance-altitude relationships. The ELA of each glacier was calculated separately in its own shapefile. In ArcMap 10, the 100m contour map of the study area was imported and laid over the glacier polygon. Where a contour line crosses the glacial margins, a line is drawn to connect the equal height across the former glacier surface, resulting in a shape similar to that in figure 4.

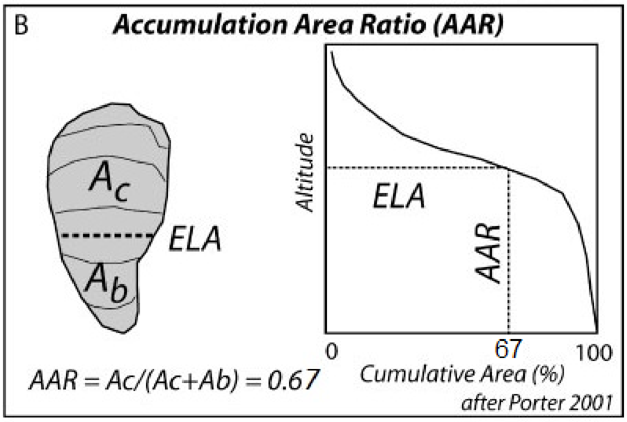

Figure 4: Schematic diagram of calculating the ELA using the AAR method *(Ramage et al., 2005).*

Subsequently vector overlays were mapped over the glacier margins on the orthophotos (using Arcmap). Specially developed fields were added to the vector attribute table in order to calculate the surface area in km^2 and to extract the altitudes. The attribute table was then copied into excel for further calculations. For each glacier, all polygons were binned into 100m categories of equal heights in order to calculate the total area in km^2 per altitude. This was then converted to a percentage of the total glacier area and then the cumulative area so hypsometric curves could be plotted.

The hypsometric curves can then be used to estimate the ELA using the Accumulation Area Ratio (AAR) method.

$$AAR = A_c/(A_c + A_b)$$

AAR = accumulation area ratio, A_c = accumulation area, A_b = ablation area, and $A_b + A_c$ = total area *(Ramage, et al. 2005)*.

This method implies that the Accumulation zone occupies a significant part of the total glacier area (Meier and Post, 1962). In this case we assume this area is two thirds of the area so the AAR is estimated as 0.67 according to Klein et al. (1999).

6.3. Analyses of geology cover compared to glacial extent

An analyses of the geology cover compared to the glacial extent in the research area was carried out in order to identify if there is a link between glacial retreat and iron and sulphate contamination in water. In this analysis, a geology map was used to identify the total coverage of Chicama (see introduction for more information) in the study area. This map was obtained by former research done in Peru. Using the reconstruction of former glacier, calculations were made on the surface area percentages of these glaciers through time on the same Chicama area size. In this way, calculations could be made on the of the Chicama area that was exposed by the melting of the glaciers. The amount of newly deposited glacial till being exposed was also calculated in this way.

6.4.Source stream water analysis compared to the geology

The last analysis in this research was done using acquired field data of the water quality in the study area. Water samples were taken in the study area and analysed in the lab. Iron and Sulphate data were visualized on the study area map together with the geology of the study area. Finally all the results are discussed in order to conclude if there is a link and what kind of link there is between glacial retreat and iron and sulphate contamination in water.

7. Results

The results discussed here are split into the most recent glaciers (1989-2011) and paleoglacier (18000 – 8500 years BP). Because the time lag between these timelines is too large to analyse them significantly as one time sequence.

7.1.Recent Glaciation 1989-2011

7.1.1. Glacial Extents

Figure 5 shows the decline in glacier surface area from 1989 to 2011. The glacier is found in the north west of the study area and the surface coverage has decreased by a third during this period, 2.1km^2 in total, with an average of 85 100m^2 (1.5%) per year. The largest loss comes from Glacier 2, which accounts for 57% of the total loss. Glacier 6 is the most unchanged glacier, only accounting for 2% of the loss, while the remaining decline in glacier area is split more evenly between the other four glaciers, accounting for 8-11% each (See appendix 7.1).

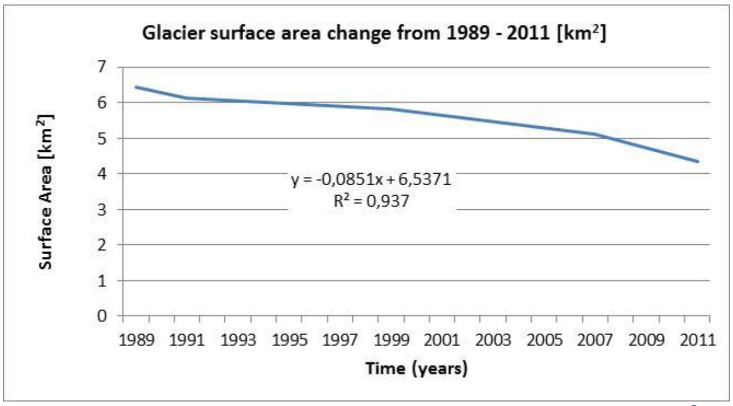

Figure 5: Glacier surface area decline from 1989-2011(km^2).

Figure 6 shows the glacial extent in relation to the landscape created in ArcGIS. There is still a significant amount of mass left in the six glaciers but if the same rate of change is applied into the future there will be no ice by 2066.

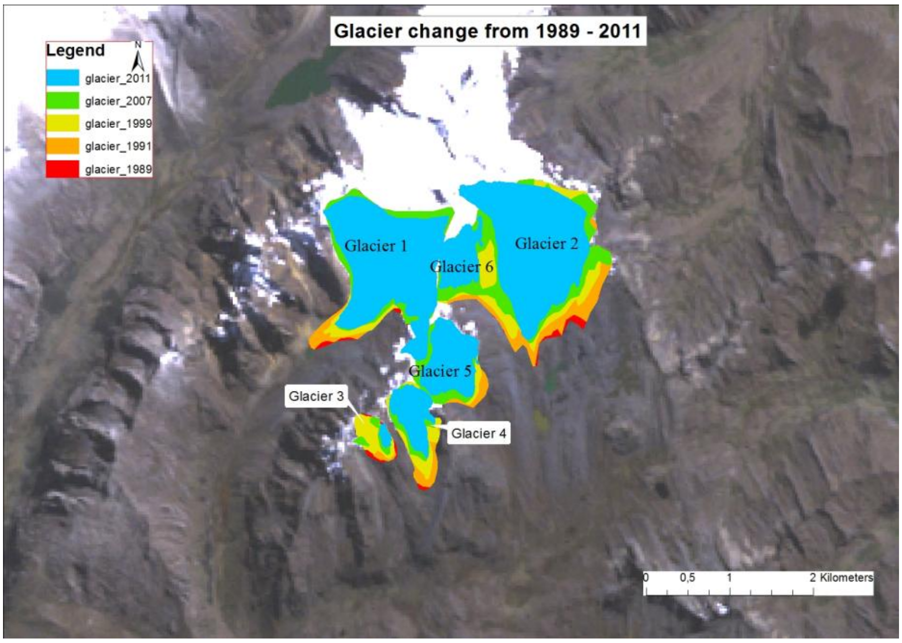

Figure 6: Outline of glacier surface area extent for five stages of retreat from 1989 to 2011.

7.1.2. Equilibrium Line Altitudes

In figure 7 below, one can see the hypsometric curves of glacier 1 from 1989 until 2011. The figure shows us a declining trend in the ablation zone through time. This trend can be seen as well for the glaciers 2 to 6 (see appendix 7.5).

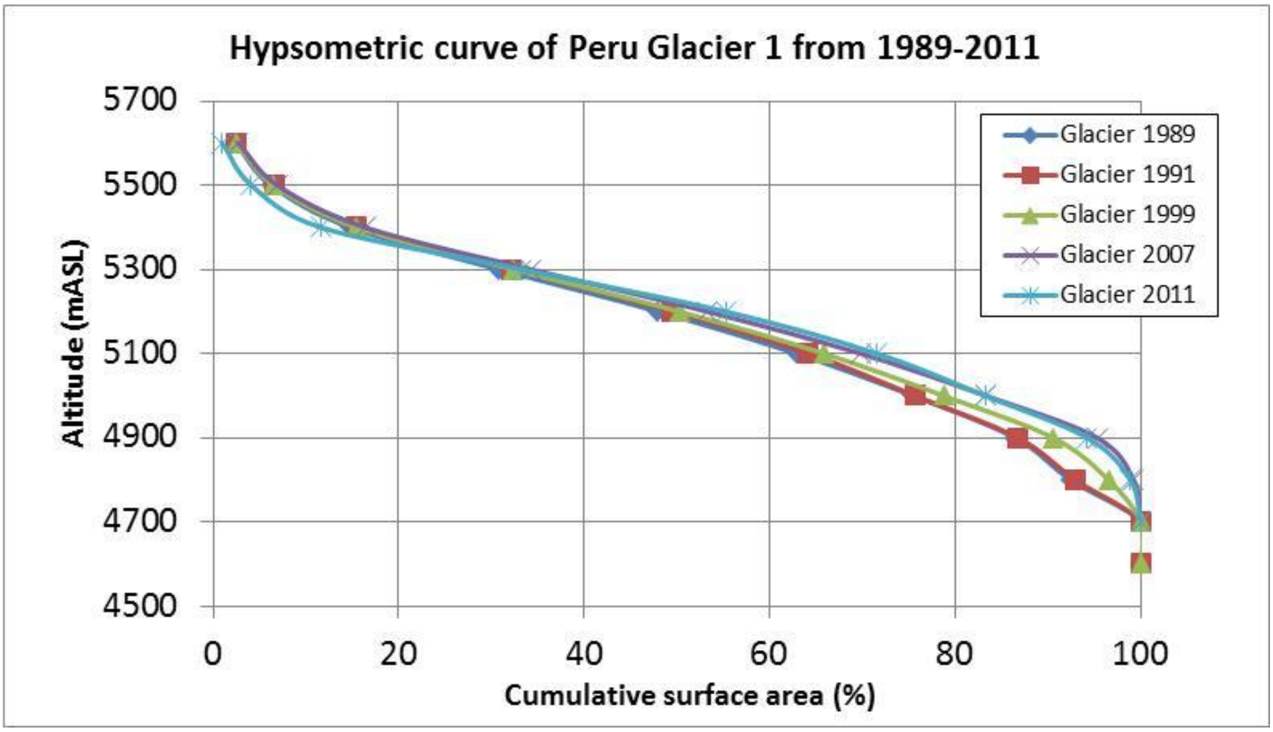

Figure 7: Hypsometric curve of glacier 1 from 1989 – 2011. A declining trend is visible in the ablation zone.

The calculated Equilibrium Line Altitudes (ELA's) of the glaciers in the study area from 1989 until 2011 are shown in figure 8. A paired t-test was performed to determine if the ELA was increased significantly from 1989 to 2011. The mean ELA increase (M=48,4m, standard deviation =17,7m, N= 6) has indeed significantly increased, t(5)=-6,71, two-tail p = 0.001, providing evidence that the ELA is indeed increasing. A 95% Confidence Interval about mean ELA increase is (29.8, 76.0). One can see a significant increase of all ELA's during that time period. This means that the glaciers fronts are retreating and thus the glacier volume is getting smaller.

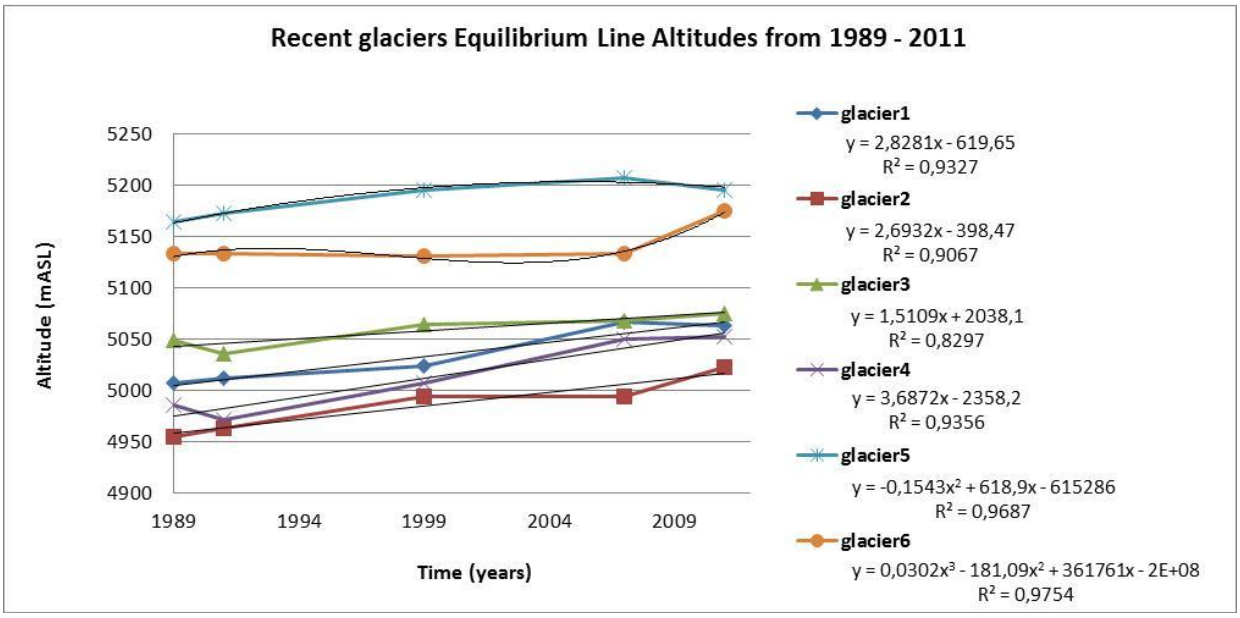

Figure 8: ELA's of the glaciers from 1989 – 2011. An increasing trend is visible through time.

7.1.3. Glacial retreat in relation to Chicama Exposure

The amount of Chicama and glacial till surface area is expressed in figure 9 below. These areas are likely to contain pyrite. There is an increase visible of around 74000m^2 per year (4%) of exposed Chicama surface area and 4700 m^2 per year of glacial till exposure (3%). The Chicama formation area is still far bigger than the glacial tills.

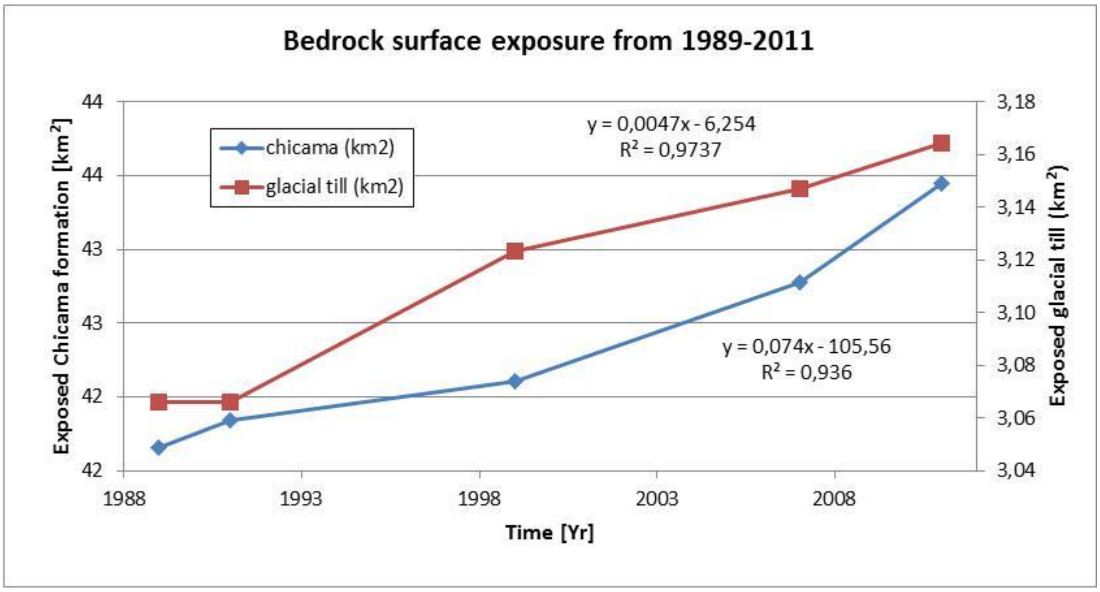

Figure 9: Chicama and glacial till surface area exposure from 1989 – 2011.

7.2.Paleoglaciers 18000 – 8500 years BP

7.1.4. Glacial Extents

The shape of the paleoglacier is outlined in figure 11 and the rate at which it decreased is shown in figure 10. The size of the glacier covered a surface area 65km^2 in 18 000 years BP, this then steadily decreased to a size of 21km^2 at 8500 years BP. During this period of 9500 years it decreased in surface area by 49km^2, this is a rate of 4800m^2 (0.01%) per year, nearly twenty times slower than the decline experienced in more recent times.

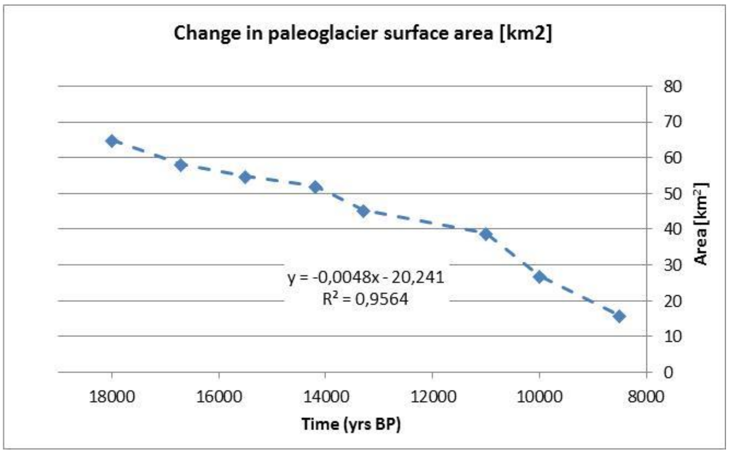

Figure 10: Change in surface area of paleoglacier from 18 000 to 8500 years BP.

The glacier shrank from west to east, towards the higher land. At its largest point it extended around 15km in length, 10km in width and nearly 2km in elevation, from an altitude of 3900m asl to 5700m asl.

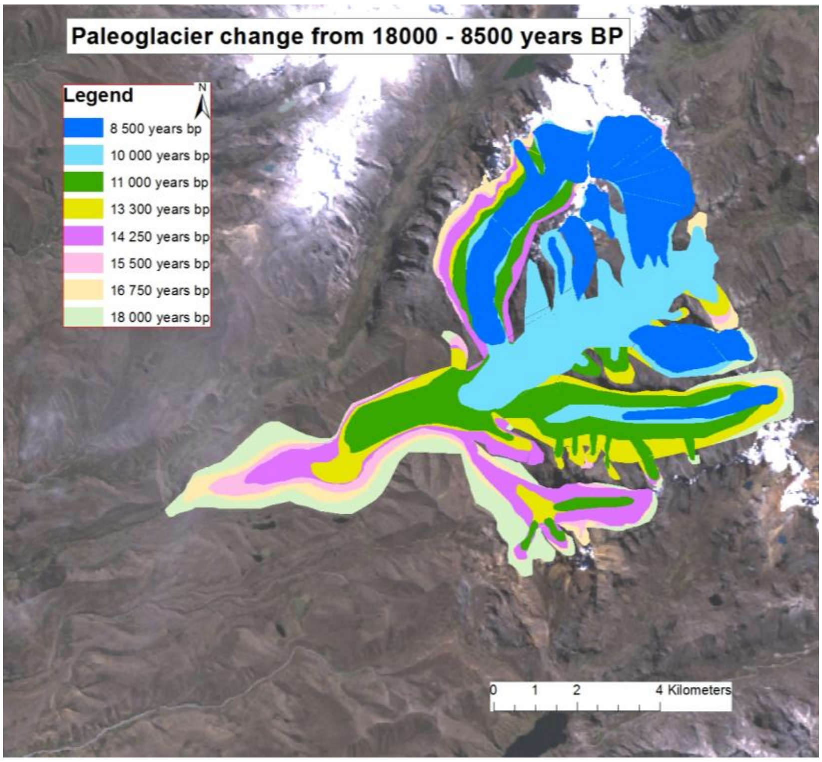

Figure 11: Outline of glacier surface area extent for eight stages of retreat from 18000 to 8500 years before present.

7.1.5. Equilibrium Line Altitudes

The paleoglaciers are divided in two hypsometric curves. Figure 12 shows us the paleo glaciers from 18000 – 10000 yrs BP, while figure 13 shows the paleo-valley glaciers from 8500 yrs BP. The paleoglaciers in figure 12 are again showing a declining trend in their ablation zones, whereas the paleo-valley glaciers are only showing their own longitudinal profiles. They are divided into 7 separate glaciers and aren't connected as one large glacier as in the period of 18000 – 10000 yrs BP. Therefore they are presented in a separate figure.

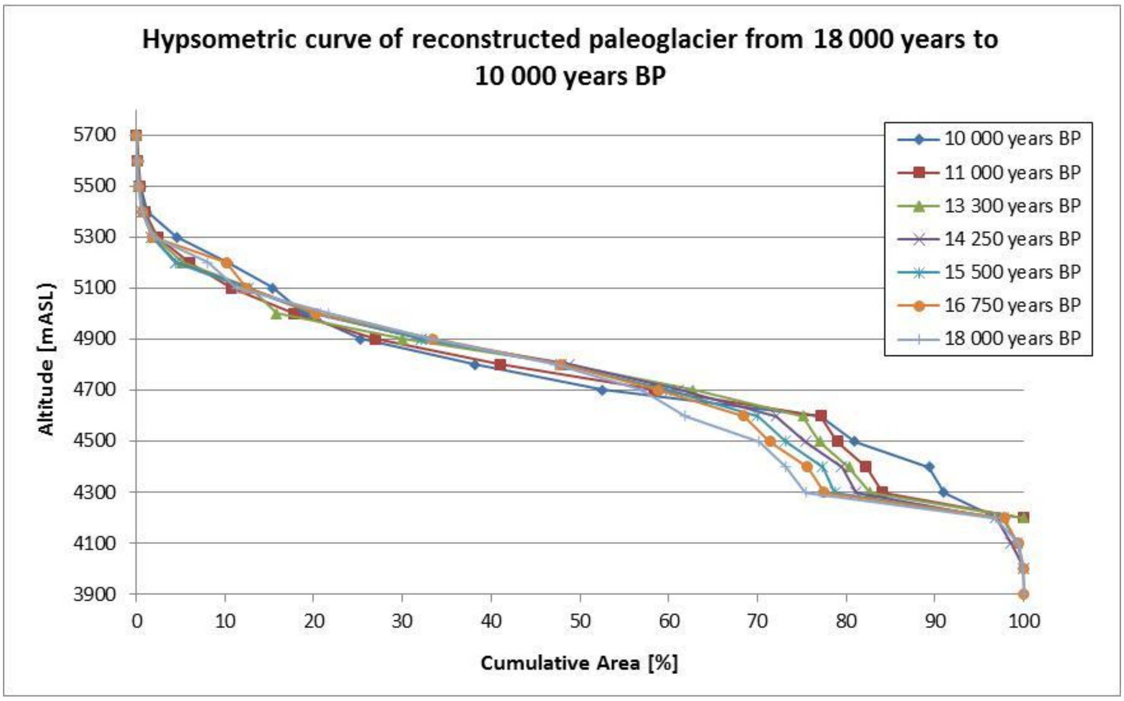

Figure 12: Hypsometric curve of the paleoglaciers from 18000 – 10000 yrs bp. A declining trend is visible in the ablation zones.

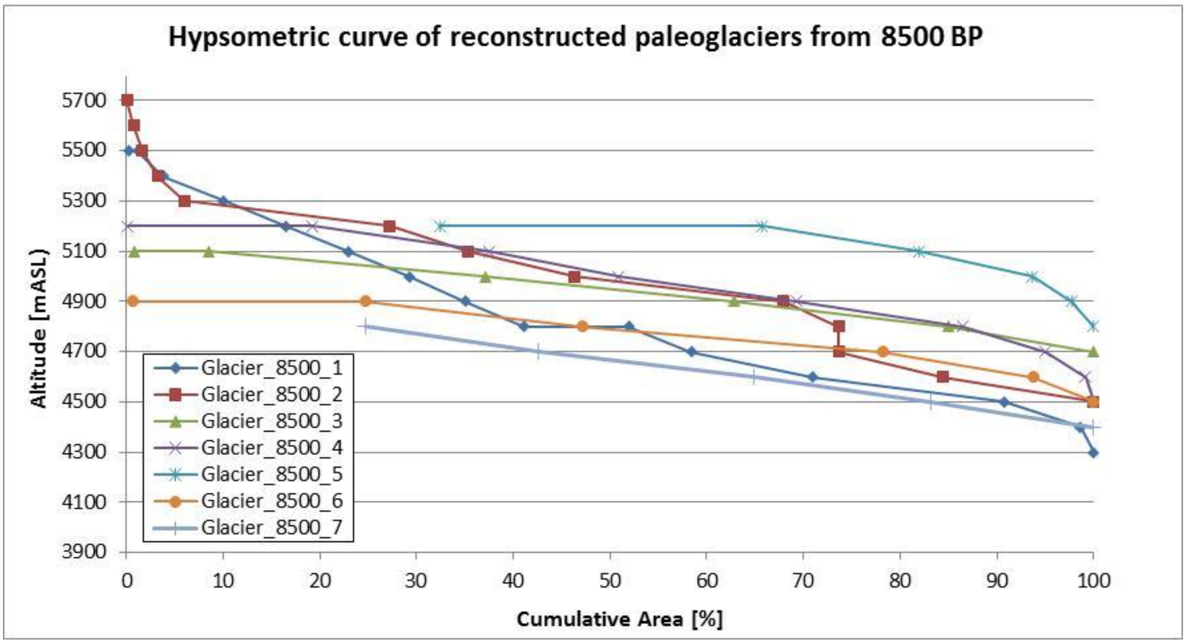

Figure 13: Hypsometric of the paleo-valley glaciers from 8500 yrs BP.

The paleoglacier ELA's from 18000 – 8500 yrs BP are presented below in figure 14. The retreating of the paleoglacier front is visible by the increasing ELA through time. The stage at 13 300 years BP appears to be an anomaly, as it does not fit the same trend as others before and after it. There is a significant increase in ELA around 10 000 years BP.

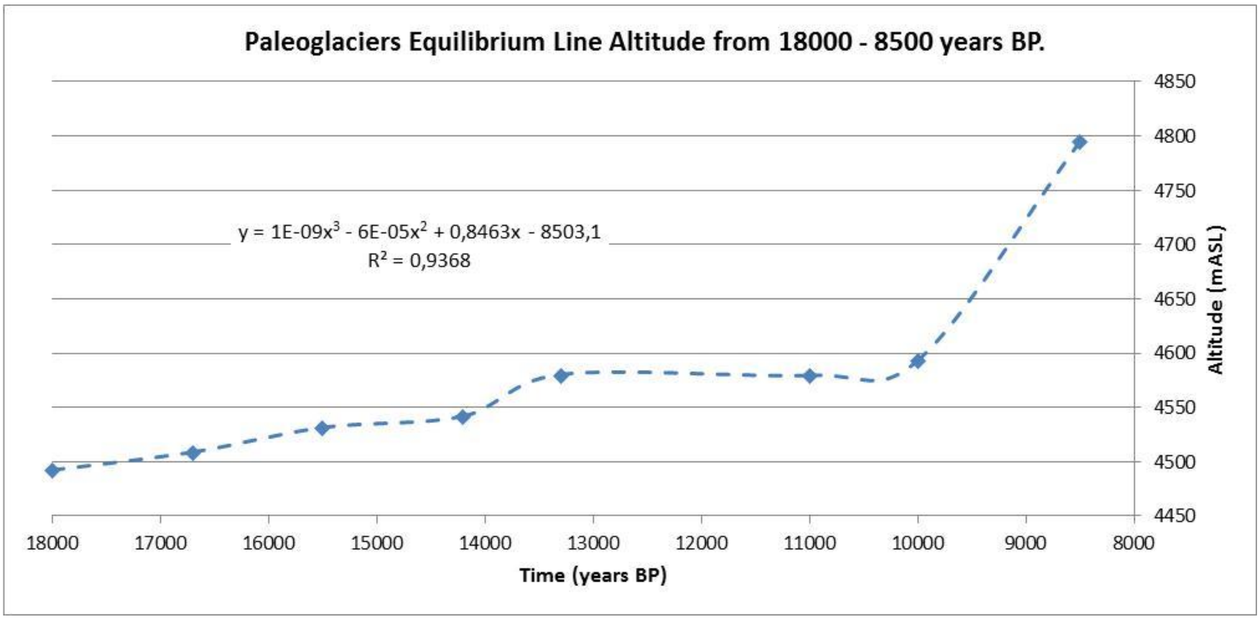

Figure 14: ELA's of the paleoglaciers from 18000 – 8500 years BP. An increasing trend is visible through time.

7.1.6. Glacial retreat in relation to Chicama exposure

Figure 15 shows the amount of Chicama and glacial till surface area. These areas are likely to contain pyrite. The exposed bedrock surface during the period 18000 – 8500 years BP has grown steadily and more than doubled for the Chicama formation in that time period. The glacial till is almost completely covered through this time period with an small increase of exposure, according to the calculations around 10 000 years BP.

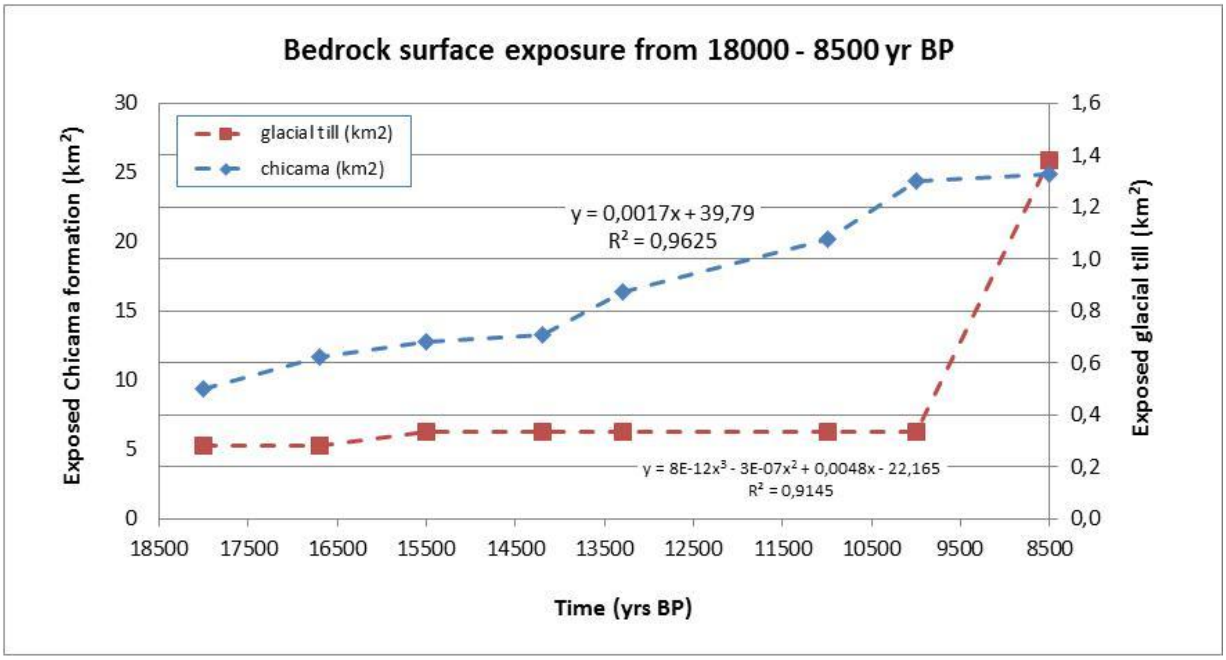

Figure 15 Chicama and glacial till surface area exposure from 18000 – 8500 BP.

7.3. Water sources and pyrite surface area

Figures 16 and 17 identify the water sources in the study area, along with the level of contamination within each of them. The Iron (Fe^{2+}) contamination shown in figure 16, is projected over the study area, together with the surface area of Chicama and glacial till (labelled “Morrenic deposits” in key). Two high Iron concentration have been found in the glacial till and one is found in the Río Negro stream. Figure 17 depicts the same style of map but shows contamination for sulphates. Again it is clearly visible that the highest sulphate concentrations are found in the glacial till, and in the Río Negro stream.

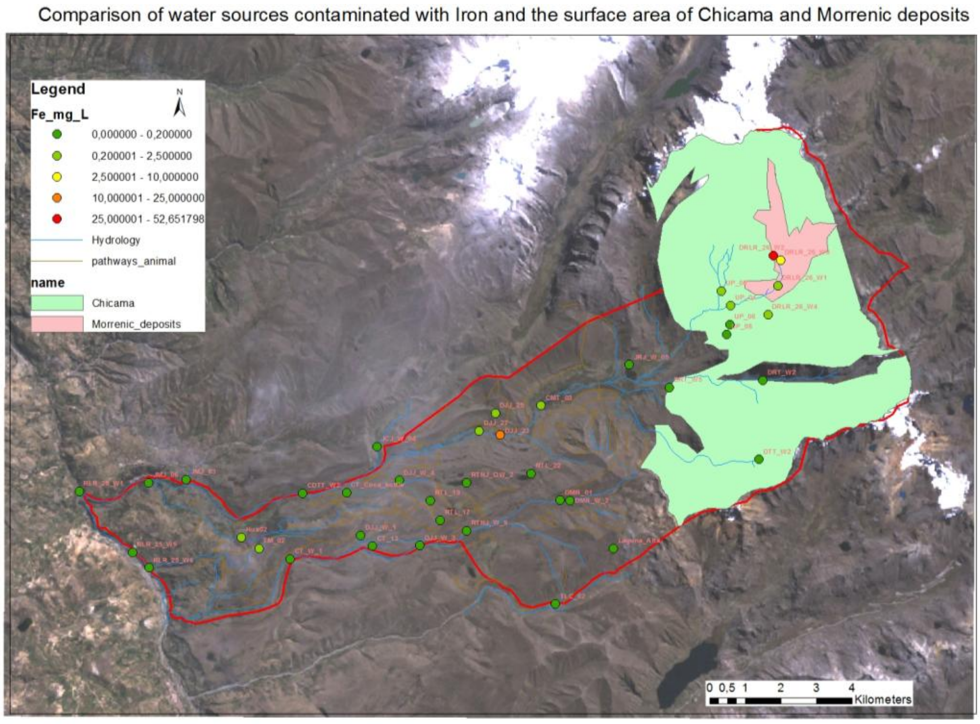

Figure 16: Iron content of water sources projected onto the study area with the surface area of possible pyrite concentrations. Areas containing pyrite are divided in two, the Chicama formation (green) and the glacial till (Morrenic deposits, pink)

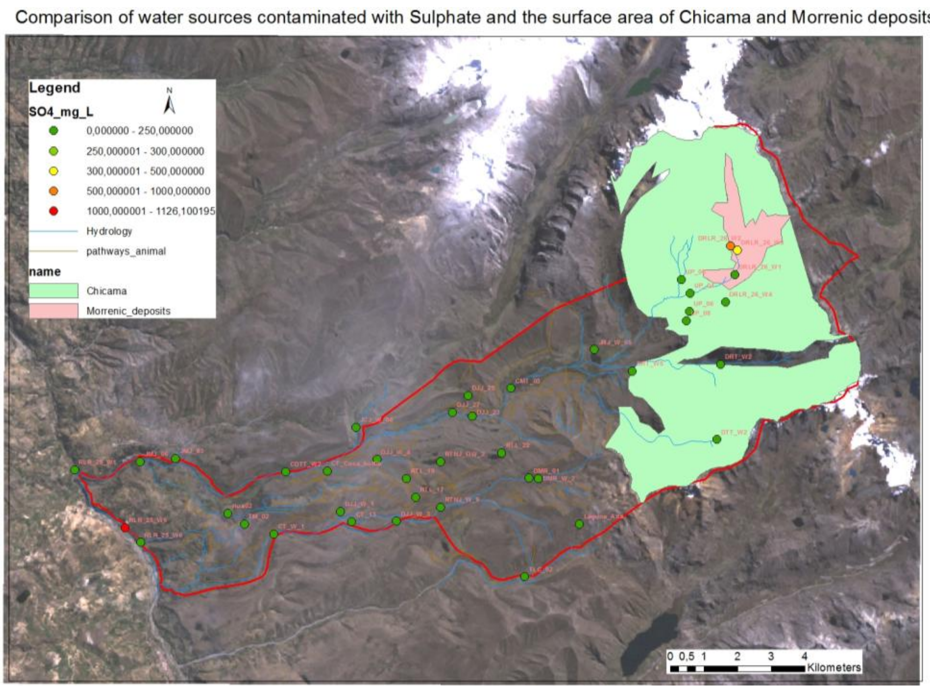

Figure 17: Sulphate content of water sources projected onto the study area with the surface area of possible pyrite concentrations. Areas containing pyrite are divided in two, the Chicama formation (green) and the glacial till (Morrenic deposits, pink)

8. Discussion

8.1.Paleoglaciers

Although the results shown here depict a clear overall trend of glacial front retreat during the eighteen thousand year period, there is much evidence to suggest there have also been stages of advance within this time *(Rodbell, 1993; Klein et al. 1999).* The discussion here focuses on the retreat of the glacial front as the prevailing trend but it is important to bear in mind that glaciers have only been reconstructed for certain points in time, what happens between each stage is not completely known.

The largest glacial extent as shown in figure 11 is from 18 000 years BP and the surface area of the glacier decreased with each time step shown in this study. If it is assumed that this decline has occurred in succession (which is more than likely not correct) then the glacial front has retreated at a rate slower than 0.01% per year. An ELA of around 4500m asl to 4550m asl has been estimated here for the glacier that existed during the Pleistocene, rising around 300m in 9 500 years. Ramage et al. (2005) also found glaciers from the same time period to have ELAs between 4250-4570m asl. The internal ELA variance can be caused by differences to topography and aspect of a glacier, because this could mean a different influence on precipitation and/or glacier form, with higher headwall elevations that correlate to smaller accumulation areas. An explanation for the overall trend of rising ELA and declining surface area could be due to increasing air surface temperature worldwide and in the Andes *(Bradley et al. 2000)*.

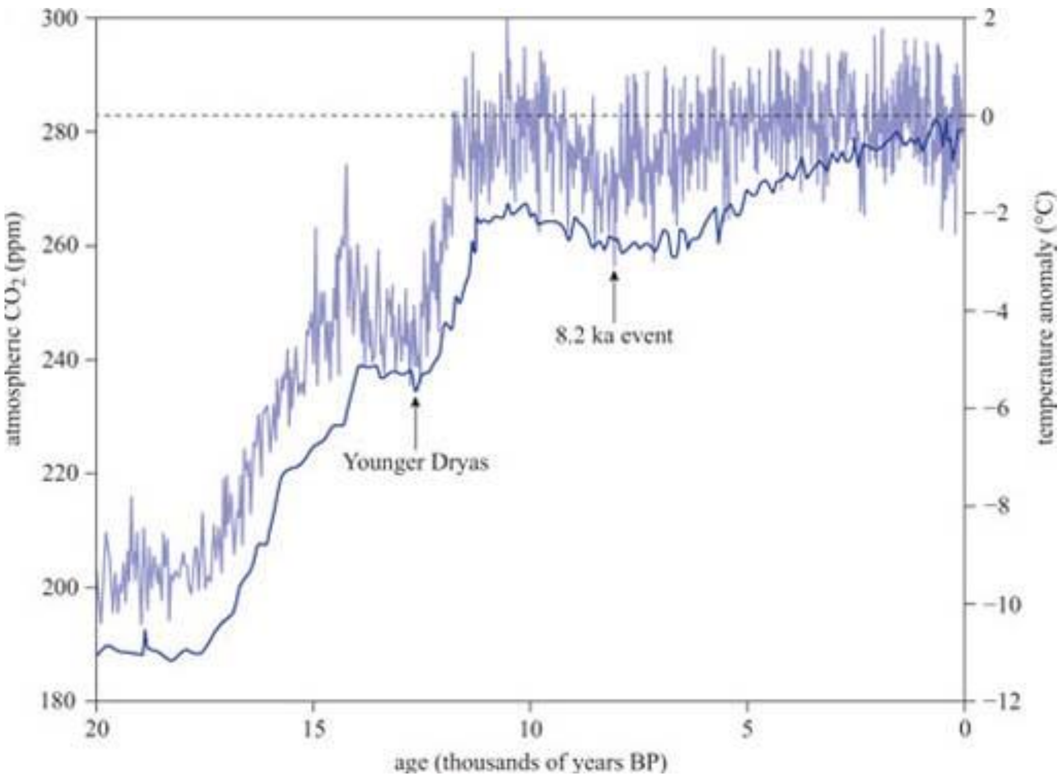

Figure 18: Reconstructed global air surface temperature anomaly (spikey line) from EPICA ice core carbon dioxide concentrations (smooth line) *(The Open University, 2012)*.

Reconstructed temperature records from the EPICA ice core in Antarctica (figure 18) show that global air surface temperatures have had an increasing trend since the Pleistocene (and further). This data can be used to explain some anomalies within our surface areal extent (figure 10) and ELA data (figure 14) of this glacier at certain time periods. Around 14 000 years ago there was a peak in global temperature that is likely to have caused the glacier to have lost mass, this coincides with the glacial stage here from 13 300 years BP having a higher ELA and lower surface area than would fit the trend. After this temperature peak in figure 18, it drops again probably leading to glacial front re-advance. The warming trend continues from around 11 000 years BP, so the glacial stage from this period, and from 10 000 years BP continue in the same manner as those before 14 000 years BP. Around 10 000 years BP temperatures are relatively stabilised at those similar to modern times, and this could explain why there is such a dramatic loss in surface area and increase in ELA after this time.

The significant ELA increase in Figure 14 at 10000 years BP also gives an indication that all the paleo-valley glaciers being assigned the same age of 8500 years BP may not be correct. A way to correct this could be to extrapolate the ELA calculations from the previous time periods, omitting the data from 8500 years BP. This would date the paleo-valley glaciers at around 5800 years BP. This ELA method could be used for an improvement of Remote-sensing-glacier dating.

8.2.Recent Glaciers 1989-2012

In recent times it can be said with confidence there has been no advance in the glacial front during the period 1989-2011 *(Kaser, 1999).* All six glaciers present a declining trend of the ablation zones in the hyposmetric curves (appendix 11.2) and an increase in ELA for the period 1989-2011 (figure 8). Therefore with the decline in glacial surface area of 1.5% per year on average within a 22-year period, it can be said in recent times this decline has increased dramatically when compared to the speed of the paleoglaciers.

This study found an average ELA of 5050 to 5100m asl from the period 1989 – 2011, this figure is slightly higher than a previous study by Wright (1983), where ELAs for the Cordillera Blanca were estimated to be 4800m asl. Another study by Kaser and Georges (1997) found ELAs to be 5056m asl in 1950, whereas if the data in this study is extrapolated to 1950 it would give an ELA of 4955m asl, a difference of 100m.

Decline in surface area [%]	From [yr]	To [yr]	Time period [yrs]	Average Decline [%/yr]	Source
18,8	1930	1970	40	**0,5**	Georges, 2004
7,5	1970	1990	20	**0,4**	Georges, 2004
14,5	1987	1996	9	**1,6**	Silverio and Jaquet 2005
26,4	1960	2003	43	**0,6**	Hindrandina, 1989; Zapata et al. 2008
22,4	1970	2008	38	**0,6**	Racoviteanu et al. 2008
15	1970	1997	27	**0,6**	Pouyard et al, 2005
33	**1989**	**2011**	**22**	**1,5**	This study

Table 1: Summary of literature comparing average loss of glacier surface area in the Cordillera Blanca.

Other studies have found different speeds of decline for different time periods, a summary of these are shown in table 1. Most of the literature has shown an average decline of around 0.5% per year where as this study finds an average of 1.5% per year. This is, however, in line with the study of Silverio and Jaquet (2005). All of the literature gives figures for the entire Cordillera Blanca, whereas this study is only for one glacier within this mountain range and there is one factor that may explain why this glacier is melting faster than others around it. This glacier is facing south-westerly, the prevailing wind in this area comes from the south-east so precipitation levels on this side of the mountain are lower than those facing east or north-east *(Kaser, 1990).* Reduced precipitation means there is less ablation, increasing the ELA and therefore the glacier front.

Studies have shown that precipitation in the whole Cordillera Blanca mountain range has declined in recent years *(Kaser and Georges, 1997)*. This decline in precipitation means there is less mass gaining on the glaciers and this combined with an increase in regional surface air temperatures has led to an increase in glacier melt in the last thirty years *(Chevallier et al., 2011)*.

8.3.Pyrite

Figures 9 and 15 show that as the surface area of the glacier declines there is an increase in the surface area of pyrite containing rock. In recent times this area per year is 74 000m^2 of Chicama and 4700m^2 of glacial till. The possibility of more pyrite being exposed each year is a concerning matter as the water sources from this area flow via the Río Negro into inhabited areas such as Ollieros. Figures 16 and 17 both show that the highest levels of iron and sulphate contamination in the Río Negro coincide with the location of high altitude glacial tills. This would suggest that the pyrite in glacial tills is more detrimental to the environment than the parent Chicama formation.

Pyrite in bedrock is concentrated in mineral veins within the Chicama formation so is not always at the surface, available for weathering. As a glacier erodes this rock and deposits it as glacial till, the deposited rock has a much larger surface area that can be readily weathered and therefore leached. The minerals that are thus leached from the glacial till will be removed faster than those leached from the bedrock, leading to higher levels of iron and sulphites in water sources close to the till. As the till ages it is likely that the contamination in water will decrease as there are fewer minerals left in the rock to leach from it. A study by Fairchild et al. (1999) compared leaching levels of various minerals from a glacial and a proglacial environment, similar to that of this study. They found that water which had percolated through the glacial environment (more recently deposited tills) had more solutes than water which had permeated the proglacial environment (older tills). This is in line with the results of figure 16, which shows iron concentration for water samples along the Río Negro. Those taken from older tills that were covered by the paleoglacier (centre of fieldwork area) show slightly higher values than those downstream, which were not covered by the glacier in 18 000 years BP but lower values than those upstream where the glacial till is younger *(Rodbell, 2000)*. Therefore it appears that water contamination of iron decreases with the amount of time the glacial till has been exposed. It should be noted, however, that this is not the case for sulphite contamination (figure 17) as all the samples show low values except for those taken in the high altitude glacial till area. This could imply that sulphite is leached quicker than iron.

The amount of contamination in each water sample also relies on various factors other than the surface area of the mineral, for example: how much contact time the water has with it, how fast the water is flowing and how far the water is percolating through it. These attributes are difficult to measure within the limits of this investigation so the previous path of the water collected from the springs in figures 16 and 17 has not been analysed in this study.

Another important point to note is that iron and sulphite contamination in the Río Negro is found in too higher concentrations to be classified as safe for human consumption therefore an alternative water source for use in agriculture or households should be found.

9. Conclusion

This paper has shown that it is possible to reconstruct paleoglaciers using ArcGIS and Google Earth. Equilibrium Line Altitudes were calculated using hypsometrical curves. Subsequently, surface areas were calculated and used to reconstruct the exposure of pyrite areas. The results show that the surface area of the glacier has had a general declining trend since 18000 years BP, although it is widely regarded within this time there had been some readvance. In recent times this decline is much more prominent, losing an average surface area of 85 100m^2 per year since 1989. If this rate continues then all the glacier mass will be gone by 2066. There is also a overlying trend of increasing ELAs since the Pleistocene, which is also much more marked in the last 22 years. Climate change is the main cause of these phenomena, specifically a decrease in precipitation and increase in air surface temperatures.

The surface area of pyrite containing rock has also increased from 18000 years BP. Iron and sulphate contamination of water has been used as signals of pyrite contamination and there is evidence to suggest the most contaminated water sources are found in more recently deposited glacial tills and not in the Chicama formation bedrock. Therefore it can be said that glacial melt is indeed affecting the water quality of springs, as the Chicama bedrock is eroded by glacial activity. The rock is deposited in tills due to a retreat of the glacial front, where the pyrites exposure to weathering is amplified by an increase in surface area. Therefore an increase in leaching occurs, thus contaminating the water sources with iron and sulphate. There is an indication that as the tills age, the contamination risk declines. Different thicknesses and ages of tills could be investigated to find out what effect this has on contamination risk.

The water from the Río Negro is not recommended for usage in agricultural or households. More research is required to relocate a cleaner water source for the Ollieros district.

10. References

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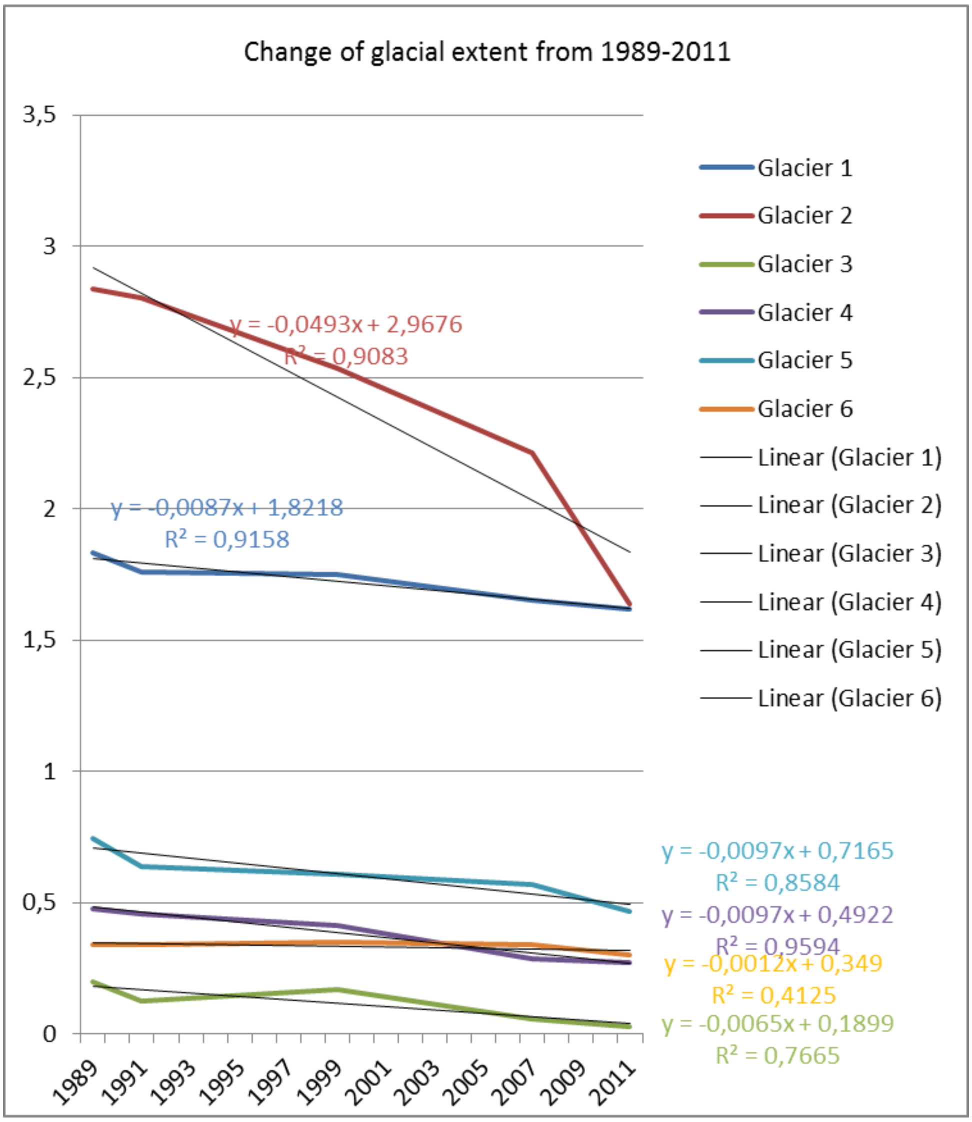
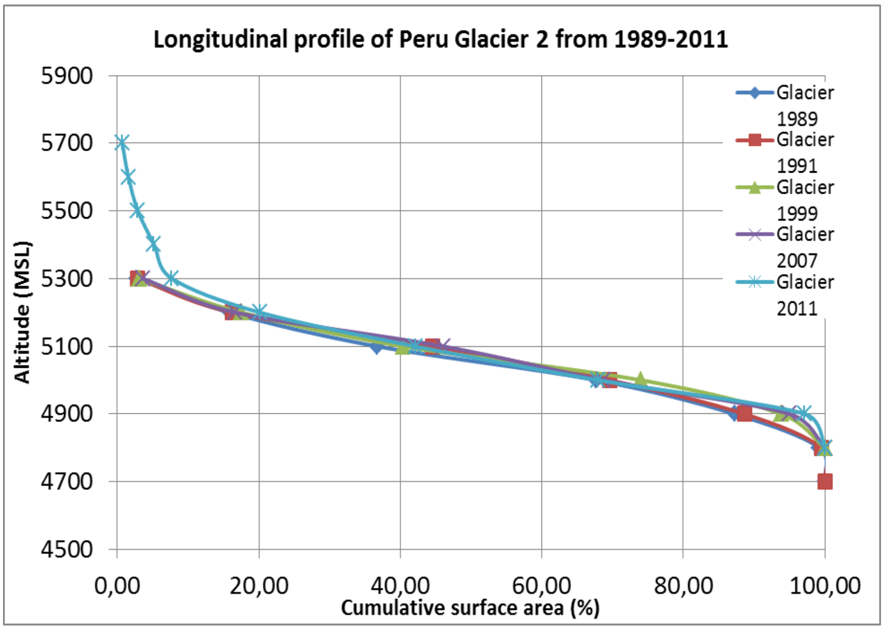
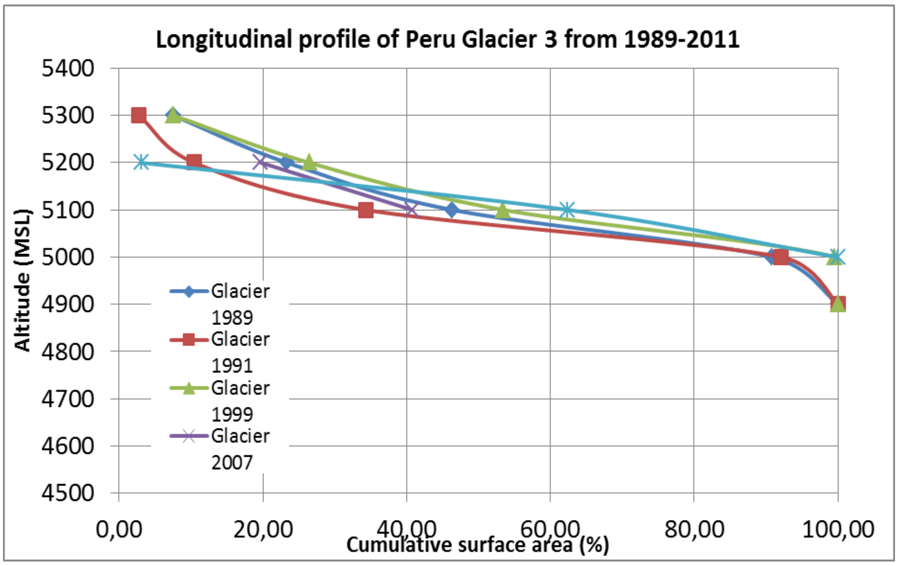
11. Appendix

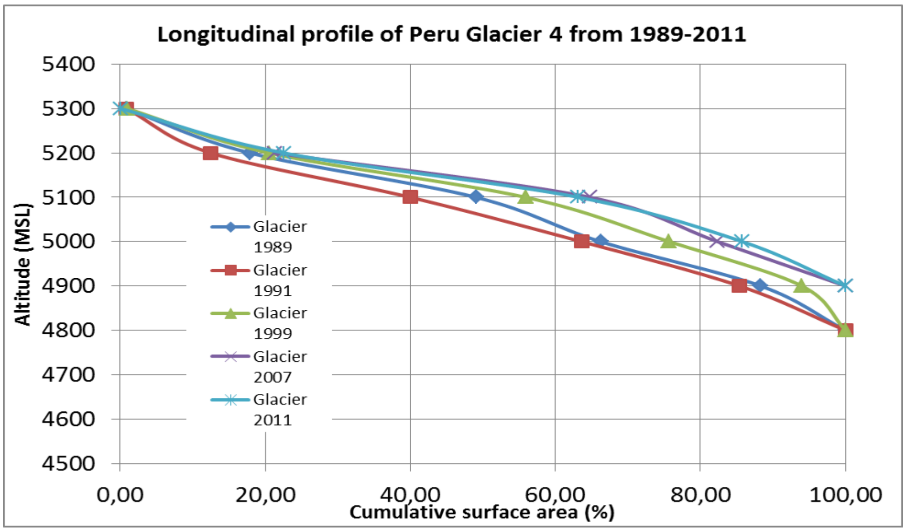
11.1. Glacial Extents



11.2. Hypsometric curves






Longitudinal profile of Peru Glacier 4 from 1989-2011
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5300
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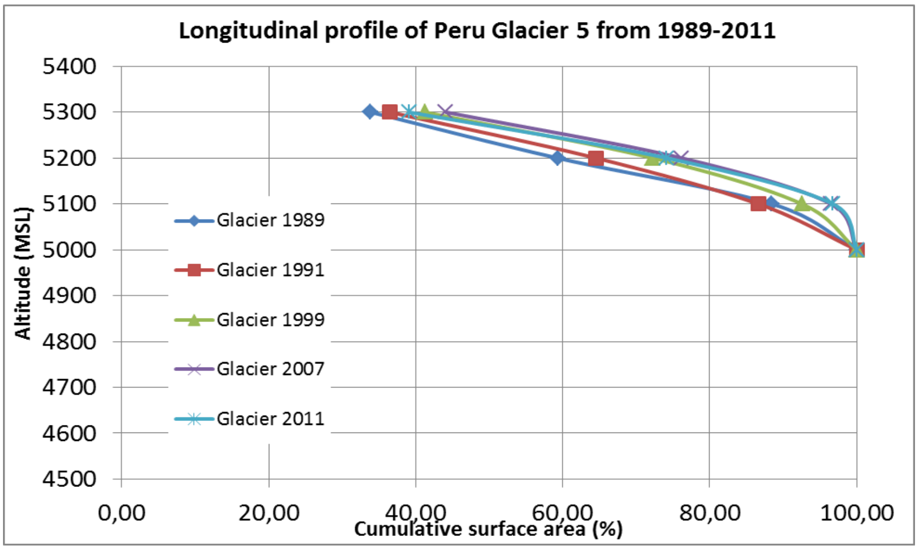
5100
5000
4900
4800
4700
4600
4500
Altitude (MSL)
Glacier 1989
Glacier 1991
Glacier 1999
Glacier 2007
Glacier 2011
0,00
20,00
40,00
60,00
80,00
100,00
Cumulative surface area (%)


Longitudinal profile of Peru Glacier 5 from 1989-2011
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Altitude (MSL)
Glacier 1989
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Glacier 1999
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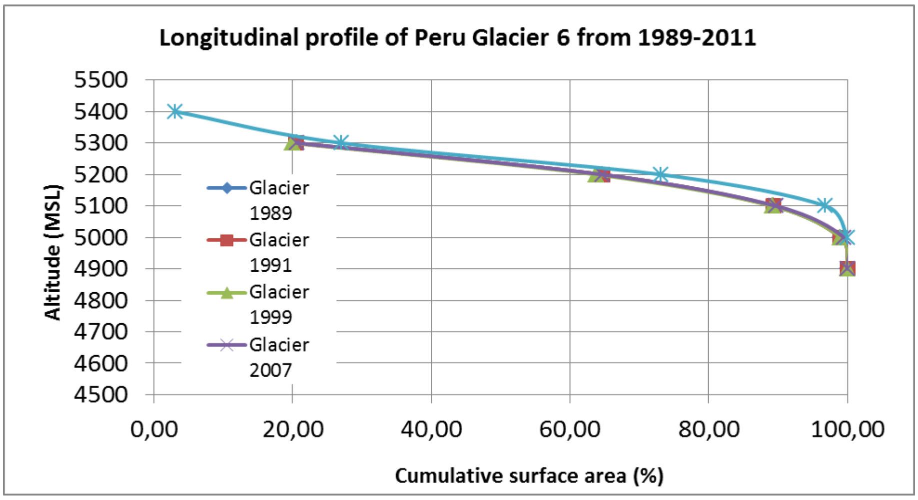
Cumulative surface area (%)


Longitudinal profile of Peru Glacier 6 from 1989-2011
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Altitude (MSL)
Glacier 1989
Glacier 1991
Glacier 1999
Glacier 2007
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80,00
100,00
Cumulative surface area (%)