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Glaciation in the Cordillera Chila, Peru

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Abstract

In this paper, glacial landforms and glaciation within the catchment area of the longest source segment of the Apurímac River in the Cordillera Chila are presented. Glacial landforms that were examined throughout the landscape enabled to sketch the glacier evolution in the study region. The modern glacial extent was mapped and compared with that mapped from 1955 aerial photographs. According to observations, the glaciation was much more extensive during the past. Three major extents of Quaternary glaciation were distinguished, with the oldest one extending far beyond the study area. Very rapid retreat of glacier termini in the second half of the 20th century was recognized. Interpretations suggest that glaciers in the catchment area experienced a 60% decrease in surface area since 1955.

Key words: Glaciers, Cordillera Chila, Peru

1. Introduction

The Cordillera Chila is a part of the source area of the world's largest river (is therefore a very interesting region from the geographical point of view), however it has not been extensively explored yet. First scientific evidences from the region were gained during 1980s when a geological mapping was carried out (Davila 1988; Palacios 1991). A few papers from this area emerged in the 1990s when source streams of the Amazon were studied (Goicochea 1997; Janský 2000). Up to the present, no observations focused on glaciers have been published. The only glaciological data, based on aerial photogrammetry, were obtained in 1955 (Ames 1989).

This paper presents observations of the glaciation in the eastern part of the Cordillera Chila Mts., extending between 15°19′ and 15°31′ of south latitude and 71°39′–72°13′ of west longitude, which is a part of the western mountain range (the Cordillera Occidental) of the southern Peruvian Andes (Figure 1). The study region (15°26′44″–15°31′38″ S and 71°40′35″–72°47′38″ W) has been delimited to include the catchment area of the Quebrada Carhuasanta and Quebrada Apacheta rivers, tributaries for the larger Rio Lloqueta, one of the main source rivers of the Apurímac river (Figure 2). Western and southern borders of the study area coincide with the main continental divide between the Pacific and Atlantic Oceans. In its southern part, the

Fig. 1. Location of the Cordillera Chila in the Andes of Peru

study region adjoins Nevado Mismi (5628 m), the highest peak of the Cordillera Chila Mts. The studied area extends over a surface of 57.15 km^2.

2. General setting

2.1. General morphology

The study area is categorized as high mountains assessed on the characteristic high amplitude relief. The vertical differences reach up to 500 m within 1 km distance and the biggest difference between the highest and the lowest point in the square area (4x4 km) exceeds 800 m. The highest values of the relief amplitude are found in the northwestern part of the mapped area where the ridge of Cerro Ccaccansa closes the glacial valley of the same name. The lowest relief amplitudes are linked with the summit plateaus of the Nevado Quehuisha and Cerro Calomoroco ridges. These plateaus are situated at about 5200 m a.s.l. The highest point of the study area – the peak of Nevado Mismi (5628 m) – is located in its southeastern part (Photo 1). The lowermost place (4712 m) lies at the confluence of the Carhuasanta and Apacheta rivers. The junction is situated in the centre of the study region on its northern boundary.

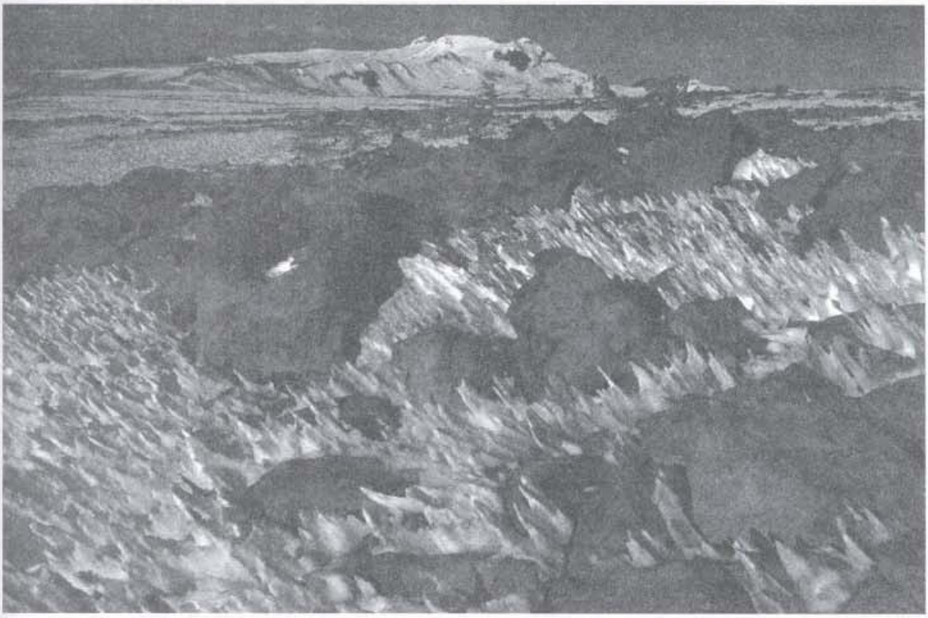

Photo 1. Glaciated dividing range in the Nevado Quehuisha area with characteristic nieve penitente. View towards Nevado Mismi (5628m)

Photo 2. Striations on the bedrock reveal the direction of Pleistocene glacier movement on the edge of the Nevado Mismi foothill plateau

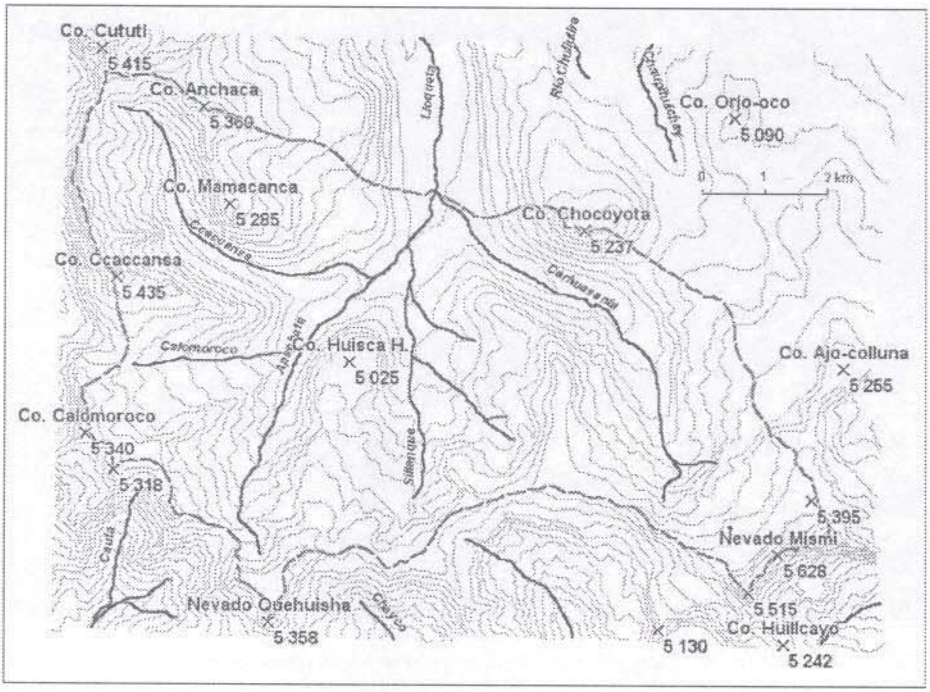

Fig. 2. Delimitation of the study area

2.2. Geology and geomorphology

The pattern of the study area, which has been organized as a part of the proto-Andean belt since the Grenvillian event (Hardolph et al. 1995), is particularly affected by the Upper Tertiary to Pleistocene Andean orogenic phase, which coincides with the culmination of the volcanic activity in this region. The study area consists of three different types of volcanic rock (Davila 1988): Miocene rhyolitic lavas (the Ichocollo Formation of the Tacaza Group) creating major part of the bedrock, Pliocene pyroclastics (the Sencca Formation) and andesitic lavas of the Plio-pleistocene Barroso Group that are exposed in higher elevations of the region. In the form of more or less thick accumulations, sediments of a different genesis represent the Quaternary.

The mountain relief displays a set of features that are characteristic for young orogenic units. Steep rock slopes, glacial landforms and structurally controlled high plateaus are spread over this region (Engel 2002). Dynamic Cenozoic orogenic processes and a climate have determined the relief development of the area. Pleistocene climatic variations have a crucial influence on the current morphology of the landscape.

2.3. Climatic setting

In consequence of the Cordillera Chila location in the western mountain range of the Andes (the Cordillera Occidental), the climate of the study area is relatively dry.

Mean annual precipitation reaches 500–800 mm, which is comparable with the nearby Cailloma (30 km to the north, 4320 m a.s.l., 663 mm/yr) and Imata (80 km to the southeast, 4405 m a.s.l., 518 mm/yr) climatic stations (Kastner 2004). The aridity is due to the constant SE-Pacific anticyclone that inhibits moisture transport from the Pacific Ocean and due to the barrier effect of the Central and Eastern Andes against the humid influx from Amazonia (Lettau 1976). The major part of the precipitation falls from November to March when closer position of the Intertropical Convergence Zone enables an increased transport of humid air from the east (Johnson 1976). The austral summer is therefore the most important period of mass accumulation on glaciers throughout the year.

Apart from small seasonal variation, the annual range of temperature is considerably low. This is due to the high altitude of the study area that varies from 4710 m to 5628 m. Diurnal temperature variations display much greater range of variability, which is the result of the dry alpine environment sensitivity to radiative heating. During the austral summer (October–March), diurnal temperature variations reach 25–30 °C (Kastner 2004) and amplitudes are even greater during the winter season (April–September).

3. Methods

3.1. Geomorphological mapping

To outline glacier evolution in the study area, glacial landforms were mapped. Global Positioning Satellite (GPS) technology allowed for collection of surface elevation data that were digitised into an integrated Geographic Information System (GIS). An existing 1:25 000 scale topographic map of the area, compiled by the National Geographical Institution of Peru (Instituto Geografico Nacional), served as the base map. The topographic map was digitised as contour lines with associated elevation attributes. The geomorphological map was then constructed with these line features and other relevant point elevations using MapInfo Professional™, ver. 6.0 for Windows.

The content of the 1:25 000 geomorphological map was created to emphasize the polygenetic character of the relief in the study area. During the processing of the geomorphological map, a genetic attitude was respected to enable recognition of the quality and succession of the landforms. The map was based upon a field mapping and other groundwork analysis. Together with 1:100 000 scale topographic maps (sheets Cailloma 31-s and Chivay 32-s) and 1:100 000 scale geological maps (INGEMMET 1988, 1993) aerial photographs were used.

3.2. 20th Century Data analyses

Characteristics of glaciers were elicited from the fieldwork and from an analysis of topographic maps, aerial photographs and satellite images. An extraction and processing of characteristics were achieved according to the methodology of Müller, Caflish and Müller (1977) that was elaborated as instructions for compilation and assemblage of data for the World Glacier Inventory. Glacier nomenclature and coordinates were taken from the Glacier Inventory of Peru (Ames 1989). Glaciers lacking official designation have been named after the summit covered by the glacier. The coordinates of the Cututi Glacier were taken from topographic maps and they are related to the highest point of the accumulation area of a glacier. A glacier typology was accomplished according to an international classification (UNESCO 1970). The other characteristics were obtained as the result of the geomorphological mapping.

Extent of glaciers was reconstructed for three different periods. The oldest was created using aerial photographs acquired in 1955 by the National Aerographical Institution, Peru (Instituto Aerofotográfico Nacional). Glacier positions from 1986 and 1999 were constructed from satellite images taken by the LANDSAT. An extent of glaciers from three different periods was digitised into the GIS. The comparison of the current glacier limit with the extent of the glaciation mapped from aerial photographs and satellite images enabled an evaluation of the development of present glaciation. For the evaluation, there was an important fact that all sources of information, used for previous glacier positions reconstruction, refer to the same part of the year. An overall decrease of glaciation was estimated from surface area of glaciers in 1955 that is mentioned in the Glacier Inventory of Peru (Ames 1989) and from digitised area of current glaciers.

4. Observations

4.1. Glacier landforms

In the centre of the mapped area, Cerro Huisca Huisca forms an elongated ridge that projects from the main continental divide to the north beneath the summit of Nevado Quehuisha. This ridge divides the source area into two almost symmetrical parts.

The western part consists of three glacially transformed valleys separated by a high mountain ridge. The Apacheta river deepens its valley along the western slope of Cerro Huisca Huisca and forms the mainstream valley of the western part of the source area. Valley floors of the Apacheta main tributaries (the Calomoroco and Ccaccansa rivers) hang above it and have positions of tributary valleys. The hanging valley of Calomoroco mouths to the western slope in the middle course of the Apacheta valley 130–150 m above the mainstream valley floor. The trough of the Ccaccansa river joins the Apacheta valley in its lower course. Both valleys are glacially widened and deepened near the confluence and have typical U-shaped profiles. Because of its larger accumulation area, the Apacheta valley is more deepened; valley floors are discordant by 30–40 m.

In the eastern part of the study area, the Sillanque valley represents an analogy to the upper course of the Apacheta and Calomoroco valleys. The valley consists of three individualized valleys: two of them have their head cut into the main divide and the third adjoins the dividing ridge (Cerro Inchopalla) between the Sillanque and Carhuasanta valleys. The glacially sculpted valley of the Sillanque river joins the lower course of the Apacheta river beneath the northern foot of Cerro Huisca Huisca and its floor is at 40–50 m higher then the mainstream valley floor. The Apacheta and Carhuasanta valleys have also a discordant junction. The Carhuasanta valley occupies the easternmost part of the mapped area and its bedrock floor is 20–25 m higher than the Apacheta valley.

The described valleys can be classified into two groups based on orientation. Most of the rivers (the Apacheta, the Carhuasanta and three tributaries of the Sillanque) flow in northern quadrant between NW and NE. Only the valleys of the Ccaccansa and the Calomoroco rivers flow toward the eastern quadrant between NE and SE.

One of the most characteristic glacial landforms – hanging valleys – occurs almost exclusively in the Ccaccansa valley. Due to its favourable orientation and geological structure, the valley is characterized by the most distinctive glacial morphology among the studied valleys. The whole course of the Ccaccansa is cut into the massive and resistant bedrock that is an important factor for typical glacier topography development and its preservation. Three hanging valleys join the Ccaccansa valley from the west (Cerro Ccaccansa) and one from the opposite direction (Cerro Mamacanca). There are pronounced rock steps where the hanging valleys join with the main trough. The steps appear in the altitude range of 4970–5120 m, 150–190 m above the current trough floor. In the rest of the study region, only one characteristic hanging valley was distinguished along the eastern slope of the Cerro Huisca Huisca ridge. A rock step in its lower edge occurs at 4900 m, 100 m above the main valley floor.

Cirques are delimited by upper edges and in some cases also by the cirque steps in the geomorphological map. In the study area, 12 cirques were identified (Table 1). Most of them bear the typical properties of well-developed cirques, including steep rock head-walls, flat floors and pronounced rock steps. These morphological aspects differentiate cirques from relatively shallow nivation hollows that are delimited from the surrounding relief only by the more or less distinct terrain edges. At present, the only glaciated cirques can be found in the Carhuasanta valley. This results from the high location of the cirques that belong to the highest in the Cordillera Chila Mountains.

Characteristic cirques are cut into the eastern ridge of Cerro Ccaccansa. In connection with high resistance of the bedrock, some of the cirque walls exceed 100 m in height and 70° in inclination. Cirque floors are relatively narrow, and despite the strong downward erosion of early glaciers, they have inclined floors. Cirque steps at 150–170 m above the Ccaccansa trough floor have the form of readily apparent terrain edges. Cirques of the Apacheta valley have the best-developed upper edges in the mapped area. The characteristic sharp shape is preconditioned by the location of the Apacheta next to the lava plateaus. These were undercut by headward erosion of early glaciers that approached the dividing range. At present time, cirque walls are cut directly into the flat relief of the summit plateau of Cerro Quehuisha. Thick debris accumulations cover the base of the cirque walls as the result of an intensive

Table 1 Characteristics of glacially transformed valley heads

River valley	*Number of cirques*	*Orientation*	*Altitude [m]*	
			Cirque floors	*Upper edge*
Ccaccansa	4	E	5150–5300	5350–5400
Apacheta	2	NW	5100–5150	5200–5300
Sillanque	4	NW, WNW (1)	4950–5100	5080–5170
Carhuasanta	2	N, NW	5400	5500–5580

paraglacial transformation. The bowl-shaped closures of the Sillanque valley are also sharp-edged. Here the upper edges are associated with the subhorizontally bedded hard rock intercalation that causes a two-step profile in the cirque walls.

Large-scale glacial polishing have been found only in the Carhuasanta valley (Photo 2). It occurs on a structural step that intersects the upper part of the valley. The step consists of andesitic lavas, with adequate hardness to resist erosion and preserve the polished surface. Glacial polishing is frequent over the whole step but most extensive along the western edge. The continuous polishing extends from the left tributary of the Carhuasanta waterfall in the form of a 250 m long belt that is up to 25 m wide. With a characteristic asymmetrical mound-like profile, intensive abrasion along stoss side and plucking on the lee side, this part of the rock step has a character of a roche moutonnée. The intensity of glacial abrasion in this area is evidenced by striations scratched into the planed surface. These scratches are meters long, 2-3 cm deep and oriented mostly to the NW. The direction of the striations on the roche moutonnée surface varies between 326 and 332°.

The only rock glacier discovered in the study area is located on the floor of the bowl-shaped depression in the western slope of Cerro Chocoyota. An accumulation of rock debris begins below the foot of walls at the altitude of 5090–5110 m. The surface of the accumulation is relatively articulated: 2 to 2.5 m high-articulated arches stretch across the accumulation and are of transversal orientation. The lower part of the rock glacier descends in the form of two individual lobes to the altitude of 5025–5035 m.

Moraines are relatively frequent throughout the area. They can be found in all mapped valleys with more or less preserved morphology. If moraines are intact and morphologically distinct, their ridges have been marked in the geomorphological map. In the mapped area, lateral and medial moraines are the best preserved; terminal moraines were, with a few exceptions, almost completely removed. Moraines cover lower parts of the particular valleys, while in the middle courses they give place to slope deposits. The largest preserved moraine forms the divide between the lower parts of the Ccaccansa and Apacheta valleys (Photo 3). It was deposited as a medial moraine between glaciers moving down the valleys. The moraine is almost 1400 m long and about 50 m high. Glacial accumulations of comparable size also appear on eastern slopes of Cerro Mamacanca and Cerro Ccalomoroco and at the confluence of Sillanque and Carhuasanta with Apacheta.

In addition to these large glacial accumulations, considerably smaller moraines were mapped in few parts of the study region. These moraines are meters high and tens of meters long. They can be found in the foreground of firn glaciers on the northern foot of the Nevado Mismi ridge and they are probably of Holocene age.

4.2. Development of the Quaternary glaciation

The geomorphological analysis of preserved glacial landforms allows the tentative suggestion of a series of proposed glacial episodes during the Quaternary within the study region. To outline the overall character and succession of early glaciers, it is necessary to deduct from the location, extent and volume of glacial accumulations and

Photo 3. Medial moraine at the mouth of the Ccaccansa valley to the Apacheta valley

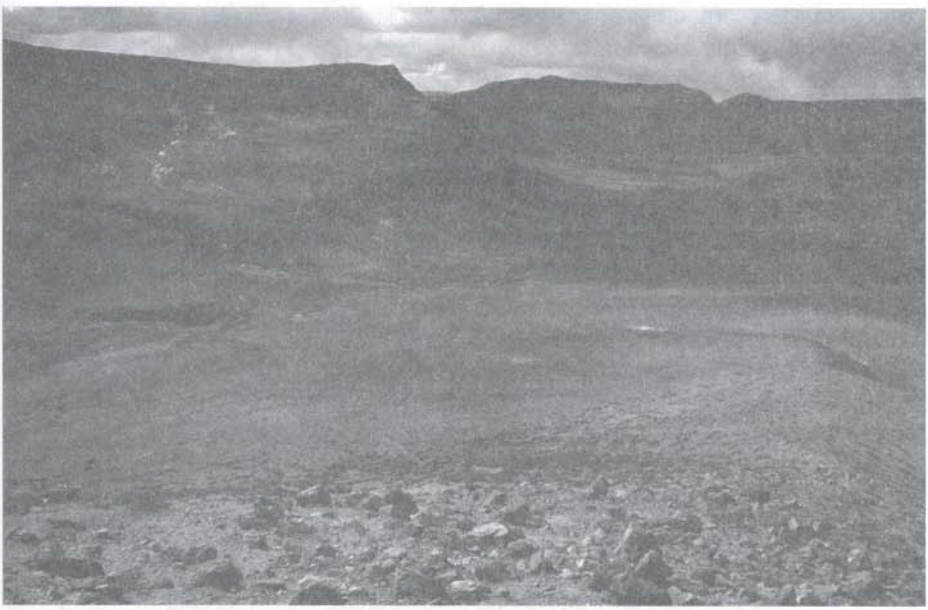

Photo 4. View from the Cerro Huisca Huisca northward into the upper part of the glacially transformed Río Lloqueta valley

from an analysis of erosional landforms of glaciers. An evaluation of the glacial sequence requires analyses of landforms that where created by glaciers outside the delimited area in the Río Lloqueta valley (Photo 4). Since moraines are incomplete recorders of glaciation, the interpretations are of very tentative nature. The most recent period of deglaciation since 1955 is observable from aerial photographs and satellite images.

The lowest relics of moraines were registered in the lower part of the Río Lloqueta valley close to Carhuacocha lake. The glacier that formed these moraines converged and extended beyond the study region boundary. The glacier was more than 15 km long and had a thickness of about 250 m at the junction of Apacheta and Carhuasanta considering the steps at the cross-section profile. Higher up in the valley, the glacier left unveiled relics of two right lateral moraines. The glacier termini of the lower one were 3.5 km below the confluence of the Apacheta and Carhuasanta valleys. By the confluence an almost 12 km long glacier reached the thickness of about 200 m. Later on, the glacier tongue was 100 m thick at the junction of Apacheta and Carhuasanta and did not flow farther then 1 km down the Río Lloqueta valley.

Considering the distribution and character of lateral moraines, it seems that the oldest evidenced phase of glaciation was characterized by massive development of glaciers in the study area. Valley glaciers moved down the four main valleys, converged in the lower part of the Apacheta and flowed further down the Río Lloqueta valley as a single unit that was about 1 km wide. At that time, the eastern slopes of Co. Anchaca and Co. Calomoroco could also be glaciated and smaller glaciers probably flowed down the Co. Mamacanca cirque and the bowl-shaped depression in the SE slope of Co. Chocoyota. Geomorphological analysis of glacial landforms suggests extensive glacial transformation of the study region within the oldest evidenced period of the glaciation. Glaciers in the Río Lloqueta valley have accumulated large amount of material that is evidenced by an extent and a height of moraines (in order of tens meters).

In the second distinguished phase, glaciers did not exceed the boundary of the studied area. Only shorter valley glaciers or cirque glaciers evolved and they did not converged at the confluence of Apacheta and Carhuasanta. The longest glacier (almost 5 km long) flowed down the Ccaccansa valley that is characterized by appropriate orientation. In addition to supplying valley glaciers from hanging valleys with snow and ice the most important precondition was the "shady" southern orientation of most of the valley. In the Apacheta and Carhuasanta valleys, evolved glaciers were much shorter, due to the unfavourable orientation. In the Sillanque valley, only particular cirques remained glaciated; the valley glacier did not arise probably. Moraines that delimit the extent of this phase of the glaciation are characterized by less extent and height than older glacial accumulations. None of the moraine relics of this period is higher than 15 m.

A limited extent of glaciers is typical for the last phase of the glaciation. In the Ccaccansa and the Carhuasanta valleys, glaciers remained restricted on cirques. The rest valleys were glaciated only on summit plateau areas. Glacial accumulations of this period are located close to current glaciers and they consist of almost unweathered material.

4.3. Recent glaciers

There are four glaciers in the study region, which cover 1.54 km^2 (Table 2). These are small glaciers of irregular shape without typically developed cirques. Current glaciation is restricted to the highest parts of mountain ranges and can be classified as mountain glaciation of UNESCO classification (UNESCO 1970). With an exception of the Ccaccansa and Cututi glaciers on mountain slopes, the glaciers cover high plateaus (an almost horizontal inclination, low activity of glacier tongues, snow supply). The Mismi Glacier (Photo 5) covers a large structural plateau below the northern foot of Nevado Mismi, and the Quehuisha Glacier occurs on a flat plateau on the dividing range. The Ccaccansa Glacier flows down the southern shoulder of Cerro Ccaccansa and its longitudinal profile resembles slope glaciers. In comparison with a typical slope glacier, the Ccaccansa Glacier features a very slow movement (according to its stable position since 1955), so it has been described as the mountain glacier. Similar features characterize a glacier on the southern slope of Cerro Cututi.

Table 2 Characteristics of glaciers

Glacier	*Latitude S*	*Longitude W*	*Type of glacier*	*Area [km²]*	*Max. width [km]*	*Max. length [km]*	*Min. alt. [m]*	*Max. alt. [m]*	*Orientation*
Mismi	15°31.01′	71°41.33′	Mountain	0.45	1.0	0.6	5628	5250	NW
Quehuisha	15°30.73′	71°45.31′	Mountain	0.20	0.5	0.7	5358	5250	N
Ccaccansa	15°28.91′	71°46.59′	Mountain	0.51	1.2	0.6	5435	5250	S
Cututi	15°27′	71°46′	Mountain	0.38	1.1	0.4	5360	5200	S

All characteristics are related to those parts of glaciers that come under the studied area.

Glaciers of the study region are oriented to N and S quadrant (Table 2). Generally, the most favourable orientation for glacier development in the Cordillera Chila is to the SW because of shading from sunshine; 30 out of the overall 87 glaciers of the mountains are oriented to the SW (Ames 1989). A discrepancy comes from the location of the study region on the eastern slope of the Cordillera Chila.

In the study area, the surface of the glaciers ranges from 0.2 to 0.51 km^2. The largest continuous firn and ice surface (0.51 km^2) appears around Cerro Ccaccansa. On the top of Nevado Mismi (5628 m), the highest occurrence of perennial snow was observed. To the lowest altitude (5200 m) descends the Cututi Glacier. It seems that while the altitudinal maximum of the glaciated area is associated entirely with it's topography, the lowest extent of the glaciation is affected by climatic conditions.

The total amount of the water content in glaciers was estimated at 0.023 km^3 (Table 3). The estimation was carried out by means of a formula that describe a thickness of a glacier:

$$h = a + b \cdot \sqrt{A},$$

where a and b represent parameters established on the basis of an experience, A marks a glaciated area. Parameters a and b have been related to values 5.4 and 15.4 that were used by Ames (1989).

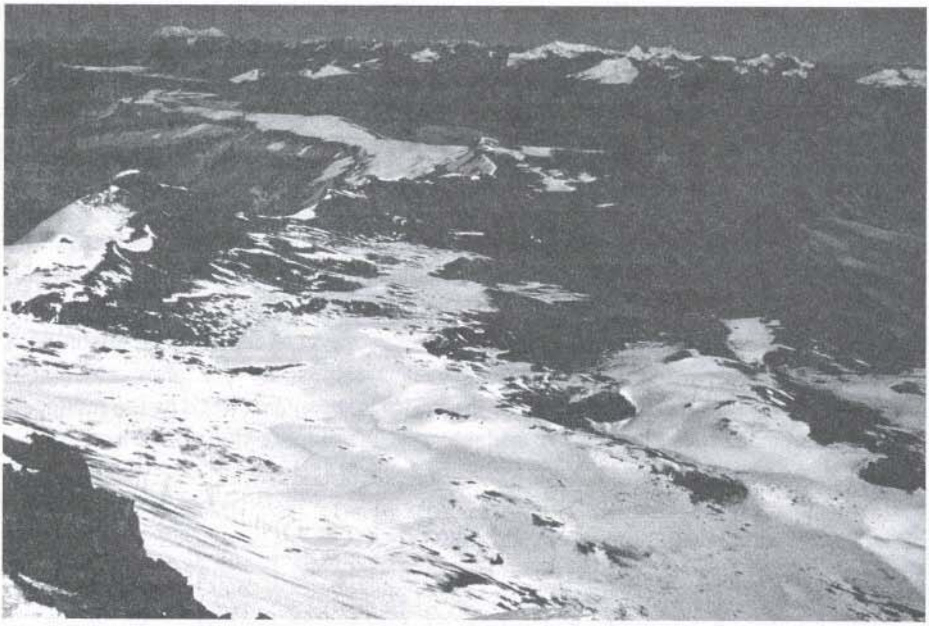

Photo 5. Western part of the glaciated area below the Nevado Mismi. Behind it, glaciers cover southern slopes of a range that form the main continental divide between the Pacific and Atlantic oceans

Table 3 Extent and volume of glaciers

Glacier	*Area [km²]*	*Thickness [m]*	*Volume [10^6 m³]*
Mismi	0.45	15.60	7.02
Quehuisha	0.20	12.20	2.44
Ccaccansa	0.51	16.25	8.288
Cututi	0.38	14.77	5.613
Total	1.54		23.361

The snowline in the mapped area was determined to 5300 m using the glaciation-threshold method (Porter 2001). Based on current firn and glaciers mapping, it was also possible to estimate snowline altitude (thus approximate boundary between accumulation and ablation areas of glaciers) for particular glaciers. The snowline altitude was derived from the level above that the snow from the previous year has not melted. Out of obtained values, an approximate snowline altitude was calculated (Table 4).

Table 4 Current snowline altitude

Glacier	*Snowline [m]*
Mismi	5300
Quehuisha	5270
Ccaccansa	5260
Cututi	5250

4.4. Modern deglaciation

Aerial photographs from 1955 show relatively extensive glaciation of the study region (Figure 3). A surface covered by firn and glaciers was almost continuous along the continental dividing range (W, S and E boundary of the study region). In addition, a limited glaciation was distinguished on Cerro Mamacanca and Cerro Chocoyota peaks. In 1955, a firn and glaciers covered almost entire area above 5200 m.

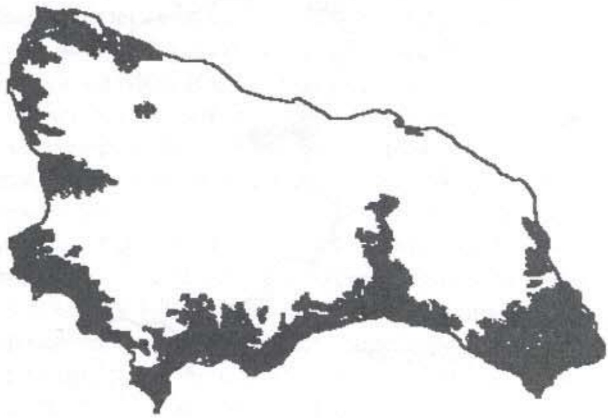

Fig. 3. Glaciated area in 1955

Over the following 30 years (1955–1986), the glaciated area rapidly decreased (Figure 4). Initially nearly continuous firn and ice cover of the divide fell into small centres of glaciation, from Cerro Mamacanca and Cerro Chocoyota vanished completely. The Calomoroco glacier and the Chayco glacier diminished essentially but the rest of them still supplied the water to the tributaries of the Apacheta and Sillanque rivers. On a major part of Nevado Quehuisha summit plateau a glacier still occurred. Relatively extensive fields of firn appeared also on the dividing range between Nevado Quehuisha and Nevado Mismi summits. The Mismi Glacier with adjacent snowfields covered an area between Nevado Mismi and Cerro Ajo-colluna.

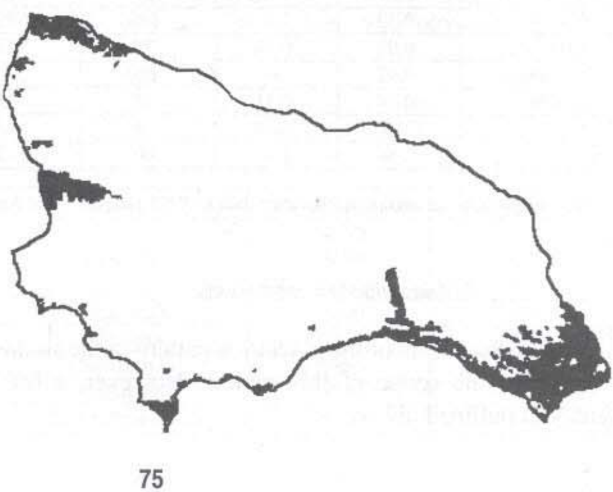

Fig. 4. Glaciated area in 1986

Over the 1986–1999 period, the glaciated area has proceeded to decay (Figure 5). The largest decrease affected the Calomoroco glacier and the Chayco glacier. These have persisted only on favourably oriented southern slopes that are located beyond the study region boundary. The Quehuisha glacier has decreased essentially, the glaciation in the Mismi area has disintegrated into two parts.

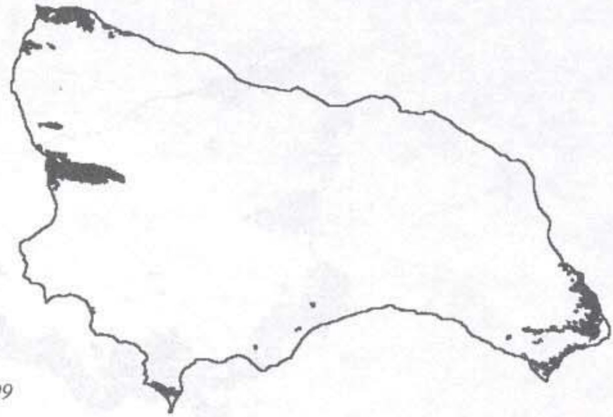

Fig. 5. Glaciated area in 1999

The development of the glaciation in the study region in the second half of the 20th century confirms the trend of global deglaciation. An extent covered by firn and ice has decreased by nearly 60% within 45 years (Table 5). Deglaciation is obvious mostly among glaciers that are lower situated and unfavourably oriented against the solar rays. Decreased ablation of southward oriented glaciers is associated with overall solar radiation that hits the southern surfaces under lower angle.

Table 5. Development of the glaciation between 1955 and 2000

Glacier	*Area [km²]*		*Difference %*	*Max. alt. [m]*	*Min. alt. [m]*	*Orientation*
	1955	*2000*				
Mismi	0.57	0.45	21	5628	5250	NW
Chayco	0.72	–	100	5200	5150	NW
Quehuisha	0.97	0.20	79	5358	5250	N
Calomoroco	0.42	–	100	5340	5200	NE
Ccaccansa	0.66	0.51	23	5435	5250	S
Cututi	0.50*	0.38	24	5360	5200	S
Total	3.84	1.54	60	5628	5150	

* Estimation from an aerial photo; other data to 1955 adapted from Ames (1989).

5. Discussion and conclusions

A full discussion of the glaciation pattern in the studied area in the Cordillera Chila is beyond the scope of this review. However, a few suggestions arise from the analysis outlined above.

1. An overall pattern of the mapped area is determined mainly by the glacial erosional morphology, but endogenous landforms are also significant. Deep, glacially transformed valleys and morphologically pronounced peaks and ridges interchange either with elongated flat elevations linked to volcanic plateaus or with dissected rock steps on subhorizontally bedded layers of tuffs. Almost all studied valleys, with exception of Ccaccansa, are characterized by similar conditions as the valley orientation to exogenous geomorphological factors is concerned. These features are determined mainly by the climatic factors, e.g. solar radiation, air temperature, precipitation, and wind action.

2. Considering an analysis of preserved glacial landforms, three major phases of Quaternary glaciation have been distinguished. Because there is no "absolute" dating for moraines of the study region, the age of proposed glacial episodes is unclear. However, the position and some qualitative features of the moraines provide some indication of the preliminary timing of these events (Table 6). With respect to location approximately current glaciers and the fresh character of accumulated material, the glacial accumulations of the youngest phase of glaciation can be considered to be of Holocene age. An approximate age of the second phase of the glaciation can be assumed from the location of moraines up to 30 m above the valley floors and from fresh morphology and relatively small height of accumulations. Comparing the above-mentioned characteristics with dated moraines from other mountainous regions in Peru (Mercer 1984; Birkeland et al. 1989; Clapperton 1991; Rodbell 1993), man can assume that the accu-mulations of the second phase of the glaciation could not develop before the Pleistocene/Holocene transition. The oldest phase of the glaciation falls probably into the period of the Last glaciation. It's witnessed by very high and voluminous glacial accumulations, their location above a valley floor (50–200 m) and relatively distinct morphology. Whether three distinguished stages of this phase fall into the LGM or whether moraines were accumulated within older periods of the Last glaciation was not find out.

Although geomorphological investigation of preserved glacial landforms provides some indication of the Quaternary glaciation within the study region, a precise geochronology of the glacial sequence remains unclear. Based on limited investigation of studied area, proposed chronology is very tentative. To test and develop these suggestions, and examine the extent and timing of glaciation phases proposed in the paper, further sedimentological research and associated lithostratigraphy analyses have to be done.

Table 6. Phases of glaciations

Phase	*Snowline [m]*	*Glacier*	*Lower limit [m]*	*Length [km]*
I.	4800	Lloqueta	4650	15.3
			4680	11.8
			4690	9.3
II.	5050–5100	Ccaccansa	4820	4.9
		Apacheta	4850	2.6
		Carhuasanta	4880	3.5
		Sillanque	4910	1.4
III.	5200–5300	Chayco/Quehuisha	5100	2.0

3. Considering their small thickness and a slight movement, present glaciers are characterized by relatively low capacity to erode and accumulate. Morphologically pronounced recent moraines are rare and were distinguished only at the foreground of the Mismi Glacier. The morphology of glacial landforms in vicinity of the other glaciers is indistinct and the material tends to be mixed with accumulations of non-glacial origin.

4. Omitting the effect of orientation, the snowline in the mapped area lies at about 5300 m. This value is consistent with the snowline in the adjacent part of the Altiplano (Table 7), where it appears at the same altitude according to Graf (1991). A comparison of the snowline altitude in the mapped area, with the one of the nearby Cordillera Volcanico (5800 m) that is situated on the edge of the western Andean mountain range, confirms generally valid dependence of snowline altitude on precipitation. A more humid eastern slope of the western Andean mountain range is characterized by lower glacier limit than on the western slope.

Table 7 Snowline altitude in the adjoining mountain groups

Mountain region	*Latitude*	*Andean Range*	*Snowline [m]*
Cord. Vilcanota	13°45′–14°05′	Eastern	5100*
Cord. Apolobamba	14°25′–14°44′	Eastern	5300*
Cord. Chila**	15°27′–15°31′	Western	5300
Cord. Real	15°40′–16°40′	Eastern	5300*
Cord. Volcanica	16°07′–16°33′	Western	5800*

* Graf 1991, ** study area

5. Over the 20th century, the glaciers of an observed area have undergone rapid retreats: glaciers experienced a 60% decrease in surface area since 1955. Current glaciation is restricted to the highest parts of mountain ranges in the eastern part of the Cordillera Chila Mts. There are four glaciers in the catchment area of the Carhuasanta and Apacheta rivers that extend over a surface of 1.54 km^2 out of total 57.15 km^2. The snowline altitude varies from 5250 to 5300 m.

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ZALEDNĚNÍ V POHOŘÍ CORDILLERA CHILA

Résumé

V rámci mezinárodní vědecké expedice „Hatun Mayu 2000", která provedla komplexní výzkum pramenné oblasti toku Apurímac v jižním Peru, byl ve východní části pohoří Cordillera Chila uskutečněn výzkum zalednění. Jeho současný stav a geneze byly zjišťovány na základě podrobného geomorfologického mapování a analýzy kartografických a fotografických podkladů. Rozsah stávajících ledovců byl vyhodnocen na základě polohových dat pořízených v terénu, která byla implementována do GIS (jako podklad posloužily digitalizované vrstevnice topografické mapy 1:25 000 s příslušnými výškovými atributy). Z leteckých a družicových snímků byl v prostředí GIS rekonstruován stav zalednění v letech 1955, 1986 a 1999. Porovnání rozsahu ledovců z různých časových období umožnilo determinovat vývoj zalednění ve studované oblasti od poloviny 20. století. Vývoj kvartérního zalednění byl posuzován na základě dochovaných ledovcových tvarů reliéfu.

Ve studovaném území byly zjištěny 4 ledovce, o celkové rozloze 1,54 km^2. Jedná se vesměs o malé ledovce nepravidelného tvaru, z nichž žádný nemá vyvinutou zdrojovou oblast v podobě typického karu. Současné zalednění je omezeno na nejvyšší partie horských hřbetů, sněžná čára se nachází v blízkosti izohypsy 5300 m.

Vývoj zalednění studované oblasti ve 2. polovině 20. století potvrzuje globální trend ubývání hmoty ledovců. Za 45 let se rozloha ledovců a firnových polí zmenšila téměř o 60 %. Patrný je úbytek ledovců především nízko položených a nepříznivě exponovaných vůči slunci. Menší ablace jižně orientovaných ledov-

ců je podmíněna především celkovým množstvím slunečního záření, které na jižně orientované plochy dopadá pod menším úhlem.

Na základě rozmístění, rozsahu a mocnosti dochovaných ledovcových akumulací a tvarů ledovcové eroze byly vymezeny tři etapy kvartérního zalednění. V nejstarší zjištěné fázi bylo zalednění studované oblasti charakterizováno velkým rozvojem údolních ledovců, které sestupovaly až do vzdálenosti 15 km od rozvodního hřbetu. Ve druhé fázi se rozvinuly pouze kratší údolní, případně karové ledovce, jejichž čela se nacházela do 5 km od akumulační oblasti. Pro poslední fázi zalednění je příznačné nevelké rozšíření ledovců svahově-karového popřípadě náhorního typu.