CLIMATIC IMPLICATIONS OF ROCK GLACIERS IN THE ARID WESTERN CORDILLERA OF THE CENTRAL ANDES

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Climatic implications of rock glaciers in the arid Western Cordillera of the Central Andes

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Table of Contents

Abstract

Between 16 and 22°S in the Central Andes the climate is seasonally arid with precipitation decreasing south-westwards. The lowest altitude of rock glacier activity corresponds closely to the 0°C isotherm, not the glacier ELA which rises to the south in response to increasing aridity. Inactive rock glaciers probably mark the position of a former 0°C isotherm which followed a similar trend but was about 400 m lower.

Extended Abstract

Six large active rock glaciers and several inactive rock glaciers were studied at three sites between 16 and 22°S in the Central Andes: Nevado Chachani (16°11'S), Cerro Arintica (18°44'S) and Volcanes San Pedro-San Pablo (21°53'S). These mountains are all late-Quaternary strato-volcanoes over 5500 m and have all been glacially dissected. The climate is seasonally arid with precipitation decreasing south-westwards. The modern 0°C isotherm in the Western Cordillera falls from north to south. In northern areas where precipitation is abundant, the Equilibrium Line Altitude (ELA) of glaciers is close to the 0°C isotherm, but as aridity increases south-

westwards, the ELA rises to more than 1000 m above the 0°C isotherm. During the last glaciation, the 0°C isotherm was about 400 m lower throughout the area, while the ELA increased from 4500 m in the north to 4900 m in the south, representing about 1000 m of ELA lowering compared to the present. Because rock glaciers can only be active within a well-constrained range of temperature and annual precipitation, the lowest altitude of non-glacial rock glacier activity at present and in the past can provide information about climatic change. Each rock glacier was mapped in the field using aerial photography as a base. Positional data were collected by a combination of the Global Positioning System and Barometric Altimetry, and the results processed in a Geographical Information System (GIS) for calculation of length, width, area, volume and gradient. Active rock glaciers are characterised by over-steepened frontal slopes (>30°) and well-defined flow lines. They terminate between 4525-4810 m at the study sites. Inactive rock glaciers are in many cases vegetated, and frontal slope angles are less than 30°; minimum altitudes range from 4250-4470 m. All of the rock glaciers lie within valleys that have been glaciated and therefore post-date the retreat of ice from its maximum extent which probably occurred about 10 000 years BP. One constraining radiocarbon date was obtained from the San Pedro-San Pablo area from peat immediately underlying a tephra layer which also overlies the maximum extent moraines at San Pedro-San Pablo. This provides a minimum age for de-glaciation at this location of 10 085 ± 45 ^{14}C years BP. The lowest altitude of rock glacier activity decreases southwards by 285 m over six degrees of latitude. This corresponds closely to the 0°C isotherm, not the glacier ELA which rises to the south in response to increasing aridity. This suggests that the lowest altitude of rock glacier activity at present is more closely related to the modern temperature regime (0°C isotherm) than to the annual precipitation signal which controls modern ELA. Inactive rock glaciers probably mark the position of a former 0°C isotherm which followed a similar trend but was about 400 m lower. Global climate models require detailed climatic records of all environments. In the absence of information about a particular area, such as that provided by this paper, assumptions have to be made that may be misleading or inaccurate. Research into differences in the timing and extent of Southern Hemisphere climatic fluctuations is beginning to fill the gaps and highlight some limitations of existing climatic models.

Keywords

Rock glaciers, Climate, Temperature, Precipitation, Andes, South America

Introduction

Two types of rock glacier have been identified by previous workers in the Andes: those that are composed of rock debris with interstitial ice, and former glaciers that are covered by debris (Clapperton 1993). Both types are known to occur in many parts of the Andes but have been studied in only a few places. In the arid Argentinean Andes at 33°S, Corte (1986) observed that the presence of active rock glaciers is largely controlled by mean annual precipitation. Active rock glaciers and debris-covered glaciers have also been observed in the northern Andes of Perú and Ecuador by Lliboutry et al.(1977) and Clapperton (1990) respectively, and similar features are present in the Torres del Paine region of Patagonia (Clapperton 1993).

Aridity is a well known feature of the Central Andean climate at present, but archaeological evidence from the Atacama Altiplano suggests that moisture availability increased during the late-glacial period (Messerli *et al.*1993; Grosjean and Núñez 1994) a factor that is believed to have been important in controlling the timing and extent of the last glaciation in the Central Andes (Clapperton *et al.* 1997; Clayton and Clapperton 1997). As glacier formation at present is inhibited by aridity on all but the highest mountains in this region, it is proposed that the study of active and inactive rock glaciers may yield the best information about palaeo-climate.

During fieldwork in the Western Cordillera of the Central Andes between 16 and 22°S, both active and inactive rock glaciers were studied in order to investigate the relationship between rock glacier activity and climatic conditions. The purpose of this paper is to present results from the investigation of six active and several inactive talus-derived rock glaciers at three sites that cover six degrees of latitude in southern Perú and northern Chile. The following discussion of the nature of rock glacier activity in the Central Andes of South America aims to increase our knowledge of the global inventory of rock glaciers and to enhance our understanding of climatic conditions in this unique arid environment.

The study area

The Andes mountains extend 7500 km along the west coast of South America between Colombia and Patagonia. In the Central Andes between 16 and 22°S, the ranges divide around the central Andean plateau or 'Altiplano' (Fig. 1), a 37 000 km^2 sediment-filled inter-montane basin with an average surface elevation of 3600–3800 m. The Western Cordillera, at the western margin of the Altiplano, is a chain of late Quaternary strato-volcanoes that formed above the east-Pacific subduction zone. The summits of the volcanoes are commonly 2000 m above the level of the Altiplano, and many are active or potentially active (de Silva and Francis 1991).

Tropical north-easterly trade winds originating over the equatorial Atlantic lose most of their moisture as they rise over first the eastern cordilleras and then the Altiplano. Consequently the Western Cordillera is exceptionally arid, with a precipitation gradient from about 500 mm a^{-1} in the northern part to virtually zero in the Atacama desert where precipitation may only be recorded once in thirty years (Miller 1976). The south-westward decrease in moisture is reflected in the altitude of the modern snow-line which is about 5500 m at 16°S but rises to over 5800 m at 22°S (Klein *et al. 1995*).

Former glaciers in the Western Cordillera terminated at around 4100–4400 m and reconstruction of former glacier equilibrium lines shows that there was a rise in equilibrium line altitude to the south and west. In valleys that were eroded during earlier glaciations at three locations in the Western Cordillera, both active and inactive rock glaciers have been identified and mapped. The lowest altitudes of active rock glaciers lie in the range 4525–4810 m.

Controls on rock glacier formation

Rock glaciers are characterised by surface ridges parallel to the direction of flow and by steep-faced lobes that are believed to move through the system in response to changing conditions of climate and debris input (Kirkbride and Brazier 1995). They form by internal deformation of an ice core or of interstitial ice or ice lenses within coarse debris under the influence of gravity, and they may be tongue-shaped or lobate. The most common types are those derived from talus slopes (non-glacial origin) and those derived from moraines (glacial origin).

For a rock glacier to form, there must be a suitable source of coarse angular sediment (talus), the thickness of accumulated talus and the slope angle must be sufficient to generate the shear stress that causes deformation, and the climate must be cold enough all year to preserve interstitial ice and dry enough to inhibit the formation of glaciers. The debris supply or the climate may be limiting factors on the activity of rock glaciers (Sandeman and Ballantyne 1996).

Debris-supply as a limiting factor

In a large proportion of cases the presence of rock glaciers can be related to former glaciation, *i.e.* they are often of para-glacial origin. For example, talus-derived rock glaciers commonly form beneath cliffs that were cut by a former glacier, whilst moraine-derived rock glaciers are the result of periglacial reworking of ice-cored moraines. The susceptibility of the bedrock to physical weathering may also affect the supply of debris of suitable size. In talus-derived rock glaciers the rate of debris input into the rock glacier is a critical factor (Olyphant 1987), controlled by climate-dependent weathering rates or by catastrophic avalanche events.

Climate as a limiting factor

The temperature and precipitation range within which rock glaciers may be active are shown in Figure 2 (after Haberli 1985). The limit is defined by a curve: at extremely low temperatures, rock glaciers can only form where the precipitation is too low to allow the formation of glacier ice. The upper limits of annual precipitation for rock glacier formation are 2500 mm a^{-1} at -2°C, and 400 mm a^{-1} at -15°C. The lowest altitude of rock glacier snouts is normally well above the limit of continuous permafrost (Corte 1987; Wahrhaftig 1987) because rock glaciers require a mean annual temperature of below -2°C for interstitial ice to exist, and above -15°C for ice to deform.

Because rock glaciers can only be active within a small range of temperature and precipitation, studying the lowest altitude of rock glacier activity at present and in the past can provide information about climatic change. Limitations are placed on the use of the palaeo-climatic information contained in rock glaciers by two factors: a lag in the response time of a rock glacier to changes in climate and debris supply rates; and geological and topographic influences on rock glacier distribution.

The lag time in the response of rock glaciers was modelled by Olyphant (1987) in terms of reaction time (r) after abrupt change in conditions, and relaxation time (a) before equilibrium (e) is reached

(Fig. 3). For example, the model suggests that a 500 m long rock glacier may take 425 years to react to an increase in debris supply, and a further 1225 years to reach equilibrium. In a longer rock glacier the lag times would be correspondingly greater. Equilibrium may never be reached in real examples because periods of climatic stability are generally shorter than the time required for rock glaciers to reach equilibrium. However on the time-scale of thousands of years, broad inferences may be made about the relationship between rock glaciers and climate.

Methods

Each rock glacier was mapped in the field using aerial photography as a base. Positional data were collected in the field by a combination of a Global Positioning System (GPS) and Barometric Altimetry. A network of ground control points was created allowing photogrammetric reconstruction of the rock glaciers using a Kern PG2 plotter connected with a computer for digital data recording. Five long profiles of each rock glacier were measured: a baseline at either edge, two lateral ridge profiles and a centre-line, and the rock glacier surfaces were contoured at 20 m intervals. Data were transferred to a Geographical Information System (GIS) for calculation of length, width, area, volume and gradient.

Glacial and climatic history of the study area

Studies of water resources from archaeological evidence at 23–24°S (Messerli *et al.* 1993 ; Grosjean and Núñez 1994) have confirmed that aridity has been a feature of the climate of this area throughout the Late Quaternary, although cooler, wetter conditions persisted between about 17 000 and 11 000 years BP. On the eastern Altiplano, glaciers expanded and lake levels rose in synchrony between 13 500 and 11 500 ^{14}C years BP (Clapperton *et al.*1997; Clayton and Clapperton 1997), much later than the last (global) glacial maximum at 18 000 years BP (CLIMAP 1981). Radio-carbon dates obtained from glacier advances in the Eastern Cordillera show that the last maximum extent of glaciation here occurred between 14 000 and 12 000 years BP, and that a late-glacial re-advance terminated before 10 000 (Mercer 1984; Seltzer 1992). Several Holocene re-advances have been described, although there is no strong chronological agreement between different sites. It seems likely that smaller glaciers responded more readily to local climatic and topographic influences during the Holocene and that at some sites there was no Holocene glaciation. Such conditions may have been suitable for rock glacier formation.

The altitude of the modern 0°C isotherm in the Western Cordillera is 4880 m at 16°N and 4520 m at 24°S (Hastenrath 1971). In areas where precipitation is abundant, the Equilibrium Line Altitude (ELA) of glaciers is close to the 0°C isotherm, but as aridity increases south-westwards, the ELA rises towards 24°S where it is more than 1000 m above the 0°C isotherm (Hastenrath 1971). The 0°C isotherm was about 400 m lower throughout this area during the last glaciation: this is consistent with a temperature drop of around 3°C (Clayton and Clapperton 1997) and an adiabatic lapse rate of 7.5°C 1000 m^{-1} above 3600 m (Graf 1981). At the last maximum extent of glaciation, glacier ELA increased southwards from about 4500 m in the North to about 4900 m in the South (Jenny and Kammer 1996a). This represents about 1000 m of lowering of the ELA compared to the present.

Rock glaciers in the Western Cordillera

Six large active rock glaciers and several inactive rock glaciers were studied at three sites in the Central Andes (see Fig. 1): Nevado Chachani, Perú (16°11'S), Cerro Arintica, Chile (18°44'S) and Volcanes San Pedro and San Pablo, Chile (21°53'S).

Nevado Chachani (Fig. 4a) is a 6057 m high, Late Pleistocene compound volcano on which well-formed lateral moraines mark the lowest extent of glaciation at 3440 m on the southern flanks. Beneath south-facing headwalls on the upper slopes, debris accumulations form several lobate mounds, the surfaces of which have long ridges parallel to the edges of the feature. Boulders up to ten metres in diameter occur on the upper surface, whilst the marginal slopes are composed of small pebbles and sand to silt grade material with a 36° angle of repose. The steep frontal slopes and levée-style ridges are typical features of active rock glaciers. Similar features at lower altitudes lack the pristine morphology of active rock glaciers: they are judged to be inactive rock glaciers because of their lower relief and vegetated surfaces.

At Cerro Arintica (Fig. 4b), former glaciers descended to 4380 m on the south-east slopes of this 5597 m high volcano, the age of which is not precisely known. In south-east facing cirques, large mounds of rock debris that have the characteristic flow lines and steep 32–35° frontal slopes of rock glaciers are present beneath scree slopes (Fig.

5). Vegetation on the frontal lobe of the largest rock glacier suggests that this lobe is now inactive. From the morphology of these features they are believed to contain no core of glacier ice but to have formed by the agency of interstitial ice. In satellite imagery, these features have been mistaken for post-glacial lava flows (de Silva and Francis 1991).

The twin volcanoes of San Pedro (6145 m) and San Pablo (6092 m) (Fig. 4c) rise more than 2300 m above the plateau; the western cone, San Pedro, is known to have been active since the last glaciation (O'Callaghan and Francis 1986). Two cirques on the southern flanks contain scree slopes beneath which lobate accumulations of debris are present. In Figure 6, ridges parallel to the direction of flow may easily be discerned on the upper surfaces of one of these features, both of which have a frontal slope angle of *ca* 32°. In a smaller valley four kilometres to the east, debris has accumulated in a broad mound terminating in 36° slopes. All three features have the characteristic morphology of rock glaciers.

The 'AZ' rock glacier at Chachani (16°S) terminates at 4810 m (Fig. 7a) and is the steepest with an average slope of 29°. Five other active rock glaciers are present on this mountain, all of which terminate above 4810 m. At Arintica, the 'CY-bajo' rock glacier terminates at 4675 m (Fig. 7b) and is the largest in terms of volume, containing an estimated 5722 □ 10^3 m^3 of debris; this volume does not include the inactive lobe on which there is some vegetation. The longest rock glacier is 'PP-east' at San Pedro-San Pablo extending over 1.2 km between 5100 and 4525 m altitude (Fig. 7c) beneath a large talus slope on Volcán San Pablo. All of the rock glaciers have over-steepened frontal slopes of up to 36°. Inactive rock glaciers are characterised by vegetated surfaces and lower frontal slope angles (<30°). The lowest inactive rock glaciers at the study sites, which in some cases are moraine-derived rather than talus-derived, terminate at 4160 m (Chachani), 4470 m (Arintica) and 4250 m (San Pedro-San Pablo).

From the location and morphology of these features, they are believed to contain no core of glacier ice but to have formed by the combined agencies of rock fall and interstitial ice growth. Nowhere is glacier ice exposed at the surface and the location of rock glaciers at the base of talus is indicative of a non-glacial origin. Furthermore, the clasts that comprise the rock glacier very rarely show signs of rounding, being predominantly angular in nature (Fig. 8). Very steep frontal slopes (Fig. 9) complete the picture of a talus-derived rock glacier.

All of the rock glaciers described above lie within valleys that have been glaciated and therefore post-date the retreat of ice from its maximum extent which probably occurred about 10 000 years BP. One constraining radiocarbon date was obtained from the San Pedro-San Pablo area from peat immediately underlying a tephra layer which also overlies the maximum extent moraines at San Pedro-San Pablo. This provides a minimum age for deglaciation at this location of 10 085 ± 45 ^{14}C years BP NERC sample no. SRR-5670).

Discussion

The lowest altitude at which rock glaciers are active at present decreases southwards by 285 m over six degrees of latitude. In contrast, the modern glacier ELA increases by around 540 m over the same distance. The altitude of the modern free-air atmospheric 0°C isotherm (which ignores the effects of topography, aspect and shade that are significant in the dry air of the Cordillera) decreases southwards. Active rock glaciers terminate at about the level of the modern 0°C isotherm. Similarly, the rock glaciers that are now inactive reached their lowest altitude close to the curve of the reconstructed former 0°C isotherm whilst reconstructed former ELA increases in altitude southwards.

The long-profile of the Western Cordillera (viewed from the west) shown in Figure 10 represents ten degrees of latitude from 15 to 25°S: north of 18°S the profile follows a direction of 130° and south of that point it continues to follow the crest of the Western Cordillera at 170°. The lowest altitudes of both active and inactive rock glaciers are plotted along with modern and former 0°C isotherms, snow-lines and ELA (Hastenrath 1971; Fox 1993; Jenny and Kammer 1996a). The topography of the Andes crest-line is also shown. The four ELA curves (red lines) increase southwards whilst the 0°C isotherm curves (blue lines) decrease southwards. This figure illustrates the correlation between the lowest altitude of active (filled squares) and the modern 0°C isotherms, and between inactive (open squares) rock glaciers and a former 0°C isotherm. Data are included from this study for Cerro Pomerape (18°08'S), and an additional five data points for the lowest altitude of active and inactive rock glaciers have been taken from Jenny and Kammer (1996b, section 6).

From an examination of Figure 10, it can be seen that, except for Pomerape, the lowest altitude of rock glacier activity at present is more closely related to the modern temperature regime (0°C isotherm) than to the annual precipitation signal which controls modern ELAs.

That the lowest altitudes of rock glaciers lie slightly below the 0°C isotherm is probably due to the effect of shade on the south-east to south-west facing slopes which, in the dry air, causes sharp temperature anomalies. At Pomerape, active and inactive rock glaciers terminate at relatively high altitudes; in the case of active rock glaciers this is due to a lack of a suitable debris supply at lower levels. The large inactive rock glacier at this site extends 0.3 km onto a plateau at 4840 m altitude which inhibited its descent to lower altitudes.

Palaeo-climatic implications

There is a problem with the synonymous use of the terms 'snow-line' and 'ELA' in the Central Andes (*e.g.* Fox, 1993; Klein *et al.* 1995) because the modern snow-line is commonly 300 m below the ELA (Fig. 10). Comparison of the lowest altitude of rock glaciers with ELA and 0°C isotherm gradients suggests that the altitude at which rock glaciers are present in the Central Andes is determined by mean annual temperature, whilst the extent and timing of glacial maxima depended on moisture availability (Clapperton *et al.* 1997; Clayton and Clapperton 1997). Admittedly the data on inactive rock glaciers are sparse, and the amount of lowering of the 0°C isotherm is open to debate, but it is proposed that it is possible to infer former temperature regimes from the position of inactive rock glaciers. From the information available, no age constraints may be placed on the longevity of these rock glaciers, and periods of inactivity during their existence cannot be ruled out. However, provided that topographic considerations are not overlooked, inactive rock glaciers in the Central Andes can supply information about former temperature change that is not available from other sources.

Global climate models require detailed climatic records of all environments. in the absence of information about a particular area, such as that provided by this paper, assumptions have to be made that may be misleading or inaccurate. research into difference in the timing and extent of Southern hemisphere climatic fluctuations is beginning to fill the gaps and highlight some limitations of existing climatic models.

Conclusions and wider implications

- Active rock glaciers in the Western Cordillera terminate between 4525 and 4810 m altitude, and extend to lower levels in the South.
- This bears no relation to the modern snow-line or ELA trend, but appears to correlate with the mean free-air 0°C isotherm. Small departures of rock glacier altitudes from the 0°C isotherm may be explained by the effects of topography providing shade or preventing debris supply.
- Inactive rock glaciers appear to follow a similar trend but the altitudes at which they occur are consistently lower.

Active and inactive rock glaciers are not rare features in the Andes. Andean aridity increases southwards to around 27°S where it reaches its greatest intensity in the 'arid diagonal' of Chile and Argentina. The area to the south of this line is influenced by different climatic conditions and moisture sources at present and this division is believed to have existed during the last glaciation. A greater number of rock glacier observations extended to cover a wider area would help to separate the temperature and precipitation signals that influenced the last glaciation in the Central Andes, and they may provide a key to understanding the record of global climatic change in this unique arid environment.

Acknowledgements

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List of Figures and Tables

Figure 1 Location of the Central Andean field sites based on a Digital Elevation Model using data from EROS (Isacks 1997).

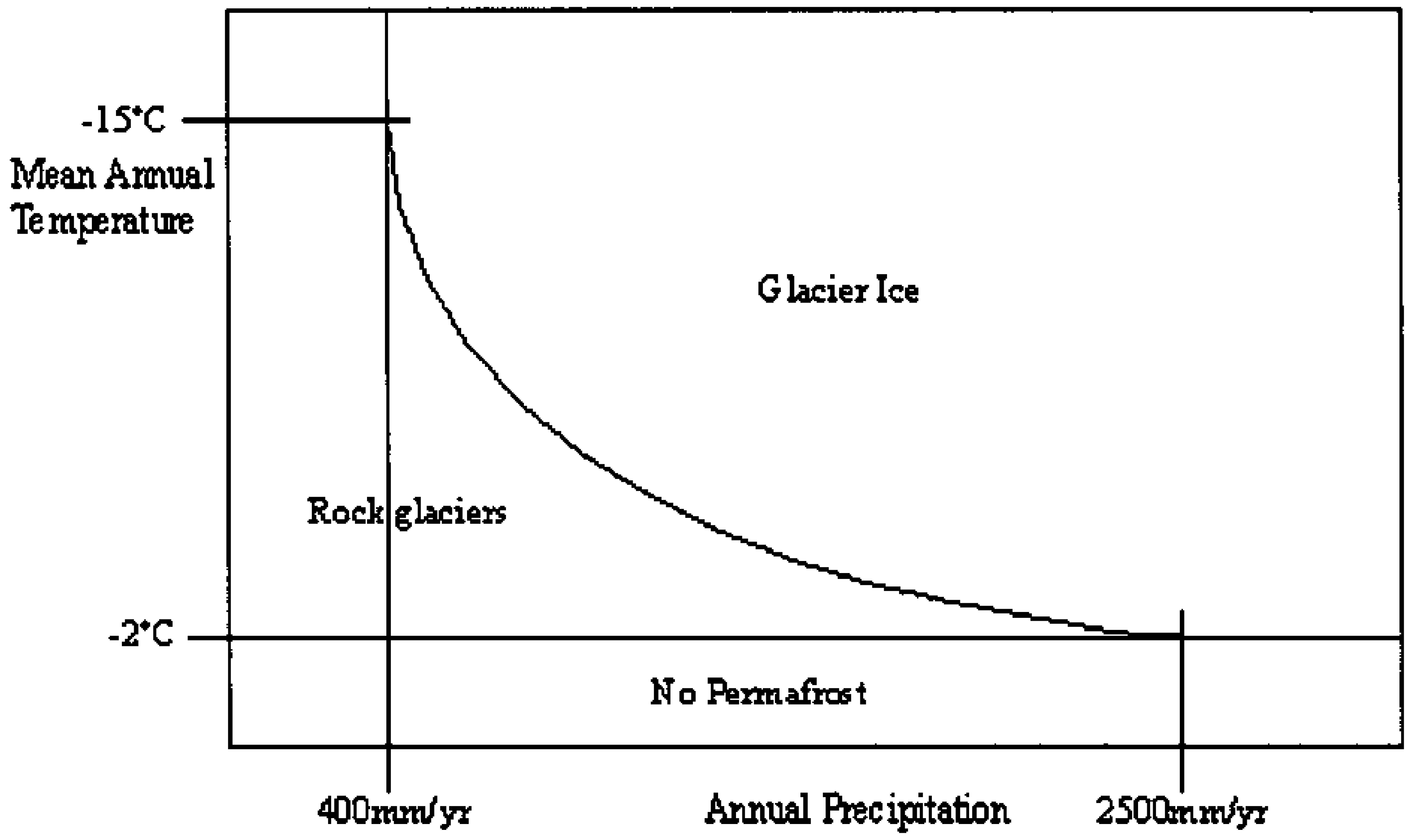


Figure 2 Climatic constraints on the formation of rock glaciers (after Häberli 1985).

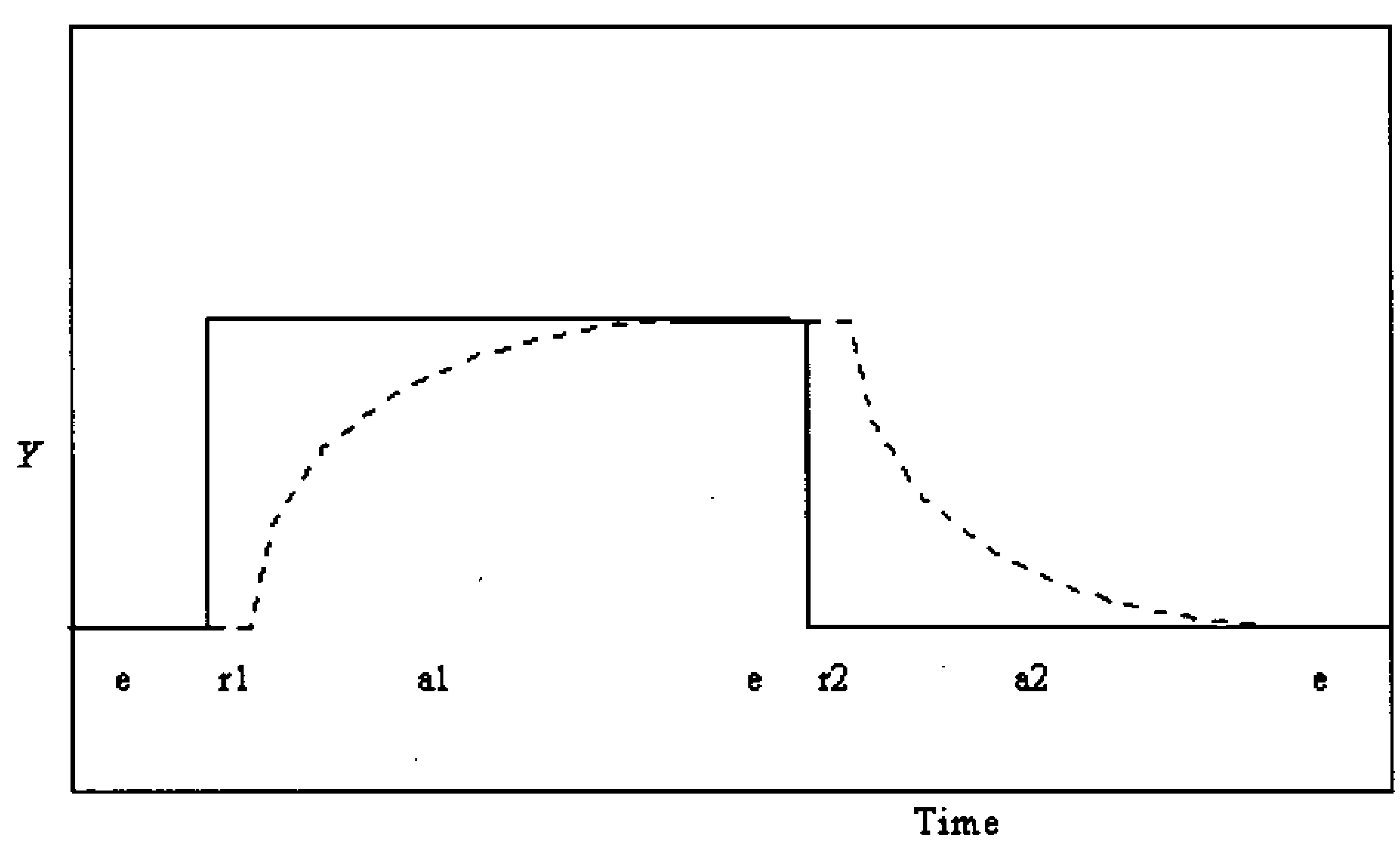
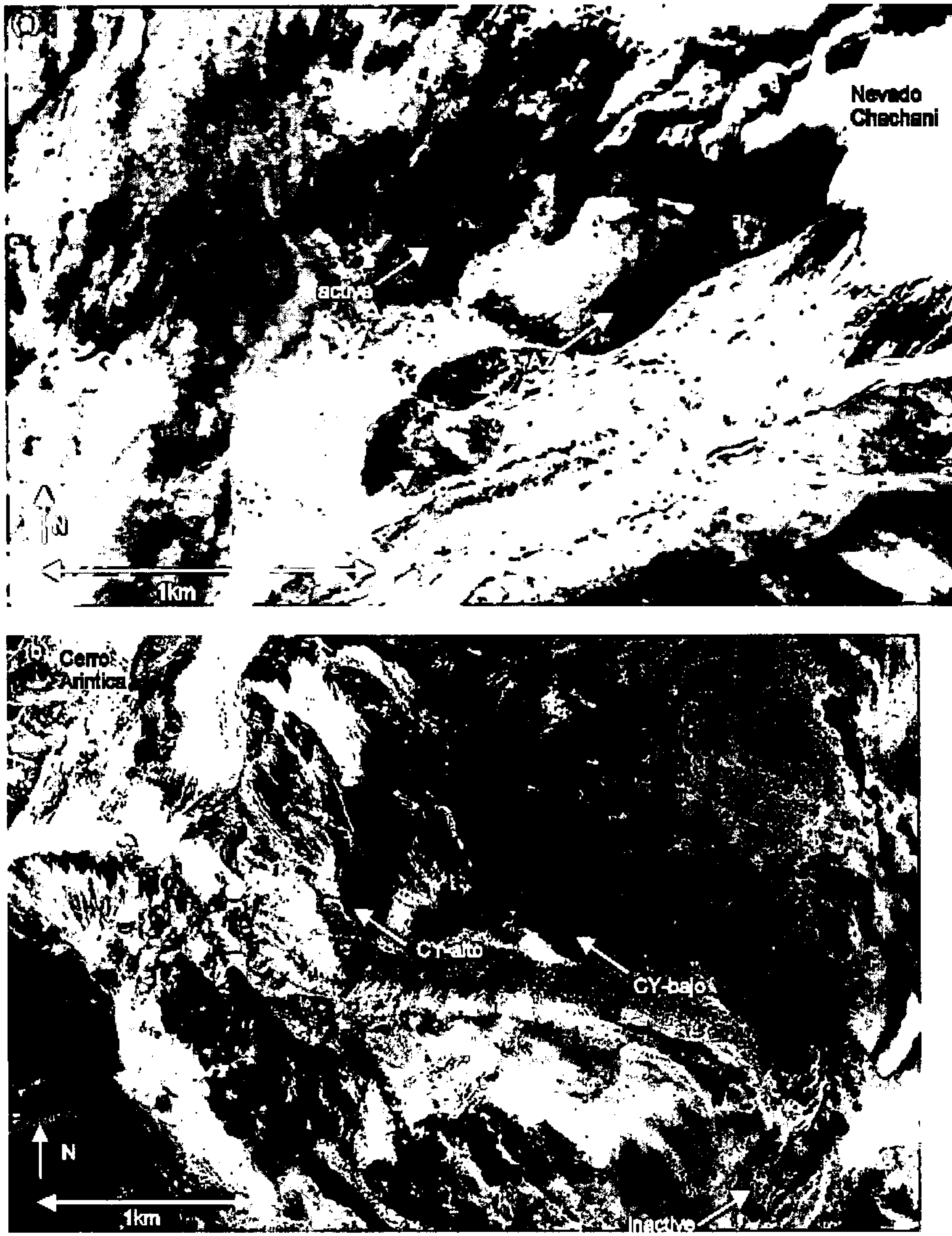


Figure 3 Hypothetical response curves for a climatically controlled system parameter (Y): (e) represents equilibrium; (r1, r2) represent reaction; (a1, a2) represent relaxation (after Olyphant 1987).


(a)
Nevado
Chachani
active
N
1km
b
Cerro
Arintica
CY-alto
CY-bajo
N
1km
Inactive

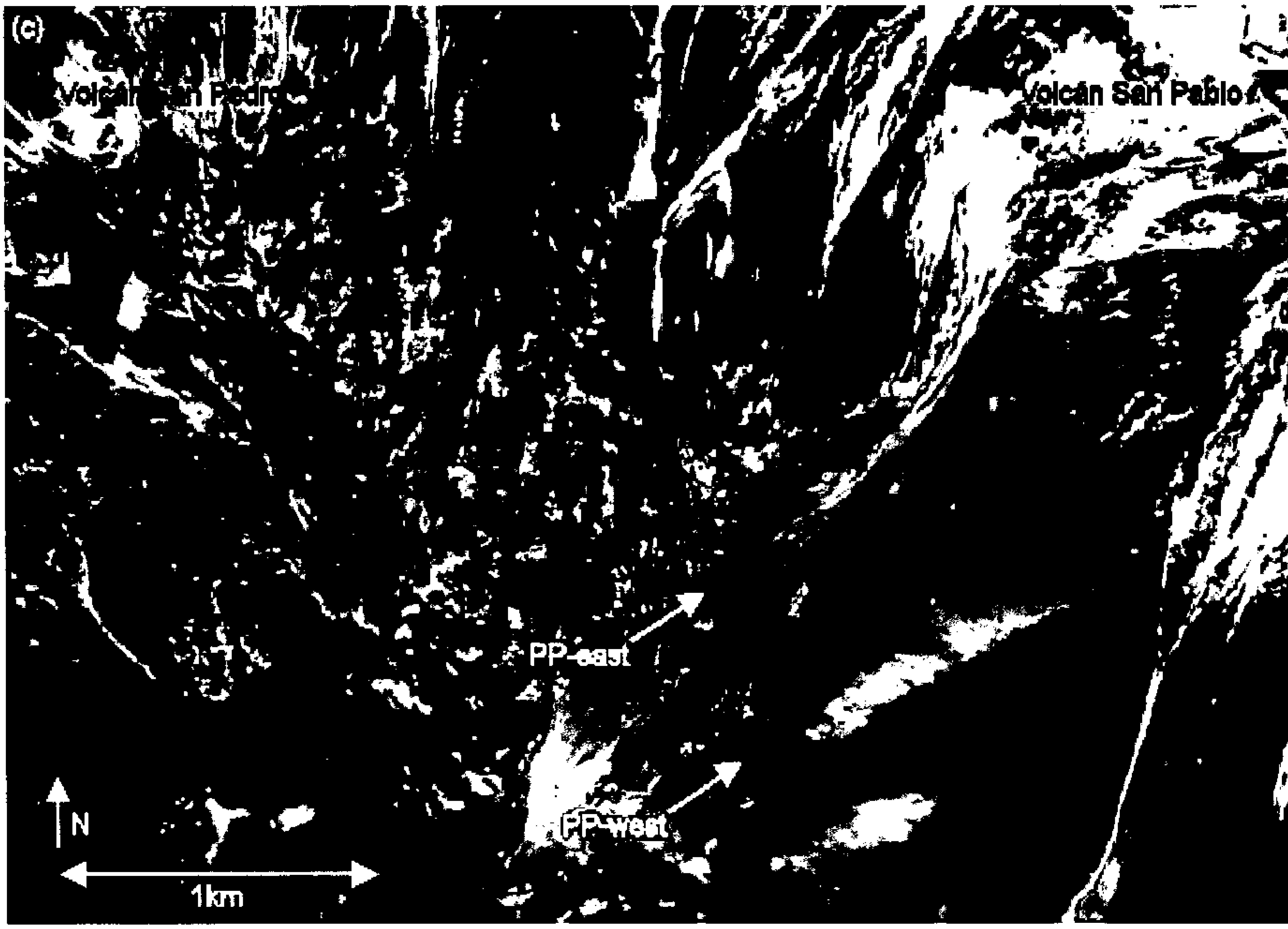


Figure 4 Aerial photographs of (a) Nevado Chachani (16° 11'S); (b) Cerro Arintica (18°44'S)and (c) Volcanes San Pedro-San Pablo (21° 53'S) showing the location of active and inactive rock glaciers.

Figure 5 Photograph of Arintica rock glaciers: 'CY-bajo' in the foreground and 'CY-alto' behind.

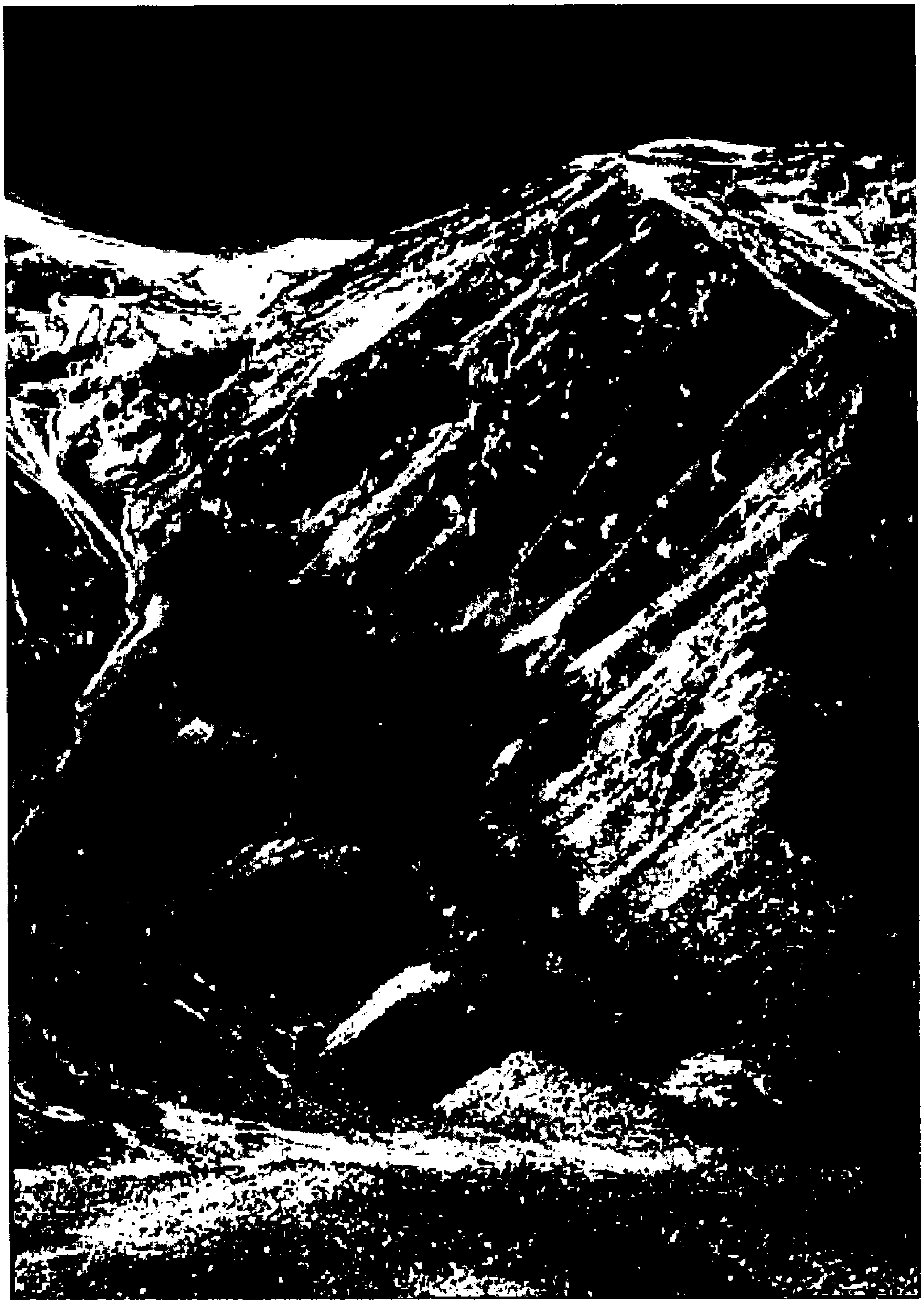
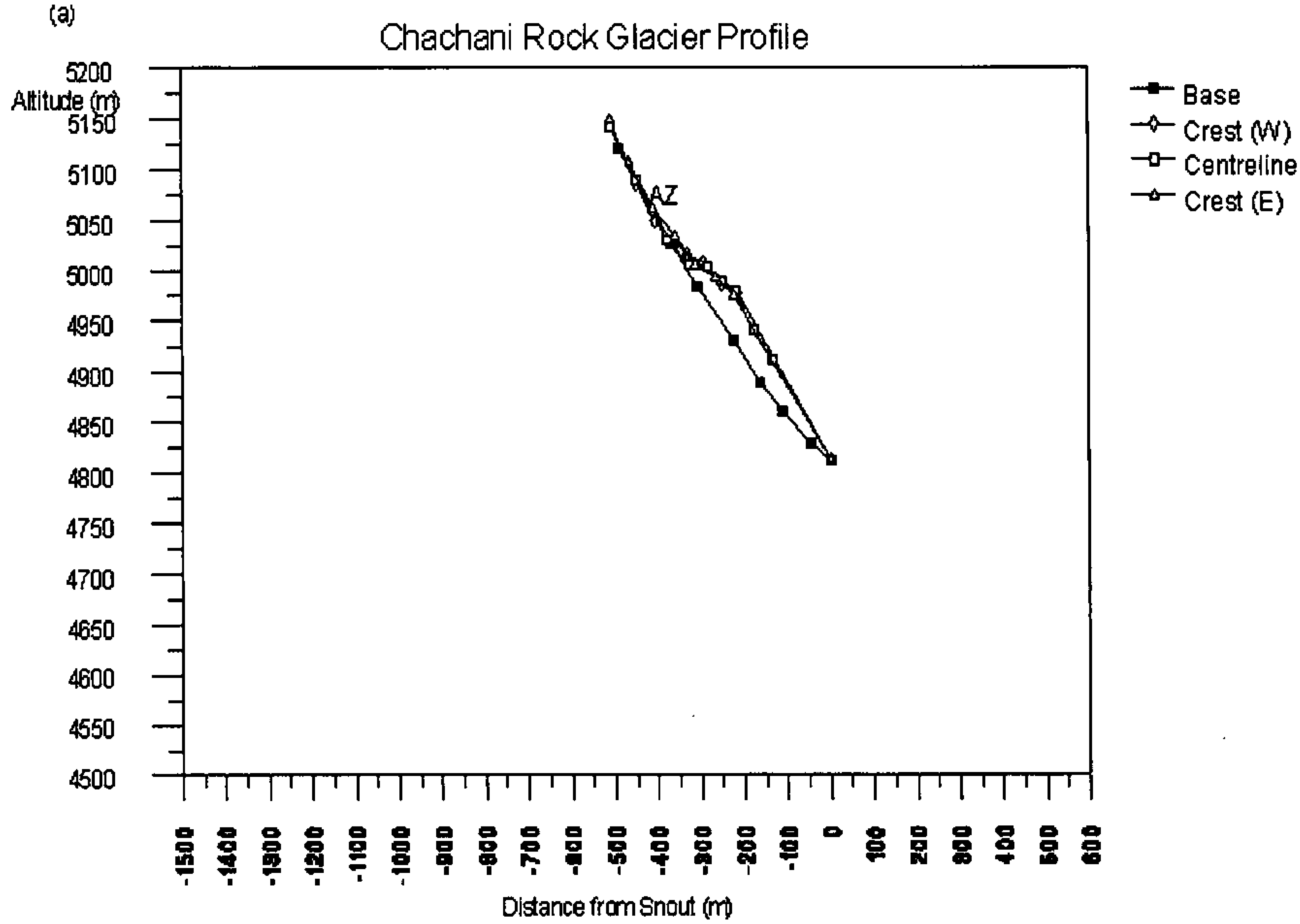
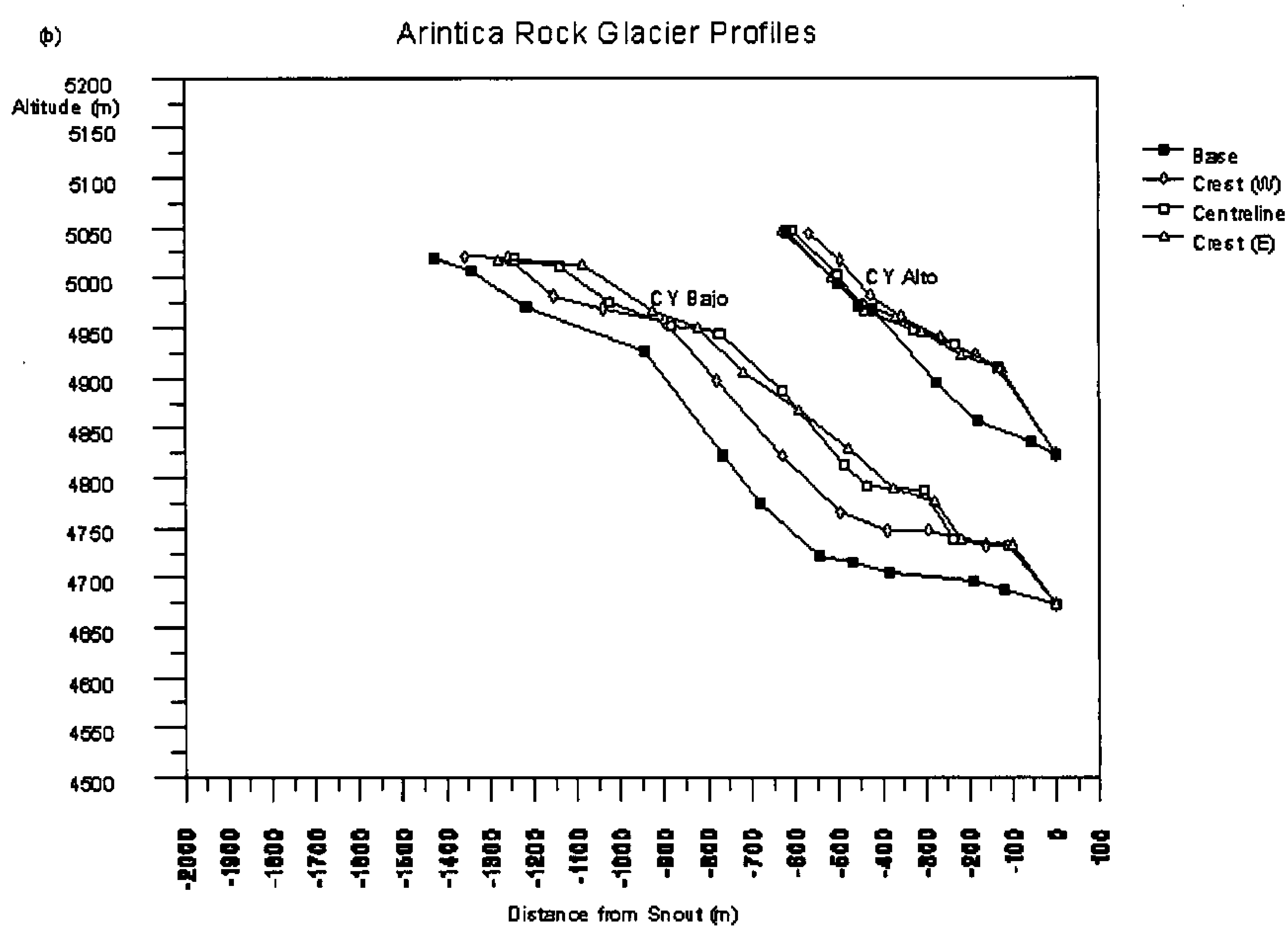


Figure 6 Photograph of San Pedro-San Pablo 'PP-east' rock glacier. The altitude range of the rock glacier in this picture is 575 m (1886 ft).

(a)


Chachani Rock Glacier Profile
Altitude (m)
5200
5150
5100
5050
5000
4950
4900
4850
4800
4750
4700
4650
4600
4550
4500
AZ
Base
Crest (W)
Centreline
Crest (E)
-1500
-1400
-1300
-1200
-1100
-1000
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
100
200
300
400
500
600
Distance from Snout (m)

(b)


Arintica Rock Glacier Profiles
Altitude (m)
5200
5150
5100
5050
5000
4950
4900
4850
4800
4750
4700
4650
4600
4550
4500
C Y Bajo
C Y Alto
Base
Crest (W)
Centreline
Crest (E)
-2000
-1900
-1800
-1700
-1600
-1500
-1400
-1300
-1200
-1100
-1000
-900
-800
-700
-600
-500
-400
-300
-200
-100
0
100
Distance from Snout (m)

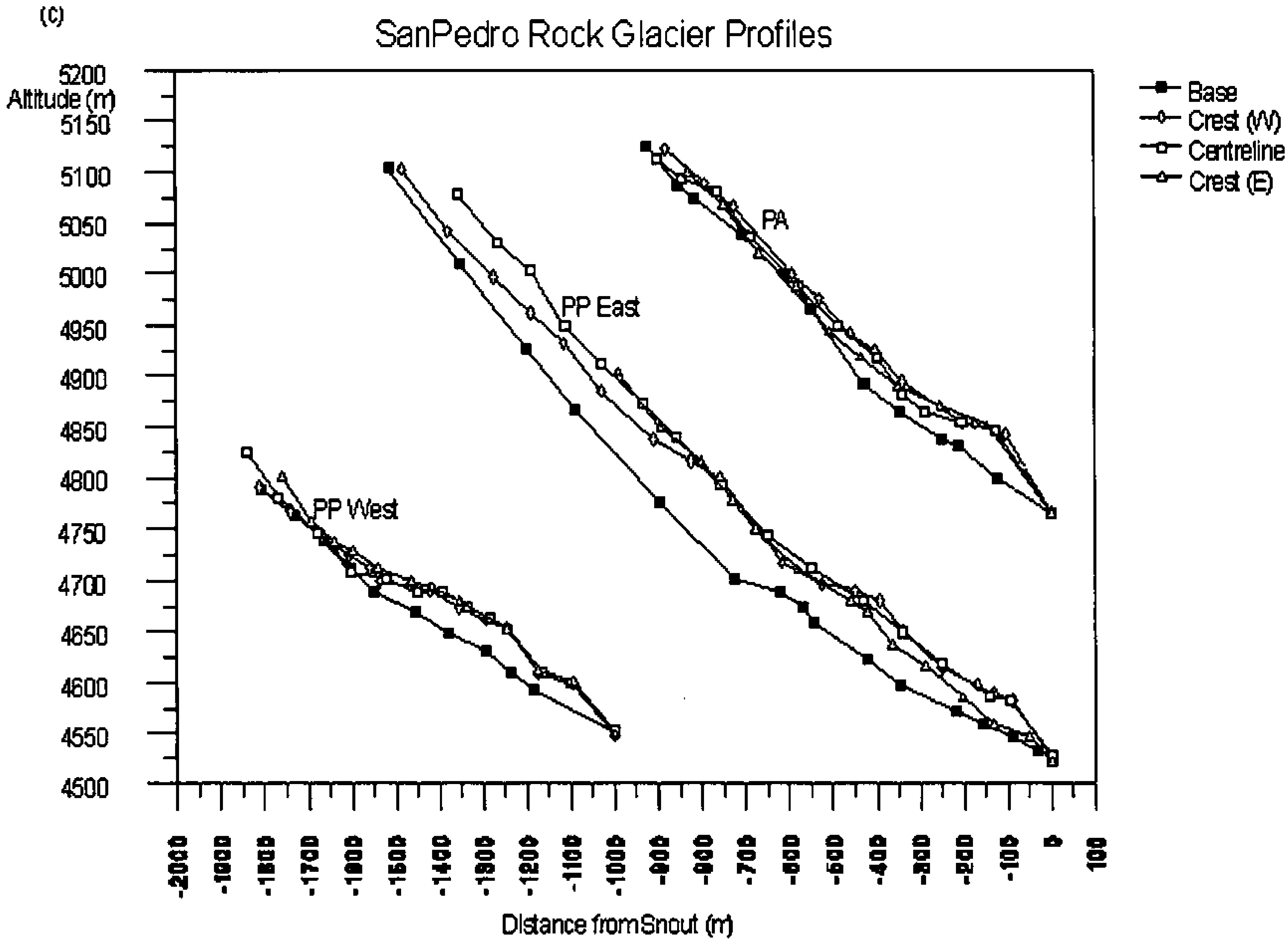


Figure 7 Rock glacier long-profiles: (a) Nevado Chachani (16°11'S), (b) Cerro Arintica (18°44'S) and (c) Volcanes San Pedro y San Pablo (21°53'S). Vertical exaggeration is approximately □ 2 and the axes have identical scales to allow direct comparison.

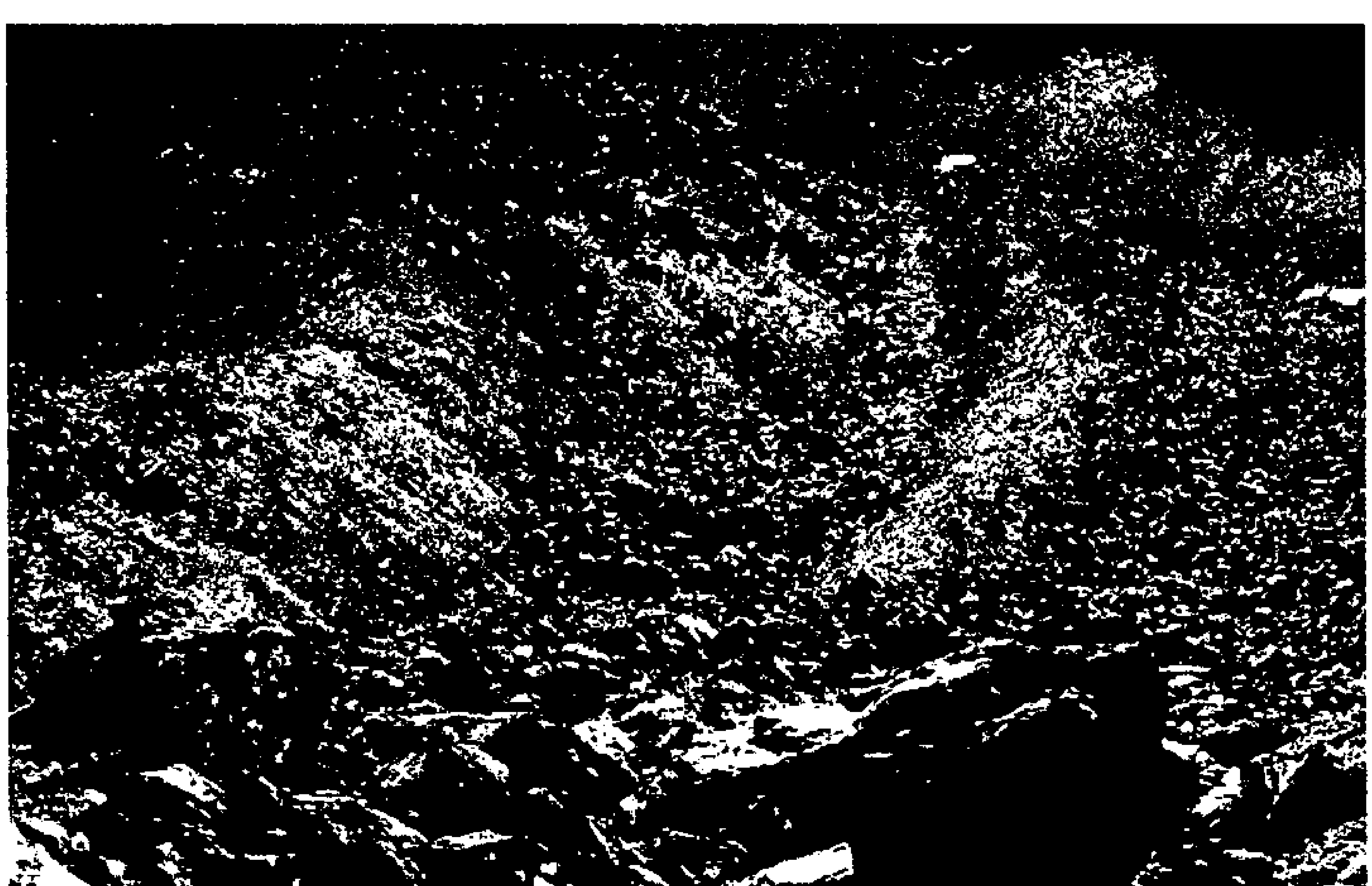


Figure 8 Photograph of the surface of the San Pedro 'PA' rock glacier; the large boulders in the foreground are 2-3m high.

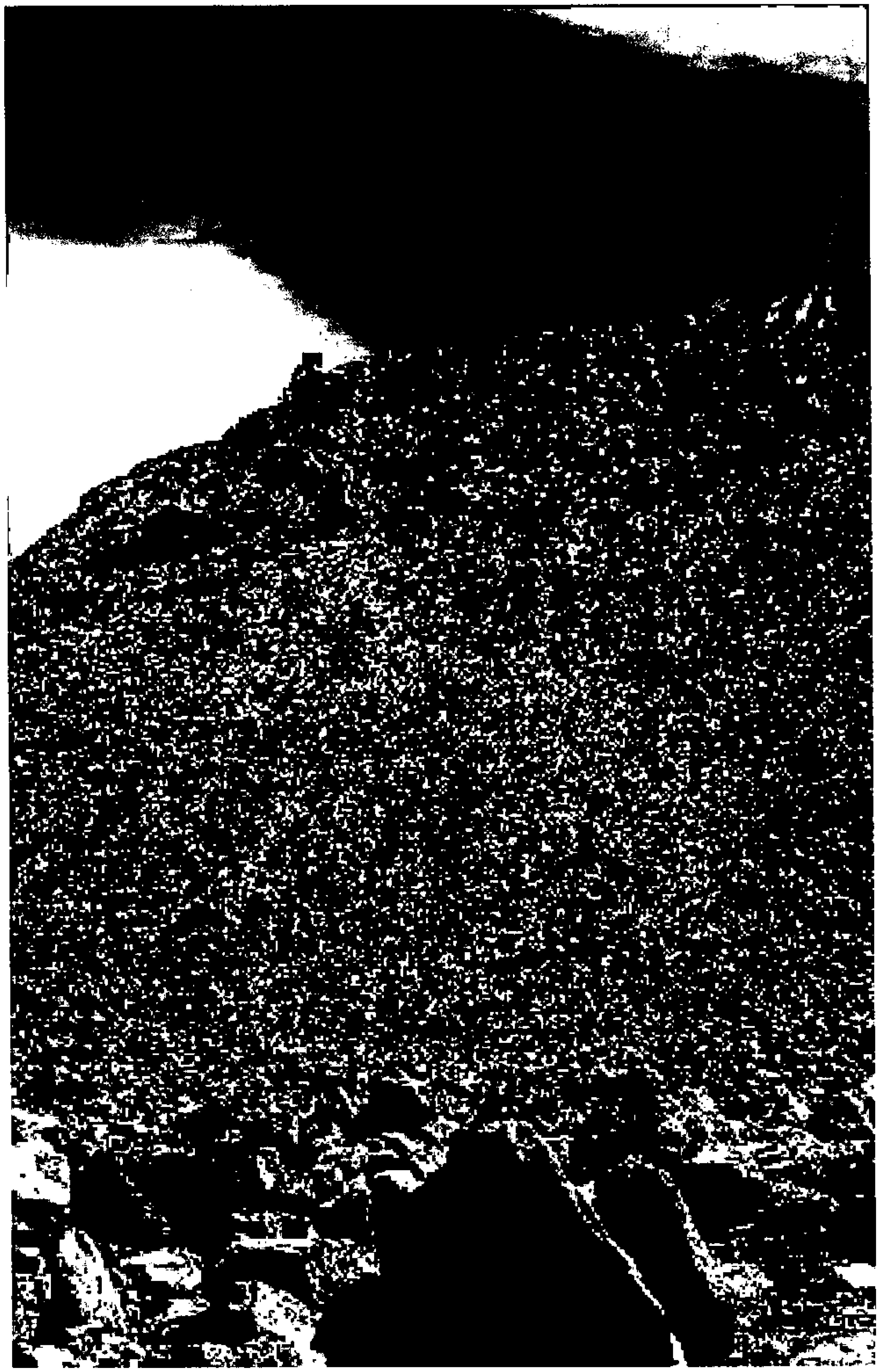


Figure 9 Photograph of the frontal slope of the 'PA' rock glacier.

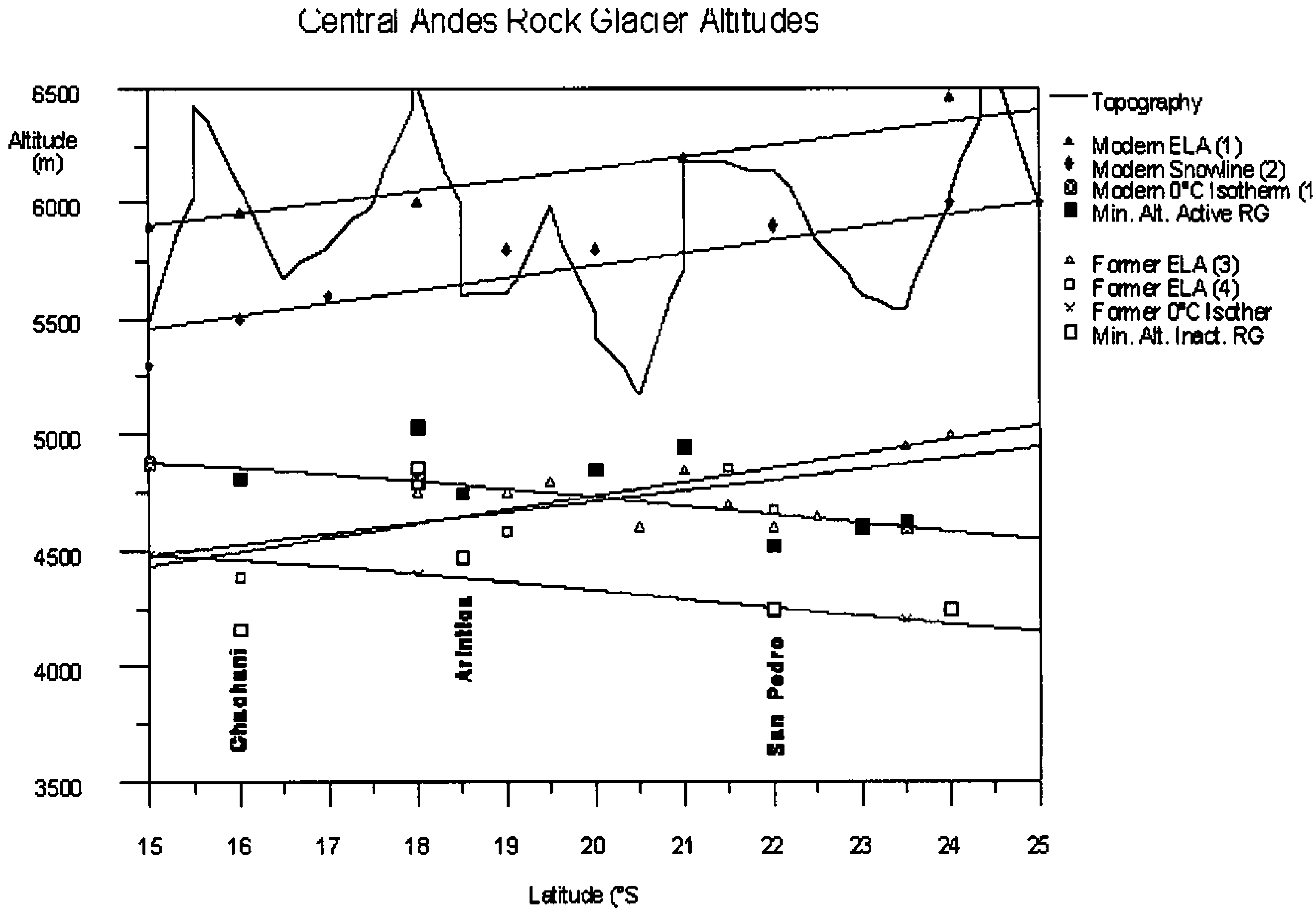


Figure 10 Long-profile of 10° of latitude of the Western Cordillera, showing active and inactive rock glacier minimum altitudes for comparison with modern and former 0°C isotherms and glacier equilibrium line altitudes (ELA). Sources: (1) Hastenrath 1971; (2) Fox 1993; (3) Jenny and Kammer 1996a; (4) This study.

	Maximum width (m)	Maximum length (m)	Mean gradient (°)	Mean frontal gradient (°)	Mean frontal height (m)	Minimum altitude (m)	Estimated maximum thickness (m)	Total volume (x10^3 m^3)
Chachani 'AZ'	102	494	29	36	141	4815	45	567
Arintica 'CY-alto'	196	605	18	32	60	4830	60	1116
Arintica 'CY-bajo'	355	1066	17	36	44	4750	113	5722
San Pedro 'PP-west'	177	803	17	27	50	4550	43	1528
San Pedro 'PP-east'	142	1276	21	32	57	4525	75	3397
San Pedro 'PA'	195	871	20	32	79	4765	53	2250

Table 1 Dimensions of the six active rock glaciers.