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Symptoms of Degradation in a Tropical Rock Glacier, Bolivian Andes

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ABSTRACT

The Caquella rock glacier (5960–5400 m ASL), approximately one kilometre long, is an important active rock glacier in the intertropical zone. In the arid high mountain environment of Bolivia, glaciers are absent. Rock glaciers represent, with salt lakes, the best indicators of climate variability. Moreover, they act as water reservoirs in the present hydrological cycle in which precipitation is very low. Direct observations and geoelectrical soundings make it possible to identify interstitial ice in the permafrost. Nevertheless, the resistivity curve profile, the ice distribution in the debris mass as well as observations from the surface topography provide clear evidence that this rock glacier is in a degradation phase. The Caquella rock glacier probably originated in the early Holocene. The presence of a recent moraine in the upper part suggests that the ELA lowered to the rock glacier surface during the Little Ice Age. The climatic conditions producing the degradation have occurred during this century. Copyright © 1999 John Wiley & Sons, Ltd.

RÉSUMÉ

Le glacier rocheux du Caquella (5960–5400 m), par sa taille kilométrique, est probablement le plus volumineux de la zone intertropicale. Dans ce milieu de haute montagne tropicale aride, les glaciers n'existent pas et les glaciers rocheux sont, avec les salars, les meilleurs indicateurs du changement climatique. Ce sont en outre des réserves hydriques qui jouent un rôle actif dans le cycle hydrologique actuel. Les observations directes et les sondages électriques montrent la présence de glace interstitielle dans le pergélisol. Cependant, les courbes de résistivité obtenues, la distribution de la glace rencontrée dans les débris ainsi que des indices venant de la topographie de surface tendent à prouver que ce glacier rocheux est engagé dans un processus de dégradation. La formation de ce glacier rocheux est le résultat d'une longue évolution qui a probablement commencé au début de l'Holocène. La présence de moraines attribuables au Petit Age Glaciaire dans les secteur amont, montre que la ligne d'équilibre glaciaire est descendue sur le glacier rocheux à cette époque et que les conditions qui ont provoqué sa dégradation se sont établies durant ce siècle. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: rock glaciers; low latitudes; permafrost degradation; geophysical investigations

INTRODUCTION

Like mountain glaciers, rock glaciers are considered good indicators of climate change over a short timescale (Barsch, 1988; Haeberli, 1992). However, the degree of activity of a rock glacier is not easy to determine. It is generally established by combining several classes of observations, the most important being: (1) evidence from the surface morphology and the front activity; (2) the quantity of ice in the debris mass and the depth of the frost

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table, as estimated by geophysical methods; (3) the variation in downslope movement and volume, as determined by topographical or photogrammetric surveys; (4) the temperature of frozen materials. Many researchers consider the response of rock glaciers to climate as being smoothed (i.e. the signal has to be strong to provoke a clear response) and delayed in time. This is unlike glaciers, which are very sensitive over a short timescale (10 years). Nevertheless, recent investigations have identified symptoms of degradation in alpine rock glaciers due to global warming during the last century (Haeberli and Schmid, 1988; Vonder Mühll and Schmidt, 1993; Assier *et al.*, 1996).

Few rock glaciers have been investigated in the tropical mountain regions (Grab, 1996). In these mountains, geocryologic processes are different to alpine and arctic environments; they are characterized by: (1) small seasonal temperature ranges; (2) high quantities of solar energy input to the ground surface all year round; and (3) absence of long-lasting snow cover, all of which have consequences for the thermal regime and albedo of the ground. The weak seasonality and aridity have two further consequences: (1) geocryologic processes and their associated forms are directly related to altimetric ranges, i.e. boundaries are clear and parallel to annual isotherms; (2) the process distribution depends on water availability in the ground. Consequently, as permafrost is generally observed above 5400–5500 m ASL in this region, rock glacier occurrence is mainly controlled by topography and aspect. In such conditions, the response of permafrost to climatic variability may be different in the tropics from mid and high latitudes. Initial investigations conducted in 1996 and 1997 on the Caquella, a rock glacier situated in the driest part of the Andean Altiplano, bring clear evidence that rock glaciers in this sector are entering a degradation process.

GLACIAL AND PERIGLACIAL CONTEXTS

Cerro Caquella (5947 m ASL) is located in the Bolivian Andes of South Lipez at 68°15′W and 21°30′S. The rocks are largely volcanic, with an andesitic substratum covered by a large accumulation of ignimbrites. In some places, volcanos are still active. The climate is dry and this region is the best example of arid high mountains in the inner tropics. Glaciers are absent because the ELA exceeds the highest peaks (>6000 m ASL). Since the annual 0 °C isotherm is at 4800 m ASL, geocryologic processes develop over a large altitude range (>1200 m) (Francou, 1993). The first inventory of periglacial forms was made by Graf (1986), and completed later by various ORSTOM fieldwork programmes. On slopes, stone-banked lobes and terraces dominate, covering more than 80% of the waste deposits. Unlike those of north Bolivia and Peru (Francou, 1990; Bertran *et al.*, 1995), these stone-banked features are not associated with stratified deposits. Banks are 2–3 metres high and can be observed above 4600 m ASL, but are fully active above 4900 m ASL. Above 5000 m ASL, flat surfaces where snow drifts last for several weeks are covered by frost-heaved blockfields and, in some places, 3–6 metre diameter non-sorted polygons are bounded by frost cracks. Geomorphic evidence, and ground temperature measurements made during the warmest period (November), demonstrate the presence of permafrost above 5400–5500 m ASL (−5 °C annual air isotherm).

Rock glaciers are generally small in size (<0.05 km^2) and strongly controlled by topography. Ice content in the permafrost depends on water concentration which is always higher in the depressions, cirques, confluences of couloirs and scree slopes. Annual precipitation is around 250–300 mm on the summits (Vuille and Amman, 1997) and is exclusively solid above 5000 m ASL. Snowfalls are frequent in summer (December–March), owing to thermo-convective processes associated with the inter-tropical convergence zone. However, snowfalls are also possible in winter, associated with the shift northwards of the cold polar fronts, or 'cut-off' events (Vuille, 1996). In some years, a discontinuous snow cover can last two or three months at high altitudes. Snow disappears half by sublimation, half by melting, producing an estimated ground infiltration of close to 100 mm a^{-1} (Chauffaut, 1997). The potential sublimation, estimated by the Penman method, totals 3.5 mm d^{-1} at 5000 m ASL, with the following average conditions: −5 °C temperature, 20% humidity, 3 m s^{-1} wind velocity, 1700 J cm^{-2} d^{-1} global radiation input and an albedo close to 60% (fresh snow). Runoff comes from perennial springs associated with ignimbrite outcrops, talus slopes and old moraines and is several times higher than the efficient infiltration. This water has three possible origins: (1) the drainage of fossil nappes, particularly in the ignimbrite massifs; (2) hydrological processes associated with volcanism (hydrothermalism); (3) the melt of permafrost.

The last extensive wet climatic phase occurred during the Tauca period (15.5–12 ka BP) (Servant *et al.*, 1995; Argollo and Mourguiart, 1995; Sylvestre, 1997). During this period, the region was covered by extensive lakes and isolated ice caps. After a dry period dated *c.* 12–9.5 ka BP, a new transgression can be inferred from the lakes of the southern Bolivian Altiplano in the early Holocene (9.5–8.5 ka BP, Coipasa event). This chronology, with the two major wet periods, Tauca and Coipasa, are also represented in north Chile (Grosjean *et al.*, 1995). As in the north of Bolivia, a system of moraines can be identified in various massifs, lying at 4500–4700 m, 4700–4800 m and 4900–5100 m ASL respectively (Figure 1). Based on the data obtained in Peru and in north Bolivia,

Figure 1 The Caquella rock glacier (RGL). The three different moraines M1, M2, M3 between 4500 and 5000 m ASL. Interpretation from IGM-Bolivia aerial photography (1964).

the two lowest moraines are related to the Last Glacier Maximum (Tauca event, 16–12 ka BP), while the highest may correspond to the end of the Late Glacial period (11 ka BP) (Mercer and Palacios, 1977; Francou *et al.*, 1995a). Evidence suggests that the south Altiplano was dry after 7 ka BP but from 3.9 ka BP to 3 ka BP (Neoglacial), the climate became colder and wetter. The most important rock glaciers could have been active for 8000–10,000 years, with degradation and reactivation phases occurring during the Holocene. However, their development probably relates to the last 3 or 4 millennia. Very few recent moraines related to the Little Ice Age have been identified in this region. One lies on the upper zone of the Caquella rock glacier at 5650 m ASL. The existence of this moraine suggests the presence of an equilibrium line on glaciers below 6000 m ASL during recent centuries.

THE CAQUELLA ROCK GLACIER

The Caquella rock glacier is exceptional in the inner tropics in its size: 0.23 km^2, 1200 m long, 180 m wide, and with an impressive front ranging from 5400 m to 5480 m ASL. Four ridges are distinguished, each clearly derived from scree-slope deposits (Figure 2). There is no evidence of a glacier origin for this rock glacier, and the Little Ice Age moraine is clearly superimposed upon the debris surface. The last 200 metres of the tongue are separated from the median part by a 30–40 m high transverse fracture, which behaves as an axis of drainage for meltwater: on the south-west external slope, an ice apron has formed owing to the presence of a permanent spring. This crevasse was open in 1996 and it was possible to observe, to a depth of 20 metres, the structure of the permafrost, to take ice samples for $\delta^{18}O$ analyses and to measure the temperature of the frozen materials. Finally, 200 m to the south-west, two smaller lobate rock glaciers exist on a steep slope.

GEOELECTRICAL FIELDWORK

Geoelectrical DC soundings using the Schlumberger method with four electrodes AMNB have been performed many times on rock glacier materials

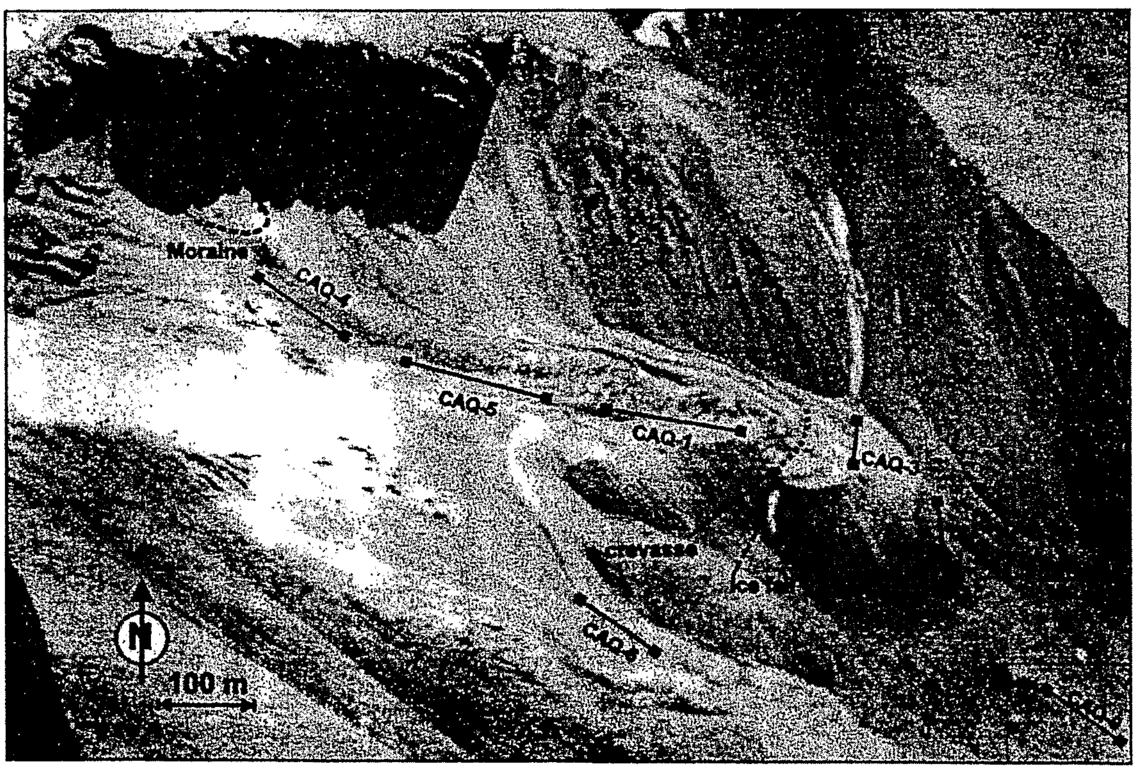

Figure 2 The Caquella rock glacier, showing the lines used for geoelectrical soundings (see text). The Little Ice Age moraine and the crevasse are represented. CAQ-0 site is 400 m downslope. Interpreted from IGM-Bolivia aerial photography (1964).

since the first experiments in Switzerland in the 1970s (Fisch *et al.*, 1978). The interpretation of the apparent resistivity curves (ρ_a versus $AB/2$, the half distance between the two injection electrodes) produces a geoelectrical profile for the terrain below the central point of the sounding where ρ_1, ρ_2, ρ_3... are the interpreted values of the layers and h_1, h_2, h_3... are their thicknesses. The results are more precise in locations where the stratigraphy is regular, the beds are homogeneous, and there is a good contrast in the electrical properties of the beds. With rock glaciers, which are composed of a mixture of rock and ice, with a possibility of ice lenses, homogeneous bed conditions are frequently not met. Some authors (Haeberli and Vonder Mühll, 1996) report values as low as 10,000 to 20,000 Ω m. The resistivity of ice is usually higher than 1 MΩ m, i.e. some 1000 times greater than that of unfrozen rock and debris. Even where ice does not occupy a large percentage of the volume, as is frequently the case with ice-cemented materials, there can be strong electrical contrasts. From measurements made in 1996, the internal structure of an active rock glacier can be summarized as follows (Assier *et al.*, 1996):

(A) a top layer without ice, with resistivities between 1000 and 15,000 Ω m, depending on particle size distribution, water content, compaction and the mineralogical nature of the debris;
(B) an icy layer with a variable ice content of a few per cent (undersaturated), 30%–40% (saturated) or greater (oversaturated; ice lenses); the resistivity of this layer, according to our measurements, may vary from 20,000 Ω m to several MΩ m;
(C) a substratum without ice, with resistivity generally lower than 5000 Ω m.

For the best interpretation of the resistivity curves, the method needs to calibrate the resistivities of both bedrock and ice in the vicinity of the rock glacier investigated. The main difficulty is to find the ice: outcrops are rather uncommon, except when there is a glacier or a glacieret above the rock glacier. Soundings directly on the ice can be problematic and the assumption is made that the interstitial ice within the debris is not electrically (ionically) different from that observed and measured. The only site where calibration of the electrical method was made adjacent to a borehole record – the Murtel–Corvatsch rock glacier (Fabre and Evin, 1990) – makes us confident of the technique. Since 1986, however, a number of successful soundings have been achieved on rock glaciers, particularly in the Alps and the Yukon. They indicate that the electrical resistivity technique gives a good indication of the amount of ice in frozen sediments (Fabre and Evin, 1990; Evin and Fabre, 1990; Evin *et al.*, 1997).

Seven electrical soundings were performed in the Caquella area during July 1997, using the Schlumberger method. The apparatus is a BM1 from Maatel Electronique SA. Owing to the high injection voltage available (2000 volts), the BM1 is well adapted for high resistivity materials such as those typically encountered in active rock glaciers.

On the surface of the Caquella rock glacier, four principal resistivity lines were drawn up (Figure 2).

(1) a 100 m long transverse line near the terminal front at 5480 m ASL (CAQ-3);
(2) a 240 m longitudinal line at 5530 m ASL (CAQ-1) (this offered a good opportunity to calibrate in materials where interstitial ice exists);
(3) a 300 m line in the median zone, at 5540 m ASL (CAQ-5);
(4) a 200 m line in the upper zone, 50 m below the Little Ice Age moraine, at 5580 m ASL (CAQ-4).

Away from the main rock glacier, three shorter lines were established:

(5) on a ridge located below the terminal front at 5300 m ASL (CAQ-2);
(6) on a little lobate rock glacier at 5400 m ASL (CAQ-6);
(7) on a gentle slope at 4900 m ASL, where stone-banked solifluction lobes are active and bedrock is close to the surface (CAQ-0).

INTERPRETATION OF GEOELECTRICAL SOUNDINGS

All the resistivity measurements show low values (see Table 1 and Figure 3). The interpreted resistivity value of layer B, when present, is always lower than 40,000 Ω m. Such values preclude the presence of massive ice in the materials.

Soundings in the Rock Glacier

In 80% of the measurements, the available intensity was as high as 25 mA. This means that contacts

Table 1 Electrical resistivity measurements in the Caquella area.

Resistivity line	Altitude (m ASL)	Description	Apparent resistivity (Ω m) Minimum	Maximum	First layer ρ_1 (Ω m)	h_1 (m)	Second layer ρ_2 (Ω m)	h_2 (m)	Third layer ρ_3 (Ω m)	h_3 (m)
CAQ-0	4900	Bedrock	1500	4000	1500 A	3	4000 C			
CAQ-1	5530	Longitudinal, central part (2 × 120 m)	3800	21,000	3200 A	3	30,000 B	40	4000? C	
CAQ-2	5300	Longitudinal, lower accumulation (2 × 40 m)	800	1800	750 A1	2	2000 A2	> 20	–	–
CAQ-3	5300	Transversal, frontal zone (2 × 50 m)	1800	7300	2500 A1	2	5000 A2	20	35,000? B	–
CAQ-4	5480	Longitudinal, higher part (2 × 100 m)	5500	14,500	10,000 A	20	50,000? B	3?	4000 C	–
CAQ-5	5540	Longitudinal, central part, right side (2 × 150 m)	1500	4100	3200 A1	1	2000 A2	3	4500 C	25
CAQ-6	5400	Nearby small form (inactive?) (2 × 70 m)	5400	12,000	15,000 A	20	4000 C			

Interpretation of soundings uses the classical multilayered earth method. Letter A, B or C refers to the type of layer when the classical structure is found (see text).

were correct between the electrodes and the materials.

In the *frontal zone*, on the CAQ-3 site, the apparent resistivity found ($\rho_a = 3000–4000\ \Omega$ m) and the variation through the first layer suggest that it is 20 m thick and that it contains no ice. Below a depth of 20 metres, values tend to rise.

In the *median zone*, close to the crevasse, on the CAQ-1 site, ρ_a value exceeding 20,000 Ω m were measured. The first 2–3 m, with $\rho_a = 3500–4000\ \Omega$ m, are without ice, but at depth the presence of ice is evident. Nevertheless, the apparent resistivity ($\rho_a < 30,000\ \Omega$ m) is characteristic of low ice content materials. According to the measurements, this layer could be 40 m thick. These results are in agreement with direct observations made in the crevasse: below the first 2–3 m, the presence of interstitial ice was observed, representing 20–30% of the total material. Lenses and other ice features were not detected across the 20 m explored (Figure 4). Measured at a depth of 20 m with a digital thermometer (resolution 0.1 °C), the ice temperature was constant at −1.6 °C, typical of 'warm' mountain permafrost. Thus, the upper 2–3 m of openwork materials may be viewed as being the active layer. On the CAQ-5 site, 250 m upslope, four layers were detected, but materials had low apparent resistivity values ($\rho_a < 5000\ \Omega$ m) and the last had an even lower resistivity ($\rho_a < 2000\ \Omega$ m: bedrock?). It can be inferred from these values that ice is absent in this zone.

In the *upper zone*, on the CAQ-4 site, at 5600 m ASL, close to the Little Ice Age moraine, apparent resistivity measured near the surface ($\rho_a = 10,000\ \Omega$ m) was not consistent with the presence of ice. Two small 'peaks' are relevant: the first, near the surface, may reflect a thin layer of interstitial snow; the second, at a depth of 20 m, may indicate the presence of a small quantity of ice (only a few metres thick) in the material. As the curve drops, the presence of ice is precluded below 30 m.

Soundings away from the Rock Glacier

On the *ridge feature* below the terminal front (CAQ-2 site), materials are dense owing to the presence of compacted sand and silt. This explains the low apparent resistivity ($\rho_a = 1000\ \Omega$ m). As a consequence, the presence of ice is impossible.

On the *small lobate rock glacier* (CAQ-6 site), the surface material is coarse and openwork. Its

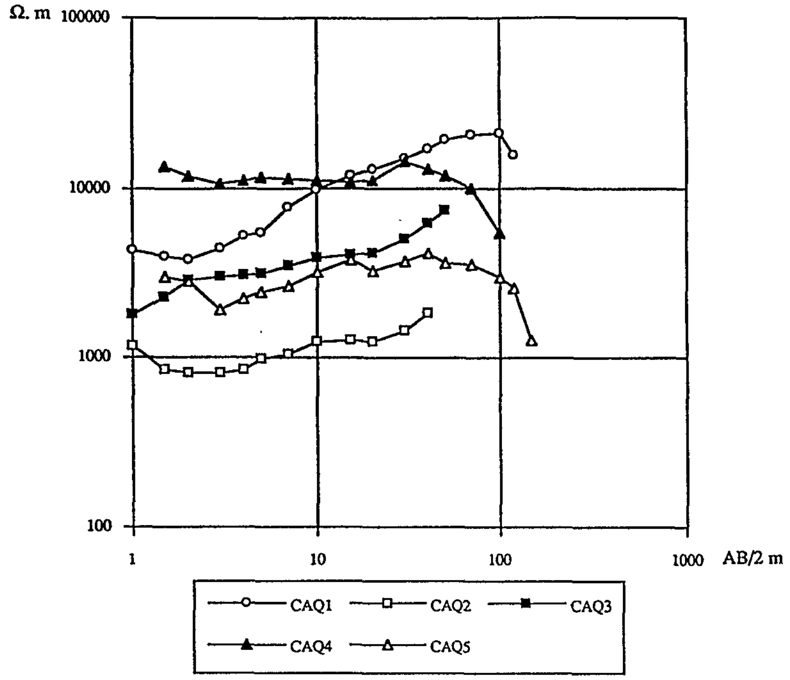

Figure 3 Geoelectrical curves at the different sites of the Caquella rock glacier.

conductivity is poor and the sounding shows a typical resistivity for scree materials ($\rho_a = 10,000\ \Omega$ m), which could be 20 m thick.

On the *stone-banked lobes and the bedrock* (CAQ-0 site), from the surface to a depth of 3 m, materials are coarse and granular. Below this layer, the apparent resistivity stabilizes at values close to 4000 Ω m. The resistivity and the presence of two layers suggest hard bedrock lies just below the stone-banked features. Ice is absent on this site.

DISCUSSION

Generally, the apparent resistivity values found are low and ice, when present, is discontinuous. This suggests a rock glacier in a degradation phase. Only one site (CAQ-1) shows clear evidence of ice, but this does not exceed 30%. In the upper zone, as well as the frontal zone in the first 20 m below the surface, ice amounts are poor. One sector of the median zone shows no evidence of ice at all. These data are confirmed by geomorphic features. The frontal part, which represents 20–30% of the total volume, is abruptly depressed some metres lower down the large fracture. The difference in elevation across the crevasse is estimated to be about 30 m, equivalent to 25–30% of the total volume of this zone. The crevasse offers a drainage line for meltwater, which runs off on the south-west front and forms an extensive ice apron. This drainage seems to be permanent, as attested by the presence of the icefall on aerial photographs taken in 1964 by IGM-Bolivia (see Figure 2). In November 1996, meltwater runoff was estimated to be $2\ \mathrm{l\ s^{-1}}$ at 1:00 p.m. The origin of the crevasse is unknown, but it has formed at the contact of materials with clear differences in ice concentrations. Laboratory experiments on frozen materials indicate increasing strength when ice content decreases below 20–30% (undersaturation) (see Williams and Smith, 1989). Thus, if the deformation and velocity were higher upslope and lower downslope, the crevasse could have formed as a result of compression causing materials to shear. A volume loss is also deduced from a 100 m × 20 m furrow-like depression located in the median part of the rock glacier, which is 15 m lower than the ridges on both sides.

Other measurements on this rock glacier are needed to confirm this diagnosis. They include: (a) analyses of aerial photographs over the last 40 years, (b) periodic topographic surveys of marks painted on the rock glacier surface, and (c) the analysis of data from an automatic meteorological station installed at 5500 m ASL. Micro-meteor-

Figure 4 Horizontal view on the vertical wall of the crevasse, at 20 m depth. Interstitial ice does not exceed 30%. The scale represents 0.30 m.

ological data from the ground and in the active layer are also needed to provide information about precipitation, snow cover, energy balance and temperature evolution at depth. Such measurements need to be coupled with direct observations on snow sublimation and melt during summer and winter.

CONCLUSION

Rock glaciers in the Inner Tropics are rare, but of a great interest as climatic indicators. Snow cover being sporadic, a rock glacier surface receives great quantities of energy all year round due to the high radiation intensity and the low albedo. Such conditions may induce a specific response to climatic variability. These rock glaciers may be particularly sensitive to climate change, as compared to their mid- and high-latitude equivalents. The Caquella rock glacier shows clear symptoms of degradation. The conditions which have given rise to this change seem to be recent, because there is clear evidence that the site was covered by a small glacier during the Little Ice Age. If verified by further investigations, the evolution of this rock glacier could be compared with that of tropical glaciers, recent investigations of which have indicated a dramatic retreat during the twentieth century, and more particularly over the last 50 years

(Francou *et al.*, 1995b; Ames and Francou, 1995; Hastenrath and Ames, 1995; Kaser, 1995).

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