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PRESENT STATUS AND DEVELOPMENT OF ROCK GLACIER COMPLEXES IN SOUTH-FACED VALLEYS (45°N, FRENCH ALPS)

ABSTRACT: BODIN X., *Present status and development of rock glacier complexes in south-faced valleys (45°N, French Alps)*. (IT ISSN 0391-9838, 2013).

The landscapes of the Vallon de la Route and Vallon de Pradieu (France) display typical geomorphological features of the Southern French Alps, with very few or no glaciers but a wide periglacial belt that extends from 2500 to 3100 m a.s.l. These valleys are unusual in that they contain several generations of rock glaciers that, from their rooting zone to their front, have developed in a topoclimatic setting characterised by high mean insolation (southerly aspect) and relatively low altitude. In this work, we determined the present status of these landforms, and more precisely the characteristics of the icy layers within the rock glaciers, *via* electrical soundings and thermal measurements, which we then combined with field observations. The permafrost zones in both areas are highly fragmented, whereas ground-ice can be present in landforms previously assumed as relict on the basis of their geomorphological characteristics alone. We used an empirical relationship between rock glacier flow velocity and terrain slope to estimate the time needed for both rock glacier assemblages to reach their present size. Our analyses therefore provide at the same time a broad relative chronological framework of the landscape setting up together with an overview of the spatial patterns of ice-rich permafrost features. It also suggests a number of hypotheses for the development of these landforms; however, further work involving more accurate dating methods is required to constrain these hypotheses.

KEY WORDS: Rock glacier, Permafrost, Landform development, Southern French Alps.

INTRODUCTION

Since the retreat of the Quaternary glaciers, the rock glaciers that have developed in relatively dry and poorly glaciated ranges, such as the Southern French Alps, are one of the most prominent features of mountain landscapes. Many valley bottoms are filled by multi-generational complexes of periglacial landforms that may extend for several kilometres (Evin, 1987), illustrating both the importance of rock glaciers as material conveyors and the variations over time in the conditions needed for their development, generally indicated by a succession of active, inactive and fossil forms (Haeberli & *alii*, 2006).

In the present context of changing climate, the stability of ice-cemented debris slopes has become an important issue (Arenson & *alii*, 2002; Gruber & Haeberli, 2009; Haeberli & Gruber, 2009), especially at the marginal boundaries of permafrost where transient equilibrium conditions may change rapidly and substantially. Nevertheless, it is difficult to determine the present state of mountain permafrost-related features, the most common of which are rock glaciers, and to discriminate between intact (presence of ground-ice) and relict (absence of ground-ice) rock glaciers, on the basis of geomorphological information alone (Barsch, 1996). This is especially true in crystalline lithology, such as in our study area, where the lack of fine material within the rock glacier body leads to a small decrease of the volume when the ice melts and to weaker morphological criteria. Additional datasets are therefore needed to decipher the state of rock glaciers: a good alternative, in a feedback approach, is to use ground-based data to improve the interpretations made from geomorphological observations.

From this point of view, the Vallon de la Route and Vallon de Pradieu rock glacier assemblages (Combeynot Massif, Hautes-Alpes, France; fig. 1) are ideal study areas, as they contain several generations of active, inactive and fossil landforms marked by high insolation (southerly aspect), and have similar geological settings. In addition, a

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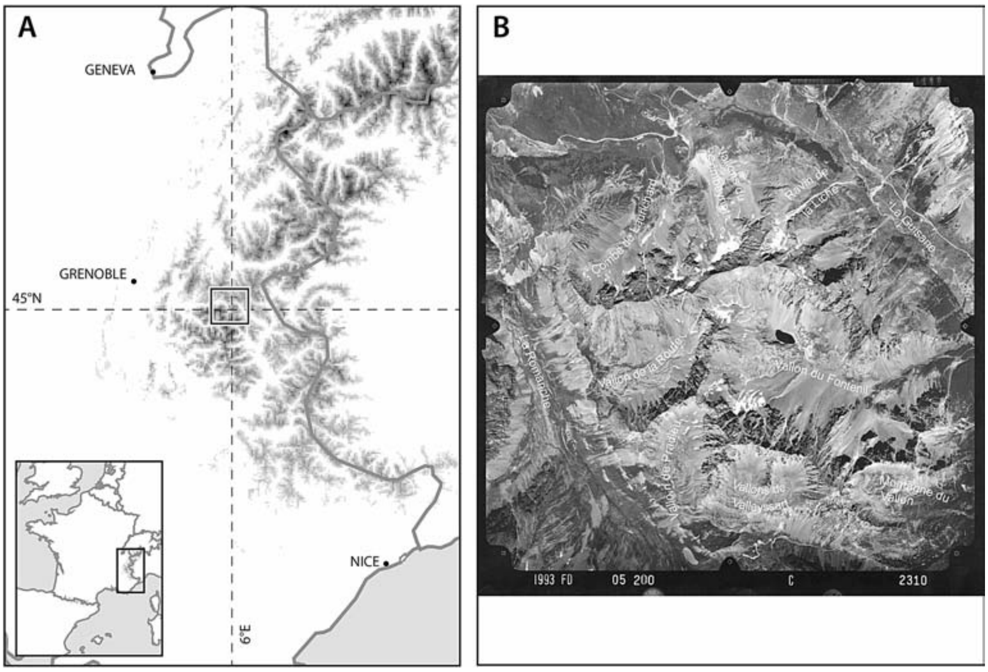

FIG. 1 - Location of the Combeynot Massif in the French Alps (A); Aerial photograph showing the Route and Pradieu valleys (A). Source: Institut Géographique National (1993 FD 05 200).

large amount of geophysical data is available for these areas thanks to a series of monitoring campaigns conducted over the last 10 years (Bodin, 2007). In order to determine the present status of the permafrost (*i.e.*, the presence of ground-ice and its spatial distribution), evaluate possible topoclimatic controls on permafrost, and draw up a chronological framework for the formation of these landforms, we combined three approaches: (i) geomorphological analysis based on field observations and measurements, aerial photographs and digital terrain modelling; (ii) thermal (winter temperature at the snow/ground interface) and geophysical (vertical electrical soundings) measurements; and (iii) a simple model of rock glacier development based on the relationship between rock glacier surface velocity and terrain slope.

We first present the general context of the study, the regional geological and climatological settings and the geomorphological characteristics of the two study sites. The Results section presents the datasets available for each investigation method, which are then used to propose a new interpretation of the area geomorphology. In the Discussion section, we highlight the significance of our results for pinpointing the current status and discontinuous distribution of the permafrost and reconstructing the possible evolution of the rock glacier assemblages during the Holocene.

STUDY AREA

Previous work on rock glaciers in the Southern French Alps

The first person to study rock glaciers in the Southern French Alps was probably Faure-Muret (1949), who produced a geological map that includes rock glaciers in the Maritime Alps. At about the same time, Michaud (1950) started surveying blocks on the Chambeyron rock glacier (Alpes-de-Haute-Provence), work that was then continued by Pissart (1964). More recently, Evin (1987) carried out a regional-scale study of the dynamics, distribution and structure of rock glaciers in the Southern French Alps (Fabre & Evin, 1990; Evin, 1996), producing much valuable data, including numerous geophysical surveys.

In the late 1970s decade, Francou began a still-ongoing geodetic survey of the Laurichard rock glacier in the Combeynot Massif, on the northern edge of the Mediterranean mountain domain (Francou, 1981; Francou & Reynaud, 1992). Recently, Francou's data have been used to assess the potential long-term reaction of ice-rich permafrost to warming air temperatures (Bodin & *alii*, 2009). Working in the Franco-Italian border area, Ribolini & Fabre (2006) and Ribolini & *alii* (2010) used the results of numerous geophysical surveys (electrical resistivity tomography) to describe the internal structure, especially the icy layers, of rock glaciers and recently deglaciated margins. By combining their results with geomorphological and stratigraphic datasets they were able to define the probable recent evolution of these environments.

Additionally, the collapse of the Bérard rock glacier (Alpes-de-Haute-Provence) in the summer of 2006 (Krysiecki & *alii*, 2008), even though it was an exceptional event, raised the question of the stability of warming ice-rich permafrost slopes (Roer & *alii*, 2008), especially close to their latitudinal and altitudinal limits. In the nearby Clarée valley, Cossart & *alii* (2010) proposed a chronological framework of the rock glaciers development, in the light of the absolute dating of Quaternary glacial landforms. Also in the Clarée valley, geomorphological studies of rock glaciers evolution combined to the monitoring of surface dynamics are performed by Cossart & Perrier (2011) and Perrier (2013).

Morphostructural setting of the Combeynot Massif

The Combeynot Massif consists of a slice of granite enclosed within volcano-sedimentary gneiss and locally covered on its eastern side by the flysch nappe of the ultra-Dauphinoise zone (Barbier & *alii*, 1973). The crystalline rock shows signs of pre-Hercynian hydrothermal activity, which causes macro-crystalline scale fragility. In addition, the massif is cut by a network of NNW/SSE faults and a high density of diaclases, producing metre and sub-metre scale jointing of the rock (Francou, 1981). The action of gravitational and nivo-periglacial processes (cryoclastic and avalanche activity) on this poorly differentiated but weakened geological structure has produced thick superficial deposits, mostly consisting of coarse material. Those superficial deposits, and especially the numerous rock glaciers, give the massif its geomorphological specificity (fig. 1).

Climatic setting

The Combeynot Massif lies in the transition zone between areas with a Mediterranean climate and areas with a more oceanic climate. As a result, the massif climate is characterised by a succession of westerly frontal situations and «*retour d'est*» situations (precipitation regimes coming from the Italian side of the Alps) and summers with low precipitation.

In terms of air temperature regimes, the analysis of regionally available datasets (1971-2000; from Bodin, 2007) from the nearest Météo France stations (Saint-Christophe, 1570 m a.s.l.; La Grave, 1450 m a.s.l.; Le Monétier, 1459 m a.s.l.; Briançon, 1324 m a.s.l.) and from shorter time series recorded in the Combeynot Massif (Institut de Géographie Alpine stations, Grenoble; unpublished data available for 1983 to 1995: Plan de l'Alpe, 2050 m a.s.l.; Arsine, 1675 m a.s.l.; Route, 2550 m a.s.l.) gives the following overview of the local climatic characteristics (fig. 2): (i) Monthly air temperatures are negative for 4 months of the year at 2000 m a.s.l., and for 8 months of the year at 3000 m a.s.l.; (ii) For the period 1961-1990, mean annual 0 °C and –2 °C isotherms were at 2560 m a.s.l. and 2910 m a.s.l., respectively; (iii) Thermal inversions occur quite frequently during the coldest months, including at high elevation (Route station, 2550 m a.s.l.).

Regarding the snow cover, despite the fact that the series is more than 20 years old, it's worth mentioning the regular snow-height measurements made by Francou (1987) over seven successive winters in the nearby Combe de Laurichard (at 2450 m a.s.l., located in the Combeynot Massif, a few kilometres further North). There is usually little snow in autumn (thickness of the snow cover <0.5 m) and that the snow cover starts to thicken in December. The snow-pack is generally more than 1-metre-thick in January and there is often a second phase of thickening in March. Maximum snow thickness is usually attained at the beginning of May. The snow-pack then melts over the period May to July.

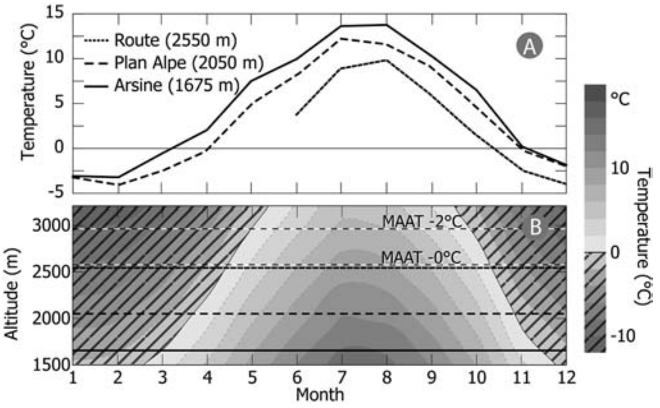

FIG. 2 - Mean monthly air temperatures recorded at three local topoclimatic stations located in the Combeynot Massif (A). Route, 1982-1998; Plan de l'Alpe: 1982-1998; Arsine: 1985-1998. Source: Institut de Géographie Alpine, Université Joseph Fourier, Grenoble. Evolution of mean monthly air temperatures extrapolated from 1500 to 3200 m a.s.l. using 1961-1990 datasets from the four stations closest to the Combeynot Massif (B). Source: MétéoFrance. The bold lines show the altitude of the above-mentioned local topoclimatic stations, and the two thin lines correspond to the altitude of the –2 and 0 °C isotherms.

Multi-decadal climate trends, obtained by analysing the above-listed regional datasets are consistent with the results reported by Durand & *alii* (2009b), showing two main phases of temperature increase (in 1980-83 and 1985-90), and a general warming of 1 to 2 °C between the 1960s and today. It corresponds to a rise in the 0 °C and –2 °C isotherms of 150 to 300 m. According to Durand & *alii* (2009a), warming is greater between 1500 and 2400 m a.s.l., whereas Kotlarski & *alii* (2012) model also predicts that warming in Europe will be higher at high elevation, by 3 to 5 °C during the next century. According to the studies of Corona (2007) and Durand & *alii* (2009a), no clear trend for rainfall and snowfall is found on the available climatic datasets.

Geomorphological setting: distribution of rock glaciers

The Combeynot Massif contains 33 fresh rock glaciers and 38 relict rock glaciers of various sizes and morphologies (fig. 3). These rock glaciers lie at altitudes of between 2000 and 2850 m a.s.l. The mean altitudes of the fresh rock glacier root zones and glacier fronts are 2700 m a.s.l. and 2620 m a.s.l., respectively. In summer (June to September), Potential Solar Incoming Radiation (PSIR) ranges from 80 to 270 W/m^2, with a mean of 200 W/m^2. The fronts of the relict rock glaciers have a similar PSIR range but extend down to between 2600 and 2000 m a.s.l., which is about 200 to 400 m lower than the fronts of the fresh rock glaciers.

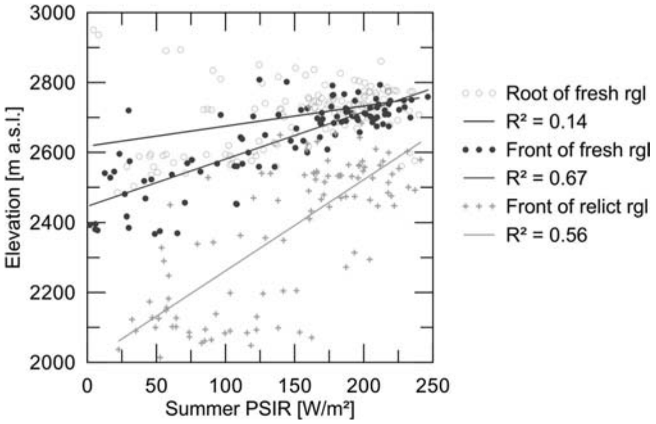

FIG. 3 - Elevation and summer (JJAS) Potential Shortwave Incoming Radiation (PSIR) at the root and front of the fresh rock glaciers, and at the front of the relict rock glaciers of the Combeynot Massif. The line shows the adjusted linear regression, and the corresponding coefficient of determination is shown in the key. We plotted between two and five points for each rock glacier front/root in order to take into account spatial variations in topoclimatic conditions across the landform.

METHODS

Geospatial datasets

We digitalised the 10-m contour lines on the Institut Géographique National (IGN) 1:25000 topographic map (drawn from photogrammetric work using airphotos taken at the end of the 1970s) in order to generate a 10-m resolution Digital Elevation Model (DEM10). Comparison with IGN benchmarks, positioned using differential GPS, showed the positional accuracy of the model to be ±5 m (Bodin, 2007). We applied the physically based, surface-energy balance model TEBAL (Topography and Energy Balance; Gruber, Zurich Univ.) to the DEM10 in order to calculate the PSIR (direct and diffuse radiation, expressed in W/m^2) at a 10-day time interval. Our study used the 10-m resolution grid of the average PSIR (PSIR10) for the snow-free period (June 20th - September 20th) to determine topoclimatic conditions for the two study areas (fig. 4). Finally, we used the IGN 0.5-m ground-resolution orthophotography for 2003, provided by the Ecrins National Park, as a base map for landform recognition.

Geomorphological analysis

Recognition of permafrost-related landforms in debris accumulations is based on morphological features that indicate the presence of ice in the ground. In the homogeneous geological setting of the Combeynot Massif, the slow (a few dm/a to 2 m/a) and steady (on a multi-decade scale) downslope creep of ice/debris mixtures (a few metres to a few decimetres thick; Haeberli & *alii*, 2006) is one of the most efficient geomorphological process in combination with active debris production and transportation activity by the above-mentioned gravitational and nivo-periglacial processes.

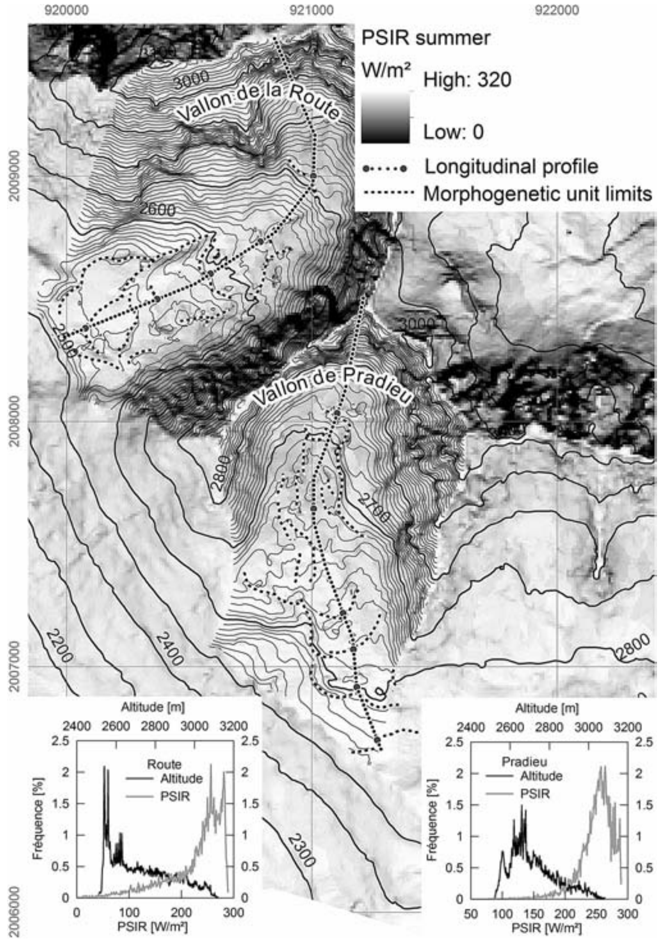

FIG. 4 - Distribution of summer (JJAS) Potential Shortwave Incoming Radiation (PSIR) calculated from the TEBAL model (Gruber, 2005) for the Route and Pradieu Valleys. Source: Institut Géographique National for the orthophotographs. IGN Top25 map contour lines, 10 m equidistance, were digitalised by the author. The longitudinal profiles are those used in rock glacier development model (see Method and Discussion sections), and the intersection with the main units limit is shown by the dot. The lower insets show the relative frequency of PSIR and elevation of the Route and Pradieu Valleys.

Morphologically, the creep of ice-rich, permafrost debris accumulations is mostly indicated by the presence of tongue-shaped landforms called rock glaciers, that display the following local features (visible in the field, on the DEM10, or on the orthophoto): (i) Loose piles of debris that compact underfoot, which can indicate stretching of the terrain or local underground downwasting due to ice-melt; (ii) Ice-rich permafrost creep may also produce a succession of ridges and furrows with wavelengths and amplitudes of several metres, parallel to the creep direction in extensive sections and perpendicular to the creep direction in compressive sections, and a general slope that is lower than the slope of the gravitational screes that supply debris to the rock glaciers; (iii) Except when they are embedded in each other, active rock glaciers are delimited by well-defined lateral and frontal talus with steeper slopes than the material angle of repose, and a vertical sorting of debris (fig. 5).

FIG. 5 - Geometrical interpretation of rock glacier stacking with examples from Vallon de Pradieu. There are two main layouts: rock glacier 2 is embedded in rock glacier 3, and rock glacier 1 is stacked on top of rock glacier 2.

In our study, we mainly want to roughly determine the general chronological sequence of the different generations of creeping permafrost landforms from (i) the landform morphology and surface state of deposits (rounded blocks, protruding quartz crystals, abundant lichens, vegetation cover) and (ii) the geometric stacking of forms (fig. 5), the two most common layouts being embedding (rock glacier 2 embedded in rock glacier 1) and stacking (rock glacier 3 on top of rock glacier 2).

Measurement of winter equilibrium sub-surface temperatures

During winter, the temperature at the snow/ground interface mostly reflects the thermal state of the ground rather than atmospheric temperature. Continuous sub-surface temperature monitoring has demonstrated the existence of a Winter Equilibrium Temperature effect (Winter Equilibrium Temperature, WEqT; Delaloye, 2004), which occurs during the last 2 to 3 weeks before the snow starts to melt and when a thick and long-lasting snow cover has insulated the ground for a long enough period. We used Haeberli's (1973) Bottom Temperature of Snow-cover (BTS) method to assess the thermal state of the ground, using 3-m long probes equipped with a resistor to measure the temperature at the snow/ground interface during late winter and before the onset of snow melt.

Geoelectrical surveys

Electrical surveys involve using two electrodes to inject current into the ground, and then measuring the potential difference at two other electrodes. The potential difference measured at these electrodes depends on the dielectrical properties of the ground. In the case of ice-rich permafrost, interpretation of the resulting measurements is facilitated by the strong electrical contrast between ice and rock. In this study, we performed, during summer 2006, two types of geoelectrical survey:

(i) Vertical Electrical Soundings (VES): the device has a fixed centre where the current is measured, but the distance between the injection electrodes is gradually increased in order to increase the sounding depth. The apparent resistivity measured at each inter-electrode distance (up to 100 m in the present study) and data inversion are used to calculate resistivity/thickness values for each of the two to four horizontal layers that theoretically make up the ground. These layers often include an upper mantle of ice-free coarse debris («active layer» in permafrost terminology), an ice-rich layer, and an ice-free layer consisting of debris or bedrock;

(ii) Lateral Electrical Profiling (LEP) is performed using an array of fixed electrodes, so the current operates at a fixed depth. Lateral variations in apparent resistivity are mapped by moving the array along profiles. We used the Wenner configuration with an inter-electrode distance of 15 m in order to investigate the uppermost 8 to 10 m of the ground, which is supposed to cover both the active layer and the upper part of the ice-rich layer. Standard values from the literature (*e.g.*, Kneisel & Hauck, 2008; Delaloye, 2004) were used to classify resistivity values into four categories: >500 kΩ.m: sediments with a high ice-content (>40%), cold ice; 100 to 500 kΩ.m: sediments with a moderate ice-content (20 to 40%), ice-cemented sediments; 40 to 100 kΩ.m: sediments with a low ice-content (<20%), temperature possibly close to –1 °C; 20 to 40 kΩ.m: very little ice, probably temperate (>–1 °C), so that liquid water is also possible.

Chronological model of rock glacier development

Using the slope/velocity empirical relationship (fig. 6) calculated for a nearby monitored rock glacier (Laurichard rock glacier, Combeynot Massif, regular measurements taken between 1986 and 1999, annual measurements taken since 1999; Bodin & *alii*, 2009), and following Kääb's (2005) conclusions about the surface velocity/advance velocity ratio (on average, 0.26 for the rock glacier kinematics datasets

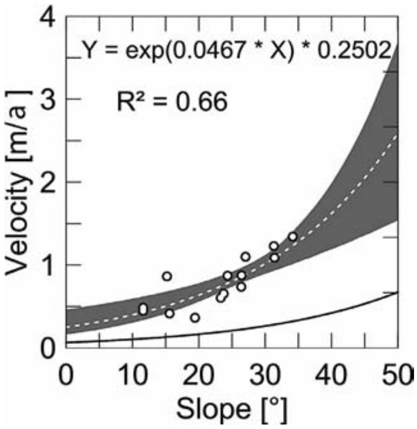

FIG. 6 - Relationship between slope and velocity at the surface of the Laurichard rock glacier (Combeynot Massif; after Bodin & *alii*, 2009). The white dashed line is the exponential adjustment, the grey envelope indicates the 95%-confidence interval and the black line is the calculated advance (26% of the surface velocity, see Method section for further explanation).

considered by Kääb, 2005), we estimated the theoretical advance rates of the Pradieu and Route rock glaciers along their main flow lines in relation to the slope angle provided by DEM10 (the profiles considered are shown in fig. 4).

This simplified model of rock glacier development does not take into account the spatial and temporal interactions between glacial and periglacial processes and landforms as no evidence of past glacier presence in the studied valleys are found. In addition, in spite of a rather well known glacial chronosequence (Cossart & *alii* 2012), our interpretations assume the highest possible initiation zone, based on present pieces of evidence, and constant climatic and glacial-geomorphic conditions during the time periods proposed for the development of the rock glaciers. In reality, this has not been the case and, particularly, the presence of a glacier could have pushed down the rock glacier initiation zone. Once again, this model is a simplification of a complex mechanical process, and is therefore only used to provide a gross quantified estimation of the time necessary for the rock glaciers to reach their present geometry.

THE «VALLON DE PRADIEU» ROCK GLACIER COMPLEX

Geomorphological and topoclimatic overview

The Vallon de Pradieu is an open, south-facing complex of rock glaciers surrounded by crests rising to between 2700 and 2900 m a.s.l. The valley floor is completely covered by both fresh and relict rock glaciers (between 2550 and 2760 m a.s.l.). Because of the aspect and slope of most of the terrain, the mean PSIR is very high (260 W/m^2), with the lowest values occurring at the foot of the steepest rock slopes, some of which face north to northwest (*ca*. 150 W/m^2; fig. 4). The foot of the west-facing valley side is marked by poorly developed creeping permafrost features such as protalus-ramparts with high frontal talus that appear to overlap relict rock glaciers. On the east-facing valley side, smaller protalus-ramparts have developed at the foot of partly vegetated screes. These ramparts are embedded in older generations of rock glaciers.

In the lowest part of the Pradieu complex, it is difficult to differentiate the various generations of rock glaciers on the basis of their morphology because of the blurring of topographic features and the numerous lateral flows that reach the main rock glacier axis. Nevertheless, the upper two-thirds of the valley clearly display at least five different units, extending down to 2530 m a.s.l., with a total length of more than 2 km and an area of 0.6 km^2. Termination of the landform has been limited by erosion of its lowest part as it advanced down the steep slope, as well as by the balance between the ice/debris feeding the root zone and the advance of the glacier front.

Results of thermal measurements

In early April 2006 we took 28 BTS measurements at between 2660 and 2750 m a.s.l. and on most of the orientations shown by the slopes of the Pradieu complex (fig. 7).

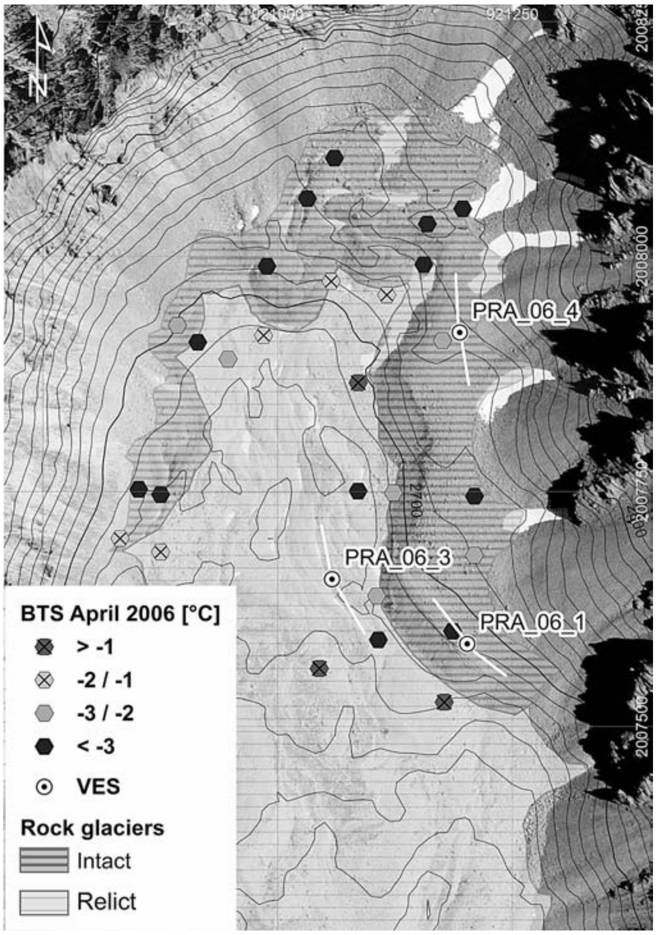

FIG. 7 - Geomorphological setting of the Vallon de Pradieu rock glacier complex, showing the location and value of the BTS measurements (carried out in April 2006) and the location of the VESs (carried out in summer 2006; the centre and the two branches of the profile are shown).

The resulting thermal footprints showed a clear distinction between the relict rock glacier in the central part of the valley, which had a BTS close to 0 °C, and the foot of slopes covered by active creeping landforms, where BTS values were mostly below –2 °C. The low BTS values (–2 to –5 °C) at the foot of the main frontal talus of the west-facing slope (near VES PRA_06_03) may be due to the presence of very coarse surface debris, which can trap cold air (Lambiel & Pieracci, 2011).

Results of geoelectrical measurements

Vertical electrical soundings (VES) are difficult to apply because the upper few metres of the ground consist of very loose and dry material with few inter-block contacts, thereby limiting electrical conduction into the ground. Nevertheless, we were able to use three of the four VES carried out for this study (fig. 8):

(i) PRA_06_1 (2690 m a.s.l., 252 W/m^2, 4-layer model interpretation) was carried out on an actively creeping ridge at the foot of the west-facing slope. This sounding indicates the presence of a 5 to 6-m-thick active layer of very coarse material (with finer sediments at its base, as observed at the rock glacier front) underlain by an ice-rich layer that is at least 20 m thick and that contains a higher resistance layer (ρ4>200 kΩ.m) at a depth of around 20 to 22 m;

(ii) PRA_06_4 (2740 m a.s.l., 245 W/m^2, 4-layer model interpretation) was carried out on the same landform as PRA_06_1 but at slightly higher altitude and closer to the rooting zone. The results suggest the presence of a 4 to 6-m-thick active layer consisting of coarse, dry material underlain by an ice-cemented layer (ρ3=96 kΩ.m) that is at least 10 to 12 m thick;

(iii) PRA_06_3 (2680 m a.s.l., 215 W/m^2, 4-layer model interpretation) was carried out on a relict vegetated ridge on a rock glacier in the bottom of the valley. The high apparent resistivity values found immediately below the surface (ρ2>100 kΩ.m on the first 2 m) are difficult to interpret, but it is unlikely that they are due to the presence of ice only a few decimetres below the surface. We rather suspect the resistive role of a dry openwork superficial layer.

We carried out two Lateral electrical profiles (LEP) on the Pradieu complex, perpendicular to the PRA_06_1 and PRA_06_4 VES sounding lines, starting from the centre of these lines, and running upslope over the protalus-rampart and the screes (fig. 9). Apparent resistivity values ranged from 40 to 93 kΩ.m, with a mean of 71.3 kΩ.m (σ=16.3). Values for PRA_06_1T LEP show a bell-shaped distribution, with a local maximum (93 kΩ.m) at the centre of

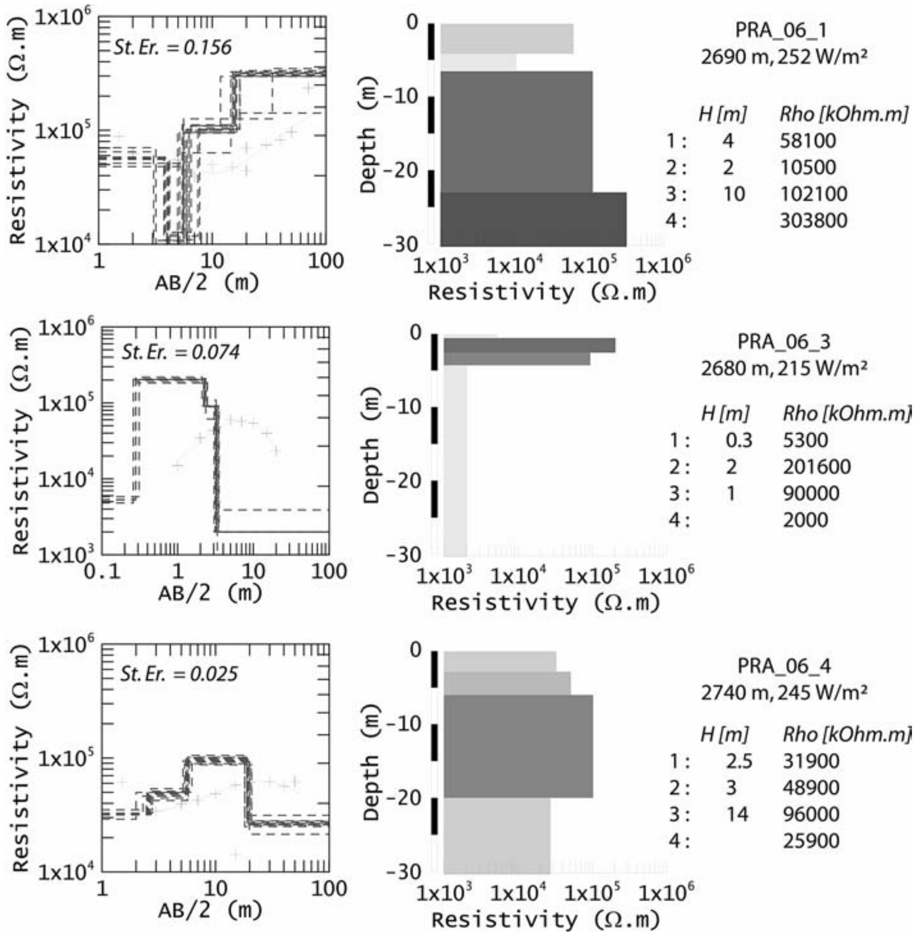

FIG. 8 - Interpretation of the vertical electrical soundings (VES) carried out in the Vallon de Pradieu in summer 2006. For each of the three VES raw data and inverted model are shown on the left, graphical scaled representation of the thickness (Y-axis) and resistivity (X-axis, the darker the rectangle the higher the resistivity) in the centre and numerical values for each layer on the right. The standard error St.Er is an estimator of the adjustment quality of the inverted model.

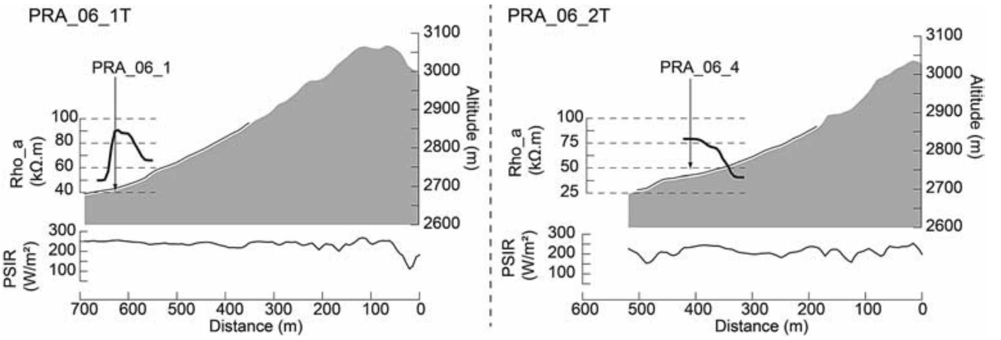

FIG. 9 - Representation, for each of the two lateral electrical profiles (LEP), along a topographic transect on the Vallon de Pradieu W-facing slopes of a) the apparent resistivity for an electrode spacing of 15 m (in kΩ.m), and b) the potential solar incoming radiation (PSIR, in W/m^2, see text for explanations). The location of the centre of intersected VESs is indicated by arrows.

PRA_06_1 VES. We find a similar distribution of values for PRA_06_2T LEP (profile started at the centre of PRA_06_2 VES) but the resistivity value at the beginning of the line is lower (79 kΩ.m). From a geometrical point of view, it is very likely that the high resistivity values found in the lower part of the PRA_06_1T and PRA_06_2T LEPs correspond to the upper part of the ice-rich layer detected by the PRA_06_1 and PRA_06_2 VESs at a depth of 5-6 m (96 kΩ.m<ρ<300 kΩ.m). In addition, we can notice the upslope lowering of the apparent resistivity suggests a change in the ice-content of the rock glacier.

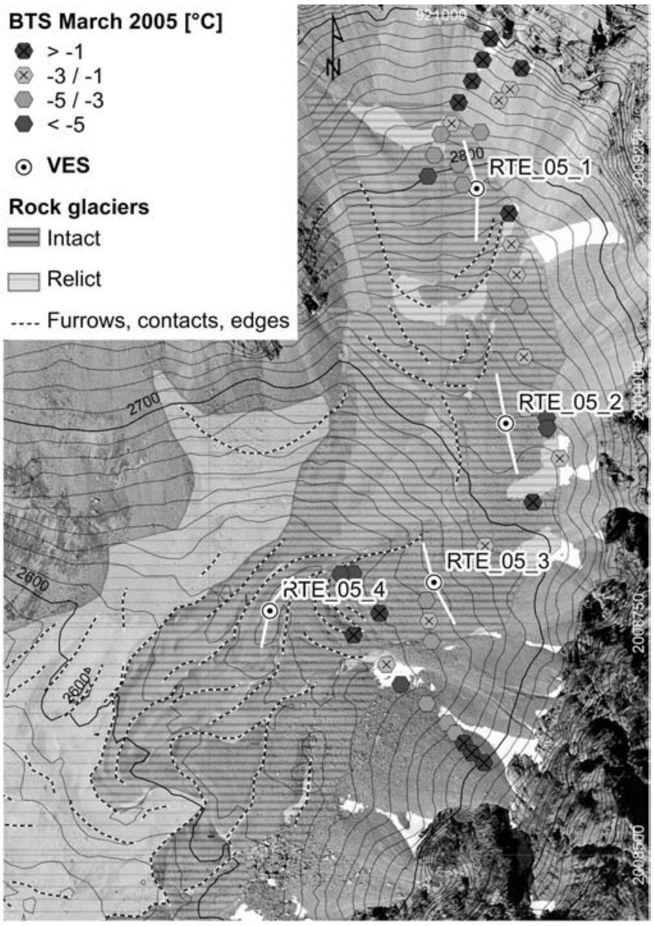

FIG. 10 - Geomorphological setting of the Vallon de la Route rock glacier assemblage, showing the location and value of the BTS measurements (carried out in March 2005) and the location of the VESs (carried out in summer 2006; the centre and the two branches of the profile are shown). The standard error St.Er is an estimator of the adjustment quality of the inverted model.

New geomorphological interpretation of the site

Our initial geomorphological interpretation of the probable distribution of permafrost in the Pradieu complex seems to be supported by both the electrical soundings and the BTS measurements. Only the latest generation of landforms, which are poorly developed and clearly connected to the upper scree slopes, can be considered fresh, as they are embedded in (east-facing slope), or overlap (west-facing slopes), the relict rock glaciers. The low LEP resistivity values measured upslope on PRA_06_1T and PRA_06_2T probably correspond to a lower ice-content in the layer immediately below the active layer. An increase in the thickness of the active layer could also lower the resistivity of the terrain, but there is no topoclimatic reason to suspect such an increase in thickness. The ice-rich permafrost is probably restricted to elongated layers within the protalus-rampart, parallel to the slope and with no clear connection to the upslope screes. This configuration has been detected by other studies (*e.g.*, Lambiel & Pieracci, 2011; Scapozza & *alii*, 2011): a decrease of the frozen layers thickness toward the upslope scree slope, possibly due to convective air circulations. The presence of the permafrost in the Pradieu complex therefore appears to be related more to upslope/downslope geomorphological effects (debris supply, snow redistribution by avalanches) than to topoclimatic differences.

THE «VALLON DE LA ROUTE» ROCK GLACIER COMPLEX

Geomorphological and topoclimatic overview

With a total length of more than 2 km, the Vallon de la Route rock glacier complex lies at between 3000 and 2500 m a.s.l. The complex runs N-S then NE-SW, and is surrounded by crests that reach 2800 to 3140 m a.s.l. The 300 to 700-m-wide valley bottom is almost completely covered by rock glaciers originating from northwest-facing and west-facing debris slopes (fig. 4). Morphological analyses indicated the presence of six different units, embedded within each other, between the upper south-facing and lower southwest-facing rock glaciers.

Results of thermal measurements

The 41 BTS measurements carried out during the winter of 2005 gave values ranging from –9 to 0 °C (mean= –2.6 °C, σ=2.4). However, the spatial distribution of these measurements is heterogeneous as we only took measurements in the upper part of the Route catchment, on rock glaciers interpreted as fresh and on scree slopes. We record large local variations in BTS values (fig. 11), probably due, at least partly, to differences in snow cover (thickness and timing). These variations make our results difficult to interpret in terms of the presence/absence of permafrost. Nevertheless, the scree slopes exhibit consistent thermal footprints, with low values at the foot of the talus and progressively higher values with increasing altitude. Although outside temperatures during the measurement campaign were well below 0 °C, we noted the presence of open melting windows through the snow pack. As Lambiel & Pieracci (2011) suggested, these melting windows may indicate local seasonal air circulations within the accumulations of coarse debris, leading to an over-cooling of the bottom of the talus and a relative warming of the upper part.

Results of geoelectrical measurements

Vertical electrical soundings (fig. 12) indicated the presence of a 4 to 8-m-thick active layer with remarkably constant resistivity (20 < ρ1 < 60 kΩ.m). This latter is underlain by a layer that may contain ice. The resistivity values for this lower layer (ρ2) ranged from 100 to 200 kΩ.m, which are typical of ice-cemented permafrost.

We interpreted our VES results as follows:

(i) RTE_05_1 was performed on the highest (2790 m a.s.l.) and sunniest (242 W/m^2) creeping landform and re-

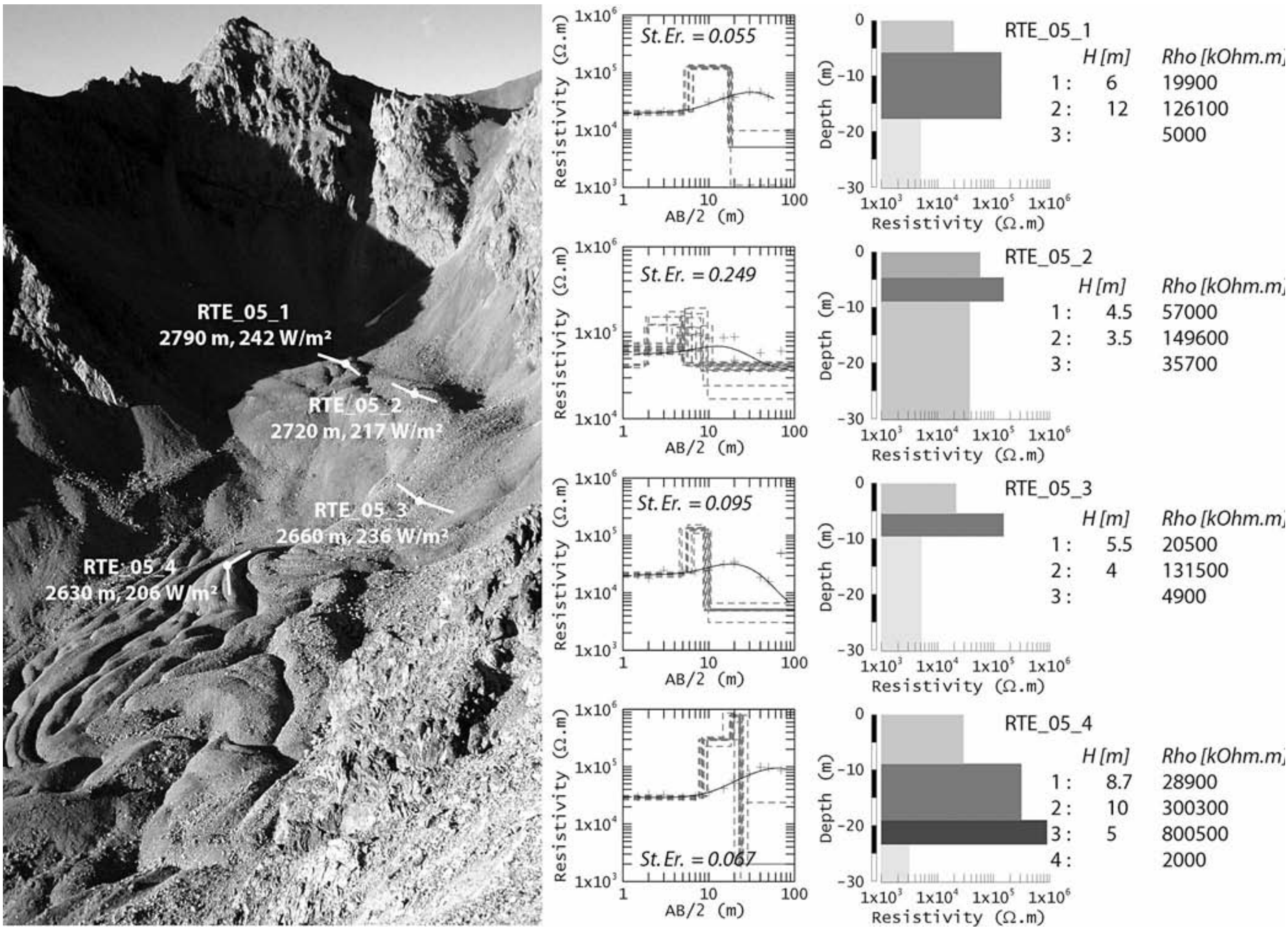

FIG. 11 - Interpretation of the vertical electrical soundings (VES) carried out in the Vallon de la Route in summer 2006. In addition to an overview of the VESs location on the left panel, on the right panel, for each of the four VES raw data and inverted model are shown on the left, graphical scaled representation of the thickness (Y-axis) and resistivity (X-axis, the darker the rectangle the higher the resistivity) in the centre and numerical values for each layer on the right.

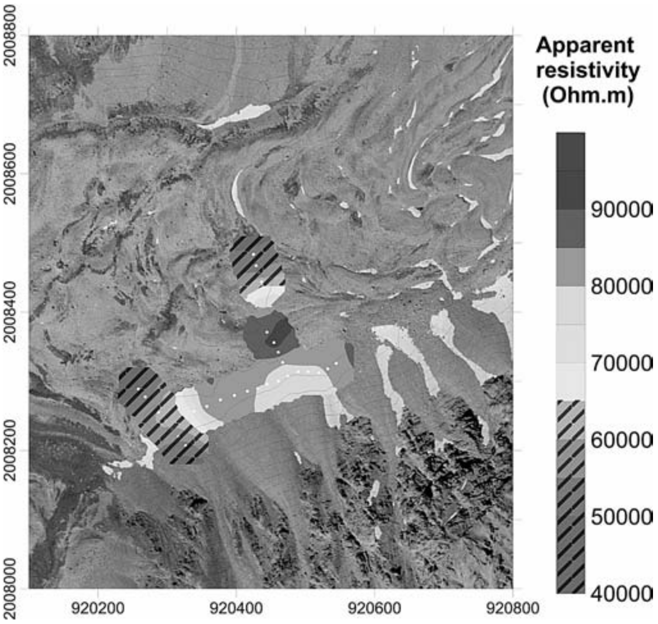

FIG. 12 - Apparent resistivity (in Ω.m) measured by the lateral electrical profiles (LEP) carried out in summer 2006 in the Vallon de la Route for an electrode spacing of 15 m (depth prospected *ca.* 8-10 m). The resistivity fields are voluntarily extrapolated over a 25-m radius for visual purpose but do not have a physical significance over such large area.

vealed a more than 10-m-thick ice-cemented debris layer (ρ2=110-135 kΩ.m) below a 5 to 7-m-thick active layer;

(ii) RTE_05_2 VES (2720 m, 217 W/m^2), at the foot of a 200-m-high scree cone on which avalanche deposits generally persist late into the summer, suggested the presence of a layer with a moderate ice-content (ρ2=120-180 kΩ.m), underlying a 2 to 7-m-thick active layer. However, it also displayed scattered values, implying important lateral variations in resistivity;

(iii) RTE_05_3 (2660 m, 236 W/m^2) indicated the presence of a relatively thin (4 to 5 m) ice-cemented debris layer (ρ2=120-155 kΩ.m) within the rock glacier, which is overlain by a 4- to 6-m-thick active layer. These low thicknesses may be due to stretching of the rock glacier body over a section of steeper terrain (25°);

(iv) RTE_05_4 (2630 m, 206 W/m^2) was located on a massive and very well defined ridge, in front of the rock glacier sounded by RTE_05_3. VES measurements were facilitated by the fact that the ground in this location contains a high percentage of fine materials (sands and gravels). The results suggest the presence of an 8 to 10-m-thick active layer, overlying a high resistivity layer (ρ2=300-800 kΩ.m), which suggests a high ice-content within a 15-m-thick layer. The morphology of the narrow ridge could also explain such resistivity patterns, the case being too far from the ideal semi-spherical configuration required by the model inversion of the geoelectrical datasets.

Lateral electrical profiles for the upper 10 to 15 m of the terrains measured exhibited apparent resistivity comprised between 35 and 145 kΩ.m (30 points, mean=72 kΩ.m, σ=30.2; fig. 12). Except for the ridge on the southern side of the study area (RTE_05_2T) and the inner part of the main relict rock glacier (RTE_05_3T), where we recorded the lowest apparent resistivity (ρa<60 kΩ.m), it is probable that all the creeping ridges at the foot of northwest-facing scree slopes that were prospected by LEP contain ground ice. The maximum resistivity value recorded in these locations was 90 kΩ.m.

New geomorphological interpretation of the site

Our geoelectrical measurements suggest that all the landforms we surveyed in the Route catchment contain ice below an active layer that thickens downslope to reach a maximum thickness of 9 m at 2630 m a.s.l. The thickness of the ice-rich layer probably does not exceed 15 m and may consist of ice-cemented debris, with occasional layers with higher ice-contents. Although the permafrost distribution indicated by these measurements concords with the morphological analysis, topoclimatic parameters do not seem to be the most important controls on permafrost distribution at a local scale, as shown by the abundance of landforms containing ice on very sunny slopes. In addition, geophysical survey results suggest that recent generations of rock glaciers may locally contain less ice than some older units that now appear to be disconnected from direct debris/ice supply.

DISCUSSION

Assessment of the status and discontinuous distribution of the permafrost

Our results suggest that high summer PSIRs do not preclude the development of an extended but discontinuous ice-rich permafrost at comparable elevations to similar landforms in north-facing settings. On the rock glaciers that present morphological signs of activity and where geophysical investigations suggest the presence of ground ice, the rooting zones are in terrain where the 1961-1990 regional Mean Annual Air Temperature (MAAT) was around –1 °C, for PSIR value ranging from 210 to 250 W/m^2.

Although local estimation of air temperature is only roughly approximated by extrapolation of regional climatic datasets (see Climatic setting), the fact that permafrost is most probably present under relatively warm surface topoclimatic conditions suggest that (i) a strong thermal offset (see Schneider & *alii*, 2012 for quantitative assessment of thermal offsets in mountain areas) is influencing the ground thermal regime, dropping it down by several degrees and (ii) a potential disequilibrium may affect the permafrost as regional air temperature have significantly increased since several decades (by 1-1.5 °C; Casty & *alii*, 2005; Durand & *alii*, 2009b).

Other insight from the geophysical approach is the low apparent resistivity found on the upslope part of the LEPs on both sites: it could indicate that the conditions favourable to rock glacier growth at the scree/rock glacier contact are not anymore encountered. Though hardly evidenced, the combined contribution of the coarse-debris insulation to protecting the subjacent permafrost and of the downslope export of permafrost by the creeping may explain that the investigated landforms are still active.

Possible Holocene evolution of the rock glacier complexes

According to the slope/advance relationship described in the Method section, the Route and Pradieu valleys main rock glacier would have needed around 10 ka to reach its lower, morphologically distinguishable front position at 2600 m a.s.l. (fig. 13). In the Route valley, the most recent creeping landform, whose front lies at around 2740 m a.s.l. and which lies on slopes of between 25° and 10°, would have needed approximately 1.1 ka to form.

As an element that could help to better understand the Quaternary evolution of our study sites, Cossart & *alii* (2010) proposed a regional chronological frame of the glacier retreat and rock glacier development based on absolute dating of geomorphological features by Cosmic Ray Exposure. On the basis of the altitude of 31 landforms and of their position relatively to dated glacio-geomorphological features, three main classes of rock glaciers are identified, which fronts stand at around 2400, 2500 and 2600 m a.s.l., respectively.

As the steepness of the slopes below 2500 m a.s.l., our study sites impeded the landforms to creep at lower altitude (see Geomorphological overview in the Results section), it is questionable whether the Route and Pradieu lowest rock glaciers should be attributed to the Late Glacial (± 11 ka), *i.e.* Cossart's oldest class, or to the Class 2, dated back to the Subboreal period. Nevertheless, the large extent of those lowest rock glaciers could point toward a Subboreal origin, as these authors suggest that a bigger amount of source debris was probably available at that time than during the Late Glacial, due to a higher altitude of glaciers allowing wider free faces to supply rock glaciers with debris.

CONCLUSIONS

The permafrost status and the potential Quaternary development of two rock glacier complexes located in the Southern French Alps, in very sunny conditions, were investigated using geomorphological and geophysical methods and by a simple empirical assessment of the rock glacier advance rate.

In terrains that receive summer irradiance generally greater than 210 W/m^2, high amount of ground ice was detected by geoelectrical measurements down to 2600 m a.s.l., under an active layer that varies from 4 to 8 m. As inferred from geophysical interpretations, the distribution of this ice in the ground is laterally heterogeneous, and, on protalus-rampart, the resistivity lowering towards the debris-supplying screes suggests a possible disconnection from the source area. The use of resistivity tomography could help in the future to specify the vertical and horizontal distribution of permafrost in the landforms and to better understand their present status, under warming climatic conditions.

In coherence with regional schemes of glacio-geomorphological evolution, the development of the various units of the Route and Pradieu rock glaciers assemblages amounts to at least 10 ka for the oldest rock glaciers. However, a Subboreal origin is also possible owing to the influence on ice and debris supply that might have had glaciers in the upper part of the valleys. Further relative and absolute dating works are required to constrain these assumptions and define a chronological frame that could explain the development of such large rock glaciers in very sunny environment.

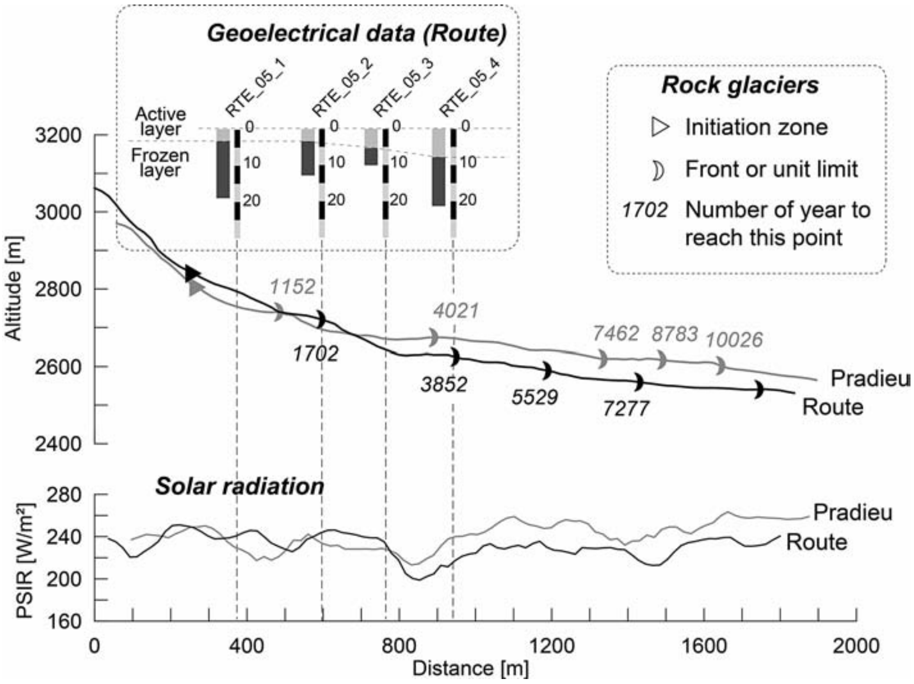

FIG. 13 - VESs interpretation along Vallon de la Route profile (A; see fig. 4 for location of the profile); Computed time necessary for the different units of Vallon de Pradieu and Vallon de la Route rock glaciers complexes according to the slope/advance relationship (B; see text for details); Potential shortwave incoming radiation (PSIR, in W/m^2) along a topographic profile across the two study sites (C).

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