MAPPING PERMAFROST AT A REGIONAL SCALE: INTERPOLATION OF FIELD DATA BY GIS APPLICATION IN THE UPPER DURANCE CATCHMENT (SOUTHERN FRENCH ALPS)

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ABSTRACT

Southern French Alps are mostly non-glaciated areas, but permafrost was locally evidenced at high altitudes (above 2800 m.a.s.l.). A clarification of permafrost spatial extent is currently needed because it constitutes a water resource. We suggest here a new method to map the permafrost. This method is based upon water temperature measurements, providing many observations (presence or absence) about permafrost in various physical settings. Such point-based data are integrated in a spatial database to realize an interpolation of the presence of permafrost. The study area is subdivided in many classes according to the incoming solar radiation. For each class, two thresholds are specified, one above which permafrost can possibly be observed, the other one above which permafrost can probably be observed. This method seems to complete previous models which were mostly based upon rockglacier inventories or BTS measurements. A map of permafrost extent is proposed, showing that it may possibly occur above 2500 m.a.s.l. in highly shielded areas. Some ice may be still stored within some footslope deposits, constituting a possible water resource.

Keywords: Southern French Alps, Permafrost, GIS modelling, water temperature, rockglacier, water resource.

CARTOGRAFÍA DE PERMAFROST A ESCALA REGIONAL: INTERPOLACIÓN CON SIG DE DATOS DE CAMPO EN LA CUENCA ALTA DEL DURANCE (ALPES FRANCESES MERIDIONALES)

RESUMEN

Los Alpes franceses meridionales no se hallan totalmente glaciados, pero existen numerosas evidencias locales de permafrost en sus tierras más altas (por encima de los 2800 msnm). A pesar de ello, resulta todavía necesario definir mejor sus límites y extensión, dado que constituye un importante recurso de agua para la zona. El método propuesto aquí para cartografiar la extensión del permafrost se basa en medidas de temperatura del agua y observaciones (presencia o ausencia) bajo

diferentes condiciones físicas. Con la base de datos puntuales así obtenidos se efectúa una interpolación espacial, dando finalmente como resultado seis clases según la radiación solar incidente. Para cada clase, se especifican dos umbrales, uno por encima del cual el permafrost sería posible, y otro que marca el límite del permafrost probable. Este método puede completar otros modelos anteriores basados principalmente en inventarios de glaciares rocosos o medidas BTS (temperatura basal de nieve). El resultado es un mapa del área de permafrost en la cuenca alta del Durance, donde se apunta como posible su presencia por encima de los 2500 msnm en áreas sombreadas, sobre todo en la base detrítica de algunas vertientes que permiten almacenar hielo y constituyen una fuente potencial de agua.

Palabras claves: Alpes franceses meridionales, permafrost, SIG, temperatura de agua, glaciar rocoso, recurso de agua.

1. Introduction

For the last two decades the alarm on global climate change has caused a renewed interest in the scientific topic of periglacial geomorphology (Haeberli, 1990). Geographers currently aim at reconstructing the distribution patterns of permafrost to survey its possible degradation. Permafrost is indeed considered as a main water resource (Corte, 1976). Estimations of both the volume of water which is stored inside (Burger *et al*., 1999; Hoelzle *et al*., 2001) and the rate of water release (Schrott, 1999) are needed. These developments on periglacial geography are asking for investigations and mapping of permafrost at a regional scale, requiring an interpolation from many point-based data to build a large geographical database. Fortunately, such interpolation can be computed thanks to GIS facilities. The geomorphic signatures of permafrost are now well known, and this geomorphic data is often integrated within the geographical databases (Harris, 1981; Harris, 1982; Humlum, 1998). For instance, in many papers rockglaciers inventories (Fraunfelder *et al*., 2001) or Basal Temperature of Snow measurements (BTS) (Delaloye *et al*., 2003; Julián Andrés and Chueca Cía, 2006; Lambiel and Delaloye, 2005) are used as permafrost geo-indicators.

Spatial interpolation of point-based data is thus required and many attempts of empirical and statistical modelling were recently developed. In many cases, the spatial interpolation is based upon topoclimatic models, in which the occurrence of permafrost is defined according to some thresholds of altitudes for various aspects of mountain slopes (Hoelzle *et al*., 2001; Bodin, 2003). Other methods of interpolation are based upon statistical techniques, such as multi-linear regression analyses: the relationship between the indicators of permafrost and some predictor variables (solar radiation, elevation, aspect, texture of superficial deposits, etc.) is then defined (Gruber and Hoelzle, 2001; Julián Andrés and Chueca Cía, 2006; Bodin, 2007). Finally, some physical models can also be established, to calculate the Mean Annual Ground Surface Temperature. For instance, in the PERMACLIM model, calculations are based upon the heat conduction theory, which uses both a climatic database and field measurements of snow thermal characteristics (Guglielmin *et al*., 2003).

Whatever is the method of spatial interpolation, the results are highly dependant on the quality of the input database, acquired on the field. The geo-indicators of permafrost should thus be chosen cautiously and their significance discussed.

First, rockglaciers are not directly linked with permafrost conditions: both the glacio-nival setting (massive ice supply, avalanches) and the geomorphic setting (especially debris supply) can complicate the relationship between rockglaciers and permafrost (Evin, 1987; Humlum, 2000; Humlum *et al.*, 2007). For instance, the scarcity of debris supply can induce the lack of rockglacier while permafrost may occur. Furthermore, rockglaciers are characterized by an important inertia, the presence of frozen sediments may reveal former climatic conditions and not the current ones (Barsch, 1996; Schrott, 1998). The identification of rockglacier can also be controversial, leading to misinterpretations of permafrost extents (Fort, 2003; Berger *et al.*, 2004; Humlum *et al.*, 2007). Finally, rockglaciers providing firm assumptions on permafrost occurrence are quite rare and a database of rockglacier may not be sufficiently large for depicting permafrost conditions in various locations. Thus a rockglacier database is not necessarily well fit for reconstructing the distribution patterns of permafrost at a regional scale.

Secondly, BTS measurements are a complicate signature of the occurrence of permafrost because it highly depends on snow conditions: time at which the snow cover appears and thickness of snow cover (Haeberli, 1973). In many cases low BTS measurements are linked with a snow cover which sets later in the winter (frost can penetrate the ground at the beginning of the winter) but not with permafrost (Lambiel and Delaloye, 2005). This often occurs in the French Alps (in particularly the Southern French Alps), hampering the application of the method (Bodin, 2003).

However, other criterion may be used to reveal the occurrence of permafrost; the temperature of water, measured at springs (Evin, 1987; Frauenfelder *et al.*, 1998). Water springs at the front of rockglacier are recognized as a good criterion to decide whether a rockglacier remains active or not: low temperatures of such water may express the presence of ice bodies or frozen sediments (Monnier, 2006). However, the threshold under which the water temperature reveals the occurrence of ice bodies remains non-documented. Once such threshold is specified, water temperature measurements may constitute a promising method to determine easily the occurrence or not of permafrost in many locations within a study site. Field observations can be integrated in a GIS database, then interpolated at a regional scale according to topoclimatic conditions.

To test and improve this method, we apply it in the Southern French Alps. We have chosen this study area for two main reasons. Firstly, in Europe most of the studies led at a regional scale focus on Swiss or Austrian Alps, such a regional approach has just begun in France (Bodin, 2007). Few studies document the distribution pattern of rockglaciers and the derived assessment of lower limit of permafrost remains local estimations (Evin 1987, Francou 1988, Monnier 2006). Thus, this paper aims to document the distribution in parts of French Alps. Secondly, the Southern French Alps are characterized by the scarcity of glaciers, while permafrost may occur at a wide range of altitude. This area is thus ideal for an investigation at a regional scale. We focus particularly on a valley where no study on permafrost has occured: Clarée Valley (Briançonnais, Hautes-Alpes).

In this paper the threshold below which the temperature of water may reveal the occurrence of permafrost is discussed, to begin a reconstruction of the spatial extent of permafrost in this valley by GIS application.

2. Study area

2.1. Description of Clarée valley

The Clarée Valley corresponds to the upper part of the Durance catchment, in the Southern French Alps. It covers an area of approximately 250 km², stretching from 44°59' N to 45°6' N, and from 6°27'N to 6°37'N. The altitudes of the valley range from 1320 m.a.s.l. to 3090 m.a.s.l.. In detail, the topography of the valley can be subdivided in two parts. The Upper Valley is upstream Nevache and covers 170 km². The highest summits are 3000 m.a.s.l. (figure 1). In this area some small tributary valleys, whose lengths range from 2 to 5 kilometers, merge to the trunk valley. Downstream from Nevache the valley gets narrower and the altitudes of summits range from 2400 to 2600 m.a.s.l..

Glacial erosion has occurred over a long time span and highly influences the topography of the valley: the valley was covered by a 700 to 900 meter-thick glacier tongue during the Last Glacial Maximum, around 25 ka [10]Be BP and the valley became ice free at the beginning of the Holocene (Cossart *et al.*, 2007). As a consequence, glacially shaped cirques are widespread. They are characterized by high cliffs (>300 meters) and steep faces (>80 to 100 %). Locally, such steep relief shields the solar rays, and implies a high variability of incoming solar radiation. The minimal value is about $1 \cdot 10^6$ WH.m^{-2}, this value is observed at the bottom of steep north faces. The maximal value is about $3 \cdot 10^6$ WH.m^{-2}, which is observed on the south faces, especially next to summits where there is no relief shelter. Permafrost distribution patterns are probably highly influenced by such variability, the map of incoming solar radiation should thus be integrated within the GIS-based modelling.

The valley is characterized by continental climatic influences as it is partly sheltered from oceanic influences by the Massif des Écrins (figure 2). For instance, precipitations are about 1200 mm per year at La Grave (1550 m.a.s.l. in the western flank of Massif des Écrins) and about 700 mm per year at Nevache (1600 m.a.s.l. in Clarée valley) (Meteo-France, quoted by Garitte, 2006). As a consequence, the area is currently completely deglaciated: the Equilibrium Line Altitude (ELA) indeed ranges between 3100 and 3200 m.a.s.l. (Cossart *et al.*, 2006), while summits locally reach 3000 m.a.s.l..

No investigations have focused on permafrost or periglacial features in this catchment. According to some inventories of rockglaciers realized westward or southward, the Lower Limit of Permafrost may be located around 2800 m.a.s.l. (Francou, 1988), but the accuracy of these estimations should be examined. As a consequence, the upstream part of the valley is probably characterized by a wide range of altitudes in which permafrost conditions may develop (figure 2). This feature makes this area suitable for our topic: improving a method to specify a signature of permafrost and to map its spatial extent.

2.2. Description of cirques

We thoroughly investigated four different cirques, characterized by distinct aspects and topography ([figure 4](#)).

2.2.1. Muandes cirque

Muandes cirque is a westward facing cirque located next to the Mont-Thabor (highest point of the area). Muandes cirque is characterized by moderately high (100 to 200 meters) and moderately steep (70 to 100 %) faces, topographic shelter is thus quite low. Rocky faces are scarce and most of the mountainslopes are now covered by scree – avalanches deposits. Bedrock is made of carboniferous sandstones which provided large amounts of debris after the glacier retreat (Cossart and Fort, 2008). Some sources of sediments (cirque faces) are now exhausted; debris supply thus seems to be very low, hampering the genesis of rockglacier because. Only small protalus lobes are observed, each one affects a surface lower than 1 km². They are located from 2490 to 2700 meters in east-facing and north-facing mountain slopes. Most of them seem to be active. In south-facing slopes, no active rockglacier, even small protalus lobe, are observed. However we cannot know if it is due to the lack of permafrost or to the low rate of debris supply (shrunk sources of sediments).

2.2.2. Béraudes and Moutouze cirques

Beraudes and Moutouze cirques are characterized by high (200 to 300 meters) and steep (>100%) faces, which create a significant shelter for solar rays. Faces are composed by steep and large rocky faces of limestones and dolomites that fed large scree taluses. Such taluses are affected by creeping processes, shaping many rockglaciers on north-facing and west-facing mountain slopes. Such rockglaciers seem to be active at 2500 meters a.s.l..

2.2.3. Cassille Cirque

Cassille cirque is very similar to Beraudes – Moutouze, but it is southward facing and well exposed to incoming solar radiation: its floor is not really sheltered by surrounding mountains. However, some rockglaciers are developed from the large taluses which cover the lower part of the mountainslopes. One of them is located at 2680 m.a.s.l. and presents some characteristics of an active rockglacier (steep front and lack of vegetation).

3. Methods

To map the spatial extent of permafrost the signature of permafrost is firstly defined according to water temperature at springs. Secondly, the topoclimatic conditions (shading, altitude),

in which permafrost probably occurs, are specified. Finally, in order to reconstruct the permafrost pattern, specified topoclimatic conditions are queried in a raster GIS, thanks to a DEM.

3.1. Definition of permafrost signature

The method of permafrost detection is based upon the hypothesis that the temperature of water, measured at springs, may vary according to the presence or the absence of ground ice. Particular areas where permafrost occurs, and areas where there is no permafrost, are evidenced on the field. Presence (and absence) of permafrost is identified according to geomorphic and glaciological observations.

3.1.1. Water temperature in case of presence of permafrost

The water temperature (with a precision of 0.1°C) is measured at springs located in front of firm active rockglaciers. The activity of rockglaciers was documented according to well-known geomorphic criteria (scarcity of vegetation cover, steep front, grain size sorting between the coarse-grained upper part and the fine-grained lower part of the deposit as quoted in Barsch, 1996) and ice observation. Ice has indeed been observed on the field during the summer 2007, at 1 to 1.5 meter-depth, within the debris: it corresponds to a clean translucent ice (without neither debris nor air bubbles), without any visible crystalline structure. This kind of ice is often interpreted as the result of the freezing of snow melt-water (Bodin, 2007): it thus reflects the conditions of permafrost occurrence. Finally, rockglaciers are considered to be active only where both geomorphic and ice criteria are acceptable.

The presence of a firn may of course influence the water temperature. Two cases can be compared: active rockglaciers where a firn is observed, and active rockglaciers without firn. On rockglaciers without firn, the temperature inside the debris (in the openwork structure) at 1 meter-depth is strictly below 1.6°C. The water temperature at the spring is also strictly below 1.6°C. In places where a firn is observed, temperature measurements were acquired at the base of the firns, inside the debris, and at the spring. In all cases, the air temperature within the debris and the water temperature at spring are below the firn temperature. Water temperatures are below or equal 0.9°C, it may locally be very low, close to 0°C (0.1°C next to "Sagnes Froides").

3.1.2. Water temperature in case of absence of permafrost

Water temperatures are also measured at springs where there is no evidence of permafrost (no geomorphic feature of permafrost creep, vegetation cover). Such springs were selected at random, but located at various altitudes and aspects. The measurements are compared, and significant differences appear with the cases of springs probably fed by permafrost melting. Temperatures vary from 2.5°C to 8.4°C at springs which are probably not fed by permafrost melting, whithout firn. If the spring is located close to a firn, the water temperature remains higher than +2.0°C.

We thus estimate that a water temperature strictly below 1.0°C may be a good indicator of frozen sediments if the spring is located next to a firn, and strictly below 1.6°C if no firn is observed (figure 3).

3.2. Database acquisition

After the definition of temperature thresholds, a large database of water temperature, measured at springs, is acquired. An inventory of all springs we observed on the field was realized. Each spring was localized on the field by a GPS, particular attention is paid to the altitude which is determined with an accuracy of 5 to 10 meters. We measure the temperature according to the following protocol. Firstly the thermometer is sheltered from the solar rays, to prevent a possible warming. Secondly, the measurements are acquired between 12 a.m. and 4 p.m. to reduce the possible effect of night cooling. Some comments are added to specify the environmental setting: aspect, shading due to relief, presence or lack of firns… A database is drawn and automatically integrated within a GIS software (©ARCGIS). Springs are represented by points in the GIS, their position is compared with a geomorphic map (to prevent some misinterpretations), and DEM derived layers.

The DEM is realized according to Institut Géographique National (IGN) topographic data. The RMSE error is calculated by comparing the calculated altitude (DEM pixels) with hypsometric points where altitude is known and quoted in topographic maps by IGN (summits, particular houses). RMSE error is below 10 meters (7.8), and may be considered as significantly low. The raster cell size of the DEM is 10 meters by 10 meters. Various maps can be derived from the DEM, in particular the incoming solar radiation (©ARC Toolbox). Calculations are performed using weekly intervals. For a week, the solar radiation is assessed for each pixel, according to the sun position, the duration of the days, and the shading effect due to relief. The calculation finally sums the results to evaluate the incoming solar radiation during the whole year. Cloud cover is not taken into account. We bear in mind that the model is based upon the hypothesis of a homogenised cloud cover over the study area. According to its dimensions and climatic data (Meteo-France, quoted by Garitte, 2006), this hypothesis is highly probable. Finally, the values are to be considered as a potential radiation (figure 5).

3.3. Mapping the permafrost

In previous GIS-based models, the reconstruction of the permafrost distribution is computed from the altitude and the aspect (Haeberli, 1973; Hoelzle, 1992; Hoelzle *et al*., 1993; Bodin, 2003). However, the aspect may not reveal the surface energy fluxes due to topographic shelter (Schrott, 1991 and 1998; Happold and Schrott, 1992; Funk and Hoelzle, 1992; Hoelzle *et al*., 2001). For instance, in the case of a steep relief some south-facing mountainslopes can be shaded by mountains and may receive low solar radiation… Our model is based upon the assumption that the occurrence of permafrost may be explained by the altitude and the potential incoming solar radiation.

The pixels were classified according to their incoming solar radiation value. We performed a quantile method (6 classes). For each class, we plotted both the water temperature and the altitude at which the measurement was realized. According to the results assemblage, each class of solar radiation is subdivided into three categories, following a method performed by Bodin (2003). At altitudes where all measurements indicate the presence of permafrost the adjective "probable permafrost" is attributed, at altitudes at which results are mixed the adjective "possible permafrost" is attributed, at altitudes at which there is no evidence of permafrost the adjective "improbable permafrost" is attributed. We thus define some altitude thresholds at which the occurrence of permafrost is possible and probable for each class of incoming solar radiation. According to such thresholds, we have to query the pixels which correspond to each possibility according to the DEM (altitudes) and incoming solar radiation layers. Results will be compared with other permafrost distribution patterns drawn in the Alps (Switzerland and Austria) and with local observations of permafrost in France.

4. Results

4.1. Water temperature measurements

Water temperature measurements greatly complete previous geomorphic observations. By classifying the measurements according to incoming solar radiation conditions we can highlight three main configurations.

On highly shielded mountainslopes (class 1, solar radiation incoming lower than $1.3 \cdot 10^6$ WH.m^{-2}), low temperatures appear at altitudes from 2500 m.a.s.l.. For instance in Beraudes and Moutouze cirques, a temperature of 1.1°C was acquired at the front of probably active rockglaciers (without firn), suggesting the occurrence of permafrost. Moreover, at the bottom of the north-facing mountain slopes of Muandes cirques a low temperature (1.2°C without firn) was acquired at 2605 m.a.s.l.. It confirms that observed rockglaciers or protalus lobes can be active at such altitude. However two measurements correspond to temperatures higher than 2.0°C at altitudes of 2630 meters a.s.l.. It leads us to consider the possibility of permafrost at altitudes ranging from 2490 to 2650 m.a.s.l., and its probability above (where all water temperatures are indeed significantly low). In areas where the incoming solar radiation ranges between $1.3 \cdot 10^6$ WH.m^{-2} and $1.7 \cdot 10^6$ WH.m^{-2} (Class 2), the altitude thresholds are higher: the possible permafrost is considered to occur above 2550 m.a.s.l., and the probable permafrost above 2675 m.a.s.l..

Two classes (3-4) can be qualified as moderately shielded mountain slopes (solar radiation incoming from $1.7 \cdot 10^6$ WH.m^{-2} to $1.9 \cdot 10^6$ WH.m^{-2}, and from $1.9 \cdot 10^6$ WH.m^{-2} to $2.6 \cdot 10^6$ WH.m^{-2}). It mainly corresponds to the west-facing mountain slopes of Muandes cirque, to the east-facing mountain slopes of Béraudes – Moutouze cirque, and to the top of north-facing mountain slopes. In class 3, a low temperature appears at 2630 m.a.s.l., next to the Roche des Béraudes. All temperatures are well below 1°C (0.3 to 0.7°C) above 2710 m.a.s.l. In class 4, the altitude thresholds are similar. Low temperatures appear at altitudes of 2664 m.a.s.l.. In detail, low temperatures are mixed with higher temperatures (above 2°C) at altitudes ranging from 2660 meters to 2750 meters: we consider the occurrence of permafrost possible at such altitudes. At altitudes

higher than 2750 m.a.s.l. all water temperatures are well below 2°C: the occurrence of permafrost is considered as probable.

On lowly shielded mountain slopes (class 5 and 6) low temperatures only appear above 2700 m.a.s.l., especially on the south-facing mountain slope of Muandes cirque. It highly suggests that rockglaciers located in Cassille cirque are now inactive. Above the altitude threshold some very low water temperatures have been locally measured (around 0.5-0.7°C). On class 5, probable permafrost is identified above 2815 m.a.s.l.. The occurrence of permafrost is thus suggested, even on south-facing mountain slopes. Such results imply that the absence of rockglacier is not necessarily linked with the lack of permafrost. It can be explained by the insufficient altitudinal range of permafrost zone: the lower limit of permafrost is close to the altitudes of summits, implying scarce sediment sources. However, in class 6, there is no evidence of probable permafrost.

4.2. Permafrost distribution patterns

On the Upper Clarée Valley, the zone of probable permafrost covers an area of 13 km², it corresponds to 7.5% of the area of the entire Upper Valley. The zone of possible permafrost covers 33.5 km², which corresponds to 19% of the area of the entire Upper valley. Permafrost affected areas are therefore not negligible.

The main part of the probable permafrost is of course located next to the Mont Thabor and Massif des Cerces areas, areas of maximum altitude. Probable permafrost constitutes there a continuous belt.

Permafrost may occur in all cirques but, let's highlight in detail significant differences in altitudinal limits of permafrost in relation to the topoclimate. (i) On well-exposed mountain slopes, the occurrence of permafrost is only possible. Only the very upper part of the faces (made of rocky faces), at altitudes higher than 2800 m.a.s.l., can be probably affected by permafrost. (ii) In highly shielded areas next to Pointe des Cerces, Cassille (Beraudes, Moutouze) the zone of probable permafrost lies 200 meters below. Moreover, possible permafrost covers the lower part of cirque faces and cirque floors. It implies that permafrost may be preserved within the large scree – avalanches taluses which cover the lower part of the cirque faces and the cirque floors.

A volume assessment of sediment stores is currently in progress (Perrier, 2008), and rough estimations can be made from Béraudes cirque. For instance, at the bottom of Pic des Béraudes, large scree taluses are developed: the volume of slope deposits is about $2 \cdot 10^6$ m^3. The occurrence of permafrost is possible in this area. Previous studies on permafrost evaluated the ratio of ice-contents in rockglaciers from 30% (Fabre *et al*., 2001) to 60% (Burger *et al*., 1999). Such ratios imply that 0.6 to $1.2 \cdot 10^6$ m^3 of ice may be still stored at the foot of this cirque face. According to such an example, huge volumes of water may be stored here. It would be interesting to study next an accurate assessment of the volume of water stored in permafrost in this high mountain environment, coupling the regional mapping of permafrost and the topographic modelling of sediment stores (figure 6).

5. Discussion

5.1. The significance of "probable" and "possible" permafrost

The signification of the limits we defined should be discussed. The results can be compared with point-based data acquired from other parts of French Alps. Francou (1988) and Evin and Fabre (1990) evidenced permafrost occurrence at higher altitudes (around 2800 m.a.s.l.), according to rockglaciers investigations. They estimate the Lower Limit of Permafrost at 2825 or 2850 m.a.s.l., which is very close to the current altitude of the isotherm -2°C. Some discussions are thus required to understand why permafrost can be evidenced at altitudes well below this isotherm.

First, a recent study locally identified permafrost at 2500 m.a.s.l., according to geological radar investigations (Monnier, 2006). Secondly, the location of permafrost cannot always be linked to such simple isotherm -2°C: local conditions such as snow inputs by avalanches, shielding effects, may highly influence the genesis of permafrost (Evin, 1993). Moreover, air circulation inside slope deposits can generate a cooling of the substratum at low altitudes (below 2500 m.a.s.l. in Switzerland): it can generate permafrost even in areas devoid of rockglaciers (Lambiel and Delaloye, 2005). Studies based only on rockglaciers inventory and investigations can lead to some simplifications of permafrost extents. Because of the high importance of local parameters in the genesis of permafrost, a database as large as possible must be acquired, covering various physical conditions.

The interpretation of the results should also be discussed. In previous modelling, possible permafrost was interpreted as "discontinuous permafrost", probable permafrost as "continuous permafrost". Yet, the signals reflecting the occurrence of permafrost are all concordant in the "probable zone", while they are mixed, reflecting only local occurrences, in the possible zone (Bodin, 2003). However, such kind of reconstitution is only a snapshot: do the specified limits reflect only current conditions? Permafrost is indeed characterized by a great inertia to the climatic changes (Evin, 1993, Schrott, 1998; Monnier, 2006). Next to the study area, in Massif du Combeynot (Vallon de la route), ice was identified deep inside inherited creeping landforms (depth > 8 m), well below the altitude of the isotherm -2°C (Bodin, 2007). Such ice body is disconnected from the atmosphere and from zones where permafrost is generated by large volumes of unfrozen sediments. This body is interpreted as a remnant of past cooler periods (possibly Little Ice Age). As a consequence, the "possible permafrost" belt, characterized by mixed signatures of presence and absence of permafrost, may also reflect the preservation of permafrost remnants in the study area. This zone should be considered as a belt of current degradation of permafrost since the Little Ice Age. The "probable permafrost zone", where all signals of permafrost occurrence are positive, may be in better accordance with the current or recent (i.e. last few decades) climatic conditions.

5.2. Forthcoming issues

The discussion about permafrost degradation reveals a forthcoming issue in non-glaciated mountain areas. Permafrost is indeed an important source of water which is released during the

warm season. As the permafrost is degraded, the ice-content and the possibilities of water release are decreasing. This melting water is of prime importance because it can generate an increase of water discharge during the summer season in spite of dryness of the climate (Corte, 1976; Schrott, 1998).

To go further, an assessment of water volumes stored inside permafrost is needed. The map of permafrost extent must be coupled with geometric reconstitutions of sediment stores: superficial deposits are the main stores in which permafrost can occur and in which water is transferred (Caballero *et al.*, 2002). An evaluation of the volume of sediments can be derived in an evaluation of ice-content, according to some ratio previously defined. Topographic models for glacially-shaped landforms should be applied to realize this work (Cossart and Fort, 2008). Water springs probably supplied by permafrost melting should also be surveyed to measure the influence of permafrost on water discharge. Understanding the hydrological consequences of permafrost degradation is of prime importance because water in rivers is utilized for the irrigation of cultivated surfaces during summer in the Southern French Alps.

6. Conclusion

This work tries firstly to provide a clarification of permafrost extent in Clarée valley. It appears that permafrost may occur at lower altitudes than previously expected: first pieces of evidence of ground ice are observed just above 2500 m.a.s.l.. Permafrost may thus occur in some slope deposits, serving as alpine aquifers: is its current degradation the origin of a shifting of discharge river regime? Further research is of course needed, but it may be a promising perspective since rivers supply water for irrigation.

Secondly the applied method, based upon water temperature measurements, can be useful for providing a large database of permafrost observation. The influence of firn seems to be of prime importance: two temperature thresholds are needed, one in case of the presence of firn, one in case of the absence of firn. Such large databases are now crucial in order to investigate permafrost at regional scale to survey its extent and observe its possible degradation. Current debates on water resources management clearly ask for this kind of study.

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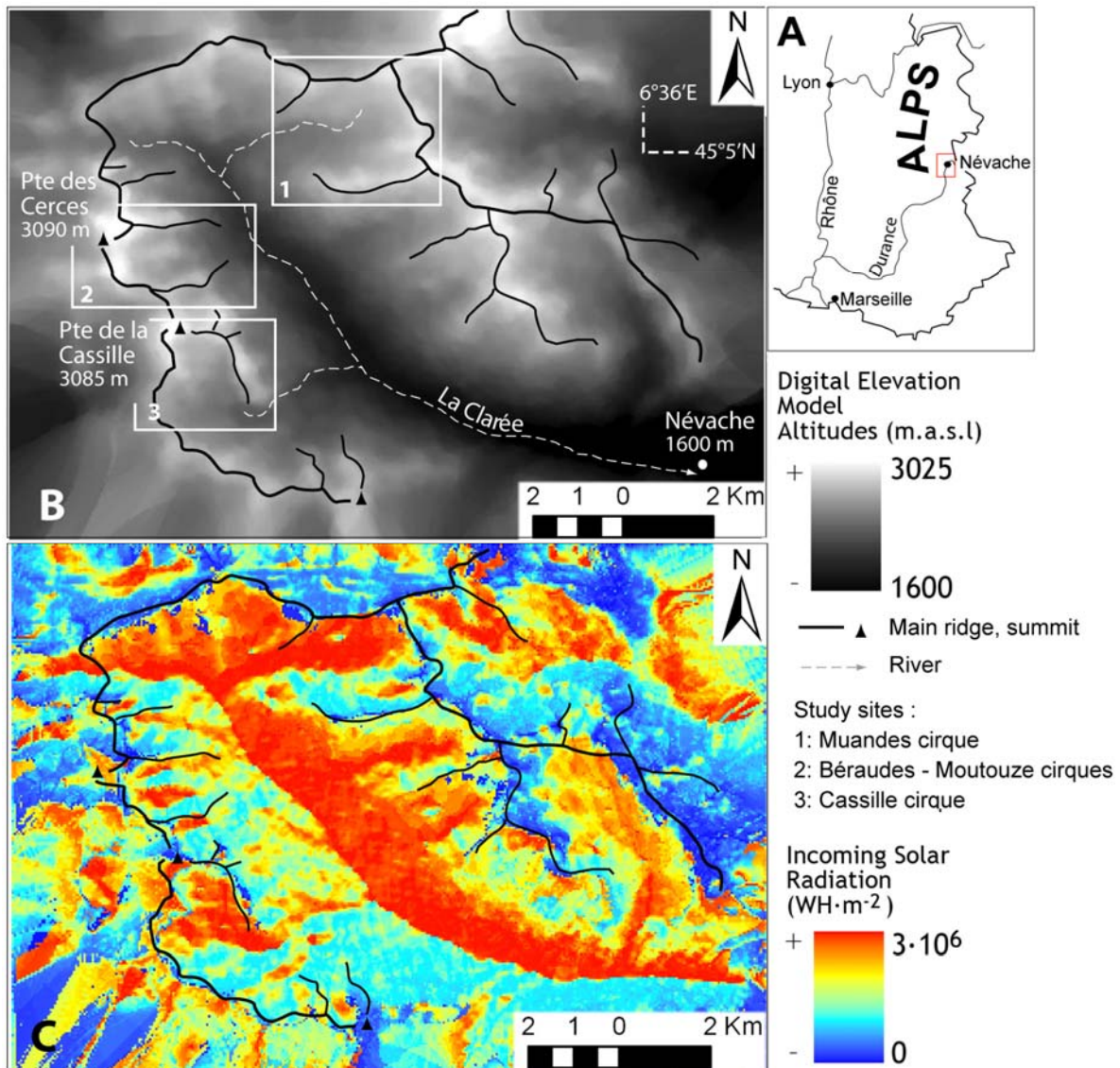
FIGURES

Figure 1. Physical settings.
A) Location of the Clarée Valley, in the Upper Durance catchment. B) Hypsometric map of the Upper Clarée Valley. Map extracted from a DEM (IGN data). C) Incoming solar radiation. Note that radiation values are not necessarily linked with aspect. Map derived from map B, drawn from ©Arc Toolbox.
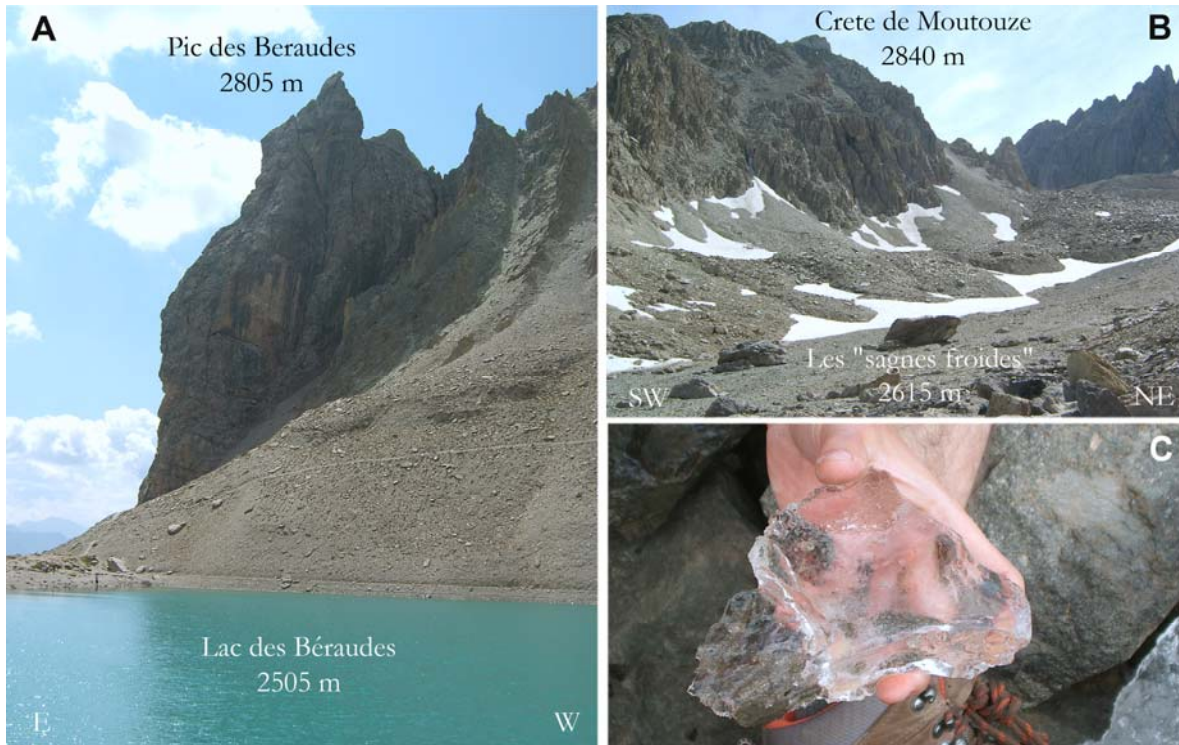
Figure 2. Photographs of the study area.
A) North-facing mountain slope of Béraudes cirque, note creeping features affecting the scree deposit (acquired by E. Cossart, July 2007). B) North-faced mountainslope of Moutouze cirque. Note the well-shaped rockglaciers which are reworking scree deposits (acquired by E. Cossart, July 2007). C) Ice encountered within an active rockglacier in the Muandes cirque (altitude: 2700 m.a.s.l.).
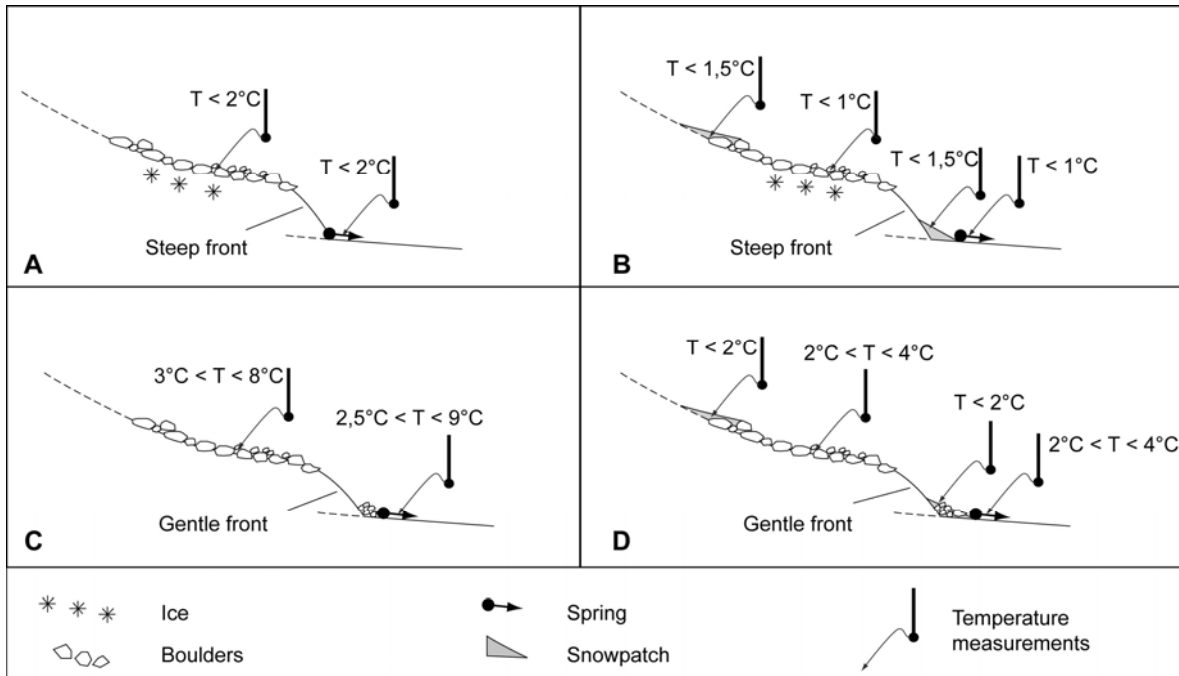
Figure 3. Typology of springs setting.
A) Ice was observed, but there is no firn. B) Ice is observed and there is some firn. C) Neither ice or firn is observed. D) There is no evidence of ice, but a firn is remaining.
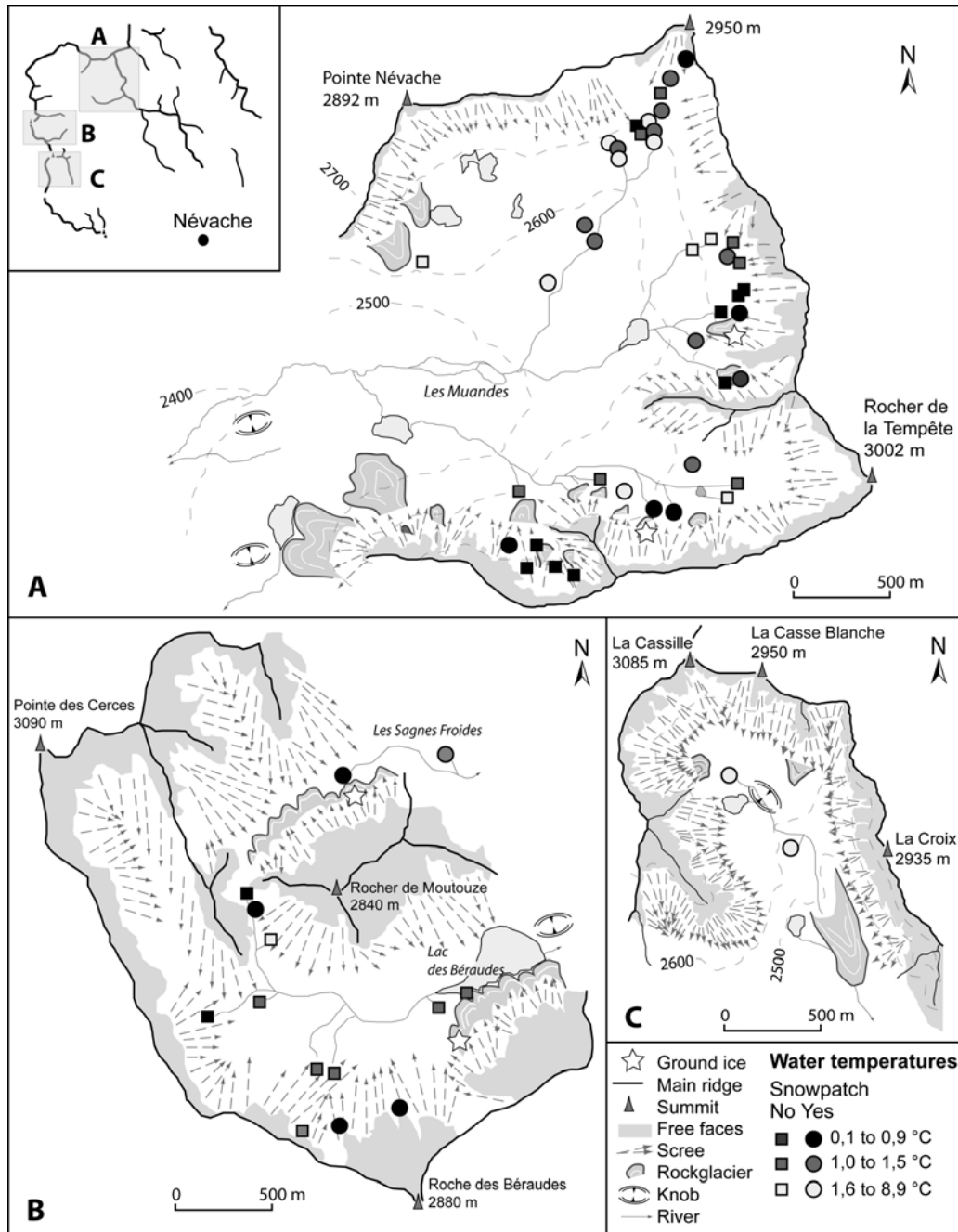
Figure 4. Geomorphic maps.
A) Muandes cirque. Note the scarcity of sediment sources (i.e. free faces). B) Beraudes and Moutouze cirques. Note the large scree deposits. C) Cassille cirque. Very few springs are located in this cirque. It may reflect the scarcity of permafrost, confirming the temperature measurements.
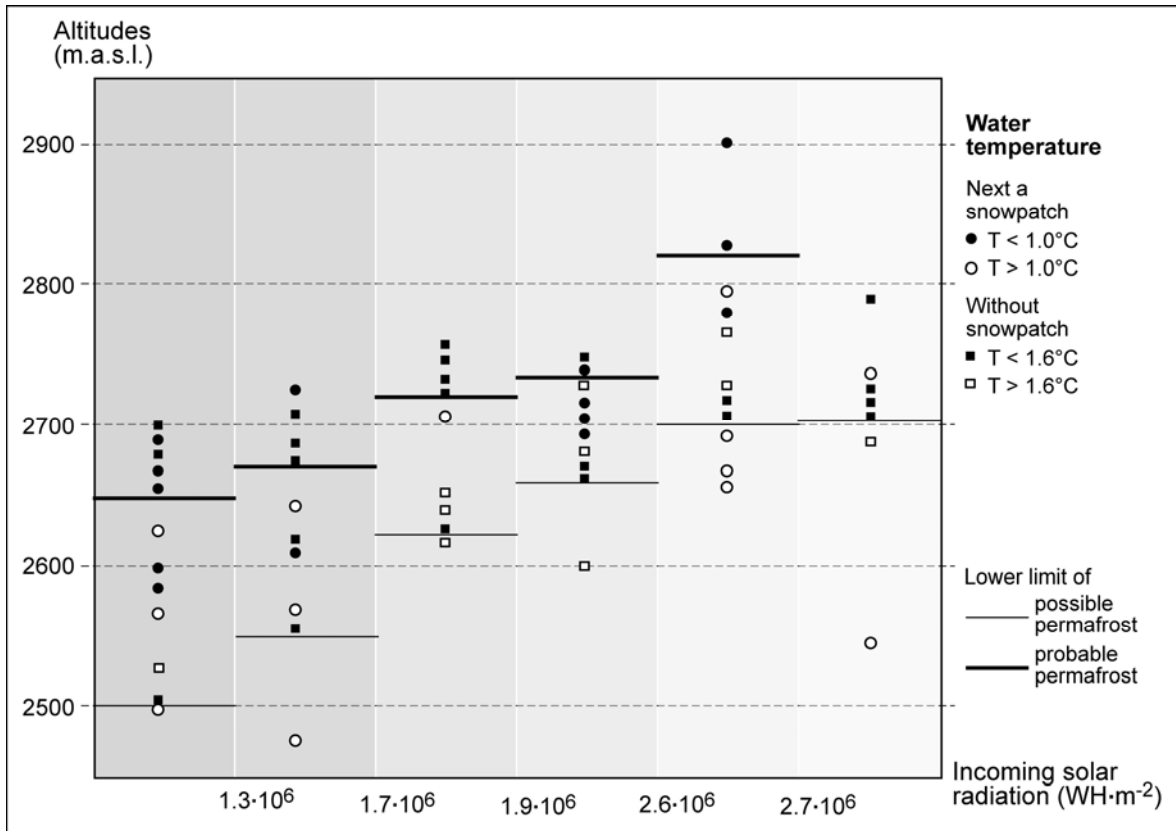
Figure 5. Diagram plotting water temperature measurements for each class of solar radiation.
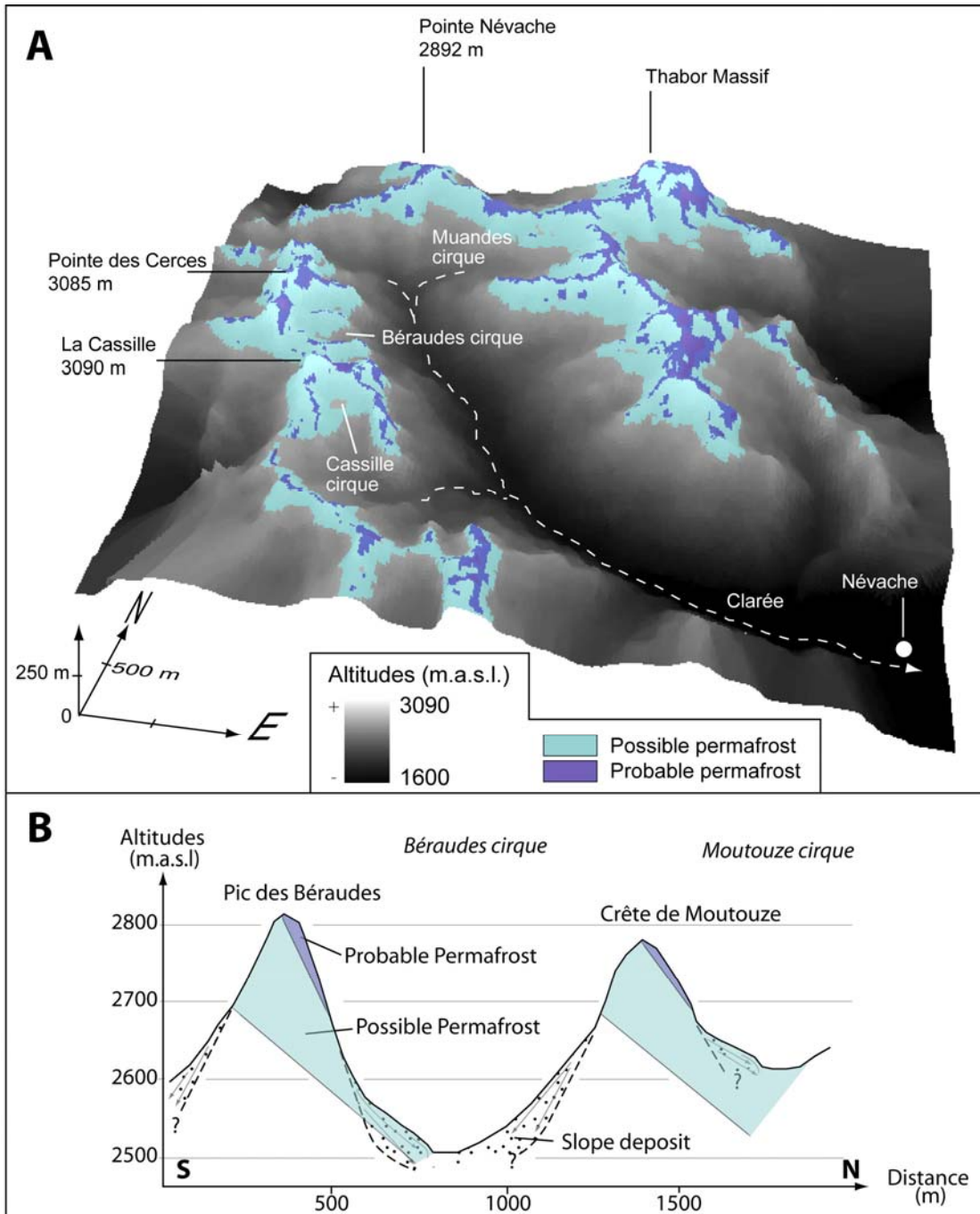
Figure 6. Spatial extent of permafrost.
A) Three dimensional view of the study area and permafrost occurrence. B) Cross-section of Béraudes and Moutouze cirques. Note that permafrost may occur within north-facing footslope deposits, constituting a possible store of water.