# *Glaciological and geomorphological map of Glacier Noir and Glacier Blanc, French Alps*

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*Published in:*
Journal of Maps

*DOI:*
10.1080/17445647.2015.1054905

*Publication date:*
2016

*Citation for published version (APA):*
Lardeux, P., Glasser, N., Holt, T., & Hubbard, B. (2016). Glaciological and geomorphological map of Glacier Noir and Glacier Blanc, French Alps. *Journal of Maps*, *12*(3), 582-596. https://doi.org/10.1080/17445647.2015.1054905

# Glaciological and geomorphological map of Glacier Noir and Glacier Blanc, French Alps

**This is an Accepted Manuscript of an article published by Taylor & Francis Group in Journal of Maps on 17th June 2015, available online:**

**http://www.tandfonline.com/doi/full/10.1080/17445647.2015.1054905**

## Abstract

This paper presents and describes a glaciological and geomorphological map of Glacier Noir and Glacier Blanc, French Alps. Glacier Noir is a debris-covered glacier and is adjacent to Glacier Blanc, a clean-ice (debris-free) glacier. The glaciological and geomorphological evolution of Glacier Blanc is well-known, but the evolution of Glacier Noir is poorly understood, as is the case for many debris-covered glaciers globally, despite their importance in a number of mountain ranges around the world (e.g. European and Southern Alps, the Himalayas and the Rockies). The accompanying map was created by manually digitising aerial ortho-images and historical georeferenced photographs from 1952-2013. The main glacial and geomorphological features of both glaciers were mapped including: debris cover, crevasses, moraines, hummocky terrain and scree areas. Hydrological features (supra- and pro- glacial streams and meltwater ponds) were also mapped. The map illustrates the key differences between Glacier Noir and Glacier Blanc, and is important for understanding future glaciological and geomorphological changes.

## Keywords

Debris-covered glacier, Glaciology, Geomorphology, Hydrology, Glacier Noir, Glacier Blanc

# 1. Introduction

Mountain glaciers are currently contributing ~27 % of the observed global sea level rise with a large uncertainty of more than 20% (Jacob et al., 2012). Although the contribution of debris-free or clean-ice glaciers is well-known, debris-covered glaciers and their contribution are still poorly understood. Debris-covered, or debris-mantled glaciers, are those where part of the surface of the ablation area, is covered by a layer of rock debris including dust, ash and boulders of various sizes (Hambrey et al., 2008, Cogley et al., 2011, Singh et al., 2011).

Debris-covered glaciers represent ~5% of all mountain glaciers worldwide (WGMS and NSIDC, 1989, updated 2012) and the rate of sea-level rise attributed to them differs from clean-ice glaciers due to the insulating effect of the debris layer (Reznichenko et al., 2010). A better understanding of long-term glaciological processes on debris-covered glaciers is needed to reduce the uncertainty of their contribution to global sea level.

The debris layer on debris-covered glaciers derives from a number of sources, most notably valley-side rockfalls (Deline and Kirkbride, 2009). These rockfalls can be significant at the glacier-scale, such as is the case for the Black Rapids Glaciers (Shugar et al., 2012) and the Sherman Glacier (Marangunic, 1972) rock avalanches. These rock avalanches form specific deposits characterised by the regular thickness of the debris layer and angular grains (Hewitt, 2009). Other sources of debris include collapsing lateral moraines (Hambrey and Ehrmann, 2004) and debris elevated from subglacial and englacial positions to supraglacial positions (Goodsell et al., 2005). The debris from these latter sources is more heterogeneous and may contain a mix of sub-angular to sub-rounded grains.

The supply of surface debris to the glacier's terminus has great control over the geomorphological processes occurring on and adjacent to that glacier (Reznichenko et al., 2011) and often results in the formation of very large geomorphological features, such as the Waiho

Loop moraine in the Southern Alps, New Zealand (Tovar et al., 2008). From a glaciological point of view, the elevation of the snout of a debris-covered glacier would be lower than a similar clean-ice glacier. Specific glaciological and geomorphological dynamics of a debris-covered glacier are beginning to be considered in the interpretation of glaciated landscape and landforms (Reznichenko et al., 2012, Carrasco et al., 2013). Accurate interpretation and attribution of features to debris-covered glaciers can lead to re-interpretation of palaeo-climatic conditions contributing to their formation (Shulmeister et al., 2009, Vacco et al., 2010).

Here, a detailed map is presented in order to provide the basis for investigating the geomorphological context of, and relationships between, a debris-covered glacier (Glacier Noir) and an adjacent and morphometrically-similar clean-ice glacier (Glacier Blanc). This map will also help the re-interpretation of palaeo-landforms where debris-covered glaciers may have contributed to their formation.

## 2. Study site

Located in the Haute Vallée de St Pierre in the "Écrins" National Park (Parc National des Écrins) in the French Alps (Figure 1), Glacier Noir is a 4.5 km long debris-covered glacier with a surface area of 3.8 $km^2$. In contrast, the surface of adjacent Glacier Blanc is debris-free. Both glaciers were confluent in the Pré de Madame Carle field during the Little Ice Age (LIA, 16$^{th}$ to mid-19$^{th}$ century, [Mann, 2002]). Pré de Madame Carle was a grazing field before it was transformed into an outwash plain by the advance of the glacier during the LIA (Letreguilly and Reynaud, 1989).

Glacier Noir (44°54'58" N, 6°23'03" E) has an elevation range of 2200 to 3600 m and comprises a main trunk (2200 to 2900 m in elevation) of 1.1 $km^2$ (2.6 km long), orientated WSW-ENE with a single tributary (2500 to 3600 m in elevation) of 2.7 $km^2$ (3.2 km long), orientated SSW-NNE.

The tributary is now an independent glacier - named here as Glacier Noir Sud - having separated from the main glacier between 2009 and 2013.

Glacier Blanc (44°56'25" N, 6°22'42" E) has an elevation range of 2500 to 4000 m and is 5.5 km long (4.8 $km^2$), being orientated SW-NE in its upper section (3050 to 4000 m in elevation), which is relatively flat and then NW-SE in the steep crevassed area approaching its terminus (2500 to 3050 m in elevation). This main trunk is fed by six individual accumulation basins (cirques).

Both glaciers have attracted previous glaciological research, with Glacier Blanc being more widely studied (Allix, 1922, Allix, 1929, Vivian, 1967a, Letreguilly and Reynaud, 1989, Reynaud and Vincent, 2000, Rabatel et al., 2002, Reynaud and Vincent, 2002, Thibert et al., 2005, Rabatel et al., 2008, Rabatel et al., 2013), than Glacier Noir (Allix, 1922, Allix, 1929, Vivian, 1967b, Cossart et al., 2006, Stott and Mount, 2007, Mount and Stott, 2008). The most recent studies have focused on sediment transport in the proglacial stream at Glacier Noir and on the variation of the equilibrium line altitude (ELA) at Glacier Blanc and its determination by optical remote sensing.

# 3. Data and methods

## 3.1. Data sources

Mapping was conducted by manually digitising aerial ortho-images (six RGB tiles of 5 km by 5 km with a 50 cm resolution) using QGIS software (Section 3.2). The National Institute of Geographic and Forestry Information (IGN) provided the ortho-images. These images are part of the French national database, ©BDORTHO, and were taken during summer 2013.

The toponymy comes from the IGN topographical map (Meije-Pelvoux 3436 ET), which is included in the database ©SCAN25. The scale of the map is 1:25000.

The dates of formation of the moraines are from various sources:

- A public engagement booklet edited by the "Écrins" National Park (Écrins, 2005) on the glaciers present in the park.
- Unpublished historical and archive documents owned by the "Écrins" National Park.
- Archived ortho-images and georeferenced aerial photographs extracted from the historical IGN database. This database is the compilation of previous versions of the ©BDORTHO, grouping aerial scenes from 1952 to 2009.

The archived ortho-images were also used for the photo-interpretation of moraines, which is sensitive to the position of shadows (Otto and Smith, 2013).

The interpretation of the ortho-images was verified and refined by direct field observation between mid-August and mid-September 2014, particularly where the ortho-images have shadowed areas or other areas where a misinterpretation is possible. All ground-based photographs presented in this article and on the map were taken during the same period.

## 3.2. Software and digitising tools

All mapping and digitising was conducted in ©QGIS software (QGIS, 2014), a free and open source geographic information system. Multiple versionsof QGIS have been used (see Software Section below) as well as the updated versions of the following plugins:

- autoSaver plugin, for automatic saves of the work in progress
- Digitizing Tools plugin, for additional digitising options
- GdalTools plugin, for elevation data extraction
- Georeferencer GDAL plugin, for the georeferencing of the aerial images
- GPS Tools plugin, for the import of field data
- Multipart Split plugin, for better management of multiple features in the same layer

The map was designed using the composer module of QGIS. The ground-based photographs presented on the map were modified using ©Adobe Illustrator CS2.

The digitisation of the ortho-images was conducted within a scale range of 1:1000 to 1:10000, allowing a global view of each feature across the study site's large altitudinal range.

## 3.3. Map design

### 3.3.1. General principles

The mapped features are divided into four themes with additional background data: glaciological, geomorphological, hydrological and anthropogenic. The different colour schemes used are theme dependent. Glaciological features are depicted using only black and white colours. Geomorphological features are depicted in brown to yellow colours.In addition, vegetated features are presented in dark green. Hydrological features (ponds and streams) are depicted using different hues of blue. Although not essential to the map's principal purpose, anthropogenic features which provide important context (e.g. buildings) are depicted in grey. To bring contrast to the map, the background contour lines are depicted in light green.

### 3.3.2. Specific digitising cases

Moraines have been digitised only as moraine ridges. Ridges are the best indicators of the position of a moraine and so help to understand the retreat history of glaciers. The extent of moraines has not been digitised to not overload the map with more polygons. From field observations, crevasses and crevasse traces represent the large majority of the structural features on Glacier Blanc and Glacier Noir. However, due to the ortho-image resolution and the heavily disturbed area in the curve of Glacier Blanc, the recognition of foliations and/or lineations was particularly difficult, and consequently, some might have been digitised as crevasses.

In addition to digitising active and relict meltwater ponds, their areas of topographical influence (see Section 4.3.1) was also  mapped as separate features because of their importance in the melting of debris-covered glaciers (Sakai et al., 2000).

# 4. Description of the mapped features

## 4.1. Glaciological features

### 4.1.1. Glacier outlines

Glaciers were identified using the following definition: "mass of ice presenting active flow pattern" which is a simplified version of the GLIMS definition (Rau et al., 2005). This definition was used as a guide to outline digitization of both glaciers, although defining the lateral and frontal boundaries was easier for Glacier Blanc (i.e., between clean ice and proglacial debris) than for the ablation area of Glacier Noir, where the debris cover makes the identification of the glacier limit (Figure 2) and flow patterns more difficult (Cogley et al., 2011; Paul et al., 2013).

### 4.1.2. Debris cover

For this map, we defined debris cover as where there is no clean ice visible. The precise limits of debris-covered areas are difficult to define because of the continuous variations in debris concentration that are encountered in the field. In addition, the debris cover must have been persistent, i.e. appearing in images separated by at least one year. By these criteria, no debris cover was mapped on Glacier Blanc because the debris cover areas are temporary and localised, and are rapidly buried by snow in the accumulation area, or removed from the surface through crevasses in the ablation area.

### 4.1.3. Crevasses

Crevasses form when the extension strain exceeds a critical threshold (Vaughan, 1993) resulting in fields of fractures with distinctive lengths and orientations. This fractured area is particularly visible on the lower section of Glacier Blanc where the glacier changes direction and becomes steeper.

On Glacier Noir, most of the crevasses are filled by debris that leaves only traces of the crevasses visible on the surface. These crevasse traces create only low relief perturbations and are consequently not visible by direct observation in the field.

### 4.1.4. Nunataks and bare-rock areas

Nunataks are areas of glaciers where the bedrock is exposed (Singh et al., 2011). Nunataks and other bare-rock areas are mainly present on the south-facing side of Glacier Blanc. The locations of these rock exposures vary, as they are dependent on the ice thickness and the ice flow. Consequently, the features mapped are only those present when the aerial images were taken in 2013, as for streams (Section 4.3.2).

## 4.2. Geomorphological features

These features are all related to the former presence of a glacier.

### 4.2.1. Moraines

Moraines are landforms built by the deposition by glaciers of glacial sediments (Singh et al., 2011). There are many types of moraines (Bennett and Glasser, 2009); around Glacier Noir and Glacier Blanc these are mostly frontal and lateral moraines and were mapped accordingly.

During the LIA, Glacier Noir and Glacier Blanc had a common terminus and produced a large moraine, like many other alpine glaciers. This LIA frontal moraine has been partially washed away by the proglacial stream, and currently, the only large LIA moraine intact is the lateral moraine of Glacier Noir. This moraine is recognisable because of its large size compared to the surrounding moraines (Figure 3).

#### 4.2.2. Gullies

Gullies are formed in areas of unconsolidated sediment where the runoff from rain and snowmelt creates micro-valleys. In the study site, most of the gullies are on the ice-proximal flank of moraines.

The process of gullying is an active phenomenon (Figure 4) and was observed during heavy rainfall events during the fieldwork period. This process contributes widely to the erosion of moraines.

#### 4.2.3. Scree areas

According to Singh et al. (2011), scree material (also called debris) is "Unconsolidated sediment, larger than 1 mm, of angular or rounded angular fragments of boulders (clasts), predominantly originating from physical weathering". Scree areas are steep zones of scree material. All the active scree areas around Glacier Noir and Glacier Blanc face SW to SE. Scree clast size is variable, ranging from pebble to boulder-size.

Three types of scree areas were mapped:

- Active scree areas where traces of rock falls are visible and where regular rock falls have been observed in the field. They are mainly located around the Glacier Noir catchment.
- Stabilized scree areas without traces of active rock falls located on the eastern side of the terminus of Glacier Blanc and above the outwash plain.
- Vegetated scree areas near the entrance of Haute Vallée de St-Pierre.

Figure 5 presents the geological context for the scree production. Production appears to be independent of lithology (gneiss or granite) and to be primarily driven by the slope orientation (Nagai et al., 2013).

### 4.2.4. Hummocky terrain

On the map, hummocky terrain (Figure 6) designates an assemblage of debris and glacial sediment pits and mounds including small, possibly ice-cored moraines (Singh et al., 2011).

The hummocky terrain is located in the proglacial area of both glaciers and in a former lower accumulation cirque of Glacier Noir Sud. Like gullies, these areas are particularly active and their morphology evolves closely with the variation of the proglacial streams, especially during heavy rainfall events.

### 4.2.5. Bedrock with incised channels

Large areas of bedrock (gneiss) with incised channels are visible in front of Glacier Blanc, revealed as the glacier receded. Field observations confirm that some of the channels have subglacial origins and are probably Nye channels. Nye channels (or N-Channels) are subglacial channels directly carved into bedrock by meltwater discharge (Nye, 1973). .Most of the visible channels are now abandoned except for those occupied by the glacier's main proglacial streams.

### 4.2.6. Outwash plain

An outwash plain is a large flat area covered with well-sorted glaciofluvial sediment. Braided rivers often develop widely in outwash plains, for example in Iceland where they are called "sandur" because of the predominance of sand- and gravel-sized sediment across such plains. The proglacial streams of Glacier Noir and Glacier Blanc converge in the upper part of the outwash plain to form a dynamic braided stream system as shown in Figure 7 at two different dates.

## 4.3. Hydrological features

### 4.3.1. Meltwater ponds

Meltwater ponds are depressions on the ice surface that are filled with water released by the melt of snow and ice. Numerous, often large, supraglacial meltwater ponds are a common feature on debris-covered glaciers. Indeed, such ponds form the basis of one key classification of the morphological evolution of debris-covered glaciers (Benn et al., 2012).

Meltwater ponds form by differential melting between debris-covered and clean ice areas. Ablation of the latter is faster than the former, creating a depression – here called the area of topographical influence – where water can be stored. This process involves a positive feedback loop where the edge of the depression becomes steeper and so less debris-covered, inducing further melting and consequently steepening of the side. This feedback loop gradually extends the area of topographic influence of meltwater ponds.

However, these meltwater ponds are eventually drained supraglacially via a channel or englacially via crevasses. The drainage process creates relict/trace ponds (Figure 8) where the difference between the pond itself and the area of topographic influence is still visible.

#### 4.3.2. Streams

Water streams on the study site are produced by the melt of glaciers. They are found in two different positions: on the surface (supraglacial streams) and in front (proglacial streams) of both glaciers. Due to the dynamics (water discharge, deposition of sediment) and ephemeral nature of proglacial streams, especially in the outwash plain, only principal active channels were mapped, illustrating the situation at the time the aerial images were acquired.

Supraglacial streams could only be observed on the debris-covered surface of Glacier Noir. Most of the mapped streams were restricted to the ablation area. No visual expression of supraglacial streams was found on aerial images of Glacier Blanc despite their presence in the field (Figure 9). Therefore, supraglacial streams were not mapped on Glacier Blanc.

### 4.4. Anthropogenic features and elevation data

The Glacier Noir and Glacier Blanc site is a tourist attraction in the "Écrins" National Park and so buildings (three refuges, one visitor centre and public restroom facilities), roads and hiking trails were additionally mapped to provide context.

Contour lines from the IGN 1998 digital elevation model (DEM) were added as background information. To clarify the topographical context of the map, arêtes lines were added on the DEM as well as some altitude points.

## 5. Conclusion

We describe here a new glaciological and geomorphological map of Glacier Noir and Glacier Blanc in the French Alps. The mapped features were divided into four different themes (glaciological, geomorphological, hydrological and anthropogenic) to facilitate the understanding of the map and future studies and comparisons. However, these four themes interact closely. Glacier Noir and Glacier Blanc are the main actors of sediment transport and deposition, creating a range of geomorphological features, from sand layers in the proglacial area to LIA moraines. The streams are, on the contrary, the main actors of erosion on the surface of Glacier Noir, acting to transfer sediment of the debris layer from the top of the glacier to the terminus, as well as eroding the proglacial terrain of both glaciers to create an outwash plain further downstream. Meltwater ponds are the perfect example of the interaction of glacial (melting of debris-free ice cliffs), geomorphological (back wasting of debris from the layer) and hydrological (storage and drainage of significant quantities of water) processes. Finally, anthropogenic features such as roads and bridges modify erosional/depositional patterns in a complex way, especially in the outwash plain.

Understanding these processes and their interactions is part of a larger research project on the impact of variations in supraglacial debris cover on glacier evolution and dynamic response to climatic forcing.

# Acknowledgements

The aerial images and orthophotographs were provided by the French National Institute of Geographic and Forestry Information under an education and research licence. The fieldwork season was possible thanks to the "Ecrins" National Park (activity authorisation 060/2014) and has been funded by the British Society for Geomorphology under the Postgraduate Research Grant programme and by the Department of Geography and Earth Sciences of Aberystwyth University under the Postgraduate Discretionary Research Fund programme.

We would like to thank Stephen Jennings for his useful comments on the map and Patricia Gongal for her helpful comments on the manuscript.

# Software

Mapping and composing: QGIS 2.2, 2.4, 2.6, and 2.6.1.

Digitizing tools (up to date version): autoSaver plugin, Digitizing Tools plugin, GdalTools plugin, Georeferencer GDAL plugin, GPS Tools plugin, Multipart Split plugin.

Figures on the map: Adobe Illustrator CS2



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# Figures

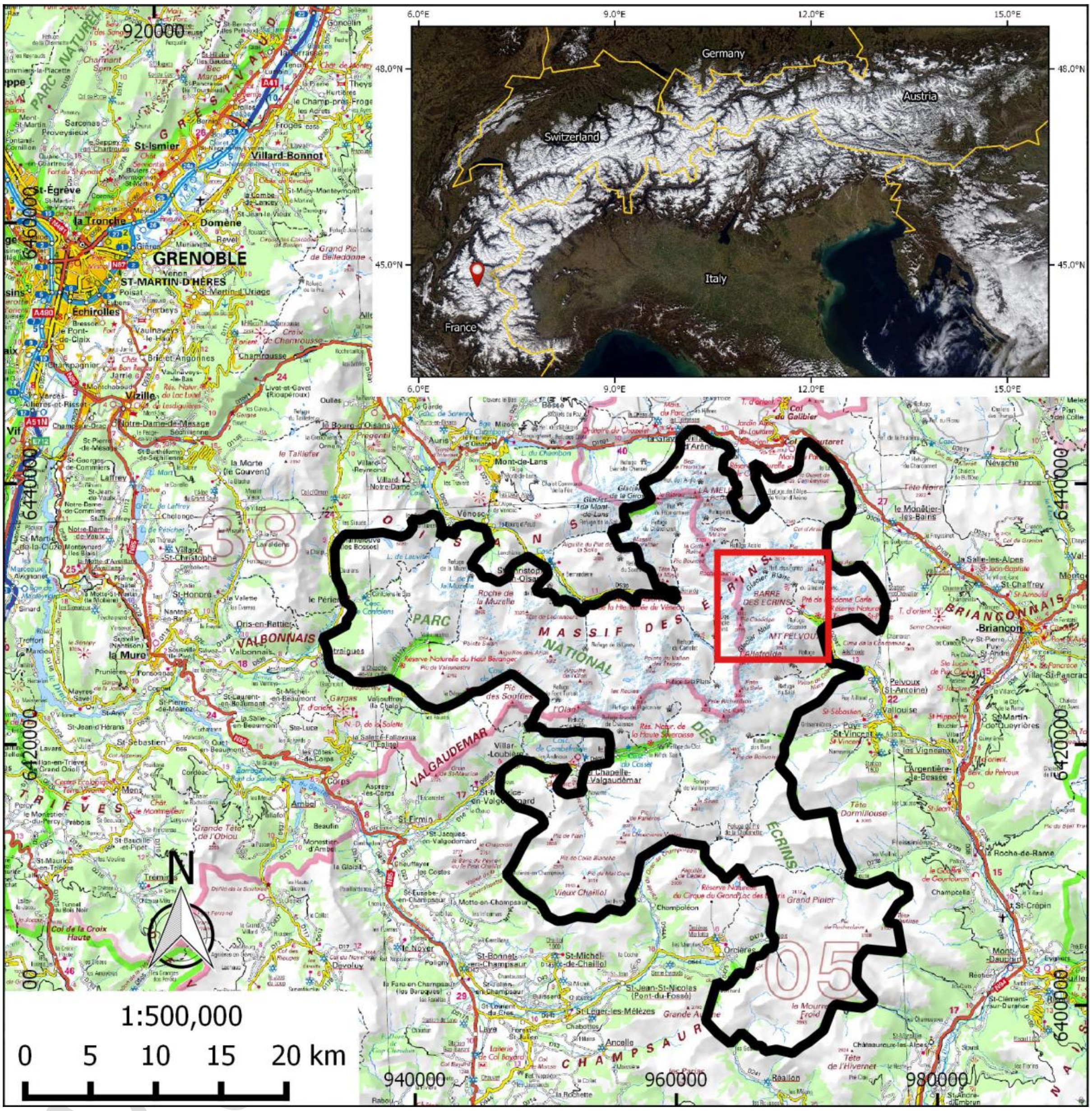


Figure 1: Overview map presenting the position of the study site (red rectangle) in "Écrins" National Park (solid black line). Background map: IGN ©SCANREGIONAL. Inset: location (red marker) of the study site in the European Alps. Background image: ©NASA.

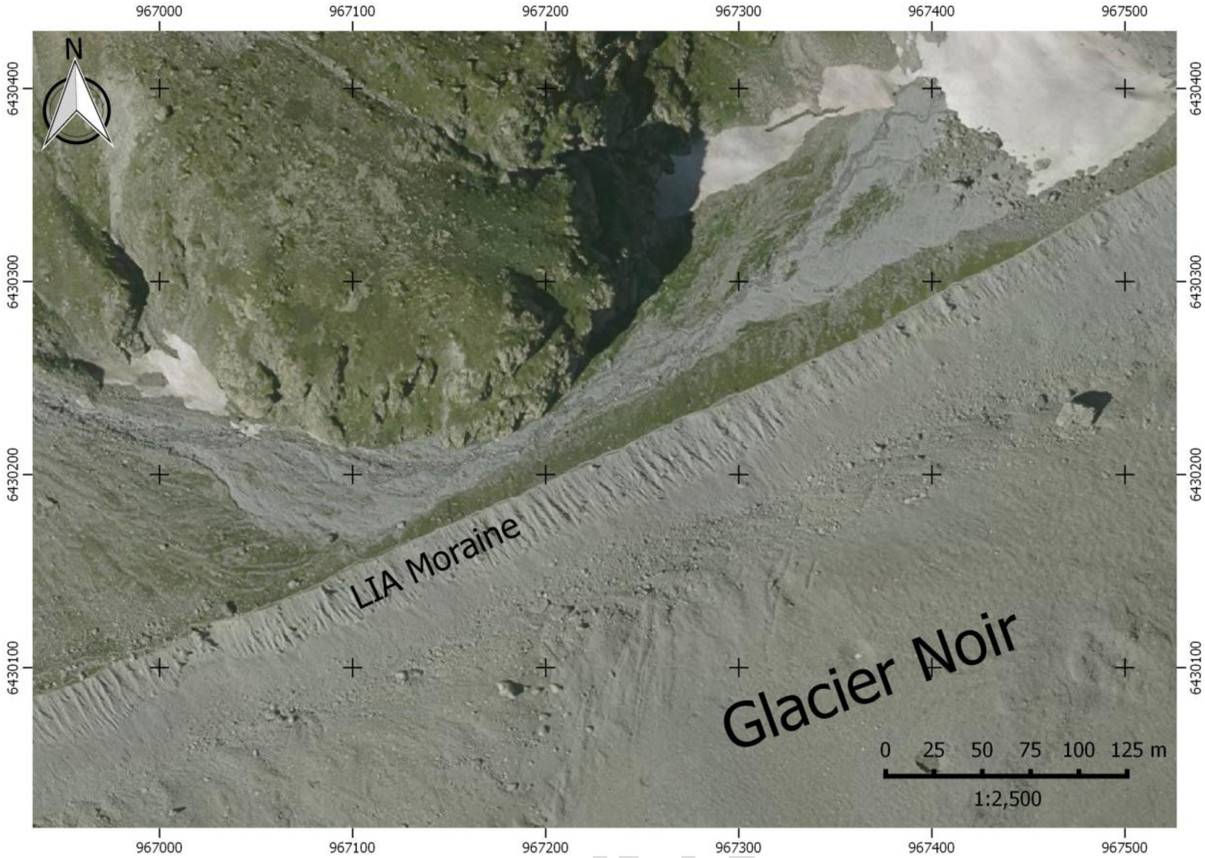


Figure 2: Extract of 2013 orthophotograph illustrating the difficulties in determining the edge of Glacier Noir, especially in the area between the northern border and the LIA moraine.


Figure 3: Glacier Noir (white dotted line) and its LIA moraine (black dashed line). The LIA moraine is the largest geomorphological feature i the study site and its ridge is constantly ~50-60 m above the surface of the glacier from the terminus to the headwall.


Figure 4: The new gullies (white arrows) created during a heavy rainfall event (26/08/2014) on the southern side of the LIA moraine of Glacier Noir.

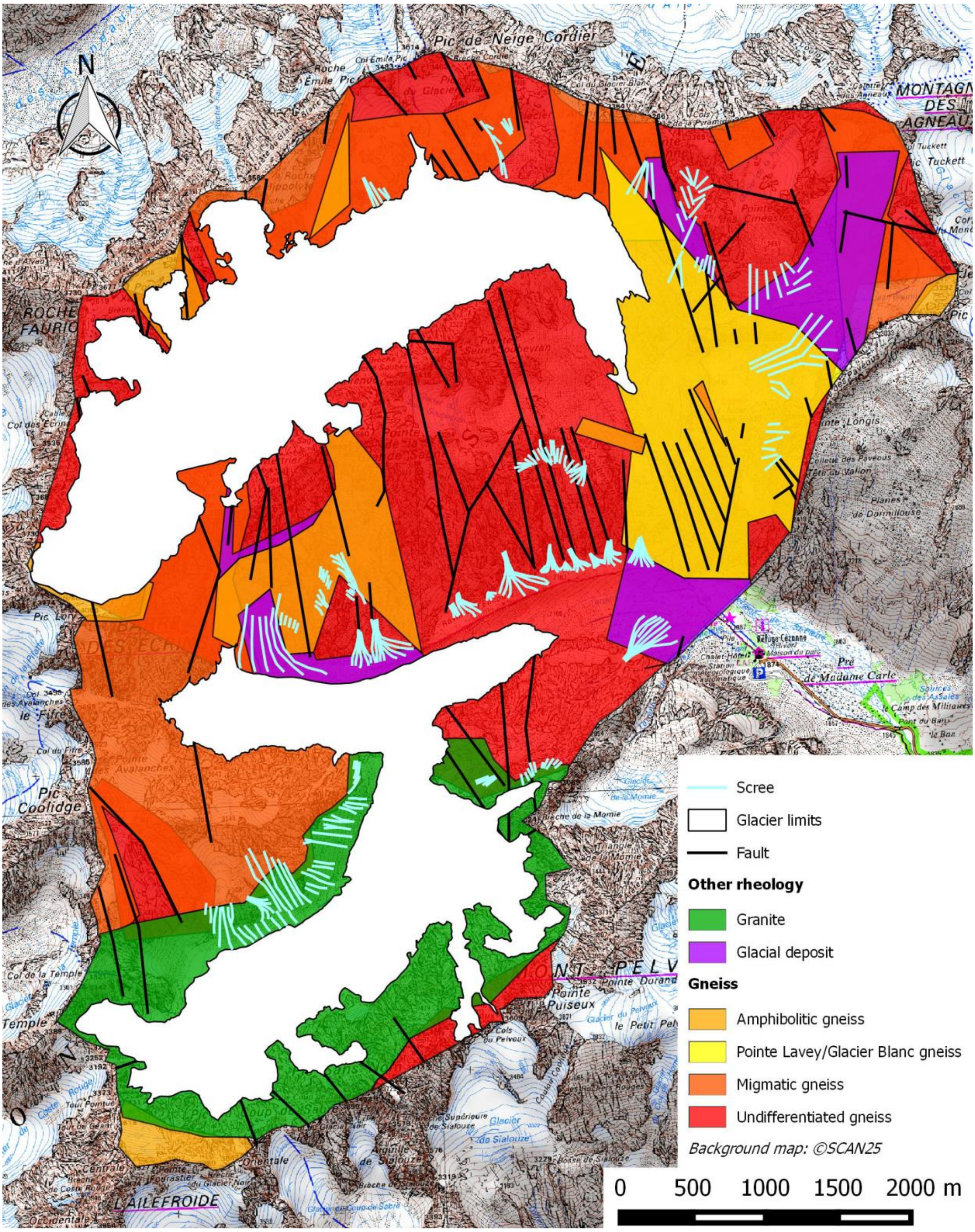


Figure 5: Geological map of the study site with superimposed scree areas. Geological variations (mainly gneiss except for Glacier Noir Sud with granite) in the study area cannot explain the origin of the scree areas. Slope orientation is the main factor in the scree production. Adapted from Bureau de Recherche Géologiques et Minières (BRGM) maps 0822N and 0823N.


Figure 6: Hummocky terrain in the proglacial area of Glacier Blanc. The hummocky moraine (green) are easily eroded by the proglacial stream. The frontal moraine (white) marks the lower limit of this hummocky area.

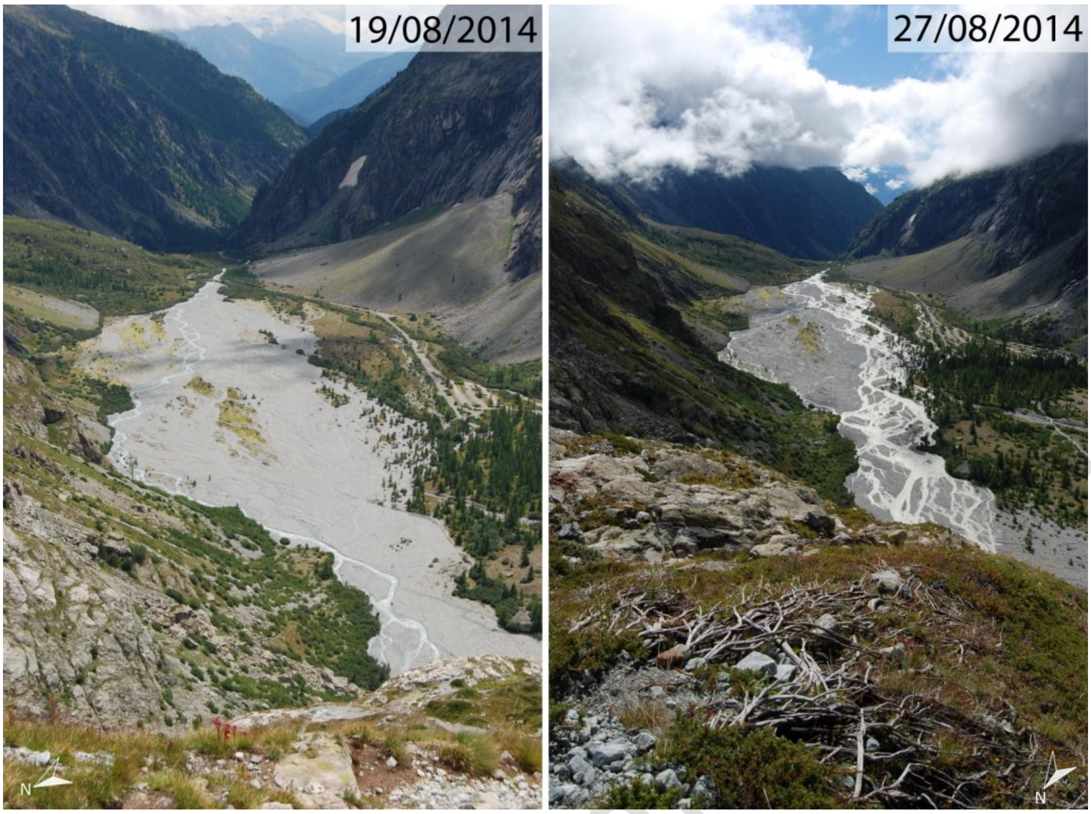


Figure 7: Outwash plain of Glacier Noir and Glacier Blanc. As a consequence of the heavy rainfall event of 26th August 2014, the proglacial stream shifted from the northern edge of the outwash plain to the southern edge, illustrating this highly dynamic environment.

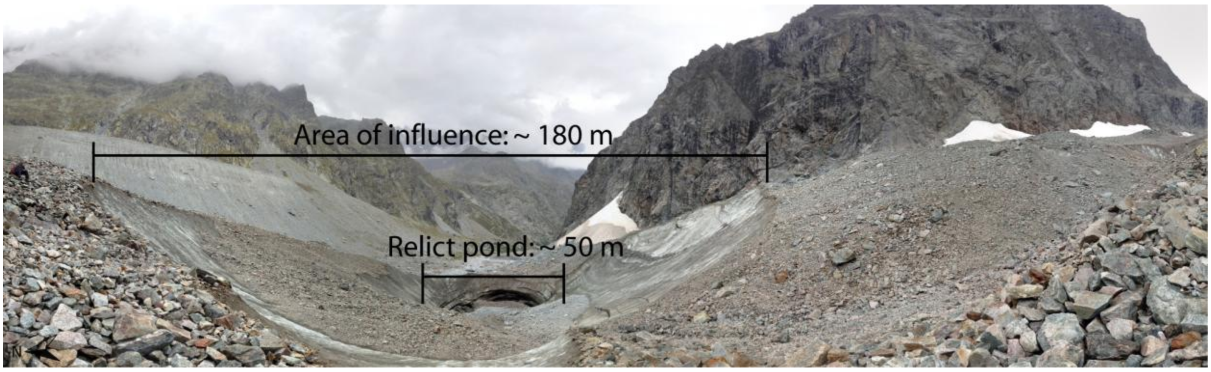


Figure 8: Relict meltwater pond and its area of influence at the terminus of Glacier Noir. The bottom of this pond collapsed in a subglacial channel between 2013 and 2014.

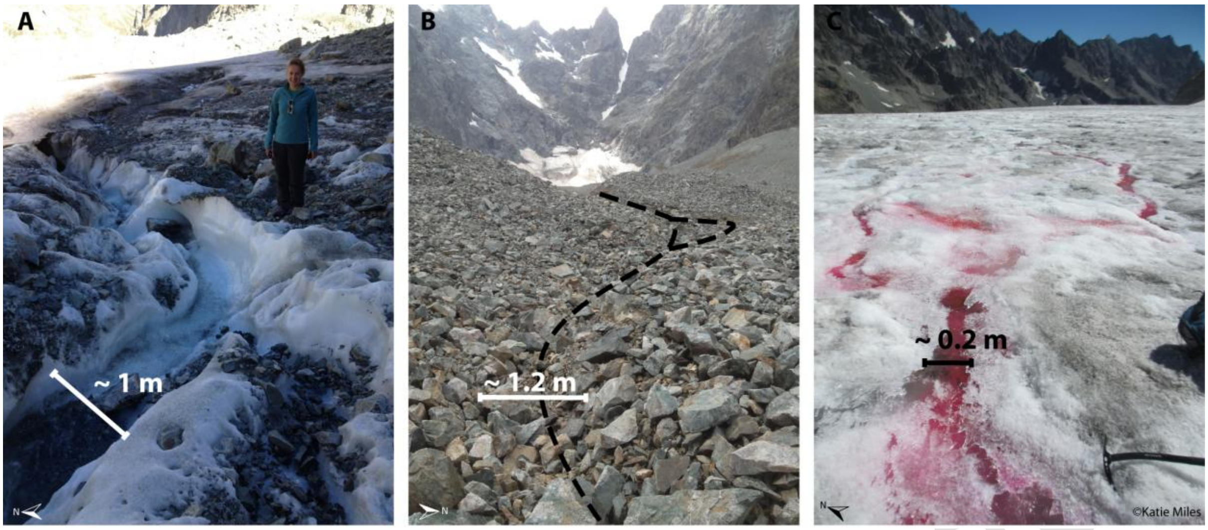


Figure 9: Various meltwater channels in the study area. (A) Active meltwater channel just below the accumulation area of Glacier Noir. (B) Trace of meltwater channels in the ablation area of Glacier Noir. (C) Active meltwater channels on Glacier Blanc highlighted by pink dye. Note the difference in scale between these images.