Geostatistical modeling of ice content within the *"Glacier Bonnard"* (Switzerland)

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Abstract: The Bonnard glaciated mass (Valais region, Switzerland) overhangs the village of Zinal and its slow downward constant creep constitutes an environmental hazard. Ice content data have been acquired to better assess globally and locally the ice amount within the area, in order to evaluate the glacier's global dynamic and future evolution. Two ice content modeling approaches are tested: (i) a direct modeling using 3D simulations and (ii) to account for the relationship between the presence of ice and the lithology, a nested approach which consists in (1) simulating lithology with the plurigaussian method and then (2) populating each facies with ice content values. Both approaches are compared in terms of ice content prediction and of global ice mass.

Keywords: environmental hazard, Bonnard, ice content, facies modeling, plurigaussian.

1. Introduction

The "*Glacier Bonnard*" is a complex paraglacial complex located in the Canton of Valais (Switzerland). The glacier overhangs a settlement and its slow downward constant creep constitutes an environmental hazard. It is therefore important to understand the glacier's internal structure, particularly in terms of ice content, in order to evaluate its current global dynamic and future evolution.

Following preliminary geological and geophysical investigations, ice content data have been measured within several drillholes. Such data should allow to assess globally and locally the amount of ice within the "*Glacier Bonnard*" area.

Two geostatistical modeling approaches are considered: a direct modeling of ice content and an indirect approach which accounts for the relationship between lithology and ice content. Both approaches are presented and compared in terms of ice content prediction and of global ice mass among the sampled area.

2. Material

The studied area is part of catchment that ranges between the altitude of 2750 and 3000 m (cf. Fig 1). At this geographical location, cold temperature (freezing) and snow play an important role in the annual water balance. Approximately 80 % of the surface is composed by creeping permafrost. The geology of the source area is located on the contact between the thrust sheets of the Dent Blanche and Tsaté systems (Pilloud & Sartori, 1981). The granitic gneisses of the Dent Blanche covering the glacier Bonnard fall from the cliffs that surround summital crests. The outcrops and the cliffs are much fissured and produce a very large amount of blocks.

As basis for determining the bedrock top, 11 lines of refraction seismic have been acquired and treated in tomography due to the chaotic relief. Even if the overall results seem to be consistent, small discrepancies were found between the lines (artefacts, unlikely geological features). A 3D managing sources software (Adhoc 3D solutions) has then been used to fit seismic refraction tomographic sections with drillholes and field geological mapping information. Along the refraction lines, points representing the bedrock top have been generated every 5 m. Those points are used to make an ordinary kriging of the bedrock top.

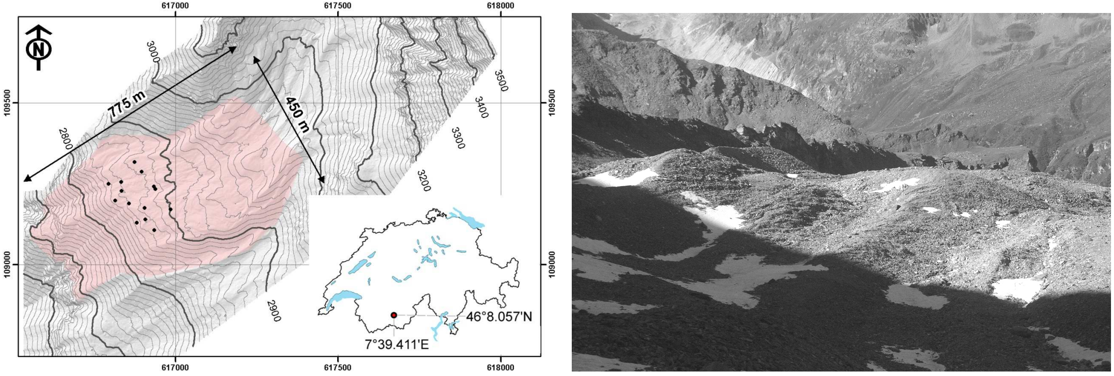

Figure 1. Left: global view of the studied area with drillholes location (black dots). Right: view from the top of the studied area in mid-summer 2009.

Fourteen boreholes have then been drilled using the Down-The-Hole Drill method (Fig. 1). This is a fast but completely destructive way to drill, which makes interpretation quite difficult. Indeed the only material available is cuttings smaller than 2 cm. All this information helped in determining homogeneous areas in terms of glaciated mass behavior, as illustrated on Fig. 2.

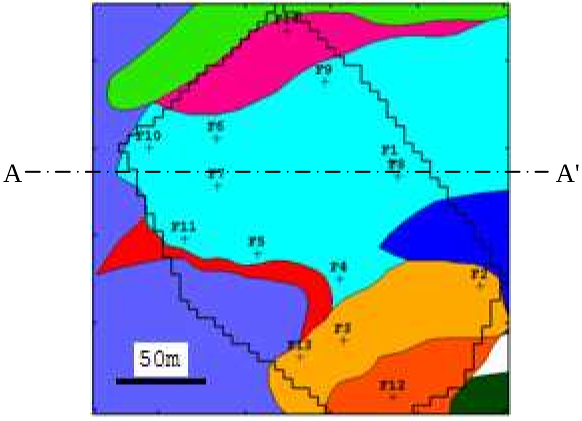

Figure 2. Outline of the studied area (broken line), drillholes (+) and polygons displaying homogeneous areas regarding the glaciated mass behavior.

3. Methodology

Several approaches might be applied to assess locally the ice content distribution and its variability. 3D conditional simulations have been first performed using the Turning Bands approach, after a Gaussian anamorphosis transformation (Chilès & Delfiner, 1999). This approach accounts for the spatial variability of the ice content, captured by a classical variogram analysis.

A strong relationship is expected between the lithotype and the ice content. Therefore, in order to account for that, 3D facies simulations are computed using the Plurigaussian algorithm (Armstrong et al., 2003), which allows integrating the geological knowledge about the expected transitions between facies (inferred from field survey). The algorithm consists first in determining the proportions of each lithothype over the 3D domain using drillholes information. The proportions are locally modified using the definition of homogeneous areas. Then a lithotype rule is chosen (Fig. 3) to describe the relationship between the facies. Variogram models for the two Gaussian variables are fitted such as to reproduce the spatial continuity of the lithotypes. Finally, Gaussian variables are simulated and truncated so as to get the facies simulations (Fig. 3).

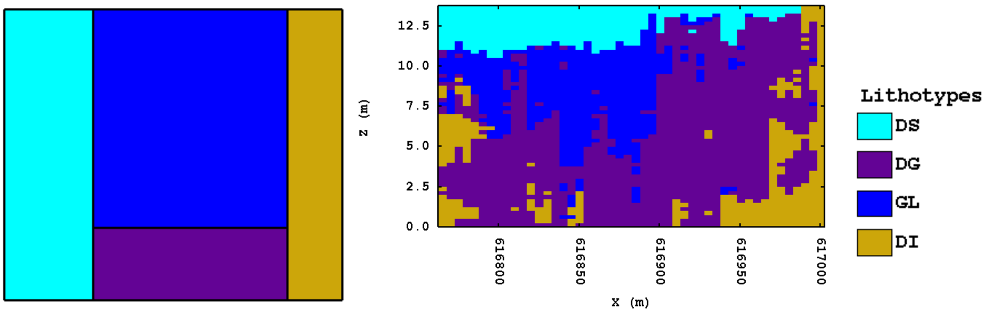

Figure 3. Left: Lithotype rule displaying authorized transitions between the facies. Right: Example of a lithotype simulation (along A-A' on Fig. 2) using plurigaussian (see Table 1 for lithotype meaning).

Once obtained, the facies simulations are populated with ice content values. The distribution of ice content within each facies is assumed random and to follow a triangular distribution.

For both approaches, a preliminary flattening has been performed to increase the lateral consistency of facies and ice content data. Once the 3D ice content simulations are obtained in the flattened space and converted back to the structural space, a post-processing is applied to determine the global distribution of ice content mass. The results will interestingly be compared with the computation of a statistical global mean and standard deviation, which assumes that the ice content is purely random within the area of interest.

3. Results & Discussion

The global simulated volume, for the area of interest (Fig. 2), is equal to 465 000 m^3. Classical statistics show the strong link between lithotypes and ice content (Table 1). Merging all data together contributes to largely increase the ice content variability.

Lithotype	Count	Min.	Q50	Max.	Mean	Std. Dev.
All	352	0	10	95	29.02	34.37
Superficial diamict (DS)	48	0	0	0	0.00	0.00
Glaciated diamict (DG)	137	0	20	60	21.42	13.18
Ice (GL)	86	60	87.5	95	84.65	10.45
Diamict (DI)	81	0	0	0	0.00	0.00

Table 1. Elementary statistics of ice content (in %) globally and for each lithotype.

Fig. 4 shows one ice content simulation obtained for each approach (turning bands simulation and plurigaussian simulation followed by a population with ice content values). Differences clearly appear: with the plurigaussian simulations ice content patterns are well defined due to the consideration of lithology. Furthermore, the horizontal changes suggest the presence of 2-3 ice bodies of which at least 2 are almost disjoint. Those features are consistent with field observations.

Finally, global estimates of ice mass are displayed in Table 2 within the area of interest. Similarity between the means is obvious whereas the standard deviations are very different. The statistical approach ignores data redundancy due to the spatial continuity and therefore underestimates the variability. Regarding geostatistical simulations, TB overestimates standard deviations; indeed, lithology being ignored, a lot of unrealistic intermediate values are simulated. On the contrary, PGS integrates the lithology and therefore produce more realistic results. PGS fits better with the field knowledge, particularly in producing simulations presenting discrete elements (ice-bodies, lateral moraine, etc.). These results are coherent with the genesis of those different features that are more colliding than mixing together.

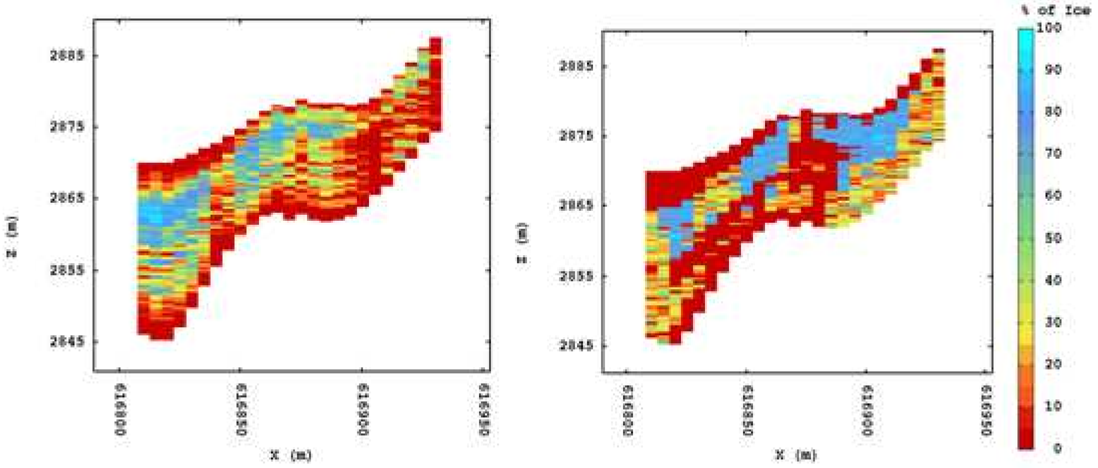

Figure 4. Cross-section along A-A' of the ice content simulations using turning bands (left) or indirectly via plurigaussian (right),for the same simulation.

Approach	Mean (kt)	St. Dev. (kt)	CV (%)	Q5 (kt)	Q95 (kt)
Statistics	123.69	2.26	1.83%		
Direct (TB)	130.08	21.87	16.81%	90.45	166.22
Indirect (PGS)	129.61	10.82	8.35%	111.08	147.33

Table 2. Classical statistics related to the global ice content mass estimated within the area of interest (in kilo tons of ice).

4. Concluding remarks

In this context of complex material with quick spatial changes, classical approaches like the single use of geophysics failed in providing an appropriate framework for detailed hazard assessment. Plurigaussian simulations allowed quantifying the total ice mass while taking into account the available information (lithology, homogeneous areas).

Acknowledgments

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References

Armstrong M., Galli A., Le Loc'h G., Geffroy F and Eschard R. (2003), *Plurigaussian Simulations in Geosciences*, Springer, 160 p.

Chilès J.P. and Delfiner P., (1999), *Geostatistics: Modeling spatial Uncertainty*, John Wiley & Sons, 720 p.

Pilloud, C., Sartori, M. (1981), *Etude géologique et pétrographique de la région des Diablons (Val de Zinal, VS)*. MSc. Thesis, Université de Lausanne.