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# Formation of authigenic sulfates in cold dry glaciers: terrestrial and planetary implications

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## 1. Introduction

Salts are commonly found on planetary surfaces, and sulfates have been widely observed on Earth, Mars [1] and on some of Jupiter's and Saturn's icy moons [2]. These minerals can form under a wide range of conditions, from warm environments with high water/rock ratioes to cold environments with low water/rock ratioes [3, 4]. The accurate determination of sulfate formation can thus provide key elements for deciphering past planetary surface conditions.

If terrestrial sulfates are mainly formed with a high water/rock ratio, this condition is rarely encountered in the solar system. A formation process involving cold and dry conditions is thus perhaps more relevant for Mars and icy moons. Sulfate formation in this kind of environment is however poorly documented on Earth. As planetary sulfates are often associated with ice deposits, this study focuses on the formation mechanism of cryogenic sulfates in extreme cold and dry environments. For that purpose, we performed a detailed analysis of sulfates found on a Chilean glacier. The obtained results are then compared to planetary data.

## 2. Terrestrial cryogenic sulfates

Two mechanisms of cryogenic sulfate formation have been documented so far: (1) post-depositional chemical reaction in ice [5, 6], and (2) crystallization during ice destabilization [4]. However, the first mechanism is very anecdotic and the second one has been observed only in Antarctica, where ice impurities include an important oceanic contribution.

The Guanaco glacier (29.3°S, 70.0°W) is located in the Pascua Lama region in the "South American Arid Diagonal", above an altitude of 5000m (Fig. 1a). According to the surrounding geology, the glacier ice is mostly contaminated by continental impurities and volcanic aerosols. Field analyses [7, 8, 9] reveal a cold-based glacier and a surface temperature that remains below 0°C throughout the year. The annual mass balance is negative and ablation occurs mostly by sublimation.

Sublimation leads to the formation of ice cliffs where deep ice layers are exhumed (Fig. 1b). Field observations on the cliffs reveal the presence of gypsum crystals interstratified in dust-rich ice layers and accumulated at the foot of the cliff (Fig. 1C). The fine needle morphology of these crystals suggests that the gypsum is neoformed and has not been transported in the ice. This interpretation is supported by the absence of gypsum crystals in ice cores drilled through the glacier. Gypsum thus seems to have crystallized as the ice cliffs retreated by sublimation and by sublimation.

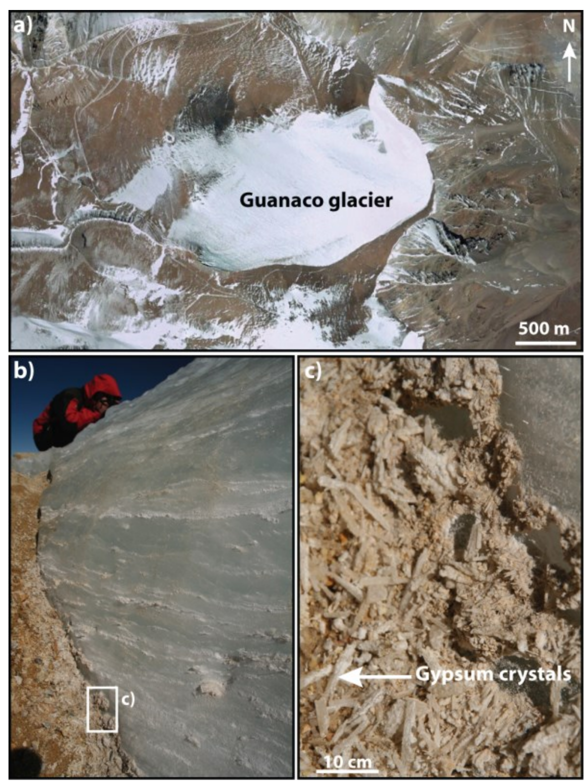


**Figure 1:** a) Landsat satellite image of Guanaco glacier, b) Sublimation cliff observed on Guanaco surface, c) Gypsum crystals released from the cliff.

# 3. Planetary implications

On Mars, sulfates have been found in two main areas: (1) in equatorial regions and (2) close to the North Polar Cap.

Conditions observed on the North Polar Cap are particularly similar to those of the Guanaco glacier with: cold and dry climate, ablation by sublimation only, and impurities coming from martian dust or volcanic aerosols. Mineralogical analyses of the North Polar Cap reveal the presence of gypsum on all superficial sediments [10] (Fig. 2a-b). These gypsum-rich sediments derive from the ice deposits and have been exhumed in ablation areas such as sublimation cliffs (Fig. 2). These sediments are then reworked and transported by katabatic winds in the circumpolar dune fields [11]. As gypsum appears on sublimation areas, we infer that the crystallization process is the same as the cryogenic process observed on the Guanaco glacier and due to sublimation.

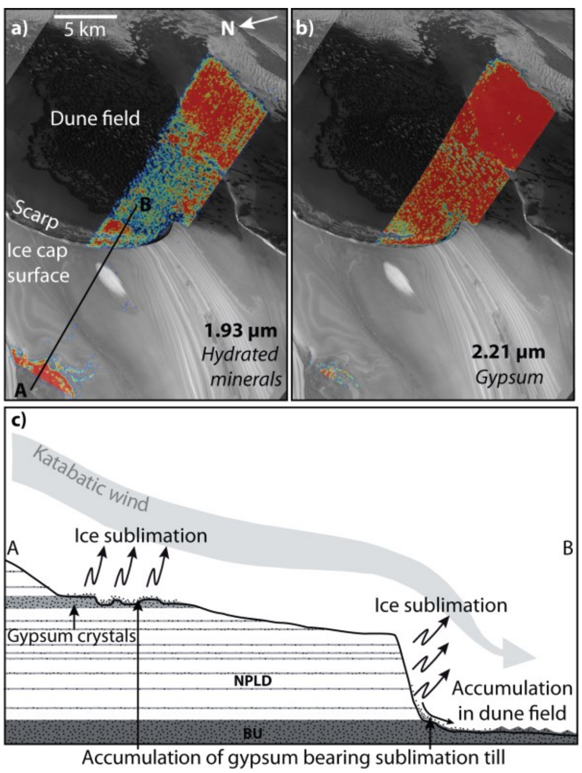


**Figure 2:** Sublimation cliff and associated superficial sediments observed on the North Polar Cap of Mars [10, 11]. a) Detection of hydrated minerals signatures, b) Detection of gypsum signature, c) Interpretative scenario for the formation of superficial gypsum bearing sediment in the North Polar Cap.

Martian equatorial sulfates were formed in the past with a low water/rock ratio [12]. One of the last hypothesis thus suggests that these sulfate deposits may have a glacial origin, but the exact formation mechanism remains unclear [12]. This hypothesis is consistent with the presence of glacial landforms in the same areas [13]. We propose a cryogenic origin for these sulfates during sublimation, consistent with the formation of large volumes of sulfates deposits, on widespread and various terrains and at various altitudes.

Sulfates have also been detected on icy moon surfaces, particularly on Europa [2]. Liquid water can't exists on the icy satellites surface. A completely dry formation process lead by ice sublimation thus has to be considered, and is supported by the observation of sublimation processes on icy moon surfaces [14].

# 4. Conclusions

The analysis of a cold and dry glacier located in the Chilean Andes reveals that authigenic sulfate crystals can form by cryogenic processes at the surface of glaciers. The crystallization occurs during ice sublimation and does not involve liquid water. Though this original formation process is uncommon and generates minor quantities of sulfates on Earth, it may be dominant in the Solar System because sublimation is a common process at the surface of other planets. The Guanaco glacier is thus a particularly relevant analog for the Martian North Polar Cap, but sulfate formation by ice sublimation has also to be considered for the formation of sulfates in martian equatorial regions and on icy moons.

# References


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