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The force of crystallization When gypsum tears the varves of the Trièves!

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The force of crystallization

When gypsum tears the varves of the Trièves!



Figure 1 : Varves, Sinard, Alps, France

Photo Bernard BARAILLER, 2024

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Introduction

"The varve, the gypsum and the force of crystallization" could have been the title of a fable by La Fontaine.

Gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, is a very soft mineral. Its hardness is 2 on the Mohs scale. It can be scratched with a fingernail, which has a hardness of 2.2 to 2.5. Varves are lacustrine clays that pile up with the seasons. As a crystal grows, it exerts a force on its external environment called the crystallization force.

In the foothills of the Vercors, these varves have preserved gypsum crystals. These are present between certain layers of clay. Although these crystals are soft, they deform the clays and even tear them. How is this possible?

To answer this question, I invite you to go back in time, to the Würm ice age.



Figure 2 Grouping of gypsum crystals (20 cm) on its clay matrix, Sinard, Isère

2024 Louis DALLARD

1 Geological context : Grenoble during the Würm period

The Würm is a Pleistocene ice age in the Alps. It lasted from 115,000 to 11,700 years before present (BP)¹. The following map shows the position of the Isère Glacier at this time. At this time, glacial lakes formed in the south in the Trièves area. Erosion of the Vercors and Dévoluy foothills cyclically brought sediments, particularly clays, which were deposited at the bottom of the lake (Jongmans et al., 2009 ; Thomas, 2021).

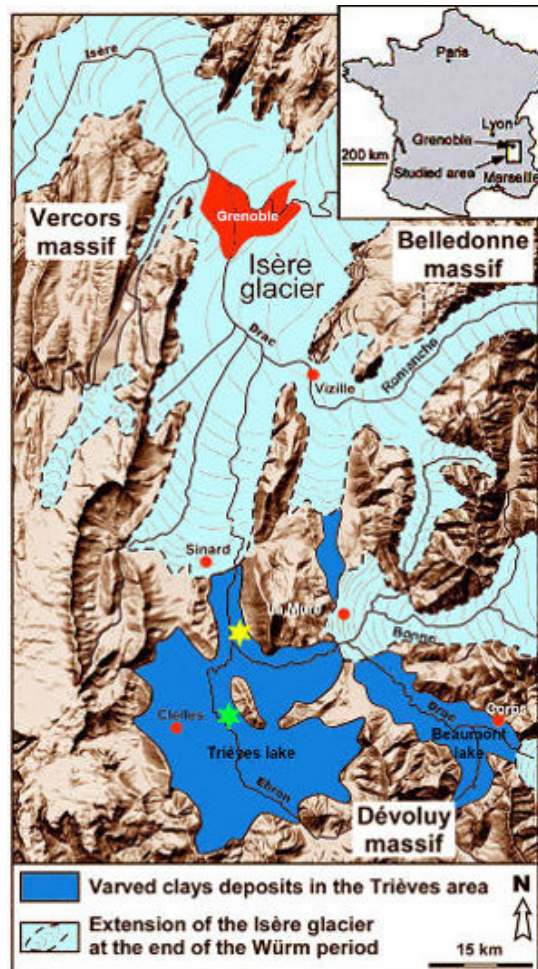


Figure 3 The Isère glacier and Lake Trièves at Würm
2009 according to Jongmans et al.

1 In the international chronostratigraphic chart, AP dates (before the present, BP before present in English) have as “year zero” the year 2000 (AD 2000) (we sometimes have the notation b2k (before 2k), while radiocarbon ages have as reference the year 1950 (AD 1950) cf. <https://doi.org/10.18814/epiiugs/2008/v31i2/016>).

2 The varves of Trièves

2.1 Glaciolacustrine clays

The Trièves varves are clays. They are actually mixtures of clays, silts, and fine, layered sands deposited in a glacial reservoir. During the Würm period, in a cold and frozen environment, biogenic input was reduced. These varves are therefore mainly of clastic origin (resulting from erosion). The following figure shows the mineralogical composition of the Trièves varves.

Mineral composition	Monestier-du-Percy sector	Sinard sector
Quartz (%)	10–20	14–16
Calcite (%)	25–50	15–20
Feldspar (%)	5–10	5–10
Illite (%)	10–15	42–47
Chlorite (%)	6–10	14–16
Kaolinite (%)	5–6	–
Montmorillonite (%)	5–12	0–5
Vermiculite (%)	–	–

Figure 4 Mineralogical composition of the Trièves varves (Sinard)

According to A. Giraud et al. 1991

We notice disparities in mineralogical composition depending on the sites. This is mainly linked to the geology of the watersheds. For the Sinard area, we will take as an example the most abundant mineral, illite. At the atomic level, clays are like sandwiches stacked on top of each other. We can also imagine them as a book. Indeed, each layer is called a sheet. The following figure illustrates the TOT (Tetrahedral Octahedral Tetrahedral) structure of illite.

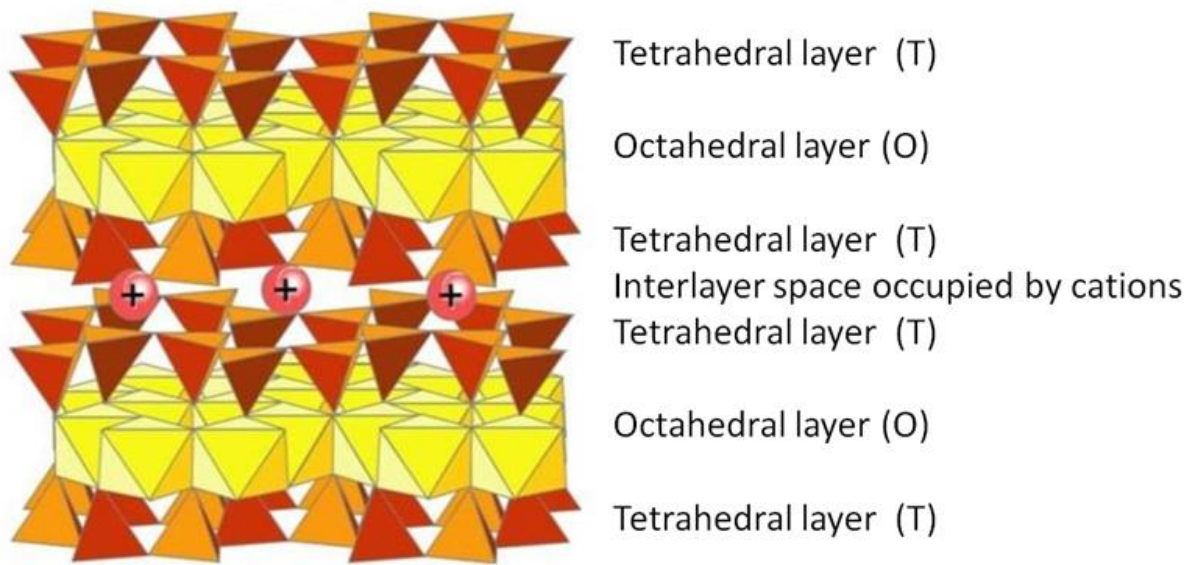


Figure 5 TOT structure of illite

Each layer of the illite structure has an octahedral layer (in yellow) located in the center of the layer with $Al(OH^-)_5O$. This layer is sandwiched by two tetrahedral layers (in orange) with SiO_4 . The interlayer space is occupied by potassium ions (K^+).

2017 According to A. Wissocq, 2017

2.2 The genesis of varves

Varves are formed with the seasons. The following diagram shows an example of an annual cycle of sediment input into a glacial lake.

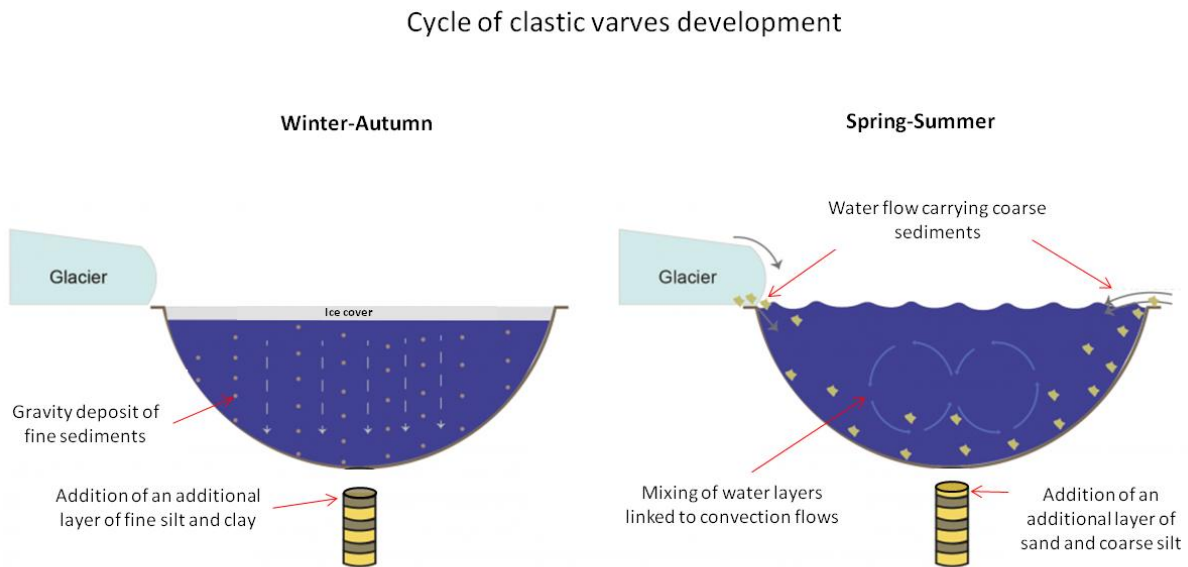


Figure 6 Pattern of seasonal sediment inputs and deposition in a glacial lake

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In spring, when the current is stronger, the sediment particles carried along are coarser. When the lake is frozen, the water layers stabilize, and the fine suspended particles are then deposited. For each annual cycle, this forms two layers, one coarse and lighter (spring-summer) and the other fine and darker (winter-autumn) (Figure 7).



Figure 7 Glaciolacustrine varve deposit, Patagonia 2014 in Boyal 2023 AntarcticGlaciers.org

<https://www.antarcticglaciers.org/glacial-geology/varves/>

The existence of varves also implies a lake deep enough that there is no mixing of sediments by water convection currents.

An ideal lake is deeply incised in the watershed, surrounded by uplands that limit the influence of wind-driven mixing. Lake Suminko (Figure 8) in northern Poland is an example of this and shows that continuously laminated sediments are restricted to the deepest, oxygen-free part of the water column. Furthermore, it is characterized by a lake depth profile with a relatively flat depositional center, a relatively high sedimentation rate, and stable slopes that avoid subsidence and turbidite sedimentation. Finally, depositional centers can be located close to river inlets and receive allochthonous mineralogical material. This requires a depth typically greater than 20 m (Zolitschka et al., 2015).

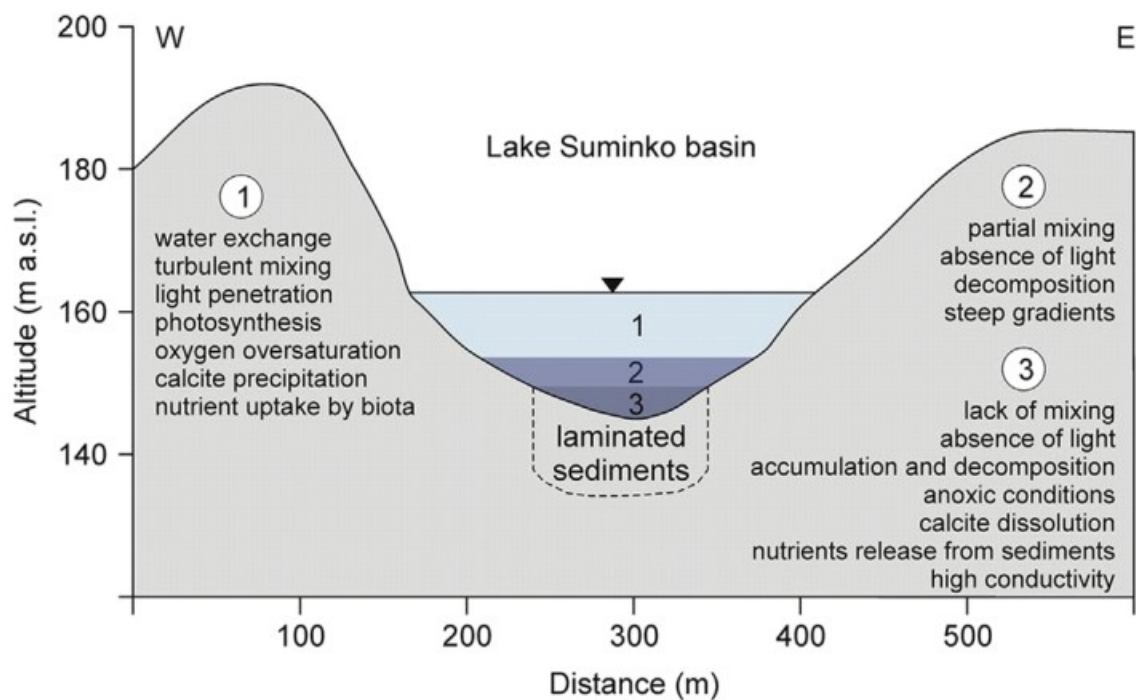


Figure 8 Schematic section of Lake Suminko, Poland, Zolitschka et al., 2015

The situation at Lake Trièves during the Würm period could be comparable to that of Lake Suminko. In the area where the layered sediments (varves) develop, there is no water mixing, light no longer reaches, and anoxic conditions are then possible.

The following geological section (Figure 9) of the Sinard area shows the layered clays and the profile of the rivers and lakes that gradually appeared. The Drac changed its course over time, each time cutting into the limestone substrate. Fluvial alluvial siltation may have occurred during the Riss-Würm interglacial. These latter deposits, as well as the topology of the area, were then conducive to the creation of varves.

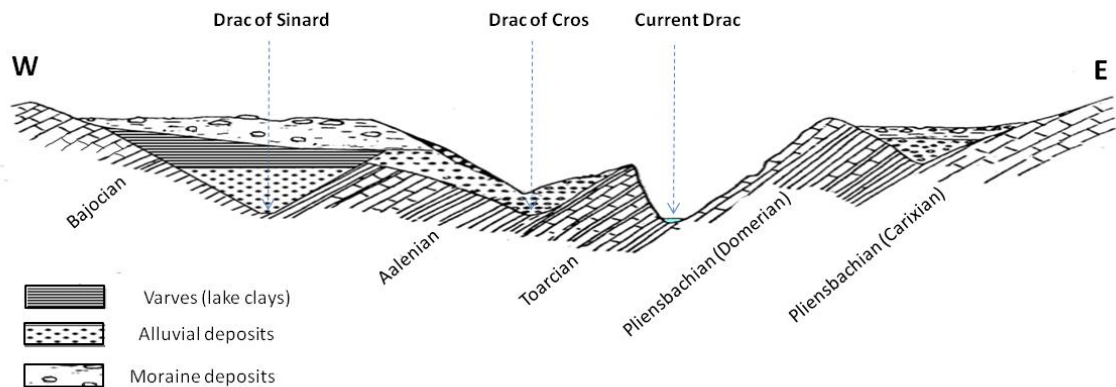


Figure 9 Geological section of the Sinard area (Isère)

Bernard BARAILLER, 2024, after Monjuvent (p197) 1978 and an extract from Gignoux and Moret (p319) 1952, retouched by Maurice Gidon geol-alp

The following figure shows the depths of lakes with varves as a function of their surface area (Zolitschka et al., 2015).

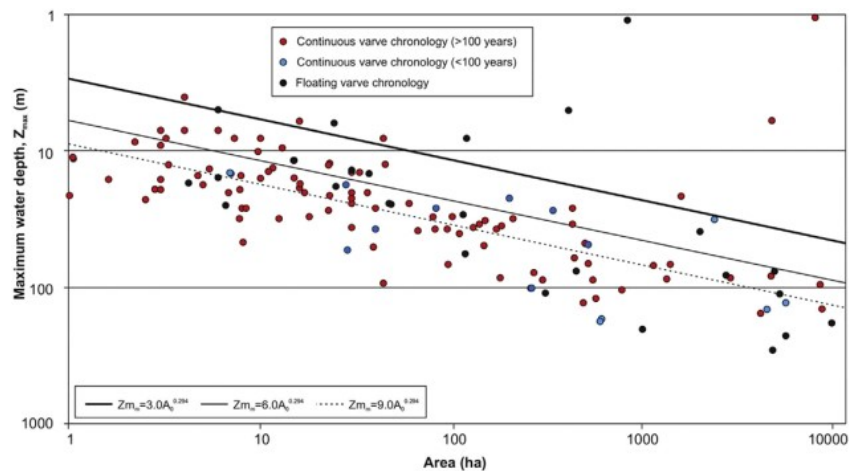


Figure 10 Relationship between maximum lake depth and surface area, based on published data from 136 glaciolacustrine varve lakes, Zolitschka & Al, 2015, figure9

The surface area of Lake Trièves is around $700 \text{ km}^2 = 70,000 \text{ ha}$. According to the previous figure, the lake must have been more than 200 m deep.

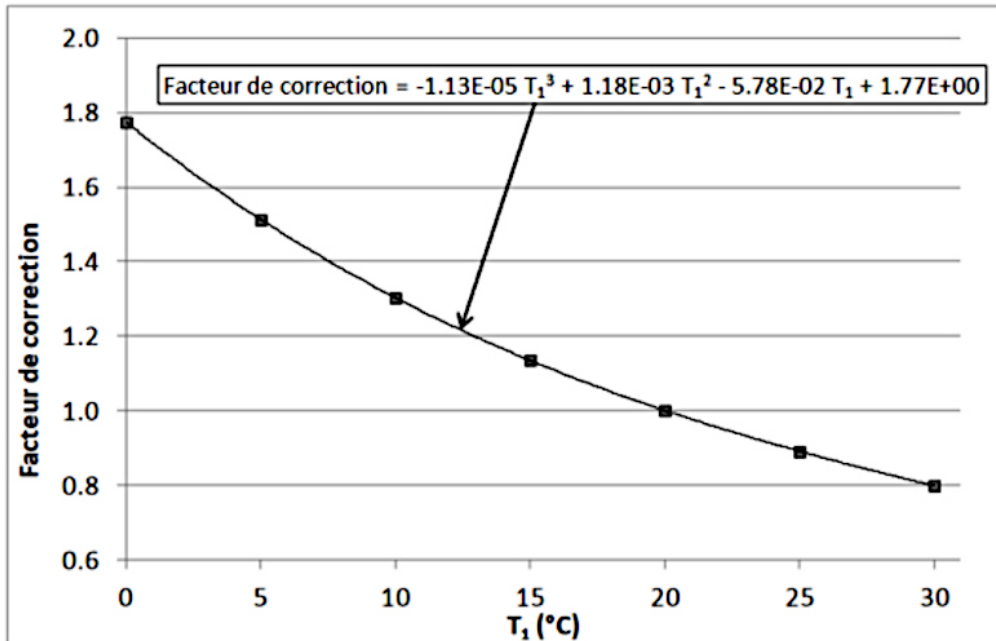


Figure 11 Correction of permeability k as a function of water temperature, F. Duhaime, 2012

The water in Lake Trièves was at about 4°C. A correction factor of 1.56 is therefore necessary to obtain the permeabilities associated with the conditions of formation of the varves and gypsums included therein. The water in the lake is not distilled water, but for the following models we will take $k_{4^{\circ}\text{C}} = 6.4 \cdot 10^{-11}$ m/s for simplicity.

This anisotropy of permeability, as well as the gravitational contribution of pebbles on certain layers, modifies the water flows in the varves. Thus, the mechanical behavior of these clays is such that numerous landslides can occur within the very sedimentary structure of these varves. In the Sinard forest which descends towards the lake, numerous rotational landslides with curved pines are observed. This is likely to complicate the local analysis of the gypsum layers (Giraud et al., 1991). The following section (figure 12) shows a varve thickness of more than 200 m.

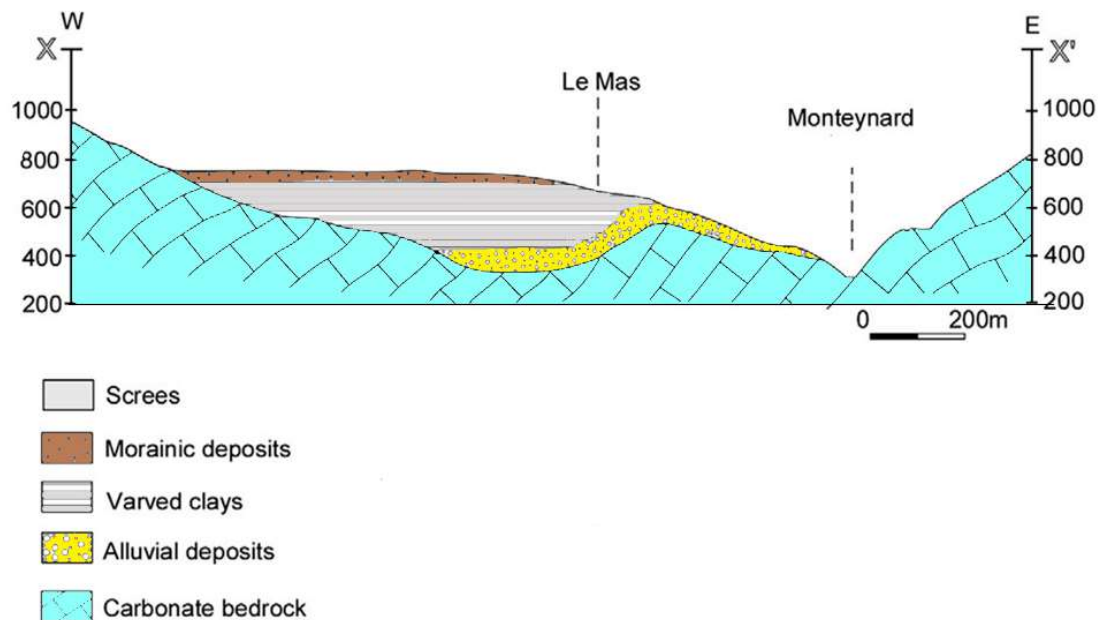


Figure 12 Geological nature of the land in the commune of Sinard (Isère), 2009 in Institute of Major Risks, https://irma-grenoble.com/05documentation/04dossiers_PJ.php?id_PJ=114 &id_DT=7

When collected, the Sinard gypsums were tightly sealed within the clays. They showed no evidence of water infiltration. Under more than 20 meters of clay, the oxygen supply also appears to be reduced.

Density. At shallow sediment depths, an order of magnitude for density is $\rho_{\text{varve clay}} \approx 1170 \text{ kg/m}^3$ (Loso, 2008). Experimental measurement of Sinard varved clay gives $\rho_{\text{varve clay}} \approx 1733 \text{ kg/m}^3$ (measurement on a personal sample of $m \approx 26 \text{ g}$, $V \approx 15 \text{ ml}$; this clay belonged to a 3 cm gypsum layer). It should be noted that if a piece of varve is placed in water, it quickly loses its initial shape and sediments again at the bottom of the container. These laminated clays are therefore subject to a transition from the plastic state to the liquid state when the water content increases. This may explain the innumerable solifluction flows and the associated civil engineering problems of building a highway in the area.

3 When gypsum deforms clays

Varved clays are the matrix in which gypsums grow. In a classic growth model, crystals grow in voids (air, water). This results in veins or geodes. Here, on the contrary, the porous environment of varved clays is devoid of voids to the naked eye, that is the reason why a confined growth model is used. In that case, crystals grow in the porous environment of varved clays.

By analyzing in-situ oriented samples (located in gangue), we see that the clays above the gypsums have undergone plastic deformation (figure 13). Furthermore, concerning the resistance of the materials, beyond a certain threshold (plastic limit) the clay layer has torn (figure 14). The underlying clay layer on which the gypsum is placed is little deformed and appears more homogeneous and denser.

This suggests that these deformed clay layers experienced a bottom-up force in alignment with their radius of curvature.

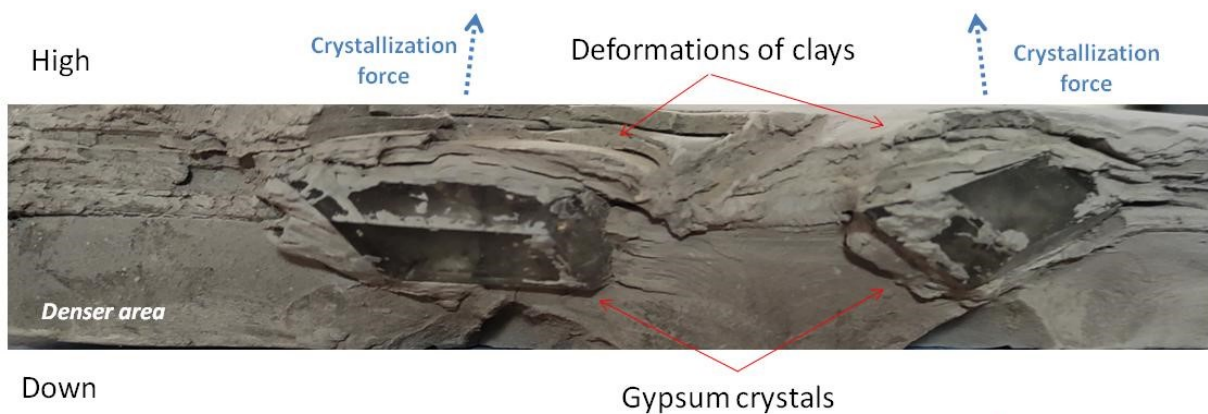


Figure 13 Side view, deformation of the varves by two gypsum crystals, 2024

Bernard BARAILLER



*Figure 14 Figure 14 Top view, opening of a crack in a varve by a gypsum crystal
2024 Bernard Barailler from a photo by Louis Dallard*

The following figure illustrates the plasticity of Sinard clays.



Figure 15 Clays from the Sinard varves (Isère) deformable by “plates” (plasticity)

Bernard BARAILLER, 2024

The following figure (figure 16) shows a stress-strain diagram. In case 1 (figure 13), the clays are plastically deformed, they do not return to their initial state. The plasticity threshold has been reached, they keep their deformation (green circuit noted 1). In case 2 (figure 14), the rupture threshold is reached, the clays are torn.

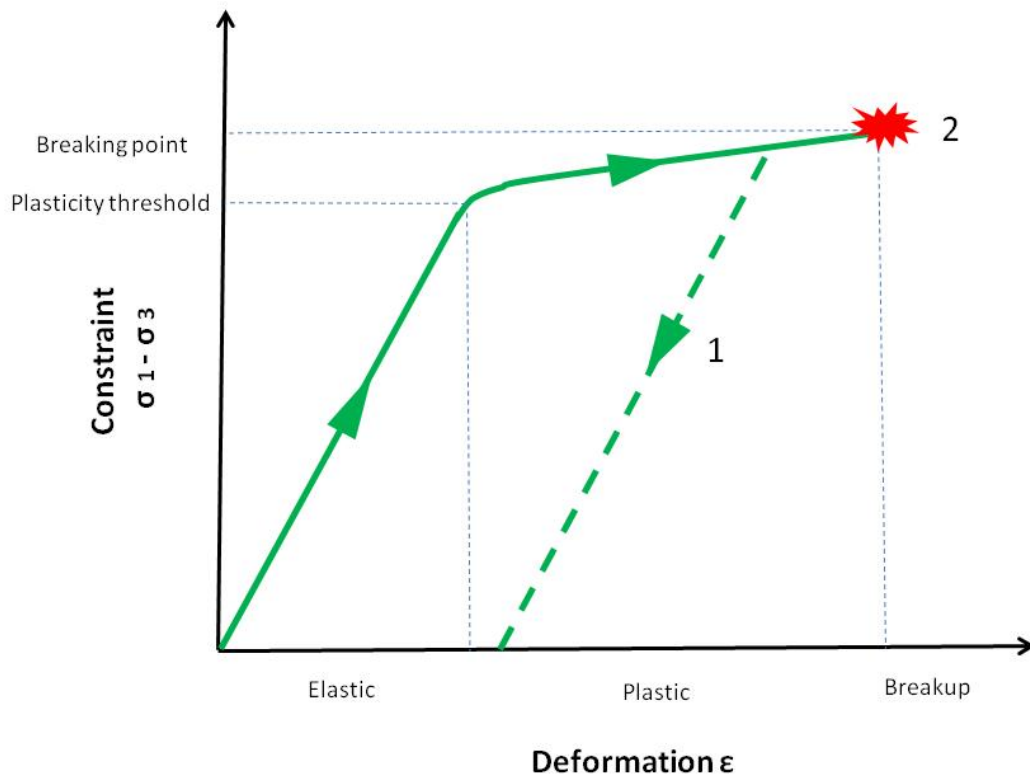


Figure 16 Stress-strain diagram, plasticity threshold and failure threshold

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In a similar context, varved clays formed by sedimentation at the bottom of a Canadian lake about 10,000 years ago following the retreat of the Laurentide ice cap. Studies report stress thresholds of around 70 kPa (Darve, 1983). However, the compressive strength of clays can be very variable and depends on many parameters : lithostatic pressure of the upper layers, water content, clay content, degree of consolidation, porosity of the varves, etc.

For the Trièves varves, tests in drained consolidated conditions (CD) give a stress threshold perpendicular to the strata of between 13 and 23 kPa (Giraud et al., 1991).

Let us now see how a crystal (gypsum) can exert a force on its external environment (clays) during its growth.

4 The force of crystallization

In a 1939 article, Correns and Steinborn explained the concept of crystallization force for a macroscopic crystal. Part of the experiments was carried out with a pressure compensator built by Correns (figure 17). This device made it possible to observe the growth of an alum crystal (in red) in a supersaturated solution. A crystal growth of $1\ \mu\text{m}$ gave, by mirror transmission, 15 mm on the final graduation (Sk). Alum is, like gypsum, a hydrated sulfate : $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$.

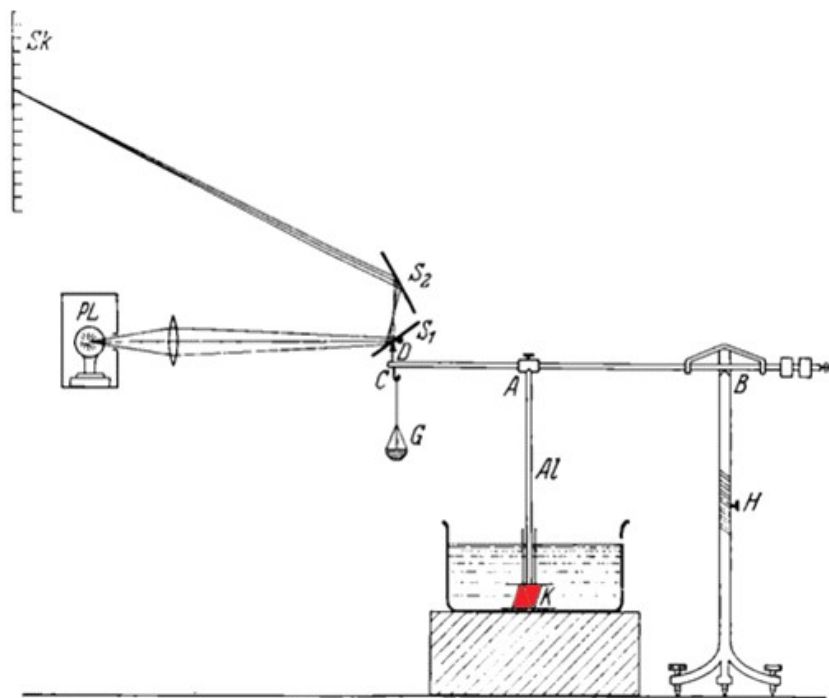


Figure 17 Pressure compensator for continuous monitoring of growth pressure

Schematic sketch: Tungsten spot lamp PL, movable mirror S1, fixed mirror S2, graduated scale Sk, axis D which rotates the mirror, suspension point C of the scale G, crystal K, notch A, punch Al, cutting edge B, thread H for height adjustment.

figure <https://www.semanticscholar.org/paper/Experimente-zur-Messung-und-Erk%C3%A4rung-der-Correns-Steinborn/c6316f8869944b47e0324a6717f8564ee09f12c1> in Correns and Steinborn, 1939

During its growth, a crystal can exert a force called crystallization. This is manifested by pressure exerted by the crystal on its external environment.

A simplified formula makes it possible to explain, in an ideal dilute solution (figure 18), the equilibrium crystallization pressure : $P = (RT/V) \cdot \ln(C/C_0)$, where C is the equilibrium

concentration of gypsum for pressure P , C_0 the equilibrium concentration in the standard state $T=25^\circ\text{C}$ and $P=1$ atm, V is here the molar volume, R the ideal gas constant ($R=8.314 \text{ JK}^{-1} \cdot \text{mol}^{-1}$) and T the temperature in Kelvin.

As soon as the supersaturation is no longer reached, the crystal stops growing. Equilibrium is reached, the pressure exerted by the crystal on its external environment is then zero (Correns and Steinborn, 1939). For gypsum, a more precise theoretical calculation, based on the activities, gives the values shown in the following figure (figure 18).

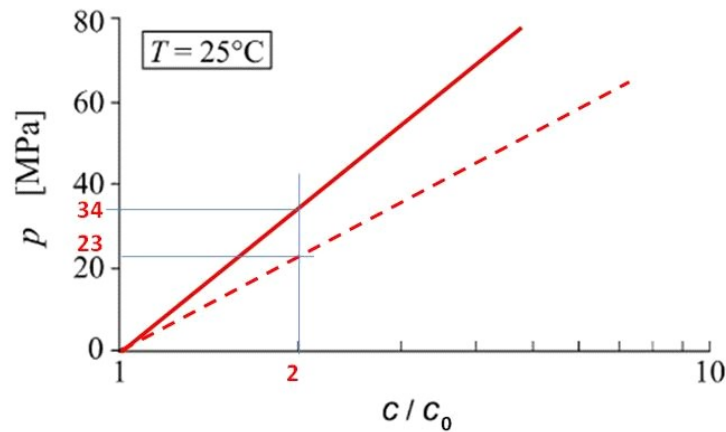


Figure 18 Gypsum crystallization pressure as a function of relative supersaturation (logarithmic scale)

$P = (RT/V) \cdot \ln(K/K_0)$ where T is the temperature in Kelvin, R is the ideal gas constant $R=8.314 \text{ JK}^{-1} \cdot \text{mol}^{-1}$, V the molar volume (here of gypsum), K denotes the product of the ionic activity of the solution and K_0 the equilibrium solubility product of gypsum under standard conditions. This corresponds to the solid red curve. To simplify the calculations, for low supersaturations (C/C_0 close to 1), we see that we can approximate the value of P by $P=(RT/V) \cdot \ln(C/C_0)$. This corresponds to the red dotted curve.

2024 Bernard BARAILLER after Serafeimidis and Anagnostou, 2014

The molar volume of gypsum is $V = 74.3 \text{ cm}^3 / \text{mol}$. At equilibrium, $C/C_0 = 1$, the pressure is therefore zero, since $\ln(1)=0$. For $C/C_0 = 2$, for example, we then have $P = (8.314 \times 298 / 74.3 \cdot 10^{-6}) \cdot \ln(2) \approx 23.1 \text{ MPa}$, even if the calculation here is approximate because we are far from 1 for C/C_0 , the exact value being of the order of 34 MPa (figure 18).

Let us return to the case of gypsum at the bottom of Lake Sinard: at a temperature of 4°C (277 K), in order to reach the value of the stress threshold of the Trièves varves, estimated at 23 kPa (high value, Giraud et al., 1991), a fairly low relative supersaturation is required. Indeed, we then have $C/C_0 = \exp(PV/RT) = \exp(23 \cdot 10^3 \times 74.3 \cdot 10^{-6} / 8.314 \times 277) = 1.0007$.

According to the solubility curves of gypsum and its saturation and supersaturation values (see Barailler 2024 “How are crystals formed? From the beaker to hydrothermal growth” and Barailler “An exemplary monoclinic crystal. How are the gypsums of Trièves formed” 2025), during gypsum growth episodes, the relative supersaturation is $C/C_0 = 1.94/1.84 = 1.05$, the pressure exerted by the crystal on its external environment is then: $P \approx 1.6 \text{ MPa}$ (= 16 bar = 16 kg/cm²). During nucleation, the relative supersaturation is $C/C_0 = 2.75/1.84 = 1.49$, the pressure exerted by the crystal on its external environment is therefore: $P \approx 13.3 \text{ MPa}$ (= 133 bar = 133 kg/cm²).

These thermodynamic formulas are approximations. Other factors influence the crystallization pressure: chemical activities, surface tension, geometry and pore size distribution, non-equilibrium kinetics, presence of other ions (Na⁺ in particular), possible anhydrite-gypsum phase transitions (Gagliardi, 2018)...

However, the pressures measured, for example, in the three Swiss tunnels crossing a Keuper formation (Upper Germanic Triassic, see case study in Chapter 5) are relatively similar to those estimated here: $1.6 < P < 14.6 \text{ MPa}$ ($16 < P < 146 \text{ kg/cm}^2$) (Serafeimidis and Anagnostou, 2014). In view of all these elements, it appears that, even with low supersaturation, the crystallization force of gypsums can deform, or even locally tear clays (whose rupture threshold is of the order of 23 kPa), as seen in the photographs of the previous varves (figures 13 and 14).

5 Geological Implications: Sculptures and Tunnels

Crystallization pressure has varied effects on human constructions.

The statues are crumbling. The growth of salt crystals (halite) in the grain boundaries of the ashlar stone causes the rock to shatter. The statues are crumbling as shown in the following figure (Figure 20).

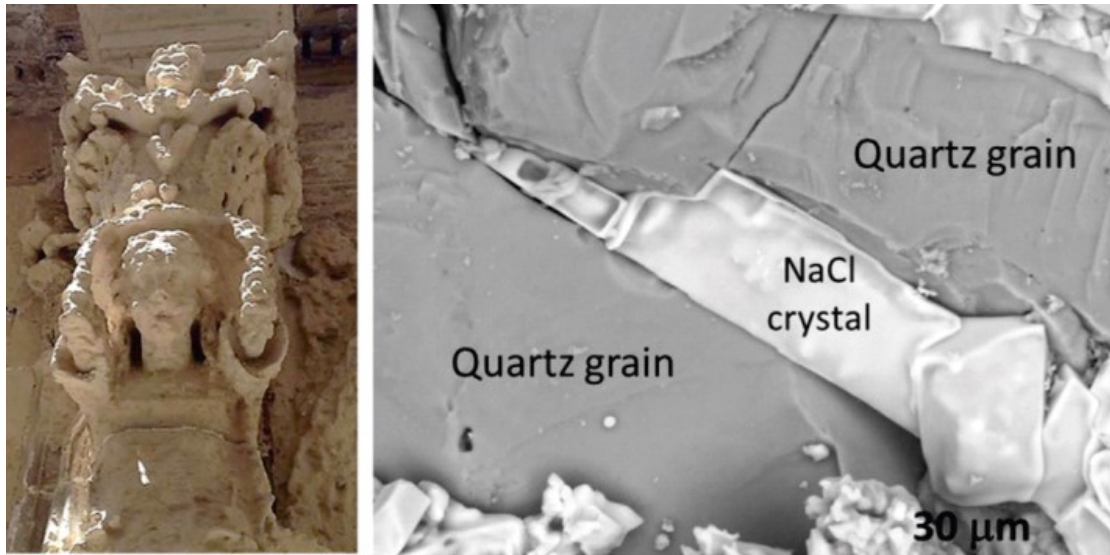


Figure 19 Figure 20

Degradation of a statue linked to the growth of salt in the porosity of the rock

Left: Degradation of a historic stone sculpture in Lecce, Italy. Right: Scanning electron microscopy image of a NaCl crystal (white) in the pore space of the sandstone after evaporation of the saline solution. Désarnaud et al. 2016

Tunnels are at risk of collapse. In several tunnels in Switzerland and Germany, the pressure of crystallization of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) from anhydrite (CaSO_4) causes the clays to swell. This then causes significant structural damage to the tunnel linings (Serafeimidis and Anagnostou, 2014).

Cements are damaged. The action of sulfate ions is also likely to degrade some unconstrained cements (Wagner, 2023).

Rocks are lifted. Another illustration of the force of crystallization is provided by aragonite. Indeed, travertine veins are capable of lifting the strata above them (Gratier et al., 2012).

6 Conclusion

By studying the environment, the formation conditions, and the characteristics of varved clays, it appears that the conditions were conducive to the growth of gypsum exerting pressure on its surroundings. Thus, although the gypsums were soft, they deformed the clays and even tore them in places. This is the effect of the force of crystallization, observed in various geological and technical environments: "it lifts mountains"!



Figure 21 Single crystal of Sinard gypsum

An "exemplary" monoclinic crystal.

Photo and collection Bernard BARAILLER

While gypsums are generally known from the evaporitic series formed by evaporation in a basin with intermittent and/or periodic marine or continental supply, the Sinard gypsums developed at the bottom of a glacial lake, under clays. These are the particular conditions of formation and distribution in clays that I invite you to discover in the following article, "An exemplary monoclinic crystal. How the Trièves gypsums are formed."

Acknowledgments

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This article is the reworked translation of an article on the Planet-Terre website :
<https://planet-terre.ens-lyon.fr/ressource/force-cristallisation.xml>

Bibliography

- B. Barailler, 2024. How do crystals form? From the beaker to hydrothermal growth, Planet Earth - ISSN 2552-9250 <https://planet-terre.ens-lyon.fr/ressource/cristallogenese-filons.xml>
- B. Barailler, 2025. An exemplary monoclinic crystal. How the gypsums of Trièves are formed, Planet Earth - ISSN 2552-9250 <https://planet-terre.ens-lyon.fr/ressource/monoclinic-crystal.xml>
- D. Jongmans, G. Bièvre, F. Renalier, S. Schwartz, N. Beeuros, Y. Orenge, 2009. Geophysical investigation of a large landslide in glaciolacustrine clays in the Trièves area (French Alps), Engineering Geology, 109, 1-2, 45-56 <https://doi.org/10.1016/j.enggeo.2008.10.005> [pdf] https://www.researchgate.net/publication/47280314_Geophysical_investigation_of_the_large_Avignonet_landslide_in_glaciolacustrine_clays_in_the_Trieves_area_French_Alps
- P. Thomas, 2021. Automorphic gypsums from the Würmian glacial lakes of Trièves, Cornillon-en-Trièves, South of Isère, Planet Terre - ISSN 2552-9250 <https://planet-terre.ens-lyon.fr/ressource/Img712-2021-05-17.xml>
- A. Giraud, P. Antoine, TWJ Van Asch, JD Nieuwenhuis, 1991. Geotechnical problems caused by glaciolacustrine clays in the French Alps, Engineering Geology, 31, 2, 185-195 [https://doi.org/10.1016/0013-7952\(91\)90005-6](https://doi.org/10.1016/0013-7952(91)90005-6)
- A. Wissocq, 2017. Study of the reactive transport of Sr and Cs in a carbonate sandstone-clayey sediment from the Cadarache site, doctoral thesis, Univ. Paris-Saclay, 249p <https://www.biblio.univ-evry.fr/theses/2017/2017SACLE027.pdf> [online access]
- L. Boyall, 2023. Glacial Varved Sediments, AntarcticGlaciers.org <https://www.antarcticglaciers.org/glacial-geology/varves/>
- B. Zolitschka, P. Francus, AEK Ojala, A. Schimmelmann, 2015. Varves in lake sediments – a review, Quaternary Science Reviews, 117, 1-41 <https://doi.org/10.1016/j.quascirev.2015.03.019> [pdf] https://www.researchgate.net/publication/274838745_Varves_in_lake_sediments_-_a_review
- Gignoux and Moret, Geology of Dauphinoise, 1952, p.319 <https://bibliothèque-des-alpes-grenoble.eu/boutique/science-nature/geologie/geologie-dauphinoise-gignoux-et-moret-2357/>
- extract from Gignoux and Moret, Géologie dauphinoise, 1952, p.319, retouched after G. Monjuvent, 1978, p.197 http://www.geol-alp.com/drac/_draclieuxN/Sinard.html
- Monjuvent, 1978. The Drac. Quaternary morphology, stratigraphy and chronology of an Alpine basin. Thesis, 1 vol., 431 p., Dolomieu Institute, USTMG, Grenoble <https://theses.hal.science/tel-00441486>
- JD Nieuwenhuis, PMB Van Genuchten, 1986. Feasibility of highway crossing through landslide area on varved clays, International Congress - International Association of Engineering Geology, 5, 3, 1705-1712
- F. Duhaime, 2012. Measurement of the hydraulic conductivity of the Champlain clay deposit of Lachenaie, Quebec: theory and applications, thesis (PhD), Univ. Montreal, 490p <https://publications.polymtl.ca/929/>
- IRMA, 2009. When clays no longer stay in place https://www.irma-grenoble.com/05documentation/04dossiers_numero.php?id_DT=7
- MG Loso, 2008. Summer temperatures during the Medieval Warm Period and Little Ice Age inferred from varved proglacial lake sediments in southern Alaska, Journal of Paleolimnology, 41, 1, 117-128 <https://doi.org/10.1007/s10933-008-9264-9> [pdf] https://www.researchgate.net/publication/226209803_Summer_temperatures_during_the_Medieval_Warm_Period_and_Little_Ice_Age_inferred_from_varved_proglacial_lake_sediments_in_southern_Alaska

al_Warm_Period_and_Little_Ice_Age_inferred_from_varved_proglacial_lake_sediments_in_southern_Alaska

- F. Darve, 1983. Rupture of natural clays by shear surfaces in triaxial testing, *Revue Française de Géotechnique*, 23, 27-38 <https://doi.org/10.1051/geotech/1983024027> [free access]
- CW Correns, W. Steinborn, 1939. Experimente zur Messung und Erklärung der sogenannten Kristallisationskraft, *Zeitschrift für Kristallographie – Crystalline Materials*, 101, 117–133 <https://doi.org/10.1524/zkri.1939.101.1.117>
- K. Serafeimidis, G. Anagnostou, 2014. On the crystallization pressure of gypsum, *Environmental Earth Sciences*, 72, 4985-4994 <https://doi.org/10.1007/s12665-014-3366-7> [pdf] <https://typeset.io/pdf/on-the-crystallization-pressure-of-gypsum-1a9o7mzsnk.pdf>
- L. Gagliardi, 2018. Thin film modeling of crystal growth and dissolution in confinement, doctoral thesis, Univ. Lyon 1, 179p <https://theses.fr/2018LYSE1211>
- J. Desarnaud, D. Bonn, N. Shahidzadeh, 2016. The Pressure induced by salt crystallization in confinement, *Scientific Reports*, 6, 30856 <https://doi.org/10.1038/srep30856> [Open access]
- M. Wagner, M. Decker, W. Kunther, A. Machner, RE Beddoe, A. Heisig, D. Heinz, 2023. Gypsum formation mechanisms and their contribution to crystallization pressure in sulfate resistant hardened cement pastes during early external sulfate attack at low sulfate concentrations, *Cement and Concrete Research*, 168, 107138, <https://doi.org/10.1016/j.cemconres.2023.107138>
- J.-P. Gratier, E. Frery, P. Deschamps, A. Røyne, F. Renard, D. Dysthe, N. Ellouz-Zimmerman, B. Hamelin, 2012. How travertine veins grow from top to bottom and lift the rocks above them: The effect of crystallization force, *Geology*, 40, 11, 1015-1018 <https://doi.org/10.1130/G33286.1> [pdf] https://www.researchgate.net/publication/232345381_How_travertine_veins_grow_from_top_to_bottom_and_lift_the_rocks_above_them_The_effect_of_crystallization_force