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Médard Thiry, Anthony Milnes, Jean-Louis Grimaud. Periglacial paleohydrologies reconstituted from sandstone morphologies. 2024, 17 p. hal-04545306

**HAL Id: hal-04545306**

**<https://hal.science/hal-04545306>**

Submitted on 18 Apr 2024

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# AstroGeo Workshop

Thursday, April 11, 2024

## **Field trip** **Sand pit, Bois de l'Abbesse at Treuzy-Levelay**

Periglacial paleohydrologies reconstituted from  
sandstone morphologies

**Médard Thiry**  
**Anthony Milnes**  
**Jean-Louis Grimaud**





# Periglacial paleohydrologies reconstituted from sandstone morphologies

## Field trip guide

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### Key words:

sandstone, morphology, groundwater, paleohydrology, proxy, periglacial, permafrost.

## Introduction

Late silicification (cementation) of the Fontainebleau Sands by groundwater flows to form quartzitic sandstones was demonstrated more than thirty years ago (Thiry et al., 1988) and different aspects have continued to be clarified (Thiry et al., 2015; Thiry et al., 2017; Thiry et al., 2020, Thiry and Milnes, 2024a). The linking of silicification to comparatively recent landscapes was established by:

- 1) highlighting the regional and local limit of sandstones to the edges of plateaux and to valleys, leading to;
- 2) a suggested Plio-Quaternary age for these silicifications with reference to the ages of river and landscape incisions; then by
- 3) dating calcites (Fontainebleau Calcites) included in the sandstone because they specifically pointed to silicification (cementation) during glacial periods; and finally by
- 4) introducing the concept that the precipitation of silica from groundwaters, for which no clear answer had formerly been provided, was triggered by cooling of groundwaters on approach to periglacial landscapes.

This is how, over the decades, an increasingly well-argued model has been constructed, with each step consolidating the model and reinforcing its coherence. The periglacial model led to the questions of dynamics relating to the establishment of cold/frozen landscapes and, in particular, to considerations of hydrological constraints imposed by the possible presence of a permafrost over several thousand years.

This note aims to show how the morphologies of the silicified sands reveal the hydrological conditions that prevailed during their formation. It is a completely new approach which ultimately makes possible a demonstration of the presence of thick frozen soils (permafrost) in the Paris Basin during Quaternary glacial periods and provides proxies for determining the minimum depth reached by the permafrost.

## Geological setting

Our study focusses on the Sables and Grès de Fontainebleau that consist of a 50 m thick, generally unconsolidated sand formation in which there are quartzitic sandstone lenses, often superimposed, 1-3 m thick and extending for 100 m to several kilometres. They occur in a landscape of distinctive plateaux and scarps forming part of the Cenozoic Paris Basin in the southern Paris region (Thiry et al., 2017). The Sables de Fontainebleau (Rupelian age, Oligocene) form a regional scarp between the limestone-armoured Brie and Beauce plateaux (Fig. 1a). Outcropping quartzitic sandstone pans hem the plateau while lenses in underlying unconsolidated sands crop out in valley sides (Fig. 1b). Erosion of the host sands during progressive incision and retreat of the Beauce Plateau resulted in the fracturing and collapse of the quartzitic sandstone pans and the accumulation of their fractured and jumbled remains as pluri-metric blocks in lag deposits ('chaos') characteristic of the Sables de Fontainebleau landscapes.

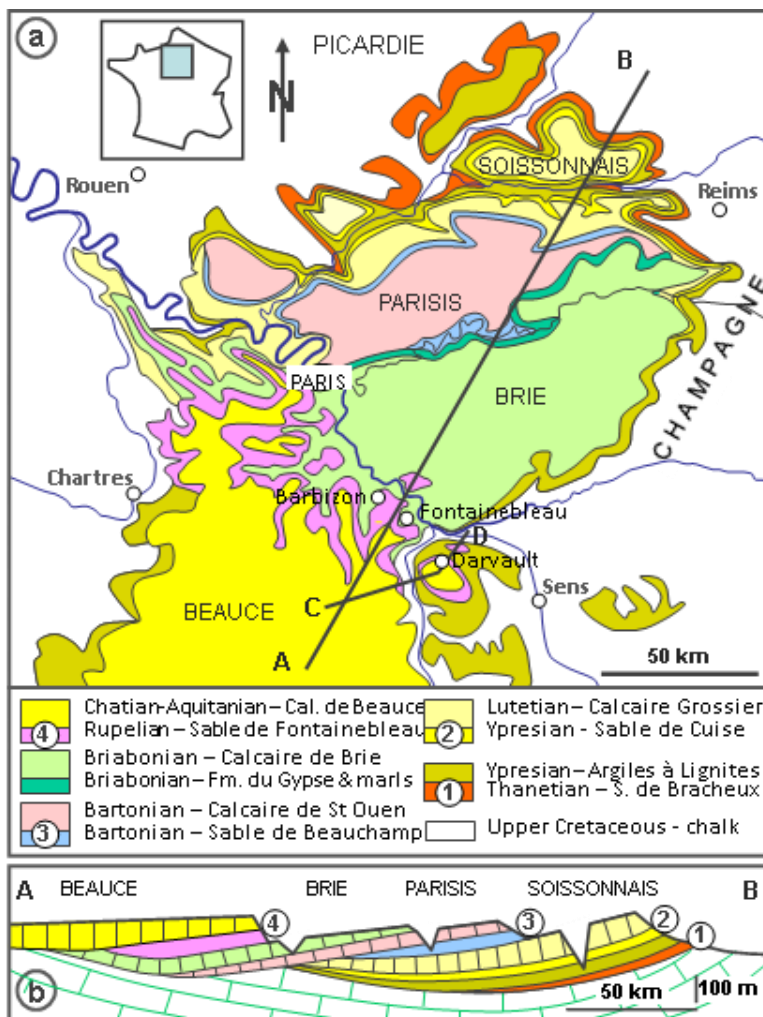


Figure 1 – Geomorphological settings. (a) Geological map of the Paris Basin. (b) Schematic cross-section A-B through the superimposed plateaux. The Sables de Fontainebleau form the escarpment between the Brie and Beauce Plateaux, Quartzites occur in all sand formations intercalated between limestones armouring the plateaux. Trace C-D links to the section in Figure 2.

It should be noted that the Grès de Fontainebleau in outcrop are massive and arranged in 1-4 m thick horizontal slabs extending laterally for 10-1000 m. This is indeed how the outcrops appear along the escarpments and valley sides that incise the Plateau de Beauce. In fact, there is a much greater variety of sandstone morphologies and arrangements in fact than are discerned in outcrop because they disintegrate downslope during the formation of the lag deposits. Certain convoluted and thin-walled sandstone morphologies are very fragile and do not even survive in outcrop. Consequently, most of the critical observations we've made are in fresh exposures of Sables de Fontainebleau in excavations and sandpits.

## The constraints imposed by the sandstone

Analysis of all boreholes that intersect the Sables de Fontainebleau (more than 400), together with detailed sections from infrastructure (public) works and in sandpits, show that the quartzitic sandstone slabs in sand only crop out at the edges of plateaux and valleys (Fig. 2a) and do not exist further than 200-500 m into the plateaux (Thiry et al., 1988; Thiry et al., 2015). In addition, quarries and some natural outcrops show superimposed sandstone horizons (Fig. 2b). This particular spatial distribution of sandstones indicates:

- the close connection between the sandstones and the current geomorphology, suggesting that cementation of the sands occurred in relatively recent times only in the vicinity of the outcrop zones, after valley incision, and is therefore of Plio-Quaternary age; and
- the arrangement of the sandstones into subhorizontal slabs points to a groundwater origin, with each silicified horizon corresponding to a watertable and water flows that controlled its formation.

To satisfy geometric constraints, a silicification model within a groundwater outflow regime has to encompass the quartzitic sandstones forming in the vicinity of their outcrops by precipitation of dissolved silica contained in the groundwater which flowed towards discharge in springs at the base of sandy slopes (Thiry et al., 1988).

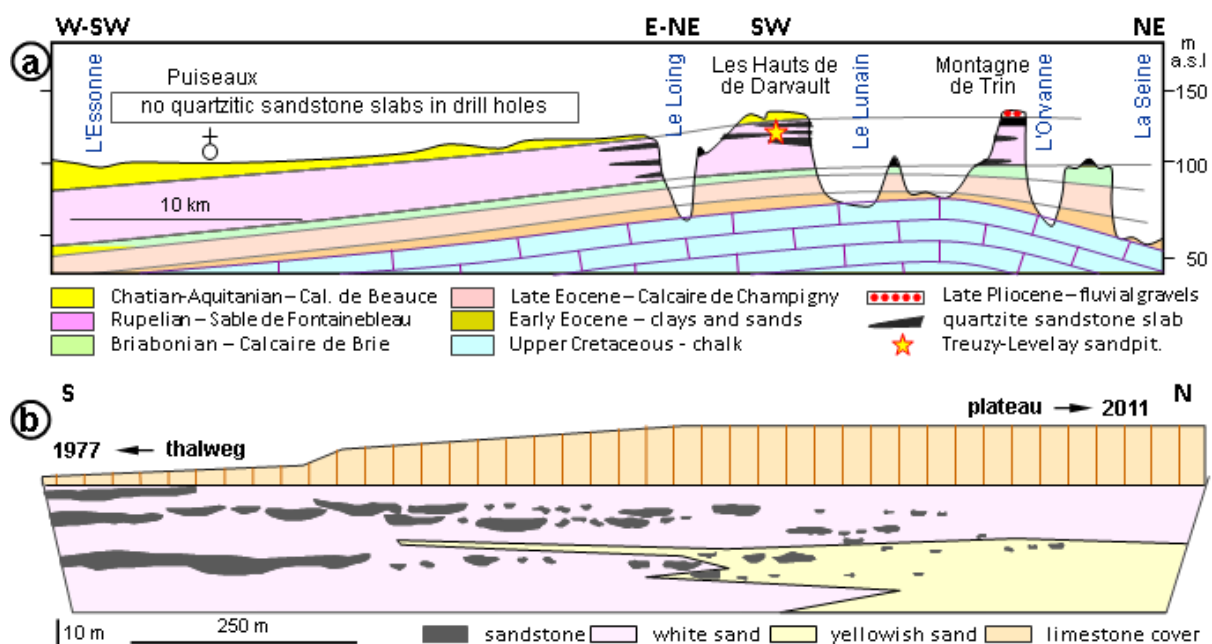


Figure 2 – The distribution of quartzitic sandstone slabs in Fontainebleau Sand outcrops. (a) Geological section through the dissected southeastern Plateau de Beauce, based on borehole data, Denizot (1970), and MT field survey; Nemours-Treuzy-Levelay area. Section trace C-D on Fig. 1a. (b) Diagram of the sandstone bodies recorded in a sandpit between 1977 and 2011; the sandstone lenses disappear away from the thalweg outcrops of sand where ferruginous sands occur beneath the limestone cover of the Plateau de Beauce; Larchant.

The age of the silicification has been determined by dating Calcites de Fontainebleau that crystallised within the sandstones prior to, or contemporaneously with, the silicification. These calcites are specifically linked by their distinctive crystal habit to cold environments and their ages are centred on glacial periods (Thiry, 2015; Thiry et al., 2020). The most recent date of around 25,000 years ago corresponds with the Last Glacial Maximum (LGM). This association between silicification and cold periods suggests that silica precipitation from groundwaters was triggered by the cold.

Indeed, silica solubility in water depends on temperature: it increases with temperature and decreases and therefore precipitates when the temperature falls. This law has been known for a long time and has been applied by geologists to deep hydrothermal systems in which water cools as it rises to the surface. On the other hand, silica precipitation by cooling of water has never been considered for surface silicifications. In these examples, the concentration of silica and its precipitation was considered to occur via evaporation in hot and dry climates, as in the case of surficial silicifications (silcretes) which cover wide areas of South Africa and Australia (Summerfield, 1983). In the case of silicification of the Sables de Fontainebleau, silica precipitation was triggered by cooling of the groundwater as it approached and was discharged through cold near-surface formations during glacial periods (Thiry et al., 2017).

The silica responsible for the cementation of the sand was imported in solution. Considering that the solubility of silica in surface waters is very low, about 10-20mg/L SiO<sub>2</sub>, it would have been necessary to provide 50 to 100m<sup>3</sup> of water to cement 1dm<sup>3</sup> of sand to form quartzitic sandstone (Thiry et al., 1988). A huge volume of water would have been needed to form a 2m thick sandstone slab stretching laterally over several tens of meters. This silica supply involved discharges from an aquifer through the sands for several thousand years (Thiry et al., 1988).

Silica deposition and cementation occurred along groundwater flow paths through the primary sands. Thus, the primary morphologies of the quartzitic sandstones reflect, in particular ways, the water flow paths. It is important to emphasize that silicified bodies did not form in a single episode. Initial cementation of the sand would have caused a decrease in its porosity and therefore permeability such that the groundwater flows were diverted through neighboring non-cemented and more permeable sands. To form fully cemented pans, the silicified bodies thus grew by the progressive addition of centimetre-thick ‘waves’ or ‘sheets’ of silicified sand (Thiry and Maréchal, 2001). These are sometimes visible on the surface of the quartzitic sandstone masses: they reflect gradual changes of flow pathways (Fig. 3a). The interiors of some spindle-like sandstone masses display this structure of concentric sheets that overlap centrifugally from a central silicified body (Figs 3b & c). This growth form indicates that it is the surface of the sandstone that promotes the precipitation of silica. Thus, the sandstone mass itself was the cold body that cooled the water and triggered silica precipitation. This arrangement resulted from the greater thermal conductivity of the sandstone than the water-saturated aquifer.

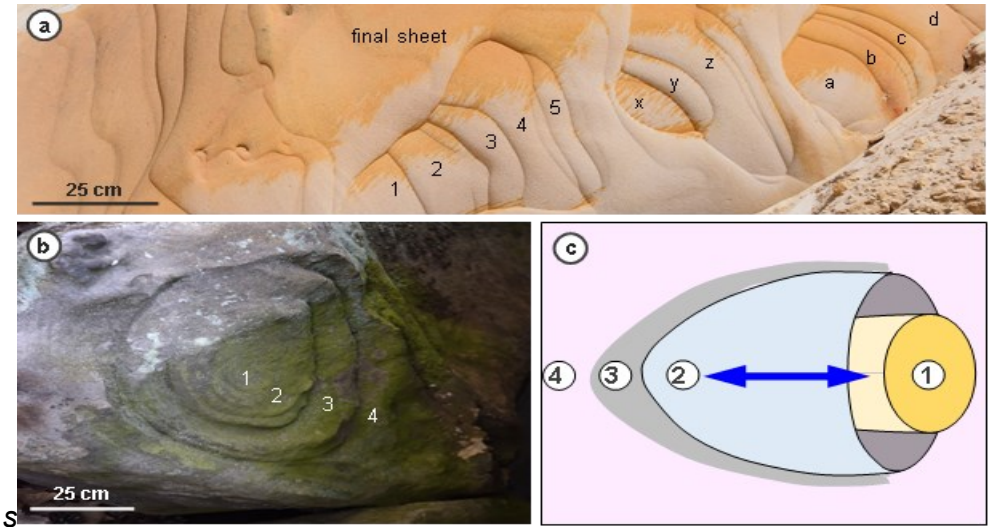


Figure 3 – Formation of quartzitic sandstone bodies via successions of envelopes of silicification. (a) Superimposed sheets of silicified sands showing centrifugal development of sandstone bodies; sandpit Buthiers. (b) Concentric envelopes of silicified sand that shape a spindle-like body; Larchant. (c) Schematic for the formation of a concentric structure in relation to the incoming silica-laden groundwater flow (blue arrow).

It is also of note that the thick sandstone pans that hem the plateaux are cut by vertical and horizontal fractures but those beneath a sedimentary cover, or freshly exposed in sandpits, are never fractured, suggesting that the fractures relate to recent landforming processes (Thiry et al., 1984). We suggest that this fracturing was induced by thermal expansions and retractions linked to climate (Thiry et al., 2017). The vertical and horizontal fractures, as well as sandstone dissolution features, are commonly coated by deposits of secondary silica that formed after exhumation of the slabs, since they are only found on outcropping slabs (Fig. 4).

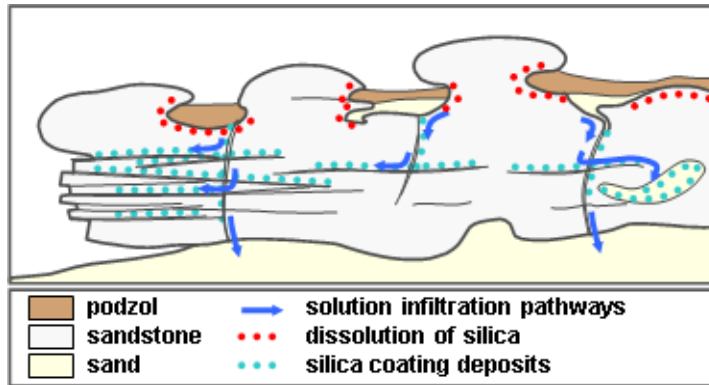


Figure 4 – Sketch of silica dissolution and precipitation along discontinuities (fractures and weathering features) in sandstones exposed in the escarpments hemming the plateaux. After Thiry et al. 2017.

### Model for formation of the Fontainebleau Sandstones

All observations made on the Fontainebleau quartzitic sandstones are constraints that must be considered in any model for their formation. A synthesis of all observations leads to a topographical model that explains the distribution of the sandstones at the edge of the Beauce Plateau. This arrangement incorporates groundwater outflows at the foot of sandy scarps and allows for a cold zone behind the spring discharge against which silica precipitates (Fig. 5a). Climate dynamics and erosion directly influence this arrangement. The establishment of persistent cold leads to the deepening of the cold zone, then to the formation of permafrost. Deepening permafrost can result in superposed sandstone levels, with the youngest ones at the base of the series. Erosion between glacial periods leads to the backwearing of scarps and causes the entire arrangement to move towards the plateau where younger silicified horizons may eventually interpose or even superimpose on older ones formed during a previous cold period. Silica precipitation may also occur at the top of the permafrost by cooling of infiltrating water and groundwaters in a thawed active zone coming into contact with the permafrost (Fig. 5b).

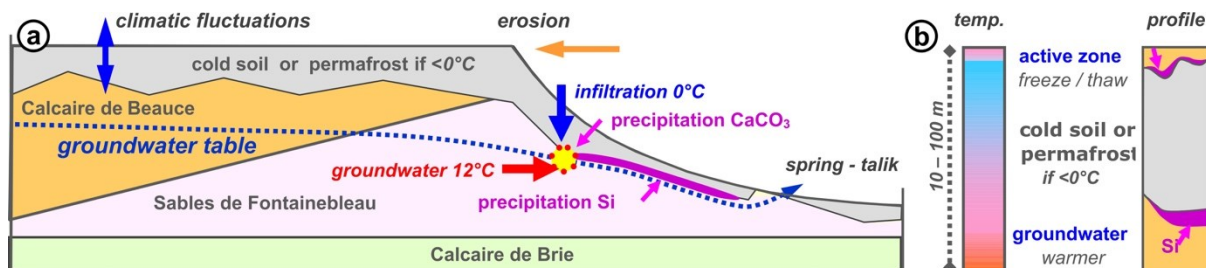


Figure 5 - Hydrogeological and thermal diagram of silica precipitation zones during Quaternary cold periods. (a) Silica precipitates by cooling of groundwater at the base of cold soils or permafrost at the edge of the plateaux where calcite precipitates by warming of surface water at depth in subsoil. (b) Silica in surface water infiltrating the vadose zone precipitates by cooling at depth in contact with the permafrost.



## Hydrological characteristics of periglacial environments

Permafrost affects regional hydrological regimes (Lemieux et al., 2008; Dobiński, 2012): for example, (1) lateral flow of near-surface groundwater is limited by permafrost which acts as the lower limit of an impervious horizon; and (2) freezing of groundwater increases pore water volume and thus may increase pressure within the aquifer. If permafrost develops at depth, the increase in pressure may force the lateral flow of groundwater deeper, even well below the water table. Under these conditions, groundwater flows are no longer driven by gravity and their paths may become very tortuous and narrow, bypassing not only less permeable aquifer zones, but also frozen aquifer volumes (Yoshikawa and Kane, 2021). When flows occur under pressure they are squeezed against the frozen volumes and may take a contorted ‘roller coaster’ appearance (Fig. 6).

However, even if the permafrost is thick, groundwater will continue to discharge in valleys through non-frozen structures like taliks. This is because the relatively warm water originating in deeper parts of the aquifer will prevent taliks from freezing as long as flow rates are sufficient. If permafrost continues to develop, discharges in the valleys may gradually freeze, causing an increase in pressure within the aquifer to the point of generating hydraulic fracturing through which the water can actually escape to the surface. Thus, in northern Canada, water flowing at 16.8°C in a river has been recorded (Clark et al., 2001). It has been shown elsewhere that water rising to the surface comes from 600 m depths through permafrost (Andersen et al., 2002). On the other hand, the groundwater level can drop following the thawing of the permafrost through loss of volume during melting of the ice. If this occurs, infiltration from the surface can penetrate deeper into the permafrost through unfrozen areas such as taliks and thermokarsts.

Above permafrost there is usually an ‘active layer’ which thaws in summer and into which surface water infiltrates and shallow groundwater can form. The active layer may reach over 20 m depth during periods of global warming (Dobiński, 2020). This infiltrating water may cool down by 5-10° from its temperature at the surface as it encounters the permafrost (Boike et al., 1998). Depending on climatic conditions, the active layer may operate seasonally or even perennially as a shallow zone of flow of a perched supra-permafrost aquifer (Walvoord and Kurylyk, 2016).

These specific hydrological arrangements in permafrost make it possible to interpret particular configurations and morphologies of the quartzitic sandstones in the Sables de Fontainebleau to which no special attention has been paid until now.

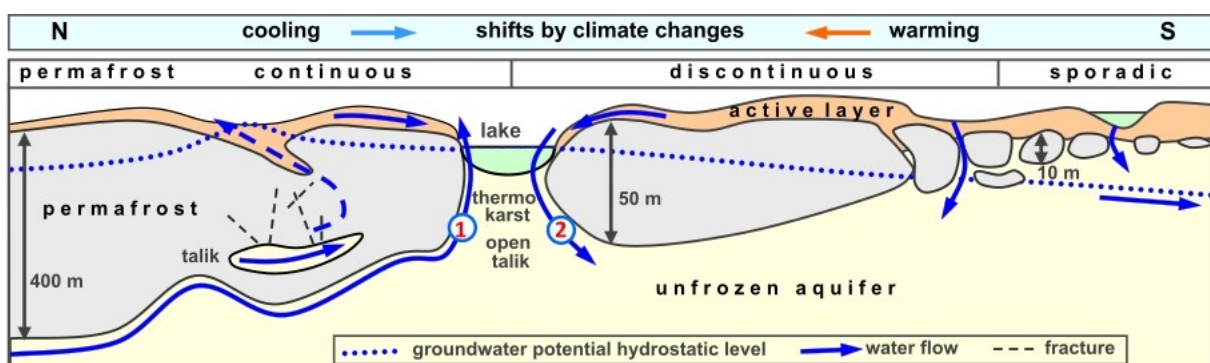


Figure 6 - Diagram of permafrost with variations that may be ‘read’ as linked to a latitudinal climatic gradient or as a climatic evolution over time (cooling or warming). When the permafrost thickens, part of the water in the aquifer freezes with a resulting volume increase and therefore pressure within the aquifer, and possibly leading to fracturing of the permafrost. The water flows vary depending on climate change: (1) artesian rise during cooling periods, (2) infiltration during permafrost thawing periods. According to Lemieux et al. (2008) and Dobiński (2012).

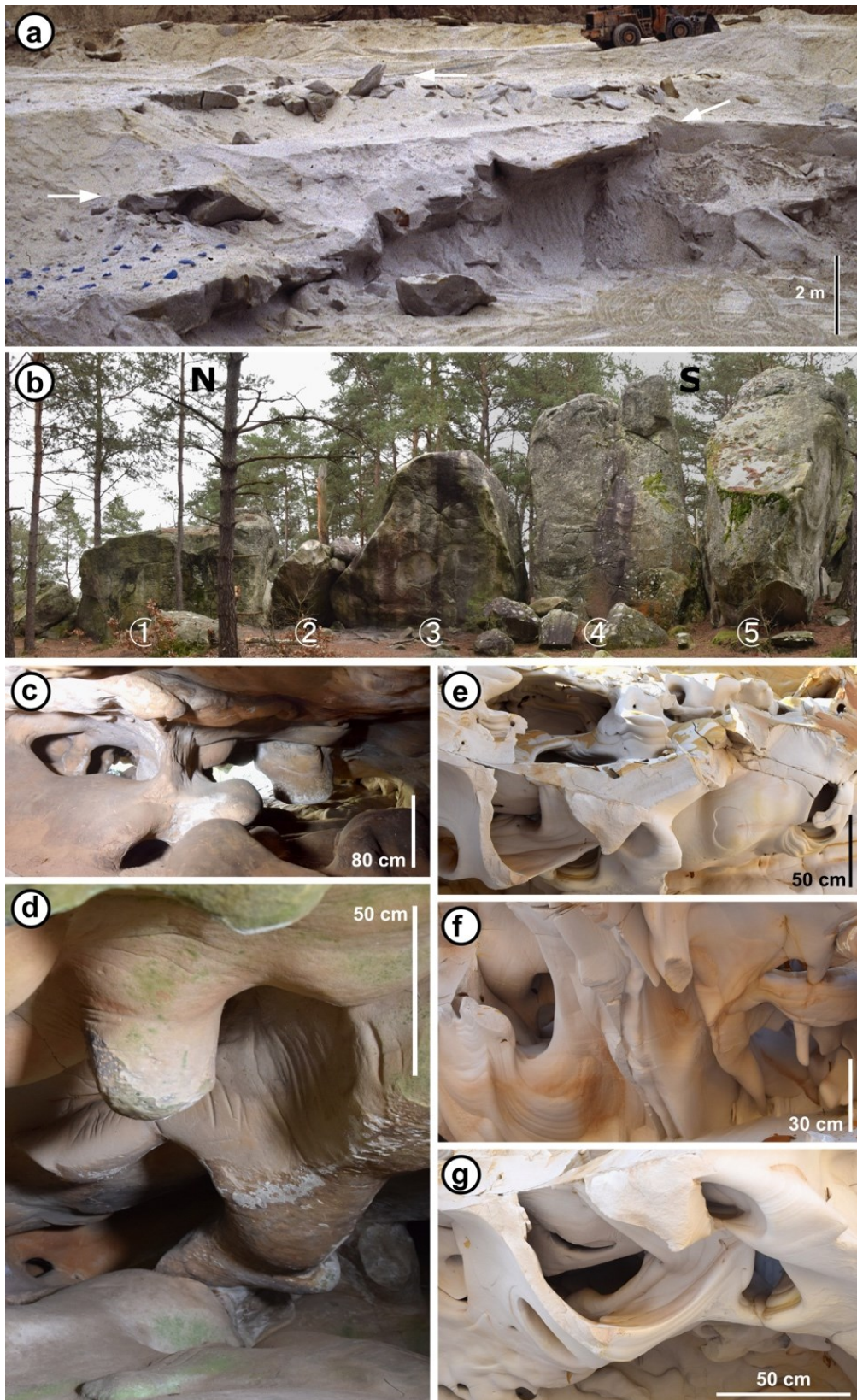
## **Silicified masses and groundwater flows**

We aim to interpret the arrangements and morphologies of the quartzitic sandstone masses in terms of groundwater flux. Knowing that very large volumes of water are necessary to generate silicification (cementation) of sands, we suggest that the morphologies of the sandstones reflect groundwater flow paths. Furthermore, as compact sandstones have greater thermal conductivity than a water-saturated sand aquifer, they will ‘carry’ the cold front and hence induce centrifugal growth of the sandstone bodies. Accordingly, sandstone morphologies tend to fossilize the responsible groundwater flows and thus retain a record of the hydrological conditions that prevailed during silicification.

### ***Evidence from unusual morphologies***

Non-horizontal sandstone slabs have been occasionally observed in Sables de Fontainebleau sandpits. An oblique sandstone slab (Fig. 7a) was exposed and blasted out in 1995 in a sandpit at La Chapelle-la-Reine. An approximately 1.5 m thick subvertical slab was also encountered in 2013 in a sandpit in Larchant. As well, a vertical sandstone wall over 2 m thick and cut by vertical fractures (Fig. 7b) occurs on the flat area around 100 m altitude in the lower part of the rock lag which covers the western escarpment of the Rocher de la Reine south in Arbonne. It is inconceivable that these masses were derived by solifluction from a horizontal slab (Thiry and Milnes, 2024b) but were cemented *in situ*, most likely along fractures that opened through a cohesive host material.

Sandstone morphologies with a pronounced vertical or oblique component are relatively common in sandpits as well as in outcrops. A rock shelter in Boigneville shows ‘pendant’ morphologies and pillars that connect two superimposed sandstone slabs (Fig. 7c & d). The sandpit at a place called Rochefort near Buthiers displays the most spectacular morphologies. These are extremely tortuous bodies with relatively narrow curved and anastomosed silicified walls, 2-30 cm thick, that sometimes intersect, and which delimit and surround decimetric to metric volumes of uncemented sand. During sand extraction, the uncemented sand spills out, leaving hollows that expose the complexity of the silicified structures (Fig. 7e-g). These morphologies and the arrangement of the sandstone walls are interpreted in terms of permeable passages which channelled water flows through an impermeable domain. It should be noted that this sandpit corresponds to a very southern extension of the Sables de Fontainebleau. It is topped by a thick limestone cover and is the only known site where a silicified level has been found 7 m below the current water table and, moreover, below the current valley bottom.



**Figure 7 - Sandstone bodies with unusual morphologies. (a) Superimposed sandstone slabs intercalated with a slab inclined at around 20°; sandpit, La Chapelle-la-Reine, operating front in 1995. (b) Alignment of 5 vertical sandstone blocks (block 2 collapsed) that match to a 'wall' in situ in the sands; Arbonne. (c-d) Pillars and pendants between two superimposed sandstone slabs, Boigneville. (e-g) Sandstone partitions formed by interweaving of horizontal and vertical structures that surround and delimit unconsolidated sand pockets which emptied during sand mining operations; Buthiers.**

### Evidence from particular arrangements

The sandpit in Treuzy-Levelay is outstanding for its quartzitic sandstone morphologies and its particular sequence of sandstone slabs as well as and more massive sandstone masses (Fig. 8). It has at least four superimposed sandstone horizons and each has specific morphological features (Fig. 9).

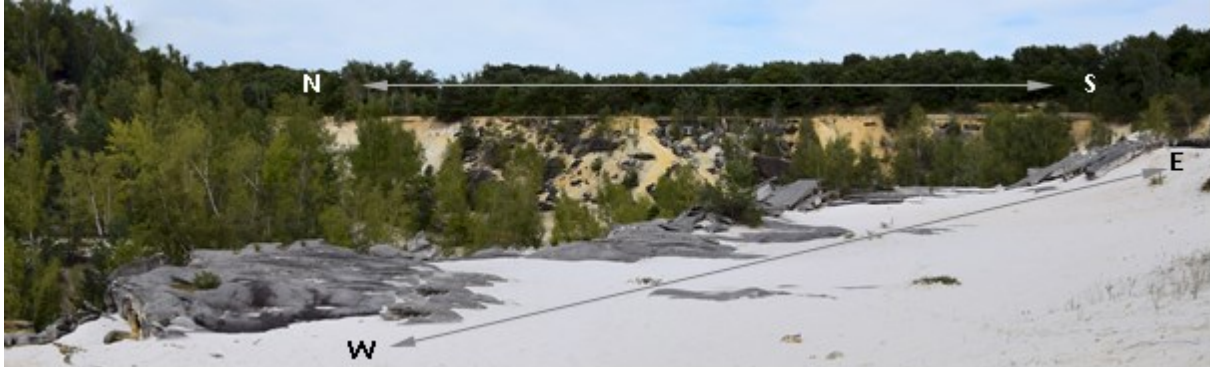


Figure 8 - Overview of the sandpit at Treuzy-Levelay. The yellow sands of the N-S section result from the crumbling of the summit sands which are oxidized. The E-W working face in the foreground is formed of white sands that separate sandstone masses that appear dark due to lichens which develop there.

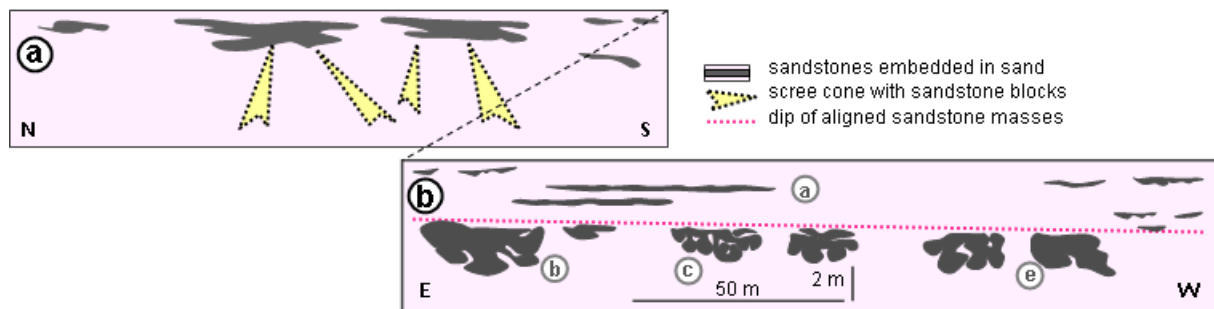


Figure 9 - Diagram of the arrangement of the sandstone masses in the Treuzy-Levelay sandpit and which show different morphologies depending on the working face: (a) Seemingly regular and elongated slabs on the N-S working face; (b) cylindrical bodies on the E-W working face which intersects the elongation of the silicified bodies. The letters (a-e) refer to images in Figure 10.

Silicified masses are roughly elongated south-north, pointing towards the escarpment north of the sandpit. The internal organization of each of the silicified masses is of particular interest, as are the mutual relationships among the masses.

- 1) Sandstone lenses exposed on the N-S face of the quarry (Fig. 9a) are 1-2 m thick and have flat upper surfaces but large N-S elongated undulations on lower surfaces. They also have tapered endings, some pointing towards the sandy escarpment to the north and others towards the plateau to the south. The upper horizontal surface may correspond to a former groundwater table and the metre-sized spindle-shaped elongations are considered to be the flow paths of the waters that delivered the silicification.
- 2) Slightly deeper sandstone slabs exposed in the E-W face are thinner (0.2-0.5 m thick), flat, clearly elongated south-north, indented and with rounded terminations (Fig. 10a). Here, too, flat triangular spindle-like morphologies are considered to reflect horizontal laminar water flows close to a groundwater table.
- 3) Deeper sandstone masses are more substantial and show elongated and spindle-shaped sandstone bodies directed towards the escarpment to the north. In addition, the spindles are not level but variously dipping and straightening (Fig. 10b & c). Their orientations diverge, form sheaves, amalgamate and fit together (Fig. 10b-d & e). If they reflect to groundwater flows, the flows were no longer 'free' and governed by gravity, but

‘forced’ fluxes confined laterally and above impermeable sands (some spindles are directed upwards).

- 4) The separation of large sandstone masses in the lower level from comparable volumes of non-cemented sand raises questions (Fig. 9b). If ‘forced’ groundwater flows are responsible for the origin of the silicified masses, it is odd that they were not deflected laterally. The flows were obviously ‘forced’ along specific corridors between masses of impermeable sand. However, the arrangement of the silicified masses along a regular surface, slightly sloping towards the west, suggests that the flows were nevertheless regulated by a common base level.
- 5) Superposed sandstone laminae on the vertical walls of certain sandstone bodies (Fig. 10f) suggest that laminar groundwater flows could have taken place through the permeable sand existing between the silicified masses with continued precipitation against the cemented mass.

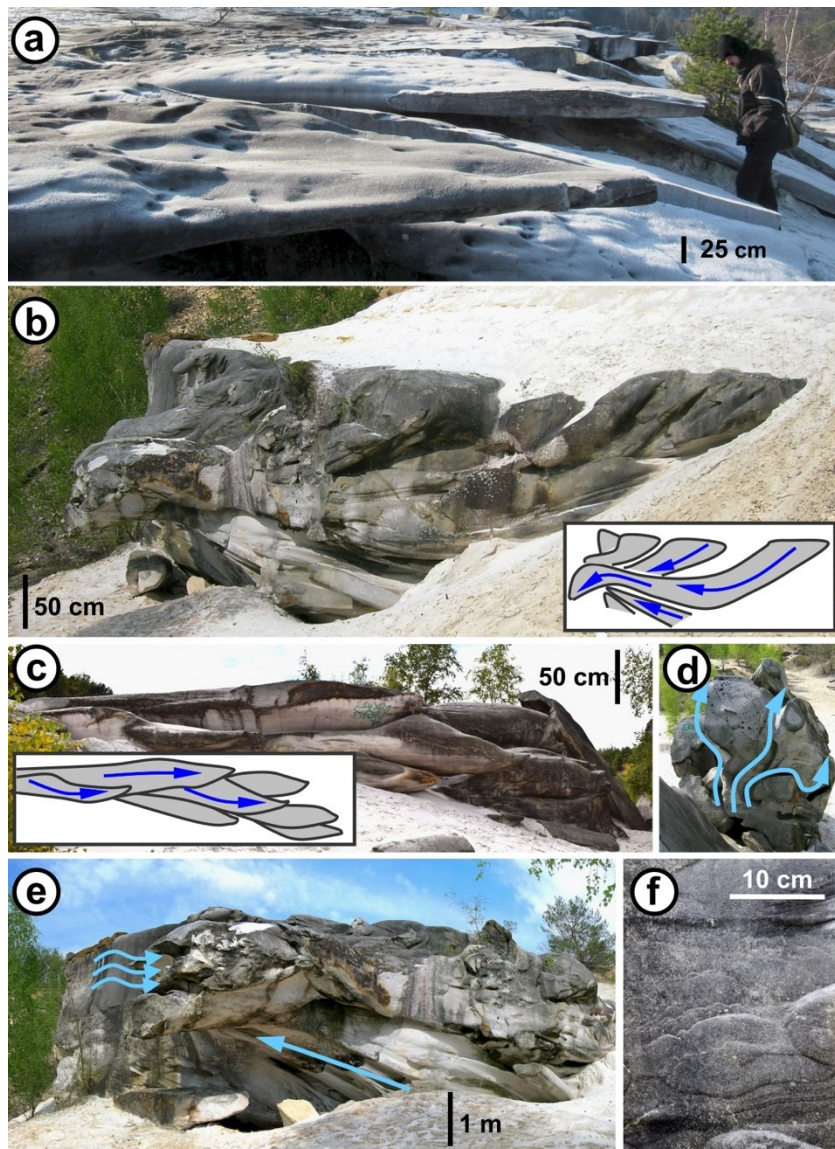


Figure 10 - Morphologies of sandstone lenses in the Treuzy-Levelay sandpit. (a) Horizontal top lens with tapered ends. (b) & (c) Fusiform and curved lenses, agglomerated into compact masses. (d) Front view of (c) and sketch of groundwater flows around the lenses. (e) Aggregation of sandstone spindles of various orientations. (f) Detail of silicified layers stacked on a vertical surface reflecting laminar flows along the quartzite wall (located on the left of the previous view). Insets show water flow paths related to cementation of the spindles. See Figure 9b for locations of images.

### Evidence for secondary silicification in vadose environments

As already mentioned, fracturing of the quartzitic sandstones is restricted to the thick pans that hem the plateaux (Thiry et al., 1984), suggesting that it relates to recent landform development. The fractures in the outcropping sandstone pans are in many places coated with

a bright white, glossy and silky-looking, silica skin (Fig. 11a) which may cover areas up to 250 m<sup>2</sup>. In places, these silica skins also occur on more irregular, rounded surfaces that mark the surface contours of the sandstone pans and lenses (Fig 11b). They may also coat the interior of pseudokarstic dissolution hollows (Fig11c) and fill erosion channels on top of the quartzitic sandstone slabs (Fig. 11d). These silica ‘skins’ have geotropic characters (oriented according to gravity) and are related to water percolating along fractures through, and over surfaces on, the sandstone.

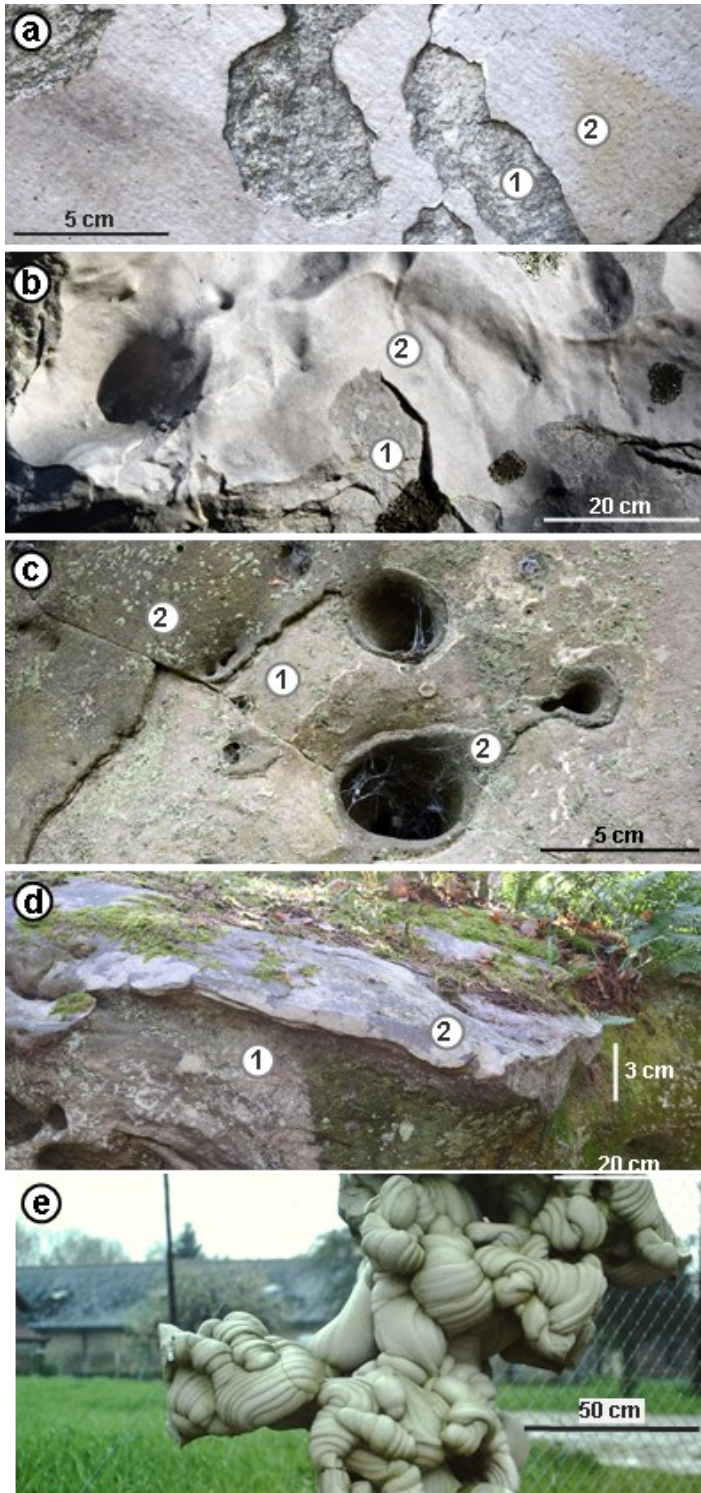


Figure 11 – Secondary silica precipitated in a vadose environment. (a) Silica skin on a vertical fracture wall; Noisy-sur-Ecole. (b) Silica skin wrapping pseudokarst; Buno-Bonnevaux. (c) Silica skin on a vertical fracture and lining pseudokarst pipes, Boigneville. (d) Secondary silica confined to an erosion channel on the surface of a sandstone slab, Buthiers; (e) Silica ‘puppets’ with botryoidal envelopes marking successive overlapping concretionary growths (view upside down); sandpit Maintenon. (1) Primary quartzite, (2) secondary silica.

It is likely that the curious concretionary silica ‘puppets’ in the Sables de Fontainebleau, also named ‘gogottes’ (Guillemin, 1978), were collected in sandpits where the Sables de Fontainebleau rest directly on the Cretaceous chalk. They display botryoidal envelopes featuring successive overlapping concretionary growths (Fig. 11e). Their *in-situ* orientation, particularly the downwards-projecting character of the concretionary growths, is considered to reflect a geotropic process linked to waters infiltrating through the vadose zone towards the watertable.

### **Sandstone morphologies and periglacial dynamics**

The morphologies and arrangements of the quartzitic sandstone masses can be interpreted in the context of a gradual settlement of periglacial conditions in the landscape (Fig. 12).

- 1) As glacial conditions set in, the surficial regolith cooled but did not freeze. The groundwater table remained free and water flowed horizontally towards discharge zones (springs) at the base of scarp and valley incisions in the landscape. Silica precipitated from warmer groundwater when it met cooled sands. This is how the horizontal sandstone slabs formed (Fig. 12a).
- 2) Permafrost developed as glacial conditions persisted. Groundwater flow paths continued due to a constant flow of warm water to spring discharges. But the deepening of the impermeable permafrost forced flows to divert around the irregularities of the frozen front. It is along these ‘perturbed’ flowpaths that convergent and inclined ‘spindle’-shaped silicifications formed. (Fig. 12b)
- 3) As the permafrost thickened, phreatic flows were eventually forced into pressurized pipes (taliks) within the permafrost (Fig. 12c). At this point, previously formed sandstone masses may have been partially encased in permafrost. Depending on the flow rate of water, and its temperature, a dynamic equilibrium was established between silicification of sand against the cold quartzitic sandstone wall and thawing of the adjacent permafrost. Laminar flows of varied orientations could have formed all around the silicified masses with silica precipitating to form thin sandstone layers like those in Figure 10f.
- 4) With further deepening of the permafrost the groundwater outflows to the valleys gradually froze and closed. In the confined aquifer, the water volume increased due to freezing in its upper part and this led to excess pressures and possible hydraulic fracturing (Fig. 10d). Complex, narrow flow paths in all directions were able to open and silica precipitated there in contact with the permafrost. Such phenomena explain the formation of the steep slabs (Fig. 7a & b) and the spectacular tortuous morphologies, with silicified walls which surrounded volumes of non-cemented sand that had been frozen (Fig. 7d-f). The same is probably true for hanging structures or pillars between relatively regular slabs (Fig. 7b & c).

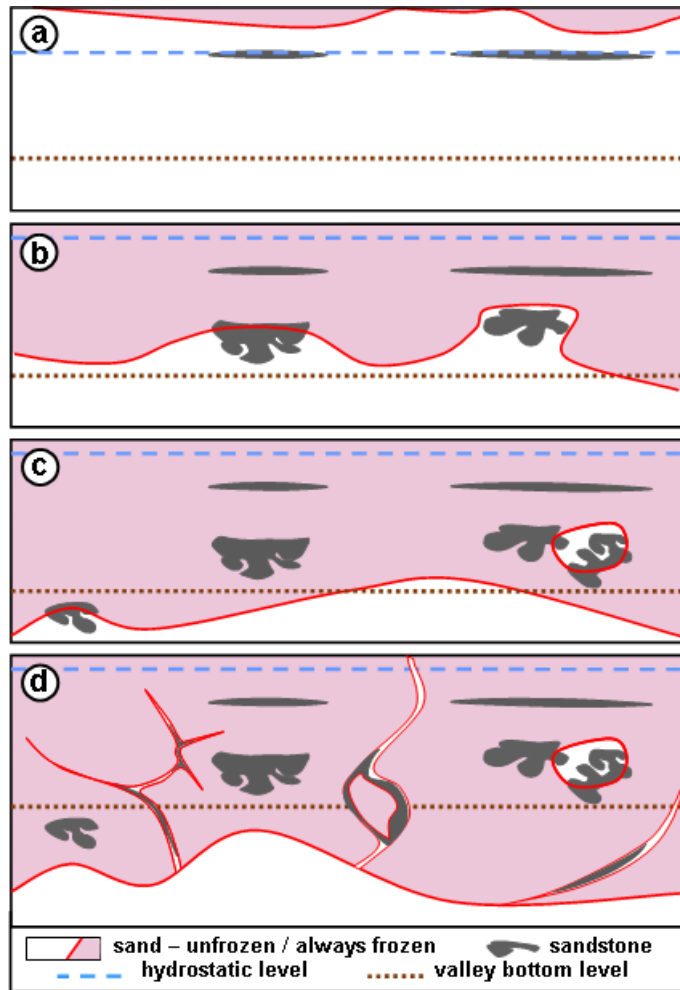


Figure 12 - Diagram of thermal and hydrological arrangements in valley side zones when cold environments developed. (a) The cold front, beneath the permafrost or not, induced the silicification of the sand into horizontal slabs. (b) With deepening of the permafrost, springs in the valleys remain functional, but groundwater flows are forced against the base of the impermeable permafrost. (c) With even deeper permafrost, some flow paths may be isolated within frozen sands. (d) With further deepening of permafrost below the level of the valley floor, and the increase in pressure due to groundwater freezing, hydraulic fracturing is likely and artesian groundwater flows can reach the landsurface.

1 On the other hand, the occurrence of geotropic arrangements points to silica precipitating  
 2 from downward moving waters. If the mechanism of silica precipitation by cooling of water is  
 3 applied, consistent with the principles relating to all other cemented morphologies encased in  
 4 loose sand, then we contend that the infiltrating waters cooled at depth and that a cold zone was  
 5 present beneath a warmer surface zone. It may be that all of these geotropic silicifications are  
 6 symptomatic of unfrozen soils overlying a frozen zone, and that they developed at the contact  
 7 of an active zone with the underlying permafrost. This implies that they are witnesses to an  
 8 active zone and possibly to the depth to permafrost, which increases in the context of warming.

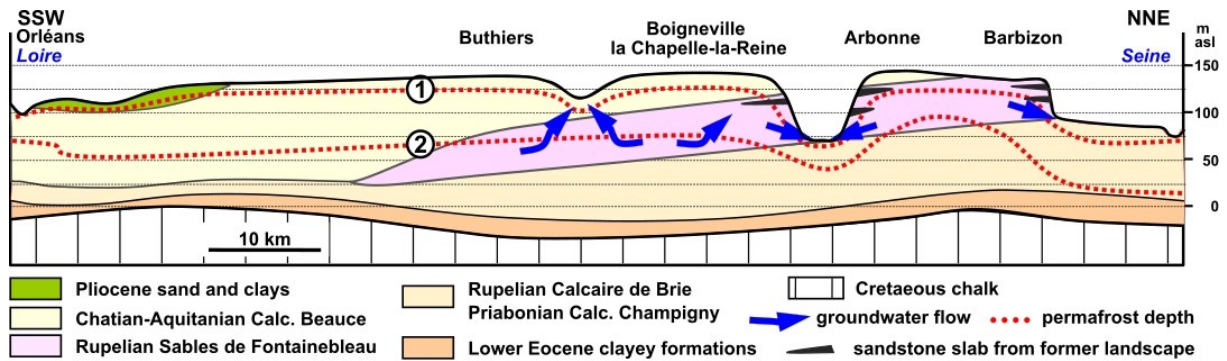
9 **Notes on the spatial distribution of morphological varieties**

10 Horizontal sandstone slabs predominate in the north, along the Plateau de Beauce  
 11 escarpment, under a thin limestone cover or no cover (north of the Fontainebleau Forest). More  
 12 irregular sandstone masses, with curved shapes and concavities, are common further south  
 13 under a thick (~10 m) limestone cover alongside valleys which incise the Beauce Plateau  
 14 (Boigneville, Treuzy-Lavelay). The ‘exotic’ morphologies are mainly found in the  
 15 southernmost and deepest sites of the Sables de Fontainebleau (Buthiers area).

16 This spatial distribution results from the conjunction of two independent factors: depth of  
 17 the Sables de Fontainebleau aquifer and depth of the permafrost (Fig. 13). Thus, on the northern  
 18 edges of the Plateau de Beauce, where the Sables de Fontainebleau are at shallow depth,  
 19 silicification occurs mainly in water table-related horizontal slabs. If the permafrost had attained  
 20 greater depths there, with groundwater confinement and excess pressure, the sand would have



21 been completely frozen and the excess pressure phenomena may have affected the Calcaire de  
 22 Brie aquifer which is beneath. On the other hand, in the southern areas, where the Sables de  
 23 Fontainebleau are buried under 20-30 m of limestone and possibly below the level of the  
 24 valleys, it is above all the conditions of aquifer confinement and pressurization that would have  
 25 predominated, with the formation of quartzitic sandstone ‘shells’ around frozen sand and  
 26 intersecting cracks induced by hydraulic fracturing.



27  
 28 *Figure 13 - Geological sketch showing the deepening of the cold front over time: (1) No permafrost at the*  
 29 *start of the glacial period and thus horizontal quartzitic sandstone slabs linked to the water table; (2) Thick*  
 30 *permafrost during the glacial maximum, with freezing of groundwater outflows and pressure increases in the*  
 31 *aquifer leading to hydraulic fracturing and the formation of irregular silicified masses. After Thiry and Milnes,*  
 32 *2024a.*

### 33 Perspectives

34 Most of the data currently used to estimate the extension and depth of permafrost during  
 35 the Quaternary glaciations comes from paleoclimatic simulation models (Levasseur et al., 2011;  
 36 Bertran, 2022). There are few direct-evidence tools to determine the presence, extent and depth  
 37 of palaeo-permafrost.

38 The isotopic analysis of current groundwaters makes it possible, in certain cases, to show  
 39 that they were not recharged during the last glaciation. Hence, we deduce that these regions  
 40 were either covered by an ice cap or affected by a continuous and relatively thick permafrost  
 41 (Jiraková et al., 2011). Likewise, patterned ground, characterized by decametric polygonal  
 42 structures (15-30 m) formed by seasonal frost to a depths of 3–4 m over long periods, does not  
 43 provide any indication of deeper zones of permafrost or their continuity. It has also been  
 44 suggested that landforms resulting from solifluction could be used as proxy of the depth of  
 45 freeze-thaw in former periglacial landscapes (Matsuoka, 2011). At best this may indicate the  
 46 minimum depth reached by an active layer (above a permafrost or not). But for all the above  
 47 proxies there is no indication of the depth reached by the permafrost.

48 The only tangible elements currently available to ensure that permafrost existed at a certain  
 49 depth are provided by karst cavities. When karst cavities filled with water become frozen, pure  
 50 water is incorporated into the ice and the residual water is enriched in calcium which ultimately  
 51 precipitates as calcite crystals. The isotopic composition of these calcite crystals shows that  
 52 they come from water concentrated by frost and therefore testify that permafrost had reached  
 53 these cavities (Žák et al., 2004; Richter et al., 2010). These cryocalcites (calcites formed by  
 54 freezing) record the deepening of permafrost and are an archive of the minimum depth that it  
 55 reached (Žák et al., 2012). But less than ten cryocalcite karst cavities have been recognized to  
 56 date in Central Europe. Moreover, not all cryocalcites indicate deep permafrost. Indeed, calcite  
 57 silts composed mainly of aggregates of 3–5- $\mu\text{m}$  euhedral crystals have been recorded in alluvial  
 58 fans in southwest France and are interpreted as cryocalcites precipitated by ice freezing in platy  
 59 soil structures (Bertran et al., 2023). They occur in shallow deposits and may date the Last  
 60 Glacial Maximum but cannot be used as a proxy for permafrost.

61 In the Paris Basin, in the groundwater silicifications that characterise the Sables de  
62 Fontainebleau, curved sandstone ‘spindles’ and sandstones arranged in oblique and vertical  
63 slabs, as well as those forming envelopes around masses of non-cemented sand, allow us to  
64 argue that:

- 65 • permafrost reached at least the depth at which these quartzitic sandstone masses  
66 currently occur,
- 67 • the deepest record is 50m in Buthiers (Fig. 13); and
- 68 • overpressures existed in the paleo-watertables as a result of it being confined by frost.

69 This is a new toolbox. These observations are still somewhat sporadic, as in the case of frozen  
70 karst cavities, but they provide valuable anchor points and will hopefully generate new  
71 observations elsewhere to assist in establishing the depths of paleo-permafrost elsewhere in  
72 regions (by considering topographical variations across mountains and valleys) and across  
73 continents.

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