Groundwater silicification as a proxy of paleo-permafrost depth and a constraint for a fluid flow and geothermal modelling
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1. Introduction
In the Paris Basin, the Fontainebleau Sands (Early Oligocene) contain superposed flating lenses of very thinly cemented sandstones, the origin of which was connected to periglacial groundwater (Thiry et al., 1988). Recent dating of calcite cements, sometimes included in the quartzites, has provided an age constraint that refers to cold periods of the Quaternary. It suggests a new mechanism of sand cementation, favoured by the decrease in silica solubility when feeding warm groundwater would discharge close to a freezing front (Thiry et al., 2013). Quartzite lenses would therefore act as a proxy for the presence and thickness of periglacial groundwater. Model calculations allow to investigate the temperature and pressure conditions associated with a cold front propagation near the groundwater outlet. We discuss them in terms of conditions fluid flow and geothermal profile to provide sustainable conditions to achieve sica deposition.

2. The Fontainebleau Sands and Sandstones
The highly pure silica marine sands of Fontainebleau (Early Oligocene) form a 50 to 80 m thick unit between the Beauce and Brie limestones before thinning and disappearing southwards, beneath the Beauce Plateau (fig. 1a-b). The limestone plateaus and the Fontainebleau Sands are deeply eroded by the hydrographic network.

Silicification in the Fontainebleau Sands produced up to 4 principal levels of superposed flating lenses of very thinly cemented sandstones (0.5 to 8 m thick, to 100 m long, see fig. 2). Drill hole data indicate that these sedimentary quartz layers are related to outcrops on the valley slopes and do not extend more than a few hundred meters beneath the overlying limestone cover of the plateau (fig. 1a-b). The sandstone levels are discontinuous and of variable size, from a few dm³ to several thousands of m³.

3. Mechanisms of silicification
The discontinuous distribution of the silicified bodies, as well as the correlation between their localisation and the recent or present meandering river networks (fig. 2), suggests that the presence of permafrost is a relatively recent silicification, near the outcrop zones.

The general arrangement of the sandstone layers (fig. 3), between Fontainebleau and Champagne, corresponds to the paleodunes morphologies of the top of the sand along which groundwater would flow and first discharge as englacial or interlobal meltwater. This may explain the sharp boundary between cemented sandstone and loose sand.

Mechanisms of sica deposition could be induced by mixing of discharging regional groundwater and local recharge water that flowed through a thin limestone cover.

The Fontainebleau Sands often contain calcite cements (fig. 5), the -C1 and U-th dating of which shows formation during the past two cold periods of the Quaternary, around 300 ky and 50-30 ky. They would be equivalent to the cryptokalcs related to loam karst cavities (Leboyer et al., 2012), but would have developed in the sand aquifer. They are sometimes incised in the quartzite (fig. 5), suggesting that sand silicification also has to be related to Quaternary cold periods. Silica precipitation would be facilitated by a decrease in solubility with decreasing temperature of groundwater outflow in contact with permafrost (fig. 6, Thiry et al., 2013).

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4. Numerical modelling
A representative SW-NNE cross-section (70 km long, 125 m thick, fig. 1c) of the Beauce Plateau serves as a basis for 2-D coupled fluid flow and heat transport simulations.

We used a newly developed numerical code that simulates groundwater flow and heat transport in the (2-D) plane with integrated geochemical processes (De Backer et al., 2018). An average geothermal gradient is calculated as 30°C/km in the Beauce plateau for a uniformly base heat flow of 70 mW/m² (fig. 9). A modified Peccat parameter Pe at the aquifer scale (van der Kamp 1984) lower than 0.1, groundwater flow does not affect the thermal regime (fig. 8).

How long a relatively warm groundwater flow could have prevailed in the Beauce aquifer? Starting from modern conditions, the top boundary condition was altered to simulate a cold surface temperature (-0.5°C). It is assumed that frozen ground prevents recharge from the surface; however, positive groundwater outflow temperatures are maintained. As a result, hydraulic heads decrease slowly (fig. 8b). A thin layer of frozen ground (0.2 m thick after 500 yr, fig. 8b) developed on top of the plateau, spatially depending on the heterogeneous properties of sands and limestones. Geothermal profile (fig. 9) varies accordingly. Temperature as high as 11°C can be maintained during at least 500 ky after (fig. 8b & 9) at the base of the sands aquifer (~60 m deep) upstream from the edges of the plateau.

5. Discussion & Conclusions
The duration of silicification is geologically short but in view of the weak solubility of silica in sub-permafrost fluids, it would be needed to supply the silica precipitated from the solution. It shows the importance of a high ground water flow rate to sustain silicified sandstone cementation in a time span comparable with the hydraulic time constants. Therefore, although the numerical experiments may play an additional insulator role.

Future research will be conducted accordingly. Fluid and thermal conditions during thawing of permafrost should also be considered. Running a geochemical model would eventually allow to refine our hypotheses and verify if several hundreds of years of silica precipitation in these conditions are sufficient to generate the Fontainebleau Sandstones.

References

**Image 1:** Hydrogeologic framework
- Geological map of the Beauce Plateau with location of the cross-section line.
- Type A 2-D hydrogeologic section of the Beauce Plateau with the simplified version used for modelling.

**Image 2:** Sandstones, Drummond (1977)
- Contorted morphologies of the sandstone lenses with often asymmetrical profiles, elongated towards valleys and interpreted as evidence of the paleo-groundwater flow direction.

**Image 3:** Regional distribution of the Sandstones
- The sandstone levels are discontinuous and of variable size, from a few dm³ to several thousands of m³.

**Image 4:** Preferential cementation of sands along dune ridges resulting in parallel stripes of sandstone layers
- Unleached and unleached Fontainebleau Sands.

**Image 5:** Calcite cements, Fontainebleau Sands, Late Heald (177)
- The Fontainebleau Sands often contain calcite cements (fig. 5), suggesting that sand silicification also has to be related to Quaternary cold periods. Silica precipitation would be facilitated by a decrease in solubility with decreasing temperature of groundwater outflow in contact with permafrost (fig. 6, Thiry et al., 2013).

**Image 6:** Quartz solubility as a function of temperature
- Sica solubility relatively quickly decreases with decreasing temperature.

**Image 7:** Model of silicification associated with a cold front propagation
- During cold periods of the Quaternary, sica precipitation would occur at the abrupt temperature interface between permafrost and warmer groundwater.