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 fluting layers of very tightly cemented sandstones, the origin of which is linked to cold-groundwater (Thiry et al., 1988). Recent dating of calcite crystals, 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 permafrost. Model calculations aimed to investigate the temperature and pressure conditions associated with a cold front propagation near the groundwater outlet. We discuss them in terms of comparison fluid flow and geothermal profile to provide sustainable conditions to achieve silica 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 hydrogeological network.

Silicification in the Fontainebleau Sands produced up to 4 principal levels of superposed fluting layers of very tightly cemented sandstones (0.5 to 8 m thick, to mm long, see fig 2). Driehole data indicate that these sedimentary quartzite 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 plateaus (fig 1a). The sandstones are discontinuous and of variable size, from a few dm³ volume 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 groundwater flow, suggest a relatively recent surficial silicification, near the outcrop zones. The general arrangement of the sandstone layers (fig 3), which preferentially cemented along edges at the top of the formation, suggests that the Fontainebleau sands developed in the sand formation to the falling water table levels during the downcutting of the valleys, in a first silicification model. The Fontainebleau Sands often contain calcite crystals (fig 5), the C14 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 cypacites related to frozen kame cavities (De Kock et al., 2012), but would have developed in the sand aquifer. They are sometimes incised in the quartzite layers (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).

4. Numerical modelling
A representative SW-NNE cross section (70 km long, 125 m thick, fig 1c) of the Beauce Plateau serves as the basis for 2D coupled fluid flow and heat transport simulations. The data are used from various studies on the Fontainebleau Sands and the Beauce aquifer.

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°C). It is assumed that frozen ground prevents recharge from the surface; however, positive groundwater outlet temperatures are maintained. As a result, hydraulic heads decrease slowly (fig 8b). A thin layer of frozen ground (~2 m thick after 500 kyr, fig 8b) developed on top of the plateau, spatially depending on the heterogeneous properties of sand and limestone. Geothermal profile (fig 9) varies accordingly. Temperature as high as ~11°C can be maintained during at least ~500 kyr (fig 8b & 9) at the base of the sands aquifer (~10 m deep) upstream from the main outlet.

5. Discussion & Conclusions
The duration of silica precipitation is geologically short but in view of the weak solubility of silica in surficial waters, substantial groundwater flows may be needed to supply the silica precipitated from the solution. The results show that the importance of a high groundwater flow rate to sustain sandstone cementation in a time span comparable with the hydrothermal constants. Nevertheless, the behaviour of the Fontainebleau Sands in the numerical experiments may play an additional stabilising 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

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