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Anne Jost[1] (*Anne.Jost@upmc.fr*), Médard Thiry[2], Agnès Rivière[2], Sophie Violette[1] & Julio Gonçalvès[3]

[1]Metis, UPMC, [2]Mines ParisTech, [3]CEREGE

Université Pierre et Marie Curie

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1. Introduction

In the Paris basin, the Fontainebleau Sands (Early Oligocene) contain superposed flat-lying lenses of very tightly cemented sandstones, the origin of which was related to paleo-groundwater (Thiry et al. 1988). Recent dating of calcite crystallarias, 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 aims to investigate the temperature and pressure conditions associated with a cold front propagation near the groundwater outlet. We discuss them in terms of constraints on 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 hydrographic network.

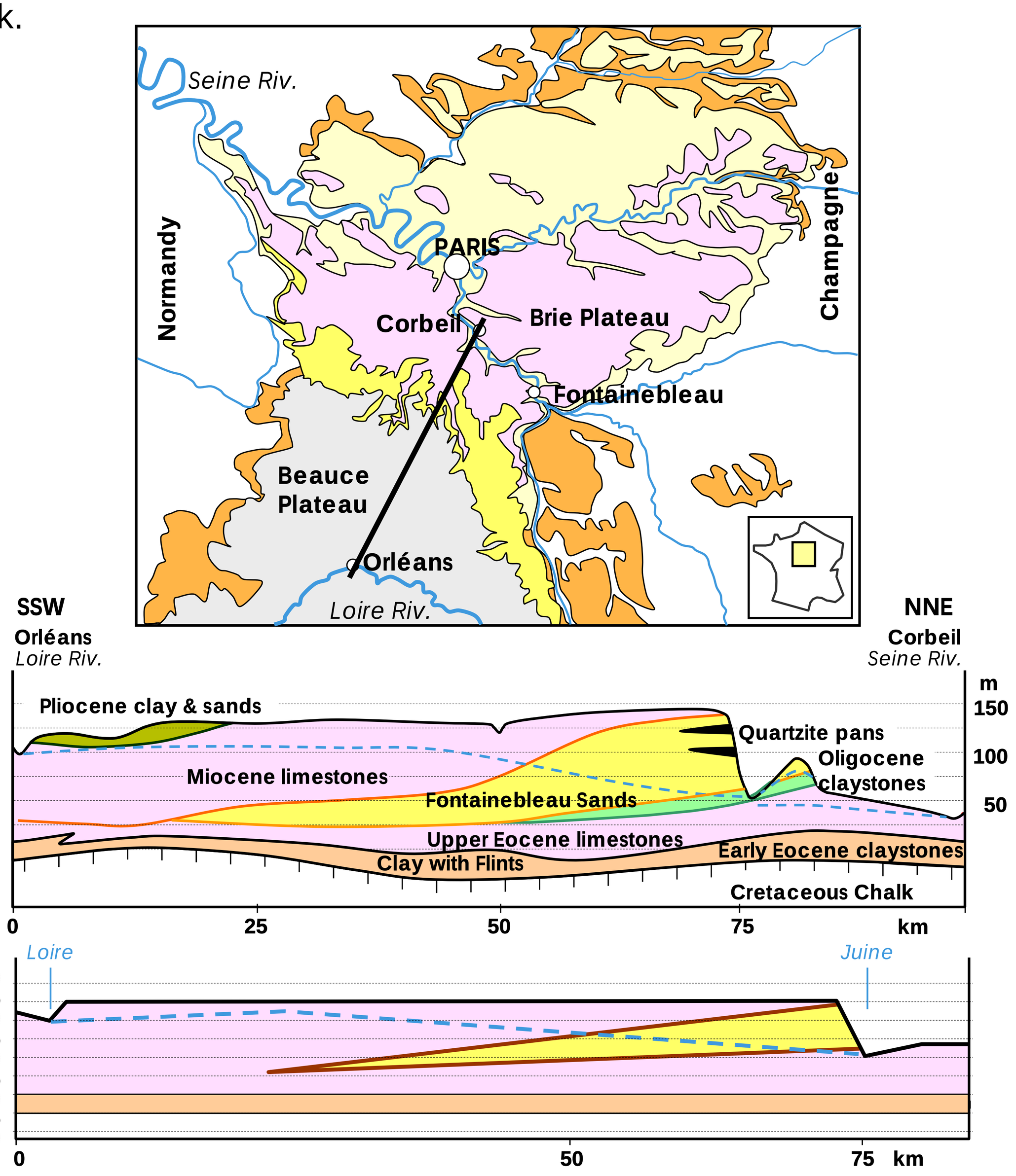

Fig. 1 – Hydrogeologic framework

(a) Geological map of the Beauce Plateau with location of the cross-section line.

(b-c) Typical 2-D hydrogeologic section of the Beauce Plateau with its simplified version used for modelling.

Silicification in the Fontainebleau Sands produced up to 4 principal levels of superposed flat-lying lenses of very tightly cemented sandstones (0.5 to 8 m thick, m to hm long, see fig 2). Drill-hole data indicate that these sedimentary quartzite layers are restricted 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 1b). The sandstone lenses are discontinuous and of variable size, from a few dm³ volume to several thousands of m³.

Fig. 2 – Sandstones, Darvault (77)

Contorted morphologies of the sandtone lenses with often asymmetrical profiles, elongated towards valleys and interpreted as evidence of the paleo-groundwater flow direction.

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3. Mechanisms of silicification

The discontinuous distribution of the silicified bodies, as well as the correlation between their localisation and the recent or present morphology, suggest a relatively recent surficial silicification, near the outcrop zones.

The general arrangement of the sandstone in subhorizontal layers and their elongated morphologies towards valleys may also indicate a control on their genesis by paleo-groundwater (Thiry et al. 1988, fig 2). Each sandstone level would correspond to an old groundwater level and form at the groundwater discharge zones. Thiry et al. (1988) thus associated the successive sandstones development in the sand formation to the falling water table levels during the downcutting of the valleys, in a first silicification model.

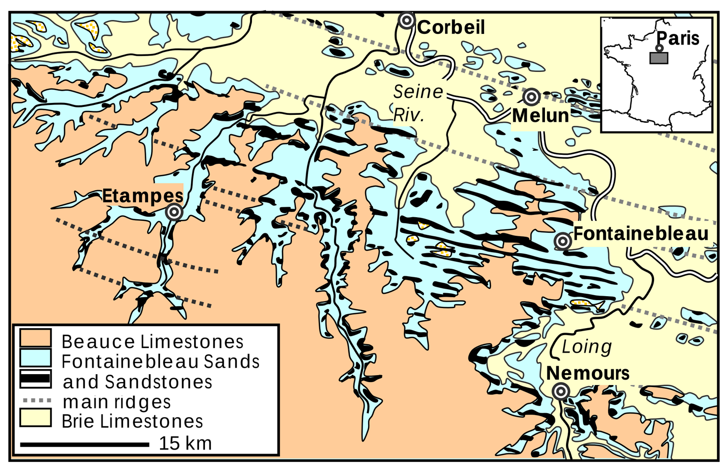


Fig. 3 – Regional distribution of the Sandstones

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

Furthermore, sands are preferentially cemented along ridges at the top of the formation. The parallel arrangement of the sandstone layers (see fig 3, between Fontainebleau and Etampes) corresponds to the paleodunes morphologies of the top of the sands along which groundwater would flow and first discharge as erosion cut secant valleys (fig 4). This may explain the sharp boundary between cemented sandstone and loose sand.

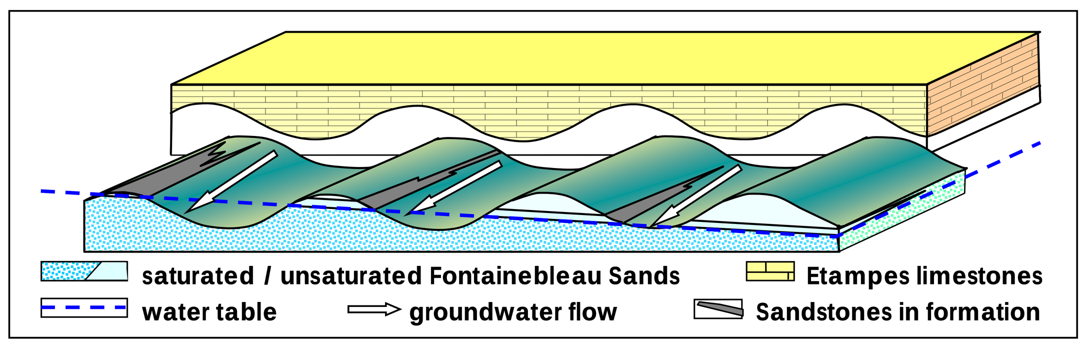


Fig. 4 – Preferential cementation of sands along dune ridges resulting in parallel stripes of sandstone layers

The Fontainebleau Sands often contain calcite crystallarias (fig 5), the ^{14}C and U-Th dating of which shows formation during the past two cold periods of the Quaternary, around 300 kyr and 50-30 kyr. They would be equivalent to the cryocalcites related to frozen karst cavities (Zak et al. 2012), but would have developed in the sand aquifer. They are sometimes included 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).

Fig. 5 – Calcite crystallarias, Fontainebleau Sands, Larchant (77)

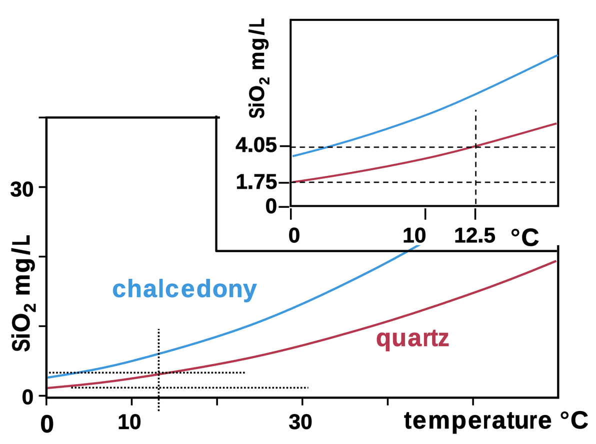


Fig. 6 – Quartz solubility as a function of temperature

Silica solubility relatively quickly decreases with decreasing temperature.

This new model of silicification during cold periods only differs from the previous one (Thiry et al. 1988) by its mechanism of silica precipitation. It leads to the same distribution of quartzite layers, restricted to the edges of the plateaus and the valleys, near the groundwater discharge zones which provide silica. However, superposed silicified lenses would be related to permafrost propagation (fig 7) and hence, would act as a proxy for the presence and thickness of permafrost.

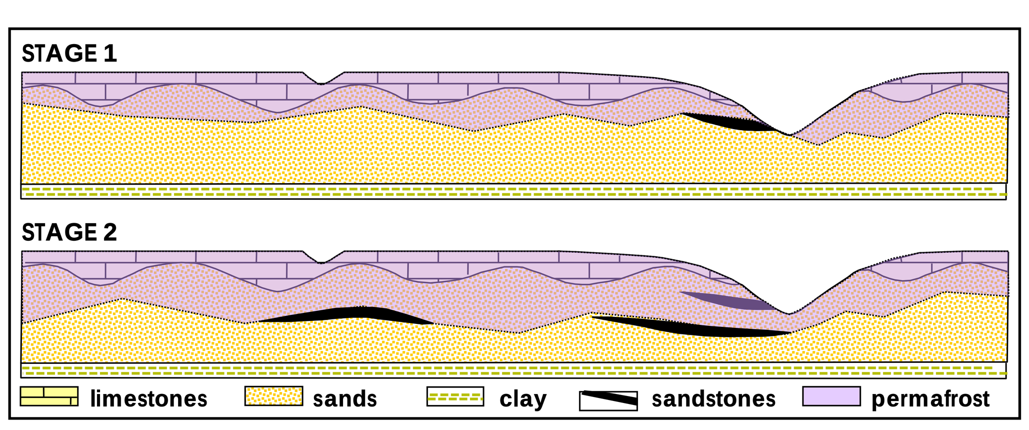


Fig. 7 – Model of silicification associated with a cold front propagation

During cold periods of the Quaternary, silicification would occur at the abrupt temperature interface between permafrost and warmer groundwater.

4. Numerical modelling

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

The data used are from various studies on the Fontainebleau Sands and the Beauce aquifer:

	Limestones	Sands
Horizontal hydraulic conductivity ($m.s^{-1}$)	$2 \cdot 10^{-5}$	$2 \cdot 10^{-4}$
Porosity	0.06	0.3
Effective thermal diffusivity ($m^2.s^{-1}$)	$9.5 \cdot 10^{-7}$	$1.7 \cdot 10^{-6}$

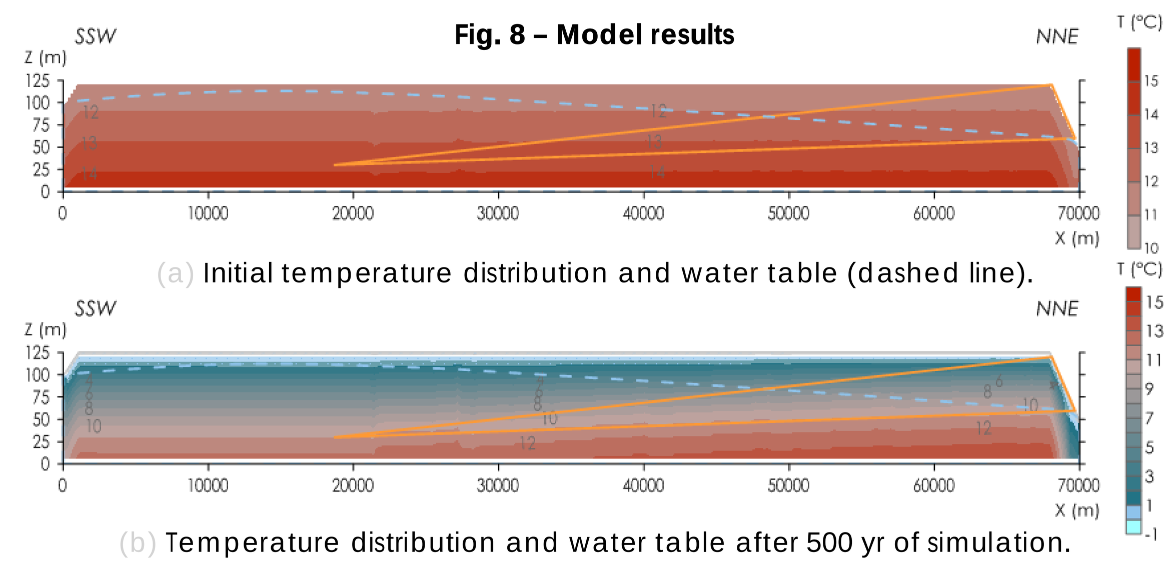
We used a newly developed numerical code that simulates groundwater flow and heat transfer in the (x,z) plane with integrated freezing and thawing processes (latent heat effects and modifications of hydraulic and thermal properties due to ice formation; Rivière et al. 2013). It solves the following equations:

Groundwater flow
$$\frac{\partial}{\partial x}\left(\frac{\rho_w k k_r(T)}{\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\rho_w k k_r(T)}{\mu}\frac{\partial p}{\partial z}+\rho_w g\right)=\frac{S_s}{g}\frac{\partial p}{\partial t}+\phi\left(\rho_w-\rho_i\right)\frac{dS_i}{dt}$$

Heat transport
$$\nabla\cdot\left(\kappa_e \nabla T\right)-\rho_w C_w \nabla\cdot\left(Tq\right)=\rho C\frac{\partial T}{\partial t}-\rho\phi L_i\frac{\partial S_i}{\partial t}$$

Steady state simulations were run under modern conditions (annual surface temperature of 11°C, recharge of ~10 mm/yr) to generate initial conditions, characterized by a vadose zone up to several tens of meters and a groundwater flow rate of 1-10 m/yr. A continental divide crosses the section, between the Loire and Seine catchments (fig 8a). An average geothermal gradient is calculated as 30.7°C/km in the Beauce plateau for a uniforme basal heat flow of 70 $mW.m^{-2}$ (see fig 9). With a modified Peclet number Pe^* at the aquifer scale (van der Kamp 1984) widely lower than 0.1, groundwater flow does not affect the thermal regime (fig 8a).

Fig. 8 – Model results



(a) Initial temperature distribution and water table (dashed line).

(b) Temperature distribution and water table after 500 yr of simulation.

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 outlet temperatures are maintained. As a result, hydraulic heads decrease slowly (fig 8b). A thin layer of frozen ground (1-2 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 kyr (fig 8b & 9) at the base of the sands aquifer (~60 m deep) upstream from the edges of the plateau.

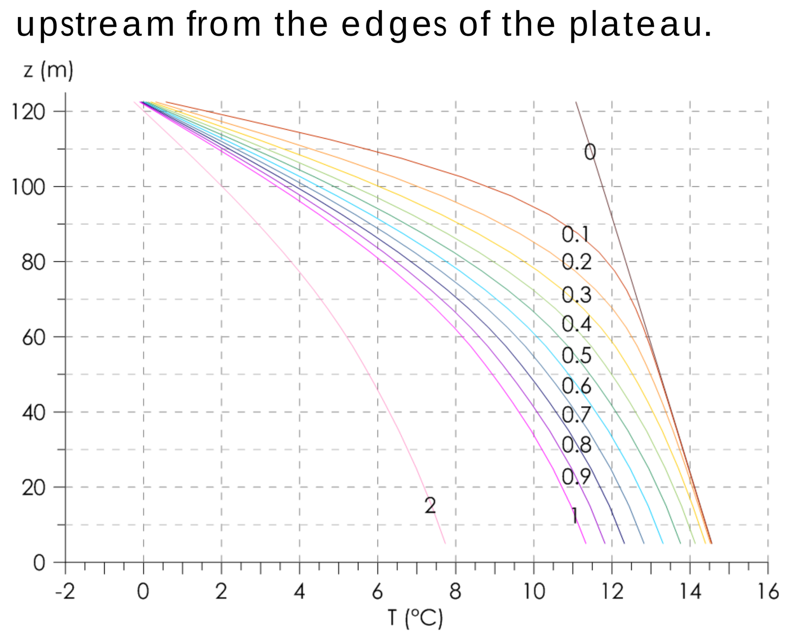


Fig. 9 – Geothermal profile evolution in the course of the simulation

Location: ~6 km upwards from the main outlet; time in kyr.

5. Discussion & Conclusions

The duration of silicification is geologically short but in view of the weak solubility of silica in surficial waters, substantial groundwater flow is nonetheless needed to supply the silica precipitated from the solution. It shows the importance of a high groundwater flow rate to sustain silica for sandstones cementation in a time span compatible with the hydrothermal constraints. Near the groundwater oultets, where present springs flow at a rate of 3-150 m³/hr, higher velocities would allow a convective thermal regime to maintain the warmer temperatures of the sand aquifer and a sharp geothermal gradient on contact with discontinuous permafrost, expected to provide favourable conditions to achieve silica deposition. An abrupt transition towards a cold period is somehow also needed (our modelling assumes it is instantaneous) to prevent the geothermal gradient from slowly adjusting to decreasing surface temperatures. However, the presence of a large vadose zone on the plateaus (not yet taken into account in 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 hypothesis and verify if several hundreds of years of silica precipitation in these conditions are sufficient to generate the Fontainebleau Sandstones.