A burning question: how transfer processes in soils can enlighten archaeological fires?

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Humans and fire

- The control of fire by early humans was a turning point in the cultural aspect of human evolution that allowed humans to cook food and obtain warmth and protection.
- Claims for the earliest definitive evidence of control of fire by a member of *Homo* range from 0.2 to 1.7 million years ago.
- Evidence of widespread control of fire dates to approximately 125,000 years ago and later.
- From this date, surface artifact scatters are very often associated with the remains of one or more hearths.
- Hearths are an important part of the archaeological record because they are an easily recognizable indicator of past occupation.

Goal

- Obtain information on the human behavior in relation with the use of the fire

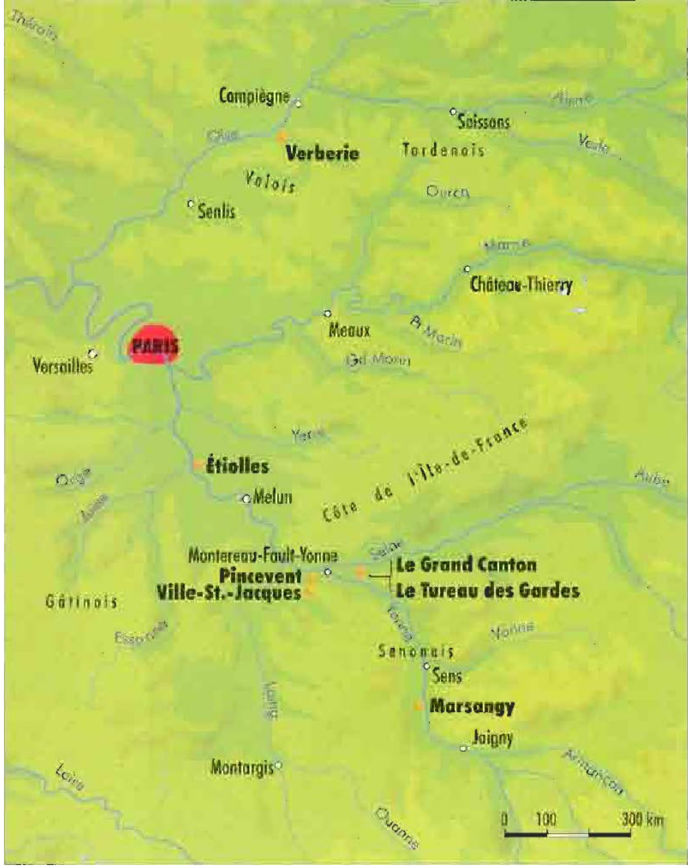
- Some questions to adress :
  - What was the shape of the hearths?
  - What were they used for?
  - What was the duration of use?
  - ...

- The answers could help to validation (or invalidation) of the scenarii deduced from other observations.

Exemple

- Magdalenian : late culture of the Upper Paleolithic in western Europe (17,000 to 11,000 BP).
- The Upper Paleolithic (glacial conditions) Magdalenian seem to have been concentrated in the sheltered valleys of the Périgord, (caves and rock shelters).
- As climatic conditions ameliorated, they moved south into the Pyrenees and north into the Paris Basin.
- The culture was geographically widespread, and later Magdalenian sites have been found from Portugal in the west to Poland in the east.

- Magdalenian sites in the Paris basin are particularly well known for their excellent preservation and for the quality of excavation.
- Gentle, overbank flooding of the Seine and Oise rivers resulted in the low-energy deposition of silts on open-air campsites, preserving artifacts, hearths and their spatial distributions.
- The open-air sites of the Paris basin include Etiolles, Pincevent, Verberie, Marsangy.
- A program of preventive archaeology (due to TGV rails) recently motivated the excavation of new sites (Grand Canton and Tureau des Gardes).

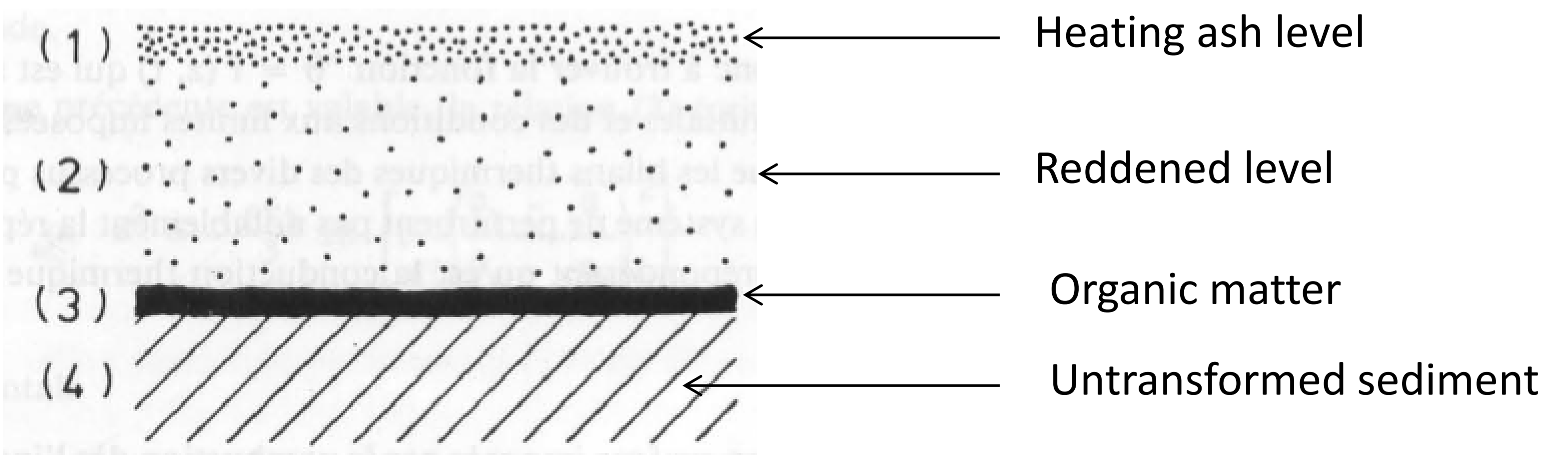


- These all are supposed to be relatively short-term seasonal occupations.
- Magdalenian were hunter gatherers, they did not settle permanently they often followed herds and moved depending on seasons.
- It is difficult to know whether the sites where occupied during the same period by the nomadic hunters , moving from site to site according to the season, or if one the site has been settled during a period, and the other one latter, by other people.
- It could be useful to know how long hearths have used to get an estimation of the time of residence of the hunters.

Laloy and Massard Method

(Revue d'Archéométrie, 8, 1984)

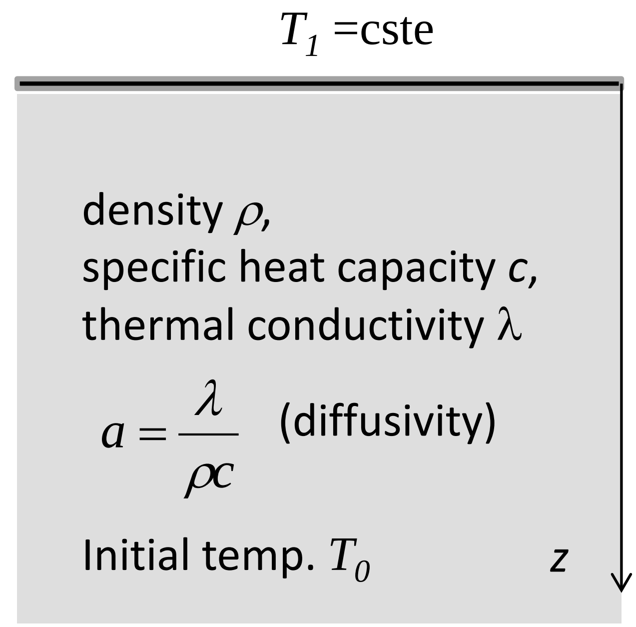
- Their approach consists in using the observed aleration of the constituents of the soil underlying hearths.
- Under the simple flat hearths of Etiolle, the clayey sediments are layered :



- Their interpretation is that heat produced at the surface is transfered by conduction through the soil. The sediments in the reddened level have been « cooked ».
- The limit between (2) and (3) corresponds to the temperature at which the organic matter is destroyed.
- This thermometric marker allows, knowing the temperature of the fire, to determine the duration of the burning.

- Laloy and Massard use a very simple model : 1D, homogeneous medium with constant and uniform physical properties.
- The heat conduction equation is thus reduced to :

$$\rho c \frac{\partial T(z,t)}{\partial t} = \lambda \frac{\partial^2 T(z,t)}{\partial z^2}$$



- With the boundary conditions :

$$T(0,t) = T_1 \qquad T(z,0) = T_0$$

$$\lim_{z \to \infty} T(z,t) = T_0$$

- Laplace transform :

$$\theta(x,p) = \int_0^{+\infty} T(x,t) e^{-pt} dt \text{ with } p > 0$$

$$\int_0^{+\infty} \frac{\partial T}{\partial t} e^{-pt} dt = \left[T e^{-pt} \right]_0^{+\infty} + p \int_0^{+\infty} T e^{-pt} dt = -T(x,0) + p\theta$$

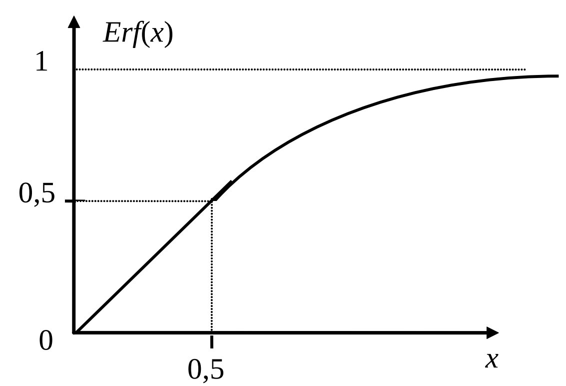
$$\begin{cases} p\theta - T_1 = a\dfrac{\partial^2\theta}{\partial z^2} \\ \theta(x, p) \rightarrow \dfrac{T_1}{p}, \text{ when } z \rightarrow -\infty \\ \theta(0, p) = \dfrac{T_0}{p} \end{cases} \Longrightarrow \quad \begin{array}{l} \theta = A\exp\left(\sqrt{\dfrac{p}{a}}z\right) + B\exp\left(-\sqrt{\dfrac{p}{a}}z\right) + \dfrac{T_1}{p} \\ A = 0 \\ B + \dfrac{T_1}{p} = \dfrac{T_0}{p} \end{array}$$

Solution : $$\theta(z, p) = (T_0 - T_1)\frac{1}{p}\exp\left(-\sqrt{\frac{p}{a}}z\right) + \frac{T_1}{p}$$

$\dfrac{1}{p}\exp\left(-\sqrt{\dfrac{p}{a}}z\right)$ is the Laplace transform of $erfc\left(\dfrac{z}{2\sqrt{at}}\right) = 1 - erf\left(\dfrac{z}{2\sqrt{at}}\right)$

With : $$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp(-u^2)du$$

$$\boxed{\frac{T(z,t) - T_0}{T_1 - T_0} = erf\left(\frac{z}{2\sqrt{at}}\right)}$$



Estimation of the duration

- We can measure a (soil properties),
- T_0 is given by paleoclimatology,
- T_1 is the combustion temperature that can be obtaine from anthracological studies.
- As the Gauss error function *erf* is monotonic, we see that if we know the temperature reached at some level z, we can get the time t.
- Conversely the diffusivity a of a medium can be deduced from measured temperatures $T(z,t)$, knowing T_0 and T_1 (cf. Edouard Canot talk).

Where could this model fail?

- Hearth :
  - Finite size of the hearth $\rightarrow$ 1D?
  - Shape (not necessarily flat)
  - Variation of T_1 (in time, space)
- Soil :
  - Heterogeneities in the initial soil
  - Variation of the physical properties of the soil with temperature during the burning
  - The soil is a porous medium containing fluids (air, water)
    - $\rightarrow$Possible phase transition (liquid-vapor) for water
    - $\rightarrow$The fluids (air, liquid water and vapor) can move : convection
    - $\rightarrow$The effective thermal properties may vary with the concentration of water
    - $\rightarrow$Possible dissolution and deposition (crystallization) of solid phase
  - Added matter during burning (ashes, fats,…) may change the properties near the surface

\+ Taphonomy (transformation having modified the archeological record)

$\Rightarrow$ Where is the z origin?, did the soil change?

Some comments

- Even if we knew everything concerning the hearth which was used and the characteristics of the soil underlying it, taking into account the full complexity of the problem would lead to :
  - 3D non stationary models
  - In heterogeneous unsaturated porous media
  - Submitted to heat and mass transfer
  - Phase change
  - Pressure gradients induced by temperature gradients giving birth to fluid motion
  - Capillary motion (hysteretic)
- In a medium whose physical characteristics may vary with temperature and time
- So it would be difficult to produce a tractable simulation

$\Rightarrow$ It is highly recommended to find a simplified model

A comparative analysis of multiphase transport models in porous media

(K. Vafai, M. Sozen, Annual Review of Heat Transfer)

Table 2 Momentum transport details in different models

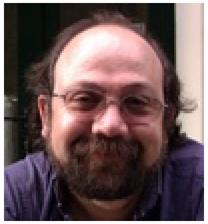
	Whitaker	Luikov	DeVries	Berger and Pei	Eckert
Vapor					
Molecular transport (diffusion)	Yes	Yes	Yes	Yes	Yes
Dispersion	Yes	No	No	No	No
Darcy's flow (convective)	Yes	Yes[a]	No	No	No
Gravity	Yes	No	Yes[b]	No	No
Liquid					
Molecular transport (diffusion)	Yes	Yes	Yes	No	Yes
Dispersion	Yes	No	No	No	No
Capillary motion	Yes	Yes[c]	Yes	Yes	Yes
Darcy's flow (convective)	Yes	Yes[a]	Yes	No	Yes
Gravity	Yes	No	Yes	No	Yes
Noncondensables					
Molecular transport (diffusion)	Yes	Yes	No	No	No
Dispersion	Yes	No	No	No	No
Darcy's flow	Yes	No	No	No	No
Gravity	Yes	No	No	No	No

Table 3 Heat transfer details in different models

	Whitaker	Luikov	DeVries	Berger and Pei	Eckert
Conduction					
Solid phase	Yes	Yes	Yes	Yes	Yes
Liquid phase	Yes	Yes	Yes	No	Yes
Vapor phase	Yes	Yes	Yes	No	Yes
Noncondensables	Yes	Yes	No	No	No
Convection					
Liquid phase	Yes	Yes	Yes	No	No[a]
Vapor phase	Yes	Yes	Yes	No	No[a]
Noncondensables	Yes	Yes	No	No	No
Dispersion	Yes	No	No	No	No
Heat sources or sinks	Yes	No	No	No	No

- The difference between different models usually arise from :
  - simplifying assumptions made for actual phenomena
  - Combination of physically different transport components into a single term

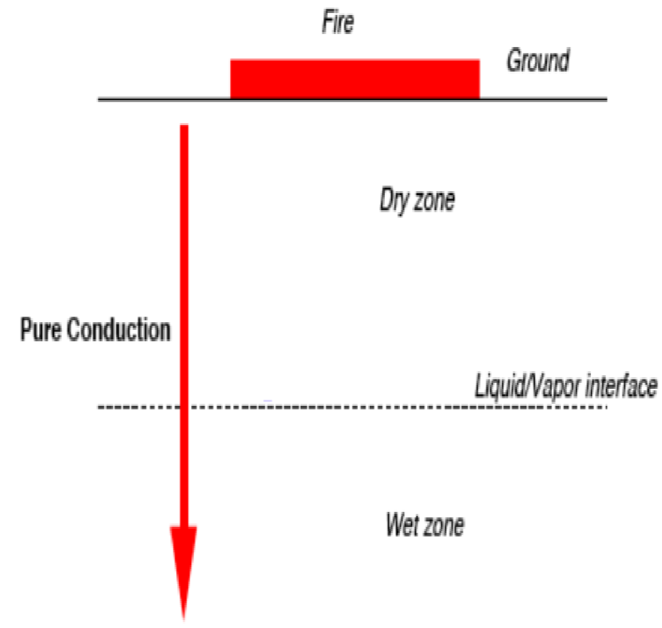
The J.C. Ferreri code



R. March

- This model has been developed by J. C. Ferreri (Argentina) in collaboration with Ramiro March to study archaeological hearths and the thermal alteration of soils due to heat.
- It takes into account the presence of water in the soil through its effect on the physical properties of the medium (ρ, c, λ) and through the latent heat of phase change L.
- The motion of the fluids is not taken into account and the effect of noncondensables is neglected.
- Due to the complexity of the structure and internal processes, a number of simplifying assumptions are made:

- The solid matrix :
  - cannot deform
  - is free of chemical reaction or dissolution.
  - contains no liquid or gaseous component (no bound moisture)
  - its properties may vary in space.



- The moisture:
  - The vapor-phase moisture content is negligible compared to the liquid phase
  - Does not react chemically with other constituents.

  $\Rightarrow$ Moisture = free incompressible liquid water

- Phase change :
  - Local thermodynamic equilibrium exists between the different phases
  - The dry front appears immediately at the open surface when the heating begins.
  - Phase-change temperature T_v=100◦C

Heat transfer

- Radiative heat transfer and free convection are neglected
- As in the Laloy Massard approach, the equation to be solved is the unsteady heat conduction equation :

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T \right)$$

where ρ, c and λ are the effective density, specific heat capacity and thermal conductivity tensor at a given point and a given time.

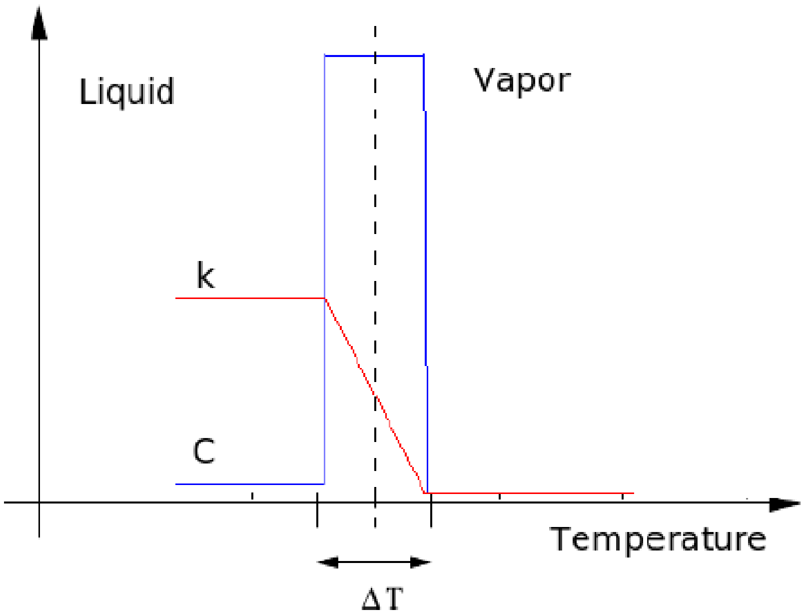
$$\rho c = \phi \left(\rho c \right)_f + \left(1 - \phi \right) \left(\rho c \right)_s$$

$$\lambda = \phi \lambda_f + \left(1 - \phi \right) \lambda_s$$

where ϕ is the porosity , the subscript f and s denote the fluid (liquid or vapor) and solid phases respectively.

Phase transition

- The apparent capacity method of Bonacina (1973) is used.
- The phase change is supposed to take place in a small temperature interval :



$$(\rho c)_f = \begin{cases} (\rho c)_l & T < T_v - \Delta T \\ \dfrac{(\rho c)_v + (\rho c)_l}{2} + \dfrac{L}{2\Delta T}, & T_v - \Delta T \le T \le T_v + \Delta T \\ (\rho c)_v & T > T_v + \Delta T \end{cases}$$

$$\lambda_f = \begin{cases} \lambda_l, & T < T_v - \Delta T \\ \lambda_l + \dfrac{\lambda_v - \lambda_l}{2\Delta T}[T - (T_v - \Delta T)], & Tv - \Delta T \le T \le T_v + \Delta T \\ \lambda_v, & T > T_v + \Delta T \end{cases}$$

Some comments

$$\rho c = \underset{\substack{\uparrow \\ \text{Weight : porosity}}}{\phi}\left(\rho c\right)_f + \left(1-\phi\right)\left(\rho c\right)_s$$

Weight : porosity — Only water (noncondensables are ignored)

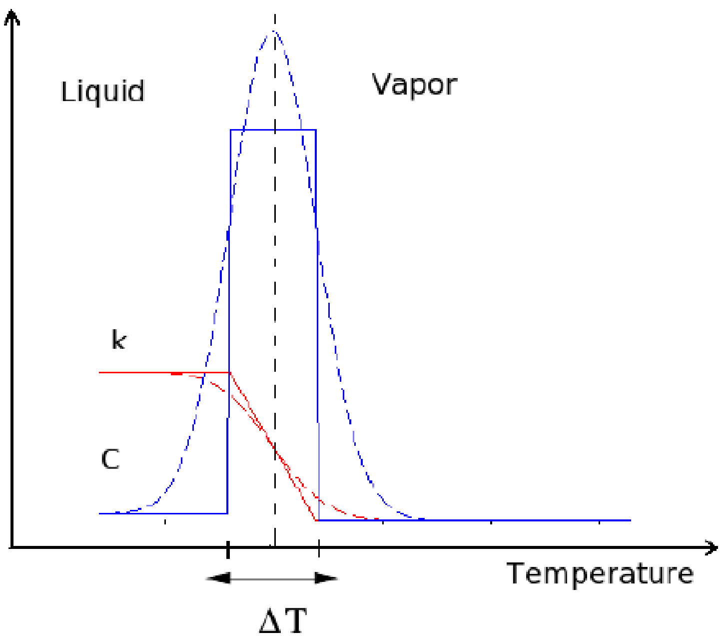
- implicitly supposes that the pores are initially water saturated.
- Soils are generally far from being water saturated. The authors used the model for unsaturated media
- They replace ϕ by the liquid fraction ϕ_l in the calculation of the effective quantities :

$$\rho c = \phi_l\left(\rho c\right)_f + \left(1-\phi_l\right)\left(\rho c\right)_s$$

- The “solid” quantities $(\rho c)_s$ or λ_s are no more relative to the solid matrix, but to the dry effective medium (which correspond to $\phi_l = 0$).
- This is an approximation, valid when $\phi_l \ll \phi$.

The « Arphymat » model of Edouard and Mohamad

- The assumptions are the same than for the preceding one.
- They use a regularized version of the apparent capacity method (to avoid singularities).

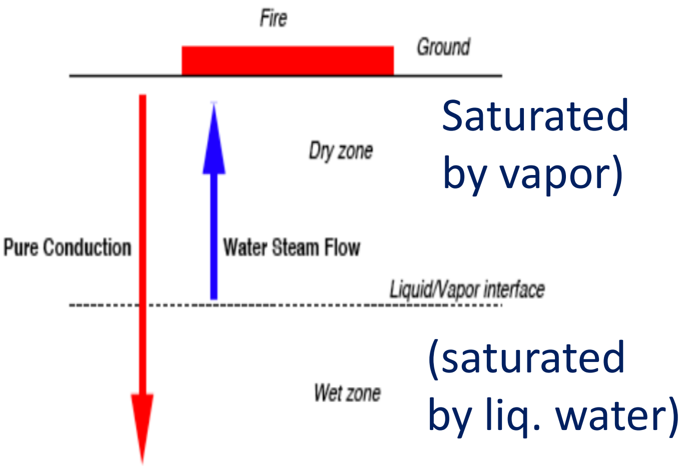


- And used a different way of averaging the thermal conduction :

$$\frac{1}{\lambda_e} = \frac{\phi}{\lambda_f} + \frac{1-\phi}{\lambda_s} \qquad \text{(harmonic)}$$

Motion of vapor : heat and mass coupling

- The main difference is that the water steam flow in the dry zone is taken into account (
- It is the pressure-driven convective flow governed by Darcy's law.



$$V_f = -\frac{K}{\mu}\nabla P$$

Where K = permeability of the porous medium,
P and μ are the pressure and viscosity of the fluid (vapor here) and V_f its filtration velocity.

- Continuity equation (for the vapor) : $$\frac{\partial\left(\phi\rho_f\right)}{\partial t}+\nabla\cdot\left(\rho_f \mathbf{V}_f\right)=0$$

- Ideal gaz law $$\frac{P}{\rho_f T}=\beta$$

- Energy conservation $$\rho c\frac{\partial T}{\partial t}+\left(\rho c\right)_f \mathbf{V}_f\cdot\nabla T=\nabla\cdot\left(\lambda\nabla T\right)$$

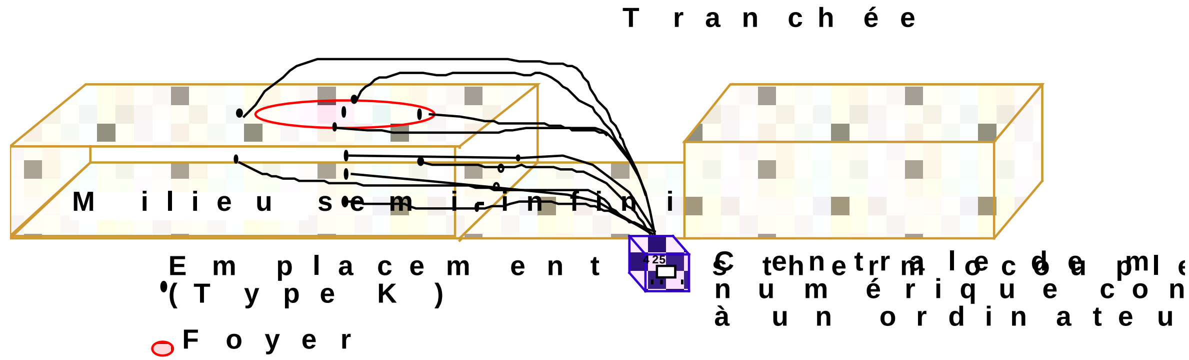
- With Darcy's law, it gives 4 equations for 4 unknowns : (ρ_f, $\mathbf{V}_f$, T, P).
- The domain is now split in two zones $\Rightarrow$ boundary conditions at the interface between the zones (continuity of the temperature, heat flux discontinuity due to the latent heat)
- New boundary condition at the surface : $P = P_{atm}$

What are the parameters of these models?

- Ferreri (without water steam flow):
  - The physical properties of water (liquid and vapor) are supposed to be known : (ρ, c,λ)
  - We have to measure or obtain from handbook the physical properties of the dry porous medium : (ρ, c,λ)
  - We have to measure the liquid fraction.
  - The input is the distribution of temperature of the fire $T(t)$ at the surface (boundary condition)
- With water steam flow :
  - The physical properties of water (liquid and vapor) are supposed to be known : (ρ, c,λ) and the viscosity of the vapor.
  - We have to measure or obtain from handbook the physical properties of the dry porous medium : (ρ, c,λ) and the permeability
  - We have to measure the liquid fraction.
  - The input is the distribution of temperature of the fire $T(t)$ at the surface (boundary condition) and the pressure at the surface (supposed to be constant, but if the wind is blowing…)

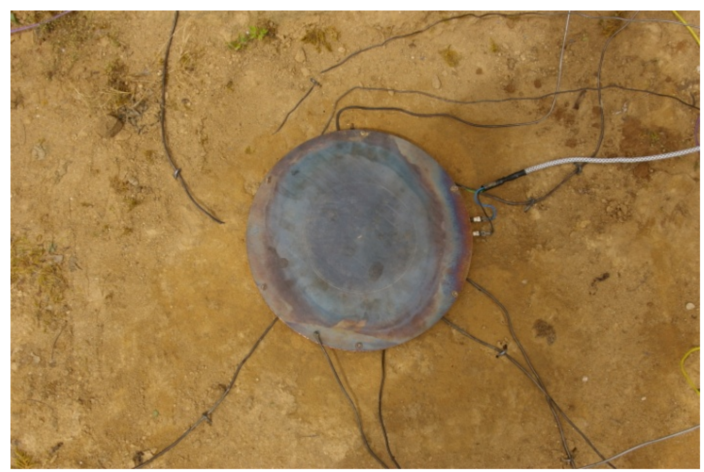
Testing the models

- Numerical simulations based on the models have been used for comparisons with experiments.
- Experiments have been performed in archeological sites, directly on the natural soil.

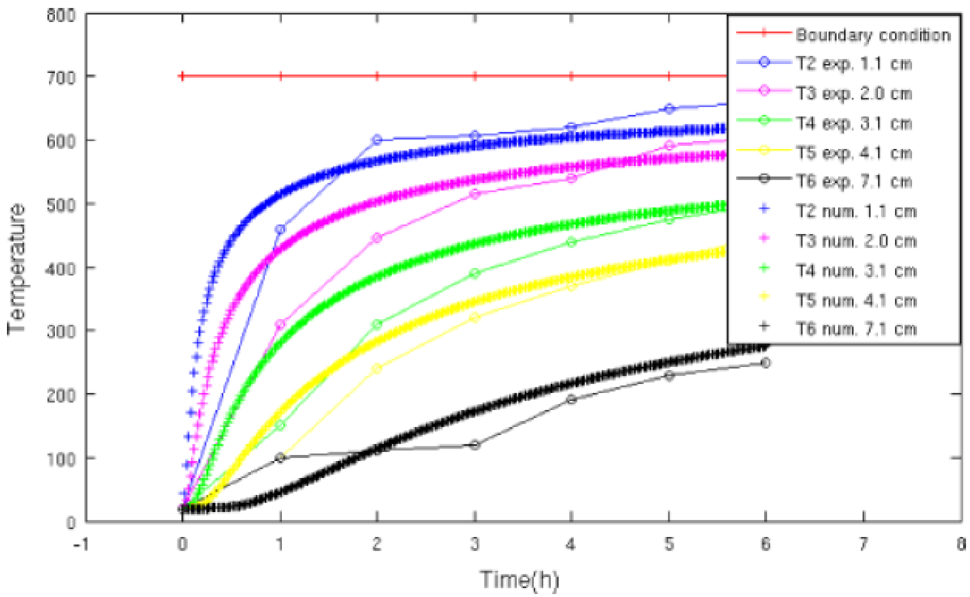


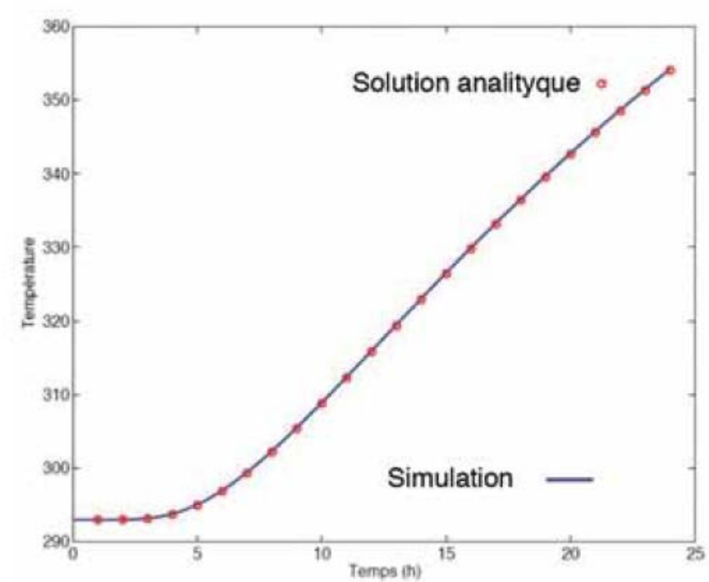
Dispositif expérimental

- Temperature probes are put at different depth in the soil under the hearth (and in the hearth)
- Temperature is recorded during the whole burning
- Excavation at the end to determine the sensor positions.



First test : Laloy Massard experiment

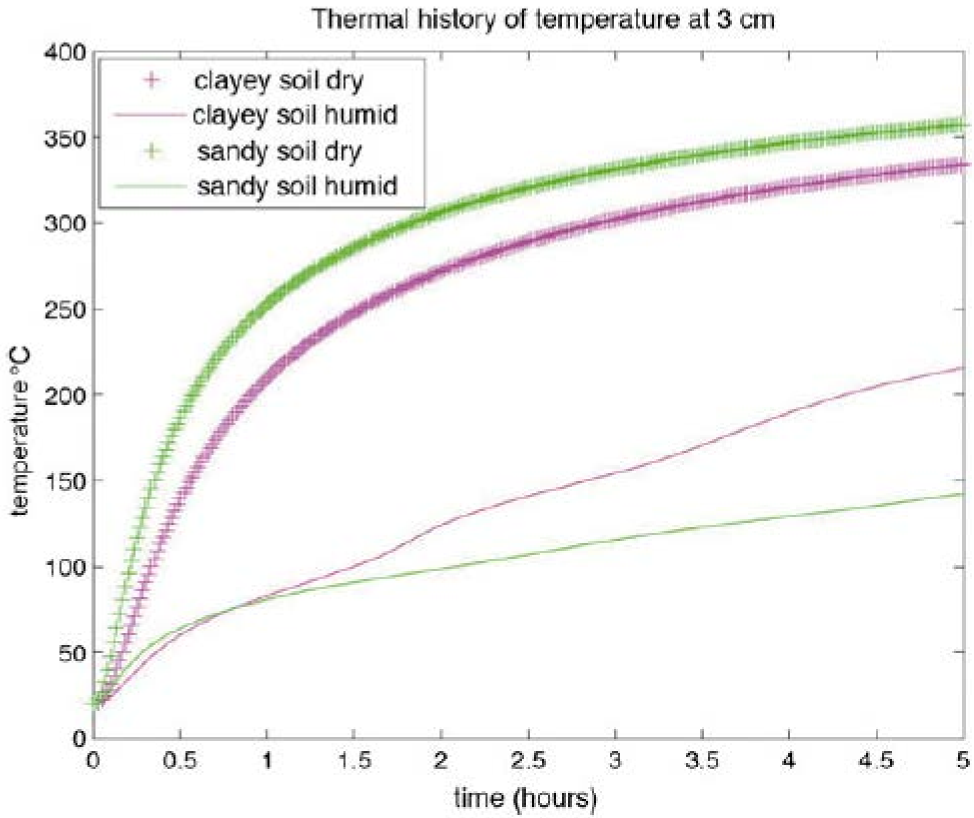




numerical /analytical solutions

- Experiment on a dry clay soil from the archaeological site of Etiolles ; the temperature at the top of the soil was 700◦C. Simulation with $\phi = 0$.
- The numerical results grow faster than the experiment , especially at the beginning
- The plateau observed at the depth 7.1cm is typical of the effect of humidity in the soil
- So even a small amount of water has an relatively strong effect

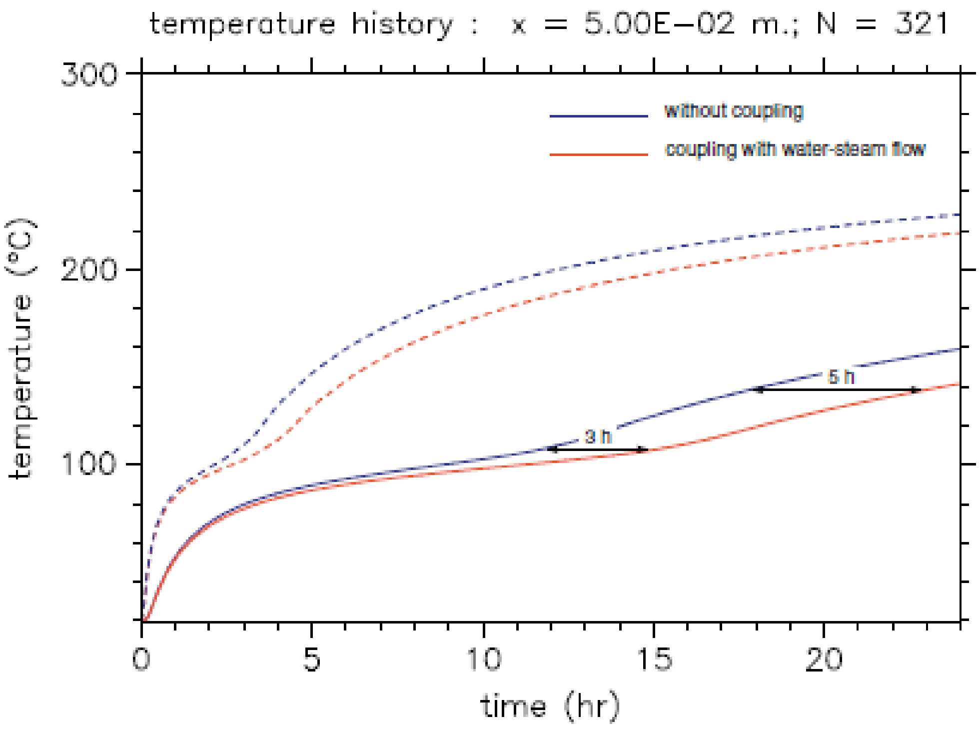
Parametric study (numerical simulation)



Thermal behaviour of « soils » subjected to a constant temperature of 600°C at 3cm depth

- The penetration of heat is slower when the soils are wet,
- Consistent with the experiments, but we don't observe the plateau at 100°C

With and without steam flow



- Plain curves (resp. dashed curves) represent the temperature histories at the depth 5cm (resp.2.5cm).
- Taking into account the steam convection introduces a delay in the heating that can reach few hours.

Replication experiments/ simulations (with coupling) on a wet soil

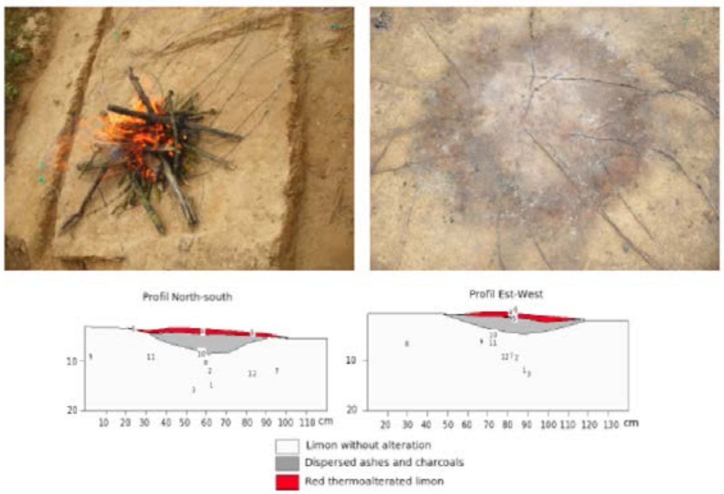


Fig. n° 13 Expérience n° 167 foyer à plat sur sol limoneux humide en bas croquis de la zone fouillée avec position des capteurs de températures

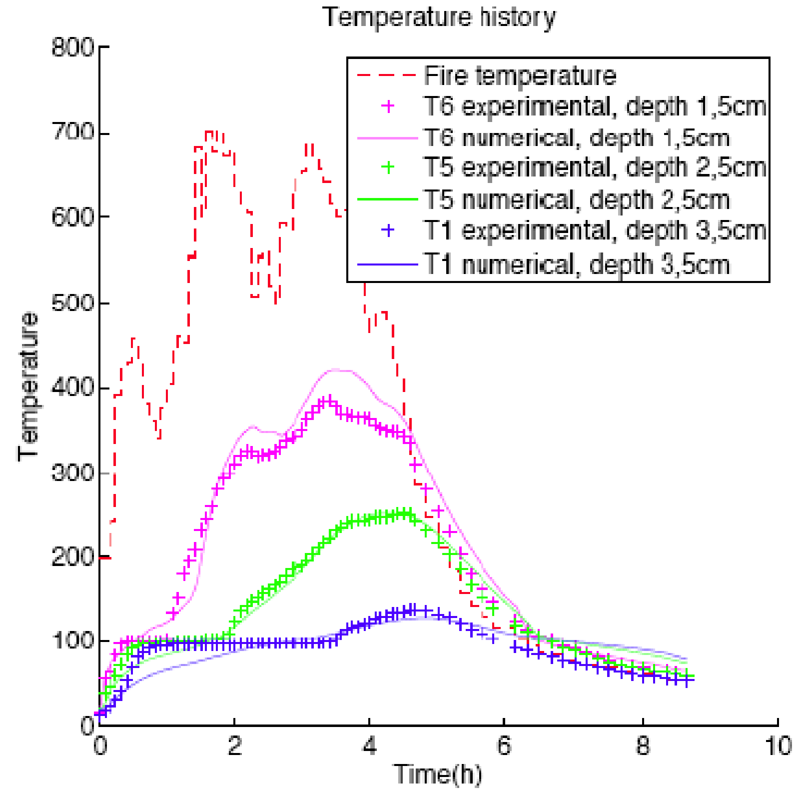


Fig. n° 16 Les courbes de température de l'expérience n°167 et sa réplication numérique

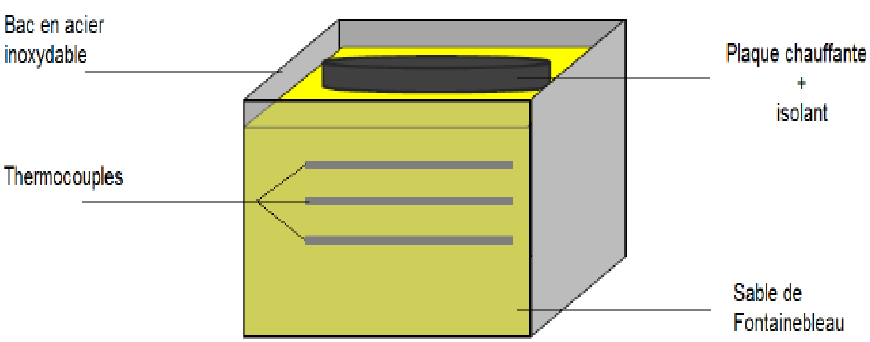
- Reasonable concordance between the experiments and the computer results
- The plateaus at the phase-change temperature are not reproduced by the simulation.

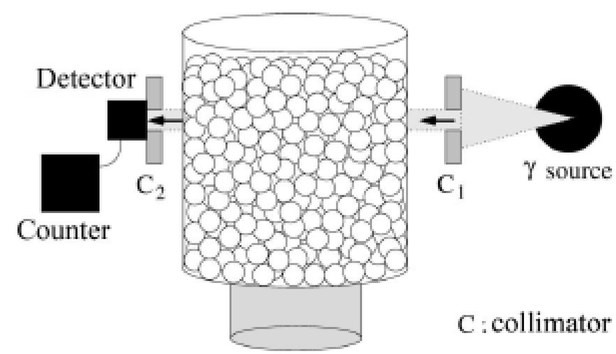
What is a good code ?

- At this point we have to decide whether we are satisfied by this code or not.
- The archaeologist will say that it is better than guesswork
- The physicist says that there is a risk that an essential ingredient is missing whose influence could be important in some situations, and more specially when used for inverse problems.
- So we need precise tests in the lab with controlled experiments which could be used to understand what is missing and what is the effect.
- It would also be interesting to have a more complete code (even if the simulation is much longer) which has already been tested, to compare the results in some typical configurations.

Laboratory experiments

Gamma ray experiment

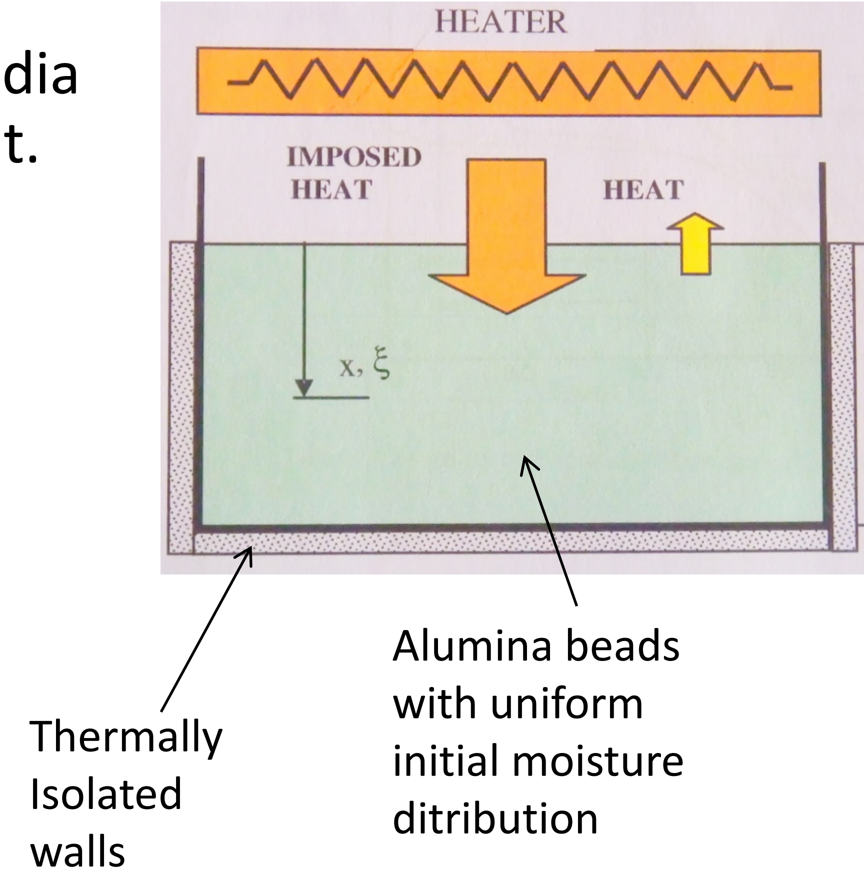




K. Min and H. Emmons

The drying of porous media, 1972

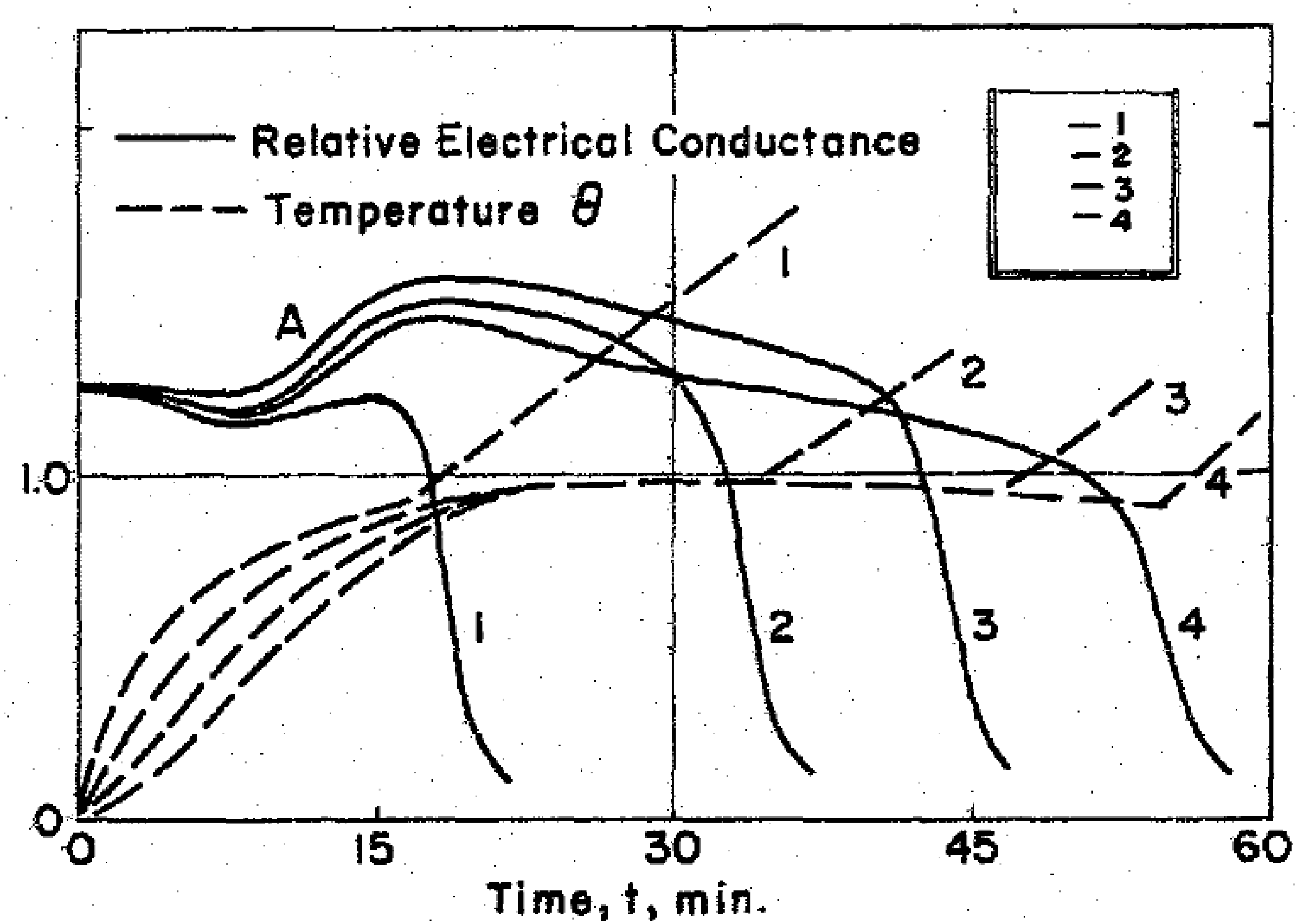
- Experiment : drying of a porous media with relatively low moisture content.
- Measure of the temperature and pressure at different depths.
- Measurement of moisture with conductance probes.
- The packing of beads is initialy at uniform temperature T_0



Moisture and temperature versus time

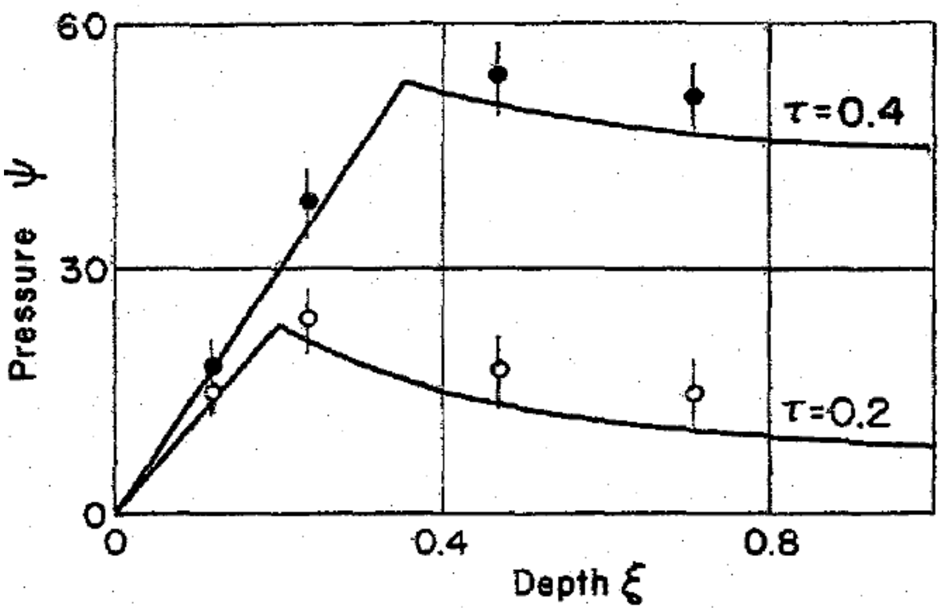
$$\theta = \frac{T - T_0}{T_b - T_0}$$

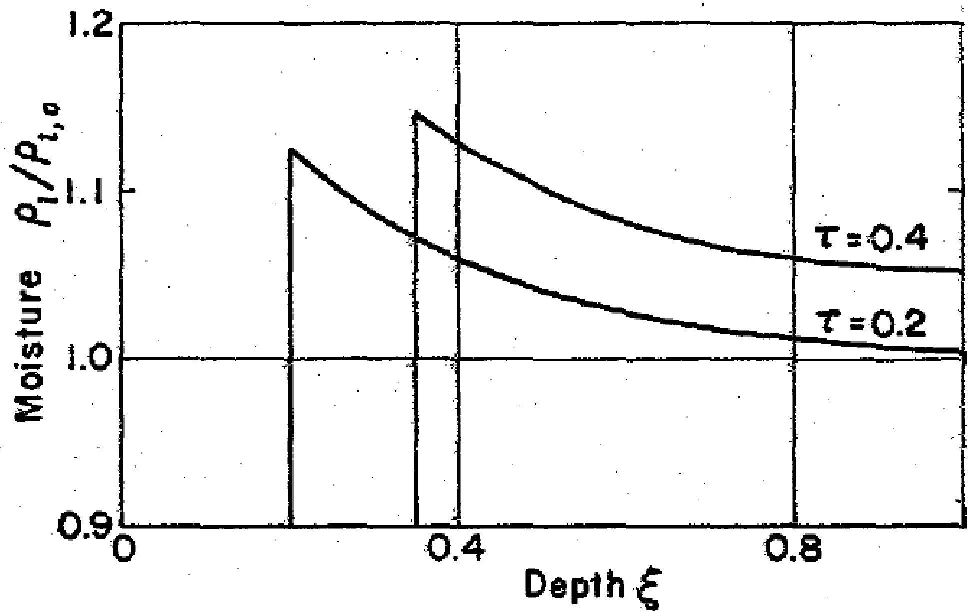
T_b : boiling temp.



- Plateaus at $\theta \approx 1$, then, sharp rise up at the arrival of the interface between dry and wet zones
- Plateaus more prominent with increasing depth
- Simultaneous appearance of plateaus at different depths

Pressure and moisture distribution





- Pressure peak located at the front, flow of air-vapor in both directions.
- The water vapor produced at the front migrate both toward the dry and the moist (not saturated) sides
- The vapor in the moist region condenses to be re-evaporeted later when the front
- It is consistent with the observed rise in the moisture prior to the arrival of the front (preceding slide)
- The condensation warms up the wet zone and creates the plateau.
- If this mechanism is actually at the origin of the plateau, it means that the code should incorporate the presence of noncondensables (and the Darcy's motion in the wet zone) to be able to capture this plateaus.

- Notons que dans le cas saturé en eau, des mouvements du liquide sous l’effet de l’ascension capillaire sont à prévoir.