



# DATA PROCESSING USING PHYSICAL MODELING APPLIED TO PREHISTORICAL FIRE REPLICATIONS ON SOILS OF THE ATACAMA DESERT, NORTHERN CHILE

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DATA PROCESSING USING PHYSICAL MODELING APPLIED TO PREHISTORICAL FIRE  
REPLICATIONS ON SOILS OF THE ATACAMA DESERT, NORTHERN CHILE

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## ABSTRACT

Soils of the Atacama Desert have not been subject of thermophysical parameters estimation from archæometric experimental field. Archaeological site Quebrada Mani 12 (QM12), located upon a fluvial Miocene terrace, is one of the few well-dated late Pleistocene hunter-gatherer camps . Here we present the results of physical analysis of *in situ* fire experiments on salty soil in the Atacama Desert to define accurate parameters to understand fire and hearth performance. The results show that the presence of water, the heterogeneity of the thermal properties of the soil, and non-uniform temperature of the fire affect subsurface thermal diffusivity, yielding heterogenous numerical figures. As a conclusion we emphasize that the combination of field and laboratory experiments coupled with numerical simulations is a solid way to yield physical modeling for interpreting field and experiment results, as a contribution of physical sciences to archæology site formation on hyper arid environments and beyond.

**KEYWORDS:** physical modeling, in situ hearth experiments, Atacama Desert, late Pleistocene hunter-gatherers, soil thermophysical properties, numerical simulations, inverse problem.

## INTRODUCTION

Archaeological site Quebrada Mani 12 (QM12; 21°S, 1240 m asl., placed on top of a fluvial Miocene terrace) is one of the few well-dated late Pleistocene hunter-gatherer open-air camps (Figure 1a), who colonized the core of the Atacama Desert by the end of the Pleistocene when its current extreme hyper arid condition were ameliorated by an increasing in precipitations rates over the western slope of the Andean Cordillera and a lower mountain chain (Sierra Moreno), 80 to 30 km away from the Desert respectively. Consequently, this territory was not a barrier for the early human dispersal and niche formation 13,000-12,000 cal years B.P. throughout South America (Gayo *et al.* 2012; Joly *et al.* 2017; Latorre *et al.* 2013; Quade *et al.* 2008; Santoro *et al.* 2017). This camp was revisited for around 800 years, according to raw radiocarbon datings, and shows that people controlled modern hunting local resources of mammals (rodents, and camelids) and perfectly knew where these and other basic resources were located (water, paleowetland, lithic sources, etc.). They also managed resources from outside of the Desert, including the Pacific coast and the Andes, from where they brought shells, fish, and stones for lithic manufactures, respectively, covering a range of more than 160 km. Their trade journeys or network of interaction went even beyond that perimeter as they also obtained small quantities of wood from the tropical forest (Santoro *et al.* 2018).

Another significative issue of these people was the management of several type of wood for their fire and hearths (Joly *et al.* 2017). At QM12 a prepared fireplace was dated to 12,200 and 11,900 cal years BP (Latorre *et al.* 2013), containing the use of four woody taxa (*Scallonia angustifolia*, *Mirica pavonis*, *Schinus molle*, *Prosopis tamarugo*) (Joly *et al.* 2017). Despite all these archaeological features we still do not know the performance of certain behavioral activities carried by these people. For instance, radiocarbon dates and the stratigraphic refuse accumulation of this site show that people returned to camp in Quebrada Mani 12, yet the frequency and time of permanence are still unknown.

In this context, physical analysis of prehistoric salt soil fire in the Atacama Desert was developed to estimate certain parameters necessary to understand fire and hearth utilization as mean to unfold certain characteristics of settlement organization in term of time of permanence and intensity of occupation.

Soils of the Atacama Desert, composed by sand, silt and a high concentration of salts, have not been subject of modeling physical parameters derived from archæometric experimental field and laboratory data analyses.

Modeling, based on simulation or experimentation upon different archaeological materials to define prehistoric behavioral patterns, involves the integration of engineering, archaeology, experimental physics and numerical simulations (Backhouse and Johnson 2007; Bland *et al.* 2016; Zhu *et al.* 2014).

Here we present the results of physical modeling techniques aiming to understand combustion structures and its concomitant stratigraphic structures as a mean for interpreting late Pleistocene archaeological site formation in the Atacama Desert of northern Chile. Complementary, in situ experimental fires were made with the scarce combustible materials currently available in the hyperarid core of this Desert *algarrobo* (*Prosopis* sp.) and *molle* wood (*Schinus molle*), and placed over its sandy, silty and salty soils. These experimental fires were recorded in terms of short-term transformation of sand, silt sediments, and ashes.

## MATERIAL AND METHODS

### *Field Experiments: hearths replication*

Three experimental hearths were performed and located on different natural soil layers (figure 1b): layer 1 under the desert pavement constituted mainly by silt, plus gypsum and anhydrite; layer 2 and layer 3 composed of sand, very fine white silt, and caliche respectively (Bastos 2018). Hereafter, these three experiments are denoted by the FE-L1, FE-L2 and FE-L3 respectively. Two types of firewood were used: *algarrobo* and *molle*. In each experimental hearth 9 kg of each type of firewood were used. Temperatures were measured with a portable digital temperature reader with thermocouples distributed on the surface and inside the soil under the hearths. Combustion was maintained for few hours by adding wood regularly, and no further firewood was added to the hearths after this duration. Twenty-four hours later, each hearth was excavated following the same protocol and a laser theodolite was used to measure: (a) the perimeter, depth and thickness of the hearth, (b) the dispersion of ashes, charcoal and the thermo altered sediments based on N-S and E-W axes, and (c) the spatial location of each thermocouple. Samples of charcoal and ashes were taken from the surface. Sediments samples were collected from each of the thermo-altered layers. Initially, these replications were used to understand the functioning of the hearths (March *et al.* 2014; and ref. herein), but they can also provide the thermal conductivity of the soil (Muhieddinhe *et al.* 2012). For archaeologists, the knowledge of this thermal conductivity could allow to estimate the time duration of ancient hearths (Laloy and Massard 1984). This is particularly critical when actual evidence of charcoal and ashes may have

vanished through time because conservation problems. Sediment oxidizes at 300°C, but the oxidation is clearly visible at 400°C, because its natural color tends to fuse with the oxidation generated by exposure to heat. The anhydrite does not change color as it concretes at high temperature and rapidly recrystallized from contiguous and compact salt grains. In the outer surface of these concretions, oxidized silty sediments are adhered. These concretions are not of extreme hardness and craquelan easily with the weight or pressure, except in the presence of blocks of salt. Altered and unaltered combustion contexts could help to interpret pattern of occupation of a particular site. For these purposes, the parameters described here should be recorded from both experimental and archaeological contexts.

#### *The Laloy & Massard method*

Laloy and Massard (1984) proposed a simple method for determining the duration of a hearth, knowing the thickness of some altered zone in the upper part of the heated soil, and applying a well-known mathematical solution (the “Gauss Error Function”) of the diffusion equation in a semi-infinite medium of constant thermophysical properties. Their method included two steps: (a) determination of the thermal diffusivity of the soil, by heating it under some conditions, by processing the temperatures measured along the time at some location inside the medium; (b) estimation of the thermal diffusivity to recover the duration of a real or ancient hearth, by using the same mathematical formula, knowing the thickness of a thermoaltered colored layer of the soil.

The main advantage of this model is its simplicity. The computation can be easily programmed using a spreadsheet of Excel-type. The assumptions for the application of this method are numerous, which are listed below:

- Heat transfer must be purely diffusive (no change phases in the soil), which means that soil must be dry and that endothermic or exothermic chemical reaction cannot occur.
- The sensors location must be known with a good precision because the value of the computed thermal diffusivity depends strongly on it.
- Heat diffusion must be one-dimensional. The thermal sensors for measuring the temperature in the finite heating device, like the electric plate (Laloy and Massard 1984), must be very close to the device and centered with respect to the plate. Such a configuration tends to increase the relative error in sensor positioning.

- Heating device must provide a steady uniform temperature. This could be technologically challenging.
- Medium must have an initial uniform temperature. This can be easily prepared and checked in laboratory.  
On real soil, due to the environmental conditions, it is not easy.
- The heating condition must be a thermal shock i.e. a sudden jump in temperature. This condition is impossible to realize exactly.
- Constant thermophysical properties. These properties must be spatially uniform and shouldn't depend on temperature, which, for example, is never the case for the air enclosed in the pores of the medium.

These constraints are severe and, when some of them are not verified, the Laloy and Massard (1984) method can yield erroneous results. Determining quantitative relations between the relaxation of some constraints and the accuracy of the results is possible by using numerical simulations, but it is out of the scope of this study. Given the difficulty of the application of the Laloy and Massard method to the measurement of soil properties by use of hearths replication, we had to develop an alternative approach.

#### *Determination of the thermophysical properties of the soil: Numerical model and inverse methods*

For several years we worked in the ArPhyMat project (<http://arphy.mat.univ-rennes1.fr/>), dedicated to numerical modeling of heat and mass transfers in soils below fires. The numerical model and tools presented here concern only with dry soil without chemical reaction. The constraints of this numerical model are much less severe than those of Laloy and Massard method:

- The geometrical configuration and the heating must be axisymmetric (invariant by rotation around the vertical axis). This is easier to realize than a true 1D configuration. If the soil is not homogeneous, the heterogeneity must also respect the axisymmetric configuration (for example, horizontal layers do not violate this constraint).
- The heating device must be circular (due to the previous constraint), and its temperature profile has to be radial and known.
- The soil surface outside the heating device should be insulated. This is generally well verified, since air has a lower thermal conductivity than the soil, but it also means that radiative and convective heat transfers at the surface of the soil are neglected.

- The medium temperature doesn't need to be initially uniform but the axisymmetry constraint remains. This implies that a great number of thermal sensors has to be used in order to know the temperature field along the  $(r, z)$  coordinates.
- The heating temperature doesn't need to be constant; it can be any time-dependent function.

The above-mentioned model is named the forward problem: knowing the domain geometry and the boundary conditions applied to its boundaries, the associated numerical code can provide the temperature field at any time. The determination of the thermal diffusivity is obtained by resolution of an inverse problem, formulated as a non-linear least-square problem (Mansour *et al.* 2016; Muhieddine *et al.* 2012): after choosing an initial guess for the diffusivity, we iterate it by minimizing the discrepancy between the measured temperatures and those provided by the forward problem. The validation of this procedure has been achieved using synthetic data.

It must be emphasized that our inverse method can be used in two ways:

- The Global Inverse Problem (GIP) uses all sensors for the whole measurement domain, to determine a global estimation of the thermal diffusivity. This is preferable, because the result is more reliable when the measurement uses a great number of well-located sensors. This is only fully relevant when the soil is homogeneous, so that the diffusivity is constant throughout the whole domain (i.e. down to infinity), or when the soil has a priori known structure (if the soil has been artificially built for example). Only one sensor (the highest one) is used to get the upper boundary condition along the time. The temperature is supposed to be stationary and uniform, with a known value, at large depth.
- The Local Inverse Problem (LIP) uses only three sensors, generally close to each other, in order to determine a local value of the thermal diffusivity. This is necessary if we suspect that the soil is not homogeneous. Though this second approach may appear more interesting, it uses a one-dimensional equation and assumes that the diffusivity is constant in the layer that embeds the three sensors. Moreover, two of these sensors are used to give temperature boundary conditions and only the values of the middle sensor drives the iterations of the inverse problem. Outside the subdomain defined by the three sensors, the soil may have any thermal properties. The LIP approach is more sensitive to errors because only one

sensor data is used to find the local diffusivity, but it is complementary to the GIP approach since it allows local measurements.

These inverse methods are more versatile than the Laloy and Massard method for applications to our hearth's replication, and can be used to measure fire duration diffusivity, based on the thickness of the thermoaltered layer at the soil surface. Such numerical recovery, is relatively easy to perform when the soil structure is homogeneous. In contrast, when experimenting heterogeneous soils regarding thermal properties, accurate measurements of diffusivity are difficult to obtain. Even in presence of a layered medium where the depth of the thermoaltered layer is uniform, it may yield highly erroneous measurements. Appendix B discusses the experimental case where a deeper layer, not known after the excavation, has a thermal diffusivity that differs significantly from the diffusivity of the upper layer. The results show how difficult it is to achieve accurate estimation of time duration of the fire, when thermal properties of soil are not well known. Irregular deepness and shape of the thermoaltered zone, however, show how heterogeneous are the thermophysical properties of the soil.

Considering the hyper aridity of the Atacama Desert, it seems reasonable to assume that the soil is dry. A dense fog, known locally as *camanchaca* or *garua*, however is a common phenomenon originated in the Pacific coast. Although this fog does not produce rain, the moisture droplets measure between 1 and 40  $\mu\text{m}$ ; during the night and early in the morning some humidity condense on the cold surface of the soil. Another, much rarer, source of soil moisture is organic matter (Aldeias *et al.* 2016). We also mentioned (see figure 1b) that hydrate minerals like gypsum (dihydrate) are present in some layers of the Atacama Desert soil. These factors have to be kept in mind, because humidity in porous medium or hydration, even in low quantity, may have a significant influence on the thermal properties (see Appendix A) and strongly affects the thermal energy balance. As mentioned before, the numerical model used concerns only with dry soil; a humid model (EWGM: Evaporation in Wet Granular Media) recently developed in our laboratory (IPR), was not sufficiently tested to be used here.

## RESULTS

It is worth noting that our practice of diffusivity determination from hearth replication dissuades us from using blindly the experimental data. This is why this section has two parts: the first one allows deducing

important and useful information, which leads to some restriction about the application of the inverse method; the second one will present numerical results.

For each experiment, the radius of the hearth has been estimated from the colored surface after oxidation (after removing ashes and spreading some water on the soil, the heating zone appears more clearly). In the numerical codes, the configuration must be axisymmetric, therefore an equivalent radius of the heating is computed in such a way that it has the same area than the colored surface appearing after cleaning the hearth. Temperature used in the numerical model comes from one of the sensors, usually the sensor located just below the surface. On all figures (2a, 2b, 2c), continuous curves correspond to the measured temperature whereas dotted curves are built from the estimated thermal diffusivity computed by the global method GIP.

#### *Qualitative description*

Figure 2a shows the temperature curves of the first field experiment (FE-L1). Black dashed line is the temperature of the upper sensor, and we take its position as the reference depth  $z=0$ ; the reference level may be warped and corrugated, and this is an additional uncertainty. Colored solid curves correspond to other sensors, whose relative depth  $z$  is reported on the right side of the graph. Note that the sensors are not all located along the same vertical line (see Fig. 4b) but are arranged in a relatively small volume surrounding the central axis. As explained in the figure's caption, the dotted lines correspond to the best fit after a first try of the GID approach, using all the sensors and all the time range.

It appears that for three curves (red, purple and yellow), a discrepancy is observed between the experimental curves and their reconstruction; this discrepancy could not be explained by some heterogeneous layers in the soil, nor by a non-uniform heating by the embers. If this were the case, the curves of same color should be parallel. In our case, we think that this discrepancy reveals the presence of water, because (i) the slope of the temperature decreases before increasing again (this is reminiscent of the phase change behavior described in the appendix (A) and (ii) the weak slope jump occurs at temperature ranging from 70 °C (for the yellow curve) to 85 °C (for the red one). It may come from free water inside the pores or from hydrated minerals. In this case we know, from stratigraphic analysis, that some gypsum was present at a depth that ranges from 6 to 13 cm. The gypsum (dihydrate) lose water at a temperature close to 100°C to produce Bassanite (hydrate) in an

endothermic reaction. Consequently, we cannot treat this experiment by our inverse method GIP. However, we can check on figure 2a that the soil at  $z = -6.5 \text{ cm}$  is dried for  $t > 2.2 \text{ hr}$ ; therefore, the LIP is applicable for the second half time range, by using the three first sensors which are in the dry zone at this time.

In the third field experiment (FE-L3, figure 2b), the soil appears as dry but not strictly homogeneous: indeed, with respect to the simulated dotted lines, the orange and yellow continuous curves cross the dotted ones at some time; it may be due to a non-uniform initial condition in terms of temperature. Note also the strange behaviors of yellow and purple sensors; their temperature curves are not coherent. Though the purple sensor is located at a deeper position than the yellow one, the purple curve starts at a higher temperature than the yellow one and the two experimental curves cross each other after two hours. We think that it is a consequence of the heterogeneous thermal diffusivity of the soil.

The second field experiment (FE-L2, figure 2c) is quite different. An important remark concerns the orange and the green curves (for the sensors located resp. at  $z = -0.7 \text{ cm}$  and  $z = -1.0 \text{ cm}$ ). For the time ranges between 4 and 5.5 hr, the black dashed line representing the fire temperature increases but the orange and the green curves have like a plateau and begin to decrease before the black one. The only possible explanation is that the orange and green sensors are not located on the same vertical line that the black one (indeed the spatial coordinates measured by the theodolite indicates a horizontal shift of 6 cm). This indicates that the temperature of the fire was not uniform (due to the wind? or due to a non-uniform distribution of the embers?).

The behavior of thermograms, however, seems reasonable for all sensors, except the blue one, for the first half of the time range. Even restricted to this sub-interval of time, a closer inspection of the curves shows that the soil is not homogeneous. The fact that two curves (orange and green) are below the dotted curves of same color, whereas two other curves (red and purple) are above the corresponding dotted curves, indicates different values of the thermal diffusivity for the depth  $z = 0$  to  $-2.5 \text{ cm}$ , and for the depth  $z < -2.5 \text{ cm}$ . Estimation of the thermal diffusivity in each layer will be presented in the next subsection.

### *Quantitative estimations*

Hereafter are presented the numerical values of the thermal diffusivity, considering the restrictions pointed out for each field experiment. The results are summarized in Table 1 (only two digits have been retained, due to the uncertainties).

Table 1. *Summary of the values of the thermal diffusivity of the soil, estimated from three different field experiments at Quebrada Maní.*

Experiment #	Thermal diffusivity ( $m^2/s$ )	Remarks
FE-L1 2015-08-13	$2.7 \times 10^{-7}$	Upper dry layer of the soil (about 6 <i>cm thickness</i> ), containing gypsum: layer 1 of Fig. 1b.
FE-L3 2015-08-17	$4.4 \times 10^{-7}$	Upper layer of the soil (about 4 <i>cm thickness</i> ): layer 3 of Fig. 1b.
FE-L2 2015-08-15	$0.43 \times 10^{-7}$	Upper layer of the soil (about 4 <i>cm thickness</i> ): top of layer 2 of Fig. 1b.
FE-L2 2015-08-15	$41. \times 10^{-7}$	Lower layer of the soil (below 4 <i>cm thickness</i> ), containing salt blocks: bottom of layer 2 of Fig. 1b.

The first experiment (FE-L1) is treated by applying the LIP approach for the three upper sensors, for the second half-time range, as explained in the previous subsection. In addition to compute the thermal diffusivity, our numerical procedure provides what we call a normalized residue, which is closely related to the discrepancy between the temperature measured by the middle sensor and the temperature reconstructed by the inverse problem. The normalized residue is reported here using two different ways: an average and a maximum value over the entire time range; they are both presented in terms of percentage. For FE-L1, the agreement is acceptable (though not very accurate) and so we may take as a first approximation for the thermal diffusivity, noted hereafter  $\alpha$ :

$$\alpha = 2.7 \times 10^{-7} \text{ m}^2/\text{s}$$

$$\text{Normalized Residue (average)} = 2.7 \%$$

$$\text{Normalized Residue (maximum)} = 7.5 \%$$

Concerning the third experiment (FE-L3), we applied the LIP method to the three upper sensors only, because the two other sensors (yellow and purple curves) seem to be located in a heterogeneous part of the soil. We obtained:

$$\alpha = 4.4 \times 10^{-7} \text{ m}^2/\text{s}$$

$$\text{Normalized Residue (average)} = 1.2 \%$$

$$\text{Normalized Residue (maximum)} = 2.1 \%$$

Concerning the second experiment (FE-L2), five sensors have been selected for the inverse problem but, as the orange and green curves are very close (figure 2c), we discard the green one. Our previous discussion about this case mentioned a multi-layer soil, so we have to apply twice the LIP approach: one simulation for the first layer (using the three first sensors: black, orange and red on figure 2c) and another one for the second layer (using the three last sensors: orange, red and purple on figure 2c). We obtained respectively:

$$\alpha = 0.43 \times 10^{-7} \text{ m}^2/\text{s}$$

$$\text{Normalized Residue (average)} = 6 \%$$

$$\text{Normalized Residue (maximum)} = 9 \%$$

and

$$\alpha = 41. \times 10^{-7} \text{ m}^2/\text{s}$$

$$\text{Normalized Residue (average)} = 4.3 \%$$

$$\text{Normalized Residue (maximum)} = 7 \%$$

These results show that the upper layer has a very low thermal conductivity, whereas the lower layer has a much greater value; therefore, the soil is definitely very heterogeneous. This last conclusion is in good agreement with many pictures taken during the excavation of the soil, in particular those presented in figure 2d, where the presence of salt may affect strongly the diffusivity of the soil. Appendix B details the role of simple heterogeneity (layers of different thermal diffusivities) and the consequences about the estimation of the duration of the hearth. See also Fig. 4, which shows the distorted shape of the oxide sediment in the case of FE-L3.

## DISCUSSION AND CONCLUSIONS

Three field experiments were made in real situation (wood burning) to estimate the thermal diffusivity of the soil of the Atacama Desert (Quebrada Mani) using temperatures measured inside the soil during the heating process. These three experiments were located in the same area but not exactly at the same place. A first step consisted in applying blindly a global inverse problem for each whole experiment, keeping as many sensors as possible to reveal some defects of each experiment and to allow us to discard some measures. In a second step, a local inverse problem was applied to 3-sensor sets selected among the available sensors. This approach revealed the subsurface heterogeneity regarding its thermal characteristics. Overall, the estimation of the subsurface thermal diffusivity field in the Atacama Desert is a complicated problem and, for future analyses, the following factors should be considered:

- Presence of water, either free or in hydrated minerals (even small water contents may affect the temperature curves, and then lead to erroneous values of the thermal diffusivity, cf. Appendix A).
- Heterogeneity of the thermal properties of the soil (different structures, presence of salt, silt cemented with gypsum and anhydrite [*chusca*]). Heterogeneity restricts the use of the global GIP method and requires a great number of sensors to achieve meaningful results.
- Non-uniform temperature of the fire, neither in space (wood pieces positioning in the hearth) nor in time (wind activates part of the embers).

This interdisciplinary study is a contribution of physical sciences to archaeology site formation on hyper arid environments and beyond. It represents the first steps regarding time of residence and intensity of occupation in the settlement organization of early South American human groups, who colonized the Atacama Desert. The identified physical measured parameter on fire and hearth features requires, however, the combination of field and laboratory experiments associated to numerical physical simulations. In other words, this is the only way to get a satisfactory physical modelling, for interpreting field experimental results. Moreover, physical modelling allows also to suggest improvements in the measurement of field experiments. For example, for complex soils as those of the Atacama Desert, it is necessary to have a better control of the heating process during the experiments. The use of an electric heating plate could be considered. We can also conclude that measurements with an adequate number of well-located thermocouples are absolutely necessary to provide more accurate and useful information and data. This number should be larger as heterogeneity of the soil gets stronger. The characterization of the thermal behavior of the Atacama Desert soils shows clearly that the

values of thermal diffusivity can be much higher than that of dry but not salty, clayey or sandy soils. We suggest that future laboratory experiments should test whether some salts, in association with other factors like transitory humidity for example, could have a strong effect on thermal behavior of the soil.

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## APPENDIX A: ROLE OF HUMIDITY IN THE HEAT TRANSFER IN A SOIL

Laboratory experiments can be useful to understand how heat transfers occur in a dry or wet porous medium, and how the thermal properties are affected by humidity. They also allow the validation of some numerical codes based on simplified physical models. Moreover, laboratory experiments provide a way to improve field experiment processes. They give some insight on the priority information one should get with those experiments. Heat transfer by conduction in a homogeneous solid medium with constant properties is simple and has been modeled for a very long time (Carslaw and Jaeger, 1959). However, the case of a granular medium is more complex. Even if the pores contain only dry air, a first problem is to estimate the effective thermal conductivity. This property is strongly dependent on the structure of the grain pile and on the quality of the solid contacts between the grains. A second problem is the gas expansion during the heating because the gas thermal properties change a lot with temperature (for example, thermal diffusivity of dry air is multiplied by 4 between 25 C and 325 C). The case of a humid granular medium is even worse, especially when temperature reaches 100 C: liquid water entrapped between the grains may absorb an important part of heat energy to change from liquid to vapor, and the presence of vapor in the gas changes its thermophysical properties. Moreover, the presence of liquid bridges between the grains can increase dramatically the thermal conductivity (Smits *et al.* 2010; Canot *et al.* 2016).

To give a better insight, the results presented below show some typical behaviors of a heated soil. We have used here a very simple soil made of Fontainebleau white sand, which is quasi monodisperse (grains are more or less spherical, 200  $\mu\text{m}$  in diameter). This sand is used to fill a cylindrical box (30 cm in diameter, 30 cm high). It is heated by an infrared electric bulb (power 100 W), located inside an aluminum cylindrical foil (diameter 12 cm) in order to get a uniform infrared flux on the sand surface after multiple reflections. All has been done in such a way that the configuration is axisymmetric (see figure 3a).

Heating duration ranges from one hour to few hours, and temperature is measured by the way of thermocouples; these sensors are located under the sand surface and spread along the depth (see figure 3a).

## Dry case

For this first experiment, the Fontainebleau sand is stored for few weeks in a room having standard humidity (relative humidity about 40 or 50%) and actually the equilibrium state implies that some water vapor condenses inside the porous medium (Kelvin equation effect), but this water quantity is extremely small. However, there is no apparent internal cohesive forces because the sand can easily flow through the fingers when we take it in our hand, therefore we consider it as dry. The aluminum reflector has been put in contact with the sand, as shown in Figure 3a. On figure 3b, temperature curves are always strictly increasing, with smooth variations, because the heating is constant; in particular the slope of each curve must be continuous, without any break.

## Humid case

To prepare humid sand we mixed water and dry sand, but this is not so easy, especially when the water content is very small. In our case, water is spread in small quantities at the surface of the sand, by using an appropriate spray device, and we alternate that with a manual mixing of the sand. We put this humid sand in our cylindrical box and packed it layer by layer using a flat plate with a constant vertical force. The box filling procedure is very important, because the humid sand can contain a great quantity of small air pockets. This packing procedure is not perfect but we think that most of the air pockets have been removed. The initial theoretical ratio of liquid volume to pore volume (called water saturation) can be predicted by use of simple formulas, knowing the initial volume ratio of water to sand on one hand, and the measured solid fraction of our dry sand (0.62) on the other hand. By measuring the humidity of some samples (we weight humid sand, dry it in an oven, and weight again the dried sand) we found a water saturation of 8% instead of the predicted value of 10% (this discrepancy comes mainly from the variation of the pore volume during the process).

In this experiment, the aluminum reflector has been moved up from the sand surface by a distance of 1 *cm*, in order to allow a good escape of the water vapor out of the cylindrical reflector.

On figure 3c, many curves (green, light blue, orange ...) present a slope decrease followed by a slope increase; this is typical of phase change, and is due to energy absorption (latent heat) to change liquid water into vapor. Usually a sudden slope jump is observed during phase change in the saturated case (Muhieddine *et al.* 2009). Here, the fact that the water content is always small leads to a weak jump, smoothed by the fact that water liquid bridges are disconnected, allowing the vapor to move and diffuse easily in the porous medium (Min and Emmons, 1972).

The upper curve (the red one) records the temperature at the surface of the sand; the perturbation of the values comes from air displacement in the experimental room.

It should be emphasized that, as opposed to the saturated case ( $S=100\%$ ) or the pure Stefan problem, the slope jump observed on the temperature curves don't occur at  $100^{\circ}\text{C}$ , which is the vaporization temperature of water at atmospheric pressure. Here, the strong shift in temperature vaporization (on figure 3c, the slope break occurs from  $35$  to  $50^{\circ}\text{C}$ ) is related to the very small size of the concave liquid bridge between the grains: due to the Kelvin equation (Bohren and Albrecht, 1998), the presence of a strongly curved interface modify the temperature of vaporization, for a given pressure.

Anyway, the presence of a true plateau at  $100^{\circ}\text{C}$ , or a pseudo plateau at lower temperatures can be related to the presence of water inside the porous medium (Min and Emmons, 1973).

## APPENDIX B: THE EFFECT OF A LOWER LAYER OF HIGHER THERMAL CONDUCTIVITY

We have seen, at least from the field experiment FE-L2 that strong differences in local values of the medium conductivity may occur. In the case where a deep layer of higher thermal conductivity, located below the sensors, exists this can lead to dramatic behavior. Figure 5a shows the results of simulation when a deep layer (here for  $z < -2$  cm) has a great thermal conductivity: the different curves present the temperature profiles for different values of the deep layer diffusivity  $\alpha_d$ , without change of the upper layer diffusivity  $\alpha_u$ . It shows that the temperatures in the upper layer depend strongly of  $\alpha_d$ , it shows also a shift of the depth of the altered layer (here, constant temperature of 290 C).

In figure 5b, we show that the presence of a more conductive deep layer can lead to big errors for the time duration estimation. This is because the oxidation limit grows slowly with time in the central part: this means that a small error in the oxidation thickness leads to a great error in the duration estimation. For example, here, the time duration goes from 6h to 18h when  $\alpha_d$  varies of a factor 10, which is much less than the factor 100 observed in experiment FE-L2.

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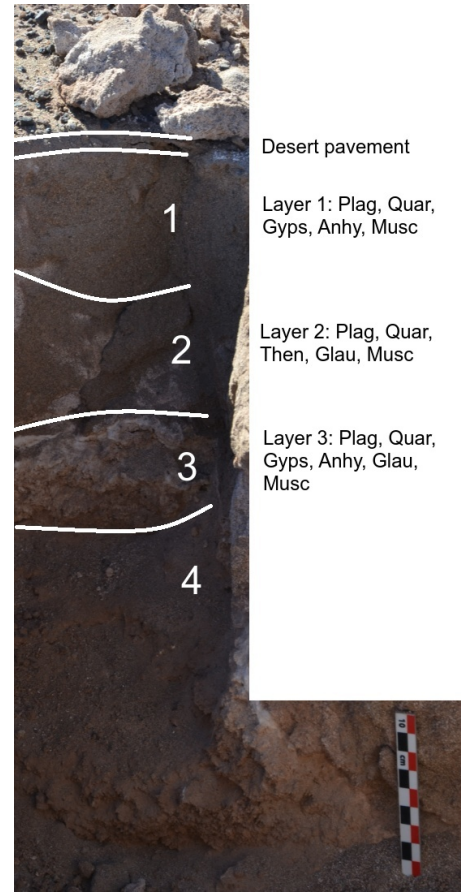
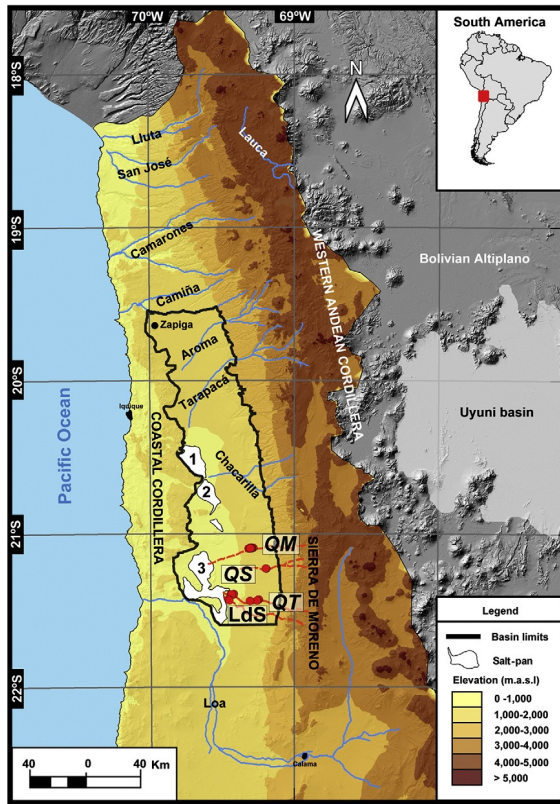


Figure 1a (left): Location of the archaeological site. The Quebrada Mani 12 site is indicated by the QM annotation on the map.

Figure 1b (right): Stratigraphic view of the soil (scale given by the colored ruler). Layer #1 is very loose (like sand), whereas layer #2 contains a mixture of loose sediment and salt blocks; layer #3 is the stiffest one, very difficult to dig; layer #4 is not described in this paper. Most frequent minerals are reported on each layer (Bastos, 2018), using the following abbreviations: Plag = **Plagioclase**, Quar = **Quartz**, Gyps = **Gypsum**, Anhy = **Anhydrite**, Musc = **Muscovite**, Then = **Thenardite**, Glaub = **Glauberite**.

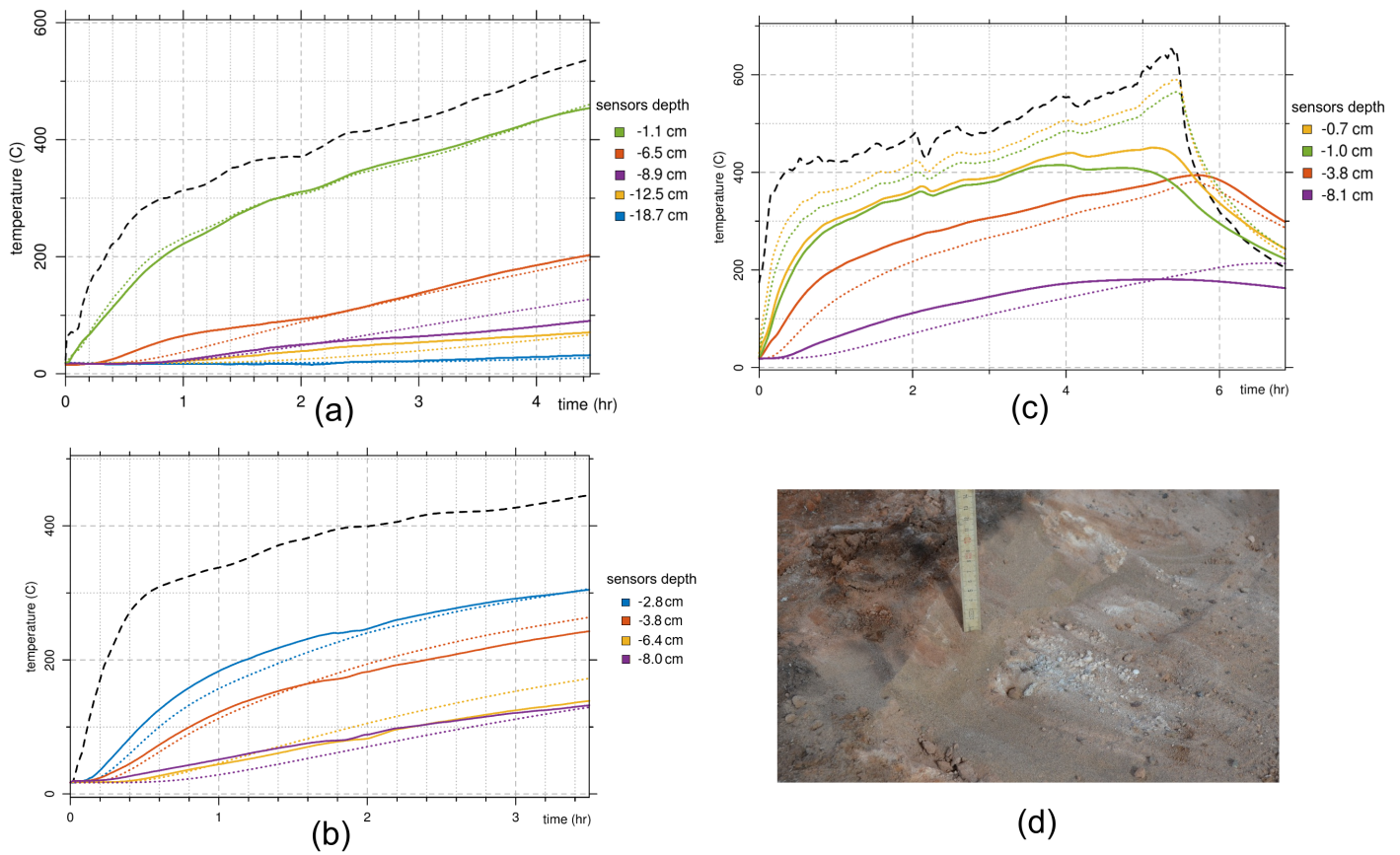


Figure 2: Field Experiments FE-L1, FE-L3 and FE-L2 (resp. in a, b, c locations). The black dashed line is the temperature of the fire. Colored solid curves are the experimental temperatures, whereas the dotted curves are reconstructed temperatures after the global inverse problem (GIP). The picture in (d) shows that white fragments during excavation of hearths may indicate the presence of some salts.

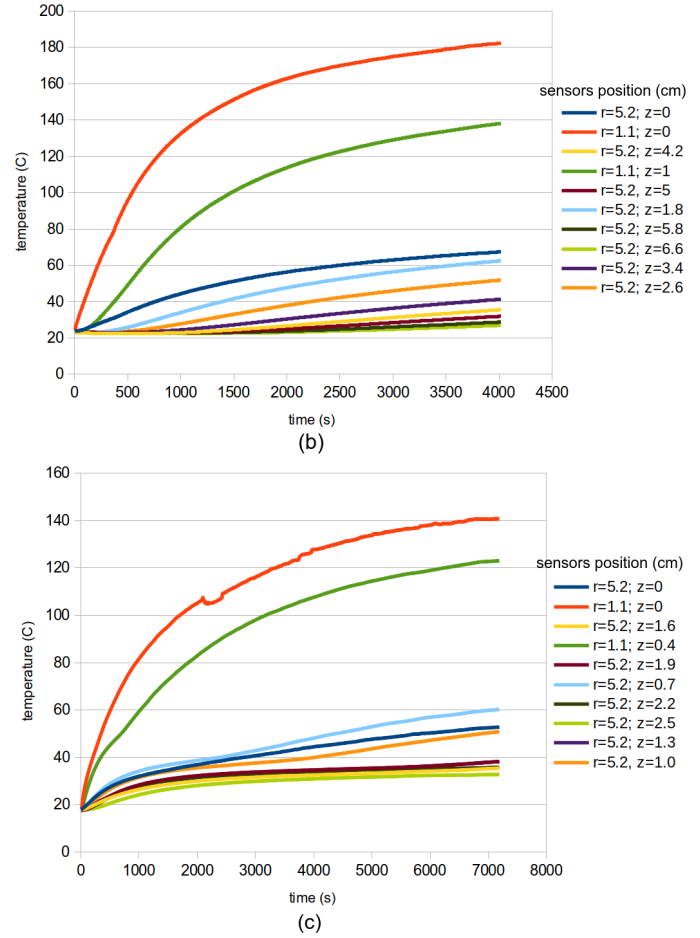
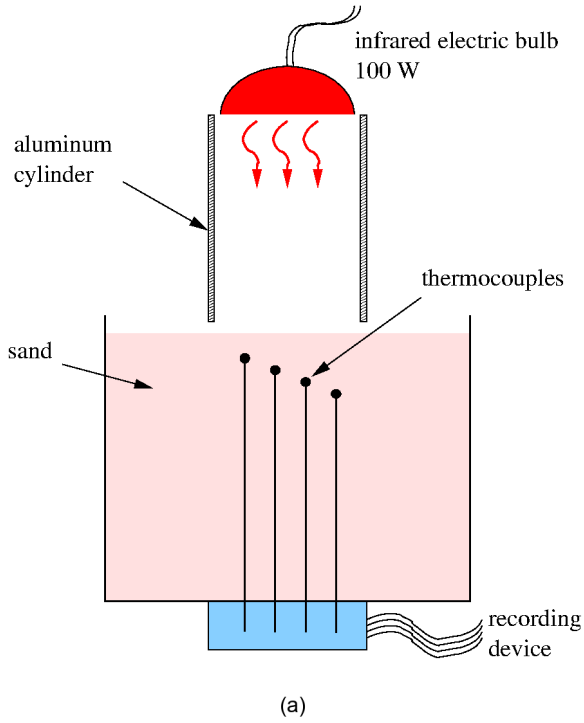
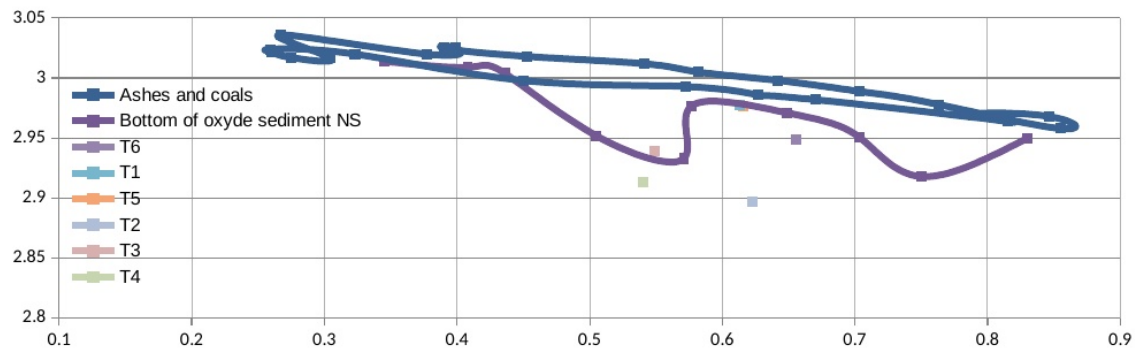


Figure 3: (a) Sketch of the laboratory heating device. The multiple reflections of the IR rays inside the aluminum cylinder produces a uniform heat flux at the surface of the sand. The sand box and the heating are both axisymmetric. On right: Laboratory Experiment #1 (LE#1, above) and #2 (LE#2, below). Temperature versus time, at different position (cm) in the sample. Dry sand (b) or humid sand (c) with saturation  $S=8\%$ , heated by a constant flux infrared device. Curves are typically smooth in case (b), but may present an inflection point (c), related to the evaporation of a low water content in the sample.



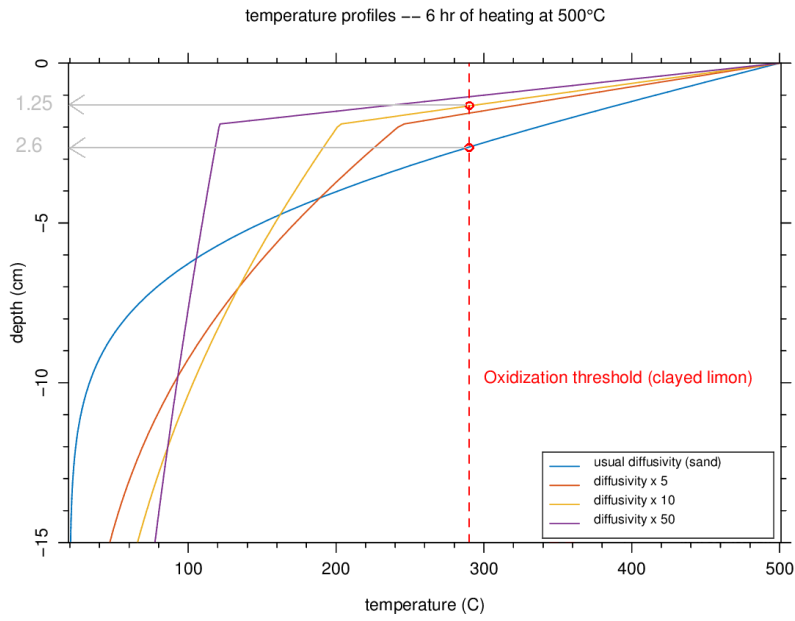
(a)



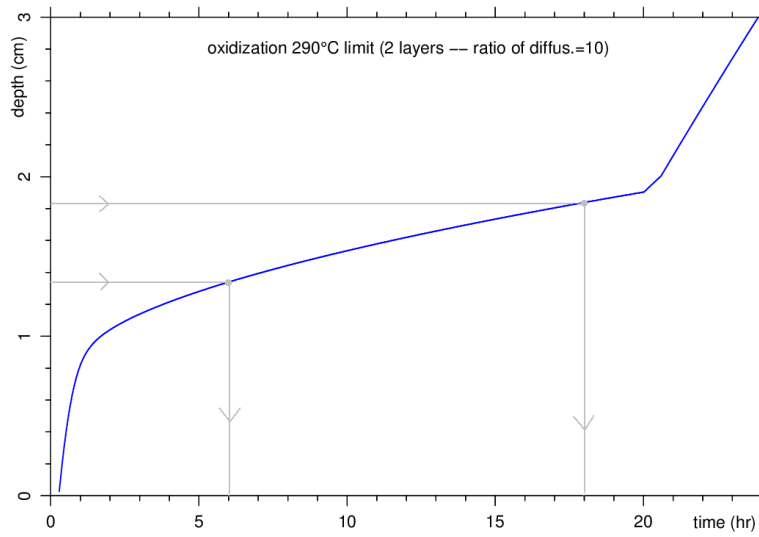
(b)

Figure 4: (a) Picture of one typical cut of the soil after excavation (FE-L3). Colors reveal oxydation of the sediment and the cut shows clearly the strong heterogeneity of the soil.

(b) Measurement of the position of the top of the soil (after removing ashes and coals), and the bottom of the oxidized layer. Position of six thermocouples are also shown. Lengths are reported in meters.



(a)



(b)

Figure 5: (a) Influence of the presence of a deep layer more conductible than the upper one. Temperature profiles are simulated for various values of the diffusivity. (b) Possible uncertainties in the estimation of the fire duration, in the case of a more conductive deep layer (same as a). A 4 mm error in the measure of the altered zone gives a large range for the fire duration estimation.