Benefits of an accurate 3D Documentation in Understanding the Status of the Bronze Age Heritage Cave "Les Fraux" (France)

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Abstract

An interdisciplinary team of archaeologists, surveyors, environmentalists and archaeometrists has jointly carried out the study of the Bronze Age “Les Fraux” (Saint-Martin-de-Fressengeas, Dordogne, France) since 2007. This archaeological decorated cave, registered as a French Historical Monument, forms a wide network of galleries, characterized by the exceptional richness of its archaeological remains such as ceramic and metal deposits, parietal representation and domestic fireplaces. This cave is the only protohistorical site in Europe wherein testimonies of domestic, spiritual and artistic activities are gathered. This project has been labelled by the Institute of Ecology and Environment of the French Research Council (CNRS), who wants to promote new methodologies and experimental studies in Global Ecology. Accurate 3D models of the cave constitute the common framework for the different partners. We present in this paper an overview of methods of data recording based on contact-free measurement techniques in order to acquire a full 3D-documentation of the site. Different techniques based on Terrestrial Laser Scanning, Digital Photogrammetry ad Spatial Imaging have been used in order to generate geometric and photorealistic 3D models from the combination of point clouds and photogrammetric images, for both visualization and accurate documentation purposes. Various scales of acquiring and diverse resolutions have been applied according to the subject, e.g. global volume of the cave, parietal representations, and deposits. Measurements from an original method of 3D indoor magnetic field recording are combined with the 3D models in order to locate magnetic anomalies in the cave. All the surveys are conducted in compliance with the integrity of the site.

1. INTRODUCTION

This paper deals with 3D reconstruction and visualization of the exceptional heritage site « les Fraux » in which new methods of data acquiring based on contact-free measurements techniques have been improved in order to acquire a full 3D-documentation without damaging the underground anthropic network, registered in the French Historical Monuments. The purpose is to present experiences and a selection of results gained during the recording of the cave. In this study we propose to explain the recording methodology applied on this site since 2007, as part of a interdisciplinary and multiscale approach. Besides, main methodological key issues faced will be exposed.

2. ARCHAEOLOGICAL AND SCIENTIFIC CONTEXT

The Bronze Age cave of "Les Fraux" is located in the South-West of France in the "Périgord-Limousin" Regional Natural Park, precisely in the commune of Saint-Martin-de-Fressengeas (Fig. 1). The cave is the most important Bronze Age wall art site in France. It is considered as the "Lascaux" of the Bronze Age. It forms the only protohistorical site in Europe wherein testimonies of domestic, symbolic, ritual and artistic activities are gathered in the same place, while there is no evidence of funeral vocation.
The cave forms a wide underground network of narrow horizontal galleries of more than 1km (Fig. 1, 5). It is characterized by the exceptional richness of its archaeological remains such as many ceramic and metal deposits (Fig. 2, 3), numerous parietal representations and clues of domestic occupations (Carozza *et al.,* 2009). Fortunately, the cave has been closed at the end of the Bronze Age, following to the collapse of its entrance. This collapse preserved intact the archaeological remains until today. After closure, the site was accidently re-discovered in 1989. Following its expertise, which highlighted its extraordinary archaeological and heritage interest, the cave registered in the French Historical Monuments in 1995. According to the French Office of Geological and Mining Research (BRGM), the cave may unfortunately collapse in the coming years. Therefore, the cave has been sealed off to the public and access is now severely restricted.
Based on radiocarbon dating and archaeological investigations, the cave appears to have been used by humans during nearly 3 centuries, from the middle to the final Bronze Age (1450-1150 BC). It is highly probable that the site has been occupied during numerous short but regular periods during this interval. There is no evidence of human occupations before the Middle Bronze Age, nor after the final Bronze Age. Multiple lines of evidence indicate the presence of bears before human occupation: the soft clay-like walls of the cave retained the paw prints of cave bears and we identified some depressions that are believed to be the nests where the bears slept.
The Bronze age occupations, which concerned nearly 70% of the sections of the cave, left the remains of very well preserved archaeological soils, domestic facilities (such as stairs dug into the clay, torches and post holes) together with about sixty domestic fireplaces and twenty four clues of hearths, mostly used for their function of lighting and baking. The same galleries left thirty two ceramic and metal deposits which are organized with domestic whole or incomplete used objects (Fig. 2). By the way, it is interesting to note that some ceramics are coated with charred remains of animal butterfat (Fig. 3). Analyses revealed that these potteries have been used to cook dishes containing meat and fat, long before their deposition. Most of the deposits (18) are organized in a visible or showy way, however some others are intentionally masked behind stones or fallen pieces of walls (14). Often, deposits are staged under decorated panels.
Work in progress has revealed that the cave contains, amongst other evidence of Bronze Age life, many manmade depictions on the wall and the ceiling, perfectly preserved (Fig. 9). There are thousands graphical entities but art is not highly varied. Most of the wall art discovered in the cave is fingered or engraved in the clayey and follows linear, schematic and geometric design. There are no figurative images, but geometrics signs, sometimes organized in panels. Some sections of the cave present an almost uninterrupted distribution continuous of patterns, drawn in a random composition. People (or artists) who produced these parietal representations used several ornamental techniques as fingerings and engraving (essentially), but also painting, slip… In some place, patterns has been engraved by using a metal or wooden tool on the soft clayey surface of the rock. Somewhere else, one, three or four fingers were deliberately pressed several times onto the watery clay of the wall and moved vertically, horizontally or obliquely, forming sequential unexplained patterns. All available evidence suggests that wall art should be assigned to the Middle Bronze age period. 14C method has been used to estimate the age of a charcoal found in a pattern of a decorated panel. It is worthwhile at this stage to consider that we have no idea of the meaning of the cave depictions. Explanations remain largely speculative (artistic expression, narrative support, fetish or religious practice, proto-pictogram, utilitarian function…). The difficulty is when the culture and its traditions (responsible for the art) have disappeared for a long time.

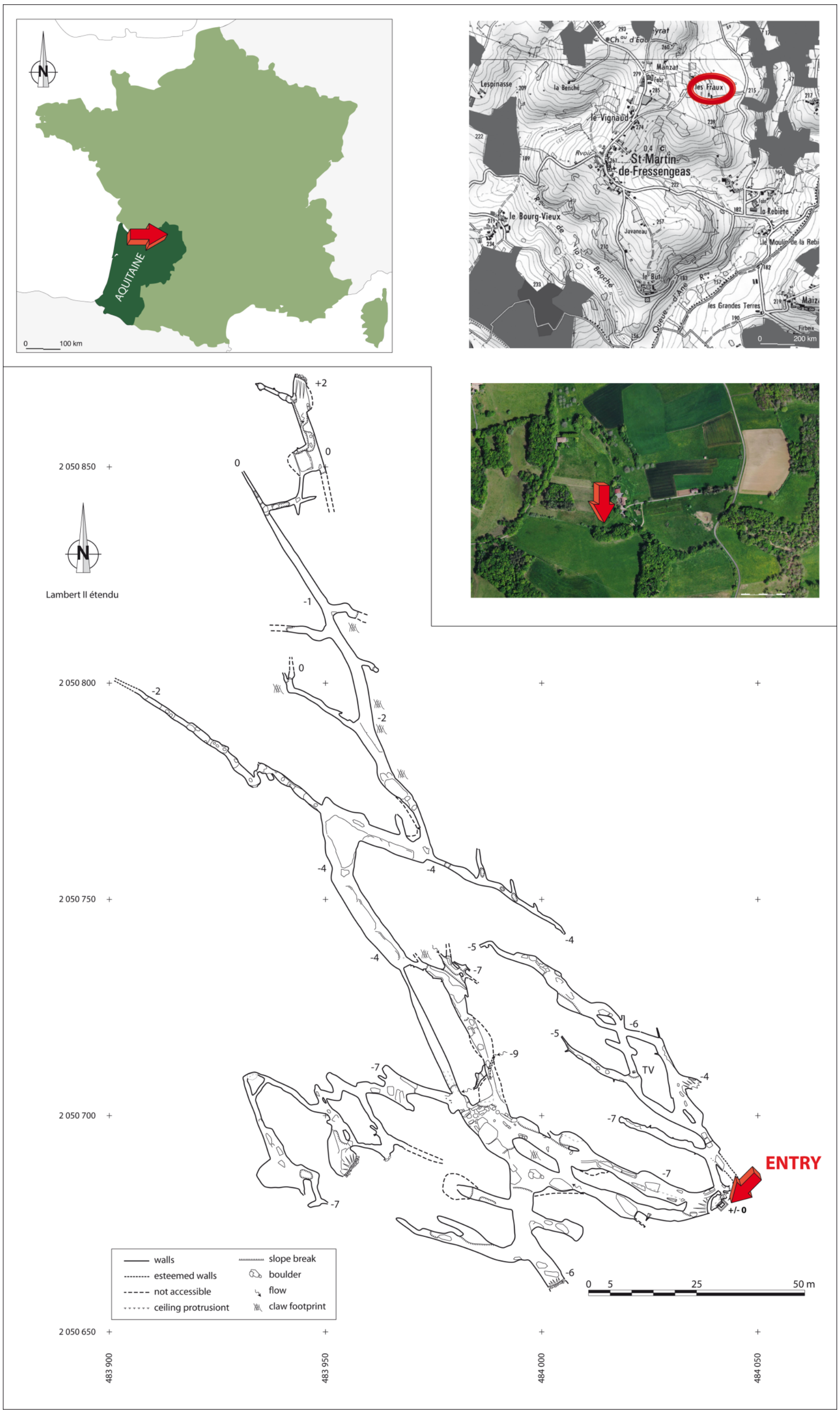

Fig. 1: Location of the Bronze Age cave of Les Fraux (Saint-Martin-de Fressengeas, Dordogne, France) and map of the underground network (survey: Y. Billaud 2013).

It must be kept in mind that the cave of Les Fraux is a unicum in Europe, as that there are no another examples of sites gathering together Bronze age wall art, ritual deposits and remains of domestic occupations. When comparing the site with other French Bronze Age caves, there are several similarities, but mainly distinct differences (such as the absence of wall art or the almost systematic attendance of funeral vocation in association with deposits).

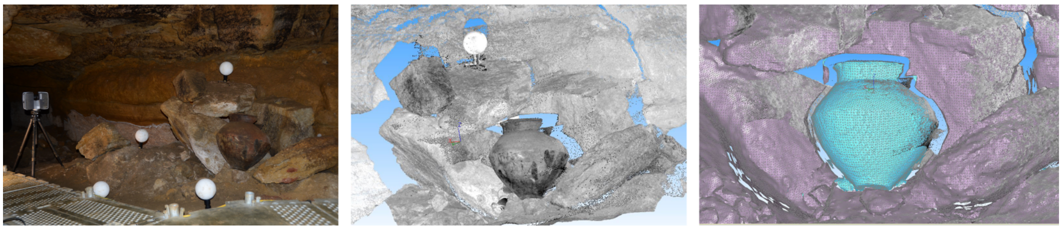

Fig. 2: 3D-recording of a Bronze Age ceramic deposit from the cave (using the FARO Focus 3D). Center and right: visualization of the deposit from the point cloud.

The difficulty is in understanding the unusual (practical versus symbolic) status of the site: domestic occupation, worship place or sacred place? In our point of view, the only way to solve this problem could be studying the cave by using an integrative and interdisciplinary research, which preserves the integrity of the site and promotes non-invasive techniques of study with contact-free measurements, thanks to a common work support: 3D documentation.

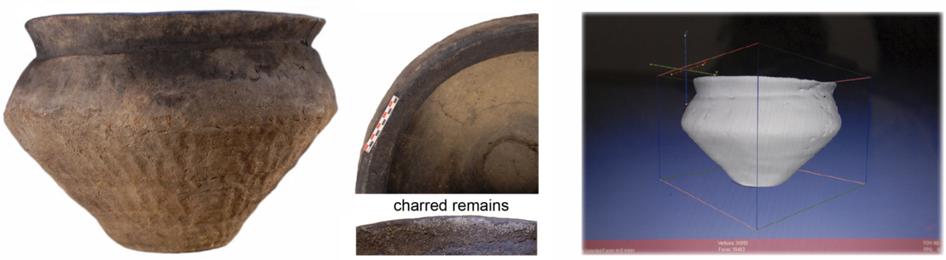

Fig. 3: 3D-recording of a Bronze Age ceramic from the cave, coated with charred remains of animal butterfat.

That is the reason why, since 2007, a multidisciplinary project is bringing together different specialists for the surveying and recording, excavations, recording of parietal art, setup of magnetic field measurements. The study in progress takes place in a new kind of tool founded by the CNRS’ Institute of Ecology and Environment. The purpose of this observatory is the promotion of new methodologies and experimental studies in Global Ecology and the analysis of interactions of Bronze Age societies with their environment. These interactions are studied by analyzing the alternating phases made of strong anthropic constraints and steps back to natural functioning. The remarkable state of the cave is an invaluable asset to the study these interactions. Our aim is the interpretation of archaeological data for the development of studies combining time and space (paleo-environment, archaeometry, geochemistry, laser scanning, 3D modelling...), in an approach where all stages of the research are integrated, from data acquisition, implementation of protocols of observations, experimentation, or simulation until restitution. In that framework, 3D models of the cave constitute the common work support and the best way for scientific communication for the various studies conducted on the site by nearly forty researchers and students. In this peculiar context, a partnership among archaeologists and surveyors from INSA Strasbourg allows the team to develop, in an interdisciplinary way, new methods of data acquiring based on contact-free measurements techniques in order to acquire a full 3Ddocumentation for the whole structural elements of the cave and the archaeological remains (Grussenmeyer *et al.,* 2010; Burens *et al.,* 2011, 2013). This work is conducted in compliance with the integrity of the site which must be preserved in a Heritage order: it is essential that archaeological soils, ceramic and metal deposits, fireplaces, engravings walls and fingerings remain intact in the cave. Neither remains should be handled or get out of the site: they have to be studied, registered, measured and drawn in situ, without any contact, or in the basis of 3D-models. This requirement has a very important impact on how to study the site and on the data acquisition conditions. Working with non-invasive techniques like contact free measurement of ceramic deposits and parietal representations is really challenging.

3. METHODOLOGY

It comes to no surprise that nowadays main projects dedicated to the recording of archaeological caves combine terrestrial laser scanning and close range photogrammetry (Lerma *et al.,* 2009; Gonzales-Aguilera *et al.,* 2009). These techniques not only yield to drawings such as sections and elevations, but also to photo-realistic perspective views and visual navigation worlds in 3D environments. Since 2007, work in progress in the cave involves different techniques based on Terrestrial Laser Scanning, Digital Photogrammetry and other Spatial Imaging Systems, in order to generate a geometric and photorealistic 3D model of the whole structural elements of the cave and archaeological main artefacts (Fig. 4, 5). This model is determined by the combination of point clouds and photogrammetric images, for both visualization and accurate documentation purposes. It is conceived as a common research tool, usable by all partners of the scientific and multidisciplinary team. By the way, our approach is based on the complementarity of data, which are produced by the different scales of 3D recording used in the cave: global volume cave, parietal representations, and deposit. In this study we showed evidence that it is possible to merge together, in the same depiction system, several roots of information as it is shown in the recent work conducted on magnetic field mapping. Furthermore, we wanted to test innovative and experimental approaches combining photogrammetry and terrestrial laser scanning, including for parietal works (photorealistic rendering). For the archaeologists, the documentation and recording work shall contribute to the accurate indexing and georeferencing of the whole set of surveys and images of the remains, collections as well as structural elements and relief drawings acquired in the different parts of the cave. Furthermore, another purpose of the recording is to deliver data and models in formats that can be handled by most of the partners involved.

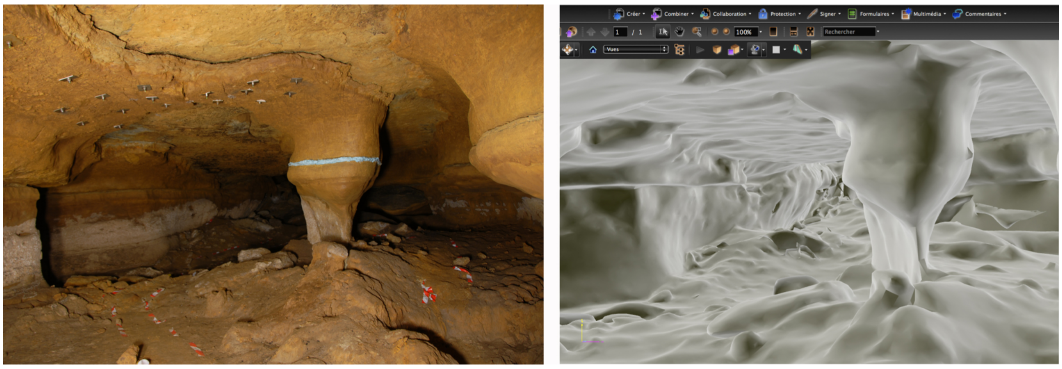

Fig. 4: Picture of the sector 13 of the cave (on the left) and 3D model of the same gallery in PDF 3D format (on the right).

3.1 Overall 3D-recording of the cave's structural elements

The overall recording of the cave by terrestrial laser scanning was our first goal since it ensures the georeferencing of any type of object, image or measurement and an accurate indexing compatibility of the data between the researchers involved in the project (Fig. 5).

The study began with the consolidation of the topography and the creation of a polygonal network inside the cave thanks to a total station. This network is connected outside by several geodetic points measured by differential GNNS techniques. All the data was recorded in the French Geodetic Reference System (RGF93). First TLS campaigns were done with the FARO Photon 120 scanner, which was well adapted in the middle underground passage. Since 2012, data acquisition has been performed using a FARO Focus 3D. The expected accuracy of both scanners is about 2 to 5 mm at 25 m. Spheres and targets have been used for the registration of the point clouds and the georeferencing (Fig. 2). The scanner is translated along the galleries and an overlapping area between two stations is routinely provided (for the details of the recording methodology by TLS, the reader can refer to Grussenmeyer et al., 2010a et b). One TLS station requires about 7min for forty Million points. The distance between the stations varies between 2m to 5m depending on the complexity of the cave sections. More than 430m of galleries have approximately been recorded at this stage. This required more than one hundred stations and 24 days of recording in the cave. If we consider a point density of 1pt/mm, each meter provides approximately 10 Mo points. The post-processing work and the merging and georeferencing of the point clouds have been thoroughly processed by B. Cazalet, V. Léglise, E. Moisan (Master students from INSA Strasbourg). Handling data from multiple stations requires a resampling of the point clouds, saved in ASCII format and afterwards imported and merged into a uniform point cloud. Georeferencing of the individual point clouds avoid a time-consuming consolidation step. The need to facilitate the exchange and dissemination of data within the team led us to export the global 3D model of the cave, resampled at 1 pt/cm, in PDF 3D format (Fig. 4). This format allows as well some measuring functions and toolkits (distances, sections, etc.) and visualization options such as wireframe, shaded, solid, vertices, etc. Incidentally, the team is actually working on the 3D-recording of ceramic deposits placed along the galleries using FARO Focus 3D. Work in progress has revealed that the 3D-model thereby obtained and transformed in PDF 3D allows us to draw, measure and define the section and the typology of every ceramics without any contact. It is worthwhile at this stage to consider that this approach is not relevant for unattainable deposits (pottery almost entirely hidden in rocky chaos for instance). But that kind of contactless study prevents all technological analysis.

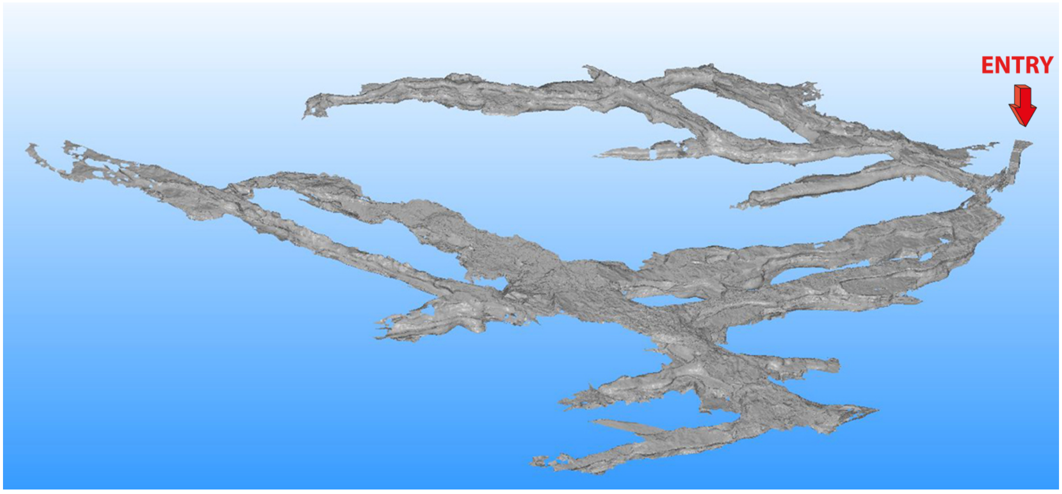

Fig. 5: Global 3D-model of the underground network of the cave. Data are recorded in the French Geodetic Reference System.

3.2 3D magnetic field mapping

Among the various methodological developments conducted in «Les Fraux», the «magnetic field mapping» project , which is managed by F. Lévêque (AIR program; CPER University of La Rochelle), is particularly interesting in terms of 3D modelling (Lévêque *et al.,* 2010). Indeed, it succeeded to merge together, in the same depiction system, several roots of magnetic, topographic, archaeological information. On outdoor archaeological sites, cartography of local distortions of the earth magnetic field (generated by thermal impact on soil or sediment for example) allows researchers to try to locate ancient fireplaces (visible, or not) or other structures. For the first time,

F. Lévêque and colleagues have adapted successfully this technique of magnetic survey to underground network (Fig. 6, 7).

Fig. 6: Protocol of 3D magnetic prospection in the cave of "Les Fraux". Left: in 2011, sensors (white cylinders) were moved by the hand of the operator. The 360° prism reflector (located between the both sensors) allowed us to obtain a geolocalization of the measurements by the tracking method of the total station (in the back of the picture). Right: In 2012, a better control of the space covered was obtained thanks to a device made-up with a telescopic pole fixed on a tripod.

The very complex topographic configuration of the underground galleries required a full 3D acquisition protocol (instead of the usual planar acquisition protocol) together with higher resolution. All the rocks interact more or less with the earth magnetic field, depending of their nature and their thermal history for example. The situation is different when working outdoors, because the local variation of the magnetic field decreases going upward. In caves, the cavity generates a deformation of the local magnetic field, often in the range of a metric scale, which intensity depends on the nature of the rocks. Moreover, the micro-topography, such as the roughness of the blocks on the soils or the walls, generates variations of the local magnetic field in the decametric or centimetric range. Thus, the interpretation of the local variation of the magnetic field requires to clearly identifying the source of an anomaly (i.e. the highest or the lowest values of intensity of the local magnetic field, generally coupled due to the inclination of the local earth magnetic field). In order to be able to distinguish topographic effects from fire impacts, both magnetic and topographic information are merged in the same 3D-model of the cave. Therefore, each variation of the magnetic field intensity is represented by a colour scale, in a space divided in elementary volumes (voxels) (Fig. 7).
Measurements of magnetic field are recorded using a dual sensor magnetometer coupled to a 360° prism reflector (10 measurements/s ongoing). Geolocation of measurements is ensured by tracking with a Trimble S8 total station following the 360° prism. In the previous surveys, the sensors were held by hand and moved in the area of study. This protocol did not provide a homogeneous density of measurements due to the irregular path followed by the operator. In order to obtain a better and regular survey, the sensors movements are control mechanically with a pole. The whole equipment is hanged at the end of a telescopic boom pole and fixed on a tripod (Fig. 6). It becomes thus possible to cover a volumetric space up to 5 meters from the operator, allowing measures in areas made of complex topography (Fig. 8) or access limited due to very high preservation constraints.

Interpretation of the data is currently limited to a comparison of the location of magnetic anomalies compared with volumes of the cavity obtained by laser scanning. Standard physical models developed to identify magnetic objects for surveys carried outdoors are not applicable for the analysis of cave's data. In fact, these physical models are based on a simplification whereas the measures are carried out strictly above sources. Thereby, this assumption is not valid for caves. Lack of a physical model applicable to caves makes difficult to achieve the representation of the results, especially as the final desired representation is 2D.

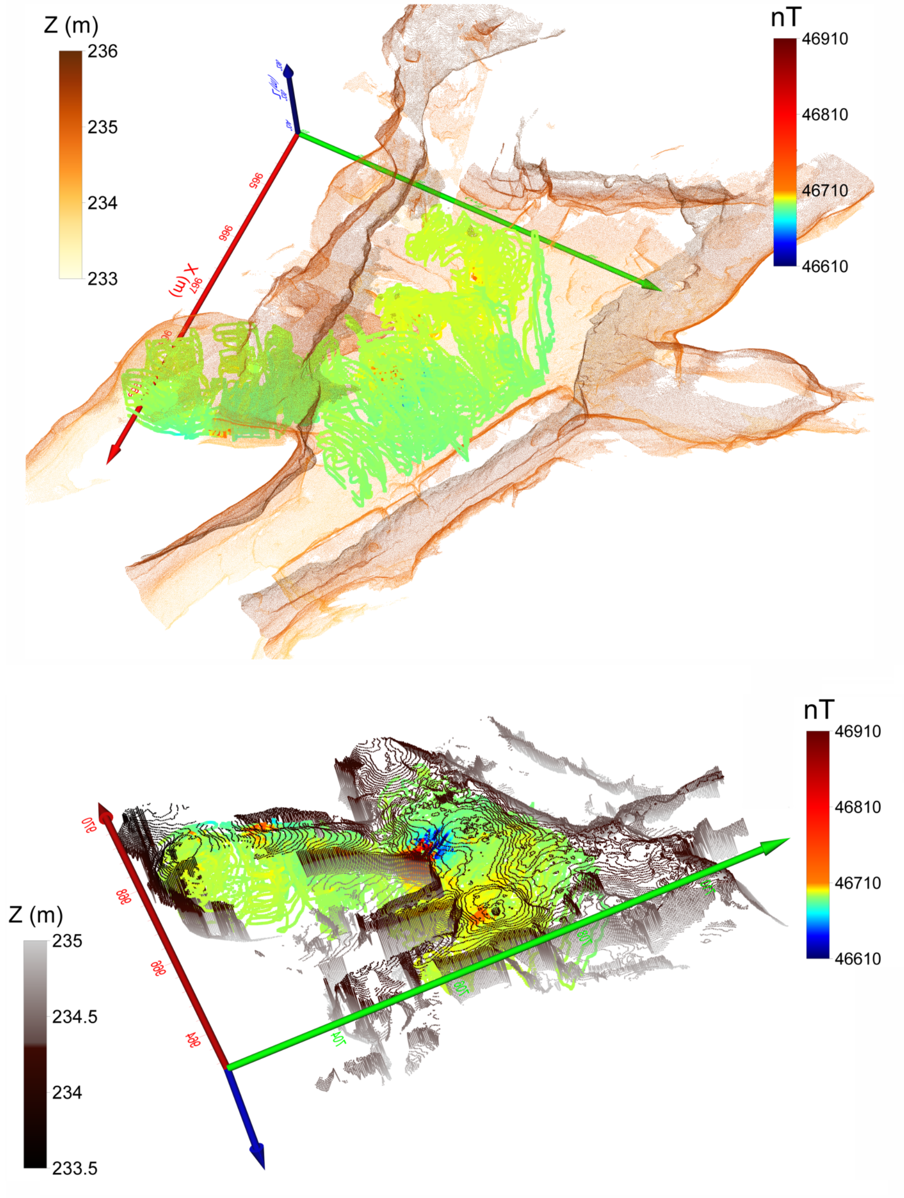

Fig. 7: Views of the results obtained in 2011 for the sector 29 of “Les Fraux” cave, thanks to the first device. Top view: the topography is provided with approx. 1 point for 1 cm. Elevation (Z) is represented in a colour scale. The roof of the cave is cut horizontally. Some high and low values of the magnetic field intensity are viewable through the point cloud. They correspond to bottom points. Bottom view: the cave topography is represented by a contour map (oblique bottom view). High and low intensity values reflect the presence of clayed material which has been heated above 200°C.

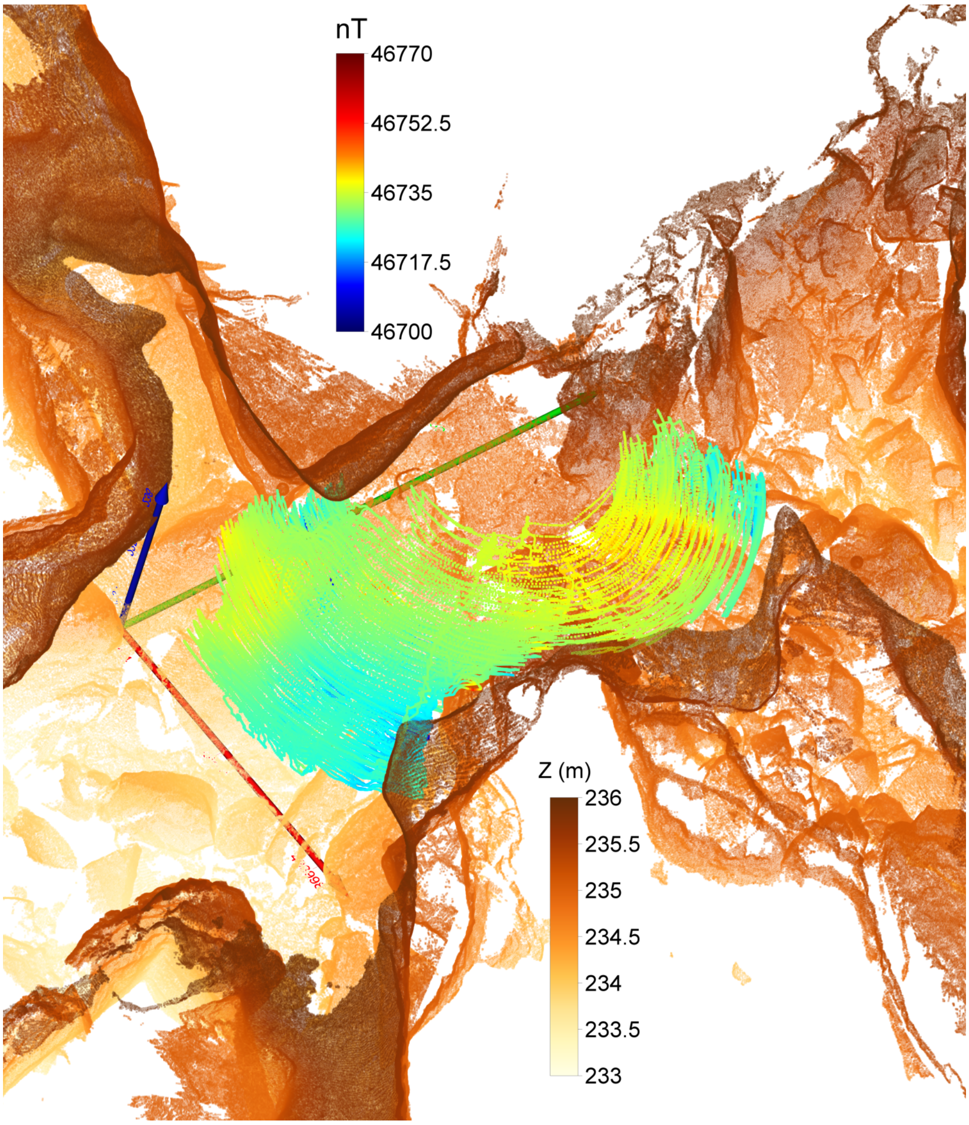

Fig. 8: Results obtained in 2012 for the sector 40 of the cave. View showing the magnetic field intensity point cloud and the topography of the cave's walls, merged together thanks to a telescopic pole device. Same condition as figure 7. Both density and regularity of spatial distribution of the magnetic cloud is increased. Contrary to the gallery represented on the figure 7, the top of the magnetic cloud presents large variations induced by a more complex topography.

3.3 Photorealistic rendering

In archaeological caves, parietal representations studies require the processing of very high definition images (El-Hakim *et al.* ,2004 ; Fryer *et al,* 2005), in a more accurate scale from that usually used for the volume of the underground network. A common solution is the correlation between high resolution digital photographs of panels and 3D volumetric model of the cave.

The aim of the experimental work which is developed in « Les Fraux » since 2008 is to find an interface between the 3D imaging methods and the photographic and manual works of parietal art specialists. That method allows a better reading and superposition of the archaeological tracings (relative chronology), analysis of the section of tracings and nature of the impacts on the rock, as well as identification of tools by their stigmas. This is not a view shared by everyone, but the generalization of parietal representations' drawings using orthophoto based on the 3D-model (Fig. 9) should be very useful for archaeologists.

In the cave "Les Fraux", the team wanted to test the simultaneous acquisition of the 3D model coupled with the digital shots and automatically georeferenced by the Trimble VX Imaging Total station equipped with an internal camera (unfortunately limited to 3,2 Mpixels).
The recording of point clouds with a Faro Photon 120 laser scanner equipped with a Nikon camera colour kit was not either considered satisfactory since it was not possible to change the camera settings during the automated recording process of the images. As a result, we were unable to process automatically the produced photographs.
In 2010, we took a series of very high resolution digital images of a large clay panel, using a Canon EOS 5D equipped with 85mm and 20 mm lenses and mounted on a panoramic pan head, in order to realize accurate panoramas views with a pixel size in the object below 0,5 mm. The camera tripods were placed at two different locations in front of the clay panel. The exterior orientations of the different photographs of the panoramas were processed in a photogrammetric bundle and imported in the point cloud processing software in order to get a very accurate colored point cloud and meshed model. The same area has been scanned at several times and different angles to overcome the problem of incidence of the laser in order to fill the holes of the model. The georeferencing of these very accurate point clouds has been obtained after registration with the global 3D model of the cave. The use of this generation of point cloud is undoubtedly a methodological advance.
Finally, we decided the same year to get down for the first time in an archaeological cave the latest generation of a Faro ScanArm V3 (19 200 points/sec and 0,035mm accuracy). The exceptional quality of the acquisition of this point cloud is due to the accuracy of the FARO fusion arm and the laser V3 head maintained by the operator at a few centimetres of the object during the time consuming recording (Fig. 9). This new equipment, providing sub-millimetre resolution, has enabled the team to carry out experimental work on identifying the various techniques used and tools used to achieve the decorated panels. The study is conducted on several panels of the cavity and their experimental duplicates (made of clay materials using a wide range of tools: flint, bone, bronze and copper spikes, dry wood, freshly cut branches, fingertips, etc.). The objective is to discriminate different techniques as fingering, engraving, or etching from the traceology. The flexibility of the ScanArm was able to record the bottom of the prints and the finest carvings, including oblique ones. We afterwards want to compare archaeological models and experimental duplicates to compare sections drawn in order to discriminate the morphology or the type of tools used.

3. 4. Discussion

In the specific context of archaeological heritage cave, 3D-recording using contact-free measurements techniques is henceforth considered like the best way to acquire georeferenced information, without handling material nor damaging the site. Today, there is no more any technical difficulty to get an overall 3D-geometry of the cave's structural elements. Several possibilities emerge, but it is obvious that the latest generation of compact terrestrial laser scanners, including integrated cameras, allow an optimized global 3D-digital cave model, conceived as a common research tool, incorporating various types of georeferenced objects, images or measurements. Since 2008, diverse challenges have been faced by the team, including the processing of very high definition images (and their mapping onto the 3D-model) in order to obtain a photorealistic rendering, by combining photogrammetry and TLS. Our results show that it is not only possible to produce high resolution textured 3D-models, but also to develop new traceological approaches or to yield an alternative to the manual drawing technique of parietal art specialists by extracting orthophotos from the 3D-model.
The issue of the integration of heterogeneous data, acquired at different scales and resolutions, in a global 3D-model, has been too poorly investigated. This is still among the things we must do. Firsts results obtained show that we are able to merge together in the same depiction system, several roots of information, as for instance the indoor magnetic field mapping.

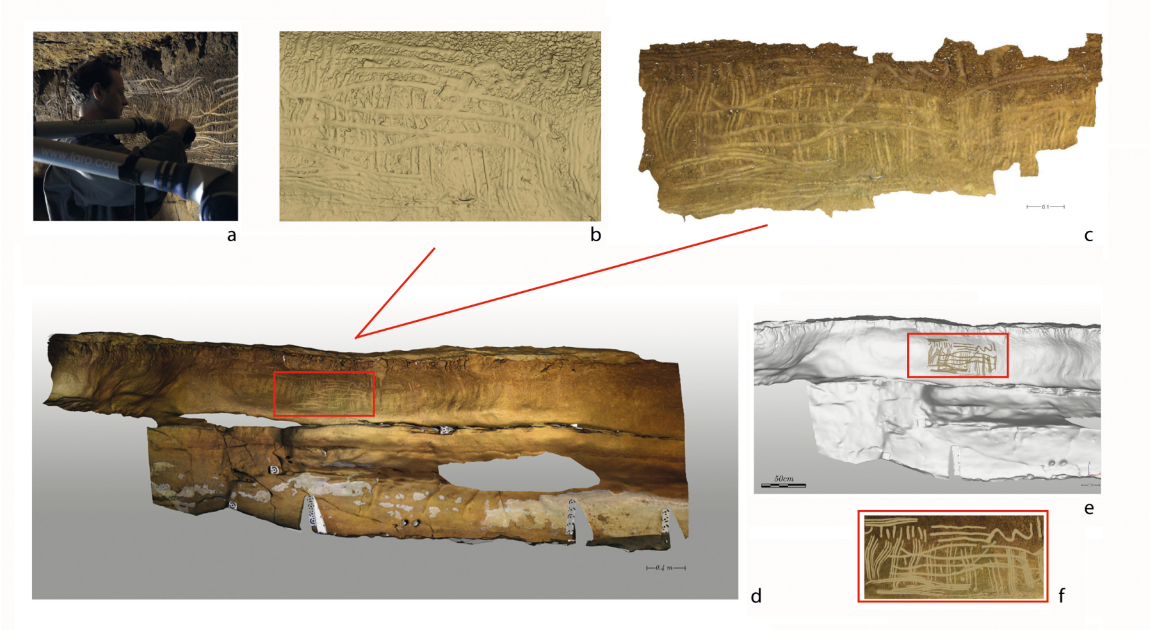

Fig. 9: 3D-recording of Bronze age fingerings in the clay-wall of the main panel from the sector 13 of the cave. a: recording test with the Faro ScanArm; b: view of the high density point cloud recording using ScanArm ; c: digital surface of a selected piece of the panel; d: textured 3D-model; e: projection of drawn fingerings on the 3D-model; f: detail of the digital drawing from the orthophoto extracted from the 3D-model.

4. CONCLUSION & PROSPECT

At this stage, it is worthwhile to recognize that, despite of the accurate solutions found to repulse several methodological locks allowing the accuracy of 3D-recording while preserving the site, we are still looking forwards for solutions to optimize the integration of heterogeneous data acquired at different scales and resolutions in a common depiction system. This requirement is clearly related to our interdisciplinary framework, which occurs an integrated research. The work related to the magnetic field mapping shows a very important methodological progress. But the exploitation of data is hampered by the necessity to expand mathematical developments and specific data processing tools (work-platform dedicated to the exploration of 3D data).

The entire 3D-recording of the whole cave is among the things we plan to finish in 2014, in order to find a way to put an end on the issue of merging several roots of information in the same reference system.

Afterwards, our goal will be using the global 3D-model of the cave to develop modelling approaches that can be done at different levels. Thereby, in association with geomorphological analysis, 3D modelling will be used to test various hypotheses on the existence in the cave of one or more active entries at the end of the Bronze Age. We plan also to formalize first views of the chronology of the closing of the galleries of the underground network, and to determine the chronology of various human and animal penetrations.

Moreover, thanks to our knowledge of the climatic actual behaviour of the cave and its seasonal variations in CO2, we will attempt to propose scenarios of the cave occupation during the Bronze Age related to the quality of its atmosphere, according to the seasons.

Finally, we are looking forward testing the simulation in the 3D models of simultaneous operation of several hearths in underground environment, and understand the flow of smoke in the cave's galleries.

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