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Petro-physical characterization and 3D digital modeling for geometric reconstruction of the Neolithic "domus de janas" of Sedini field (North-Sardinia, Italy)

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Abstract

The subject of the investigation is a volcanic rock in which a group of Neolithic tombs named "domus de janas" have been excavated. this operation is quite common in Sardinia, even if in this specific case it assumes some even more interesting characteristics. The research started gathering the 3D digital models with a high level of details and developing this virtual model with its great accuracy within its geographical -virtual-environment. The further steps were aimed at providing the information about its petrophysical characteristics, alteration processes and the evidences of the missing parts fallen during an ancient collapse. The main task is showing how to put together the 3D survey of this monument with all the data about its decay. The further development of this research will be aimed to: the definition of a searchable model with all these information linked in it, to produce a complete reconstruction of the original structure of the tombs, the definition of the potential threats on the future for this monument conservation.

Keywords: *Stones, Decay, Laser scanner, 3D modeling, Physical features, Geology.*

1. Introduction

The "domus de janas" are sepulchral structures made of rock-cut tombs during the prehistoric age with very various shapes and are typical of the Mediterranean area, in particular they are a common feature in the Sardinia Island. The name means “houses of the fairies” (or witches) and the common term used to indicate them on the island is "forrus" or "forreddus". Often they are linked together to form real underground necropolis with a common access corridor and an anteroom, often very spacious and high-ceilinged. Archaeologists claim them to have been built between the fourth and third millennia BC and attributed them to the Ozieri Culture at that time completely extended in the way of living of the Sardinian people. At the center of the Sedini village (in the North-west of Sardinia) there is the largest Sardinian "domus de janas" which in time was converted into a real house and now is used as an ethnography museum. The "domus de janas" object of this research are well known also because the stone where they are carved, it recall a zoomorphic shape similar to an elephant, and is placed in the field of Anglona area between the villages of Sedini and Castelsardo. Going beyond this particular appearance, the stone is a big block (Fig. 1) of volcanic rock (probably rolled down the slope of the near volcanic structures of the Casteddazzu Mountain) that belongs to the Sardinian Oligo-Miocenic volcanic cycle. The volcanic rocks of Sardinia (including also those of the Plio-Quaternary cycle) had a wide use throughout the historical period. The ignimbritic facies (as in the elephant stone), due to their petro-physical characteristics have optimal characteristics in regard to workability, for example they are often used as millstones, ashlars and decorative elements in the historical architecture, until the Roman period [1, 2, 3, 4, 5, 6, 7]. Other volcanic lithotypes (e.g. obsidian, phonolite) are used for other aims, as ancient war and work tools (for example: arrow tips, Aeneolhitic chipped-stone or Neolithic polished-stone axes) [8, 9, 10, 11, 12, 13].

The elephant stone boulder is significantly altered by weathering [14, 15], which is one of the factor of its odd shape. The first task of this research was to analyze the decay processes of the monument and gather actual geometric data of the stone structure, this was done operating an original laser scanner survey to realize a detailed 3D representation and a complete new set of

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drawings. The second task was to put together the 3D survey and all the data about its decay in a complete and well working descriptive 3D model.
The following developments of this research will be aimed to the exploitation of the digital documentation to develop:
- the definition of a set of specific digital models, which will make available all data obtained, allowing the virtual exploration in 3D through with the scaling of the structure to produce a variable resolution 3D model ;
- the completion of a virtual reconstruction of the original structure of the Neolithic tombs, including the parts collapsed and now missing, a meaningful operation for any restoration and replacement of the lost pieces.

Fig. 1: Photos of the “elephant volcanic stone" with views from the North (up) and from the South (down). On this latter photo it’s possible to see the access/window to the "domus de janas".

2. Historical and archaeological data

The Neolithic "domus de janas" of Sedini, was already known in the XIIth Century, when it appears in two medieval documents relating to donations of lands made in 1147, to the church of *St. Maria* of Bonarcado, and in 1153 to the monastery of *Nostra Signora* of Tergu.
The hypogeum complex was indicated from the past century using the dialect words "Sa pedra pertunta" (or "Pedra pertusa"), which means “the perforated stone” [16], whose name was later taken by Taramelli [17].
The first official mention of it is done by Angius [18]. The Anglona area, where the stone is located, was the place of important prehistoric settlements, both Neolithic ("domus de janas" of the elephant, of Scala Coperta and of Rocca Bianca) and Chalcolithic (ancient fortress and village of Monti Ossoni) and Bronze age (Nuragic period). The Neolithic hypogean tombs of this area are probably the more isolated, and are often characterized by being dug in erratic boulders, clearly visible from the distance, sometimes placed in a dominant position or halfway up a slope (like it is for the "elephant domus de janas"), or on the edge of a deep valley (as for the "domus de janas" of *Via Nazionale* in Sedini). The complex of the "elephant domus de janas" consists of two subterranean tombs (named I and II). The tomb I (Fig. 2) is opened a little under the tomb II; it's composed by four cells: three along a single pseudo axis disposed according to a N-S orientation, and one in a lateral position, in this way the whole plan can recall a sort of "L" shape. In origin it was preceded by a short corridor opened to the sky (*dromos*) but today only little traces of it remain, and probably it would be covered only in the last section, where there was also a step now very worn [19].

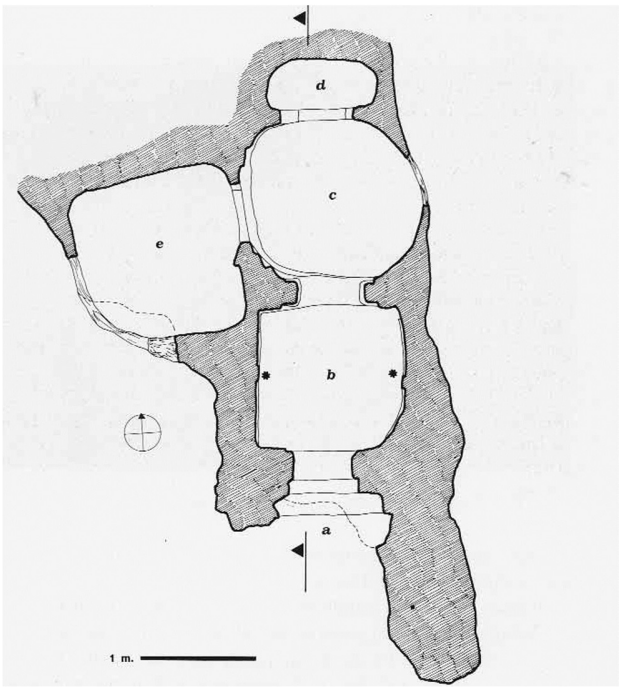

Fig. 2: Plant of tomb I of "domus de janas" within the volcanic stone (from Melis [19]).

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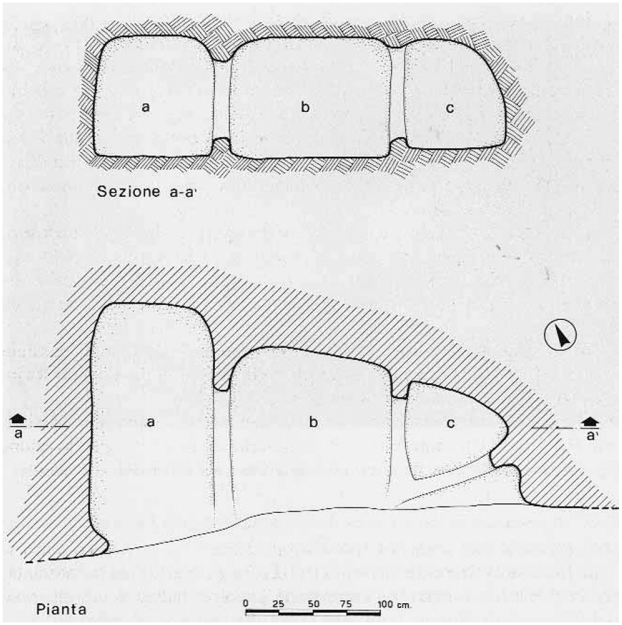

Fig. 3: Plant (down) and section (up) of tomb II of "domus de janas" within the volcanic stone (from Melis [19]).

Inside the main room (Fig. 2) there are two representation of bovine heads (*protomi*), there is a certain discussion about the proper reading of these symbol, but their most immediate interpretation recall directly a taurine shape with a small head and large horns. They show a curvilinear style, recalling the TANDA A, III, 2 type [20], and testify an evolved artistic phase, in which it turns out already started a geometrizing and simplifying process.
The tomb II is the most spoiled. It's partially collapsed, thus there are traces of the three original rooms that have a NW-SE orientation (Fig. 3). On the right it is possible to see an open space (compartment a), composed according to a small plant with a vaguely sub-triangular shape. At the center there is compartment b; it's square shaped. On the left there is the compartment c, with a rectangular shape. The ceilings are mainly flat (although very eroded), the walls are almost vertical, except for a small room (a typical compartment recalling in the shape a sort of "oven") which has slightly concave walls. All this testifies that the ruin of the front of the tomb has been pretty consistent: the entire entrance area is now missing, and it is quite problematic to attempt a reconstruction albeit hypothetical [19].)

3. Methods

3.1 Petro-physical characterization

In order to study the petrophysical characteristics of the volcanic stone, according to the "Raccomandazioni Nor.Ma.L. 3/80" [21], some fragments, yet partially detached from the substrate, were sampled out of the main rock. The description of the samples was done preliminarily through a microscope with magnification from 12x to 56x and then on thin sections with a polarizing microscope (in transmitted light) for petrographic determinations of minerals and textural features of rocks.
The physical properties were determined according to the following methods: the samples were dried at 105 ± 5°C and the dry weight (m_d) was determined. Uning an automatic helium pycnometer (Ultrapycnometer 1000, Quantachrome Instruments) the real volumes (V_r) of samples were determined as:

$$V_r = V_s + V_{cp} \quad (1)$$

where: V_s = solid volume, V_{cp} = closed porosity to helium. Through the use of hydrostatic balance the bulk volumes (V_b) of specimens were measured as:

$$V_b = V_r + V_p \quad (2)$$

where: V_p is the total volume of open pores. Open porosity to water (p_oH_2O), open porosity to helium (p_oHe), bulk density (ρ_b), real density (ρ_r) were computed as:

$$p_oH_2O\ (\%) = \frac{m_w - m_d}{\rho_w T_X} \cdot 100 \quad (3)$$

$$p_oHe\ (\%) = \frac{V_b - V_r}{V_b} \cdot 100 \quad (4)$$

$$\rho_b = \frac{m_d}{V_b} \quad (5)$$

$$\rho_r = \frac{m_d}{V_r} \quad (6)$$

where: m_w = wet weight; $\rho_w T_X$ = water density at the temperature T_X considered. The weight absorption coefficient (A_b) was computed as:

$$A_b\ (\%) = \frac{m_w - m_d}{m_d} \cdot 100 \quad (6)$$

3.2 Laser scanner technologies

3.2.1 Survey

In 2006 the Survey Laboratory of the "Dipartimento di Progettazione dell'Architettura" from the "Facoltà di Architettura" (since 2013 "Dipartimento di Architettura"), University of Florence decides to start a self supported research project on the ancient "domus de janas" starting with the elephant's stone [22, 23]. To face this work a Leica Geosystem HDS 3000 panoramic scanner was chosen (Fig. 4), it is a scanner based on the time of fly technology. This was done for two reason: for first this scanner is capable to gather a very accurate set of points

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from a very short distance and this was a very important feature to allow the survey of the inner parts of the graves. Secondly this scanner is also capable to gather a very accurate result from a long distance, so it was possible to place the scanner in the upper parts of the hill in front of the stone and take the survey of the elephant stone upper parts with the same quality of all the rest of the monument. To allow a high quality result in the overall operation the laser scanner survey was supported by a complete topographical survey. The survey was completed in two single days, the operated scan stations were twelve, the gathered points were almost 25 millions (Fig. 5). The accuracy obtained was around six millimeters for all the scans. When the scanner was placed inside the graves the use of a wireless access point was very useful to have a remote control of the scanner from the outside (Fig. 6).

Fig. 4: The laser scanner Leica HDS 3000 inside the carved tombs.

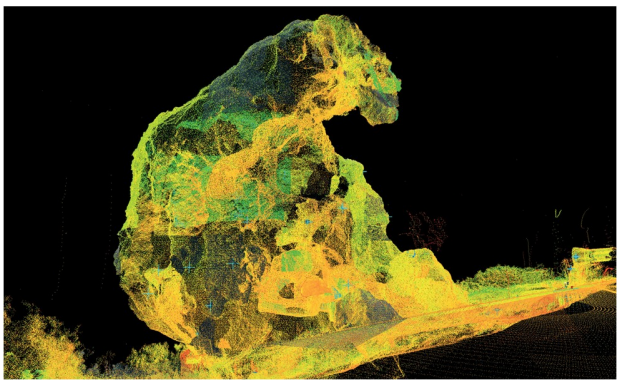

Fig. 5: Point cloud of the elephant's stone.

The topographical network was based on six topographical stations and took care about the survey of the almost forty specific targets applied on the stone (then removed at the end of the whole scanning session).

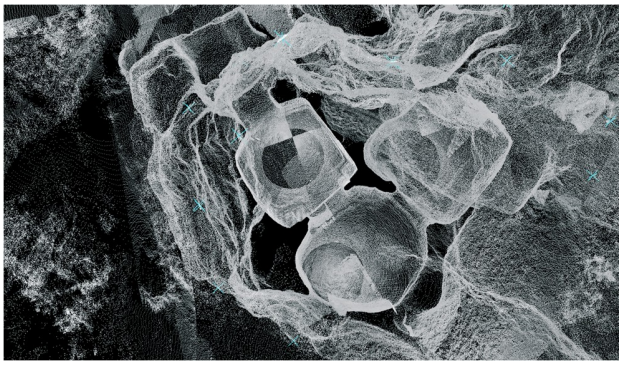

Fig. 6: Point cloud of the carved tombs.

3.2.2 Data treatments

The first step in the treatment of the gathered data was, as usual, the registration of all the singles scans into an unique digital model. After the registration, the first operation taken on the resulting point cloud were aimed to produce some simple sections all around the monument and a first, simplified, surface model with almost all the occlusion holes fixed (Fig. 7).
The whole first treatment was aimed to produce a massive, basic model of the monument. This was a first surface model useful to verify the quality of the gathered data. On the surface digital model a first texturing treatment was applied to have a better visual evaluation of the results.

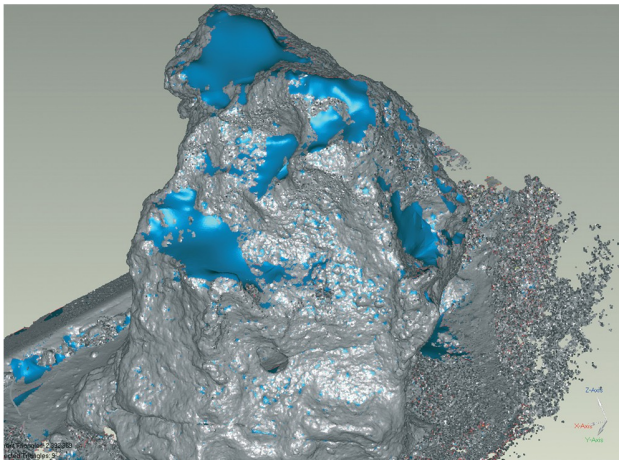

Fig. 7: The first polygonal mesh reconstructing the shape of the stone.

To produce a more versatile 3D digital model, the direct modeling from the point cloud was left behind and the further workflow was based on the mesh generated from

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the points. The starting mesh was processed to became a subdivision surface model, allowing a better development of the geometrical features and a more complete control over the level of details.

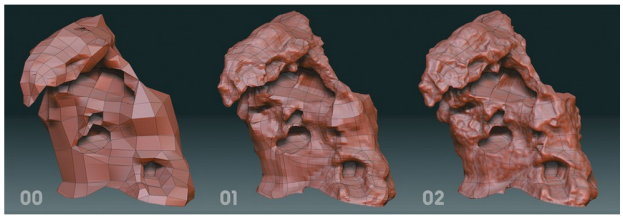

Fig. 8: The 3d model in different resolutions after the retopology process.

The following steps in modeling produced a variable resolution model, capable to switch gradually from a full resolution representation to a lower polygon representation, crossing all the intermediate steps (Fig. 8).
The keywords for this process of variable simplification were: edge loop modeling and Re-Topology modeling.
To greatly enhance the representation two advanced digital modeling and texturing solutions were adopted, the classical texture Unwrap procedure based on the photographical documentation campaign of the stone and a specific Normal Mapping procedure based on the information coming from the high resolution model itself. In this way a whole new model was produced, not aimed to monitoring or accurate information extraction, but greatly suitable for multimedia and representation.
The whole process was aimed to develop a specific solution useful to create an accurate memory of the real shape of the item and a versatile multimedia model, capable to adapt its level of detail to the representation scale and to the environment in which it will be planned to be inserted to.
The points of strength that link the procedure to the monument the stone of the elephant represents are the natural shape, the human artifacts producing smooth parts in the stone carving, the impossible task to define a regular geometric pattern as real solution to the description of the monument; the real need to have a continuous variation of the level of details while changing the representation scale.

4. The volcanic rock and its geology settings

The rock of the “elephant domus de janas" belong to the Oligo-Miocenic volcanism that forms a magmatic arc running along the western margin of Sardinia and southern Corse microplates [24]. Three extensional phases can be recognized in Anglona area, where this “domus de janas" is located, during a 15 My period which spanned Corsica–Sardinia continental microplate separation and western Mediterranean back-arc basin opening [25].

- On the first phase, the initial late Oligocene extension has created a half-graben geometry with syn-rift clastic deposits shed locally from fault-bounded highs, passing laterally to lacustrine marlstones. Subsequently, the volcanic activity has predominated with volcanic centers developed along one half-graben bounding fault; The Oligo-Miocene volcanic cycle has calcalkaline affinity l.s. and began around 32.4 My ago [26, 27], producing on Sardinia basaltic and andesitic lavas, and ended about 13 11 My ago, showing a climax between 23 and 17 My. This activity products crop out in vast areas of Sardinia [3] and is generally related with a subduction of oceanic lithosphere in a N-NW direction along the European continental paleomargin (along the Apennines-Maghrebides subduction zone) that produced the Oligocene rift between Sardinia and Provence [28].
- On the second phase, mid-Aquitanian–early Burdigalian extensional faulting, recognized from localized clastic syn-rift strata wedges, truncated and subdivided the half-graben. The syn-rift sediments were sealed by a regionally correlated ignimbrite that in turn was offset by late second-phase faulting.
- On the third phase, an extensional fault movement has reactivated the original fault trend then occurred.

5. Results and discussion

5.1 Petrographic features

Microscopic analysis on thin sections of the samples examined from the "domus de janas" elephant's stone indicates that the ignimbrite has a porphyric structure (with porphyritic index from 10 to 15%) for phenocrysts of opaque minerals, plagioclase and rare clinopyroxene and quartz immersed in a ipocrystalline groundmass consisting of plagioclase microliths and glass.

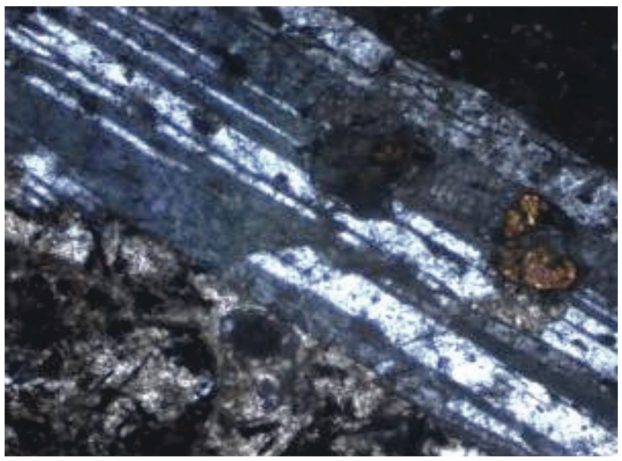

Fig. 9a: (crossed Nicol). Pyroxene enclosed within a crystal of plagioclase.

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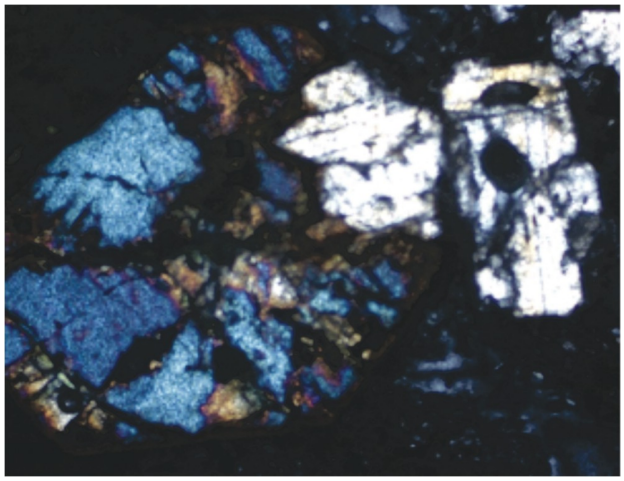

Fig. 9b: (crossed Nicol). Altered pyroxene.

The texture is fluidal, weakly oriented. The plagioclases (on average about 95% of total phenocrysts present) are mainly elongated, from euhedral to subhedral, and are distributed uniformly in all the examined sections. With crossed Nicol, we see the characteristic twins according to the law of albite and albite-Carlsbad.
By examining several individuals (according to Michel-Lévy statistic method), the maximum symmetrical extinction angle measured in sections orthogonal to the plane (010) was 35°, which corresponds to the 61% of anorthite content (labradorite composition).
The pyroxene is rare, sometimes as inclusion into plagioclase (Fig. 9a), tend to be rounded and altered (Fig. 9b). The opaque minerals appear rounded and are included in the phenocrysts being the first to crystallize; it is probably magnetite and/or Ti-magnetite.

5.2 Physical properties

Of about thirty samples taken from the "domus de janas" volcanic rock the following physical properties were determined: the open porosity to water (p_oH_2O) and to helium (p_oHe), the bulk density (ρ_b), the real density (ρ_r), the absorption index of water (A_b) after total immersion to atmospheric pressure. T
he values of open porosity to water and bulk density show a wide variability.
The samples have an water open porosity from 14% to 36% (Fig. 10). The open porosity ranging about from 8% to 26% in litho-clasts and lithic fragments of ignimbrites with strongly welded; the matrix of these pyroclastic rocks is characterized from low- to medium-welded grade: the open porosity varies about from 15% (into unaltered matrix) to 42% (in altered matrix). In some strongly altered sample, the porosity comes up to 48%.
This happens inside the glassy matrix when this latter is already characterized by original poor welding.

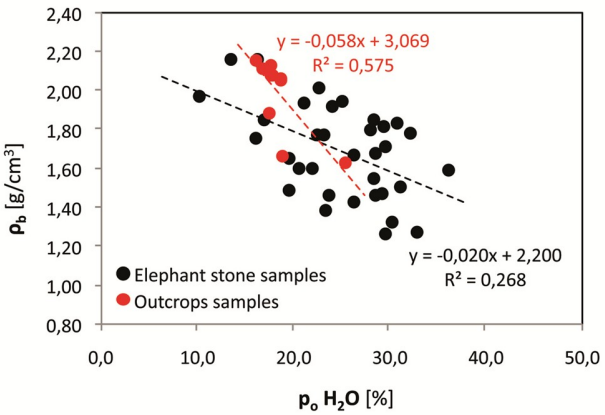

Fig. 10: Water open porosity (p_oH_2O) versus bulk density (ρ_b) of the "elephant" volcanic stone samples.

The average value of open porosity, considering the whole set of samples, is 25% with a standard deviation of 6%. The bulk density is ranging between a minimum of 1.27 and a maximum of 2.16 g/cm^3 (Fig. 10) with a mean value of 1.69 ± 0.24 g/cm^3.
The variability of these two parameters (with low correlation coefficient: R^2 = 0.268; Fig. 10) is due to the high compositional heterogeneity consequently to variable incidence of pumice, cognate fragments, litho-clasts, crystal-clasts respect to matrix.
The samples of near volcanic outcrops are less altered, show a more low variability and consequently a more high correlation coefficient (R^2 = 0.575; Fig. 10).

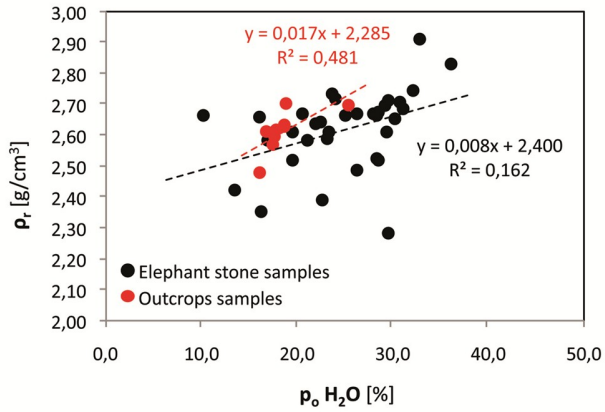

Fig. 11: Water open porosity (p_oH_2O) versus real density (ρ_r) of the "elephant stone" samples.

The real density is influenced by varying mineralogical composition and by the presence of non-crystalline phases (i.e. glass). It varies between a minimum of 2.28 g/cm^3 and a maximum of 2.91 g/cm^3 (Fig. 11); this latter value together with the other of 2.90 g/cm^3 coming from another sample, however, are not representative because the values of real density varies more frequently between 2.45 and

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2.70 g/cm^3. The real density average of this latter population of samples is 2.60 ± 0.20 g/cm^3. It is recognizable a weak correlation between this property and the water open porosity (Fig. 11). This correlation can be tied indirectly to the closed porosity decreases with the increase of the water open porosity. In figure 12 it is reported the moisture contents determined immediately after sampling. The samples taken from the part of stone facing North have a higher humidity content compared to the samples taken from the zones addressed to W-S-E, because these latter are more affected by daily cycles of absorption/desorption of water.

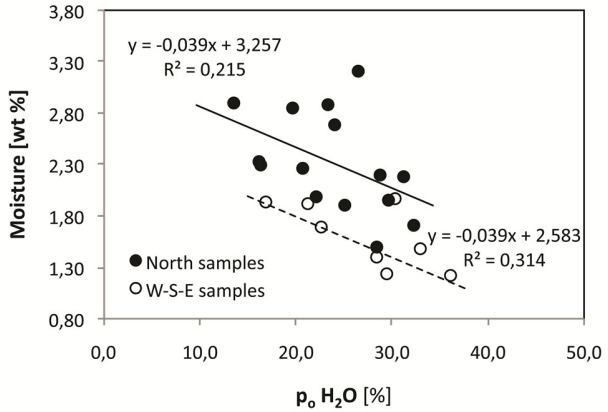

Fig. 12: Water open porosity (p_0H_2O) versus moisture content (calculated as weight %) present within the "elephant stone" samples, divided between the samples taken from the part of stone exposure to north and these from west-south-east.

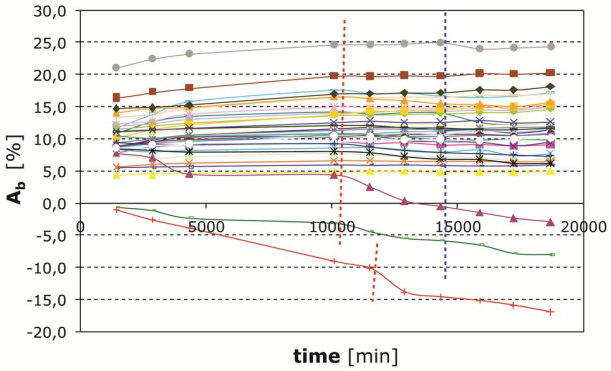

Fig. 13: Absorption kinetic for immersion on water (until to 14 days) of the "elephant stone" samples.

Water absorption (A_b) is also known as weight imbibition coefficient. It is variously linked to the open porosity of the rock, in particular parameters such as size, shape and degree tortuosity of pores and is positively correlated with their degree of interconnection.
The absorption kinetics (Fig. 13) shows that some samples lose weight already after 2 days of immersion; later, a part (about 20%) of samples lose weight after 7 days. After about 11 days the majority of samples loses weight. These results show a different degree of alteration of the samples.

5.3 The decay processes

The volcanic rock of "domus de janas" shows a greater extent of epigenetic alteration [14].
The decay depends, on the one hand, by atmospheric agents (meteoric water, solar radiation, air humidity, etc.), different exposure and, on the other hand, by different physical and mineral-petrographic characteristic. These rocks are more heterogeneous, due to the variable presence of cognate fragments, litho-clasts, pumice presence into the glassy matrix. Generally, in the Sardinian Oligo-Miocene volcanic stones used to create artifacts like sculptures or architectural parts the alteration is mainly concentrated where the rock is more porous and shows a low welding degree [1, 2, 4, 5, 6, 7]. The late-stage chemical alteration has transformed the original composition of the “elephant volcanic stone”, altering the mineral assemblage and groundmass (for devitrification) with the formation of secondary minerals. Oxidation processes were observed. Other factors that may have influenced the physical decay processes of stone are: the crystallization pressure or hydration/dehydration of hygroscopic minerals (i.e. soluble salts) and the hydric dilatation for continuous water absorption/desorption cycles [30, 31].

Fig. 14 a: Detail of alveolation processes of "elephant stone".

The water comes from atmosphere (i.e. directly meteoric precipitations, humidity condensing into water) or from the ground for capillary rise into the porous network of the stone. In this last case the water solution can reach with more facilities the salt saturation. These at last can be already present in the meteoric water as gypsum, Ca-carbonate, or, considered the distance of about 3.3 kilometers from the sea, as NaCl salts. Then, the

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differential thermal dilatation induced by the temperature daily variation and by the solar radiation may have resulted in a further process of degradation with the formation of discontinuities (i.e. micro fractures) which facilitate the water absorption.

Fig. 14 b: Macroscopic alteration forms (i.e. alveolation) on the surface of the "elephant stone".

The physical macroscopic forms of alteration (as decohesion, exfoliation, alveolation, differential degradation [22]; Fig. 14a, Fig. 14b and Fig. 15) are distributed differently on the external surface. The basal zone of the stone, directly in contact with the ground, where the water solutions circulate, is characterized by strong backward vertical profile; in this zone differential degradation (with enucleation of lithic fragments and lithoclast), exfoliation, crypto- and efflorescence were observed. The top and median zone of stone with exposition to the W-S-E show alveolation processes with strongly physical degradation, due to presence of differential thermal dilatation caused by the solar radiation and frequent daily cycles of humidity absorption/desorption. The alveolation is concentrated mainly under the “proboscis” of the elephant and into the outer room of the "domus de janas". In other zone with exposure mainly to the N-NW characterized by lower humidity range (Fig. 12), bio-deterioration agents (i.e. musk, lichens) are present. Inside the "domus de janas" rooms, on the surface of wall and on the ceiling, there are precipitation crusts. These deposits will be studied with XRD to determine the mineral composition.

Fig. 15: Macroscopic alteration forms by bio-deterioration agents on surface of the "elephant stone".

5.4 Geometric reconstruction of the "domus de janas" rooms

The hypothetical reconstruction of the Elephant Stone was based on data obtained from laser scanner survey and starts from the following considerations:
- the comparison between similar types of "domus de janas" [19, 32, 33, 34, 35, 36];
- the shape of the stone in comparison between others rocks in front of the type of boulder;
- the study of different kinds of degradation between the various parts of the rock.

Comparing the elephant’s stone with the large series of "domus de janas" present in Sardinia has evidenced that, probably, the rooms located on the upper floor of the rock had to be more than three.

Probably it should has an inlet chamber like the cells below have. Probability, in addition to natural agents, this

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is the reason of the collapse of the upper part of the rock. The excavations made to obtain these cells in fact removed a lot of material.

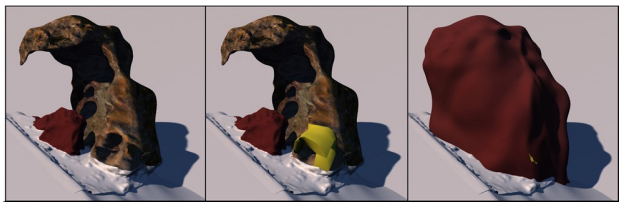

Fig. 16: Reconstruction of the entrance in the lower level

The carved rock lost its original resistance and this affected the structure and caused it the collapse. Regarding the reconstruction of the rooms at the bottom the different degradation suggest that there was another room in the lower part before the decorated room. The entrance suffered the collapse of the top part of the rock. This event at first exposed the stone and the entrance to the natural elements and a second collapse, more recently, eliminated the entrance hall (Fig. 16).

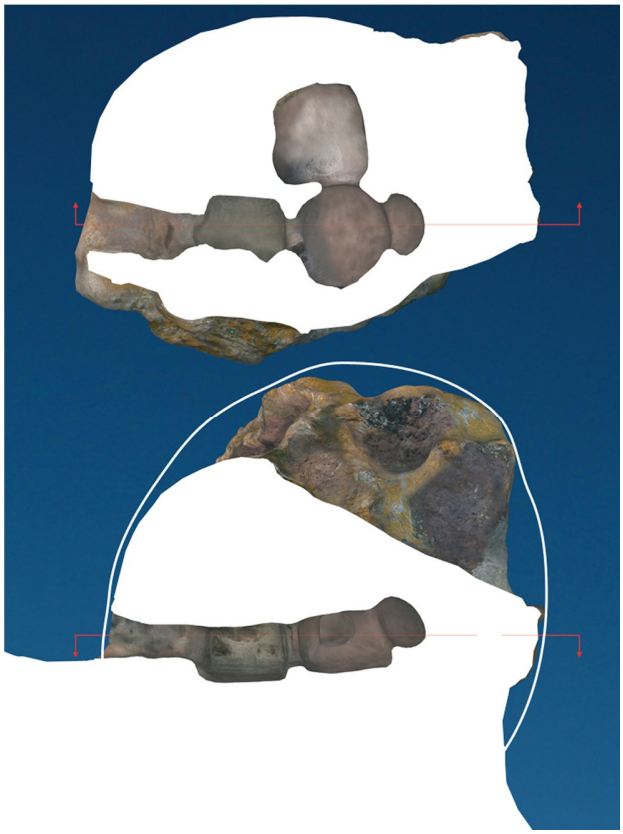

Fig. 17: The virtual reconstruction of the original plan and section of the carved tombs.

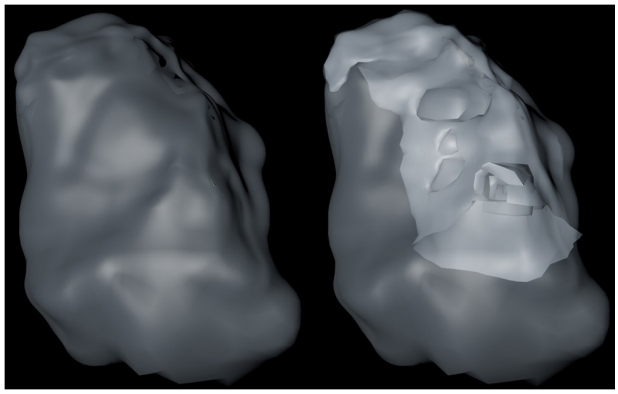

Fig. 18: A first hypothesis about the virtual reconstruction of the original shape of the stone (on the left) and the stone and its actual appearance (on the right), side view.

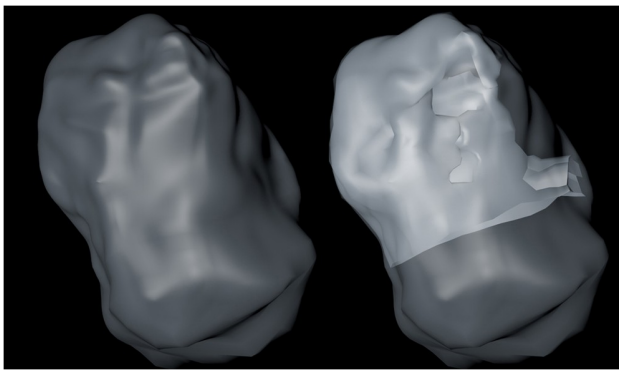

Fig. 19: A first hypothesis about the virtual reconstruction of the original shape of the stone (on the left) and the stone and its actual appearance (on the right), front view.

Probably also the others rooms were closed but the collapse of the top part open some holes on the carved tombs. Holes that, with time, grown in their size, causing a gradual decay of the inner parts of the vacuums. (Fig. 17).
The central chamber on the lower part at the time of the creation of the graves had no opening due to collapse or decay. The curvature of the room suggests that the thickness of rock was small and that weaken the wall and then caused the collapse.
It is not excluded, however, that the hole was carved later in a further use of the stone to give a view to control the valley. If this idea is true this opening was probably made by local people to allow the monitoring and observation of the territory from a protected location.
The geometry of the rock and the analysis of curvature suggest that the stone was originally characterized by a mainly oval shape.
For this reason it was decided to inscribe the reconstruction of the external shape in a shell derived from the curvature inscribable in the stone maximum dimensions (Fig. 18 and Fig. 19).

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6. Conclusions

The study of "domus de janas" volcanic stone has created the conditions to made possible to highlight important alteration processes, which in some cases, in the lowest areas of the monument and in those addressed to W-S-E, are at an advanced stage. The processes of degradation are concentrated where the petrophysical characteristic of the rock permit them, mainly in those parts with a degree of medium to poor welding and with higher porosity (starting from a percentage of about the 30%).
At the same time, the geometric and structural analysis of the volcanic stone from macroscopic observation together with the digital survey operated with laser scanner technology allowed first of all to create a trustable digital copy of the object as it is now. This important database (dated on 2006) of metric and shape information can then be used to learn over time (through other surveys repeated in future at any time) the evolution of the chemical and physical alteration processes.
All the gathered information will be then linked to the point cloud model to create specific visualizations of the decay degree of this "domus de janas" stone, with the final task of the processing of a detailed 3D map showing the variations of volume and surface in the stone induced by the decay in progress. The same map may has an invaluable rule in the planning of further restoration giving a real scientific support to any protective and/or reconstructive intervention.
Secondly, an in-depth research on the physical and mechanical properties of the rock, in the near future a more detailed survey of the smaller pieces fallen around the big stone, will allow to carry out a complete reconstruction of the object, enhancing the investigation about its real shape as it was in the Neolithic period.
The association of the two characterizations (petrophysical and 3D laser scanner survey) represents an interesting methodological approach for this type of monuments and potentially it's the starting point for a more a research in the field of conservation of Cultural Heritage.

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The further data treatment of the digital survey and digital modeling was developed by Giovanni Guccini, Federico Piras, Filippo Susca.

The geological-petrographic survey was made in 2010 and was coordinated by Stefano Columbu.

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