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Geomorphology 82 (2006) 245–254
GEOMORPHOLOGY
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The origin of the Pedra Furada sandstone tubular structures (South of Lisbon, Portugal)

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Received 4 January 2005; received in revised form 10 January 2006; accepted 5 May 2006
Available online 10 July 2006

Abstract

The Pedra Furada is a 12 m wide, 18 m high outcrop feature showing hundreds of ferruginised sandy tubes and looking in part like a giant organ. In this paper the origin of the tubes is explained on the basis of geochemical, petrographic and microscopic (optical and electronic) analytical data. The tubes are considered to represent vertical escape channels for overpressured water, exhibiting inward decreasing grain size due to water velocity gradients inside the escape channels. The ferruginisation is due to iron oxides associated with colloidal/clayey fine sediments and to goethite formed from solution. The overpressure of water may be due to seismically fluidised beds below the Pedra Furada outcrop or to artesian water ascent. In both cases, fault rupturing may have played a major role in the focussing of the ascending flow.

Keywords: Sandstone tubular structures; Ferruginisation; Water escape structures; Water escape sedimentation

1. Introduction

The Pedra Furada is a series of vertical tubular structures embedded in fluvial sandstones and is one of those peculiar features for which many explanations have been attempted over time. Many authors have described similar cylindrical and pillar structures but none seem identical to the Pedra Furada.

Pedra Furada was first described by Eschwege in (1837), reporting its size and constitution, and the shape and size of the tubes. As for the origin of the tubes, he suggested a palustrine environment where plant canes can be progressively covered and hardened by "ferruginous dissolutions", while the vegetal core rots and is replaced by fine, loose sands. In 1833, Ribeiro refers very briefly to the Pedra Furada as a "curious exemplary of ferruginous concretions on sandy rocks…" composed of "vertical tubes of different sizes grouped and adhering each other".

In 1916, Marques da Costa was able to make observations when big trenches were opened for the building of several factories. He interpreted the structure as a pyramid with a trapezoidal base, and presented sketches and images to explain the origin of the tubes

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0169-555X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2006.05.006

structures as a series of cracks grouped in a fan-like set narrowing upwards.

Based on field observations, Azevêdo (1982, 1984a,b,c; 1998); Azevêdo et al. (2003, 2004); Póvoas et al. (1993) suggested an origin involving sand liquefaction. In this work, a detailed petrographic study is presented, which together with the previous field observations and sedimentological analysis, confirms the 1982 hypothesis.

2. Location and geological setting

The Pedra Furada lies to the east of the town of Setúbal (in the Setúbal Peninsula, southwards of Lisbon, Fig. 1), and is presently about 500 m away from the bank of the Sado river estuary. At the end of the 19th century, it was located on the river bank and surrounded by a somewhat marshy environment. The Pedra Furada is the largest and the only remaining example of eight similar structures (Marques da Costa, 1916). This author shows, in a sketch, their exact position (Fig. 2), showing them to be aligned as if along a tectonic fault.

Pedra Furada is made of fluvial cream colour sands deposited by the pre-Tagus river in its mouth before the present Tagus gull was opened (Fig. 1). This thick sandy sequence (>300 m) has been studied since the 19th century and was considered of marine origin. It was only in 1982 that its fluvial deposition was proved, through a very detailed sedimentological and paleocurrent analysis; the latter showed the constant direction of the cross-bedding sets to 240° (azimuth), which is the direction of the present Tagus before it inflects to the “Tagus bottle neck” (Fig. 1; Azevêdo, 1982, 1997a,b, 1990a,b). These sands were recently dated to 3.4 My ago (Zanclean) from $^{87/86}$Sr isotopic dating of oyster shell fragments found near Lagoa de Albufeira (Fig. 1), some 30 km to the WNW of Pedra Furada (Azevêdo, submitted for publication).

Pedra Furada is distinguished by the ferruginisation of the hosting Pliocene sands, forming cylindrical

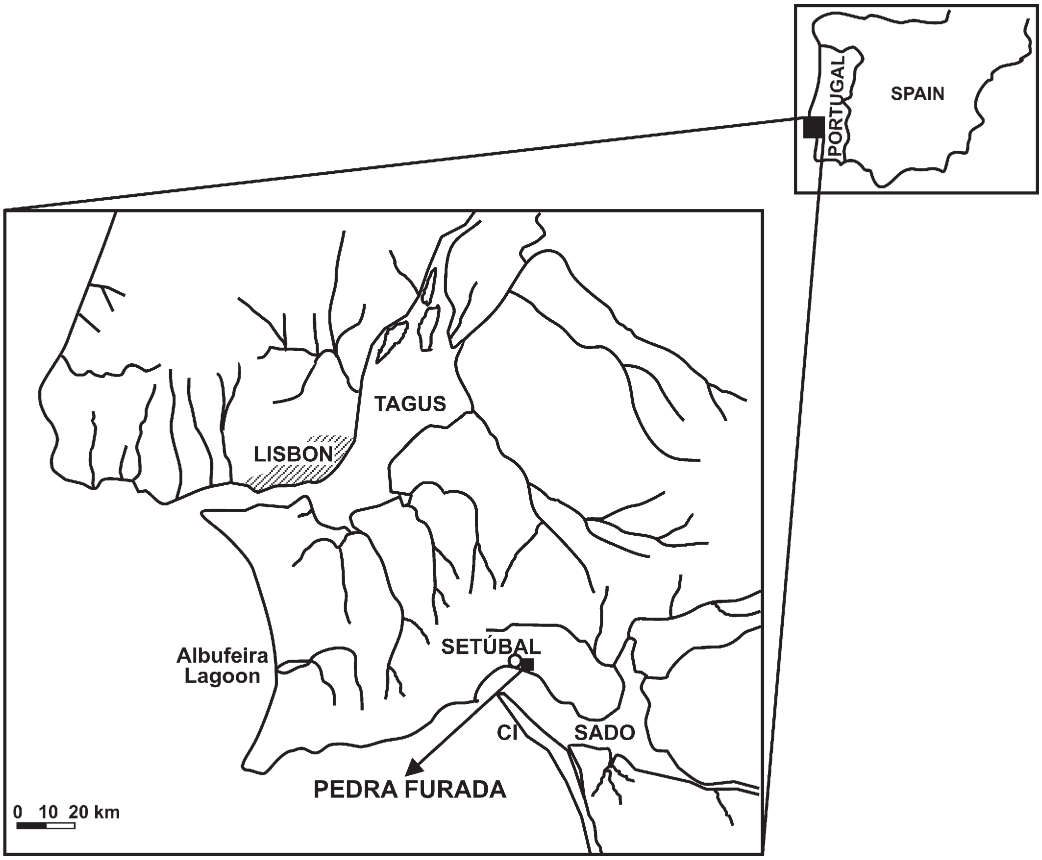

Fig. 1. Location of Pedra Furada in Setúbal Peninsula (South of Lisbon) and in the Iberian Peninsula.

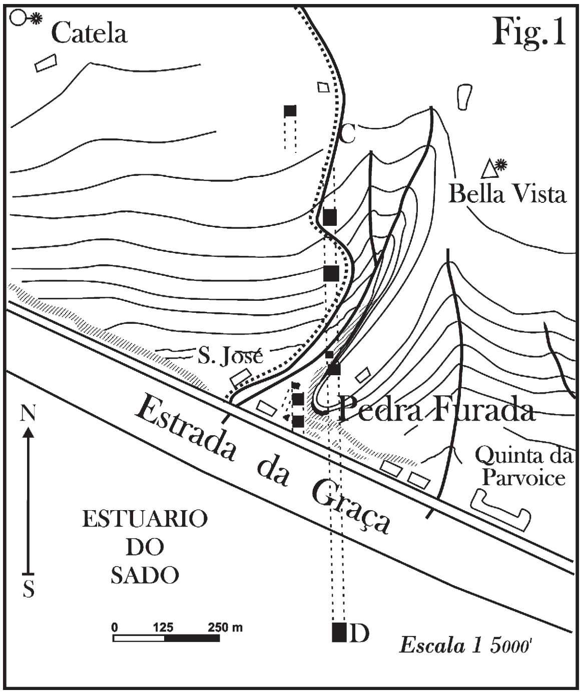

Fig. 2. Location of the eight tubular structures by Marques da Costa (1916). Legend: dotted vertical lines—alignment of the outcrops; black squares—other outcrops similar to the Pedra Furada (redrawn from the original).

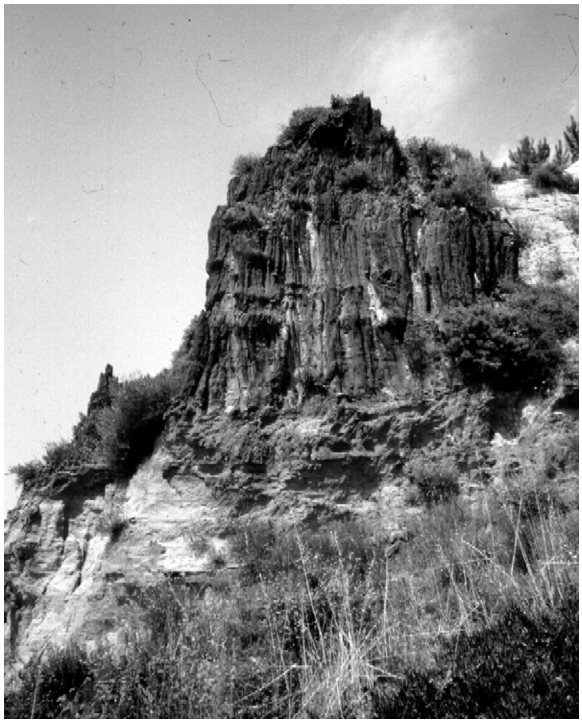

Fig. 3. The eastern side of the Pedra Furada showing the “organ structure”.

shapes, constituting hundreds of tubes in an assemblage similar to a giant organ (Fig. 3).

3. Morphological and physical characterisation

Figs. 3–7 record the appearance of the Pedra Furada showing the assemblage of tubes of dark ferruginised sandstone and strongly contrasting with the light yellow, fine to coarse loose sands hosting them.

Pedra Furada is about 18 m high and extends for 12 m in a N–S direction, the tubes being concentrated mainly in the eastern side. The western side is more homogeneous and has a different structure: it is perforated by a large number of different sized holes similar to tafoni. There is even a large cave, big and high enough for several people to stand inside (Fig. 5).

The main morphological characteristics of the cylinders are described below:

a) The tubes are vertical, sometimes running through the total height of the outcrop (Figs. 3 and 5).
b) Divisions similar to septa in canes occur across the tubes at the level of the bedding planes (Figs. 4 and 6).
c) The tubes exhibit a circular, rarely oval or irregular cross-section with diameters varying from 3 to more than 20 cm. Each tube has a constant diameter, although some rare cases of upward-decreasing diameters have been observed.
d) The tubes are filled with ferruginised light orange coloured, very fine, micaceous sands, which are easily eroded away if the tubes are damaged. The tubes have complex walls: the inner band is a strong ferruginisation of the later fine sands and the outer one is composed of coarse to very coarse lightly ferruginised sandstone; usually, an intermediate band is clearly visible (Fig. 6).

Fig. 4. Well-defined layer preserved in the tubes, similar to septa in canes. Thinner tubes enclosed inside a bigger one.

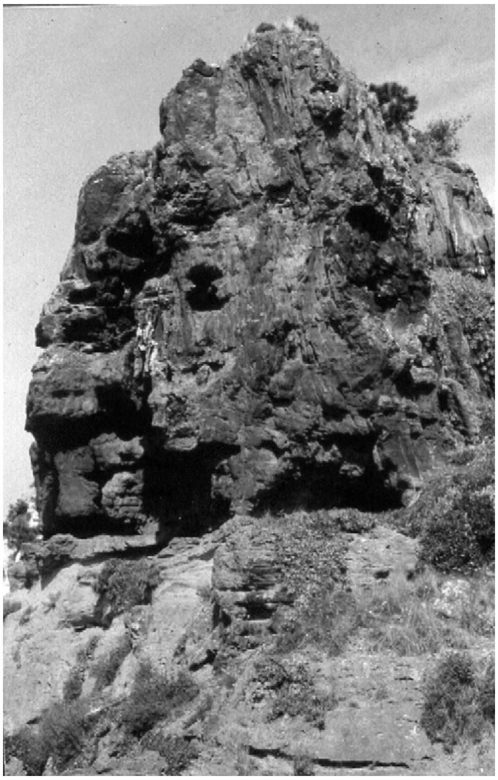

Fig. 5. The western side of the Pedra Furada showing the cave entrance and the "karstic" aspect.

e) The outer band of the tube walls has detrital grains coarser than the host sands and presents small angular quartz grains up to 5 mm size and feldspar grains up to 10 mm size.
f) Large scale planar cross-bedding structures are visible in most tubes (Fig. 7), as well as in the host sands, trough cross-bedding being very rare and of small scale. These planar structures always show the same building direction and are also present in all the walls of the cave. The host sands belong themselves to the Sp lithofacies of Miall (1977).
g) The base of the Pedra Furada is not clearly visible; but below it 2 m of very disturbed, contorted and convoluted sands can be observed (Fig. 8).

4. Methodology

Mineralogical analyses were carried out on powder and basally oriented samples of the three bands of the tubes. The analyses were made by X-ray Diffraction (XRD), using a Philips diffractometer with a graphite monochromator and Cu K-α radiation.

Total Fe and Al contents were determined by atomic absorption spectroscopy after a three acid digestion. Total silica, Mg, Na, K, Ti, and Mn were determined by X-ray fluorescence. Ferrous iron was determined by $KMnO_4$ titration after hydrofluoric and sulphuric acid digestion under controlled oxidation conditions (Washington, 1930). Free iron (MJ), meaning the Fe in iron oxides and Al (MJ), meaning the Al substituting for Fe in the iron oxides structure, were extracted by the method of Mehra and Jackson (1960). Non-crystalline Fe and Al oxy-hydroxides were extracted by Tamm's method (Schwertmann, 1964).

Scanning electron microscopic analysis (SEM) was carried out on thin sections of the three bands of the tubes and also on small fragments of the same bands after a preliminary coating with carbon and gold, respectively. This study was performed for morphology and chemical analysis using scanning electron microscopes Jeol JSM-35CF with an energy dispersive system (SEM-EDS) and Jeol JSM-5200 LV.

5. Petrographic characterisation of tubes material

A detailed sedimentological analysis including granulometry, morphoscopy, heavy and clay mineral identification, as well as a paleocurrent analysis on the tube sediments has been carried out by Azevêdo (1982) and

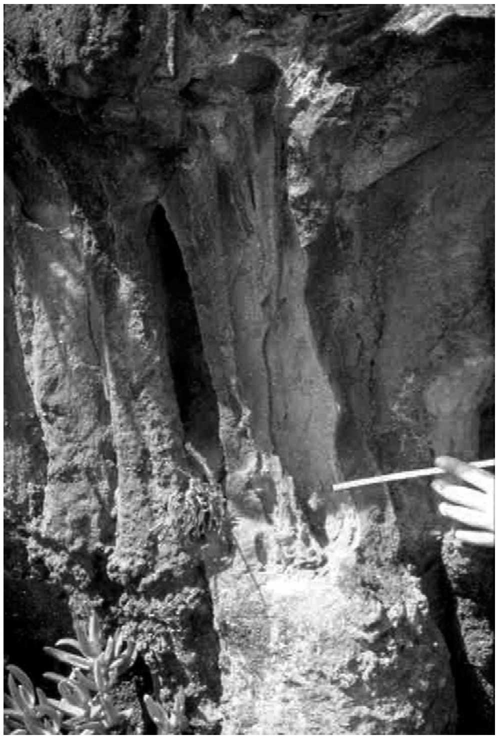

Fig. 6. A longitudinal section showing the three bands (external, intermediate, inner) and the septa at the same level in all the tubes.

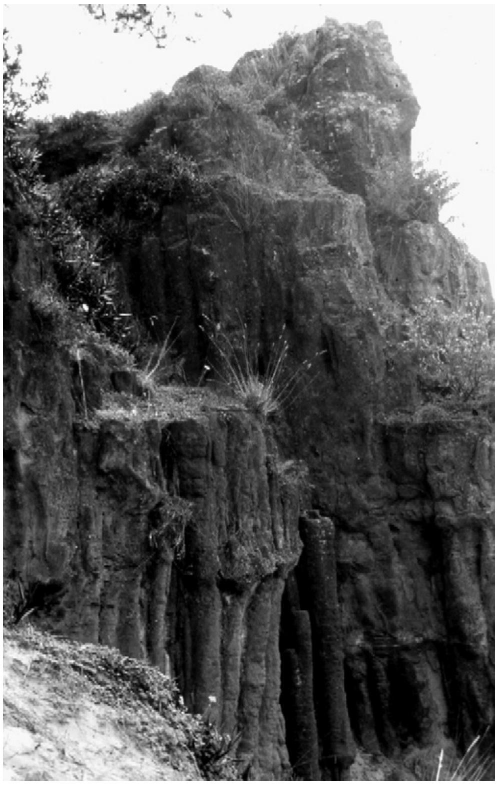

Fig. 7. View of the west side of the Pedra Furada showing a set of tubes, the septas and the flat top of the stone.

Fig. 8. Disturbed and convolute bedding at the visible bottom of Pedra Furada.

Azevêdo et al. (2003). In short, grain size distribution of the sands is bimodal with modes in the fine and coarse sand granulometric classes; kaolinite and illite are the main clay minerals; andalusite, staurolite, tourmaline, zircon and garnet are abundant heavy minerals; the morphoscopic analysis shows bright, angular to sub-angular quartz grains; and a minor population is composed of dull and rounded grains testifying an eolian contamination.

5.1. Mineralogy and chemistry

Quartz, feldspars (orthoclase and microcline), mica and kaolinite, were the main silicate minerals identified by X-ray diffraction in the three bands of the tubes (inner, intermediate and outer bands). Goethite was the only iron oxide mineral identified.

The chemical composition of the three bands is presented in Table 1. The external band of the tubes is richer in Si and Al than the internal one, which is consistent with its coarser granulometry (mean of the sandy fraction: 0.5 mm and 0.125 mm respectively). The inverse was observed for total Fe, Na, Mg, P and Mn. Ferrous iron is less than 1% of total Fe for all three bands indicating an oxidising environment for the genesis of the tubes. Also the iron assigned to iron oxides increases inwards in the tubes' walls (from 146.9 to 205.7 g kg^{-1}). However, in the external band almost

Table 1
Chemical data for the three bands of the tubes (g kg^{-1})

Elements (g kg^{-1})	Inner band	Intermediate band	External band
SiO_2*	577.9	663.4	730.9
Al_2O_3*	41.6	57.2	76.2
Fe_2O_3*	278.6	159.1	151.5
FeO*	1.8	1.4	1.4
MgO*	2.7	2.4	1.5
CaO*	<dl	<dl	<dl
K_2O*	14.4	19.7	17.9
Na_2O*	10.6	6.0	3.5
TiO_2*	<1.0	1.0	1.0
P_2O_5*	6.7	4.8	3.3
MnO*	2.6	<1.0	<1.0
H_2O	3.0	39.2	21.6
Fe_2O_3 (MJ)	205.7	128.7	146.9
Fe_2O_3 (Tamm)	3.9	2.0	1.4
Al_2O_3 (MJ)	9.1	1.1	2.6
Al_2O_3 (Tamm)	18.2	23.1	19.0
Fe_2O_3 (Tamm)/Fe_2O_3 (MJ) (%)	1.89	1.55	0.95

*: total concentration; dl: detection limit; MJ: free total Fe/Al (Fe/Al in iron oxides); Tamm: free Fe/Al (Fe/Al in amorphous phases).

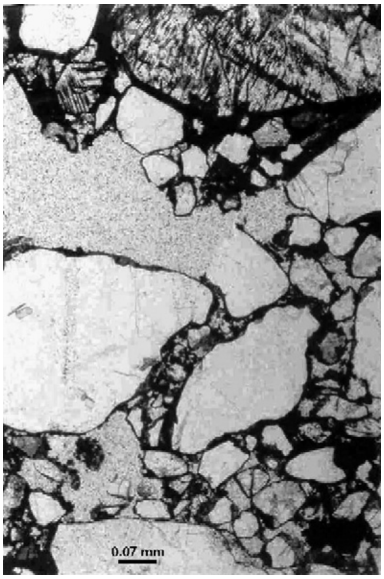

Fig. 9. Optical micrograph of exterior part of the tubes showing large quartz grains coated by a thin film of iron oxides and ferruginous clay and the empty pores between them.

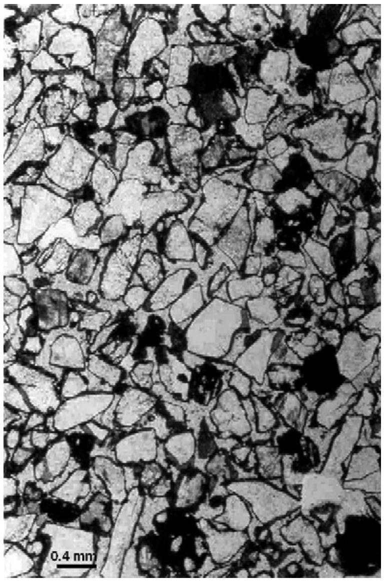

Fig. 10. Optical micrograph of exterior part of the tubes showing large quartz grains coated by a thin film of iron oxides and ferruginous clay and the empty pores between them.

all of the total Fe is in iron oxide minerals (97%) whereas in the inner zone this value reaches only 74%. These data indicate an inward increase of iron-rich heavy minerals across the tube walls, which is consistent with the finer fractions where these minerals occur. The non-crystalline iron oxide fraction ranges from 0.95 to 1.89%, increasing in the inner part of the tube. However, the amorphous Al hydroxides show a slight increase in the intermediate zone (Table 1). According to the Fe_2O_3 and Al_2O_3 (MJ) contents, there is Al/Fe substitution in the goethite structure, especially in the inner samples, as is also indicated by the d_{110} distance on the XRD diffractograms.

5.2. Optical microscopy

Seven thin-sections of horizontal cross-sections of several tubes, including the three different bands of iron enrichment, were observed with the polarizing optical microscope. A clear transitional zone between the outer and the inner zones of the tubes was observed, namely in the sand grain pattern and in the iron oxide contents as expected from the chemical data presented above. In the external part of the tubes (Fig. 9), the sand grains, mostly composed of quartz with some associated feldspar and mica, are coarser than in the transitional zone (Figs. 10 and 11), and frequently have a clear surface and form an open framework. Some grains showed a thin coating of iron oxides. Quartz grains also showed contour irregularities, which seem to be due to chemical corrosion by the iron oxides (Abreu and Robert, 1987). Empty spaces or some thin films of ferruginised clay matrix were observed between the grains.

The remaining two bands were characterised by gradual iron enrichment, consisting in an increase of the cement thickness coating the grains (Figs. 10 and 11). This cement fills entirely the empty spaces in the inner zone and penetrates the fissures presented by the quartz grains. The quartz grain contours are very irregular, sometimes serrated. In this part of the tubes a great quantity of small quartz grains that seem to result from

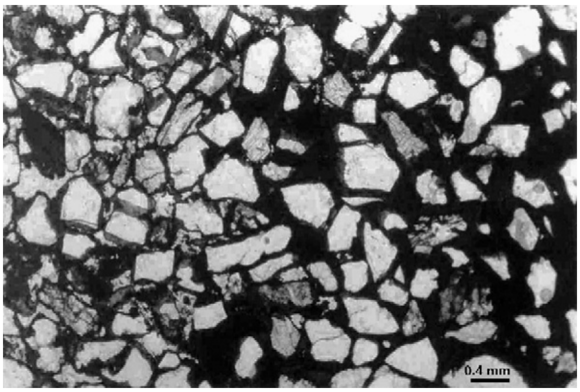

Fig. 11. Optical micrograph of the intermediate and inner parts of the tubes showing a gradual iron oxide enrichment and ferruginous clay represented by cement thickness involving the grains.

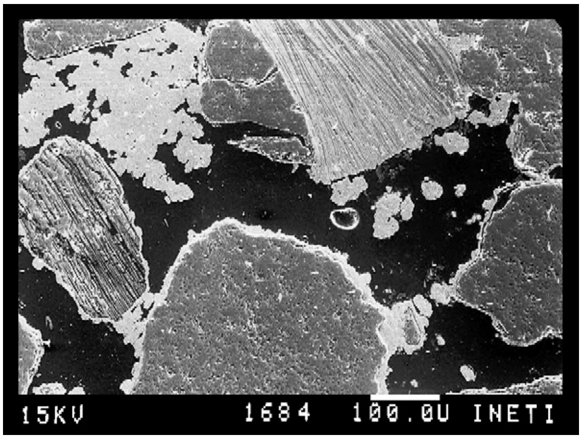

Fig. 12. SEM micrograph of the exterior band of the tubes showing a coarser structure with sand grains covered by a thin film of iron oxides and ferruginous clay, separated by empty pores.

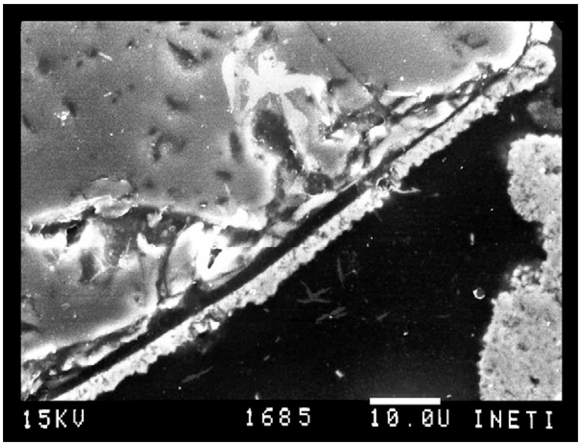

Fig. 14. Detail of a sand grain showing an empty space between the grain surface and the iron oxides and ferruginous clay coating (SEM micrograph).

the fragmentation of the original ones by the iron infilling, was observed (Fig. 11). These processes were very similar to those observed by Abreu (1986) and Abreu and Robert (1987) in quartz grains from soils. The same aspects are also true for minerals other than quartz: the heavy minerals separated from both the inner and the outer parts of the tubes, show respectively small, irregular, dented grains and large grains with regular surfaces (Azevêdo et al., 2003, 2004).

6. Scanning electron microscopy

6.1. Thin sections

Thin section observations showed clearly the differences between the three bands of the tubes. In the external band the coarse grains are separated from each other by empty spaces (Fig. 12). The grains, mostly quartz, present a thin (<10 μm) iron oxides ± kaolinite coating. From the outer to the inner zone of the tubes, the iron oxide coating thickness increases up to more than 20 μm, leading to a progressive clogging of all empty spaces, which becomes basically complete in the inner zone where sediment porosity falls to very low values (Fig. 13). It is unclear whether the ferruginous coatings of quartz and feldspar proceeded by simple physical deposition followed by chemical growth or by chemical binding to the silicate surface. However, the presence of a gap between the coating and the silicate grains seems to indicate that at least partially simple physical deposition was the case (Fig. 14).

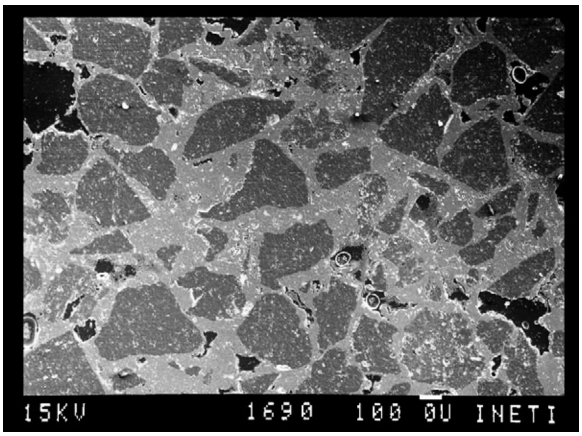

Fig. 13. Massive and compact aspect of the inner part of the tubes by almost complete infilling of the pores by iron oxides and ferruginous clay (SEM micrograph).

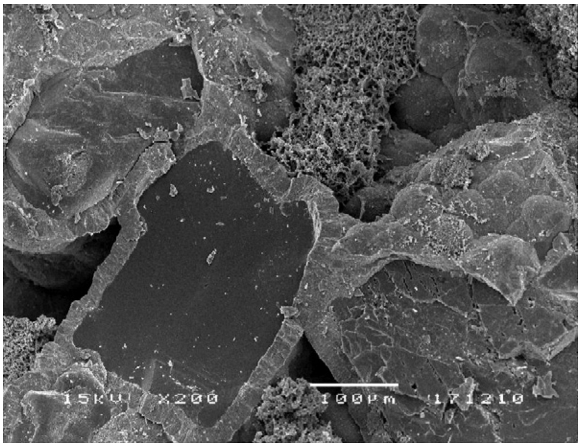

Fig. 15. SEM micrograph of the tube fragments showing sand grains completely surrounded by iron oxides and ferruginous clay coating with a fibrous fabric.

SEM-EDS studies of fragments of the three separated zones of the tubes showed sand grains wholly surrounded by iron oxides. The coatings showed a fibrous internal fabric with goethite crystallisation occurring perpendicular to the quartz surface and a botryoidal aspect at the external face of the coating (Figs. 15 and 16).

Thickness measurements confirm the values obtained from thin sections. In the three bands of the tubes, iron oxides with particular morphology such as intricate filaments like balls of thread or even rods (Fig. 17), were observed in the pores between sand grains. These morphological aspects seem to correspond to iron precipitation over organic structures like algae or fungal hyphae or even to bacterial activity (Vitoria and Abreu, 1992).

7. Hydraulic/hydrological model

The physical characteristics of the Pedra Furada and the analytical and field data obtained strongly suggest that the Pedra Furada was formed by a mechanism similar to the model proposed by Preston and Lajoie (1980) for the Mono Lake cylinders in the sense that the vertical tubes observed would have been formed as vertical escape conduits for overpressured water.

When for some reason, overpressured water escapes vertically through a sediment body, the flow, instead of diffuse, is generally concentrated in vertical channels of all sizes, sometimes branching or even enclosing several thinner channels inside one another. These channels leave cylindrical structures in the sediment after the flow has ceased.

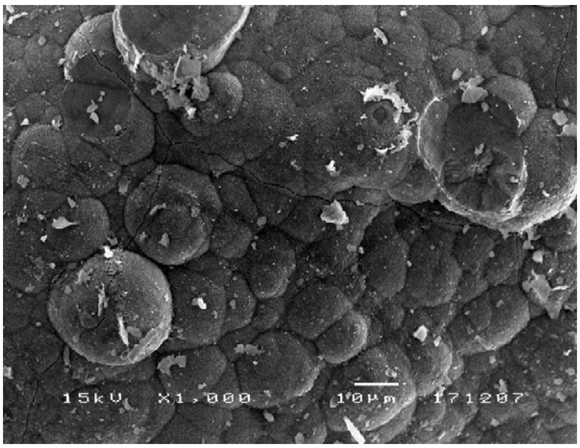

Fig. 16. SEM micrograph of the tube fragments showing a botryoidal aspect of the iron oxides and ferruginous clay on the external face of the coating.

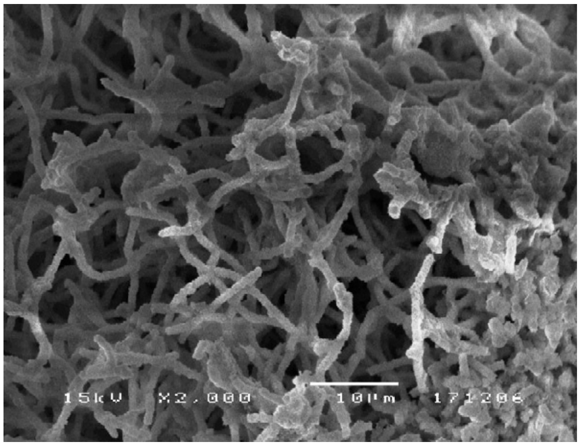

Fig. 17. SEM micrograph of the tube fragments showing iron oxides and ferruginous clay with a particular morphology, as intricate filaments like balls of thread or rod, located in the pores between sand grains.

This general process is envisaged to have occurred in the Pedra Furada. In the beginning of the process, the velocity of the ascending water is so high that it carries away all sediment particles in the channel and all but the coarsest ones in the channel walls. In the waning stages of the upward flow, the process becomes less intense, allowing fine sediment particles to settle inside the channels, which become clogged with fine sand that falls down as the upward flow ceases.

Hollow cylinders of very coarse sand are thus formed, filled with ever finer sediment inwards because the flow velocity decreases with time and simultaneously also outwards due to drag. The iron involved in the later ferruginisation would have been associated with the clay particles of the finer infill and would also be present in solution, from where it would precipitate as goethite in the most porous zones.

The well-defined layers, similar to the horizontal septa in canes observed at Pedra Furada, led some authors in the past to interpret the origin of the tubes as petrified canes. These discontinuities correspond to stratification beds, that is to planes of higher permeability; the widening of the tubes seems to be due to a localised outflow of finer sediment that escaped the normal internal erosion of the tube walls because of its greater distance to the tube centres.

For the origin of the pressure gradient responsible for the development of the vertical structure of the tubes, two basic situations can be suggested. The first situation is the escape of excess water from an underlying fluidized layer. In fact, the presence of convolute structures at the base of Pedra Furada (Fig. 8) suggests that partial liquefaction and/or fluidisation or quasifluidisation could have been a triggering mechanism for the origin of the waters making the vertical cylinders. According to Leeder (1982) "in many liquefied beds the upward displacement of pore water is not uniform and it may be concentrated in pipes where the upward fluid escape velocity is sufficiently high to entrain grains of fine material". This upward movement and suspension of the grains by the movement of the ascending fluid is termed fluidisation. When a sediment bed liquefies, usually because of seismic shaking, its upper boundary is initially a regular planar surface. Then, because the liquefied bed is hydraulically unstable, any deviation from the horizontal of the upper surface will be amplified and the excess water, together with entrained sediment particles, will flow up and, piercing the upper surface, will establish a vertical channel through which the excess water can be drained away. This was experimentally verified by Nichols et al. (1994).

The second possibility is the local occurrence of artesian water. It has been demonstrated by drilling that the region of Setúbal is over an artesian aquifer sealed by an impervious Miocene clay-rich layer (Mendonça et al., 2003, Fig. 18). It is uncertain when artesian conditions were established for the first time. However, if artesianism already existed at the time of formation of the Pedra Furada, tectonic faulting could easily break the clay layer and allow the discharge of the artesian aquifer through the Pliocene sands. This would explain the N–S alignment of the old structures documented by Marques da Costa (1916). Actually, even in the case of a fluidisation origin for the ascending waters, this inferred fault, and not the mere interplay of sedimentary processes, could have acted as the most important way of concentrating the ascending flow.

8. Conclusions

The geomorphological literature describes many anomalies in the geological record, which either have no explanation for their origin or have several alternative hypotheses to explain their occurrence. Cylinders, columnar structures, pipes and pillars are some of those aberrant and rare features challenging the notion that they are always of sedimentary origin. Most of them have appreciable impact in the landscape and are considered as Geomorphological Heritage and Geotourism sites. The Pedra Furada is one of these features. It is a rare or single geological object, formed by non-sedimentary processes. Since no other such feature is described in the international bibliography with similar characteristics and it has been recognised as geological heritage by the municipal authorities, it stands out prominently in the landscape as a giant dark organ contrasting strongly with the host light sands.

Several explanations can be given for the origin of the tubes; however, the one offered here is the best explanation for the combined sedimentological, geochemical, and optical and electronic microscopy data. The tubes are considered to represent vertical escape channels for over-pressured water and the ferruginisation is due to iron oxides associated with colloidal/clayey fine sediments, and to goethite formed from

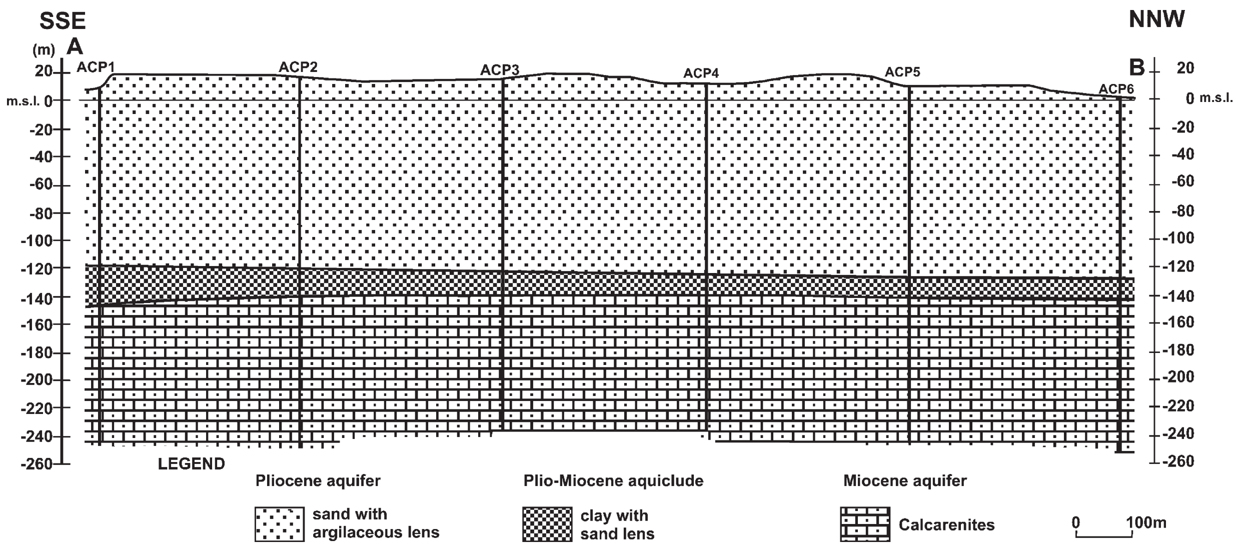

Fig. 18. Schematic geological section of the Tagus-Sado aquifer system in the Mitrena Peninsula, 7 km eastwards of Setùbal Peninsula (Mendonça et al., 2003).

solution. At present, it is not possible to establish the actual cause of the over-pressurisation of the underlying water body. Two hypotheses are presented: seismic fluidisation in beds below the Pedra Furada outcrop or artesian water ascent, with fault rupturing playing a major role in focussing the ascending flow.

Acknowledgements

We would like to acknowledge Elisabeth Nunes for her help with the photos, figures and the text arrangement.

References

Abreu, M.M., 1986. Aspectos do comportamento do ferro na crusta de meteorização. Alto e Baixo Alentejo. PhD thesis, Technical University of Lisbon.

Abreu, M.M., Robert, M., 1987. Relations Maghemite-Quartz. Etudes dans le milieu naturel (Sols Rouges du Portugal) et en conditions experimentales. In: Fedoroff, N., Bresson L.M., Courty, M.A. (Eds.). Soil Micromorphology. Proc. VII Intern. Working Meeting on Soil Micromorphology. Paris-July 1985, pp. 165–170.

Azevêdo, T.M., 1982. O Sinclinal de Albufeira. Evolução Pós-Miocénica e Reconstituição Paleogeográfica. PhD thesis, Centro de Geologia da Faculdade de Ciências de Lisboa, Lisbon, Portugal.

Azevêdo, T.M., 1984a. A Pedra Furada (Setúbal). I Cong. Nac. Geologia. Aveiro.

Azevêdo, T.M., 1984b. A Pedra Furada (Setúbal). Geonovas. Revista da Associação Portuguesa de Geólogos, vol. 7, pp. 33–37. Portugal.

Azevêdo, T.M., 1984c. O Monumento da Pedra Furada. Bol. Assoc. Port. Geol., vol. 8, pp. 7–8. Lisboa.

Azevêdo, T.M., 1990a. Areias e argilas da Península de Setúbal - caracterização e interesse económico. Semin. Rec. Min. não Metálicos. APG, Lisboa.

Azevêdo, T.M., 1990b. Implicações ambientais da exploração de areias e argilas na Península de Setúbal. VII Simpósio Geol. Apl. Amb. Dep. Geologia. F.C.U.L., Lisboa.

Azevêdo, T.M., 1997a. El tramo final del Tajo en el Plioceno Superior (Sinclinal de Albufeira, al Sur de Lisboa). Actas. III Congresso Gr. Esp. do Terciário. Cuenca, pp. 45–48.

Azevêdo, T.M., 1997b. Arquitectura deposicional del Pré-Tajo en el Plio-Quaternário. Actas. III Congresso Gr. Esp. do Terciário, Cuenca, pp. 49–52.

Azevêdo, T.M., 1998. É preciso proteger a Pedra Furada. Humanizar, Ano I, N° I, Setúbal, 38–39.

Azevêdo, T.M., submitted for publication. The terminal part of the Tagus Tertiary basin in Middle Pliocene (Setúbal Peninsula, South of Lisbon, Portugal). Sedimentology.

Azevêdo, T.M., Abreu, M., Galopim de Carvalho, A.M., 2003. The Pedra Furada again. Abstracts. Ciências da Terra, Vol. Especial, N° V. VI Congresso Nacional de Geologia, Univ. Nova Lisboa, Costa da Caparica, 36 (CD-Rom Ed., p. C8-C11).

Azevêdo, T.M., Abreu, M., Galopim de Carvalho, A.M., 2004. Uma vez mais a Pedra Furada. Musa, vol. 1. MMAS, Setúbal, pp. 155–160.

Eschwege, Baron, 1837. Memória geognóstica ou golpe de vista do perfil das estratificações das diferentes rochas do que é composto o terreno desde a Serra de Sintra até à Serra da Arrábida. Mem. da Academia das Ciências, Tomo XI, parte I, Lisboa, pp. 253–271.

Leeder, M.R., 1982. Sedimentology: Process and Product. George Allen & Unwin, London, p. 344.

Marques da Costa, A., 1916. Pedra Furada de Setúbal. Com. Serv. Geol. Port., Tomo XI, Lisboa.

Mehra, O.P., Jackson, M.L., 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. Clays Clay Miner. 7, 317–327.

Mendonça, J.L., Silva, M.O., Medeiros, A., 2003. Identification of saline contaminations by water logging in wells located in the area around the estuary of the Sado River (Portugal). Tecnnología de la Intrusión de Agua de Mar en Aquíferos Costeros: Países Meditrerraneos. IGME, Madrid.

Miall, A.D., 1977. A review of the braided-river depositional environment. Earth-Sci. Rev. 13, 1–62.

Nichols, R.J., Sparks, R.S.J., Wilson, C.J.N., 1994. Experimental studies of the fluidization of layered sediments and the formation of fluid escape structures. Sedimentology 41, 233–253.

Póvoas, L., Carvalho, A.M.G., Azevêdo, T.M., 1994. Pedra Furada de Setúbal: Geomonumento a preservar. Património e Museus Locais, 3, 2° Série, pp. 58–61. Lisboa.

Preston, C., Lajoie, K., 1980. Calcite-impregnated defluidisation structures in littoral sands of Mono Lake, California. Science 210, 109–112.

Ribeiro, C., 1833. Descripção do solo quaternário das bacias hydrographicas do Tejo e do Sado. Com. Serv. Geol., Lisboa, Portugal.

Schwertmann, U., 1964. Differenzierung der Eisenoxide des Bodens durch Extraktion mit Ammoniumoxalat-Lösung. Z. Pflanzenernähr. Düng. Bodenkd. 105, 194–202.

Vitoria, G., Abreu, M.M., 1992. Soil biological features mineralized by iron. In: López-galindo, A., Rodriguez-Garcia (Eds.), Electron Microscopy. Volume II: Material Sciences. EUREM 92, pp. 599–600. Granada, Spain.

Washington, H., 1930. The Chemical Analysis of Igneous Rocks, 4th ed. John Willey and Sons, New York.