

Karst in siliceous rocks: Pseudokarst landforms and caves in the quartz dyke of Pico Sacro (Boqueixon, Galicia)

Karst en rocas silíceas: El paisaje y las cuevas pseudo-kársticas de la vena de cuarzo de Pico Sacro (Boqueixon, Galicia)

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Abstract

In spite of the siliceous composition of the quartz dyke that forms the *Pico Sacro*, typical pseudokarst landforms can be observed as incipient karren-type forms, cavettos, tafoni, flared walls and alveolar weathering, boulder caves and an impressive deep vertical shaft named *A Cova do Pico*. The pseudokarstic character of this landscape is defined by selective weathering along the joints and fracture planes of this quartz dyke.

Key words: Pseudokarst, siliceous karst, tectonic caves, Riedel shear system, cavernous weathering forms, speleothemes.

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INTRODUCTION

The development of karst landforms in poorly soluble rocks is possible only under very particular environment conditions (PICCINI, 1997).

The best known cave complexes are developed in siliceous rocks such as orthoquartzites (Sima Auyan-tepui Noroeste, Venezuela; depth -370 m, length 2950 m) (MECCHIA & PICCINI, 1999), quartzites (Gruta do Centenario, Pico do Inficionado, Brasil; depth -481 m, length 3800 m) (MACEDO DUTRA, et alii, 1999), and quartz sandstone (WRAY, 1997).

Karst landscapes in quartzose rocks are the result of post-genetic weathering and dissolutional processes.

In our case the cave is located in a quartz dyke. Variscan tectonic activity which produce a local mylonitic facies, called here "the quartz grus", weathered by solution and flushing, probably longer than Tertiary times, are considered the main factors which have allowed the development of

pseudokarstic landforms. (GROBA & VAQUEIRO, 2003).

REFERENCES AND TERMINOLOGY

From 1998 CEM is using the genetic classification criteria of some non-karstic caves proposed by STRIEBEL (1996). These criteria have been adapted to the features observed at the Galician pseudokarstic granitic areas by CEM (1998). Terms proposed by VIDAL ROMANI (1989) are included too.

The karst terminology (FIELD, 1999) is used in accordance with similar morphologies and structures. Similar form does not imply similar genesis.

LOCATION

Pico Sacro is located at UTM (X,Y,Z) = (545366, 4739752, 534) – Boqueixón Council, near Santiago de Compostela, province of A Coruña, Galicia, Spain (Figure 1).



Figure 1. Working area.

An impressive deep vertical shaft named *A Cova do Pico* is located at UTM (X,Y,Z) = (545400, 4739750, 514). Cave entrances are located at 514 meters above sea level (main survey station or 0 m station) and 504 meters (-10 m above main survey station).

GEOLOGICAL SETTING

The quartz dyke of *Pico Sacro* is about 17 km long, 2 km wide and 400 m deep, elongated from north-west to south-east, along a normal and tearing fault named *Falla Marginal* and which is aligned to



Photo 1. *Pico Sacro* Mountain (South).

N135°E-N140°E around the peak. (IGME, 1982).

The dyke is crossed by the Ulla river, at the named *Paso de San Xoan da Cova*, in the border between provinces of *A Coruña* and *Pontevedra*.

The surface of this quartz dyke slopes smoothly southward from an altitude of 400 m above sea level to 514 m asl at the southern edge, while are sloped and

stepped northward from an altitude of 350 m asl.

The pseudokarstic area surface extends up to 450 m above the local fluvial base level. Around the peak, surface springs are located up to 400 m asl.

The southern part of the peak consists of low pressure metamorphic facies, schists and paragneisses both of Precambrian age (PC-S). The northern part consists of a

middle-high pressure complex of Precambrian-Ordovician age, named the *Basic Domain (Complex of Órdenes)*, where it is mainly amphibolites (xAQ2).

Reaching the summit of the peak at the northern edge, colluvial Quaternary deposits (QC) have been found. (IGME, 1982). (Figure 2).

HYDROGEOLOGICAL SETTING

There are three springs at the base and around of the peak, all of them located up to 410 m asl on the southern side. Note that cave and peak structure are mainly dipping 60-90° to southeast.

One spring is particularly aligned with endokarstic structures. This spring is located

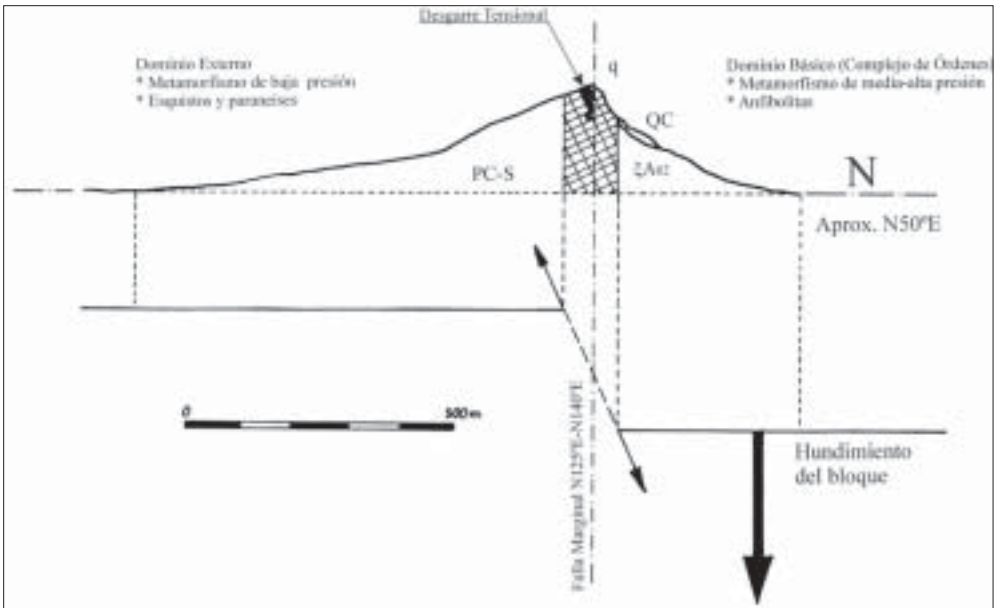


Figure 2. Southern-northern profile and geological settings (GROBA & VAQUEIRO, 2003).

at 417 m asl, and the pH ranges between 6.2 and 6.8.

The epikarst zone developed in the upper part of the bedrock is only several centimeters thick and consists of highly fissured bedrock. The water leaks out downward along major tectonic fractures. There are little tafoni-like forms and pipes, which would leak downward the surface running water.

At present the shaft do not contribute much to the ground water system, as most

the recharge enters through joint networks and feeding and piping tubes below the summit of this peak. The amount of water descending the shaft varies irregularly with seasons. Much of the water enters the cave through a subvertical joint located at -10 m depth above main survey station.

GEOMORPHOLOGICAL SETTING

The peculiar landforms on the summit surface of the peak are the result of two

different processes. In accordance with these processes, we have considered two groups of surface and underground landforms:

- Forms come from tectonic and structural movements or primary forms.
- And forms derived from selective and cavernous weathering stage. They are post-tectonic, secondary or consequent forms.

The term “consequent form” is used in the sense of post-genetic cave karst development.

Riedel shearsystem

On the landscape we survey many landforms due to tectonic processes. Dominant tectonic fractures were measu-

red in most of these relevant landforms. (Figure 3).

Endo- and exo-karstic surveys often display a systematic geometrical relationship with respect to structural elements. In surveyed structural elements, mainly directions are N110°E, N20°E, N160°E and N55°E.

The N110°E fractures are at 10-20° to the fault plane, and would be the Riedel shears or primary synthetic shears (R-fractures) on a local Riedel shearing system. Then N20°E structures would be the conjugate Riedel shears or primary antithetic shears (R'-fractures) and finally N160°E would be the secondary synthetic shears or through cutting fractures (P-fractures) of this system.

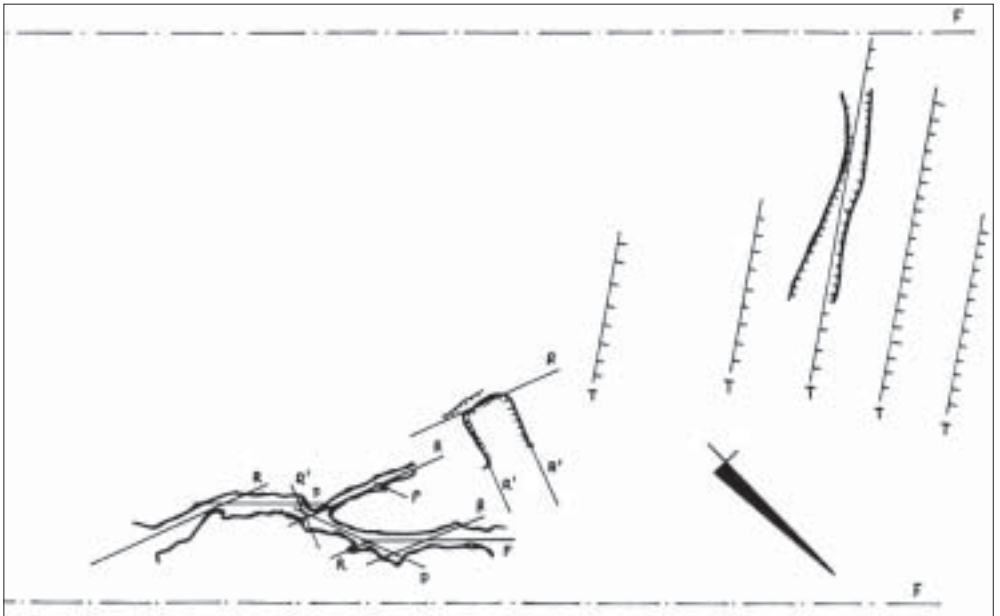


Figure 3. Endo and exokarstic forms and fractures (GROBA & VAQUEIRO, 2003). F: Marginal fault (Y), N135°E-N140°E; R-fractures: N110°E; R'-fractures, N20°E; P-fractures, N160°E; T-fractures, N55°E.



Photo 2. Local set of T-fractures. Black lines are showing main T-fractures.

All forms are enclosed to the fracture sets defined by these directions. I.e., the cave is developed along synthetic and antithetic fractures (R and R'), while many elements located on the summit surface of the peak, nearest the ruins of the castle named *Fortaleza do Montesagro*, are aligned with antithetic and throughcutting fractures (R' and P).

Moreover, there is a local set of fractures where the lips are N55°E structures at about 40°-45° to the Y shear plane. These fractures are stepped and filled by Quaternary colluvial deposits, and would be considered like stepped transtensive fractures (T-fractures) in the Riedel shear system (Photo 2).

The most important T-fracture is the one called *Camiño da Raiña Lupa*. The distance between the lips are about 2 m.

Natural erosion and a probable digging at the Middle Ages have removed these deposits reaching 10 m of depth (Photo 3).

Note that at the Middle Ages upper entrance was modified and a door was installed to make better use of the cave. At that time, lower entrance was dug and stepped along a drainage tube. This passage is called *Contramina de Juan Antón*. The modifications in the cave and T-structures made up a strategic zone around *A Fortaleza de Montesagro*. (GROBA & VAQUEIRO, 2003; VAQUEIRO, 2003).

The *Falla Marginal* would be a fault with vertical and horizontal movements (IGME, 1982). The R-, R'-, P- and T-fracture directions would determine the existence of a sinistral strike slip fault (GROBA & VAQUEIRO, 2003).



Photo 3. *Camiño da Raiña Lupa*, a well-developed T-fracture.

Forms, structures and shear fractures are resumed on table I.

Riedel shear	Fractures	Most representative examples
Y	N135°E-N140°E	<i>O Palacio da Raiña</i> passage <i>O Burato dos Mouros</i> passage
R	N90°E-N110°E	<i>A Cheminea</i> passage <i>Contramina de Juan Antón</i> gallery
R'	N20°E	<i>Montesagro</i> Castle basement (aljibe)
P	N160°E	Head of main shaft: <i>O Pozo do Pico</i>
T	N55°E	<i>A Rúa da Raiña Lupa</i> fissure

Table 1. Structures and features related to the Riedel shear system.

Dynamometamorphic breccia: The quartz grus

Pico Sacro is the most representative visual element of the quartz dyke. The quartz of this dyke is characterized by whiteness and purity (IGME, 1982).

Two endokarstic different facies have been observed. The less plentiful is like an

incipient quartz-sandstone, and it has been explained like a quartz breccia or mylonite. This facies is whiteness, softness, and has a saccharous texture like a weathered sandstone.

Incipient alveolizations, cavernous weathering and piping are related to this facies. Many little piping tubes have the rims of opal-metallic oxide coralloids.

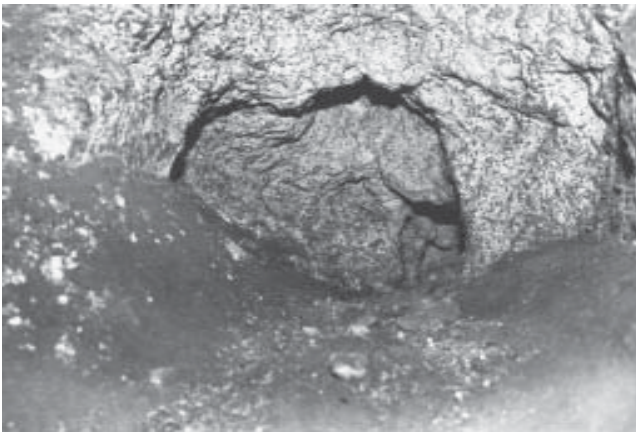


Photo 4. Weathering forms developed out of a feeding – piping tube.



Photo 5. Cavernous weathering forms developed on NE summit face of the peak. Forms are aligned to main tectonic structures.

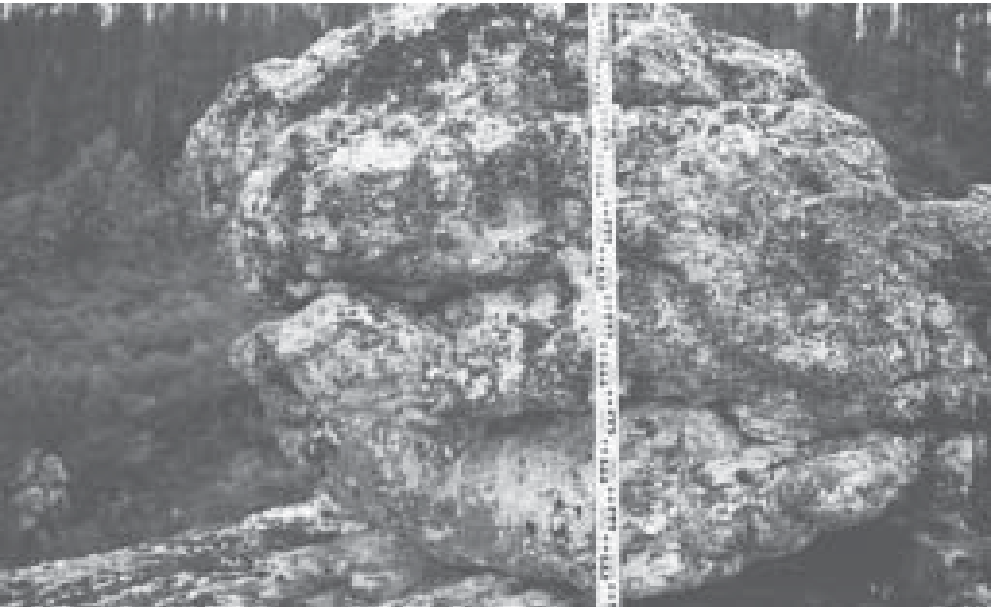


Photo 6. Boulder affected by selective weathering through sub-horizontal joints .

The second facies is whiteness and hardness, and is characterized by a fine-grain matrix. Opal and surface iron-metallic coatings are mainly related to this facies.

Weathering landforms

The peculiar landforms on the summit surface of the peak are the result of selective weathering process acting mainly along the joints (fractures, pseudobedding planes,...).

On the surface of many blocks, mainly landforms due to selective weathering through fracture sets and pseudobedding planes can be observed. The different forms are combined with cavernous weathering.

The forms developed by preferential weathering inside horizontal joints are mainly overexcavated walls, pseudo-flared forms, feeding and drainage tubes. Preferential weathering inside vertical joints produce incipient pseudokarren-type forms, tafoni forms, and gnamma forms.

Underground features produced by weathering have been studied along the main sinkhole. These features have been compared with the surface landforms. Finally, three groups of forms are considered:

- Gnamma forms. They are pan-type. The biggest is about 390 mm of diameter (Photo 7).
- Cavernous weathering forms: Flared walls and alveolar weathering forms. A special type is the tafoni form (honeycomb weathering) (Photo 5, 8).



Photo 7. An exokarstic gnamma, pan size, named “*As Pegadas do Cabalo de Santiago*”.



Photo 8. Tafoni-type forms: Cavernous weathering and alveolations weathered in honeycomb mode.

- Karren-type forms: Small karren forms occur on vertical or overhanging walls developed according to sub-vertical pseudobedding planes of the quartz dyke. These forms are related to tafoni-type forms.

Shaft characteristics: The cave like a pseudo-karstic landform

The quartz dyke related to the *Falla Marginal* fault contains several subvertical fissure caves, but only has been located a real deep vertical shaft.

This deepest and best-developed structure is the *Cova do Pico* shaft (-32 m) located on the *Pico Sacro* peak (Figures 4 and 5).

The shaft is relatively narrow, and in general contains many vertical steps with profiles resembling right angles. These steps are related to shear faults intersections. The entrances are relatively narrow and their widths were modified by anthropic activities.

Feeding and drainage passages and conduits are relatively narrow. Their entrances and passages are commonly filled with soil, recent organic detritus, and crumbling of debris from cavernous weathering, alteration or desaggregation. The main tube, called *A Cheminea*, is developed along a R-fracture and reaches the summit surface through a tafoni-like structure located in the raintank of the castle basement. This tube has no accesible connection to the surface.



Photo 9. Descending the main shaft.



Photo 10. At the bottom of the first vertical step.

All passages are related to dominant shear fractures. Their dip angles are very important in controlling the shaft shapes and conduit development. In deep vertical passages all the main fractures are sub-vertical, dipping 70-90°. Most of the

joints observed in the shafts are simple tectonic-shearing fractures and foliation structures.

The bottom of the shaft, named *Burato dos Mouros*, is filled with debris such as sinter fragments, recent organic detritus, allophane

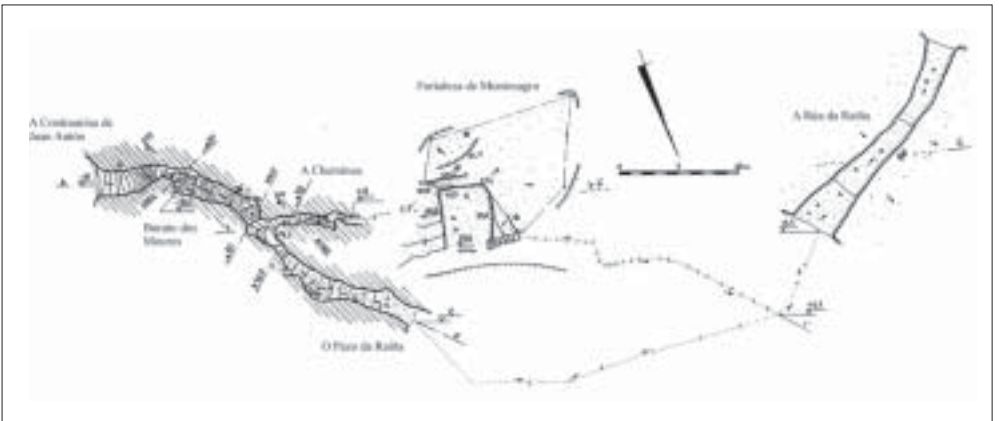


Figure 4. *A Cova do Pico*. Plant view, surveyed by C.E.Maúxo (GROBA & VAQUEIRO, 2003).

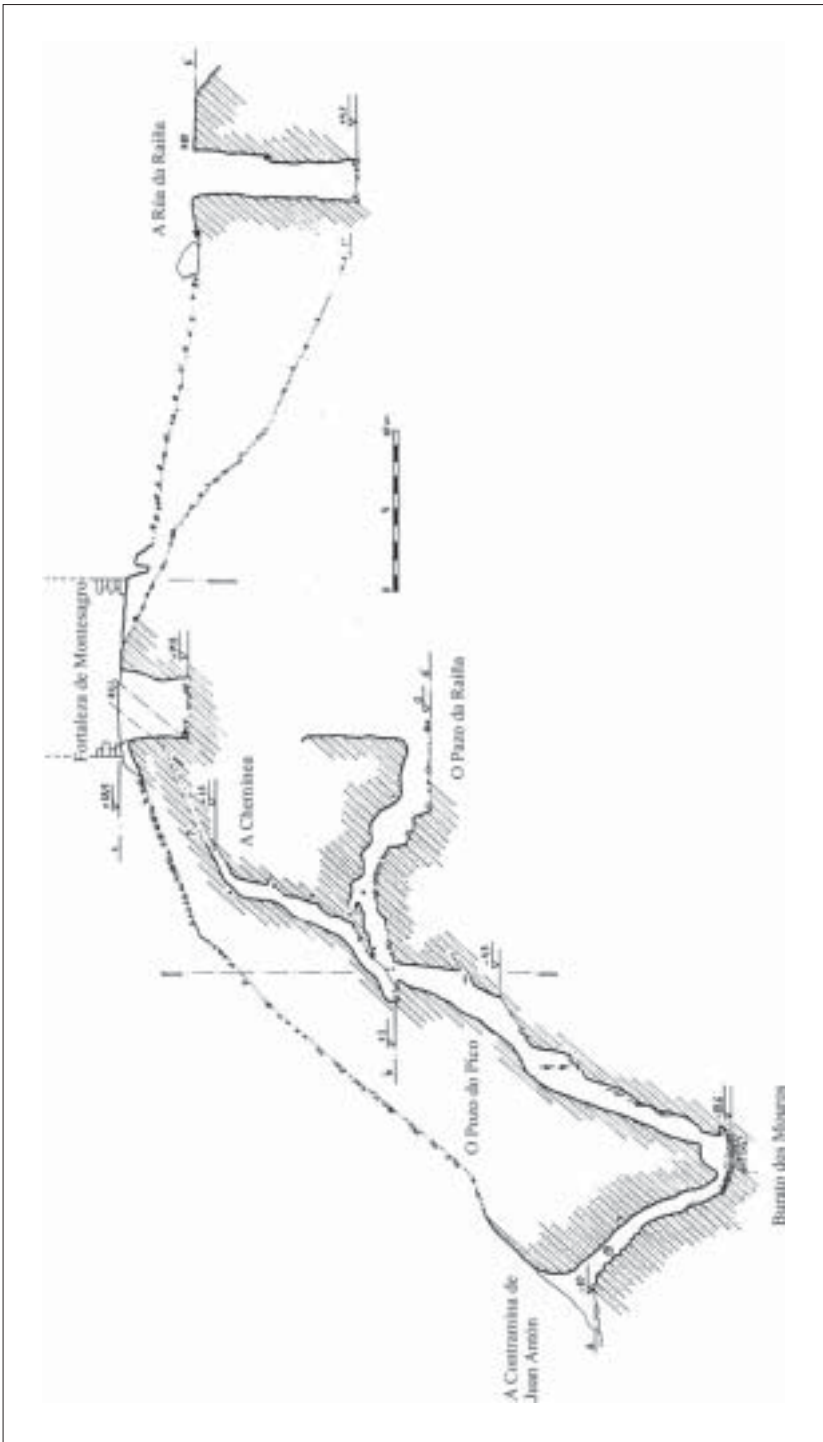


Figure 5. *A Cova do Pico. Elevation view, surveyed by C.E.Matxo (GROBA & VAQUEIRO, 2003).*

and crumbling of debris and quartz sand from cavernous weathering. No stagnant water has been located, and drainage is considered.

As the shaft deepen, weathered forms are less developed. Piping and cavernous forms would be located at the top of the main shaft, and they are mainly related to R-fractures. At the shaft bottom, only tectonics profiles and forms are present.

Shaft development would have started out from R-fractures. When these fractures reached summit surface, water drainage and piping could have initiated. Y-fractures seem to connect the conduits started out from R-fractures.

Note that at low strain, R is formed first, followed by R' and P fractures. Until strain increase, Y fractures start to form at various levels inside the gauge. Eventually, new low shear strain zones start to form between two Y fractures, reproducing the initial situation at a sub-zone inside the original shear zone. At very high strains, finally, Y fractures parallel to the moving fault blocks take up all shears.

Vertical profiles are at the intersections of R-, R'- and P-fractures. In this stepped zones, weathering forms are located at roof.

SPELEOTHEMES

Caolinite deposits, opal coatings and Al/Fe organic fulvic complex speleothemes have been located in boulder and tectonic caves.

Caolinite speleothemes are formed by water washing. This erosion produces flowstone-type forms and microgours. These concretions are located at -32 m of depth. (Photo 11).

Opal coatings and opal brotoids are mainly related to piping tubes.

Organic complex speleothemes have been located at -10 m deep on the SE wall (Photo 12). These concretions are developed rounding a sub-vertical joint into which water enters the shaft. Existence of this organic complex implies an epikarstic humic fractionation under acid environment. Postgenetic percolation is produced and water leaks downward along major tectonic fractures.

Organic complex speleothemes are composed by multiples layers of fulvic complex, organic debris and other leucocratic feldspar clays. It can be also found in granitic pseudokarstic caves where local amorphous aggregates form stalactites, stalagmites, microcascades and flowstone-like structures in which white, brown and dark mineral layers alternated. Usually, water in microrimstone dams is pH ranging from 4.0 to 4.5, and cations are Al and Fe. (VAQUEIRO, 1994; 2002).

At pseudokarst caves, well-developed speleothemes of opal-A are far rare than those of organic complex, but all they occur in a range of types including stalactites (fractal needle grown on tree mode), stalagmites (brotoids), micro-rimstone dams and flowstones.

In silica karst of the Aonda Cave System, pH diminishes with depth (MECCHIA & PICCINI, 1999). However, in the shaft of *A Cova do Pico*, pH seems to increase with depth from 4.0 or 4.5 at the epikarst zone to values as high as 6.2 near the shaft bottom.

NOTES ABOUT ENDOKARSTIC CLIMATOLOGY

Endokarstic air movements have been observed. Two stages are considered:

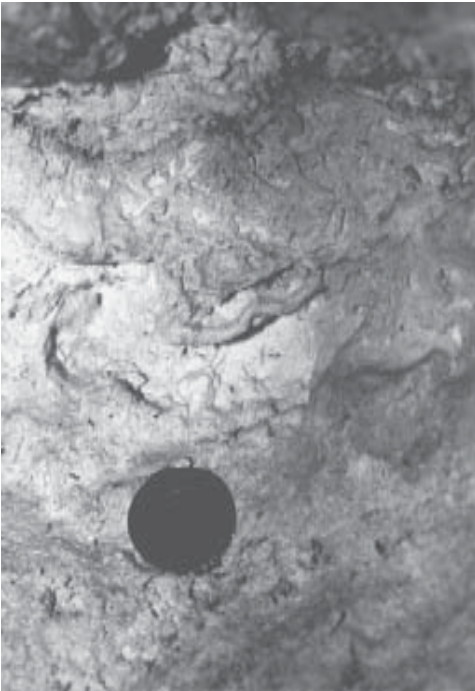


Photo 11. Caolinite deposits eroded by water washing.

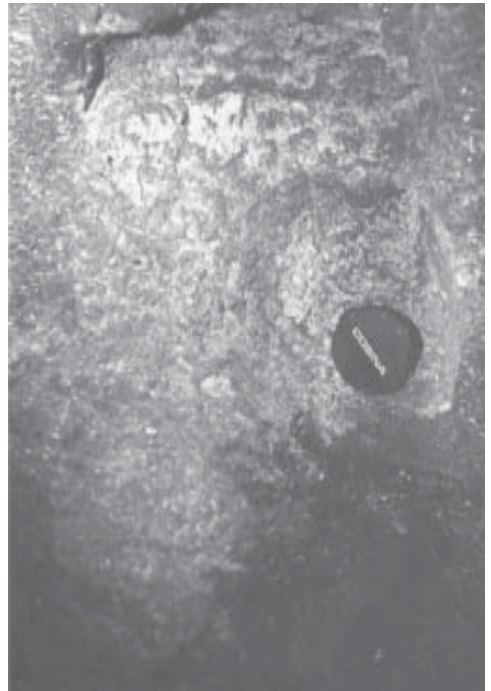


Photo 12. Organic complex speleothemes (detail).

a. External air flowing aligned to R-planes: The cave becomes a blowing pipe. Endokarstic air speed is about 10 m/s at the top of main shaft (August 2002).

b. External air flowing oblique to R-planes: Air suction is produced by Venturi's effect. Measured data is resumed on Table II.

Table 2. Endokarstic thermal gradient and air speed when Venturi's suction is produced by an external air flowing oblique to R-plane (Date: 18.10.03. Wind speed ranges between 3.4 and 4.5 m/s. Direction NW).

Station Name	T (°C)	Air speed (m/s)
Upper Entrance (+0 m)	15.1	0.0
First shaft step	14.0	0.0
Speleotems (Air)	13.0	0.0
Speleotems (water)	12.9	0.0
Allophane deposit	12.2	0.0
Burato dos Mouros	12.9	0.0
Lower entrance (at the bottom area , -32 m)	14.4	1.6
Lower entrance (at the top area, -10 m)	15.3	0.2

CONCLUSIONS

The close proximity and orientations of the *Falla Marginal* and the sets of fractures in *Pico Sacro* suggest that these two structures are related. The analysis of endo- and exokarstic surveyed forms may indicate the existence of a sinistral Riedel shear system. All forms, including the cave of *A Cova do Pico*, are enclosed to this shear system.

Forms are classified in two groups:

- a. Tectonic structures or primary forms.
- b. Secondary structures or forms developed out of quartz breccia by selective cavernous weathering.

A Cova do Pico has been classified like a tectonic cave (VAQUEIRO, 2003) (Table III).

GROUP: Caves not form directly by flowing water		
3.4	TYPE: Fissure Cave	
	3.4.2	SUBTYPE: Tectonic Cave

Table 3. Genetic classification of the shaft .



Photo 13. A nubbin surface: Epikarst fracture pattern.

Although for cave development previous tectonic movements are more important than selective weathering, endokarstic weathered forms and speleothemes are postgenetic features, which determine local pseudo-karstification.

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