Cadernos Lab. Xeolóxico de Laxe
Coruña. 2008. Vol. 33, pp. 83 - 99

ISSN: 0213 - 4497

Some minor features (tafoni, cavernous forms) in the granite terrains of Los Riojanos (Pampa de Achala, Sierra Grande de Córdoba, República Argentina). Geometric and morphologic properties

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Recibido: 1/11/2007 Revisado: 8/4/2008 Aceptado: 20/7/2008

Abstract

Several minor cavernous features can be well differentiated in the granite terrains of Los Riojanos (Pampa de Achala, Sierra Grande de Córdoba, República Argentina). The cavernous morphology always appears related to a well-defined discontinuity rock system, which is determined by the endogenous massif history. Here, all the observations about cavern-like features, usually called tafoni, are located near intrusive border of outcrop. The samples of this work were recorded from a recent research on granite landscape. Their analyses can provide significant information to explain the geomorphic evolution of the massif. Their geometric and morphologic nature analysis is the first step in order to clarify what the morphologic and evolutionary keys linked to the genetic conditions towards a better landform explanation are. The measurement system and their three-dimensional projection are only previous information to obtain the summarized data (volume). The values distribution and their fit goodness are also the previous step for a suitable statistical processing. Considering the configurative aspects and the relationships with the host rock forms, we can advance towards the knowledge of these granite landforms.

Key words: tafoni, cavernous forms, endogenous forms, granite landforms, granite landscape, Argentina

INTRODUCTION

The granite landscape is a puzzling where the diverse components or landforms are interdependent. Their generation and development pathways derive from a multi-feedback set of different signs subject to contingency along the time (THOMAS, 2001). At a local scale, the study of one landform typology analyzes their convergent or divergent behaviour on some rock masses. This behaviour is interpreted in an evolutionary context from a granite outcrop where a set of endogenous and exogenous events can define and model the rock units (VIDAL ROMANÍ et al., 2006). This work deals with the minor granite landforms usually known as tafoni or cavernous forms, although they have been termed with another names in the geomorphologic research (UÑA ÁLVAREZ, 2005). They result from a hollowing out process that commonly can be observed on the granite landscape underside the blocks or boulders and into the rock walls, always related to the rock discontinuity system (TWIDALE and VIDAL ROMANÍ, 2005). Therefore, the typology of all these cavities can provide significant information about the genetic and evolutionary landscape events. This study deals with some tafoni features in "Los Riojanos" (Pampa de Achala, Argentina).

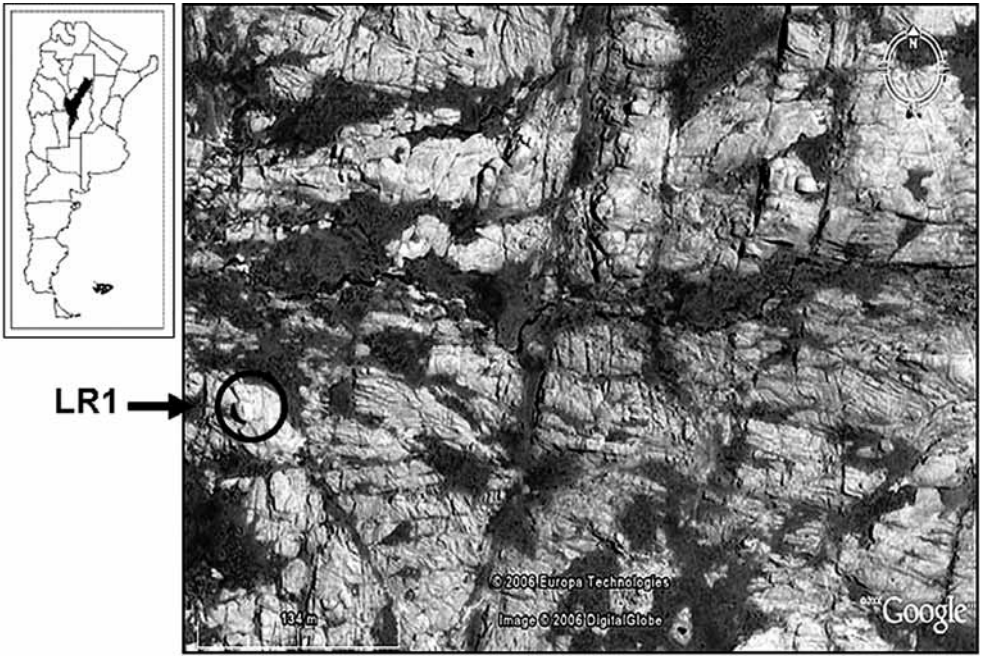


Fig. 1 Location of Sierra Grande and the study area (Google Earth).

Photo 1. General view of the granite landscape in Los Riojanos.

Photo 2. Particular view of several granite cavernous forms.

STUDY AREA

All the recorded cavities are located in the geographic unit "Sierras Pampeanas", north-western region of Argentina, concealment in Sierra Grande de Córdoba (cerro Champaquí, 2.790 m a.s.l.). The Sierra Grande de Córdoba is a granite massif intruded between the Chaco-Paraná basin and the Pre-andina range. The boundary research concerns their high plains of "Pampa de Achala", in the western area (Fig. 1), declared Natural Hydrological Reserve in 1995. From the bio-geographic viewpoint, the Pampa de Achala is a particular eco-region of the Sierras and Bolsones system with a sub-tropical dry climate. The maximum value of annual precipitation is 200 mm that is concentrated in the summer months. The mean annual temperature is 14ºC but during the winter months has been recorded -5ºC; the temperature variation along the day usually shows a wide range from 5ºC to 35ºC in a normal summer day. From the geomorphologic viewpoint, the Pampa de Achala is a horst form which has risen during the post-Mesozoic times; these events have affected a previous etch surface (CARIGNANO et al, 1999) with a multistage time sequence.

The research sample comes from "Los Riojanos" (in forward LR), extending between latitude 31º28´40´´S - 31º29´15´´S and longitude 64º55´00´´W - 64º55´55´´W (Photos 1 and 2). The studied landforms are placed between 1,686 and 1,819 m a.s.l. On the whole, the generation of granite landforms in the study area (a tectonic relief) starts from the endogenous events related to the intrusive process; their linked patterns appear in the periphery near the former intrusive border of the magmatic body where it is defined the sampling station for this research (VIDAL ROMANÍ et al, 2007).

SAMPLING AND WORK METHODS

In order to collect a significant statistical sample, the fieldwork has sustained two main selection criterions of the forms. Only just were collected the forms which hostess block remained "in situ" (not moved or not split). In addition, the sampling (n=25) was limited to the greatest forms. The measurement of the different cavities form is really free-scale in nature; thus, it permits a selective analysis which can be used to establishe a hierarchical setting. But it is clear also that this research approach simplifies the morphological features. Because of that in the present work the measures are detailed from a two-dimensional plane to a three-dimensional volume. In accordance with our recent related works (UÑA ÁLVAREZ, 2004; UÑA ÁLVAREZ and VIDAL ROMANÍ, 2006), the form attributes or the studied variables taken into account deal with the current cavities design. In this context primary and secondary data were managed.

Photo 3. Basal feature.

Photo 4. Lateral feature.

Photo 5. LR8 - Baldachin form very developed in volume.

The primary data of the landforms were recorded by the fieldwork (August 2006). They included features related to the location, the shape and the qualitative properties of the cavities. The primary measures inside a cavity were the dimension of the main horizontal axis (y, x) as well their perpendicular vertical axis (z). The values of these measures (unit = metres) were stated on a three-dimensional space. The projection in a Cartesian coordinates provided some geometric properties which were very significant to characterize an empty space inside a rock unity, in their size and their shape (Fig. 2); this field information was basic to know the opening and deepening of the cavities. Moreover, during the field research it was especially important to identify the nowadays support system of the cavities (Fig. 3): some forms preserve a central granite pillar on the adjacent rock plane whereas other forms show only lateral ringlets supports more or less differentiated; and occasionally, it can be observed a hanged granite pillar which remains of the previous support. The secondary numeric data of the landforms were the evacuated rock volume which was noted in cubic metres. This volume datum required the previous approximation about the three-dimensional shape for use an adequate calculation formula. So, the geometric bodies determined by the measured axes and their projection on a three-dimensional space represent a basic analysis tool.

All numeric data were object of a statistical processing. First, we consider some statistical descriptive measures. Between them, two standardized stats were used to explore if our sample comes from a normal distribution: the skewness which looks for lack of symmetry in the data distribution; and the kurtosis which reveals if the shape is more peaked or flatter than the normal distribution. The best distribution fit of our data was full determinated by the Shapiro-Wilks test (based upon comparing the distribution quantiles) and Kolmogorov-Smirnov test (based upon comparing the cumulative distribution frequencies).

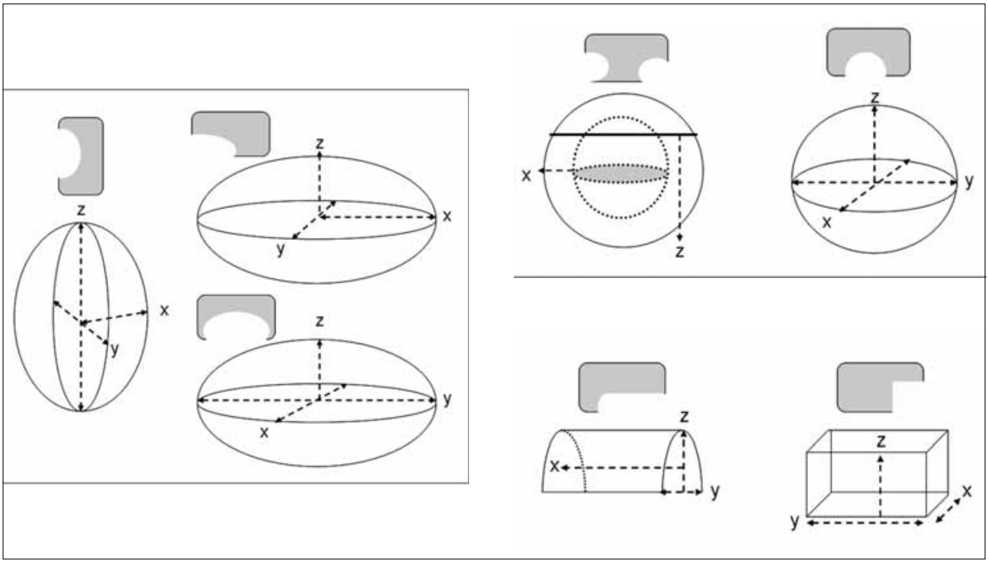


Fig. 2 Ellipsoidal, spheroid and other geometric references.

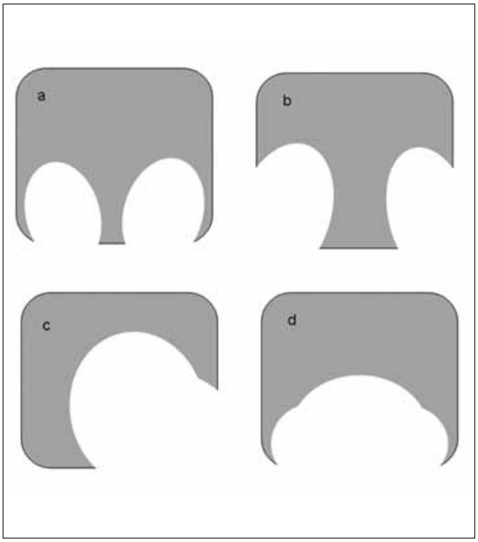


Fig. 3 Supports and rock pillars conditions.

Second, the data processing was stick to robustness with non-parametric stats. The robust measures are the most adequate descriptors for skewed or non-normal shape distribution of data. These statistics are not sensitive to the extreme values (outside values) which should be never excluded in the geomorphic research. In the box plot of the data, the median is marked by the centre vertical line; the lower and upper quartiles comprise the edges of the central box. The analysis ends with the volume data clustering for detecting stage-groups of the cavities. Here, the cluster computes normalized Euclidean distances. The median linkage method uses the median value of all observations as the reference point for distances between pairs of cases. In order to abstract the size and the form of the found cavities were drawn all cross-sections along the (x) axis (Fig. 4).

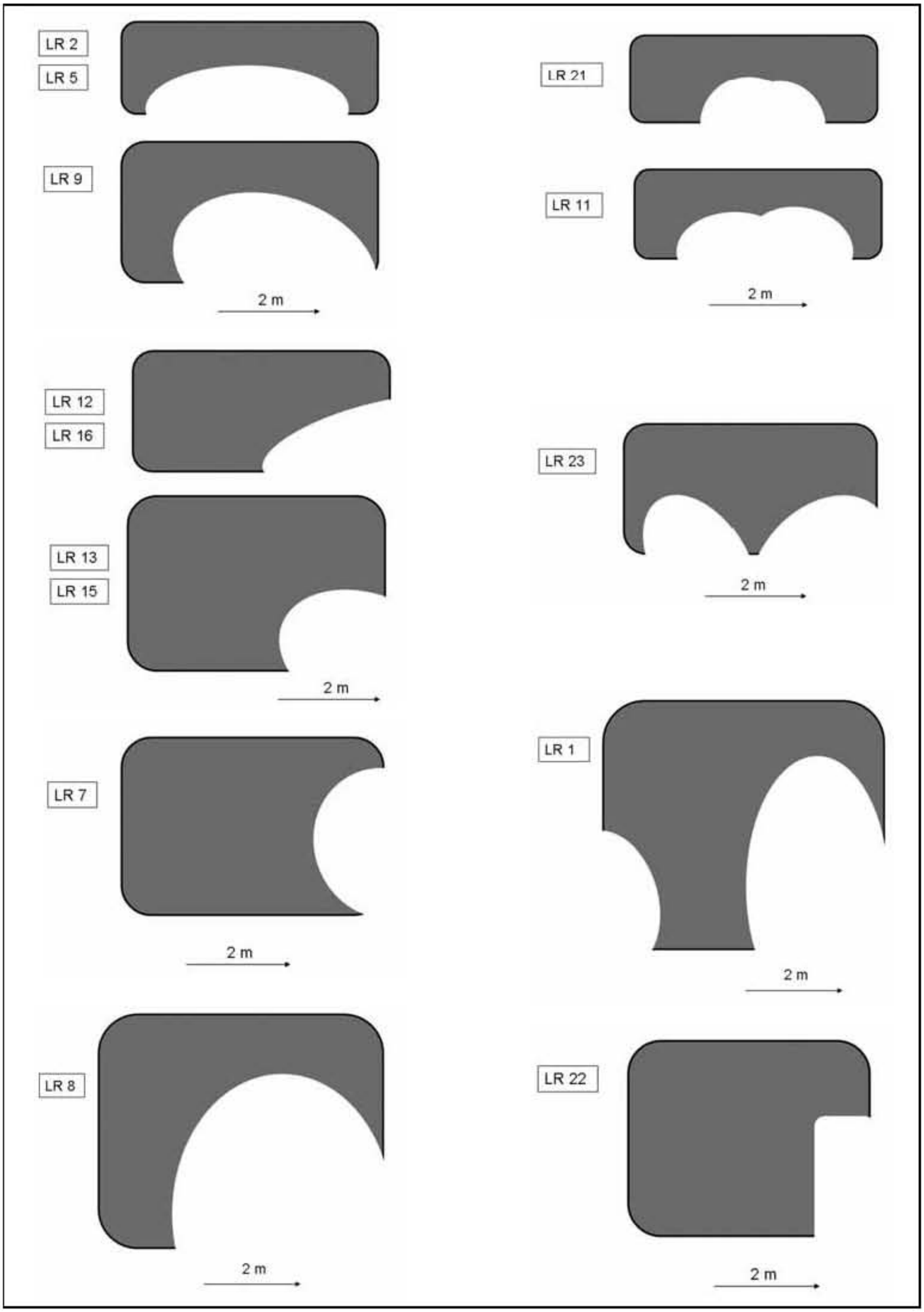


Fig. 4 Tafoni cross-section along (x) axis.

GEOMETRY AND MORPHOLOGIC FEATURES

The geometry reference appears in two ways defined by the main development of the cavities into the hostess block: basal (Photo 3) or lateral (Photo 4). The three-dimensional shape of the cavities can be usually represented as a part of an ellipsoid (Tables 1.1 & 1.2). Generally, the geometric variation of these ellipsoidal cavities (mid-ellipsoidal or quarter-ellipsoidal) implies several specific values from an oblate to a spindle-shaped geometric body.

(y, x, z) RELATION	GEOMETRIC BODY	CASE	y/x	y/z
y = x > z	mid-ellipsoid	LR2	1,00	1,50
	ellipsoid	LR8	1,11	1,56
	mid-ellipsoid	LR5	0,55	2,10
	mid-ellipsoid	LR6	0,56	2,25
y > x > z	mid-ellipsoid	LR20	5,50	6,42
	mid-ellipsoid	LR23	1,77	5,11
	two mid-ellipsoid*	LR9	1,31	3,93
	two mid-ellipsoid*	LR11	1,40	5,56
	two mid-ellipsoid*	LR24	1,20	3,50
y = x = z	mid-sphere**	LR21	1,00	1,00

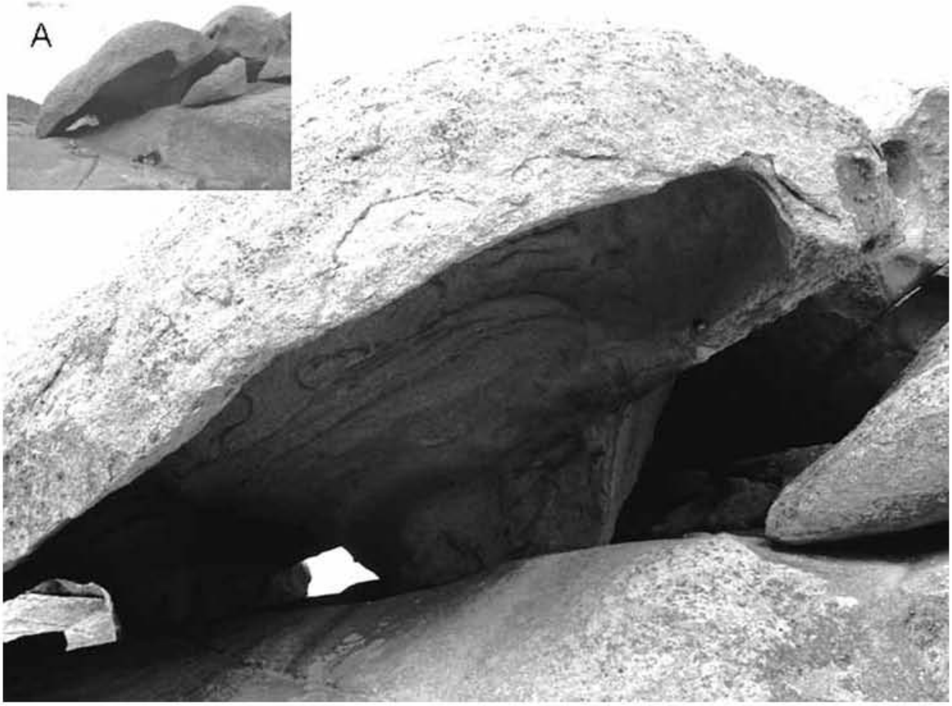
*Complex of two cavities **Complex of three cavities

Table 1.1 Geometry of the cavities with main basal development.

(y, x, z) RELATION	GEOMETRIC BODY	CASE	y/x	y/z
	empty sphere section**	LR1	6,00	8,28
	empty sphere section	LR14	7,30	8,75
	mid-ellipsoid	LR12	2,45	7,36
	mid-ellipsoid	LR16	3,91	3,07
y > x > z	quarter-ellipsoid	LR10	1,11	4,11
	quarter-ellipsoid	LR19	1,56	3,12
	quarter-ellipsoid	LR3	2,20	2,36
	quarter-ellipsoid	LR4	2,60	3,57
	quarter-ellipsoid	LR13	1,47	3,57
	quarter-ellipsoid	LR15	1,88	2,23
	triangular prism	LR17	4,76	9,00
x > y > z	tetrahedron	LR18	1,20	2,50
x > y = z	mid-cylinder	LR25	0,41	1,00
y > z > x	rectangular parallelepiped*	LR22	2,46	1,45
y = z > x	mid-ellipsoid	LR7	1,94	1,00

*Complex of two cavities **Complex of three cavities

Table 1.2 Geometry of the cavities with main lateral development.



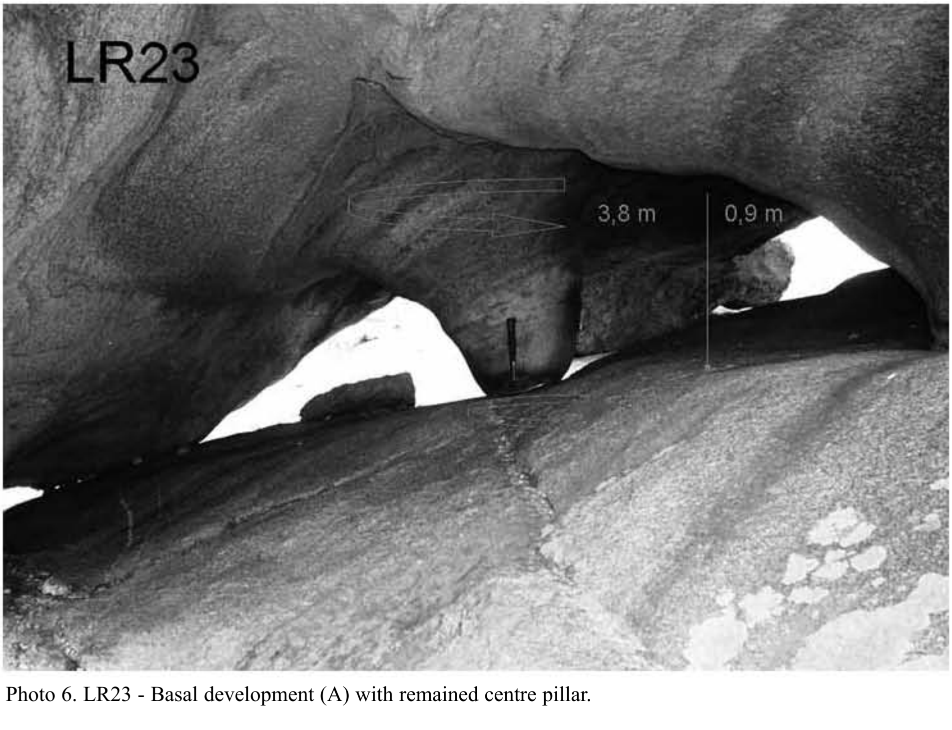


Photo 6. LR23 - Basal development (A) with remained centre pillar.

A

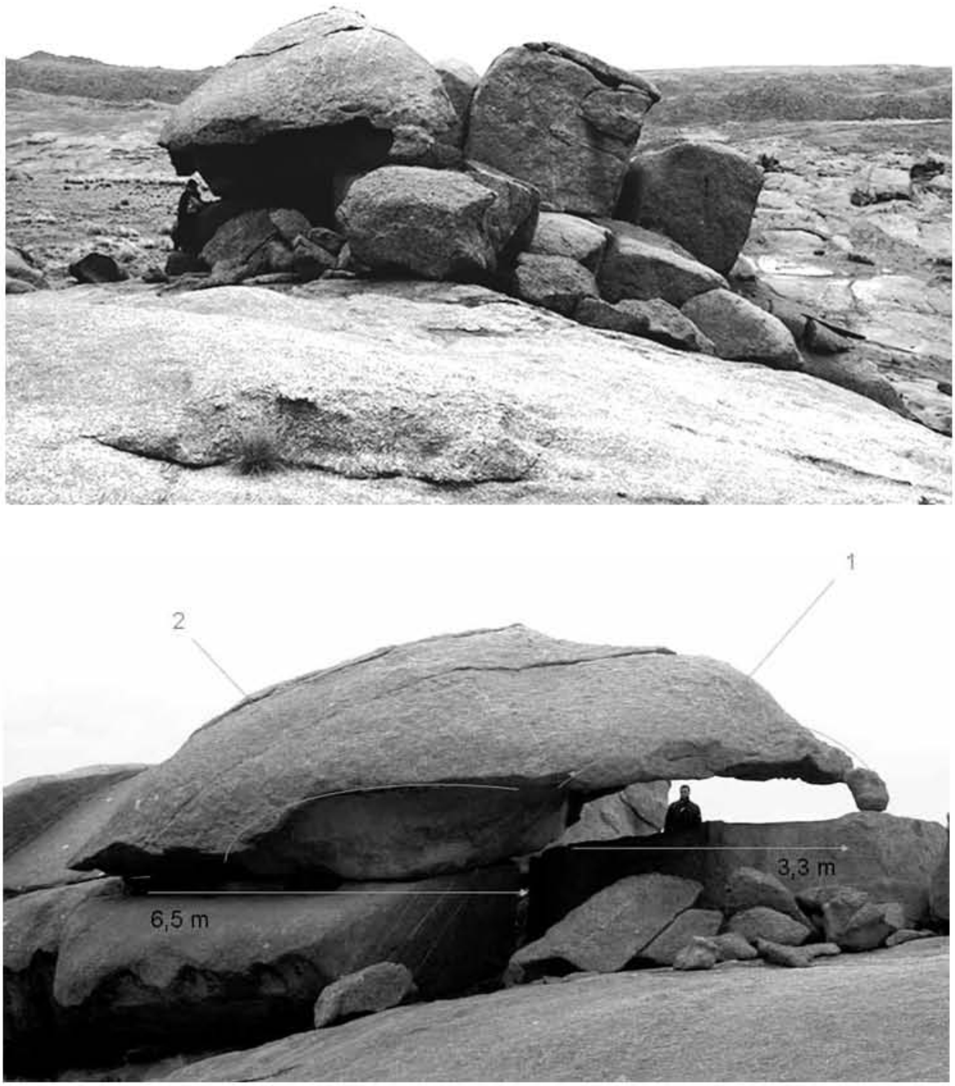


Photo 7. LR9 - Compound basal development (A) related to discontinuities.

Only just one observation was approximate to a complete ellipsoid (LR8 case, Photo 5): in this baldachin form, the volume of their hanged rock pillar (1,07 m^3) was calculated starting from a cylinder with high of 1.7 m and diameter of 0.9 m. Another basal observation with a single mid-ellipsoidal geometry (LR23 case, Photo 6) keeps a central pillar which volume (0.64 m^3) was calculate starting from a cone trunk (upper perimeter = 3.8 m; lower perimeter in support point = 1.98 m and high = 0.9 m). Some forms are compound mid-ellipsoidal bodies as the basal cavity LR9 (Photo 7). It is specially noteworthy the cases where the cavity surrounds external volume of hostess block under one rock umbrella. The greatest of them (and the greatest of the sample, LR1 case, Photo 8) is developed in a block with 26 m of total perimeter engaging the 92% of their external area; the cavity has grown in two empty sphere sections and one mid-ellipsoid section. A smallest number of observations can be represented by a part of a cylinder, one mid-sphere, a tetrahedron, a triangular prism, or a rectangular parallelepiped (LR22 case, Photo 9).

These geometric properties are interpreted as the indicators of the possible initial stress distribution between the blocks (minimum stress = maximum lengthening; maximum stress = maximum shortening) according to the discontinuity system pattern. They are also related to the more or less regular development of the cavities from that initial design.

STATS	y	x	z
Minimum	1,00	0,80	0,70
Maximum	24,00	5,10	4,00
Mean	5,87	2,75	1,53
Stand Deviation	4,82	1,24	0,82
Stand Skewness	2,35	0,13	1,67
Stand Kurtosis	6,21	-0,97	1,94
Lower Quartile	2,89	1,55	1,05
Median	4,30	2,90	1,25
Upper Quartile	7,60	3,50	1,75

Table 2. Statistics of the measures (metres).

On the whole, there are several determinant questions in the measure data analysis that implies the statistical nature of the geomorphic variables (Table 2). The data distribution of the (y) and (z) variables exhibit non-normal properties: median always smaller than mean, asymmetric shape, peaked form and presence of outside values. All probability values resulting of applied test are < 0.01 and we can reject a normal distribution with a 99% confidence level. In the opposite sense, the data distribution of the (x) variable show a mean next to the median stat, lack of outside values and more symmetric shape (the p-values resulting can not reject a normal distribution). Then, in order to explain the volume variation the research requires the use of robust statistics. Furthermore, the results of different landforms sub-sets, for instance basal and lateral, display the same statistical properties. Starting from these conditions, logically the volume data are characterized by a non-normal distribution (Fig. 5); really, they can better fit to a log-normal distribution which behaviour path is of exponential nature. And their values reflect set forth the high asymmetry and peaking of the data distribution.

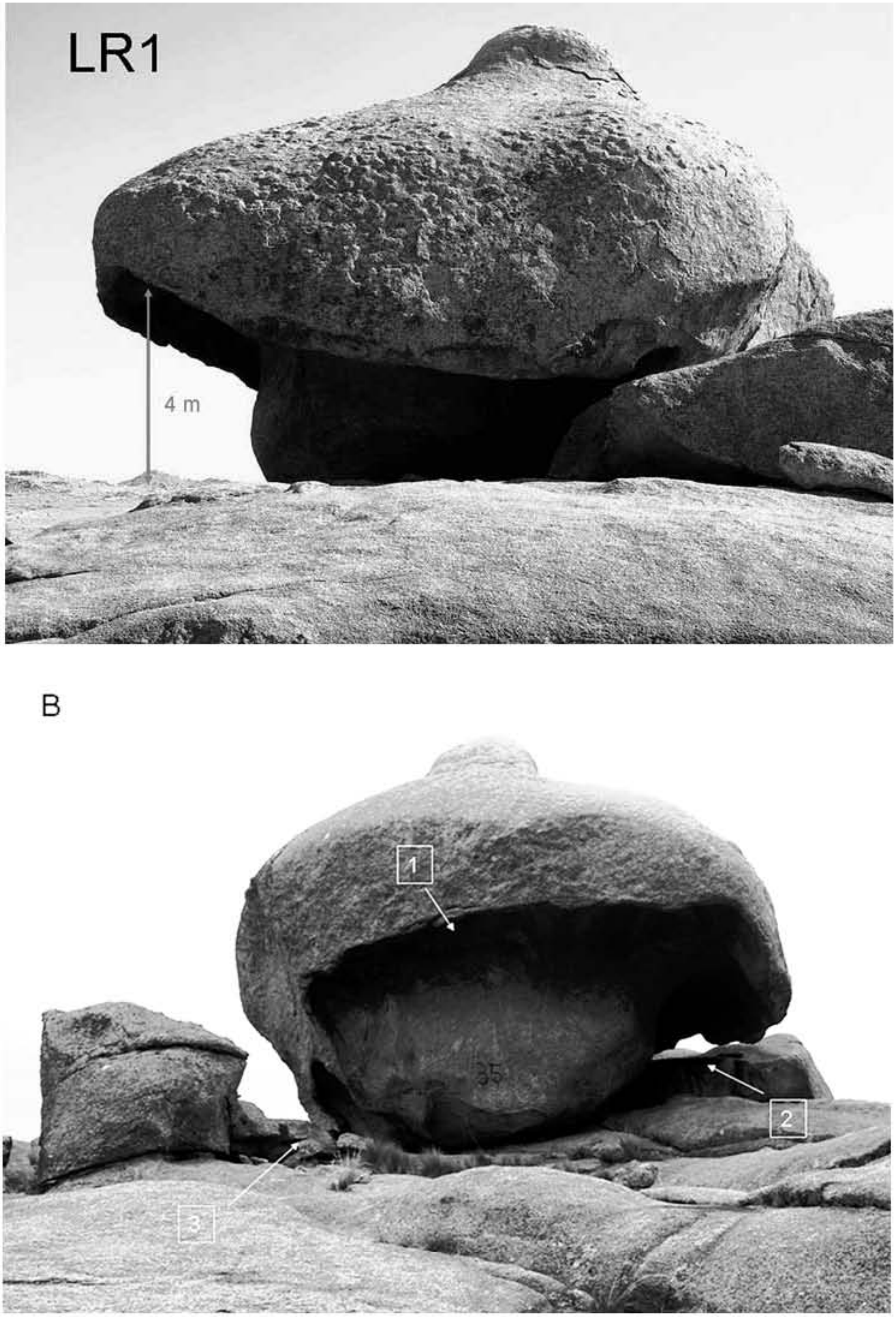


Photo 8. LR1 – Tafoni situation and differentiated cavities (B).

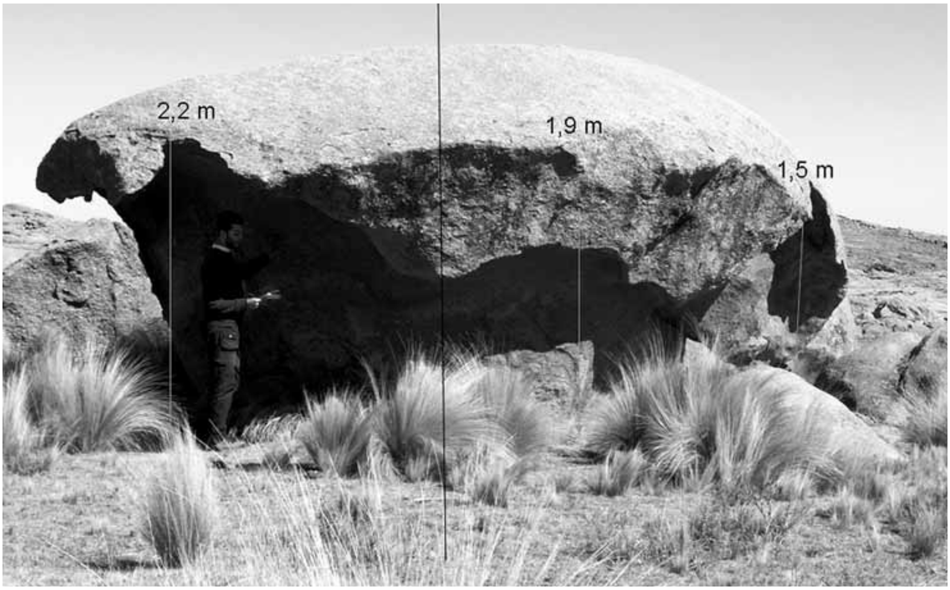


Photo 9. LR22 – Rectangular cavity form.

So, these features and the wide range of volume results in the sample or their sub-sets advice the robust stats selection as the goodness indicators for characterize the geomorphic cavities stage. The median, which describes the midpoint of the volume distribution, with their confidence interval and the quartiles has been used to determine the size stages in the sample (Table 3).

SIZE	SC	CASES RECORDED	VOLUME LIMIT
Smallest	1.1	LR2 LR4 LR6 LR14 LR16 LR18	3,53
Small	1.2	LR3 LR11 LR24	4,72
Median	2.0	LR7 LR10 LR17 LR19 1R20 LR21 LR25	8,03
Large	3.1	LR12 LR15	16,88
Largest	3.2	LR5 LR9 LR22 LR23	30,00
Outlier	4.0	LR8 LR13 LR1	> 38,00

Table 3. The size stages (volume in m^3).

As regards this classification the lower stage codes (SC) are grouping the less developed forms while the upper stage codes are grouping the more developed forms. The clustering multivariate technique provides equally different groups starting from similarity of the volume cavities (Fig. 6).

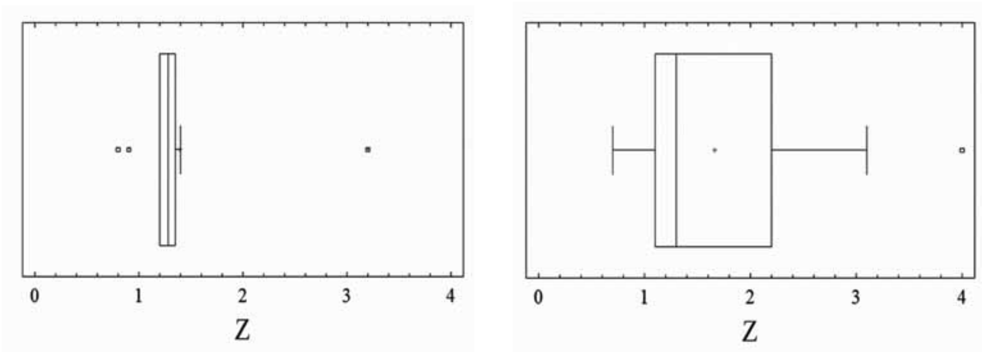


Fig. 5 Box plot for (z) values in the basal (left) and lateral (right) sets.

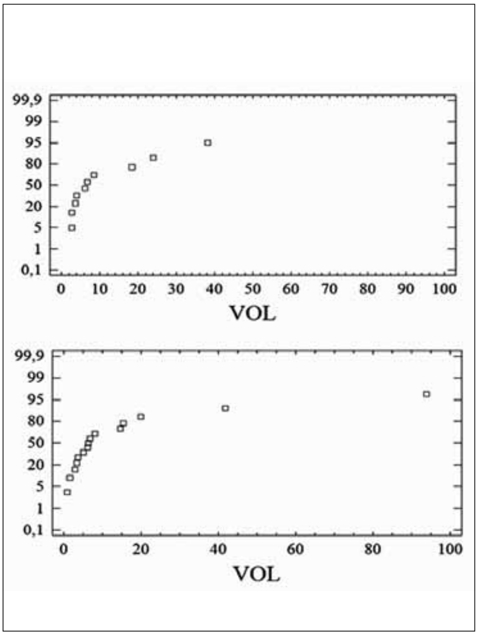


Fig. 6 Normal probability plot for volume data in the basal (upper) and lateral (lower) sets.

PROSPECT STATEMENT

The morphologic properties of the tafoni forms display a known behaviour: the results agree with those published about other similar forms in granite and non-granite terrains (MATSUKURA and MATSUOKA, 1991; SUNAMURA, 1996; NORWICK and DEXTER, 2002). These works (like MELLOR et al, 1997) also sampling in their study area only the largest tafoni (usually n = 25) and then took sub-samples or sub-sets for the detail analysis. It is clear that the tafoni in Los Riojanos (Argentina) are always related to the discontinuity rock system. The cavities start from their basal or lateral planes whatever their orientation. Many enclosed forms present here are termed as “boulder tafone” or “sheet tafone” types. But they are also many opened forms similar to which are termed “side-wall” type and “mushroom rocks”. The analysis of qualitative observations shows that we deals with forms at the growth stage II, III, IV (TWIDALE & VIDAL ROMANÍ, 2005 o.c.). The alveoli and the flaked surfaces are present in the inner walls of median size forms whereas the scalloped surfaces are present in the inner walls of large size forms.

The size of the studied cavities is larger than other published data on granitic rocks. For instance, GRENIER (1968), in the Atacama desert of Chile, pointed out the lateral hollows developed on granodiorite as the oldest forms with a maximum (z) measure of 2.0 m and a maximum (x) measure of 3.0 m. On the other hand, DRAGOVICH (1969) has provided many side-wall (x) measures in Australia with a maximum value of 1.52 m in granite. The "typical basal cavern" with alveoli (z = 1.3 m) studied in Finland by KEJONEN et al. (1988) and the lateral case presented by BAONZA (1999) as "particularly forms" (z = 1.8 m) have less size than the cavities here studied. And the data from basal forms in Doeg-Sung Mount (Korea), measured by MATSUKURA & TANAKA (2000), are equally a minor range (maximum z = 1.6 m). Hitherto the basal cavities measured in Galicia (UÑA ÁLVAREZ and VIDAL ROMANÍ, 2006) neither reach (maximum z = 1.20 m) the size of the sample from Los Riojanos (Argentina).

We think that these cavernous forms are structural landforms, in the sense that they are due to exploitation of rock weaknesses by exogenous agencies of weathering and erosion. In this way the term "weaknesses" is related to the endogenous printed features of a granite outcrop. The cavities geometry and their size variations are determined by the shape and the size variations of host blocks. All these conditions have an intrinsic link with the deformation which can affect a rocky massif. The discontinuities pattern of the granite and their time evolution (i.e. from cubic to round blocks) is significant in the present landscape. But one truthful significant process is of endogenous range (the migration and load concentration model): this process printed special susceptibility to alteration (lacunars spaces) on zones between the blocks in the solid state of rock (VIDAL ROMANÍ, 1983; 1989) later subject of external agencies.

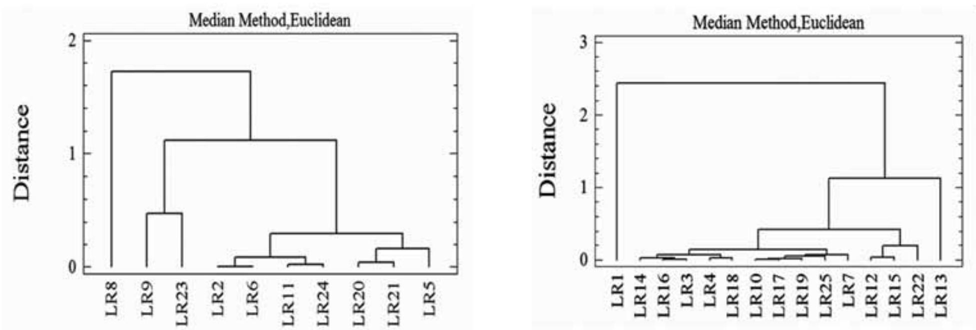


Fig. 7 Volume clustering in thre basal (left) and lateral (right) sets.

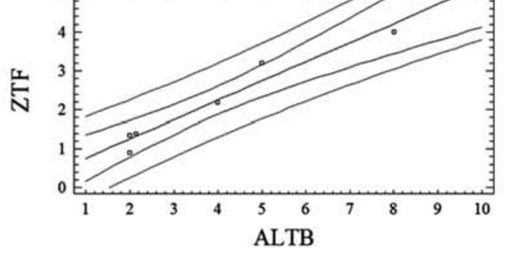


Fig. 8 Relation between (z) measures (ZTF) and host block size.

REFERENCES

BAONZA DÍAZ, J. (1999). Varios tafoni singulares en la Sierra de Guadarrama (Bustarviejo, Madrid). *Cuat. & Geom.*, 13 (1-2): 53-62.

CARIGNANO, C., CIOCCALE, M. and RABASSA, J. (1999). Landscape antiquity of the central-eastern Sierras Pampeanas (Argentina): Geomorphological evolution since Gondwanic times. *Z. Geomporph. N.F.*, 118: 245-268.

DRAGOVICH, D. (1969). The origin of cavernous rock surfaces (tafoni) in granitic rocks of southern Australia. *Z. Geomorph.*, 13: 163-181.

GRENIER, M.P. (1968). Observations sur les taffonis du désert chilien. *Bull. Assoc. Geogr. Fr.*, 364/365: 193-211.

KEJONEN, A., KIELOSTO, S. and LAHTI, S.I. (1988). Cavernous weathering forms in Finland. *Geogr. Ann*. 70A (4): 315-322.

MATSUKURA, Y. and MATSUOKA, N. (1991). Rates of tafoni weathering on uplifted shore platforms in Nojima-Zaki, Boso Peninsula, Japan. *Earth Surf. Proc. Land.*, 16: 51-56.

MATSUKURA, Y. and TANAKA, Y. (2000). Effect of rock hardness and moisture content on tafoni weathering in the granite of Mount Doeg-Sung, Korea. *Geogr. Ann.*, 82A (1): 59-67.

MELLOR, A., SHORT, J., KIRBY, S.J. (1997). Tafoni in the El Chorro area, Andalucía, Spain. *Earth Surf. Proc. Land.*, 22: 817-833.

NORWICK, S.A. and DEXTER, L.R. (2002). Rates of development of tafoni in the Moenkopi and Kaibab formations in Meteor crater and on the Colorado plateau, Northeastern Arizona. *Earth Surf. Process. Land.*, 27: 11-26.

SUNAMURA, T. (1996). A physical model for the rate of coastal tafoni development. *Jour. Geol.*, 104: 741-748.

THOMAS, M.F. (2001). Landscape sensitivity in time and space-an introduction. *Catena*, 42: 83-98.

TWIDALE, C.R. and VIDAL ROMANÍ, J.R. (2005). *Landforms and geology of granite terrains*. Balkema, Amsterdam, The Nederlands.

UÑA ÁLVAREZ, E. DE (2004). Tafoni en rocas graníticas. Primera valoración estadística sobre tasas de desarrollo en el Macizo de Ourense (Galicia, NW de la Península Ibérica). *Cad. Lab. Xeol. Laxe*, 29: 265-289.

UÑA ÁLVAREZ, E. DE (2005). Definición de formas graníticas tipo tafone: Nomenclatura y significado geomorfológico. *Minius, Revista de Hª, Arte y Geografía*, XIII: 331-341.

UÑA ÁLVAREZ, E. DE and VIDAL ROMANÍ, J.R. (2006). Estructura y forma. Estudio experimental en cacholas (tafoni) de Galicia (NW peninsular). *Actas IX Reunión Nacional Geomorfología – Geomorfología y Territorio*, Santiago de Compostela, 785-793.

VIDAL ROMANÍ, J.R. (1983). *El Cuaternario en la provincia de La Coruña. Modelos elásticos para la formación de cavidades*. Publicaciones Universidad Complutense, Tesis Doctoral, Madrid.

VIDAL ROMANÍ, J.R. (1989). Geomorfología granítica en Galicia (NW España). *Cad. Lab. Xeol. Laxe*, 13: 80-163.

VIDAL ROMANÍ, J.R., UÑA ÁLVAREZ, E. DE, FERNÁNDEZ MOSQUERA, D. and SANJURJO SÁNCHEZ, J. (2006). Proposal of nomenclature for granitic forms. *Actas IX Reunión Nacional de Geomorfología – Geomorfología y*

Territorio, Santiago de Compostela, 803-814.

VIDAL ROMANÍ, J.R., UÑA ÁLVAREZ, E. DE, FERNÁNDEZ MOSQUERA, D., CARIGNANO, C. and SANJURJO SÁNCHEZ, J. (2007). Procesos de alteración y generación del relieve en la Pampa de Achala (Sierra Grande de Córdoba, República Argentina). *Actas XII Reunión Nacional de Cuaternario*, Avila, 61-62.

This work has been carried out with the research project CGL2004-06516/BTE by Science & Technology Ministry of Spain