Sociedad Geológica de España

GEOGACETA, 59, 2016

Architecture of Pleistocene fluvial tufa systems associated with waterfalls: El Salt (Alcoy, Spain)

Arquitectura de sistemas fluviales tobáceos pleistocenos asociados con cascadas: El Salt (Alcoy, España)

Salvador Ordóñez[1,2], Jaime Cuevas[1], David Benavente[1,2] and Mª Ángeles García-del-Cura [2,3]

[1]Departamento de Ciencias de la Tierra y del Medio Ambiente, Universidad de Alicante. Campus de San Vicente del Raspeig, 3690 Alicante, España. salvador@ua.es, jaime.cuevas@ua.es, david.benavente@ua.es

[2]Laboratorio de Petrología Aplicada, Unidad Asociada Universidad de Alicante-CSIC. Campus de San Vicente del Raspeig, 3690 Alicante, España.

[3]Instituto de Geociencias (IGEO, CSIC, UCM). C/ José Antonio Novais 12, 28040 Madrid, España. agcura@geo.ucm.es

ABSTRACT

El Salt is an episodic waterfall located in the city of Alcoy (Spain), Alicante. The Barxell River Source, has calcium bicarbonate waters and an estimated flow rate of 17,000 m³ / day. It is a potential tufa generator, with an estimated generation capacity of up to 1,240 t / year. The tufa deposits located along Barxell River relates to the geomorphologic evolution of valley. Upstream the active waterfall it found a tufa river terrace T (+20 m). Downstream cascade, several types of tufa deposits links to two stages of geomorphologic evolution of the valley: a) The distal progradation tufa deposits related to a "non-effective to base-level change incision", described as piedmont or progradation tufa build-ups T-1, T-2 and T-3; and b) The post "incisional base level change" tufa deposits, Font del Quinzet (T-4) tufa barrier, associated with back-lake sediments, and finally active tufa seeps on cliff (T-5).

Key-words: *fluvial tufa, Pleistocene, carbonate build-ups, seep tufa, waterfall.*

RESUMEN

El Salt es una cascada que funciona temporalmente, situada en la ciudad de Alcoy (Alicante). El manantial que la alimenta tiene aguas bicarbonatadas cálcicas, con un caudal de 17,000 m³ / día, y un potencial generador de tobas calcáreas de 1240 t/año. Los depósitos de tobas del valle bajo del Rio Barxell están relacionados con la evolución geomorfológica del valle. Aguas arriba de la cascada activa actual se encuentra la terraza fluvial de El Sargento T (+20 m). Aguas abajo de la cascada se observan varios tipos de depósitos de tobas ligados a dos etapas geomorfológicas: a) Depósitos de tobas progradantes o de piedemonte T-1, T-2 y T-3, relacionados con un cambio en el nivel de base (Río Polop) que provoca una incisión no efectiva. b) Depósitos posteriores a la etapa de incisión efectiva y encajamiento del valle actual del río Barxel, con la formación de tobas de barrera, Font del Quinzet (T-4), con sedimentos de lago barrera asociado y, finalmente las actuales tobas de rezume sobre El Farallón (T-5).

Palabras clave: *toba fluvial, Pleistoceno, edificios carbonáticos, toba de rezume, cascada.*

Geogaceta, 59 (2016), 7-10
ISSN (versión impresa): 0213-683X
ISSN (Internet): 2173-6545

Fecha de recepción: 23 de julio de 2015
Fecha de revisión: 20 de octubre de 2015
Fecha de aceptación: 27 de noviembre de 2015

Introduction

El Salt is an episodic waterfall, located in the city of Alcoy, Alicante, Spain. There is an 80-m difference in height, from 710 to 630 m a.s.l. between the top and its base. It works episodically when the Barxell River, also known as the Riquer, rushes through it. Until the 1970s, the Barxell River was fed by the Source or *Pou* del Barxell spring (806 m a.s.l.), located 3.6 km upstream of El Salt waterfall. This spring is a discharge from the Sierra de Mariola aquifer. Hydrochemistry of the water classifies it as a calcium bicarbonate water, with a moderate trend towards calcium sulfate (Ordoñez and Benavente, 2014). Its potential as tufa generators can be estimated from hydrochemical data for pH ≈ 16, T ≈ 9 °C, and speciation using PHRERQC code, balance occurs for a log pCO_2 = -1.42, and a Ca^{2+}concentration of 2.14 10^{-3} m. In addition, rebalancing with environmental pCO_2, for a flow rate of 17,000 m^3/day, up to 1,240 t/year of calcium carbonate of potential precipitates.

The average annual rainfall is between 450-550 mm. Today, the Barxell River is dry throughout the year, partly due to the exploitation of the waters flowing naturally into the Barxell Pou.

The aim of this paper is know the tufa build-ups related to the Barxel River.

The first mention of tufa in *El Salt* is made by Visedo Moltó (1959), p.24. "... the deposits produced by waters that carry dissolved carbonates, result in some vuggy limestones tufa or "*tosca*", - its local name- that are mined at a site called *El Salt*, near Alcoy".

Geological setting

The Barxell River has a catchment area (A) of 36.42 km². The main source comes from the Carche Formation, an unit consisting of limestone and marl with occasional yellow chert nodules, dating from the Campanian-Maastrichtian-Eocene. In its early stages the river flows through marls and bioclastic limestones from the Tortonian age. A tufa river terrace T (+20 m), in the Sargento and Baradel-

Fig. 1.- General view (Google Earth) of the collapsed dome of Barxell river waterfall.

Fig. 1.- Vista general (Google Earth) de la bóveda colapsada de la cascada de rio Barxell.

lo urbanizations, has been identified in this first section of the river valley. But in the vicinity of the village of *El Salt*, highly-verticalised and brecciated massive limestone layers from the upper Cretaceous-Eocene crop out, (Almela Samper *et al.*, 1975), in a folded, faulted N040ºE direction, with minor W-E–oriented associated faults.

Upper Cretaceous and Eocene Fault breccia (local name *El Farallón*, Fig. 1) acts as aquifer seepage, draining the whole upstream. *El Farallón (the cliff)* is identified in a length of almost 100 m, in the direction from West to East, extending from the level 700 m a.s.l. up to elevation 640 m a.s.l. The area of today's cascade presents a collapsed dome structure with an elliptical morphology. Evidence of the collapse is the large tufa blocks littering the present valley. Plant view collapse shows an elliptical morphology (Fig. 1), with ~150 m in transverse section and 180 m long, following the valley axis. Currently, the collapse is active and has a system of concentric joints around the sinkhole.

In the part located behind the cliff described above, we found a Neanderthal rock shelter, dating from approximately about 60,000 years BCE. Here, the tufa U-Th age reaches 80,000 yr BCE, see Fumanal (1995) and Alamar Bonet (2002).

The presence of this previously-described cliff is linked to the fracture zone that defines the north edge of the Alcoy basin, (Montenat *et al.* 1996) and is related to a structural Prebetic diapiric process, see Martínez del Olmo *et al.* (2015), the structure corresponds to the southern flank of the Sierra de Mariola's anticline structure.

Moreover, this cliff is the knick point, main cause of the Barxel waterfall. In the lower part of active waterfall, the Lower Pliocene fluvial-palustrine deposits crop out

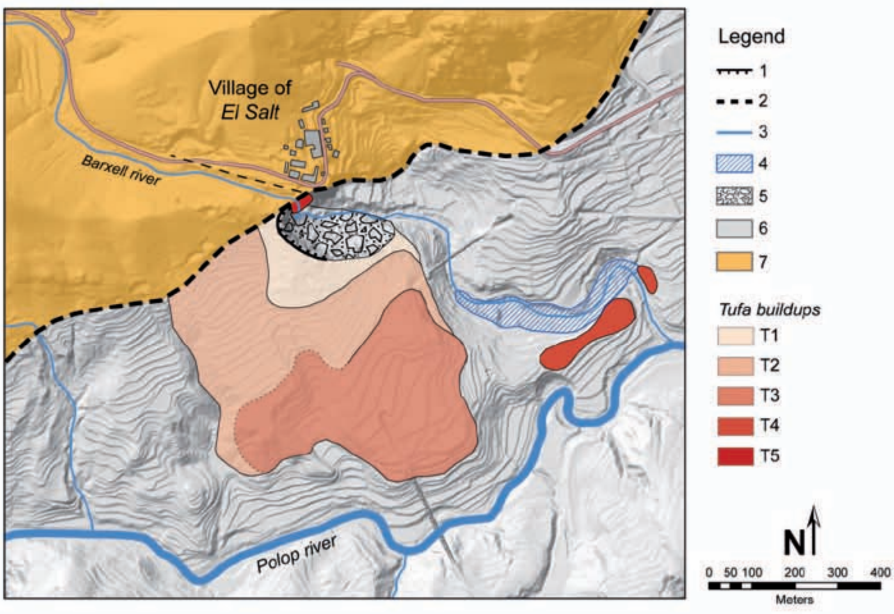

Fig. 2.- Geological map of El Salt zone. 1. Sinking, 2. Faults, 3. River, 4. Back Barrier Lake, 5. Tufa blocks, 6. Neogene and Quaternary, 7. Paleogene and Upper Cretaceous.

Fig. 2.- Mapa geológico de la zona de El Salt. 1. Frente de deslizamiento, 2. Fallas, 3. Río, 4. Lago detrás de la represa, 5. Bloques de toba, 6. Neógeno y Cuaternario, 7. Paleógeno y Cretácico Superior.

(Mansino *et al.*, 2013). Alcoy's lignite mine is located in this formation.

The recent alluvium, slope deposits and travertine constitute Holocene sediments of El Salt (Almela Samper *et al.,* 1975).

Tufa deposits and build-ups

The different build-ups and tufaceous deposits identified from the Barxell Pou (806 m a.s.l.) to the mouth of the Barxell Polop Rivers (583 m a.s.l.) along a profile of approximately 4.8 km are described below.

El Sargento fluvial-tufa terraces

In the El Sargento urbanization, an outcrop can be seen on the right side of the Barxell River, upstream of Font de los Patos. The T + 20 is located 1.14 km downstream of the waterfall. The thickness of the terrace exceeds 8 m, and in the sequence of the fluvial terrace some tufa deposits are interbedded. These become more abundant towards the upper part of the sequence of tufa levels. The development of stromatolite structures more than half a meter size with Chironomidae has been observed.

Tufa build-ups before the incision of the Barxell river valley

These may be described as sedimentary deposits of alluvial fan morphology, and consist mainly in waterfall tufa, progradating in a distal position, and detrital tufa on erosional surfaces in the proximal position. Commonly are defined as "mantle or glacis tufa" and develop in the environment of karst springs, with an arrangement of tufa coalescing bodies, which follow the natural slope. These are very common in some border-faulted basins in Southeastern Spain, especially in the mechanical contact between karst aquifers and aquitards defined by gypsum, marl and reddish clay from the Triassic age (Vazquez-Navarro *et al.,* 2014). They have also been defined as "progradating build-ups" by Fernandez (2014). These are sedimentary bodies measuring hundreds of meters in length according to the slope, and of tens of meters thick. The feature is defined by a complex architecture of detrital levels and is interlayered with tufa episodes. This latter presents sigmoidal and progradating structures in the direction of the slope and consists of highly-verticalised tufa boundstones composed of moss, rushes, reeds, and other higher plant stalks (waterfall tufa). Detrital beds erode previous tufa deposits and have some tufa and limestone pebbles and cobbles (colluvial-alluvial) ascending to tufa calcarenites and tufa mudstones (phytoclastic tufas) with edaphic features. The sedimentary layer, more than 50 m thick, rests on the extension of the cliff, with a maximum width of more than 400 m, and a length of over 650 m. The sedimentary deposits, T-1, T-2 and T-3, modify the course of the Polop River; the tufaceous structures mantling piedmont or progradating buildups.

– Build-up T-1

Consisting of waterfall tufas, morphologically descending along the El Farallón cliff. Its internal structure is nearly horizontal at the start of the waterfall and dips sharply in the most distal area, as seen in the area of *El Hundimient*o.

These build-ups consist of bryophyte tufa (boundstone of bryophytes or phytoherms).

– Build-up T-2. Coveta

Its foundation is located at elevation 670 m a.s.l., and reaches the base level of the tunnel located in the right abutment of the Barxell viaduct (620 m a.s.l.), where a massive development of tufa facies are to be seen in contrast with level of tufa layers into which several caves that served as rock shelters. These are protected by the most resistant and residual levels of tufas. Caves are located under the hardest and less erodible tufa levels. At the head of this builup there are several small tufa quarries.

– Build-up T-3. Glorieta de El Salt

It is situated at a height of 650 m a.s.l. and continues for over 300 m. This build-up extends to the top of the stratigraphic record, fossilizing the distal part of the T-2 structure. The outcrop presents development structures several meters in size with erosive contacts at the base. There are occasional stem tufa blocks within fine and very fine phytoclastic tufa, defined as a mixture of silt to clay-sized particles and massive to laminae plane-parallel stratification. Sometimes, this phytoclastic tufa also contains scattered boulders (tufa and limestone). Towards the top of the sedimentary record metric levels develop, with a sigmoidal arrangement of boundstones, layers of moss and rushes typical of a tufa barrage front. In the outcrop of the *Glorieta de El Salt,* over the erosion plain on T-2, a prograding sequence may be seen. This sequence starts on an erosional contact on T-2 boundstone moss tufa, and consists of gray phytoclastic tufa, up to one meter thick with columnar disjunction. On this level there are conglomerates with tufa pebbles and sand tufa matrix with a thickness of more than one meter. Within this level, there is an upward coarsening sequence, progressing to an upward fining sequence in the top. There is also a fan-shaped erosional contact with boulder fan gravel deposit where tufa up to 50 cm thick appears, as well as boulders and cobbles and sparse matrix. Overlying this level of conglomerates, there is a sedimentary body of over 1.5 m, consisting of several decimeter-thick levels with stromatolitic planar structures. The stromatolitic level shows great lateral continuity and almost horizontal arrangement, and it extended over the distal part of the T-2 structure. There are transition facies between stromatolites and stem tufa facies.

Massive layers of moss and rushes grow on top of the set of NE-SW–oriented boundstones which display a steep depositional slope exceeding 40° direction, and a thickness up to 6 m.

Tufa build-ups after the incision of the Barxell river valley

– Build-up T-4. Font del Quinzet

There are dam barriers, commonly formed by hanging moss boundstones and macrophytes (stems and trunks), on which epiphytic cyanobacterial mats accelerate the process of encrusting carbonate with micrite fringe and arborescent textures. In our case, the tufa dam is oriented in a W-E direction, perpendicular to the present channel of Barxell River, just before it flows into the Polop River. The crest length of the tufa dam is up to 356 m. Its development at the growth surface exceeds 20 m, and it is situated on the terrace top (T + 10 m). The visible tufa barrier thickness is greater than 6 m. In detail, it presents decimeter levels consisting of moss tufa vertically downwards, with abundant gametophytes and stems growing vertically downwards, with abundant cavities growth, which develop microkarstification processes. At the back of the barrier, a barrier lake has been identified and detrital tufa deposits consist of coated fragments of high plant stems and rushes, oncoids and oncoliths.

– Build-up T-5. Tufa seeps on the cliff

The seep tufa located on the cliff is formed by tufa with hanging moss curtains, bryophyte or phytoherm boundstone. Moss, rushes and other higher plants easily colonize wet limestone walls. This moss in turn, trap leaves from deciduous and shrubs, defining the tufa ecological environment. Adjoining the south wall of the cliff, moss with a thickness of more than six meters thick and with a hanging curtain tufa structure can be observed. Even at the cliff top large hanging deposits measuring several meters with a cauliflower-like morphology are present in both wall sides. At present, many points of the cliff are covered by dripping water. These are colonized by mosses and cyanophyta, with sparite and micrite fringe, and they have developed surface crusts with calcite crystals and cyanobacteria cells (Fig. 3).

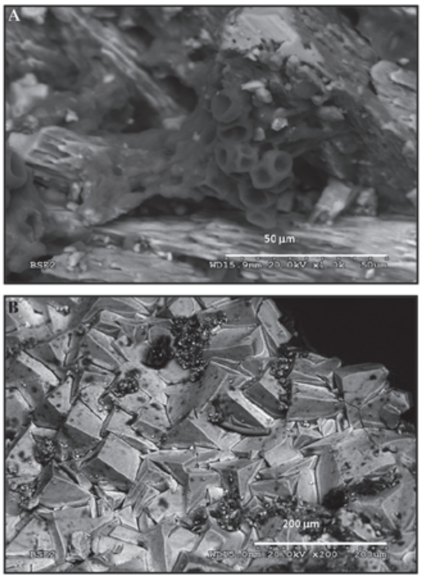

Fig. 3.- SEM images of present surface of seep tufa. A) Calcite crystals and "living" cells. B) Calcite crystal growth surface.

Fig. 3.- Imágenes SEM de la superficie actual de la toba de "rezume". A) Cristales de calcita y celulas "vivas". B) Superficie con crecimiento de cristales de calcita.

The seep tufa located on the El Farallón or the cliff of the El Salt village, consist of thicker moss hanging curtains tufa up to 6m.

Discussion: geomorphological evolution of tufa in the El Salt system

Terrace T + 20m, which is located upstream of the *El Salt* waterfall, presents a conventional geomorphology, and therefore is a stabilization stage in the incision of the Barxell River valley upstream of El *Farallón* cliff.

Following Harvey (2002), the description of the tufa structures' morphology (T-1, T-2 and T-3), resembles a "distal progradational alluvial fan" with previous tufa deposits with which they are in erosional contact contributing to their development. The fan morphometry data are: drainage area, A = 36,4 km^2; fan area, F = 0,1 km^2; and fan gradient, G = 1/6. As Harvey (2002) indicates, tectonic controls may also be local, there is a single fault running N40ºE.

In the distal portion of each of the build-ups of accretional tufa deposits predominate barrier-type tufa boundstones of moss and vertical stalks, strongly down slopping in the direction of progradation and with a structure similar to that described by Martini and Capezzuoli (2014). This evolutionary step of the tufa forming system, would relate to a "non-effective base-level change" (Harvey, 2002).

An interesting and new aspect is to explain the coexistence of erosion alternating with tufa growth, which has been approached by Hammer *et al.* (2007), Viles *et al.* (2007), Fuller *et al*. (2011), Arenas *et al.* (2014), and Martini and Capezzuoli (2014).

The most important physical factor is the depth of flow, which influence the transition to turbulent flow; and turbulence in turn may accelerate the rebalancing of the pCO_2 in water with the atmosphere.

Recently, Arenas *et al.* (2014) indicate that the growth style of the cascade or barrage cascade would be determined by the aggradation/progradation ratio (A/P). In all cases, large dammed areas would only form in relation to knick points aggradation. Decreasing aggradation at the knick points would yield smaller dammed areas, perhaps with thinner deposits, and increasing progradation would produce more extensive cascade in the flow direction, i.e. T-1, T-2 and T-3. The difficulties of the water flow to reach the growth front, during periods of low flow condition, produced the water infiltration through the building itself, and interrupted the waterfall tufa development, and started the erosion of build-ups. Both biological and hydrodynamic issues, show that the tufa are the result of a positive feedback between biology (aggradation) and geomorphology factors (water flow and slope) (Fuller *et al*., 2011).

This "incisional base level change" induces a strong lateral incision on the east side of structures, T-2 and T-3, and ultimately determines the erosion of the base of the structure T-1. As a result of this process, a gigantic dome developed at T-1. The dome is supported on the cliff, and on detrital Pliocene-Quaternary deposits. The continued head ward erosion of the foot of the waterfall caused the dome collapse, creating a sinking.

It seems evident that after incision and when the new channel of the Barxell River, reached a knick point in its longitudinal profile, the developments have led to the creation of a tufa barrier, T-4, associated with a back barrier lake.

The restoration of river flow, compatible with its use for water supply, could regenerate a system that is, from the geomorphologic point of view, totally degraded.

Conclusions

In the lower valley of the Barxell River, a set of tufa build-ups of great geomorphologic interest has developed. The most noteworthy from the landscape point of view is the build-up related to the present episodic *El Salt* waterfall.

Upstream of the present waterfall site are the *El Sargento* fluvial-tufaceous terraces.

The tufa deposits downstream of the present waterfall site may be separated into two geomorphologic steps:

a) The "non-effective incision base-level change", in which the piedmont or progradating tufa build-ups T-1, T-2 and T-3 develop. The detrital tufa fraction predominates in the proximal sediments. Aggradational/progradational tufa deposits are to be found in the distal portion of each of the build-ups, with moss and vertical stalks-type tufa boundstones predominating.

b) The post "incisional base level change" tufa deposits. The foot of the waterfall caused the collapse of the vault, creating the present sinkhole. A circular joints network is observable today. Along the new post-incision channel of the Barxell River, has developed tufa barrier T-4.

The seep waters at *El Farallón* are responsible for the genesis of tufa build-up T-5, as tufa seeps on the cliff, partially active.

Acknowledgements

We thank the suggestions of Dr. Arenas and an anonymous referee that improved our manuscript, and the encouragement of Dr. Alfaro and Dr. Cañaveras.

References

Alamar Bonet, Y. (2002). *Quaderns de Prehistòria i Arqueologia de Castelló* 23, 47-84.

Almela Samper, A., Gómez Nogueroles, E., Quintero Amador, I. and Mansilla Izquierdo, H. (1975). Mapa Geológico de España, 1:50.000, hoja nº 821 Alcoy. IGME, Madrid.

Arenas, C., Vazquez-Urbez, M., Pardo, G. and Sancho, C. (2014). *Sedimentology* 61, 133–171.

Fernández A. (2014). In: *Las Tobas en España* (J.A. González Martín and M.J. González Amuchastegui, Eds.). Sociedad Española de Geomorfología, Badajoz, 236-248.

Fumanal, M.P. (1995). In: *El Cuaternario del País Valenciano.* Asociación Española para el Estudio del Cuaternario. Universitat de València, 115-124.

Fuller B.M., Sklar, L.S., Compson, Z.G, Adams, K.J., Marks, J.C. and Wilcox, A.C. (2011). *Geomorphology* 126, 314–332.

Hammer, Ø., Dysthe, D.K. and Jamtveit, B. (2007). *Earth and Planetary Science Letters* 256, 258–263.

Harvey, M.A. (2002). *Geomorphology* 45, 1, 67-87.

Mansino, S., Fierro, I., Ruiz-Sánchez, F.J. and Montoya, P. (2013). *Journal of Iberian Geology* 39, 261-284.

Martínez del Olmo, W., Motis, K. and Martín, D. (2015). *Revista de la Sociedad Geológica de España* 28, 3-24.

Martini, I. and Capezzouli, E. (2014). *Sedimentary Geology* 299, 60-73.

Montenat, C.H., Ott D'Estevou, P. and Pierson D'Autrey, L. (1996). In: *Tertiary basins of Spain* (P.F. Friend and C.J. Dabrio, Eds). Cambridge University Press. Cambridge, 346-352.

Ordóñez, S. and Benavente, D. (2014). *Estudios Geológicos* 70, 1-18.

Vázquez-Navarro, J.A., Ortiz, J.E., de Torres, T., Domínguez-Villar, D. and Vázquez, A. (2014). In: *Las Tobas en España* (J.A. González Martín y M.J. González Eds.). Sociedad Española de Geomorfología, Badajoz, 249-266.

Viles, H.A., Taylor, M.P., Nicoll, K. and Neuman, S. (2007). *Sedimentary Geology* 195, 39-53.

Visedo Moltó, C. (1959). *Alcoy. Geología. Prehistoria*. Edición facsímil del Ajuntament di Alcoi 1995. 114 p.