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Using travertine deformations to characterize paleoseismic activity along an active oblique-slip fault: the Alhama de Murcia fault (Betic Cordillera, Spain)

Uso de deformaciones de travertinos para caracterizar la actividad paleosísmica de una falla oblícua activa: la falla de Alhama de Murcia (Cordilleras Béticas, España)

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ABSTRACT

A preliminary paleoseismic study of travertine deposits cut by an active oblique-slip fault is presented. The Alhama de Murcia fault affects late Pleistocene and Holocene travertine deposits along the Lorca-Totana segment. Travertines along oblique-slip (reverse-sinistral) active faults have not been reported. On the Alhama de Murcia fault, $CaCO_3$ rich springs are linked to an extensional step-over and to releasing fault junctions in a reverse-sinistral fault zone. The sampling methodology for U/Th dating employed to avoid contamination (by choosing material from a geochemical closed system) is described. A petrographic analysis is necessary to ensure the quality of the samples. Terrace-mound, fissure-ridge, eroded sheets and range-front travertine deposits occur in the Alhama de Murcia fault zone. At Carraclaca a 15 m amplitude monocline fold was formed by the reverse movement of this fault which has been active since the late Pleistocene. The first available absolute ages for deformed and undeformed travertines yield a vertical slip rate of 0.08 mm/yr. It is possible to estimate 4818 yr of recurrence time for the northern branch given the slip per event on alluvial deposits in the southern branch of the Alhama de Murcia fault.

Keywords: Paleoseismicity. Travertine. U/Th dating. Alhama de Murcia fault.

RESUMEN

En este trabajo se presenta un estudio paleosísmico preliminar de la actividad recurrente de una falla activa de carácter oblicuo: la falla de Alhama de Murcia que afecta depósitos de travertinos de edad Pleistoceno superior a Holoceno a lo largo del segmento Lorca-Totana. Se trata de un caso no muy común de travertinos generados a partir de surgencias asociadas a una falla con movimiento de componente predominantemente inversa. En este caso, las surgencias de aguas ricas en $CaCO_3$ aparecen asociadas a zonas de solape extensional y a intersecciones de fallas dentro de una zona de falla inverso-direccional. Asimismo, se describe y analiza la metodología usada para la selección de las muestras utilizadas para su datación mediante el método del U/Th, con el fin de evitar posibles contaminaciones y obtener así edades absolutas finales representativas. La datación de travertinos puede realizarse con exactitud y suficientes garantías si se pone atención en la selección y el análisis petrográfico de las muestras con el fin de seleccionar carbonatos que hayan precipitado en un sistema lo más geoquímicamente cerrado posible. A lo largo de la traza de la falla de Alhama de Murcia se han observado travertinos de terraza, travertinos fisurales formando crestas, travertinos laminares erosionados y travertinos frontales. El movimiento inverso de la falla ha producido un pliegue monoclinal de 15 m de amplitud en el área de Carraclaca, que ha ido creciendo durante el Pleistoceno superior y Holoceno. Las primeras edades absolutas disponibles de los travertinos afectados y no afectados por este pliegue indican una tasa de movimiento vertical de 0,08 mm/a. Utilizando valores de deslizamiento por evento equivalentes a los observados en los depósitos aluviales de la rama sur de la falla de Alhama de Murcia (42 cm) podemos estimar valores de intervalos de recurrencia próximos a 4.818 años.

Palabras clave: Paleosismicidad. Travertino. Datación U/Th. Falla de Alhama de Murcia.

INTRODUCTION AND GEOLOGICAL SETTING

The Alhama de Murcia fault (Bousquet and Montenat, 1974) is a NE-SW oblique-slip (reverse-sinistral) fault. This fault (Fig. 1), which is one hundred kilometers long, cuts metamorphic alpine material of the Internal Betic Zone and bounds some marine Miocene basins (Montenat, 1977). During the last two decades, a number of studies on neotectonic and active tectonic activity of the Alhama de Murcia fault have been undertaken; some of these relate to Quaternary morphologic features controlled by the fault activity (Silva, 1994; Silva et al., 1992) whereas other studies have used micro and mesotectonic structures to detect Quaternary activity of the fault (Armijo, 1977; Montenat et al., 1987; Rodríguez Estrella, 1986; Martínez-Díaz, 1991; Martínez-Díaz and Hernández-Enrile, 1992, 1996; Martínez-Díaz, 1998). In recent years, some of these small structures have been ascribed to paleoseismic events (Silva et al., 1997). A number of outcrops of the Alhama de Murcia fault in natural trenches produced by creek erosion have been studied (Martínez-Díaz and Hernández-Enrile, 1999). These authors demonstrate the existence of paleoearthquakes with surface rupture on Quaternary alluvial fan deposits and describe the repetition of two 0.42 cm slip events in Pleistocene materials. Martínez-Díaz et al., (in the current volume) present the first paleoseismic study based on artificial trenching in this area and the preliminary results show Holocene coseismic reactivation of the southern branch of the fault along the Lorca-Totana segment.

A number of travertine outcrops in southern Spain have been studied using U/Th dating, with very good isotopic results (Díaz del Olmo and Delannoy, 1989; Díaz del Olmo et al., 1992; Durán et al., 1988; Durán, 1989). However, only geochemical and sedimentological features have been discussed.

Hot spring travertine deposits overlap the fault zone in some places along the Lorca-Totana segment of the Alhama de Murcia fault. In this sector, the main fault is divided into two branches with antithetic dips: the northern branch dipping northwest and the southern branch dipping southeast (Fig. 2). The northern branch bounds the La Tercia range and all the springs occur along this fault. Some of the springs are currently active (Carraclaca and El Roser among others), and the depositional process may be observed. Travertines deformed by the Alhama de Murcia fault activity were identified during field work. The study of these travertines along the Lorca-Totana segment was undertaken to determine the paleoseismic and recent (late Pleistocene-Holocene) slip rate of this fault. The study was focussed on the Carraclaca spring outcrop, where Armijo (1977) described a monocline fold affecting Quaternary alluvial fan deposits because of dragging due to the reverse movement of the Alhama de Murcia fault. Silva et al. (1997) described a possible coseismic surface rupture at the base of the monocline vertical limb. Martínez-Díaz and Hernández-Enrile (1996) have correlated the vertical slip rate deduced from this site (0.1 mm/yr using preliminary U/Th dating) with the regional scale rates of uplift based on the structure and topography of the La Tercia range (0.2 to 0.3 mm/yr). All these studies are consistent with the recent reverse kinematics of the Alhama de Murcia fault but the age of the last paleoseismic events and the recurrence period remain to be clarified.

Earlier studies using U/Th dating have been applied to speleothems, particularly to stalagmites, showing growth anomalies as a result of tectonic events (Gospodaric, 1977; Forti and Postpischl, 1980, 1984). Absolute dating of travertines and speleothems to identify paleoearthquakes, in medium to high activity areas, has proved to be of great value (Bini et al., 1992; Altunel and

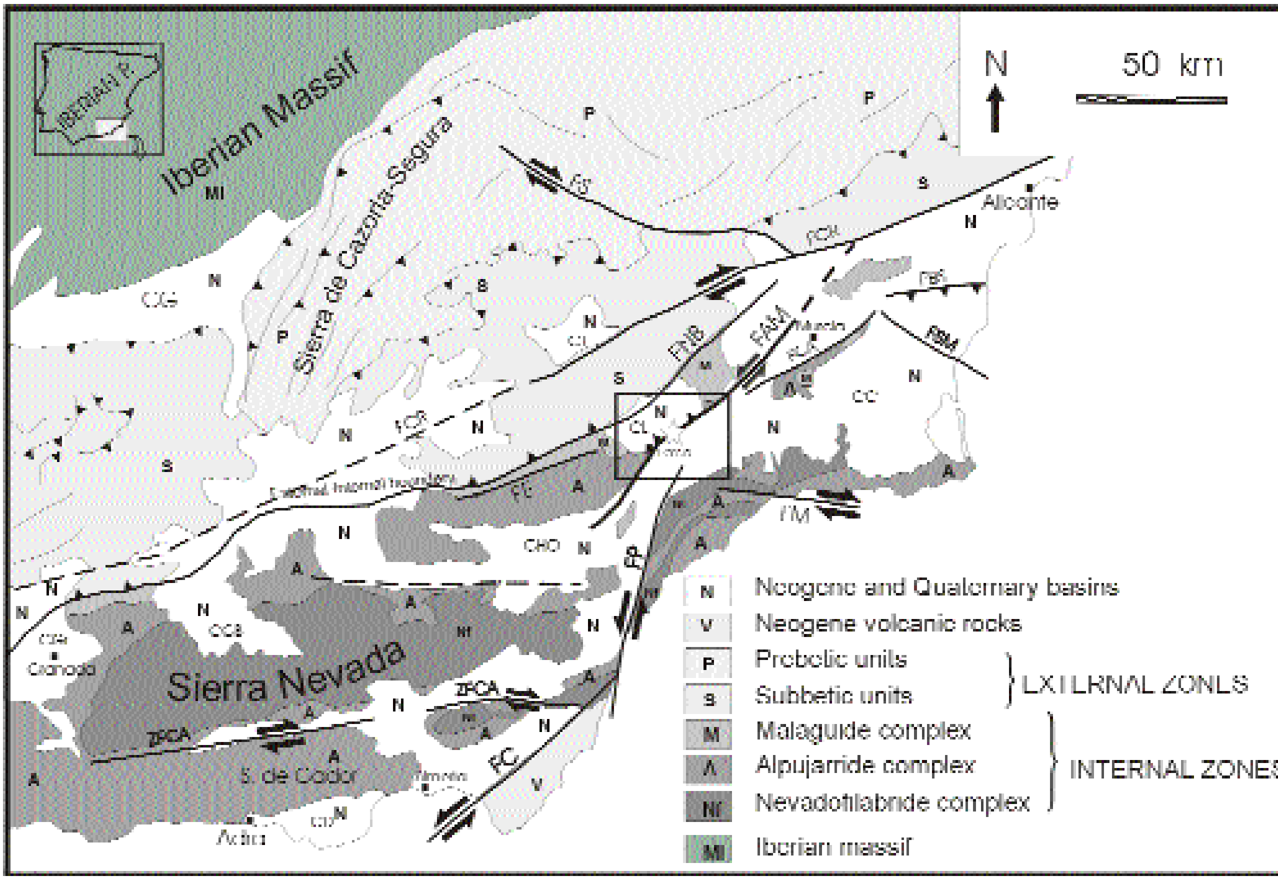


Figure 1. Geological and structural scheme of the southeastern Betic Cordillera in which the Alhama de Murcia oblique-slip fault is shown. The star indicates the location of travertines studied in this work. FS: Socovos faut; FCR: Crevillente fault; FE: Las Estancias fault; FNB: Northbetic fault; FAM: Alhama de Murcia fault; FCA: Carrascoy fault; FBS: Bajo-Segura fault; FSM: San Miguel fault; FM: Moreras fault; FP: Palomares fault; ZFCA: Alpujarras fault zone; FC: Carboneras fault. Modified from Martínez-Díaz (1998).

Figura 1. Esquema geológico-estructural del sureste de la Cordillera Bética en el que se señala la posición de la falla de Alhama de Murcia. La estrella marca la localización de los travertinos estudiados en este trabajo. FS: falla de Socovos; FCR: falla de Crevillen-te; FE: falla de las Estancias; FNB: falla Norbética; FAM: falla de Alhama de Murcia; FCA: falla de Carrascoy; FBS: falla del Bajo Segura; FSM: falla de San Miguel; FM: falla de Moreras; FP: falla de Palomares; ZFCA: zona de falla de las Alpujarras; FC. falla de Carboneras. Modificado de Martínez-Díaz (1988).

Hancock, 1993, 1996; Hancock et al. 1999). Neotectonic fracturing associated with travertines has also been studied (Chalmers, 1998; Çakir, 1996).

Recently, Hancock et al. (1999) used the term "travitonics" for the utilization of travertines (location, depositional morphology and deformation) to study active faults. The advantage of using travertine tectonics is obvious: The situation of these deposits is controlled by the location of active fault planes favoring the discharge of $CaCO_3$ rich waters. Faults play an important role in hydrothermal fluid flow in the upper crust (Sibson, 1989) with the result that hot springs are commonly located along active faults, especially normal faults. $CaCO_3$ can be dated by the Uranium series method when it is younger than 400 ka.

Given that the episodic activity of seismogenetic faults gives rise to different cycles of $CaCO_3$ precipitation, it is possible to recognize deposition episodes related to tectonism. Hancock et al. (1999) report that most of the hot springs that produce travertines are located in step-overs in normal fault zones. Since open cracks allow sub-surface fluid flow, travertine outcrops indicate the location of dilatational step-overs in regional shear zones. Dilatational step-overs are often

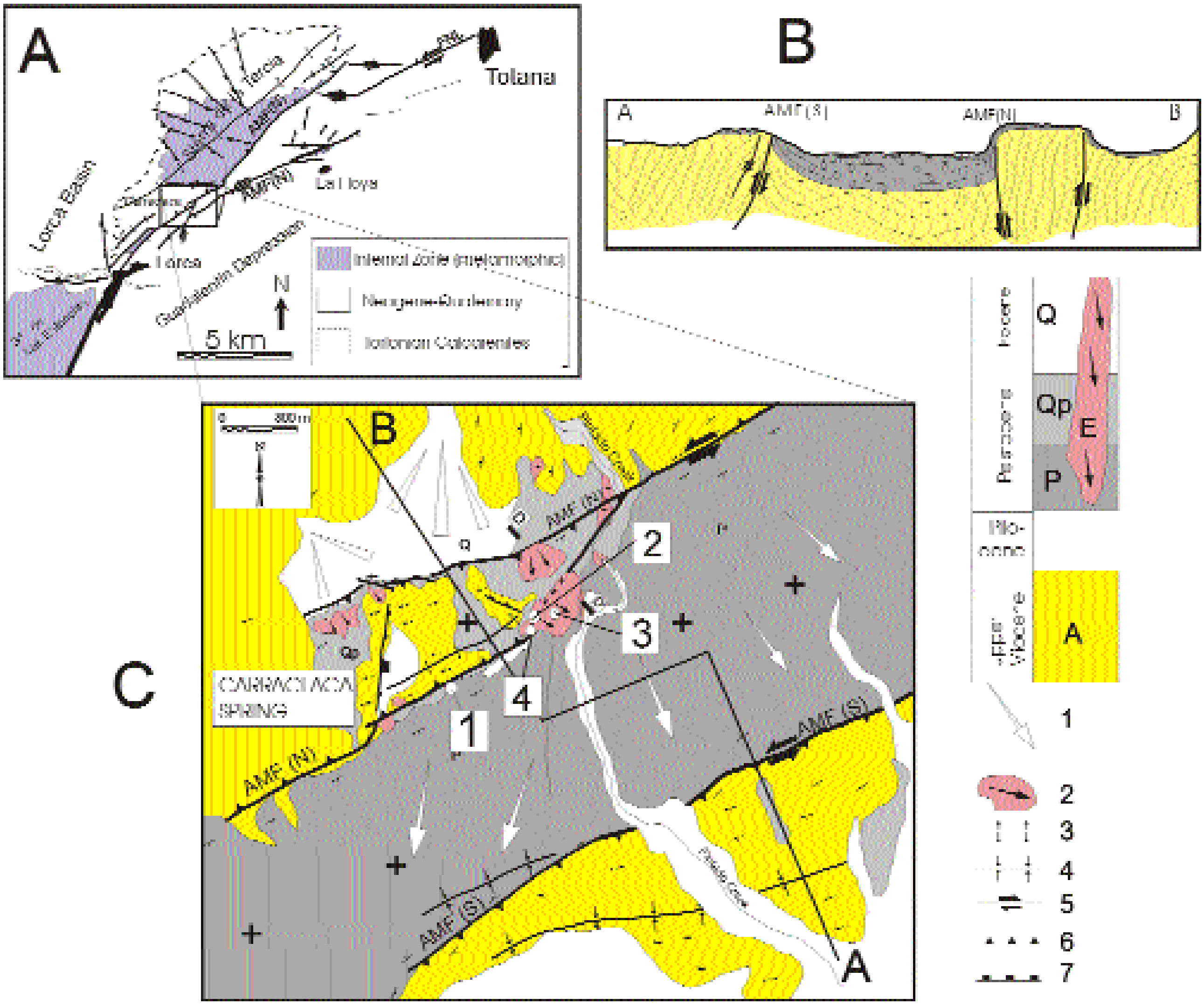


Figure 2. A: Structural scheme of the Lorca-Totana segment of the Alhama de Murcia fault (AMF). (N): Northern branch. (S): Southern branch. B: Geological cross section showing the pop-up in the northern Alhama de Murcia fault branch in which the Carraclaca travertines appear. C: Geological map of the Carraclaca spring area. This spring occurs where two fault planes of the Alhama de Murcia fault form a step-over. In some places travertines overlap main faults and are deformed in varying degrees. A: Messinian marls; P, Qp and Q: alluvial fan deposits (gravel and silt) proceeding from the La Tercia range; E: travertine deposits, the arrows showing flow direction; 1: direction of alluvial fan transport; 2: travertine patches and flow trend; 3 and 4: anticline and syncline axis; 5: strike-slip fault; 6: reverse fault; 7: normal fault; D-D': cross section shown in Fig. 11a. Numbers 1 to 4 indicate the position of the dated travertine samples.

Figura 2. A: Esquema estructural del segmento Lorca-Totana de la falla de Alhama de Murcia. (N) Rama norte. (S): Rama sur. B: Corte geológico esquemático de la estructura pop-up observada en la rama norte de la falla de Alhama de Murcia en el que se observa la posición de los travertinos de Carraclaca. C: Mapa geológico del entorno de la surgencia de Carraclaca que aparece donde dos planos de falla subparalelos se solapan. En algunos puntos los travertinos solapan estos planos, mientras que en otros aparecen afectados por ellos. A: margas messinienses; P, Qp y Q: depósitos de abanico aluvial procedentes de la sierra de la Tercia; E: travertinos, las flechas indican la dirección de flujo de las aguas de precipitación; 1: dirección de sedimentación de los abanicos aluviales; 2: principales masas travertínicas con su dirección de flujo; 3 y 4: ejes de anticlinal y sinclinal; 5: falla de desgarre; 6: falla inversa; 7: falla normal; D-D´: corte geológico de la Fig. 11a. Los números 1 a 4 señalan la posición de las muestras de travertino datadas.

Table 1. [U]ppm : Uranium content (ppm). $^{234}U/^{238}U$: This ratio has a testing value. Surface waters have a $^{234}U/^{238}U$ ratio different from 1. Then this ratio must also be different from 1 in travertines. $^{230}Th/^{234}U$: Isotopic clock. $^{230}Th/^{232}Th$: Index of outer ^{232}Th pollution. Values over 20 mean little probability of sample contamination. $[^{234}U/^{238}U]t=0$: Initial $^{234}U/^{238}U$ ratio. Sample dating was carried out at the CERAK laboratory, Centre d'Études et de Recherches Appliquées au Karst (Belgium), under the supervision of Dr. Yves Quinif.

Tabla 1. [U]ppm: contenido de uranio (ppm). $^{234}U/^{238}U$: esta relación es un valor test. Interviene en el cálculo de edad ya que, a pesar de que ambos isótopos tengan las mismas propiedades químicas, generalmente tienen una relación isotópica distinta a uno en las aguas superficiales y también debe ser distinta de uno en los travertinos. $^{230}Th/^{234}U$: reloj isotópico. $^{230}Th/^{232}Th$: índice de contaminación de ^{232}Th exterior al sistema. Valores por encima de 20 indican poca probabilidad de contaminación de la muestra. $[^{234}U/^{238}U]t=0$: relación $^{234}U/^{238}U$ inicial. Las dataciones de las muestras fueron realizadas en el laboratorio del CERAK, Centre d'Études et de Recherches Appliquées au Karst (Bélgica), bajo la supervisión del Dr. Yves Quinif.

SAMPLE	[U]ppm	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	$[^{234}U/^{238}U]t=0$	AGE (ka)
CARR1	5.120(±0.034)	1.837(±0.009)	1.074(±0.023)	197(±27)	2.967	304.7[+28,8/-23.7]
CARR2	2.014(±0.020)	2.547(±0.017)	0.21a7(±0.004)	70.7(±6)	2.663	25.9[±0.5]
CARR3	3.640(±0.044)	2.349(±0.015)	0.219(±0.004)	41.2(±2)	2.452	26.2[+0.4/-0.5]
CARR4	3.651(±0.043)	1.704(±0.010)	0.919(±0.012)	76.1(±1)	2.227	198.0[+6.7/-6.4]

linked to the situation of segment boundaries of seismogenetic faults (potential asperities or barriers, Das and Aki, 1977; Lay and Kanamori, 1981).

The main purpose of this study is to describe how travertines can be a powerful tool for detecting and dating paleoseismic features not only related to normal faults but also to oblique-slip (reverse-sinistral) fault zones such as the Alhama de Murcia fault. There is an increased interest in "travitonics" in areas of medium to low seismic activity where recurrence times are usually in the order of thousands of years or more. In these areas, the implementation of absolute dating methods covering thousands to hundreds of thousands of years should be encouraged.

METHODOLOGY

The U/Th dating method was employed to study the paleoseismic activity and determine slip rates of the Alhama de Murcia fault by means of travertine deformation. This method is based on the insolubility of Th inside the ^{238}U radioactive sequence. From this sequence only ^{238}U and ^{234}U isotopes can be removed from water solutions and added to $Ca(HCO_3)_2$, and then precipitated into $CaCO_3$ crystals in travertines or speleothems (Ivanovich and Harmon, 1983).

From the moment of the $CaCO_3$ precipitation, ^{342}U gives rise to ^{230}Th by isotopic disintegration, thereby increasing its quantity in the travertines with time: this is the geological clock. The time interval covered by this clock ranges from a few thousand years to 400 ka (Duplessy et al., 1972; Harmon et al., 1979).

Validity of U/Th dating

Earlier works show that the presence of initial Th in the carbonates invalidates the dates obtained by the U/Th method (Duplessy et al., 1972; Faure, 1977). There are some processes that introduce Th either before or after $CaCO_3$ precipitation increasing the age of the sample (Langmuir and Herman, 1980). The outer Th may proceed mainly from two sources: 1) ^{230}Th generated by ^{234}U from the host rock; 2) ^{230}Th from ^{234}U inside the detritic clay particles. These particles also contain ^{232}Th (called "detritic thorium") which is the parent of another disintegration family. In this way, the ratio $^{230}Th/^{232}Th$ is used as an isotopic purity index for the sample. Samples with a purity index value exceeding 20 are considered free of external Th (Quinif, 1989). The $^{230}Th/^{232}Th$ values in the samples used in this study range from 41.2 to 197 (Table I).

Since the samples are usually made up of multiple calcite layers, it should be borne in mind that the final age obtained from the uranium series is the mean age of all the layers forming the sample.

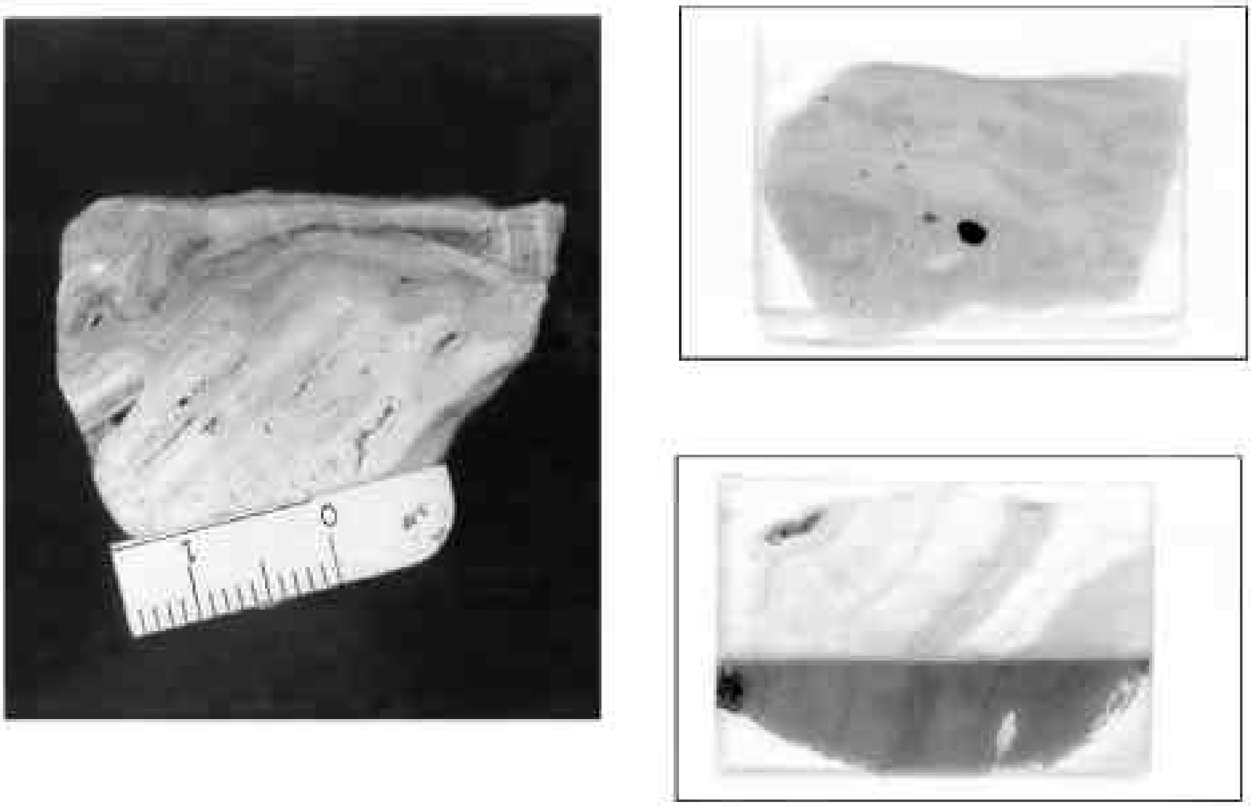


Figure 3. Polished fragment (at left) of a range front travertine (white layers) eroded and covered with speleothem calcite (darker beds). This small sample represents a micro unconformity in which the speleothem fossilizes a broken and tilted travertine. Thin sections of two different travertine samples are also shown. The upper section is from a calcite rich in detritic material, whereas the lower thin section is from a very clean laminar travertine, which is suitable for dating.

Figura 3. Fragmento pulido de travertino frontal (láminas blancas) erosionado y recubierto por calcita de cueva (capas oscuras). Esta muestra representa una microdiscordancia en la que la calcita tipo espeleotema fosiliza a un travertino erosionado y basculado. Se muestran además dos ejemplos de láminas delgadas de muestras de travertinos. La superior de una calcita rica en contaminación por detríticos y la inferior de una muestra de travertino laminar compuesto por una calcita muy pura y adecuada para la datación.

Although travertines are deposited on the earth's surface, this does not necessarily mean that it is an open geochemical system, as is sometimes assumed. To assess the validity of U/Th dating, it is necessary to ensure a maximum degree of geochemical closure. Isotopic exchanges between the crystals and the exterior must not occur in a closed system after the formation of the $CaCO_3$ crystals. The introduction of ^{230}Th into the crystal results in an age older than the real one, whereas the introduction of ^{234}U leads to a decrease in the ^{230}Th/^{234}Th ratio, giving rise to a younger age (Quinif, 1989).

^{234}U may leave speleothems by dissolution caused by channel inundation and surface fluvial water flow. Isotope mobility is also conditioned by the chemical properties of circulating water and by carbonate porosity and permeability (Harmon et al., 1979). Samples with a low permeability are more appropriate. Introduction and loss of Th isotopes are more difficult because of their insolubility. Calcite with a high porosity is able to capture the Th (in the form of a colloid) from the clay (Langmuir and Herman, 1980). Another process which interferes with the inherent properties of calcite is recrystallization. However, recrystallization usually involves mobility on a greater scale than at sample scale with the result that its effects are easily distinguishable. Given the above limitations, the samples with neither recrystallization nor clay impurities can in theory be regarded as a closed geochemical system.

A microscopic study of the samples enables us to detect dissolution processes, recrystallization areas and impurities causing contamination. These processes may be identified by the detection of oxidation-reduction rings, textural changes, discolored zones, etc. Fig. 3 gives an example of a typical travertine covered with speleothem calcitic layers at Carraclaca. Macroscopic and microscopic inspection helps us to select calcite crystals that are free of impurities.

Accordingly, the rules used for travertine sampling are as follows:

1) Location of samples. Travertines located in high topographic areas are preferable because of the low risk of overflows and floods.

2) Morphologic analysis. Samples must be free of oxidation-reduction rings, textural changes and other signs of solution and recrystallization.

3) Low porosity and low permeability samples are recommended because of the low pollution risk.

4) Samples must be as pure as possible without impurities and host rock fragments.

5) Since the final age obtained is the mean age of all the micro-bed ages, samples with a minimum number of beds are recommended.

CARRACLACA TRAVERTINES

Travertine deposits

Travertine deposits occur along the Roman hot springs at Carraclaca, which was a resort until the last century. Today the poor water flow no longer allows its use as a health resort. The Carraclaca spring is located on the Alhama de Murcia fault, 2 km northeast of Lorca (Fig. 2). This spring produced travertine layers overlapping late Miocene marls and Quaternary alluvial fan deposits extending over an area of 1 km^2. In this zone, two main faults are connected by N-S and NE-SW faults, displaying a left step-over arrangement. This produces a relatively complex tectonic structure affecting deposits from the late Miocene to the Quaternary (Fig. 2). The two main reverse-sinistral faults have opposite dips, giving rise to a pop-up (Martínez-Díaz, 1998).

The structural complexity of the area favors the existence of springs at different topographic locations. Following the morphological classification of travertine deposits proposed by Hancock et al. (1999), we can distinguish four different types of deposits in this area, depending on their position with respect to the main fault zone and the local morphologic features. Each type of deposit depends on the geometry of the structure controlling the water source. In some places, the water

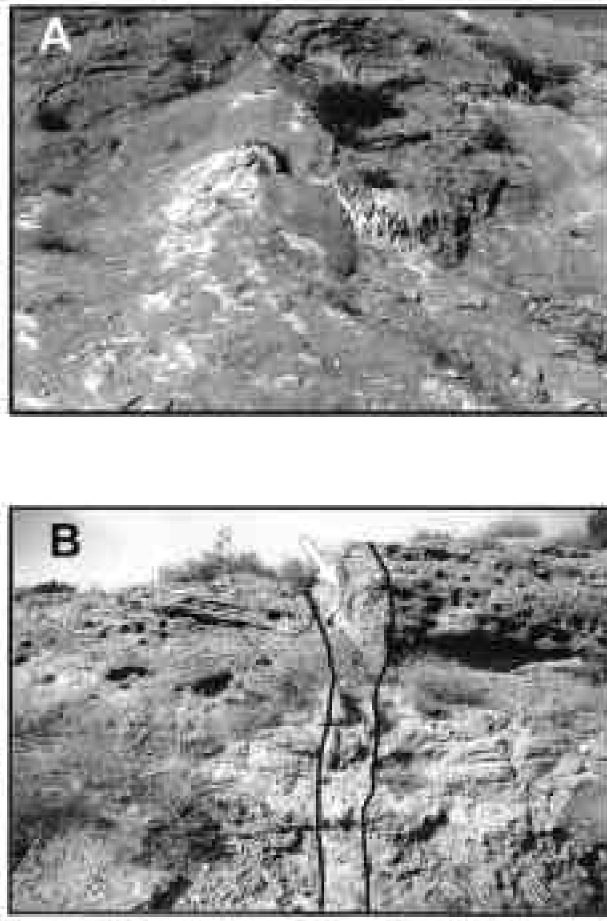


Figure 4. A: In the upper part of the photograph older eroded travertine sheets are partially covered with fissure travertines (lighter color) formed by water flowing out of small fractures. Some stalactites grow in steep zones (right) and fossilize older eroded sheets. B: Open fault affecting Pleistocene conglomerates, filled with old fissure travertines. The upper part of the travertine has been eroded away.

Figura 4. A: En la parte superior de la fotografía se observan antiguos travertinos laminares erosionados y parcialmente cubiertos por travertinos fisurales procedentes del agua que se derrama desde pequeñas fracturas. En las zonas más abruptas crecen formaciones estalactíticas que fosilizan antiguos escalones de travertinos laminares erosionados. B: Falla abierta afectando conglomerados pleistocenos rellena de travertino fisural. La parte superior del travertino ha desaparecido por erosión.

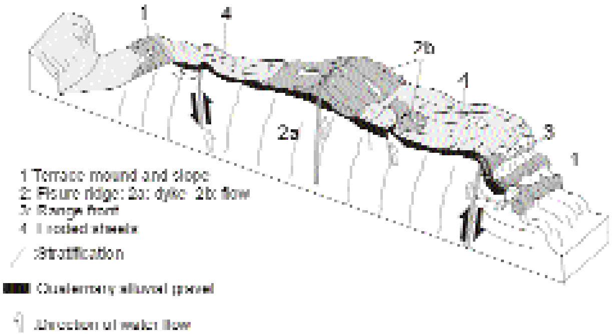


Figure 5. Schematic model showing the different types of travertine deposits observed at Carraclaca depending on the structural position of water sources and the morphology of deposits.

Figura 5. Modelo esquemático que muestra las diferentes variedades de travertinos observados en el entorno de los baños de Carraclaca dependiendo de su posición estructural y de la morfología de los depósitos.

flows out through sub-vertical fractures producing calcite precipitation over the topography (Fig. 4a) and filling the open fractures forming dikes (Fig. 4b). In other places, the water flows over the monocline flanks giving rise to precipitation, which results in layers with an original dip. It should be pointed out that the original dip of these layers may be considerable (more than 35 degrees). In order to ensure post-depositional tectonic tilting of the layers, it is necessary to study the attitude of minor speleothems such as stalagmites. A simplified model for the different kinds of travertine deposits is shown in Fig. 5. The morphologies observed at Carraclaca can be classified into four groups.

1) *Terrace-mound travertines and slope travertines*. A number of terrace shaped deposits result when carbonate rich water flows down the southern pop-up slope (Fig. 6). The water flow makes use of the stratigraphic contacts and flows horizontally, producing deposits which form different steps. These travertines also cover the steep slope of Pintado creek (Fig. 7B). They are made up of high porosity calcite with detritic contamination and present frequent gravity-controlled precipitation structures (Fig. 8).

2) *Fissure-ridge travertines*. These are fissures and minor faults filled with banded travertine over the pop-up. Inclined or vertical travertine layers are present in subvertical fissures, showing multiple calcite bands due to the cyclicity of the opening process of the fissures (Fig. 9). These are usually very good quality travertines because of the purity of the calcite. When water spills out of the fractures, small ridges or beds of travertines are produced. In this case, the degree of calcite purity depends on the substratum. Travertine beds overlapping other travertine deposits usually exhibit considerable purity. When they overlie Quaternary gravel or Miocene conglomerates, they are rich in detritic material.

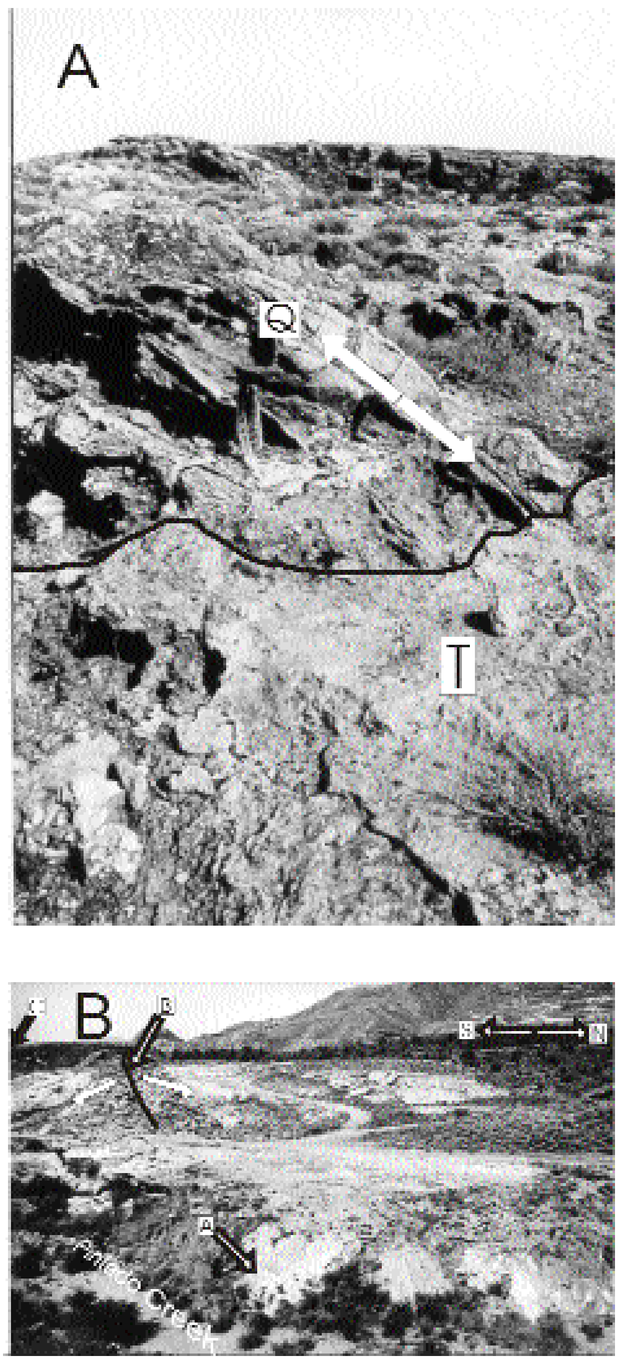
3) *Range-front travertines* are generated by springs located on the slope, giving rise to travertines which form the steep flank tilted by the activity of the fault. The Quaternary alluvial fan deposits on this flank are constituted by alternating conglomerate and silt. The hot-spring waters filter along the contacts between hard and soft strata, producing a number of travertine deposits interbedded with the Quaternary alluvial deposits (Fig.10). These travertines are formed by clean calcite and, in some places, they are covered

Figure 6. Photograph of the southern part of the Carraclaca site. We can see several terraces of travertine deposits overlapping the steep slope of the El Pintado creek valley. In the upper right corner there is the southern monocline related to the reverse activity of the Alhama de Murcia fault. Some travertines are affected by folding, but the youngest overlie the fault without deformation. C: Upper surface of the monocline observed also in Fig. 7.

Figura 6. Fotografía del sector meridional del afloramiento de travertinos de Carraclaca. En la parte inferior pueden observarse varios niveles de travertinos formando terrazas en la ladera escarpada de la rambla del Pintado. En la parte superior derecha se observa un pliegue monoclinal debido al movimiento inverso de la falla de Alhama de Murcia. Algunos travertinos están afectados por el pliegue, pero los más modernos solapan la traza de falla sin deformarse. C: superficie superior del monoclinal observable también en la Fig. 7.

with speleothems deposited in small caves between conglomerate beds (Fig. 3).

4) *Eroded sheet travertines*. These form finely bedded layers of pure calcite, which are partially eroded, covering other travertines. In general, they represent the distal parts of older range-front and terrace-mound types (Figs. 4 and 8).



Deformation structures

The main local neotectonic structure in this area is the pop-up (Figs. 2 and 11) bounded by two monocline drape folds affecting cemented Quaternary alluvial fan deposits. The pop-up is asymmetric owing to the higher amplitude of the southern monocline fold controlled by the main fault plane of the Alhama de Murcia fault. The amplitude of this fold supplies data on the vertical component of fault movement during the Quaternary.

Bearing in mind the sinistral strike-slip component of the reverse oblique-slip fault movement in this area (Armijo, 1977), the step-over is dilatational. Thus, it is possible to observe fault planes with reverse and opening movements in the pop-up. The reverse movement is more frequent along minor faults parallel to the main fault (N 55-60 E), whereas faults oriented northwards have an opening movement.

Two types of structures affecting travertines may be differentiated: those linked with the activity of the two main fault planes building the pop-up, and those distributed over the site.

Figure 7. A: Upper photograph shows flow travertine (T) overlapping tilted layers of Pleistocene conglomerate (Q) due to activity of the Alhama de Murcia fault, (located west of this picture, see Fig. 6). B: View of the northern half of the Carraclaca site. In the lower part, the El Pintado creek valley crosses the hanging wall uplifted by the reverse movement of the fault. The valley slope is covered with white travertine beds (A) that fossilize an episode of vertical fluvial incision. In the upper left part of this photo (B) we see a fracture, from which fissure travertine beds flow to the North (right) and South (left). These beds are deformed by an open NE-SW fold. C. Upper part of monocline. See the location of this surface in Fig. 6.

Figura 7. A: La fotografía superior muestra un travertino fisural de flujo (T) que solapa y rodea una capa de conglomerado (Q) del abanico pleistoceno encostrado que está basculada por la actividad de la falla situada al oeste de esta foto (ver Fig. 6). B: En la fotografía inferior se observa el valle de la rambla del Pintado al atravesar el bloque levantado por la falla de Alhama de Murcia. La ladera oeste del valle aparece cubierta por un nivel de travertinos blancos (A) que está fosilizando un episodio de incisión fluvial vertical de la rambla. En la parte superior de esta fotografía puede observarse una fisura paralela a la dirección de la visión (B) a partir de la cual fluyeron y se depositaron hacia el norte (derecha) y sur (izquierda) capas de travertinos grises. Estas capas se encuentran a su vez afectadas por un pliegue abierto de dirección NE-SW. El punto C indica la superficie de la parte superior del pliegue monoclinal. Observar la posición de dicha superficie en la Fig. 6.

Figure 8. Eroded sheet travertine forming a step partially covered with travertine (arrows) caused by waters flowing out of small fissures.

Figura 8. Travertino laminar erosionado formando un escalón parcialmente recubierto por el derrame de travertinos (flechas) procedentes de pequeñas fisuras.

As for the structures related to the main faults, the following structures can be highlighted: a) travertine layers tilted and folded by the growth of the monocline limb; b) tectonic breccia of travertine fragments fossilized by younger calcite deposits. The former travertines are observed along the scarp produced by the southern monocline (Fig. 10). Microstalagmites are evidence of the tectonic origin of tilting. An example of the latter type of deformation is shown in Fig. 12. This is a complex tectonic breccia fossilized by unbroken but highly dipping (tilted) layered travertines.

As regards the structures distributed over the pop-up, the most significant deformation structures are: a) subvertical fractures affecting travertine layers; b) tilted layers overlain by undeformed beds; c) open joints due to monocline growth; and d) folds affecting fissures and eroded sheet travertines (Fig. 7b). Travertine beds, which emanated from a fracture and overlapped either the tilted late Quaternary conglomerates or the older travertine layers, are relatively frequent (Fig. 7a). At sample scale, Fig. 3 shows a micro-unconformity of a darker speleothem on a tilted, fractured and eroded white bedded travertine sheet. We can also see bedded travertine covering a slope produced by fluvial incision of Pintado creek in the pop-up block (lower part in Fig. 7b). These deposits post-date a fluvial incision episode related to the pop-up rising. A partially eroded decametric fold of the older travertine beds is observed in the same photograph. Finally, open fractures and joints affecting different types of travertine layers are also recorded by travertine growth (Fig. 9). The opening of these fractures is concomitant with fold growth and is recorded in several phases of calcite growth in the fracture walls.

These deformation structures, which are related to the Alhama de Murcia fault activity, are not exclusive to Carraclaca. Two kilometers east of Carraclaca (close to El Roser) is another hot spring producing travertine deposits deformed by fault activity (Fig. 13). This outcrop is located at a releasing fault junction. At this point a NNE-SSW normal fault cuts the main NE-SW oblique-slip fault, giving rise to a $CaCO_3$ rich spring. A similar deformation of Pleistocene alluvial fan conglomerates is observed. The reverse movement of the Alhama de Murcia fault results in a 7 m amplitude monocline of the travertine layers.

SAMPLING

In order to bracket the age of seismic events during the late Quaternary and to establish the vertical slip rate of the

Figure 9. Frontal view (upper photograph) of the Carraclaca monocline affecting the cemented Pleistocene alluvial fan. We can also see the fissures defining blocks formed during fold growth. A) The youngest deposits filling the fissure are soil sediments resulting from hanging wall erosion. B) View of one of the fissure walls covered with several generations of travertine veins showing at least three filling phases. Each phase is composed of several seasonal calcite layers (black and white alternating). The passage from one phase to the other is evidenced by clear changes in layer orientation and different patterns suggesting major opening (probably coseismic) events.

Figura 9. Vista frontal del pliegue monoclinal de Carraclaca afectando al abanico aluvial encostrado pleistoceno. Se pueden observar las grietas que rompen y separan bloques de conglomerado encostrado a medida que el pliegue va creciendo. A) En una visión más próxima observamos que el último relleno de las fisuras son depósitos de suelo procedente de la erosión del bloque levantado. B) Vista de una de estas grietas de apertura con las paredes cubiertas de varias generaciones de venas travertínicas mostrando la existencia de varios ciclos de apertura. Cada uno de los tres ciclos está a su vez compuesto por la repetición de láminas estacionales de calcita clara y oscura. El contacto entre cada ciclo aparece marcado por un cambio en la orientación de la laminación y en el grado o carácter de su desorganización.

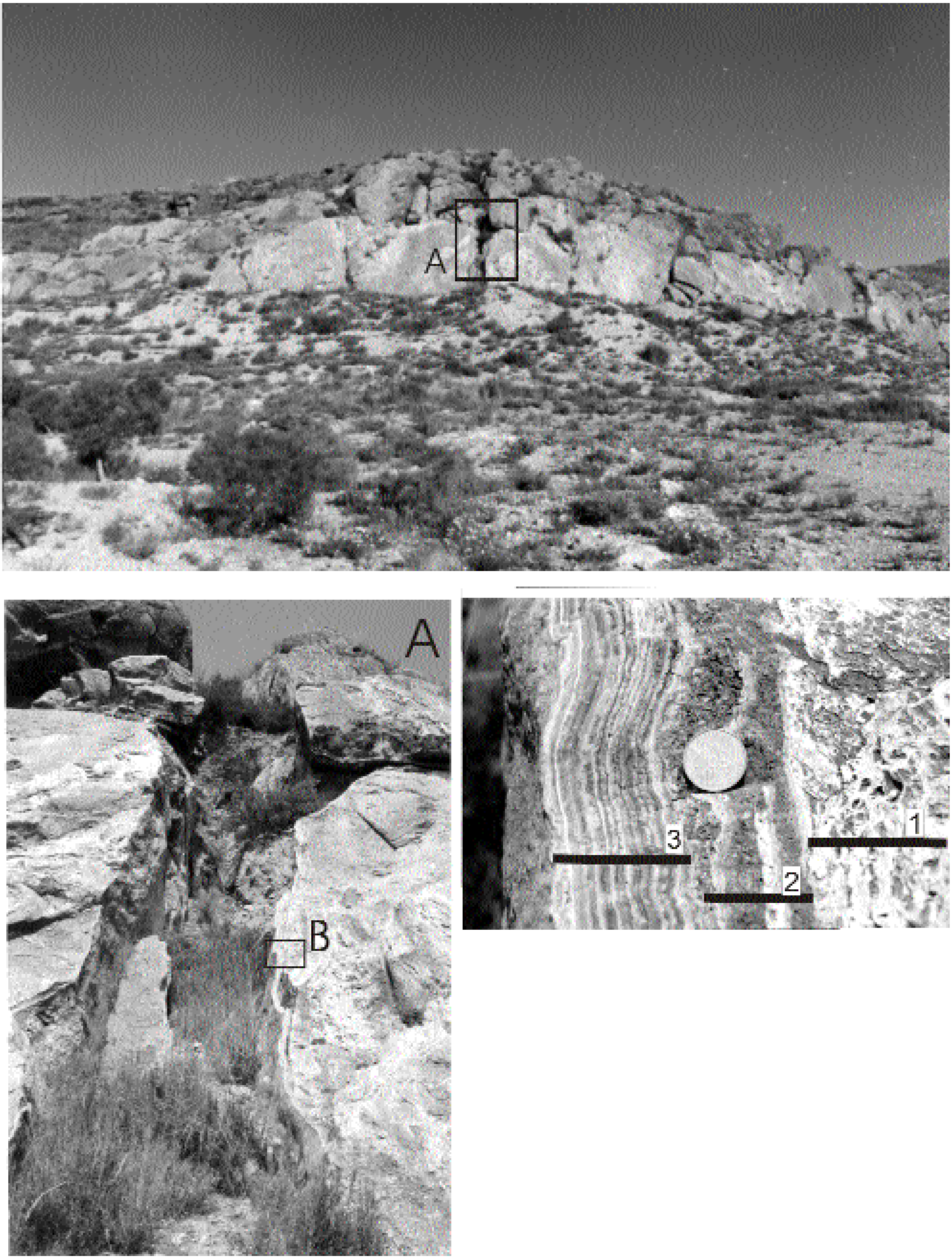

A
A
B
1
2
3

Figure 10. Travertine and veins interbedded with conglomerates forming the steep monocline flank due to the reverse activity of the Alhama de Murcia fault. A number of precipitation features indicate a sub-horizontal sedimentation origin for these travertine layers.

Figura 10. Detalle de las capas y venas de travertinos intercalados en los conglomerados que forman el flanco subvertical del pliegue monoclinal producido por la actividad inversa de la falla de Alhama de Murcia. Varias estructuras menores de precipitación indican una formación subhorizontal de los niveles de travertinos.

Alhama de Murcia fault, it is necessary to identify the travertine beds deformed by the reverse movement of the Alhama de Murcia fault, and the non deformed travertine beds onlapping the deformed ones. A number of fissure travertines overlain by younger ones are present. Moreover, several stalactites and stalagmites are tilted on the uplifted block, showing recent tectonic activity.

We selected the upper part of each significant bed, avoiding the external border of the calcite layers in order to exclude impurities and host rock fragments. In all the cases, samples located outside the channels were chosen to avoid high dissolution processes. The semi-arid climate of the area favors a low dissolution of travertines.

Twenty-five travertine samples were obtained from the monocline fold: 10 samples from the vertical flank and 15 samples from travertines overlapping the fold. Only low permeability samples free of erosion, dissolution and recrystallization were selected after a petrographic analysis. Thus, samples without outer Th were selected, i.e. samples constituting closed geochemical systems.

Twelve suitable samples were selected. Only four absolute ages using the U/Th method are currently available. Fig. 11 shows the schematic position of four samples whose ages are given in Table I. The geochemical characteristics obtained for these samples are very suitable for U/Th dating (high U content) with very low probabilities of detritic contamination (high $^{230}Th/^{232}Th$ ratio).

PALEOSEIMIC IMPLICATIONS

Prior to presenting the paleoseismic implications of the above data, it is necessary to discuss the nature of the deformation which gave rise to the Carraclaca pop-up. This pop-up is made up of fractured indurated conglomerates resulting in conglomeratic blocks floating over Messinian marls. These blocks are bounded by tension fractures whose walls are covered with many laminar travertine layers (Fig. 9). This layering is the result of episodic $CaCO_3$ rich fluids flowing along the open fractures. The periodical reverse activity of the main fault gave rise to the pop-up uplift and the rapid opening of the fractures located inside the pop-up. This cyclic opening accounts for the new precipitation layers on the fracture walls. Some open fractures are also filled with soil sediments in the last phase. Pop-up uplift induces the elevation of topographically higher fractures above the fluid circulation level, leading to their eventual filling with soil sediments (Fig. 9). Dating of these upper travertine layers and soil filling would provide information on the age of recent individual earthquakes with surface effects. At least four precipitation cycles affecting fractures were observed. Fig. 9 shows three tectonic opening episodes. Each episode is formed by the repetition of many thin seasonal calcite layers (black and white, corresponding to rainy and dry seasons). The passage from one tectonic episode to the next is marked by a change in the layering

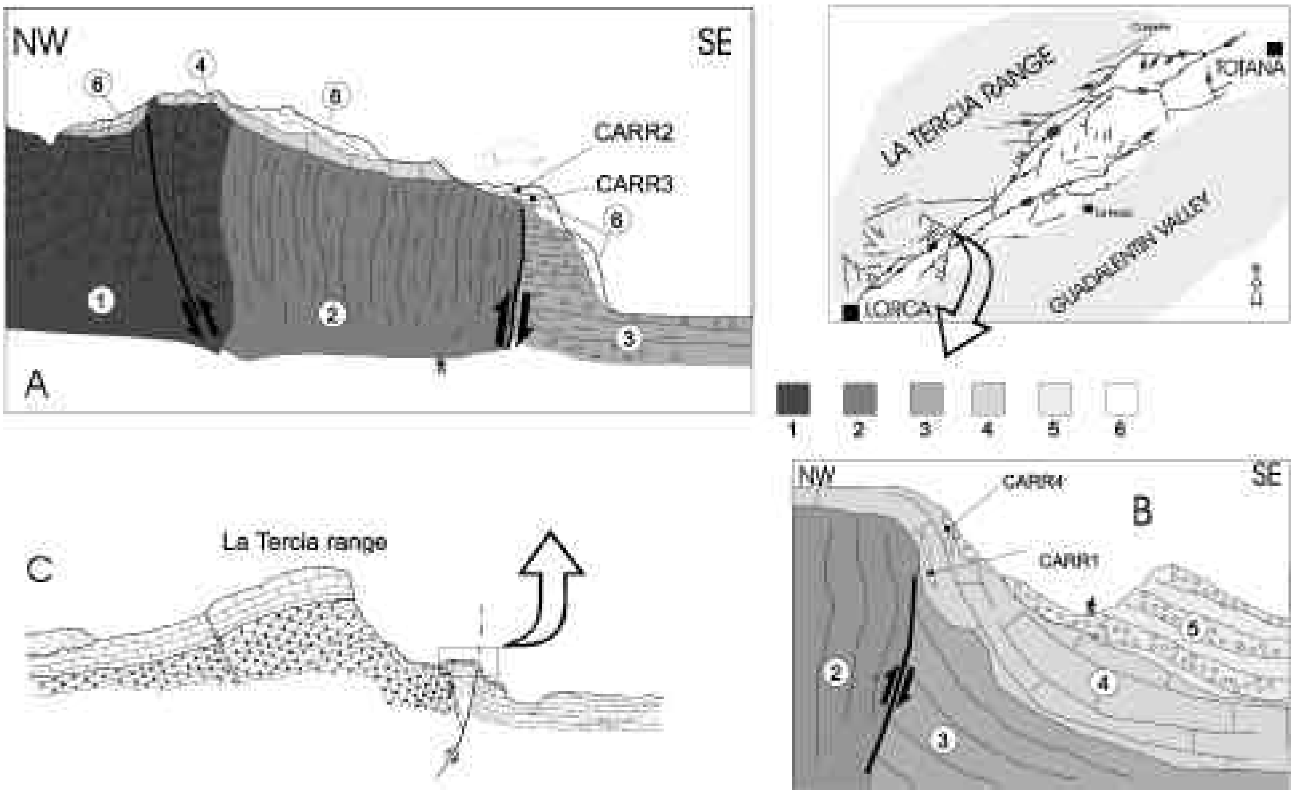


Figure 11. Structural scheme of the Carraclaca travertines. A and B: cross sections showing the structural position of dated samples (see cross-section A location in Fig. 2). Carr2 and Carr3 post-date the fold and Carr1 and Carr4 pre-date the folding process. C: Synoptic view of the Carraclaca pop-up and monocline fold linked to the La Tercia anticline (not to scale). Both structures are related to the reverse movement of the Alhama de Murcia fault. The monocline in the Carraclaca site represents the youngest steps of a regional neotectonic process during which the La Tercia range has grown since the late Miocene. 1: Red conglomerates and marls from low Tortonian. 2: Yellow marls from upper Tortonian. 3: Alluvial fan deposits from middle Pleistocene. 4: Crusted alluvial fan deposits from middle-upper? Pleistocene. 5: Fold scarp deposits from upper Pleistocene-Holocene?. 6: Travertine beds and veins, upper Pleistocene-Holocene.

Figura 11. Esquema estructural de los travertinos de Carraclaca en relación con la estructura pop-up y el pliegue monoclinal. A y B: Cortes mostrando la posición estructural de las cuatro muestras datadas (ver posición del corte A en Fig. 2). Carr2 y Carr3 posdatan el pliegue mientras que Carr1 y Carr4 están afectadas por el mismo. C: Visión sinóptica del pop-up de Carraclaca y el pliegue monoclinal en relación con la estructura del anticlinal de la sierra de la Tercia. Ambas estructuras están asociadas al movimiento inverso de la falla de Alhama de Murcia. El pliegue monoclinal de Carraclaca representa los últimos pasos dentro de un proceso neotectónico regional de crecimiento de la sierra de la Tercia desde el Mioceno superior hasta la actualidad. 1: Conglomerados rojos y margas del Tortoniense inferior. 2: Margas amarillas del Tortoniense superior. 3: Depósitos de abanico aluvial del Pleistoceno medio. 4: Abanico aluvial encostrado del Pleistoceno medio-¿superior? 5: Depósitos de escarpe del pliegue del Pleistoceno superior-¿Holoceno?. 6: Niveles travertínicos del Pleistoceno superior-Holoceno.

orientation and by changes in the fracture pattern. These features are consistent with an episodic (coseismic) growth of the pop-up. Although a creep contribution to the deformation favoring a slow opening of the fractures cannot be ruled out, we assume a coseismic growth of the Caraclaca fold to interpret the data obtained.

Two of the dated samples pre-date and the other two post-date the 15 m amplitude fold related to the Alhama de Murcia fault Quaternary activity. The deformed samples were taken from sub-vertical beds in the steep fold limb where the speleothems indicate that the original attitude of the bed was sub-horizontal, suggesting that the fold was formed after 198 ka (the age of the youngest deformed sample). The time span between the oldest non deformed sample and the youngest deformed sample yields a vertical slip rate of 0.087 (+0.003/-0.009) mm/yr. Assuming a coseismic deformation, a number of

Figure 12. Ground view of chaotic broken travertine layers fossilized by more recent laminar travertines (upper part of photograph) located on the monocline flank. These deposits were then tilted close to vertical after the breccia fossilization.

Figura 12. Vista sobre el suelo de niveles travertínicos rotos de forma caótica y fosilizados por travertinos laminares (parte inferior) localizado en el flanco del monoclinal. Estos depósitos fueron basculados hasta la vertical después de la fosilización del travertino brechificado.

earthquakes would have been necessary to produce this uplift. Lack of evidence about the size of individual events prevents us from estimating the number of earthquakes which formed the structure. Silva et al. (1997) have described a possible low dipping surface rupture at the base of the fold scarp with a 80 cm reverse slip. In our opinion, this rupture represents a small joint which was reactivated during the fold growth, a minor surface effect, not the main coseismic rupture. Two arguments challenge the interpretation of Silva et al. (1997): lack of lateral continuity of the rupture along the scarp, and low dip. The attitude of this small rupture is not consistent with the structure affecting the subvertical Miocene and Quaternary beds constituting the monocline flank. The main structure is a fault dipping 70º to 80º to the northwest. No upward refraction of the main fault, which could account for the low dip of the small rupture, was observed in the Quaternary conglomerates or in the underlying Miocene marls.

The prolongation of the fold from Carraclaca to the East, as far as El Roser, supports the lateral continuity of surface deformation linked to coseismic reactivation in the northern branch of the Alhama de Murcia fault. We used the repetition of a maximum earthquake, employing the characteristics of the earthquake observed in the southern branch of the Alhama de Murcia fault to calculate an approximate recurrence time. In this branch we identified (Martínez-Díaz and Hernández-Enrile, 1999) two paleoearthquakes with a vertical slip component of 42 cm affecting late Pleistocene alluvial fan deposits. According to Wells and Coppersmith (1994), 15 km long ruptures, such as the Lorca-Totana segment, could produce a 6.0 to 6.5 magnitude (Mw) event with a maximum slip close to 50 cm. Using the absolute ages of the Carraclaca samples, the maximum time span during which the fold developed is 171,8 ka (198 ka is the youngest age prior to deformation and 26,2 ka is the oldest age after deformation). Taking a fold amplitude of 15 m and a slip per event of 42 cm, we obtain a recurrence time of 4818 yr for surface rupture earthquakes along this fault segment.

There are other travertine outcrops along the Alhama de Murcia fault. The aforementioned travertine deposits at El Roser display deformation features similar to those observed at Carraclaca. Accordingly the surface folding and rupture related to the late Pleistocene and probably Holocene activity of the Alhama de Murcia fault involves a segment of at least 2 km in length (the Lorca-Totana segment is 15 km long).

CONCLUSIONS

We confirmed that the U/Th method could be used in travertine dating provided that attention is paid to the sampling and to the petrographic analysis of the travertines in order to avoid contamination and thus collect samples from a geochemical closed system. Given the high content of U and the high values of the $^{230}Th/^{232}Th$ ratio, the travertines analyzed are suitable for the U/Th dating method.

In this work, we show that travertines from $CaCO_3$ rich springs controlled by active tectonics may also occur along oblique-slip faults and not only in normal fault zones. At Carraclaca, the springs are related to an extensional step-over and to releasing fault junctions of the reverse-sinistral Alhama de Murcia fault zone. Dating of deformed and undeformed travertine beds enabled us to date the Carraclaca Quaternary fold. Cycling precipitation of travertine beds and veins can be related to seismic events that contribute to fold growth. These features lend support to the coseismic nature of deformation although the existence of aseismic contribution cannot be ruled out.

The first paleoseismic results in the Betic Cordillera using this methodology are presented. We calculated 1) a

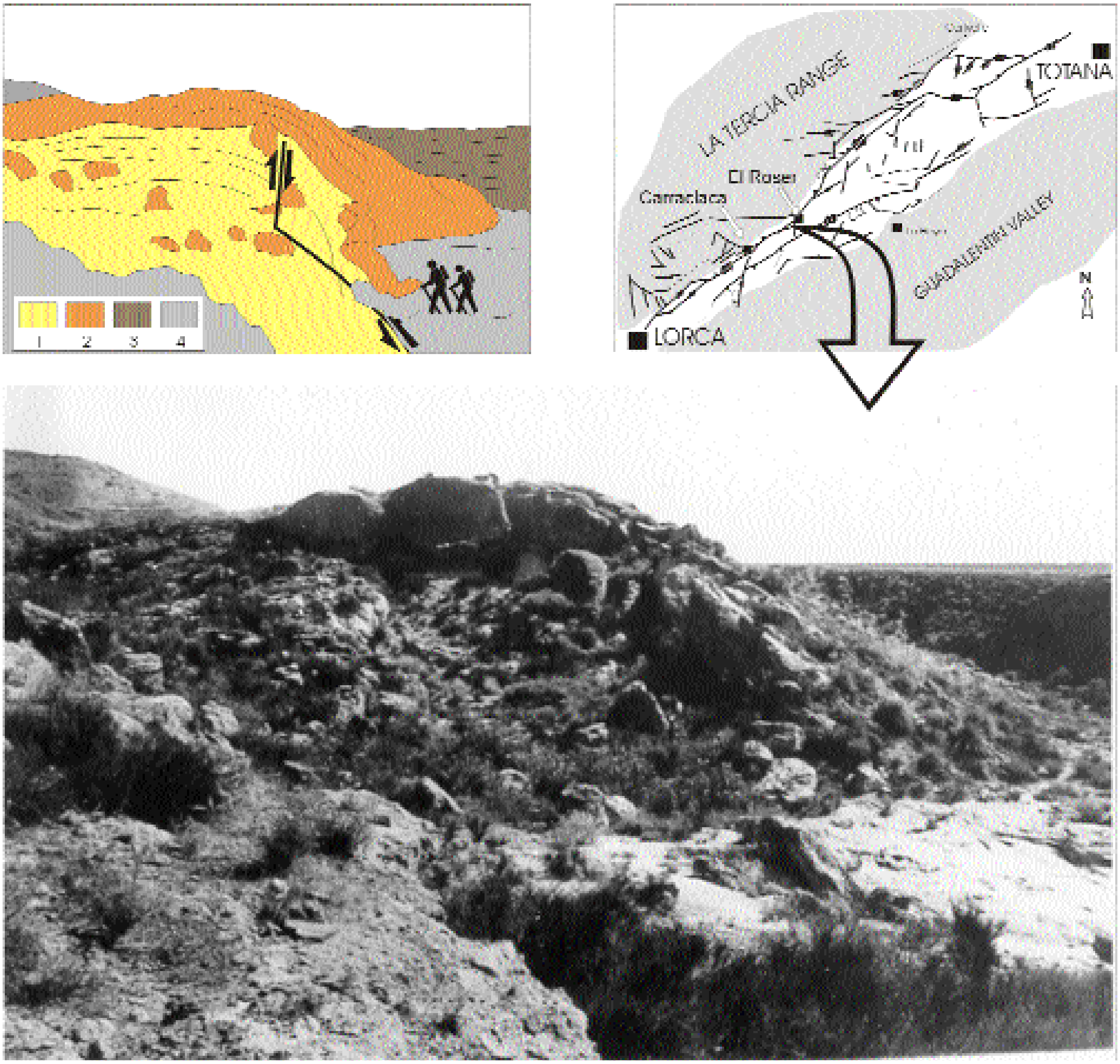


Figure 13. Crusted Pleistocene alluvial fan showing a monocline disposition at the El Roser site, 2 km east of Carraclaca. This structure and the deformation of travertine deposits are equivalent to the ones observed at Carraclaca. In the upper left corner a structural sketch is shown in which the black line and arrows show the fault and the oblique-slip (reverse-sinistral) movement, respectively. This outcrop confirms the lateral continuity of the reverse activity episodes along the northern branch of the Alhama de Murcia fault. 1: Yellow marls from upper Tortonian. 2: Middle Pleistocene alluvial fan deposits. 3: Middle-upper? Pleistocene alluvial fan deposits. 4: Upper Pleistocene-Holocene travertines.

Figura 13. Fotografía de un abanico aluvial pleistoceno encostrado y afectado por un pliegue monoclinal situado sobre la falla de Alhama de Murcia, 2 km al este del afloramiento de Carraclaca, en el paraje de El Roser. En el esquema de la parte superior izquierda se sitúa la traza de la falla así como su cinemática oblícua (inverso-direccional) responsable de la estructura. Este afloramiento prueba la continuidad lateral de los episodios de actividad inversa sobre la rama norte de la falla de Alhama de Murcia. 1: Margas amarillas del Tortoniense superior. 2: Depósitos de abanico aluvial del Pleistoceno medio. 3: Abanico aluvial encostrado del Pleistoceno medio-¿superior? 4: Niveles travertínicos del Pleistoceno superior-Holoceno.

vertical slip rate of 0.087 mm/yr for the reverse-sinistral fault which produced the Carraclaca monocline fold, and 2) a mean recurrence time of 4810 yr, employing the coseismic slip data (0.42 m per event) observed in the southern branch of the Alhama de Murcia fault. These values are consistent with the expected values in areas of intraplate-plate boundary (Scholz, 1990) and with the magnitude which would occur if the entire Lorca-Totana segment (15 km in length) was reactivated in accordance with Wells and Coppersmith (1994).

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