Geochronology of the Sencelles fault scarp and its relationships with the AD 1851 Mallorca Earthquake (Baleares Islands, Spain)

Geocronología del escarpe de Falla de Sencelles y su relación con el Terremoto de Mallorca de 1851 AD, (Islas Baleares, España)

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Resumen: La Falla de Sencelles constituye el accidente tectónico distensivo más importante de la Isla de Mallorca asociado tentativamente al terremoto de Palma de 1851 AD (VII EMS). Su terminación SE (Segmento de Sta Eugenia) presenta un escarpe de falla en roca de un máximo de 3,15 m de altura. Los últimos 840 m del escarpe presentan un notable bandeado horizontal con hasta cinco bandas diferencialmente colonizadas por líquenes y meteorizadas. Se realiza un análisis liquenométrico basado en la medida de 125 talos de *Aspicilia calcarea* y *Aspicilia radiosa* en lápidas y monumentos funerarios fechados de los cementerios de Sta. Eugenia y Sta. María del Camí obteniéndose las curvas de crecimiento de líquenes (LGR) para la zona. Su aplicación a la muestra de líquenes de las diferentes bandas del escarpe de falla en roca indica que la banda inferior (10-13 cm) está relacionada con nivelaciones del terreno realizadas en la zona a mediados del siglo XX (c. 1956 – 1953). La segunda banda (23-47 cm) se relaciona con el Terremoto de Palma (1851 AD) ya que la aplicación de los LGR para indican fechas de exposición de 1853± 18 AD (*A. radiosa*) y 1855± 59 AD (*A. calcarea*). Los desplazamientos observados pueden relacionarse con rupturas secundarias.

Palabras clave: Falla de Sencelles, liquenometría, Terremoto de Palma 1851 AD, Mallorca, España.

Abstract: *The Sencelles fault constitutes the main extensional structure of the Mallorca Island tentatively linked to the AD 1851 Palma earthquake (VII EMS.) The SE termination of the fault (Sta. Eugenia Segment) is featured by a linear bedrock fault scarp of a maximum of 3.15 m height. The last 840 m of this rocky scarp display a significant horizontal banding, with up to five bands differentially weathered and colonized by lichens. The lichenometric analysis is based on the measurement of 125 specimens of "Aspicilia calcarea"* and *"Aspicilia radiosa" in tombstones and funerary monuments (with inscribed dates) of the cemeteries of Sta. Eugenia and Sta. María del Camí, to obtain the lichen growth rates (LGR) for the zone. The application of the resulting LGR on the banded fault scarp indicates that the basal ribbon (10-13 cm) responds to ground leveling works developed in the zone during the middle 20th century (c. 1956-1953). The second fault ribbon (23-47 cm) can be related to the AD 1851 Palma Earthquake, since LGR results here in exposure dates of 1853±18 AD (A.radiosa) and 1855±59AD (A. calcarea). The associated displacements cannot be interpreted as surface faulting, but as secondary or sympathetic ground ruptures (secondary earthquake effects).*

Key words: *Sencelles fault, lichenometry, AD 1851 Palma Earthquake, Mallorca, Spain.*

INTRODUCTION

The NE-SW Sencelles fault constitutes the main extensional structure of the Mallorca Island. It has been active from the last c. 19 Ma, with a maximum accumulated throw of 750 m constituting the southern border of the Cenozoic Inca basin (Fig. 1; Benedicto et al., 1993). Geologic and geomorphologic evidence prove its activity from Late Pliocene to Pleistocene times with a mean throw of c. 100 m for the last c. 3.0 Ma (Silva et al., 2001). Following these last authors this fault (7 km length) has a segmented nature with two main segments in its SW sector: The Sencelles segment and the Sta. Eugenia segment (Fig. 1). The last segment displays a length of c. 2.8 km between Puig Son Seguí and Sta. Eugenia and has been tentatively identified as the suspect seismic source of the AD 1851 (VII EMS) Palma Earthquake (Silva et al., 2001).

The SW termination of the Sencelles Fault is featured by a NE-SW bedrock fault scarp c. 2.8 km long and 3.15 m (maximum) high facing to the NNW (Fig. 1). The scarp is developed on Plio-Pleistocene strongly cemented calcarenites of the St. Jordi fm. (Benedicto et al., 1993). In this zone scarp height diminishes from 3.15 m in the East to its eventual die-out near the cemetery of Sta. Eugenia. Fault trenching analyses in

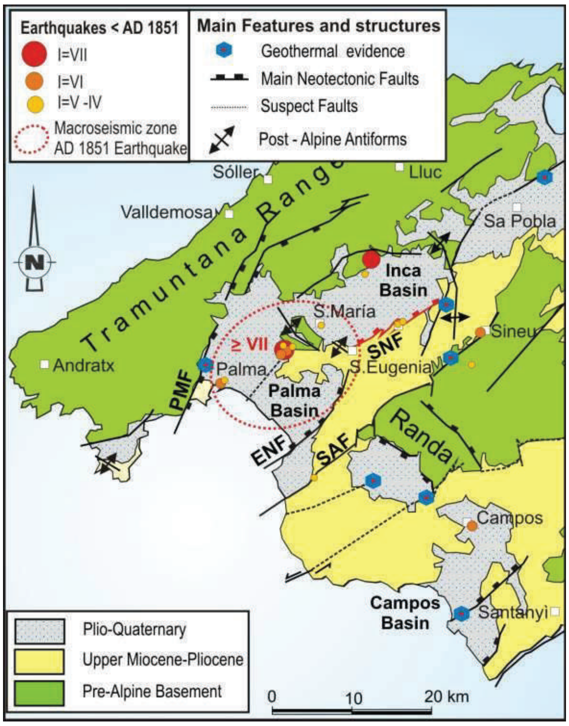

FIGURA 1. *Major geological and seismotectonic features of western zone of Mallorca Island, showing the main neotectonic faults. PMF: Palma Fault; ENF: Cap Enderrocat Fault; SNF: Sencelles Fault; SAF: Sineu-Algaida Fault..*

this zone identified an upper post-AD1851 earthquake colluvial wedge. This level comprised large blocks of adjacent stone fences built-up over the bedrock fault scarp burying artificial fillings containing post c. AD 1950 car-oil cans of "Ertoil" (Silva et al., 2005). Lichenometric analyses presented in this study intend to unravel the geochronology of the bedrock fault scarp and its potential relationships with the AD 1851 earthquake affecting the zone.

LICHENOMETRIC ANALYSIS OF THE FALUT-SCARP.

The Sta. Eugenia fault scarp shows evidence of recent reactivation, featured by the development of differentially weathered ribbons (Fig. 2) along the eastern c. 840 m of this fault segment. In fact, these different weathered ribbons are characterized by the colonization of different lichen species and different lichen sizes, which clearly decreases from the top to the base of the scarp free-face. This fault plane banding can be assumed to be produced during recent recurrent displacements of the fault (Silva et al., 2001), which is a typical feature in similar fault-scarps on calcareous materials (Wallace, 1984; Stewart and Hancock, 1989). What is common in these cases is the generation of a coseismic thin reddish pedogenic veneer staining the lower ribbon of the activated fault plane. Recurrent fault displacements generate differentially weathered fault ribbons punctuated by different lichen colonies (in size and specie), recording the maximum slip of the intervening events.

A detailed study of the fault scarp identifies five main ribbons differentially colonized by lichens (Fig.3). Two sites for lichenometric analyses were selected c. 400 m west to the fault-trench site performed by Silva et al. (2005). Fig. 3 shows a synthetic cross-section illustrating the main features in site 2, where the free-face of the scarp is 2.45 m in height. The performed analysis considered the calcareous lichen species *Aspicilia calcarea (L.)* and *Aspicilia (Lobolotalia) radiosa (Hoffm.)*, commonly used in lichenometric analyses in SE Spain (i.e. Pérez-López et al., 2012). However specimens of the orange crusty lichen *Xanthoria Calcicola (Hellb.)* and large colonies of black crusty lichens (unidentified) are present in the upper ribbons of the fault scarp (Fig. 3). The analysis involved the measurement of the *"tallus"* of 42 individual specimens over the three lower ribbons (the youngest ones), since in the two upper ones these species appeared assembled in dense lobulated colonies no suitable for lichenometric measurements (Fig. 2).

LICHEN GROWTH RATES (LGR).

In order to obtain the annual growth rate of the lichen species, common procedures to take measurements of the *tallus* diameter on rocky surfaces of know age were developed. For this purpose we selected the cemeteries of Sta. Eugenia (on the fault trace) and Sta. Maria del Camí (6 km ENE to the measured rocky scarp). Measurements were made in both vertical and horizontal tombstone surfaces, as well as in funerary monuments with inscribed date (or year) of death. Orientation data on the tombstone surfaces where taken in order to check the relative "weight" of sunlight exposure in the resulting lichen growth rates (LGR). In total, 125 data on lichen size were collected for individual *A. calcarea* (104) and *A. radiosa* (21) specimens at both cemeteries for a time period comprised from AD 1850 to 1992 (c. 140 years) in the range of the elapsed time since the last strong earthquake in the zone (AD 1851 Palma Event).

FIGURA 2. *Sencelles fault scarp near Sta. Eugenia displaying the different ribbons of lichens discussed in text.*

The performed analyses for the two lichen species indicate a strong sensitivity of LGRs to vertical/ horizontal position, orientation and location. In spite of their proximity (c. 6 km), results from the cemeteries of Sta. Maria (NE) and Sta. Eugenia (SW) are clearly decoupled (Fig. 3). This must be mainly due to the relevant N-S rainfall gradient in the Island triggered by the orographic effect of the Tramuntana range. Mean annual rainfall rates in Sta. Maria (c. 535 mm/yr) are higher than in Sta. Eugenia (c. 430 mm/yr).

LGR curves (and functions) were obtained by plotting the lichen diameter against the age of the tomb and then extrapolating the resulting curve to obtain mean ages of the different ribbons banding the bedrock fault scarp. For this approach we plotted the two-three largest specimens of each analyzed tomb for horizontal and vertical data-sets in both cemeteries. The analyses indicate that all datasets fit well ($R^2 \geq 0.85$) to lineal regression lines. The results shows that the highest LGR corresponds to *A. Calcarea* in horizontal surfaces facing to the ENE with 0.84±0.08 mm/yr in Sta. María, whilst in vertical surfaces mean LGR resulted in 0.49±0.02 mm/yr (Fig. 3). In Sta. Eugenia, the same specie shows smaller mean LGR of 0.31±0.04 mm/yr in horizontal surfaces and of **0.23±0.06 mm/yr** for vertical ones. The results for *A. Calcarea* clearly indicate that the lichen populations to be considered to establish reliable LGR functions for the vertical fault scarp are the vertical ones. Measurements of *A. radiosa* in vertical surfaces were only taken in Sta. Eugenia (onto the fault scarp), resulting in mean LGR of **0.14±0.02 mm/yr** (Fig.3). The outstanding differences of LGR between both cemeteries, point to the use of the Sta. Eugenia datasets to compute the ages of the differentially weathered fault ribbons.

DISCUSSION: CHRONOLOGY OF THE SCARP

Using mean LGR for vertical datasets of *A. Calcarea* indicate that the lichen population of the basal fault scarp ribbon (1) is dated in AD 1953 ± 9 years, the second ribbon (2) in AD 1855 ± 59 years and the upper third ribbon (3) in AD 1712 ± 24 years. Data from mean LGR of *A. radiosa* result in comparable predicted ages of AD 1958 ± 10 for the first ribbon (1); AD 1853± 18.2 years for the second ribbon (2); and of AD 1744± 57 years for the third one (3).

The first basal ribbon (15-13 cm wide) dated in the middle 20th Century can be linked to artificial excavations and ground levelling works in the area as observed in the fault-trench excavated in the zone (Silva et al., 2005). The upper levels of this trench displayed old artificial excavations buried by anthropic fillings containing oil-car cans of "Ertoil", a trade-mark mark introduced in Spain in the 1950`s decade. The second ribbon (23 – 47 cm wide) throw mean ages (AD 1853 – 1855), congruent with the AD 1851 Palma Earthquake and can be catalogued as a probable ground failure triggered by the earthquake. In this sense, Puyó (1851) reported the occurrence of "generic" ground failure cases in the macroseismic area (Sa Cabaneta, to Sta. Eugenia) during the main earthquake (VII EMS) and the stronger aftershock (VI EMS) causing the collapse of the St. Marçal Church at Sa Cabaneta (Silva et al., 2001). Since the maximum width of the ribbon is 47 cm over a length of c. 840 m, this can not be considered surface-faulting, but some kind of secondary or sympathetic rupture along the fault trace. This, in addition, could be subject of ground-levelling works after the earthquake, since the largest lichen specimens (51 to 45 mm in diameter) are found in the upper 10-15 cm of the ribbon. This can be considered the maximum displacement occurred during the earthquake. On the other hand, some of the oldest funerary monuments in Sta. Eugenia shows clear evidences of earthquake damage, such as the small mausoleum of *"Juan Castell y Los Suyos"*, dated in AD 1853, but very probably built soon before the AD 1851 Earthquake. Dropped keystone, penetrative fractures and broken dipping corners feature the main entrance of the mausoleum.

The third ribbon (58-55 cm wide) offers a mean age bracketed in AD 1712 and 1744, which can be related to a previous event. However this ribbon presents a rugged fault plane largely colonized by black lichen colonies overlapped by the orange lichen *X. Calcicola* and large colonies of *A. Calcarea* of amoeboid geometry in its upper c. 30 cm, where larger lichen specimens were measured. Therefore, the maximum predicted ages are related to the upper portion of this third ribbon and may represent the youngest age for an ancient earthquake in the zone. In fact, the predicted ages fairly match with the first period of relevant

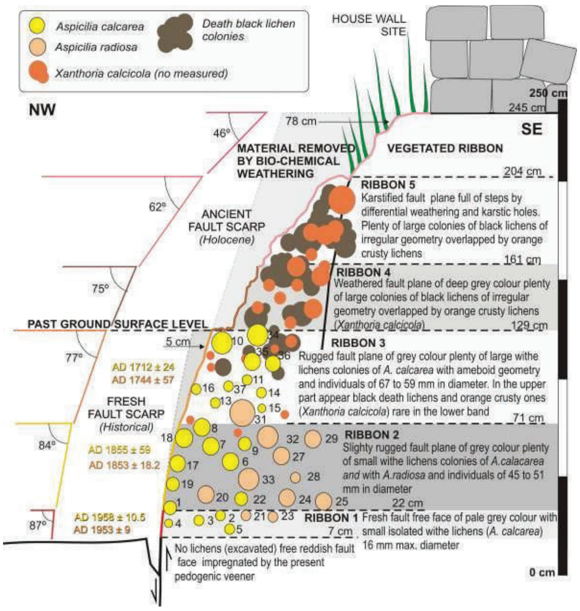

FIGURA 3. *Schematic cross-section of the Sencelles bedrock fault scarp in Site 2. Measured Lichen species are plotted attending to their position in the fault plane. Lichen ribbons, mean angles of the fault plane bands, theoretical width of removed materials and mean computed ages for the three lower ribbons are displayed.*

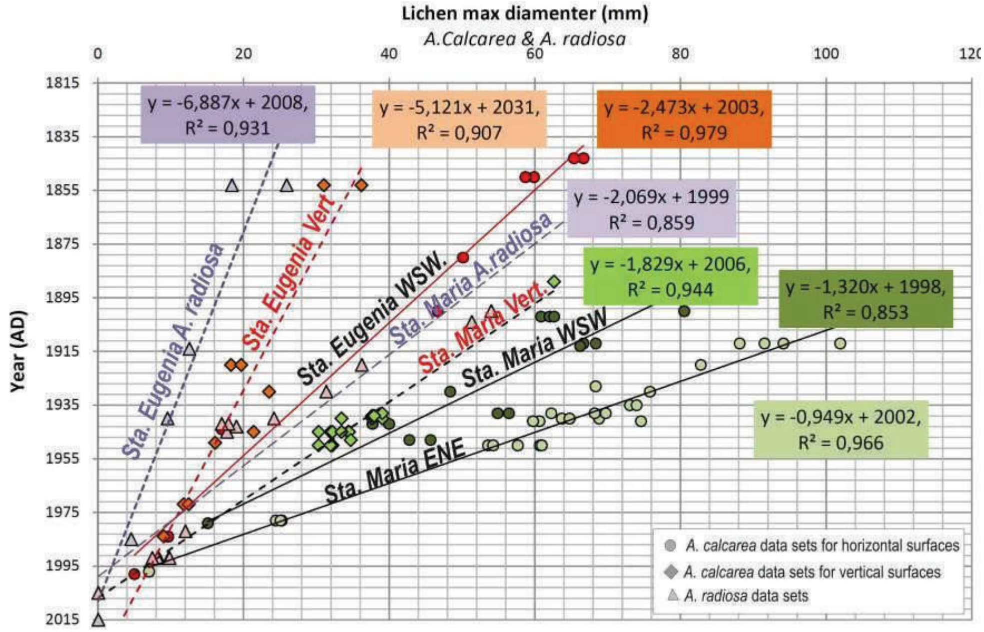

FIGURA 4. *Plot of Lichen growth rates (LGR) and resulting LGR regression lines (linear functions) for different lichen datasets measured in the cemeteries of Sta. Eugenia and Sta. Maria del Camí.*

seismic activity recorded in the island (AD 1721-1764). This period includes a VII EMS event c. 15 km away from the analysed fault scarp (AD 1721 Selva Earthquake) but also others V-IV EMS events around Sencelles and Sta. María del Camí (Fig. 1). On the other hand this ribbon finishes in a sharp centimetric shoulder which can be interpreted as the marker of an ancient ground surface. The two last ribbons featuring the upper c. 150 cm of the fault scarp display evident signals of differential weathering and karstificacion (Fig. 2). These, may represent more ancient Holocene earthquakes, but presumably within the range of the last 1,000 -3,000 years. Preliminary lichen observations on prehistoric Talayots (AC 1,000 – 1,500) in the island indicate that these display similar lichen assemblages and populations to those observed in the upper ribbons of the ancient fault scarp.

CONCLUSIONS

The Sencelles bedrock fault scarp is differentially weathered, displaying five different ribbons diversely colonized by lichens. The fault scarp is vertically segmented displaying a basal fresh fault-plane (three first ribbons) and an upper deeply weathered and karstified one, probably related to ancient Holocene events (Fig. 3). Lichenometric analyses developed on the basal fresh fault-plane suggest and historical age, younger than c. AD 1700. Within this historical scarp, the second ribbon (23-47 cm wide) can be reasonably linked to the AD 1851 Palma earthquake. This reactivation of the fault plane can be interpreted as a secondary earthquake effect (secondary or sympathetic rupture) according to the established size of the earthquake (VII EMS).

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