



Earthquake Archaeological Effects (EAEs) triggered by the Middle Age Catalanian seismic crisis in the Romanesque heritage (NE Spain)

Efectos Arqueológicos de Terremotos (EAEs) en el patrimonio Románico producidos por la crisis sísmica catalana de la Edad Media (NE Spain)

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Resumen:

A lo largo del s.XV varios terremotos tuvieron lugar en Cataluña (NE de España), generando importantes daños en las localidades y en sus edificios románicos. Los tres terremotos más importantes tuvieron intensidades entre VIII y IX (EMS 98) y tuvieron lugar durante un intervalo de tiempo de dos años (1427-1428 AD). El evento más destructivo fue el último y tuvo lugar en febrero de 1428 AD, denominado terremoto de Camprodón (I= IX). La documentación de la época custodiada en los monasterios y conventos nos ofrece información importante sobre los daños que sufrieron estas construcciones religiosas y hoy en día aún es posible observar estos efectos arqueológicos de terremotos (EAEs) en el patrimonio románico de la zona. En este trabajo se realiza un análisis estructural geológico de los EAEs, el cual indica la direccionalidad del movimiento del sustrato durante el terremoto y es congruente con la localización de la zona epicentral del terremoto de Camprodón. Estas orientaciones podrán ser útiles en el futuro a la hora de realizar intervenciones/restauraciones en el patrimonio románico catalán como medidas preventivas para futuros terremotos.

Palabras clave: Efectos arqueológicos de terremotos; edad media; patrimonio románico; Cataluña (NE de España).



Abstract:

During the 15th century several earthquakes struck Catalonia (NE Spain) triggering important damage in the main “Romanesque Buildings” of the zone. The three main events had intensities between VIII and IX (EMS-98), and occurred during a time-interval of 2 years (1427-1428 AD). The most destructive event was the last one on February 1428 AD (Camprodón, IX). The epoch documents of monasteries and convents offer relevant information on the occurred damage affecting these religious buildings and nowadays it is possible to observe earthquake archeological effects (EAEs) in the Romanesque heritage of the zone. This work deals with the analysis of the preserved EAEs by means of the application of structural geology analysis. The performed analysis indicates a directionality of the seismic ground motion consistent with the location of the Camprodón meizoseismic epicentre. This orientation could be useful in future intervention/restoration works on the Catalanian Romanesque heritage.

Key words: Earthquake Archeological Effects (EAEs), Middle age, Romanesque heritage, Catalonia (NE Spain).

1. Introduction

One of the most important seismic crises during historic times in Catalonia (NE Spain) occurred during the years 1427-1428, with three main earthquakes: Amer (1427/03/19; I=VIII), Olot (1427/05/15; I=VIII) and Camprodón (1428/02/2; I=IX) (Fig. 1). The historical chronicles describe important destruction in the region especially that related to the Camprodón event (Olivera *et al.*, 2006). Using this information and revisiting the Romanesque heritage of the meizoseismic zone, we had compiled a set of Earthquake Archeological Effects (EAEs) according to the classification of Rodríguez-Pascua *et al.* (2011). The seismogenic source of this seismic series has been related with the NW-SE Amer Fault by Perea *et al.* (2012) (Figure 1). Following these authors the three main earthquakes are aligned on the fault trace and their timing sequence migrated from SE to NW.

2. EAEs in the Romanesque heritage and structural analysis

We have analyzed different EAEs preserved in the Middle Age buildings (Romanesque style) of the area. These buildings were affected by at least one of the historical earthquakes of the studied seismic series. The application of

conventional of structural geology analyses to EAEs (e.g. Giner *et al.*, 2009, 2011, 2012; Rodríguez-Pascua *et al.*, 2012) result on preferred trajectories and directions of ground motion during the earthquake. In the following paragraphs we describe the different EAEs induced by the Camprodón earthquake (1428 AD) grouped by towns and/or monasteries:

- *Sant Joan de les Abadeses Abbey*: Located 11 km SW of the meizoseismic epicenter (Fig. 1), the main apse and the old hostel of the monastery were destroyed by the earthquake, but rebuilt after that. Nowadays it is possible to observe several EAEs inside of the church such as, dipping broken corners, displaced masonry blocks and tilted walls. All of these EAEs are compatible with a NW-SE seismic ground motion at N175°E.
- *Ripoll Monastery*: Located 19 km SW of the epicenter (Figure 1), was seriously damaged by the earthquake. The vault of the main nave and the western bell tower collapsed during the earthquake. The analyzed data indicate that the main ground motion direction was near-perpendicular to the orientation of the main nave of the church (N040°E), therefore NW-SE at N130°E.

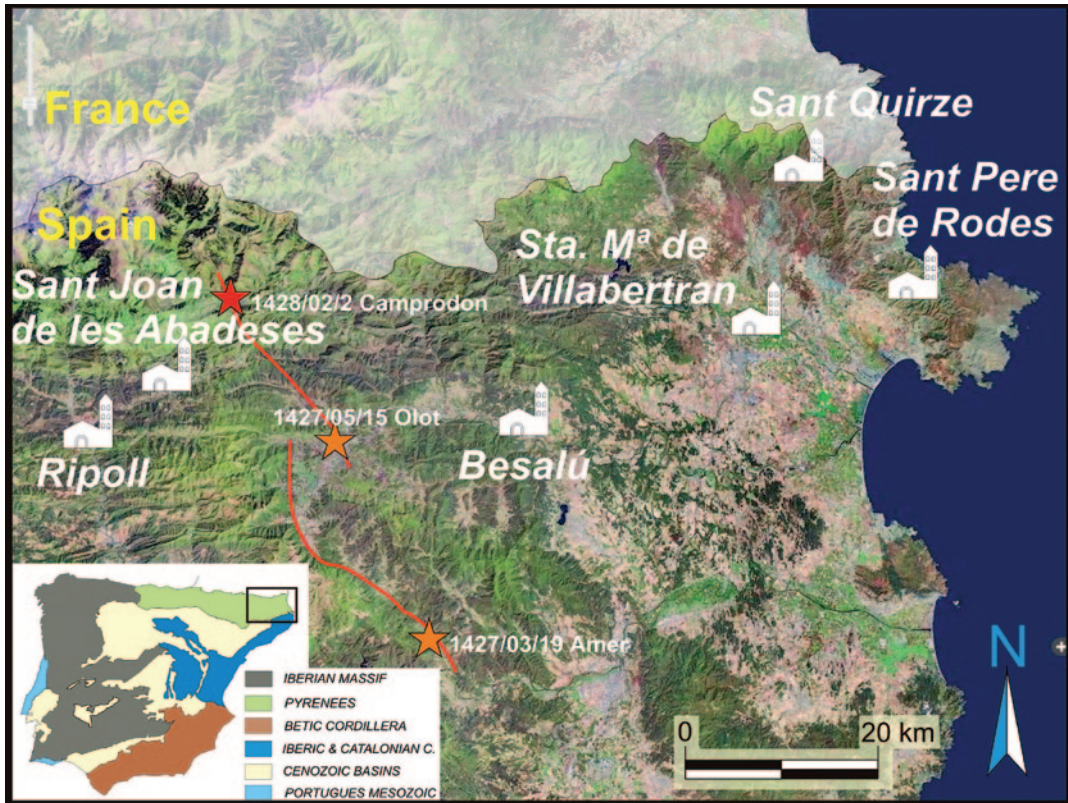


Figure 1. Geographic location of the meizoseismic area of the Middle Age Catalanian crisis. The stars represent the epicenters of the historic earthquakes (EMS98 intensity: VIII for the orange star and IX for the red star). The cities and Romanesque churches represent the locations of EAEs identified in this work.

Figura 1. Situación geográfica de la zona macrosísmica de la crisis sísmica medieval catalana. Las estrellas representan los epicentros de los terremotos históricos (intensidad EMS98: VIII para la estrella naranja y IX para la roja). Las ciudades y las iglesias románicas representan las localizaciones de los EAEs identificados en este trabajo.

- Besalú:** it is a beautiful medieval town, plenty of Romanesque monuments located 30 km at the SE of the epicentre. In this town we have studied six buildings (religious and civil), but the most interesting examples of EAEs are recorded in the Sant Vicent Church, where penetrative fractures in masonry blocks, dipping broken corners and displaced masonry blocks (Figure 2) are observed. This set of EAEs is compatible with a NE-SW seismic ground motion at N045°E. Other interesting site is the ruins of the Pujada de Santa María Church, where restored dropped key stones in the window of the main apse are nicely preserved today (Figure 3). This EAE is compatible with a similar ground motion direction at N164°E. The rest of the EAEs recorded in this Medieval town are fairly bracketed between these two reported orientations.
- Canonica de Santa María de Villabertrán:** This monastery, located 50 km east of the epicentre displays an interesting collection of EAEs. The main gate of the church was destroyed and repaired after de earthquake (Figure 4A). The window located in this same frontal facade shows displaced masonry blocks, dropped key stones

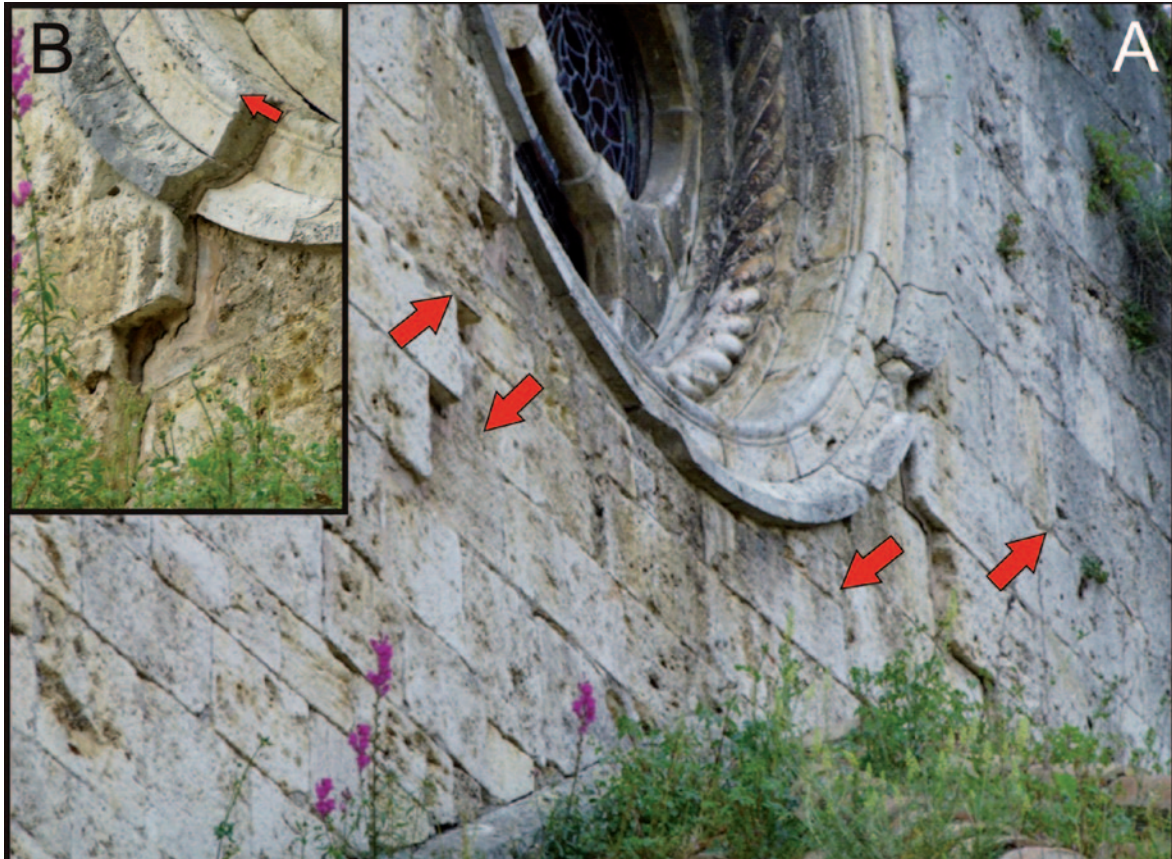


Figure 2. Displaced masonry blocks in Sant Vicent Church (Besalú): A) displaced and repaired masonry blocks in the rose window of the apse and B) close view of the displacement.

Figura 2. Bloques de sillería desplazados en la Iglesia de Sant Vicent (Besalú): A) bloques de sillería desplazados y reparados en el rosetón de encima del ábside y B) vista de detalle del desplazamiento de bloques de sillería.



Figure 3. Dropped and repaired key stones in the window of the main apse of the Pujada de Santa María Church (Besalú).

Figura 3. Claves caídas de arco en la ventana del ábside principal de la Iglesia de Pujada de Santa María (Besalú).

(Figure 4B) associated to a large crack running towards the roof of the building. These EAEs are large penetrative strain structures and it is possible to observe them inside of the church. In the cloister of this building are also preserved repaired arches and displaced masonry blocks are also preserved. In the NW wall of the refectory the key stones of a window were horizontally displaced (Figure 5). This set of EAEs is compatible with a NW-SE ground motion of N165°E.

- *Sant Quirze de Colera Abbey:* This medieval building founded in 927 AD was rebuilt in 1123 AD and it is possible to observe the original foundations with apparent anti-seismic structures formed by assembled

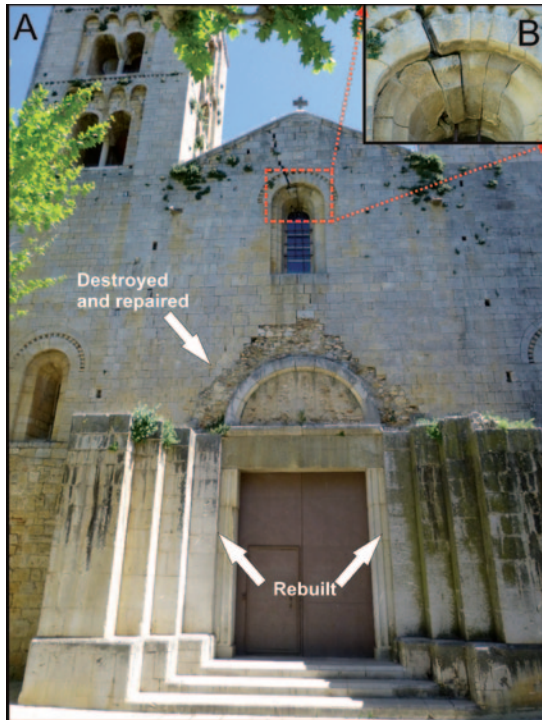


Figure 4. EAEs of the Canonica de Santa María de Vilabertrán: A) main facade of the monastery and B) close view of the dropped key stone of the window.
Figura 4. EAEs en la Canonica de Santa María de Vilabertrán: A) fachada principal del monasterio y B) vista de detalle de la caída de la clave del arco de la ventana.



Figure 5: Key stones displaced horizontally in the refectory of the monastery of the Canonica of Santa María de Vilabertrán.
Figura 5. Desplazamiento horizontal de las claves del arco en el refectorio del monasterio de Canonica de Santa María de Vilabertrán.

stones with spike-like disposition (Figure 6). Later was seriously damaged by the 1428 AD earthquake and in 1441 the abbey was eventually abandoned by ruin. The building is located 58 km ENE of the epicentre and the main set of EAEs preserved in this building is composed by tilted walls, dropped key stones, warped arches (Figure 7), penetrative fractures in masonry blocks and repaired arches. The orientations of all these EAEs are compatible with a NW-SE seismic ground motion of N170°E.



Figure 6. Apparent anti-seismic structures formed by assembled stones with spike-like disposition in the original foundations of the Sant Quirze de Colera Monastery.
Figura 6. Posibles estructuras antisísmicas formadas por disposición en espiga de mampuesto de roca en los cimientos del Monasterio de Sant Quirze de Colera.



Figure 7. Warped arch and repaired key stones (made of bricks) in the monastery of Sant Quirze de Collera.
Figura 7. Arco deformado y claves de arco reparadas (realizadas con ladrillo) en el monasterio de San Quirze de Collera.

- *Sant Pere de Rodes Monastery*: This building, located at 69 km from the epicentre, is the farthest from those analyzed in this study and consequently only displays scarce evidences of EAEs. The most relevant ones are penetrative fractures in masonry blocks, dropped and repaired key stones and fairly tilted walls. We interpreted that the main component of ground motion was NW-SE, perpendicular to the major nave of the church.

3. Discussion and Conclusions

The Camprodón earthquake of February of 1428 caused important damage in the pro-

vince of Girona (NE Catalonia). The EAEs reported in this study are located between 10 km (Sant Joan de les Abadeses) to 70 km (Sant Pere de Rodes) from the epicentre, but damage was strong in a radius of 50 km around the epicentre (e.g. Villabertran and Besalú): The extensive damage recorded in Sant Quirze de Cólera at 60 km from the epicenter can be explained by a possible topographic amplification (narrow mountain valley), but its early abandonment after the earthquake (1441 AD) might amplify some of the reported EAEs. In any case is evident that Intensity VI EMS assigned to this zone (Figure 8), mainly collected from littoral sites (Oliveira *et al.*, 2006) does not explain the observed damage.

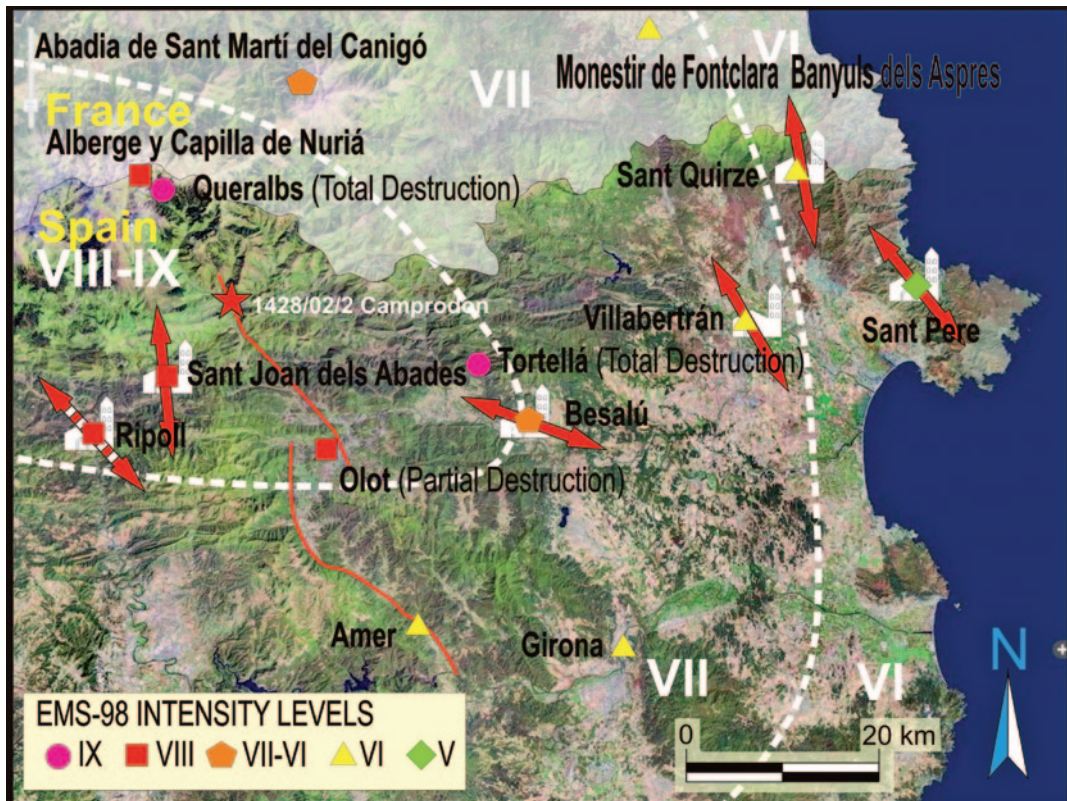


Figure 8. Isoseismal lines of the Camprodón earthquake (1428; I=IX; EMS98) (modified from Oliveira *et al.*, 2006). The red lines are segments of the Amer Fault. The solid red arrows represent the mean ground movement during the earthquake obtained by geological structural analysis of EAEs. The dashed arrows are interpreted from EAEs reported in historical documents.

Figura 8. Isosistas del terremoto de Camprodón (1428; I=IX; EMS98) (modificado de Oliveira et al., 2006). Las líneas rojas son los segmentos de la falla de Amer. Las flechas rojas sólidas representan el movimiento medio del terreno durante el terremoto, obtenido mediante análisis estructural geológico de los EAEs. Las flechas a trazos son interpretaciones realizadas a partir de los datos documentales.

This study shows the most relevant EAEs presently preserved in the Romanesque heritage of the area. The geological structural analysis of the different set of EAEs collected in six localities/sites indicates a mean and consistent NW-SE direction for the seismic ground motion (Figure 8) in the southern zone of the epicentral area. Only in the case of the locality of Besalú two perpendicular orientations of ground motion are recorded in the studied buildings. Therefore, it seems evident that this locality was also struck by the previous Amer earthquake in 1427 AD; VIII EMS) located about 28 km SW in an orthogonal direction to the Camprodón event (1428 AD; IX EMS), located 30 km NW from Besalú (Figure 1). It is necessary to highlight that all the affected towns or buildings analyzed in this work were severely affected by the 1428 Camprodón event (Oliveira *et al.*, 2006), which is the largest one recorded in the Pyrenees. The reported archaeoseismological data and analysis is useful to improve the knowledge on the seismicity of the area and on a particular event. This kind of data can be also used in future restoration works of the Romanesque heritage in the zone, identifying those elements and/or orientations of the ancient buildings prone to undergo severe damage during future seismic events generated by the same seismic source.

Acknowledgements

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