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Controls on space–time distribution of soft-sediment deformation structures: Applying palaeomagnetic dating to approach the *apparent recurrence period of* paleoseisms at the Concud Fault (eastern Spain)

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A B S T R A C T

This work describes soft-sediment deformation structures (clastic dykes, load structures, diapirs, slumps, nodulizations or mudcracks) identified in three sections (Concud, Ramblillas and Masada Cociero) in the Iberian Range, Spain. These sections were logged from boreholes and outcrops in Upper Pliocene-Lower Pleistocene deposits of the Teruel-Concud Residual Basin, close to de Concud normal fault. Timing of the succession and hence of seismic and non-seismic SSDSs, covering a time span between ~3.6 and ~1.9 Ma, has been constrained from previous biostratigraphic and magnetostratigraphic information, then substantially refined from a new magnetostratigraphic study at Masada Cociero profile. Non-seismic SSDSs are relatively well-correlated between sections, while seismic ones are poorly correlated except for several clusters of structures. Between 29 and 35 seismic deformed levels have been computed for the overall stratigraphic succession. Factors controlling the lateral and vertical distribution of SSDSs are their seismic or non-seismic origin, the distance to the seismogenic source (Concud Fault), the sedimentary facies involved in deformation and the observation conditions (borehole core vs. natural outcrop). In the overall stratigraphic section, seismites show an apparent recurrence period of 56 to 108 ka. Clustering of seismic SSDSs levels within a 91-ka-long interval records a period of high paleoseismic activity with an apparent recurrence time of 4.8 to 6.1 ka, associated with increasing sedimentation rate and fault activity. Such activity pattern of the Concud Fault for the Late Pliocene-Early Pliocene, with alternating periods of faster and slower slip, is similar to that for the most recent Quaternary (last ca. 74 ka BP). Concerning the research methods, time occurrence patterns recognized for peaks of paleoseismic activity from SSDSs in boreholes are similar to those inferred from primary evidence in trenches. Consequently, *apparent recurrence periods* calculated from SSDS inventories collected in borehole logs close to seismogenic faults are comparable to actual recurrence times of large paleoearthquakes.

1. Introduction

The use of soft-sediment deformation structures (SSDSs) induced by ground shaking generated by seismic wave (seismites) as a record of past earthquakes is a common practice in sedimentological/stratigraphical (Allen, 1986) and paleoseismological studies (Obermeier, 1996), particularly in ancient to present-day fluvial-lacustrine successions (e.g. Sims, 1975; Davenport and Ringrose, 1987; Guiraud and Plaziat, 1993; Van Loon et al., 1995; Alfaro et al., 1997; Rodríguez-Pascua et al., 2000; Migowski et al., 2004; Moretti and Sabato, 2007; Moretti and Ronchi, 2011; Stárková et al., 2015). After the innovative work by Sims (1975), many authors have tried to evaluate the recurrence time of past earthquakes by analyzing the vertical repetition of deformed beds in lacustrine successions. Nevertheless, this approach involves some limitations (Montenat et al., 2007; Owen et al., 2011; Moretti and van Loon, 2014) related with the fact that some earthquakes may not be recorded in the sedimentary succession (Moretti et al., 1999) or that a single seismic shock can induce superimposed deformed beds (Gibert et al., 2011).

Recently, after recognizing 21 seismite levels in a 75-m-long borehole through Upper Pliocene-Lower Pleistocene lacustrine deposits of the Teruel Basin (Masada Cociero site), Ezquerro et al. (2015) have proposed the concept of *apparent recurrence period*, as the inverse of the frequency of occurrence of seismites per unit time along a borehole. The term 'apparent' refers to the fact that the paleoseismic record at a given point is a partial one, since the spatial distribution of SSDSs produced by an individual event (and so its probability of being

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represented at a given site) is limited. In this way, after accepting that subsidence and sedimentation rates were fairly similar, Ezquerro et al. (2015) have estimated an apparent recurrence period of about 45–51 ka for the Masada Cociero borehole log. They also discussed the quality and representativeness of observations of SSDSs in well cores by comparing them with those in natural outcrops. The latter have the advantage of lateral continuity, hence the feasibility for recognizing large-scale SSDSs, whereas well cores, virtually continuous along the entire sedimentary succession, allow detailed observations of fresh rock at a millimeter scale. Reconstructing the paleoseismic record of an area can benefit from combining both data sources, especially if that information from multiple wells is available, allowing correlation of deformed levels in the subsoil. This work goes deeper into this issue, revisiting the same area within the central Teruel Basin (Fig. 1), collecting new surface and subsoil data, and combining multiple research lines in order to reconstruct both the lateral and vertical distribution of SSDSs.

First, a new borehole drilled at Ramblillas site, west of Masada Cociero, together with a new surface profile surveyed close to Concud village (see location in Fig. 2), have enlarged our SSDSs record in the Upper Pliocene-Lower Pleistocene succession. Since the Masada Cociero section also combines a well log and a surface profile, the final available SSDSs inventory adequately combines both data sources.

Second, we have improved the temporal framework of the paleoseismic occurrences. The age of the Masada Cociero succession was constrained by (i) overall correlation with regional lithostratigraphical units, biostratigraphically by numerous mammal sites and a few magnetostratigraphic profiles (one of them at the Concud section; Opdyke et al., 1997), and (ii) a mammal site (*Rotonda Teruel-Centro*, *RTC*; MN 17 zone) located at the Masada Cociero surface profile, which dates these materials to the middle Villafranchian (Ezquerro et al., 2012b). We now add a new magnetostratigraphic study of the Masada Cociero well log, which refines the chronostratigraphy of the studied deposits and provides a more robust correlation of the three surveyed sections. This allows the lateral continuity of deformation structures associated to each paleoseismic event to be assessed, as well as obtaining their precise time distribution along the surveyed profiles, and thus a better calculation of the apparent recurrence period.

The central Teruel Basin is a perfect target for this kind of study since: i) the instrumental and historical seismicity are well-known; ii) the Late Pliocene-Early Pleistocene is recorded by a thick, continuous alluvial-palustrine-lacustrine succession, suitable for dating by magnetostratigraphic methods; and iii) the structure and paleoseismicity of the most active fault in the area, the Concud Fault, are well known (Moissenet, 1983; Simón, 1983; Gutiérrez et al., 2008; Lafuente, 2011; Lafuente et al., 2011a, 2014; Simón et al., 2012, 2015; Ezquerro et al., 2014b).

Our objectives are: (i) to describe the SSDSs that occur at various stratigraphic levels in the Concud-Teruel area, both in outcrops and well logs; (ii) to distinguish seismically from non-seismically induced SSDSs; (iii) to establish the time distribution of SSDSs in different stratigraphic sections, achieving reliable correlations between deformed beds; and iv) to calculate the *apparent recurrence period* of paleoseismic events and discuss the significance of the results.

2. Geological setting

The study area extends along a section transverse to the Concud Fault, which is located at the junction of the Teruel and Jiloca grabens, in the NE of the Iberian Peninsula (Fig. 1a). These basins represent the most landward structures developed within the Iberian Plate in relation to Neogene rifting at the Valencia Trough, Mediterranean Sea (Álvaro et al., 1979; Simón, 1983; Capote et al., 2002). They evolved through two distinct rift episodes (Simón, 1982, 1983): the first one gave rise to the Teruel Graben (NNE–SSW trend) during the Late Miocene, and the second produced the NNW–SSE trending Jiloca Graben and reactivated the Teruel Graben in the Late Pliocene-Quaternary (Capote et al., 2002).

The northern sector of the Teruel Basin is a half graben with an active eastern boundary formed by a NNW–SSE and NNE–SSW trending fault system (Fig. 1b). The basin fill comprises Upper Miocene to Lower Pleistocene deposits whose age is well constrained by abundant mammal sites and magnetostratigraphic profiles (e.g. Adrover et al., 1978;

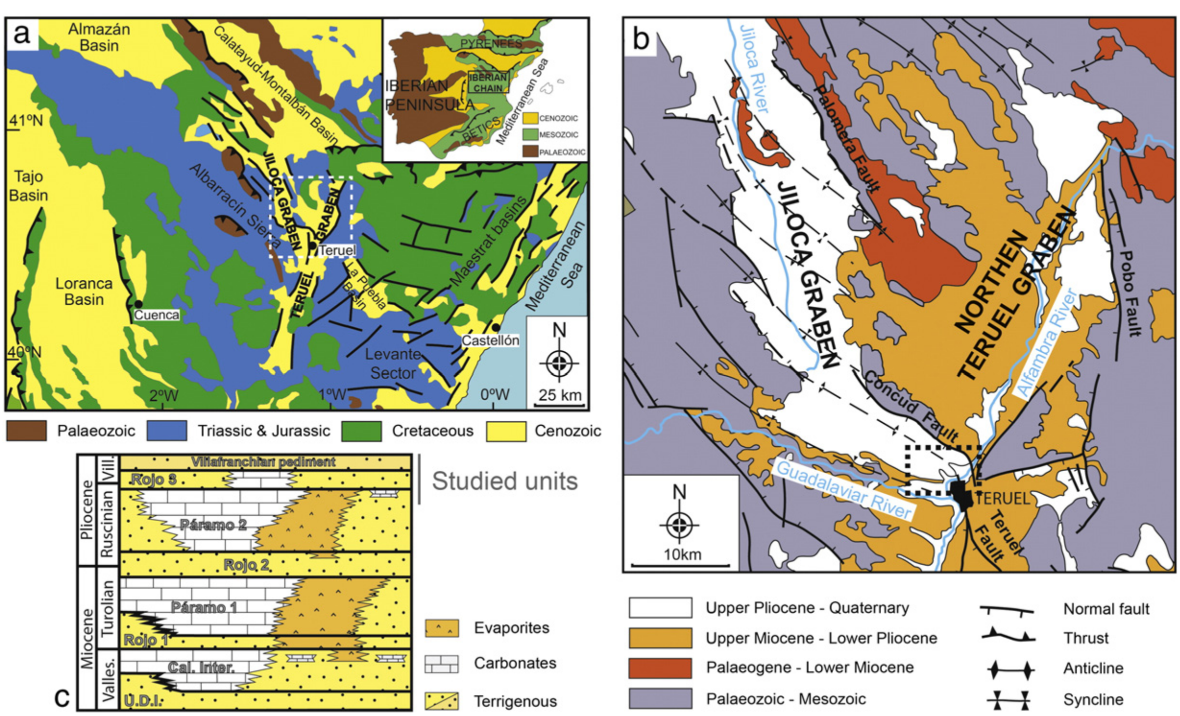

Fig. 1. (a) Neogene-Quaternary extensional basins and the main active faults in the central-eastern Iberian Chain. Inset: location of the study area within the Iberian Peninsula. (b) Geological map of the Jiloca and Teruel basins, with location of the studied area. (c) Stratigraphic units by Godoy et al. (1983a, 1983b).