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Alberto Pérez-López and Fernando Pérez-Valera

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Tectonic signatures in the Triassic sediments of the Betic External Zone (southern Spain) as possible evidence of rifting related to the Pangaea breakup

Alberto Pérez-López *, [a], [b] **and Fernando Pérez-Valera** [c]

[a] Dpto. de Estratigrafía y Paleontología, Facultad de Ciencias (Universidad de Granada), Spain

[b] Instituto Andaluz de Ciencias de la Tierra (CSIC-Universidad de Granada), Avda. de las Palmeras, 4, 18100 Armilla (Granada), Spain

[c] Dpto. de Ciencias de la Tierra y del Medio Ambiente, Facultad de Ciencias, (Universidad de Alicante), Carr. de San Vicente del Raspeig, s/n, 03690 San Vicente del Raspeig, Alicante, Spain

E-mails: aperezl@ugr.es (A. Pérez-López), fperez@ua.es (F. Pérez-Valera)

Abstract. This paper describes various soft-sediment deformation structures present in the Triassic deposits of the Betic External Zone (Southern Iberian). These structures, together with variations in deposit thicknesses, internal angular unconformities, and synsedimentary faults, point to intense tectonic activity from the Middle to Late Triassic related to a stage of rifting. The Middle–Late Triassic in the Betic External Zone shows a sedimentary record represented by Muschelkalk and Keuper facies. In the Ladinian Muschelkalk, carbonates appear slumps, breccias, load casts, slide and parallel shear surfaces, and tsunamites. In the sandstones of the Carnian Keuper facies, different seismite beds and ball and pillow structures can be discerned. Above these deposits, the carbonate Zamoranos Formation of the Rhaetian displays volcaniclastic rocks with conglomerates, slumps and synsedimentary faults. All these features and magmatism suggest some tectonic activity, possibly related to the breakup of Pangaea, especially at the end Triassic. We highlight the features that indicate this tectonic activity over time and discuss the factors that triggered the development of these structures, along with the conditions that made this possible.

Keywords. Muschelkalk, Keuper, Seismite, Soft-sediment deformation structures, Volcaniclastics.

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1. Introduction

The breakup of Pangaea is one of the most well-established geological events in the past 50 or 60 years [e.g. Bullard et al., 1965, Dietz and Holden, 1970, Smith and Hallam, 1970]. This breakup shows an initial stage beginning in the Triassic, and many studies have focused on seafloor spreading and opening of the central Atlantic after a rifting stage [Guan et al., 2021, Peace et al., 2020, Roest

* Corresponding author.

et al., 1992]. Reconstructions of the Pangaea breakup have been based on palaeomagnetic data [Sahabi et al., 2004, Schettino and Turco, 2009], the stratigraphy of rift basin systems created in the breakup zone [Olsen, 1997, Veevers, 2004], and their effects on sedimentary and climate cyclicity [Smoot, 1991] or even palaeontological implications [Jordan et al., 2016, San Mauro et al., 2005]. However, the record of this breakup, mainly based on tectonics and magmatism [e.g. Peace et al., 2020], is not always evident in the sediments deposited during the Triassic in the rift basins. The presence of so-called soft-sediment deformation structures (SSDS) has been one of the most used criterions to reflect synsedimentary tectonic activity [e.g. Gao et al., 2020, Novak and Egenhoff, 2019, Rychliński and Jaglarz, 2016] and has been widely used under the genetic term of seismite [e.g. Gibert et al., 2011, Montenant et al., 2007]. These deformation structures are the result of liquefaction or fluidization in water-saturated unconsolidated sediments, though in some cases, processes related to external pressures are important when their magnitude exceeds the shear strength of the sediments, forcing sediments to deform [Gao et al., 2020, Owen et al., 2011].

Early work on SSDS dates back to the 1960s [e.g. Potter and Pettijohn, 1963, Selley, 1969], yet numerous investigations have since addressed SSDS, discussing the deformation mechanisms that give rise to their formation [e.g. Reineck and Singh, 1980, Allen, 1982]. Also, in the last 10 years, several articles and special issues on SSDS, which have served to classify and describe the genesis of the different structures, have been published [e.g. Alfaro et al., 2016, Alsop et al., 2019, Festa et al., 2014, Van Loon, 2014]. Many of these reports have stressed their relationship with tectonic processes [e.g. Moretti et al., 2016, and references therein], and slumps and other deformed structures triggered by seismic events have also been described [Alsop et al., 2016, Basilone, 2017, Lu et al., 2017].

Triassic seismites have been especially described in the deposits of the German Basin [Bachmann and Aref, 2005, Bachmann and Brunner, 1998, Knaust, 2002, Simms, 2003] together with other seismically induced deformational structures indicating intense synsedimentary tectonic activity in the Middle Triassic [Bachmann and Brunner, 1998, Föhlisch and Voigt, 2001, Knaust, 2000, 2002, Matysik, 2010, Rüffer, 1996]. Other tectonic features, such as synsedimentary faults, could be additional data supporting tectonic controls during coeval sedimentation [Bartholomew et al., 2002]. In the case of magmatism, the occurrence of volcanic or subvolcanic rocks is usually related to the activity of deep faults, especially during the course of a rifting process [e.g. Menzies et al., 2002].

In the present study, special focus is placed on the study of features of the epicontinental Triassic deposits of the Betic basin [Pérez-López and Pérez-Valera, 2007] providing insight into tectonic and magmatic activity which could be related to the Pangaea breakup. Several carbonate units of Muschelkalk facies and fluvio-coastal deposits with evaporite sediments of Keuper facies may be seen in the Southern Iberian Peninsula belonging to the External Zone of the Betic Cordillera [Pérez-López, 1998]. Although comprehensive stratigraphic and sedimentological studies of these Triassic units exist [e.g. Busnardo, 1975, Hirsch, 1977, Pérez-López, 1996, Pérez-López and Pérez-Valera, 2012, Pérez-Valera and Pérez-López, 2008], their tectonic–sedimentary context has been scarcely addressed. The sedimentological study of numerous sections, especially of the Muschelkalk carbonates, provides information that can be related to the seismic activity of the Betic basin during the Ladinian. Also, the study of some features of the Keuper facies sandstones has made it possible to identify seismite beds for the first time in southern Iberia. This is of particular interest as there are scarce published data on seismites found in Keuper facies deposits [Bachmann and Aref, 2005]. Finally, Rhaetian carbonate deposits (Zamoranos Formation), which overlie the Keuper units, offer some data on the extent of tectonic activity and volcanism of this region in the rifting context related to the Central Atlantic Magmatic Province [Pérez-López et al., 2021b].

2. Geological setting

The Betic Cordillera (southern Spain) features three main groups of geological units (Figure 1): the External Zone, the Internal Zone and tectonic units located between both, namely the flysch deposits of the Campo de Gibraltar Complex and the Frontal Units [e.g. Martín-Algarra and Vera, 2004]. The present study focuses on the Epicontinental Triassic rocks of

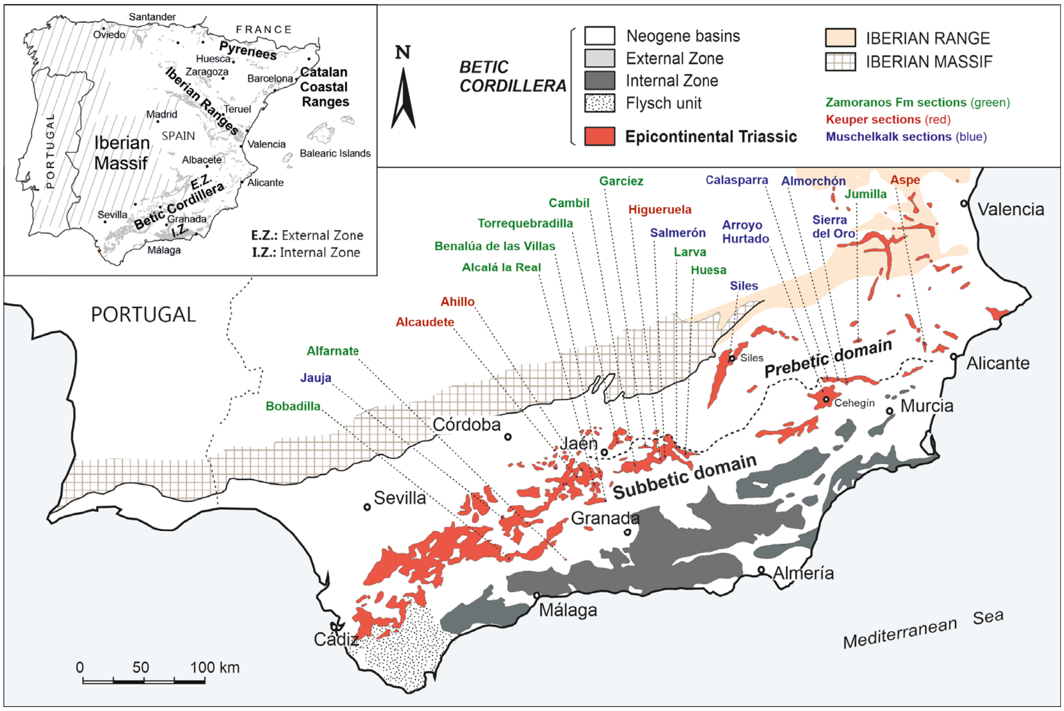

Figure 1. Geological setting of the studied sections of the South Iberian Triassic. Colours indicate the sections of the Muschelkalk facies unit (blue), Keuper facies unit (red), and Zamoranos Fm (green).

the Betic External Zone, which are represented by different lithological formations (fms) of the Muschelkalk and Keuper facies that are currently highly deformed by tectonics and emplaced as a fold-and-thrust belt. As a result of this tectonics, Triassic outcropping occurs in a notably displaced and fractured manner and reveals partial sections of the different Triassic formations.

The Triassic stratigraphic successions of these outcrops differ according to their palaeogeographic positions, which are associated with the Prebetic or Subbetic tectonostratigraphic domains. The Prebetic domain appears near the Variscan massif while the Subbetic domain is further south and shows thicker deposits with more marine facies frequently deposited in more external platform areas [e.g. Martín-Algarra and Vera, 2004].

3. Materials and methods

This work is based mainly on field observations compiled from many outcrops of the Triassic of the Betic External Zone. The interpretation of several structures related to significant Triassic tectonic activity prompted us to review numerous sections to explore how this tectonic activity, possibly related to the breakup of the Pangaea, is recorded. We take into account thickness data from the different Triassic stratigraphic units and evidence of volcanism from previous works, which is cited throughout the text.

For the present study, several partial sections of different Triassic rocks were examined, spanning from Ladinian to Rhaetian times across the entire Betic Cordillera (Figure 1). The sections analysed were 6 in carbonate outcrops of the Cehegín Formation (Fm), 1 in the Siles Fm (Muschelkalk) and 10 in the Zamoranos Fm, and 4 in sandstone outcrops of the Jaén Keuper Group. All data and field photographs are compared with observations and interpretations from prior tectonics and sedimentation studies related mainly to SSDS in the European Triassic, although they are also compared with other structures described in different basins that confirm the interpretations made in this study.

4. Stratigraphy

The lithostratigraphic units of the Triassic studied are (Figure 2): two formations of Ladinian Muschelkalk carbonates (Siles and Cehegín formations) [Pérez-Valera and Pérez-López, 2008]; five detrital and evaporitic formations constituting the Jaén Keuper Group (Carnian–Norian) [Pérez-López, 1998]; and finally, one upper carbonate formation of Rhaetian age (Zamoranos Fm) [Pérez-López et al., 2012].

The succession of Muschelkalk carbonates varies according to its palaeogeographic position. Pérez-Valera and Pérez-López [2008] define two formations, the Siles and Cehegín fms, depending on whether these carbonates are associated with the Prebetic or Subbetic domain, respectively. The Siles and Cehegín fms consist of limestone, thin-bedded marly limestone, and marl beds. In the Cehegín Fm two members can be distinguished [Pérez-Valera and Pérez-López, 2008]. The lower member is characterized by the presence of two or three massive limestone banks with thin-bedded marly limestone beds between them. In the upper member, marly limestone, marls and bioclastic beds are dominant, and are mostly marly towards the top.

The Jaén Keuper Group, deposited over the Cehegín and Siles fms (Muschelkalk facies), are formed by incomplete Carnian–Norian successions due to tectonics which deformed and broke up the lithological successions. The units of Keuper consist mainly of lutites with sandstones and gypsum beds (K1 and K3 units), although a thick sandstone unit (K2 unit) occurred in the middle of the Keuper facies successions [Pérez-López, 1996, 1998]. In the upper part of the Jaén Keuper Group, gypsum with lutites and dolostone occur (K4–K5 unit).

The Zamoranos Fm, which is 20 to 65 m thick and Rhaetian in age, lies above the Jaén Keuper Group [Pérez-López et al., 2012]. In this formation, three members of very different features and thicknesses have been distinguished: (1) the Carniolar Limestone Member (lower member), (2) the Ferruginous Detrital Member (middle member), and (3) the Limestone and Laminated Dolomite Member (upper member). The sediments of this formation are mainly fine-grained with some bioclastic beds, although the middle member shows variable lithologies, from carbonates and gypsum to siliciclastic rocks, locally with conglomerates and volcaniclastic deposits.

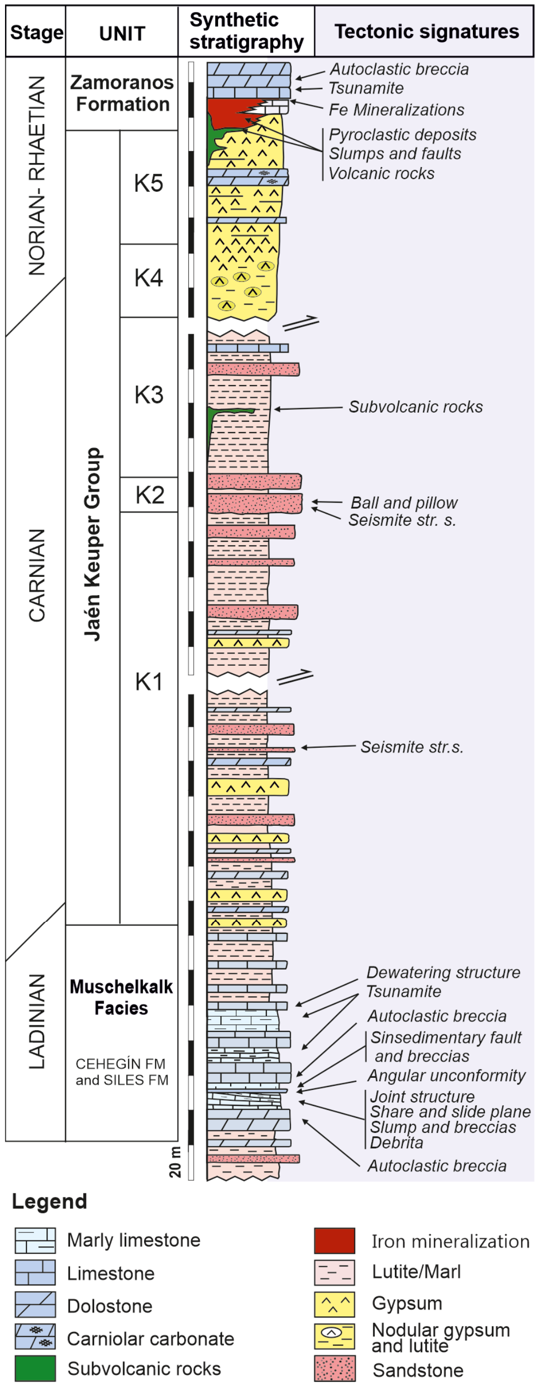

Figure 2. Synthetic Triassic stratigraphy of the Betic External Zone. Structures, deposits, and features related to tectonic activity indicated in each lithostratigraphic unit [stratigraphy modified from López-Gómez et al., 2019, Pérez-López, 1998].

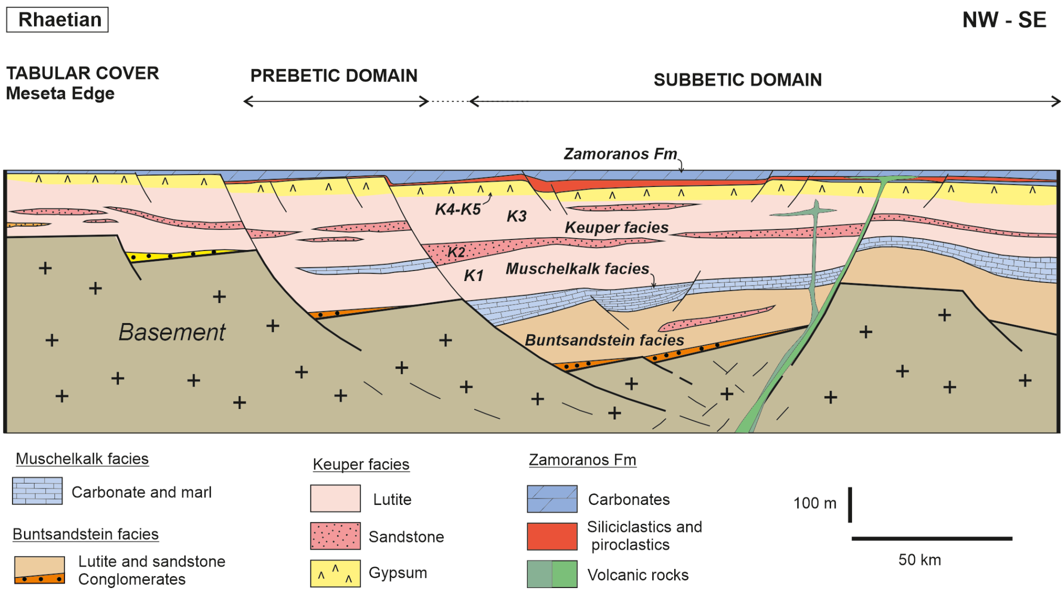

Figure 3. Geotectonic setting of the different palaeogeographic domains of the Betic Cordillera during the Rhaetian age, where thicknesses vary widely due to tectonic controls. Scheme based on López-Gómez et al. [2019], Pérez-López [1998], Pérez-Valera and Pérez-López [2008].

In addition, considerable iron mineralizations occur in the middle member, mainly haematite, although sometimes magnetite.

5. Tectonic signatures in the Betic Triassic sediments

The breakup of Pangaea took place in several stages that developed with different characteristics and were associated with successive episodes of rifting [e.g. Frizon de Lamotte et al., 2015]. The extensional tectonics associated with this breakup was recorded in the sediments of the newly formed basins. In effect, tectonic signatures within the sedimentary record have provided much insight into the evolution of basins [Frostick and Steel, 1993]. In the present study, we examine the main features of rifting phase development in the southern Iberian margin based on data for the Triassic deposits, now structured in the Betic Cordillera (Figure 3). Extensional tectonics produces effects in sediments that vary widely as they depend on many factors. Our analysis of these Betic Triassic deposits first focuses on thickness variations in each lithologic unit, as well as on the presence of unconformities and faults, which can be related to differential subsidence. Deformation structures in soft sediments and structures related to liquefaction and fluidization are also examined to assign their possible origins to earthquake shaking associated with tectonic activity.

5.1. *Differential subsidence*

Synsedimentary tectonic activity may strongly influence sediment thickness and facies distributions by local modification of subsidence rates and basin topography [Matysik and Szulc, 2019]. Because of Neogene structuring of the Betic Cordillera, mainly due to the superposition and translation of tectonic units, it is difficult to locate the original points of greatest subsidence in the Triassic Betic basin. Nevertheless, thickness variations of the different Triassic successions in the Betic External Zone are evident when comparing the available data [Pérez-López et al., 2012, Pérez-Valera and Pérez-López, 2008]. These studies indicate that different thicknesses are the consequence of significant subsidence variations in different areas, especially during the late Triassic (Figure 4).

The thickness of the Cehegín and Siles fms (Muschelkalk carbonates) decreases very quickly

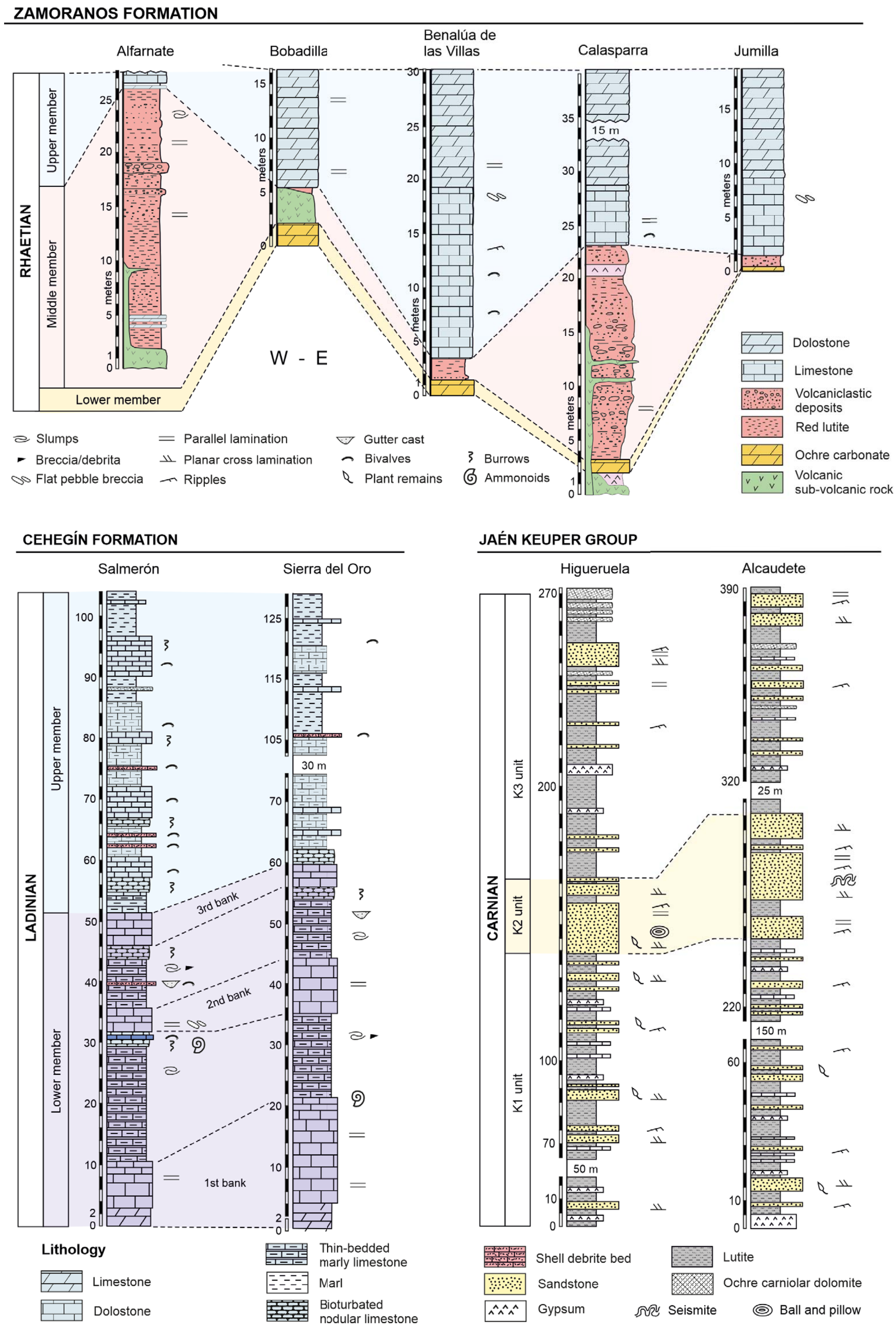

Figure 4. Stratigraphic sections studied representative of the Betic External Zone. See Figure 1 for locations. The sections of the Zamoranos Fm are modified from Pérez-López et al. [2021b].

from 80 m to 10 m over a few kilometres at the edge of the Betic basin towards the Prebetic domain [Pérez-Valera and Pérez-López, 2008]. The same applies to the detrital successions of Keuper facies or the Rhaetian carbonate Zamoranos Fm (Figure 4). This formation is particularly interesting because, although its thickness is reduced, there are significant thickness variations between the different sections of the basin [Pérez-López et al., 2012].

It can be observed that each of the younger units occupies a larger area in the south Iberian margin [e.g. Pérez-López et al., 2019]. Onlap of younger sediments on older deposits is a feature of the fault growth model, as onlap is widespread in extensional basins [e.g. Schlische, 1991]. However, another significant feature is that thicknesses also vary between different successions within the same palaeogeographic domain.

Different subsidence is also recorded in the outcrops by the presence of light angular unconformity and synsedimentary faults [Bosellini et al., 1993], as observed in the Salmerón section of the Cehegín Fm (Cabra del Santo Cristo, Figure 1), identified for the first time in the present study (Figure 3, Figure 5A). Moreover, in the same Salmerón section, it is possible to observe a synsedimentary fault system (Figure 5B, B′), which highlights tectonic activity during the Ladinian. This fault ruptures a key bioclastic bedding marker recognized in numerous outcrops over some 200 km. Other synsedimentary faults were observed in the Alfarnate section of the Zamoranos Fm. In the middle member of the Zamoranos Fm, considerable volcaniclastic deposits appear in the Alfarnate section and several types of deformed structures may be observed in these materials associated with local synsedimentary faults.

5.2. *Soft-sediment deformation structures*

5.2.1. *Slumps and breccias*

In many sections of the Cehegín Fm, SSDS such as slumps occur in the muddy sediments of the lower member of this formation (Figure 5C). Slumps appear in sediments characterized as thin-bedded limestone with 0.5–2 cm-thick intercalations of marl or marly limestone beds (Figure 4). Locally, these slumps are related to intraformational breccias and debrites (Figure 5D). In the section of Sierra del Oro (Figure 1), in the same stratigraphic position between undeformed beds, deformed thin beds of marly limestone with breccias (Figure 6A, A′) may be identified as highly contorted and partially brecciated slumps. Also in this section, debrites occur between thin-bedded marly limestones consisting of spherical and angular fragments (from 2 to 15 mm) of mudstones embedded in a micritic matrix.

These slump structures are also present in pyroclastic deposits of the Alfarnate section, which corresponds to the middle member of the Zamoranos Fm, although these deformation structures are not common in volcaniclastic deposits [Basilone et al., 2016]. In the Alfarnate section, this exceptional, very deformed horizon occurs in conglomerate beds and shows a greater thickness of pyroclasts between undeformed beds (Figure 7).

5.2.2. *Flat pebble breccias*

In the first bank of the Cehegín Fm's lower member, thin-bedded micritic limestone with flat pebble breccia are found (Figure 6B). This facies consists of muddy carbonate with some thin level alternation of different grain size (silt and clay). In this facies, flat pebble breccias are locally significant. The peculiarity of these breccias is that, in some cases, the flat pebbles show a vertical orientation and some deformation structures. In addition, in the Zamoranos Fm, in the upper part of the succession, flat pebble breccia locally occurs in several outcrops across hundreds of kilometres (Benalúa de las Villas and Jumilla sections) similar to the flat pebble breccias of the lower member of the Cehegín Fm.

5.2.3. *Slide planes and joints*

In the lower member of the Cehegín and Siles fms, it is possible to recognize slide planes with a thin shear zone at the base. These occur in marly limestone facies and, as indicated by Knaust [2000], they could be confused with erosive channel surfaces. Locally, in the Siles outcrop, a slide plane can be identified covered with redeposited sediments (Figure 6C). At another point of the Siles outcrop, sliding is associated with wrinkle and sigmoidal "vein structures" [Föhlisch and Voigt, 2001] or "joints" [Knaust, 2000]. Wrinkles develop due to sliding over incompletely lithified sediment. In the case examined, joints appear beneath wrinkle casts, which occur in marly

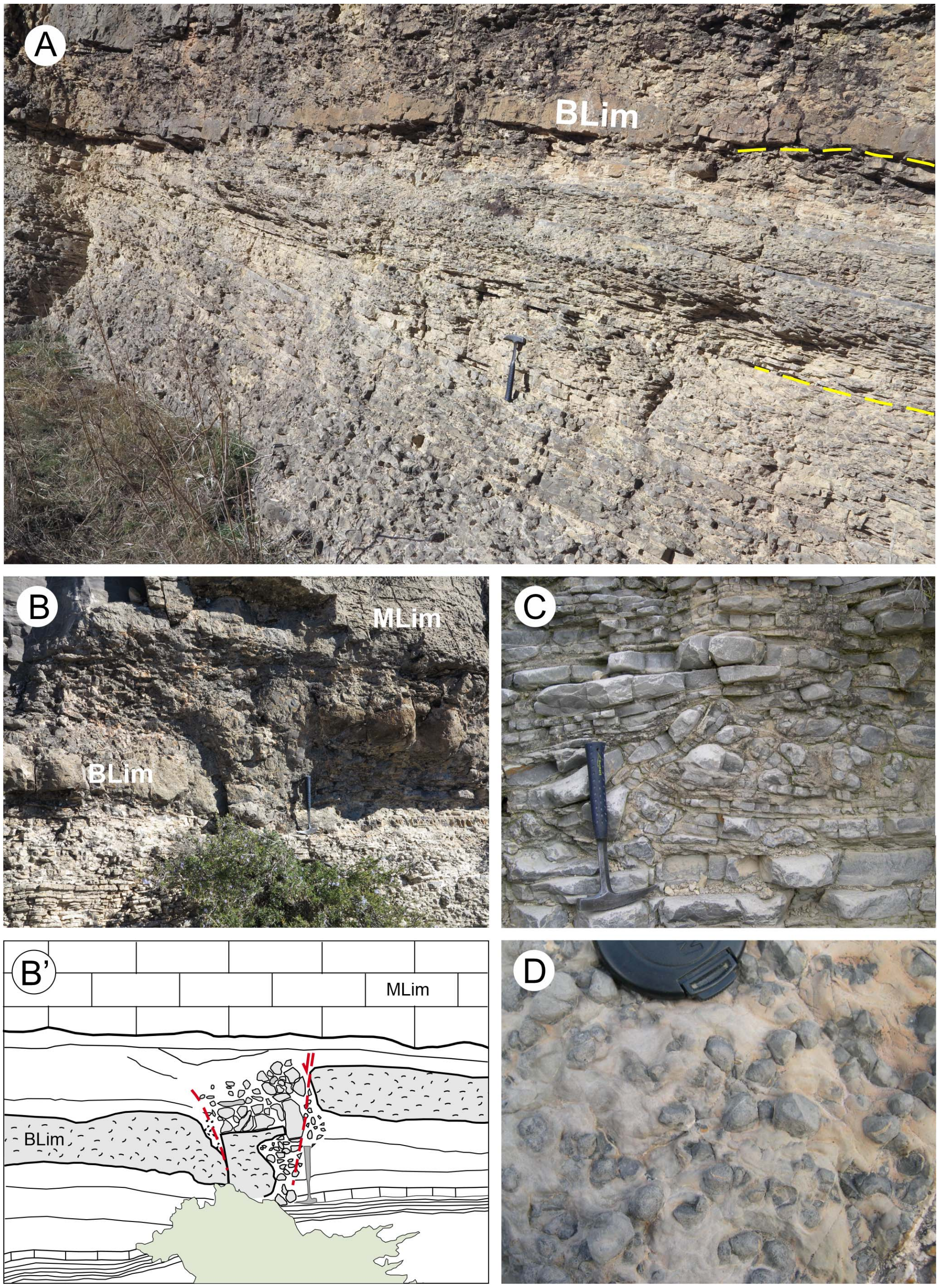

Figure 5. Tectonic signatures of the Muschelkalk carbonates in the Salmerón section (A and B) and the Sierra del Oro section (C and D). (A) Two angular unconformities in the lower member of the Cehegín Fm (BLim: bioclastic limestone marker). (B–B′) Synsedimentary fault and breccias in the lower member (BLim: bioclastic limestone; MLim: massive limestone). (C) Slump developed in thin-bedded marly limestone. (D) Debrite deposit characterized by sharp-bounded micritic intraclasts within a marly matrix.

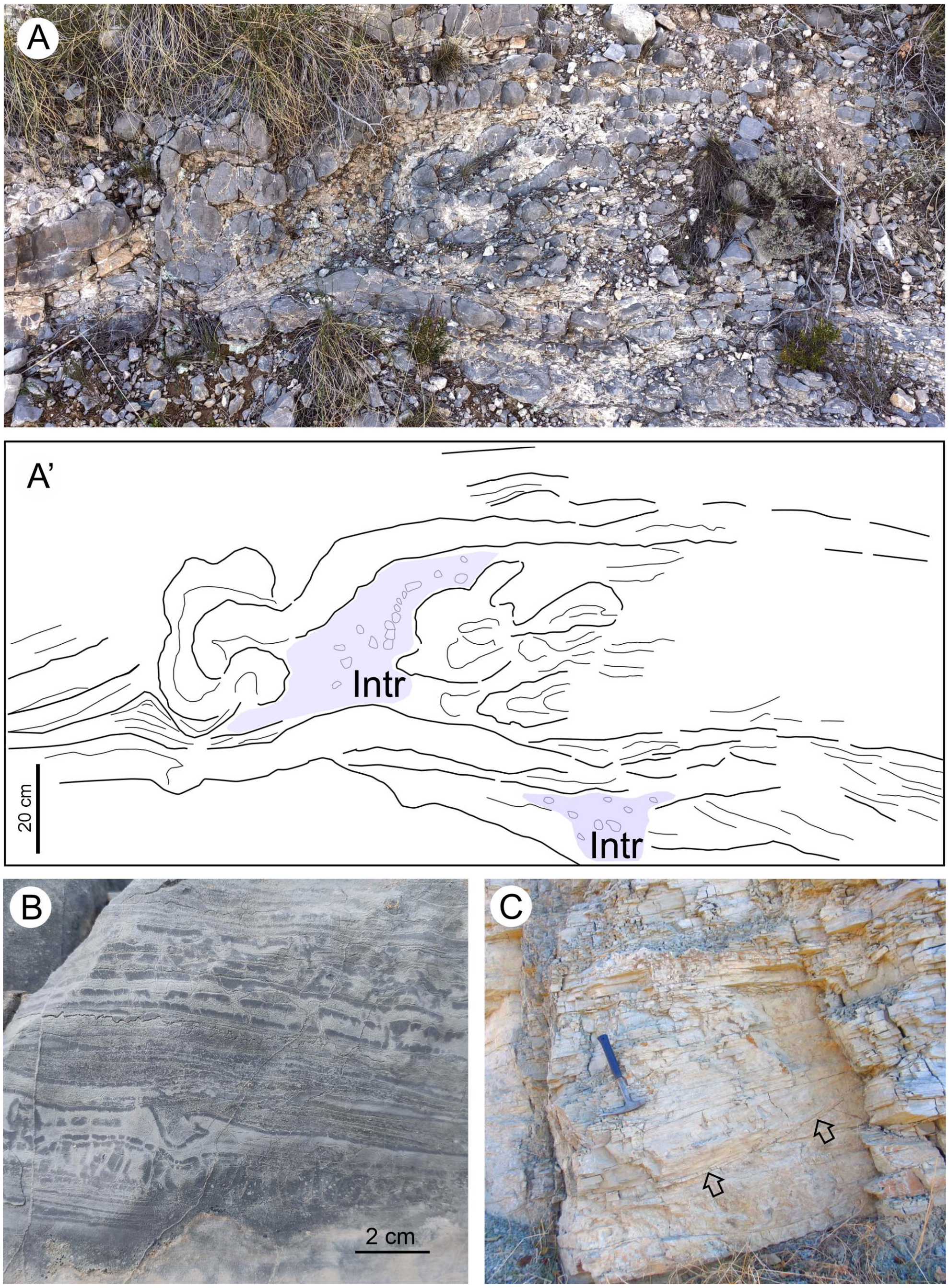

Figure 6. (A–A′) Contorted slump produced by an earthquake shock that triggered sudden movement of the thin soft mud beds (Sierra del Oro section, Murcia province). Note the complex fold associated with breccias (Intr: intraclasts). (B) Thin-bedded micritic limestone showing liquefaction and dewatering processes which form the autoclastic breccia (Almorchón section). (C) Slide plane with share zone at base in the marly limestone bed. The semi-lithified sediments glided across a trough-like shear plane and then other sediments were redeposited over this slide plane (Siles section).

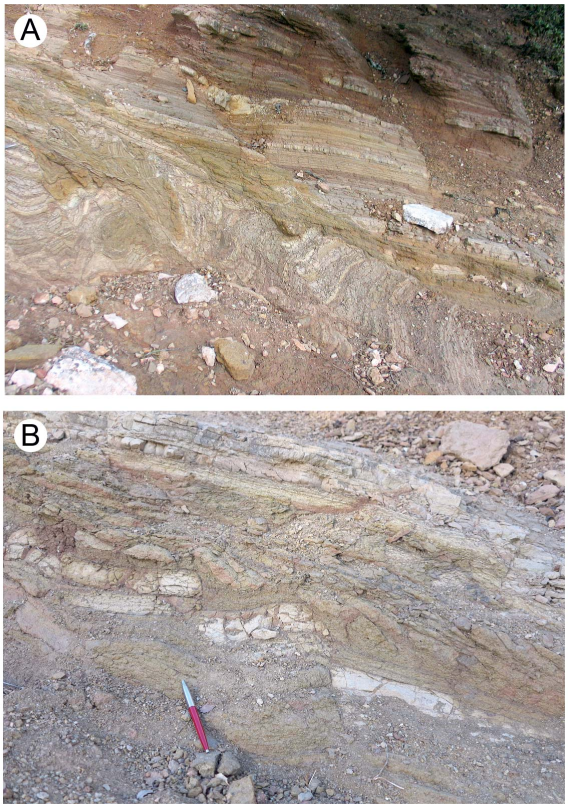

Figure 7. (A) Deformed beds (slumps) and (B) faults in volcaniclastic sands and conglomerates of the Alfarnate section, which is correlated with the middle member of the Zamoranos Fm. In both cases, these deformed deposits lie between undeformed beds. Note several episodes of slides and deformation.

limestone and pass laterally to the other joints defining several shear planes (Figure 8A, B). The joints are vertical and of the sigmoidal type with a spacing of some centimetres. Other joints associated with a shear thin zone can be observed in the Arroyo Hurtado outcrop (Figure 8D) or in the Almorchón section of the Cehegín Fm, where a thin zone of marly limestone appears disorganized with oriented planar elements (Figure 8C).

5.2.4. *Deformation structures in sandstones*

In the Jaén Keuper Group outcrops, some deformation structures are found associated with the sandstone beds. Deformed laminations can be observed in thin beds of the K1 unit between lutites in the Aspe outcrop (Figure 1). Small folds appear which show complex deformation of laminae forming irregular structures. These structures are uncommon and are here described for the first time in the Betic Keuper. An important fact to consider is that these structures appear within a sandstone bed about 17 cm thick between lutite beds and the interval of affected beds is only some 6 cm thick (Figure 9A).

In the thicker K2 unit (25–60 m) of the Keuper facies, some deformed lamination of sandstone also occurs (Figure 4, 9B). Although in thicker beds, alternations of different grain sizes can be observed, possibly influenced by loads, in the Alcaudete section (Figure 1) only a few beds are deformed, which were found laterally along the entire length of the outcrop for tens of metres. In a given bed bottom, it is possible to detect connected bodies of pillow-like morphology separated by upward-directed fluidization paths (Figure 9C). Here, dewatering structures arise in sandstones whereby sudden dewatering of the relatively fine-grained sandstone causes the destruction of the original sedimentary texture.

5.2.5. *Load casts and ball-and-pillow structures*

At the base of some bioclastic beds of the Cehegín Fm appear deformed structures. These structures are fairly uncommon and tend to occur mainly in bioclastic beds that underlie the first carbonate bank of the lower member of this formation. Beds are intercalated in thin-bedded marly limestone and their thicknesses vary. Locally, they show syndepositional deformation structures such as load casts similar to those described by Knaust [2000] in the Germanic Triassic. Conversely, no deformation structures appear in the upper member of the Cehegín Fm. This upper member nevertheless has a higher marl content and some sections feature considerable amounts of shell-debris limestones bearing bivalves of packstone to floatstone textures. These shell-debris beds, examined previously, display storm current structures [Pérez-López and Pérez-Valera, 2012]. The only structures related to post-depositional events occur in these shell-debris beds where several vertically oriented shells or with convex-down orientation appear.

Other deformation structures occur in a thick sandstone bed of the K2 unit of the Higueruela section (Cabra del Santo Cristo outcrop, Figure 1).

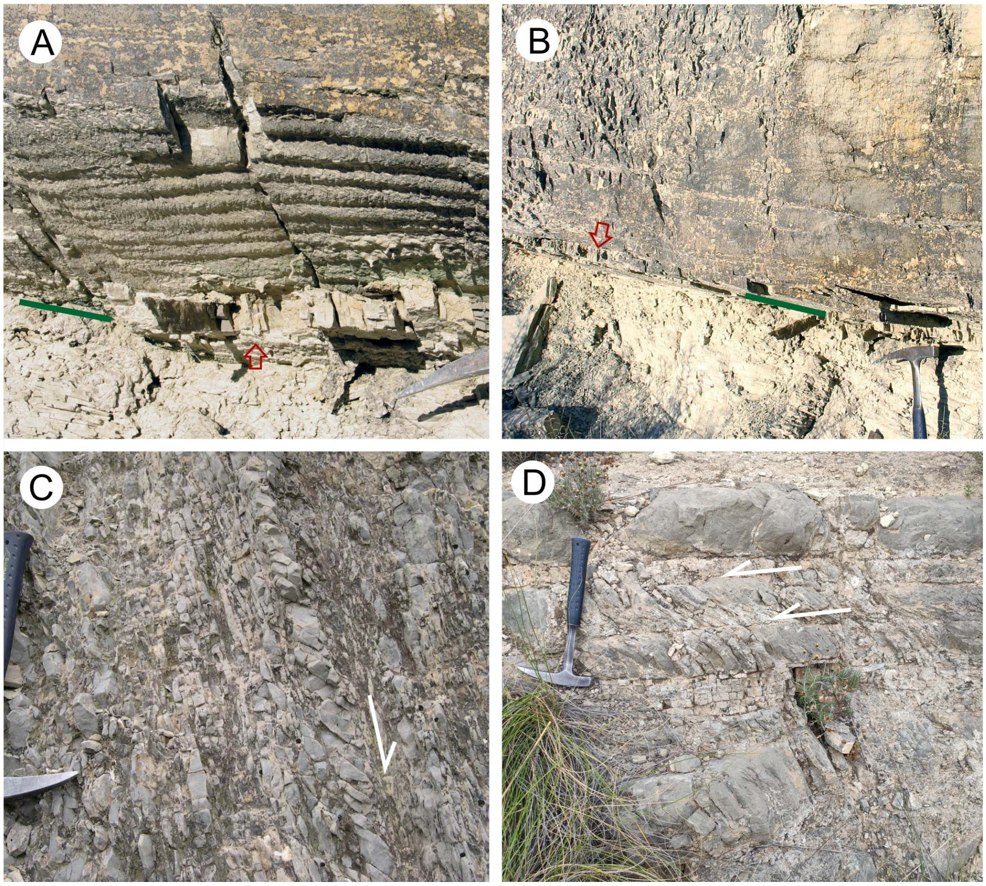

Figure 8. (A, B) Marly limestone bed with parallel shear surfaces and wrinkles due to sliding (Siles section). Note the joints in the shear zone in both photographs (red arrows). (C) Joints well developed in thin-bedded marly limestone. Note the direction of shear (Sierra del Oro section). (D) Two parallel zones of sigmoidal joints of the lower Cehegín Fm member (Arroyo Hurtado section).

In this setting, grain size varies with level. At the lower boundary of one of these sandstone levels whose grain size is larger than that of its underlying level, small ball, and pillow structures in the sense of Owen [2003] have been detected. However, in the studied section, ball structures appear within fine sandstone and not shale (mudstone) (Figure 9D). Moreover, the sand mass may become detached from the overlying sand bed and be completely surrounded by fine sandstone forming pseudonodules [Allen, 1982, Boggs Jr., 2009].

5.3. *Volcanism*

Volcanism is another feature related to the breakup of Pangaea, reflecting progression of the rifting stage in a setting of tensional tectonics [Frizon de Lamotte et al., 2015, Golonka and Bocharova, 2000, Vegas et al., 2016]. In the Betic Triassic, numerous outcrops of subvolcanic ophite rocks have been described, although it is difficult to decipher their absolute age as they are considerably weathered. Some of these outcrops are intrusions from the Triassic and others from the Jurassic [Morata et al., 1997, Puga et al., 1988]. In the Betic External Zone, the Triassic volcanic rocks arise in the Carnian–Norian age associated with detritic materials of the Keuper facies, as may be seen in the Ahillo and Cehegín outcrops. In the Ahillo outcrop, a subvolcanic body has been observed flowing into wet clayey sediments of the Keuper K3 unit according to its defined stratigraphy [Pérez-López, 1998].

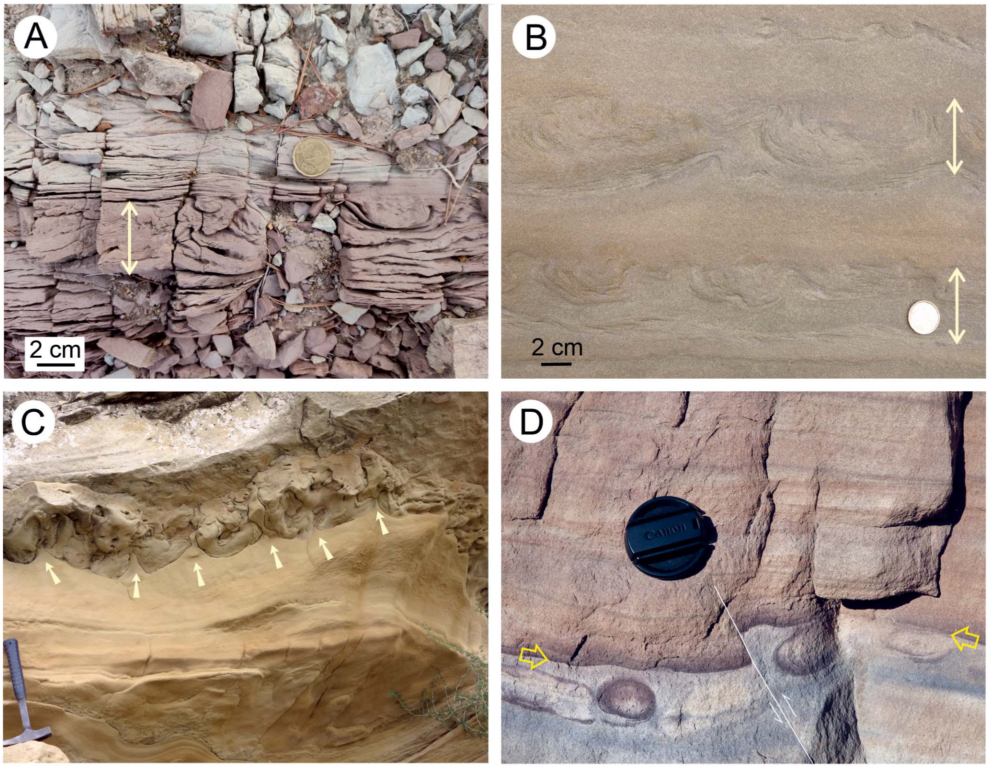

Figure 9. (A) Intensely deformed sandstone thin bed of the K1 unit (Keuper facies of Aspe section). (B) Deformed sandstone of the K2 unit (Keuper facies of the Alcaude section). Note the irregularity of folded laminations and rupture of some fold hinges due to dewatering processes. (C) Bottom bed with deformed sandstone horizon of the K2 unit (Keuper facies, Alcaudete section). Paths of dewatering indicated (yellow arrows). (D) Ball-and-pillow level in laminated sandstone of the K2 unit (Keuper facies, Higueruela section).

Above these volcanic rocks, significant volcaniclastic deposits appear in the Zamoranos Fm (Figure 4). In numerous sections such as Alcalá la Real, Calasparra, Cambil or Huesa, pyroclastic thin beds appear, which confirm the idea of an intense stage of volcanic extrusion during the Rhaetian [Pérez-López et al., 2012] related to the Central Atlantic Magmatic Province in a rifting tectonic context [Pérez-López et al., 2021b]. These are the most clearly extrusive and extensive volcanic facies that have been found in the Betic Triassic successions, from Alcalá la Real (Granada province) to the Jumilla section in Alicante province (Figure 1). In addition, iron mineralizations with pyroclastic deposits in the middle member corroborate this great volcanic activity [Fenoll Hach-Ali and García-Rossell, 1974, Pérez-López et al., 2021b] which triggered earthquakes. In all sections of the Zamoranos Fm, pyroclastic deposits are not found and volcanic intrusions are rare. However, iron mineralization is frequent in many sections.

6. Interpretation and discussion

6.1. *Tectonic instability and SSDS*

One of the main aims of this work was to demonstrate that the Triassic deposits of the Betic External Zone feature several types of post-depositional sedimentary structures that can be related to tectonic instability extending from the Middle Triassic to the Late Triassic. We therefore discuss their origins and examine their possible relationship with earthquakes to confirm them as tectonic signatures.

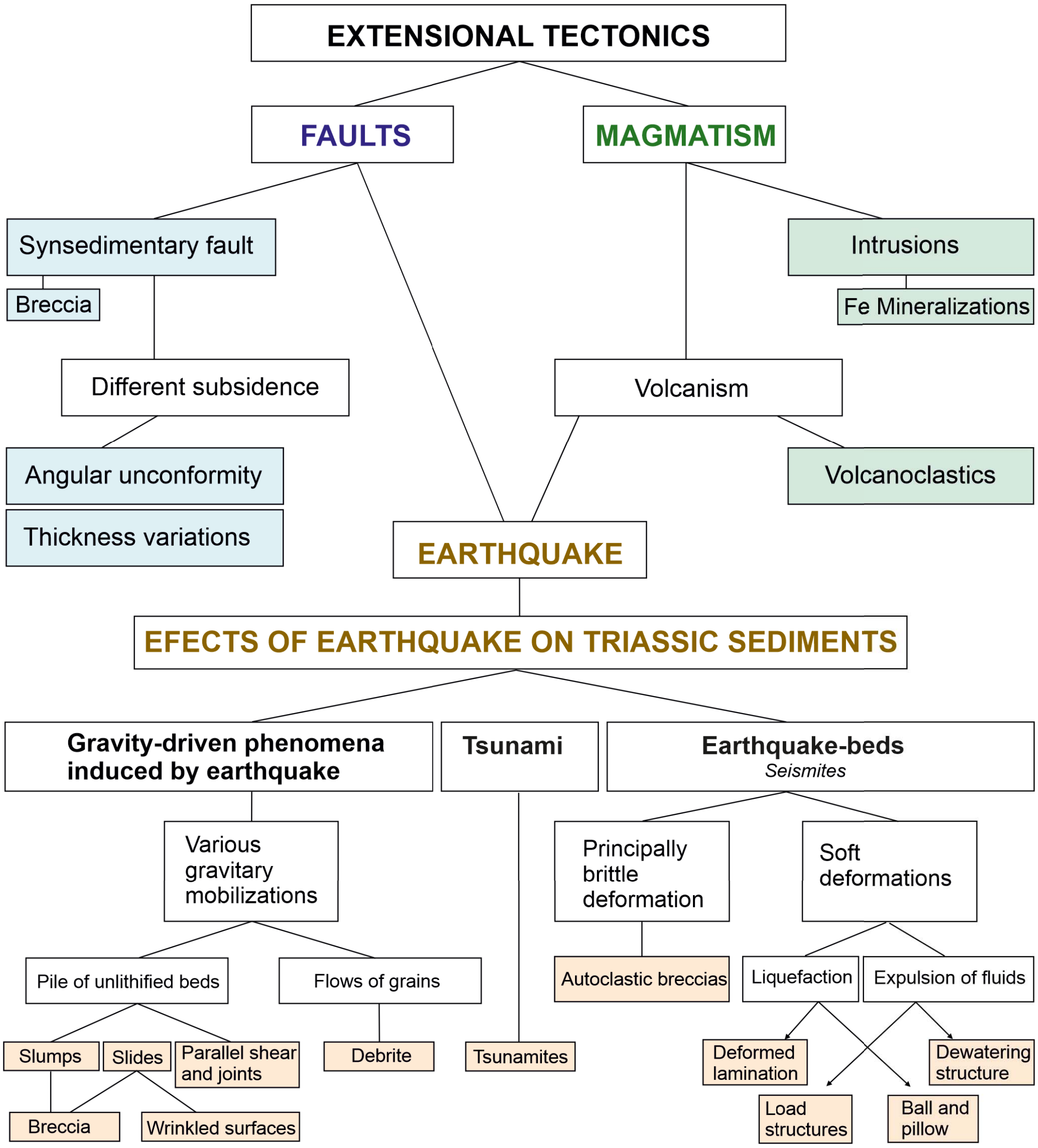

Figure 10. Diagram of features that record tectonic activity at different scales in the Triassic deposits of the Betic External Zone [general classification modified from Montenant et al., 2007].

The two factors controlling the genesis of the SSDS are prelithification deformation and liquidization [Audemard and Michetti, 2011, Obermeier, 1996, Seilacher, 1969, Shanmugam, 2016, Van Loon, 2009]. Therefore, these structures are closely related to tectonic activity or earthquakes that affected unconsolidated sediments. Although there could be other factors that could give rise to some of these structures [Shanmugam, 2017], the confluence of various types of structures in the same or in different units of possible similar seismic origin suggests tectonic activity, which is a common factor in most cases. This notion is also supported by other tectonic features such as differential subsidence, synsedimentary faults, and volcanism (Figure 10).

6.1.1. *Slumps and breccias*

Slump structures have been cited by several authors in distinct units of the Muschelkalk of the German Triassic [Föhlisch and Voigt, 2001, and references therein]. While some authors suggest that different factors can generate slumps [Martinsen, 1994], the specific trigger mechanism for slumps or SSDS may be seismic shocks [e.g. Alsop et al., 2016, Audemard and Michetti, 2011, Basilone et al., 2014, Basilone, 2017, Lu et al., 2017, Tavani et al., 2013]. For the Cehegín Fm, this interpretation is based on the extension of these structures over hundreds of kilometres on the epicontinental platform and their relation to other SSDS. In numerous sections of this formation, these structures, locally with breccias, appear between banks 1, 2, and 3 of the lower member.

The slumps present in thick beds of pyroclasts in the Zamoranos Fm suggest that slumped packages may have been reactivated and that folds were amplified by successive earthquakes [Alsop and Marco, 2011] at the end of the Triassic. In this case, faults and a complex structure between undeformed beds occur, probably affected by several earthquakes (Figure 7).

6.1.2. *Debrites*

The debrites also found in the lower member of the Cehegín Fm have been attributed to gravitational redeposition of heterogeneous muddy sediments with variable clay contents and different lithification, as described by Föhlisch and Voigt [2001] in the Germanic basin for similar lithofacies. As suggested by Föhlisch and Voigt [2001], these deposits could have originated from nodules via punctual early cementation (carbonate concretions) that, due to mass transport, may become micrite clasts immersed in a fine-grained matrix of the sediment itself. In general, the origin of intraformational breccias and debrites is frequently associated with local sliding due to earthquakes [e.g. Flügel, 2004]. Föhlisch and Voigt [2001] observed that the debrites are accompanied by slumps, vein structures, and by ball-and-pillow structures, all of which are thought to be of seismic origin.

6.1.3. *Slides, planes, and joints*

Among the possible mechanisms that can lead to the formation of slides, tectonic movements that produce earthquakes are the main cause [Knaust, 2000, Pedley et al., 1992]. Sigmoidal joints indicate seismic shaking which triggers gravitational mass movement [Föhlisch and Voigt, 2001]. The orientation of the joints, perpendicular to wrinkles, and the appearance of these wrinkles in the same stratigraphic horizons suggest a common or related trigger for the formation of these structures [Föhlisch and Voigt, 2001], which were found to be associated with the shear zone and slides in the sections examined here. Some sigmoidal deformation structures resemble those described in other studies focusing on Triassic Peri-Tethys basins [Ajdanlijsky et al., 2018, Chatalov, 2001, Knaust, 2000], where they are interpreted as structures resulting from palaeoseismicity.

6.1.4. *Flat pebble breccias*

Thin-bedded micritic limestones with flat pebble breccias are similar to the carbonates described by Chatalov [2017] or Zhao et al. [2008] in the Lower Triassic and the Cambrian [e.g. Gómez and Astini, 2015]. These levels also appear in the Middle Triassic of the Iberian Range and have been interpreted as subtidal deposits [Pérez-López et al., 2021a]. The varying grain size of the different levels determined the early cementation of laminites, in turn, leading to a significant increase in pore fluid pressure in the underlying dolomitic silt and its subsequent fluidization. Subsequent mobilization of the clasts occurred under the influence of an external triggering force, probably earthquakes [Chatalov, 2017, Chen et al., 2010]. These breccias can be compared to some Messinian deposits described by Montenant et al. [2007] which were interpreted as autoclastic breccias. The partially fragmented or broken micritic thin levels of the lower banks of the Cehegín Fm observed in the Almorchón section, together with other continuous levels of what was semi-consolidated sediment, could have been produced by a sudden dewatering process. Such flat pebble breccias or autoclastic breccias could be generated from these broken levels [Montenant et al., 2007].

6.1.5. *Bioclastic beds and dewatering*

In coarse-grained beds such as the bioclastic limestones of the lower member of the Cehegín Fm, interpreted as ramp deposits [Pérez-Valera and Pérez-López, 2008], the only structures that appear are the load cast type as mentioned above. In numerous works, these structures have been described in bioclastic carbonate beds and have been interpreted as SSDS due to the tectonic activity of the basin where they were deposited [Föhlisch and Voigt, 2001, Knaust, 2000, Matysik and Szulc, 2019].

In the sediments of the upper member of the Siles and Cehegín Muschelkalk fms interpreted mainly as lagoon deposits [Pérez-Valera and Pérez-López, 2008], this tectonic activity is not as much recorded except by some dewatering structures (punctually vertical shells) that may be observed in some bioclastic storm beds (shell-debris limestone), where the convex-down orientation and stacking of shells can be attributed to seismic events [Seilacher, 1984]. In addition, some of these bioclastic beds have been interpreted as tsunamite beds [Pérez-López and Pérez-Valera, 2012].

6.1.6. *Seismites in sandstones*

The local deformed laminations in Keuper sandstones of the K1 and K2 units (Figure 4) are interpreted as the liquefaction of fine sand as the consequence of an earthquake giving rise to a seismite bed. As deformed beds, seismites [Seilacher, 1969] represent the first significant impact of tectonic activity (seismic shock) in fine sandstones. Similar structures described in several studies have been interpreted as seismites related to an earthquake shock [e.g. Üner et al., 2017]. Although according to some authors, some of the features identified in sandstones, such as deformed lamination beds and ball-and-pillow structures, may not be clearly related to earthquakes [e.g. Shanmugam, 2016], the origins of deformed laminations of sandstones (seismite s. str.) of the K1 and K2 units are clear because of their sporadic occurrence in the succession and their considerable lateral development in its outcrops.

The structures studied significantly extend laterally in the outcrops and affect only specific thin intervals within the thick sandstone beds of the K2 unit. In the deformed sandstone bed of this unit, two perpendicular directions are observed in the irregular bottom, which can be related to surface seismic waves (Figure 9). Consequently, we interpret these beds with deformed laminations as seismic deposits *sensu stricto*.

In the K1 unit, complexly deformed lamination is rare and this affects very thin beds between lutites, ruling out other possible sediment destabilization mechanisms (e.g. sediment load) causing liquefaction and fluidization. These structures are therefore thought to arise from earthquakes as in other different examples [e.g. Alfaro et al., 2010, Bhattacharya et al., 2016].

Ball-and-pillow structures are other rare deformation structures present in the K2 unit of the Cabra del Santo Cristo (Higueruela section). In this case, the structures display different forms associated with liquefaction and fluidization under a fine sandstone bed via repeated detachment from the base of a bed undergoing load deformation. This structure type is interpreted as seismites [e.g. Berra and Felletti, 2011, Dugué, 1995, Gladkov et al., 2016, Owen, 2003, Ozcelik, 2016] and is thus a good indicator of syndepositional tectonics [Föhlisch and Voigt, 2001, Knaust, 2000, Pratt, 1994]. In the case studied here, these structures developed between sandstones of different grain size but very close densities, so that it is clear that an external factor such as a seismic shock would have been needed for their formation.

6.2. *Ramp platform control over SSDS*

In the Cehegín and Siles fms (Muschelkalk carbonates), several SSDS appear, especially in their lower members, including slumps, breccias, and debrites associated with slides, shear planes, and joints. Some of these can be explained by the presence of a gentle slope in the area where sediments were deposited due to the morphology of ramps or the differential subsidence recorded in the angular unconformity. The volume of these deformed sediments is small as the slope is gentle. However, several structures have a strong deformation component that suggests some external force triggering the slumps and brecciation of these sediments. This similar situation has been described in other Triassic ramps [e.g. Mabrouk et al., 2021]. The sediment available from these platforms is carbonate mud or carbonate silt deposits. Bioclastic facies occur in thin beds and usually in the upper member and, therefore, there is no evidence of high energy. Breccias and debrites are very rare and are of the intraformational type. In any case, they are clearly associated with slides and slumps. These structures occurred in specific bed packages, between undeformed carbonate, and they are present in many separate sections over a few hundred kilometres in the same interval of the lower member. Therefore, the trigger for the development of these slides, slumps, and debrites must have been earthquakes, as interpreted for other Triassic basins [Basilone et al., 2014, Chatalov, 2013, Knaust, 2000, Matysik, 2016, Matysik and Szulc, 2019]. Examples of seismically induced soft-sediment deformation, including slumping, debris flows, and sigmoidal joints have been described from the Lower Muschelkalk of Poland and Germany [Chatalov, 2001, 2013, Föhlisch and Voigt, 2001, Füchtbauer and Richter, 1983, Knaust, 2000, 2002, Matysik and Szulc, 2019, Rüffer, 1996, Szulc, 1993]. Also, a similar situation is observed in the German basin, in two highly deformed intervals, which are widespread in the lower part of the Upper Muschelkalk (Trochitenkalk) of southwestern Germany [Bachmann and Brunner, 1998].

From the data for the carbonate successions of the Betic Cordillera, it can be observed that intraformational breccia deposits or those related to slumps or slides occur in the lower part of the Upper Muschelkalk carbonates. In the upper part of these carbonates, the most frequent deposits are dewatering structures that appear in semi-consolidated sediments related to storm beds, which in some cases may be associated with tsunamis [Pérez-López and Pérez-Valera, 2012].

These mechanisms associated with tectonic activity, above all, affected sediments deposited on ramp-type platforms during a transgressive phase [Pérez-Valera and Pérez-López, 2008], where gentle slopes were the conditions leading in many cases to this type of structure, especially those associated with earthquakes. Hence, it seems that the slope or morphology of a ramp will determine the recorded tectonic or seismic activity of a region.

6.3. *Rifting phase in the Betic basin*

Our study identifies the features which can be observed in the Triassic rocks of the Betic External Zone that indicate a tectonic context of rifting during the deposition of the sediments of the different Triassic units. These data are consistent with prior work [López-Gómez et al., 2002, 2019] and also highlight the differential subsidence observed in the carbonate outcrops of the Middle (Cehegín and Siles fms) and, mainly, Upper Triassic (Zamoranos Fm) rocks. The discontinuities and some synsedimentary faults, identified in the carbonates and pyroclastic deposits also mark tectonic instability. Interestingly, the volcanism of the Zamoranos Fm indicates this tectonic activity was more intense at the end of the Triassic and associated with a rifting phase related to the Pangaea breakup, when a main extensional tectonics event occurred [Golonka et al., 2018]. For these reasons, the presence of SSDS in the Betic Triassic could reflect the initial phase of the Pangaea breakup. Tectonic instability due to Pangaean rupture is corroborated by other published data on seismic or volcanic activity in several Triassic basins in Iberia as, for example, the presence of Carnian volcaniclastic deposits in the Catalan basin [Mitjavila and Martí, 1986] and in Majorca Island [López-Gómez et al., 2017, Rodríguez-Perea et al., 1987] or Norian–Rhaetian volcanic activity in the Basque–Cantabria Range [Gómez et al., 2007]. This tectonic activity has been linked to a rifting phase which is recorded in the different Iberian basins [López-Gómez et al., 2019].

In the Triassic rifting stage of the Iberian basins two separate phases can be distinguished: a tectonic phase and a later mature phase [López-Gómez et al., 2019]. The first stage of tectonic rifting beginning at least in the Middle Triassic and the mature, or thermal stage, took place in the late Triassic when the carbonate sediments of the Zamoranos Fm were deposited. However, the relative changes in sea level recorded and significant volcanism in the lower part of this formation indicate some persisting tectonic activity. More detailed studies of more outcrops are needed to understand the frequency of these structures or deposits and the role of volcanism in the different Iberian basins. Data from the External Betic Zone seem to point to different pulses of a complex rifting phase.

7. Conclusions

In the Triassic of the Betic External Zone, we recognized several structures indicative of substantial tectonic activity from the Middle Triassic to the Late Triassic. Muschelkalk facies deposits feature slide surfaces, slumps, breccias, debrites, and some angular unconformities and synsedimentary faults. These structures developed in the lower member of the

Muschelkalk successions, where sediments were deposited on a muddy carbonate ramp during a transgressive stage. The development of these SSDS is triggered by earthquakes and conditioned by the tilted platform profile typical of ramp platforms.

The "seismites" found in Keuper facies units and some volcanic rocks confirm this significant tectonic activity also during Norian times. However, volcanic deposits and lateral variations in sedimentation occurring in the Rhaetian Zamoranos Fm suggest that tectonic activity was more intense towards the end of the Triassic.

These features, together with the vast changes in deposit thicknesses observed, are characteristic of tectonic activity associated with a rifting stage, probably, in relation to the breakup of Pangaea. The course of this stage was complex and perhaps involved several pulses depending on the given basin, and it was also more generalized and intense towards the end of the Triassic.

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