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RESEARCH PAPER

Largely allochthonous Triassic units in the Central Betics inferred from their contrasting paleogeographic origin (Cambil, Jaén, Spain)

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Abstract
Triassic clayey-evaporitic materials played an important role in the detachment of tectonic units when structuring the Betic Cordillera. In the Cambil sector (Jaén, southern Spain), Triassic outcrops of detrital-evaporitic materials and carbonates have been interpreted as a nappe ("Cambil nappe"). The great development of breccias with clayey-gypsiferous matrix within these materials may be related to an olistostromic unit of the Oligocene-Aquitanian. However, such a redeposit of Triassic materials in the Subbetic Zone during the Miocene is controversial. The geological mapping carried out in this study reveals the tectonic complexity of the area. Large blocks of different nature and age crop out throughout the sector. The identification of Muschelkalk carbonate units of diverse paleogeographic origin, based on the Triassic stratigraphy, implies structures undergoing displacements of almost one hundred kilometers. Largely brecciated bands would be related, in this context, to tectonic structures of brittle-plastic range developed on clayey-gypsiferous materials. Salt tectonics alone cannot explain these regional displacements; hence most of the described tectonic fabrics must be associated with the thrusting and strike-slip faulting of the Betic fold and thrust belt.

Keywords Brecciated Triassic · Cataclasite · Muschelkalk · Keuper · Prebetic · Subbetic

Unidades triásicas marcadamente alóctonas en la zona central bética, inferidas a partir de diferencias en su origen paleogeográfico (Cambil, Jaén, España)

Resumen
Los materiales arcilloso-evaporíticos triásicos tuvieron un papel importante en el despegue de las unidades tectónicas durante la estructuración de la Cordillera Bética. En el sector de Cambil (Jaén) existen afloramientos triásicos de materiales detrítico-evaporíticos y carbonatos, que fueron interpretados como un manto de corrimiento ("Manto de Cambil"). El gran desarrollo de brechas con matriz arcilloso-yesífera dentro de estos materiales se ha relacionado con una unidad olistostrómica del Oligoceno-Aquitaniense. Sin embargo, este redepósito de materiales triásicos en la Zona Subbética durante el Mioceno es controvertido. La cartografía realizada en el presente estudio muestra la complejidad tectónica de la zona con grandes bloques de diferente naturaleza y edad, aflorando en todo el sector. La identificación de unidades litoestratigráficas carbonatadas de facies Muschelkalk con diferente origen paleogeográfico, a partir de la estratigrafía del Triásico, implica estructuras con grandes desplazamientos de casi un centenar de kilómetros. Las bandas ampliamente brechificadas deben relacionarse, en este contexto, con estructuras tectónicas de rango frágil-plástico desarrolladas sobre materiales arcilloso-yesíferos. La tectónica salina por sí sola no podría explicar estos desplazamientos regionales; de ahí que la mayor parte de las fábricas tectónicas descritas deban asociarse a los cabalgamientos y fallas de salto en dirección del cinturón bético de pliegues y cabalgamientos.

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Palabras clave Triásico brechoide · cataclasita · Muschelkalk · Keuper · Prebético · Subbético

1 Introduction

In the South Iberian Paleomargin, Triassic sediments constitute the first deposits unconformably overlying the Iberian Variscan Massif, thus recording the initial stage of the Pangaea breakup (e.g. Dietz & Holden, 1970; Peace et al., 2020; Roest et al., 1992). The process led to a rifting phase that controlled the deposition of Triassic materials, as fault-controlled subsidence developed in this extensional context. Extension progressed from E to W, from the Early Triassic to the Late Triassic, showing different sedimentary and paleogeographic features between proximal and distal areas with respect to the open marine zones, associated with the formation of the Neotethys (López-Gómez et al., 2019 and references herein). The material deposited during the Triassic in the South Iberian Paleomargin (the so-called South-Iberian Triassic, Pérez-López & Pérez-Valera, 2007) consists of a variety of continental and fluvio-evaporitic sediments, with some epicontinental shallow to moderately deep marine intercalations, better represented in the more distal areas to the ESE of the South Iberian Paleomargin (Pérez-López, 1998; Pérez-Valera & Pérez-López, 2008).

During the Betic orogeny, the South-Iberian Triassic was incorporated into the External Zone of the Betic Cordillera (southern Spain), where it crops out discontinuously over more than 500 km (Fig. 1). It is noteworthy that in these outcrops, the Triassic stratigraphic successions are often truncated, incomplete, or highly deformed (Pérez-López & Pérez-Valera, 2007), due to: 1) the significant involvement of Triassic rocks in the structure of the External fold-and-thrust belt of the Betic Cordillera (Expósito et al., 2012; Luján et al., 2006); and 2) their particular rheology, characterized by the predominance of ductile and plastic materials (e.g., clays and evaporites). For this reason, many Triassic outcrops consist of incomplete, highly deformed detrital and carbonate successions, or of breccias and megabreccias (with gypsum or carbonate blocks) and brecciated gypsum. Their stratigraphic features can help to trace their origin and their relationship to specific paleogeographic domains, before tectonic shortening.

The origin of these brecciated units, with their complex lithological and structural relationships, remains a topic of debate among researchers. Triassic brecciated material has often been interpreted as resedimented Cenozoic deposits, introducing the concept of olistostrome for their interpretation (Dupuy de Lome, 1965), initially defined in the Guadalquivir Basin (Perconig, 1962; Roldán and García Cortés, 1988; Roldán et al., 2012), and later applied across the entire External Zones of the Betic Cordillera (Bourgois, 1975; García Cortés et al., 1991; Pérez-López & Sanz de Galdeano, 1994). Yet further outcrops are now being recognized and interpreted as: 1) a chaotic and complex synorogenic unit, referred to as the Subbetic Chaotic Complex (Vera & Martín-Algarra, 2004); 2) synorogenic elements reflecting the extensional geodynamic context of the Betic Cordillera during much of the Mid-Late Miocene (Rodríguez-Fernández et al., 2013); or 3) a synorogenic frontal mélange unit (Pedrera et al., 2012).

Meanwhile, several authors (Dupuy de Lome, 1965; Foucault, 1966; Sanz de Galdeano, 1973; Barástegui et al., 1998, among others) have cited diapiric processes as a key factor affecting Triassic materials at various stages. The significance of these processes has been understood in different ways (Pérez-López & Pérez-Valera, 2003), as intense tectonic deformation hinders clear interpretations of the relationship between diapirism and tectonic deformation. Recently, Pérez-Valera et al., (2017, 2020) suggested, after discussing previous olistostromic and diapiric interpretations, that the apparently chaotic Triassic brecciated units present in the Guadalquivir Basin are primarily related to tectonic processes, forming part of the frontal accretionary system of the Betic Cordillera.

Despite the controversial origins of brecciated, evaporite-bearing Triassic complexes in the External Zone of the Betic Cordillera, the stratigraphic features observed in the outcrops can be analyzed and assigned to well-known units of the South Iberian Triassic. In this way, correlation and assignment to paleogeographic units serve as key tools to deduce the original position of the units and reconstruct their tectonic history.

The aim of this work is to characterize the Triassic geology of Cambil (Jaén), in the central Subbetic Zone of the External Zones of the Betic Cordillera (Figs. 1 and 2), where brecciated units and stratigraphic successions of Triassic units crop out extensively, and from a stratigraphic perspective can be assigned to different paleogeographic domains. In addition to studying and mapping the different lithostratigraphic units, we analyze the brecciated fabrics associated with Triassic materials to evaluate their debated origin. The data obtained are crucial for comparison with other large Triassic outcrops, to better understand the structural evolution of the Betic Cordillera and the role of these materials in the tectonic processes that shaped it.

2 Geological setting

From a geographical standpoint, the Betic Cordillera — the mountain range that occupies the south of the Iberian Peninsula from Cadiz to Alicante (Fig. 1) is formed by two classic large domains of different stratigraphic and tectonic

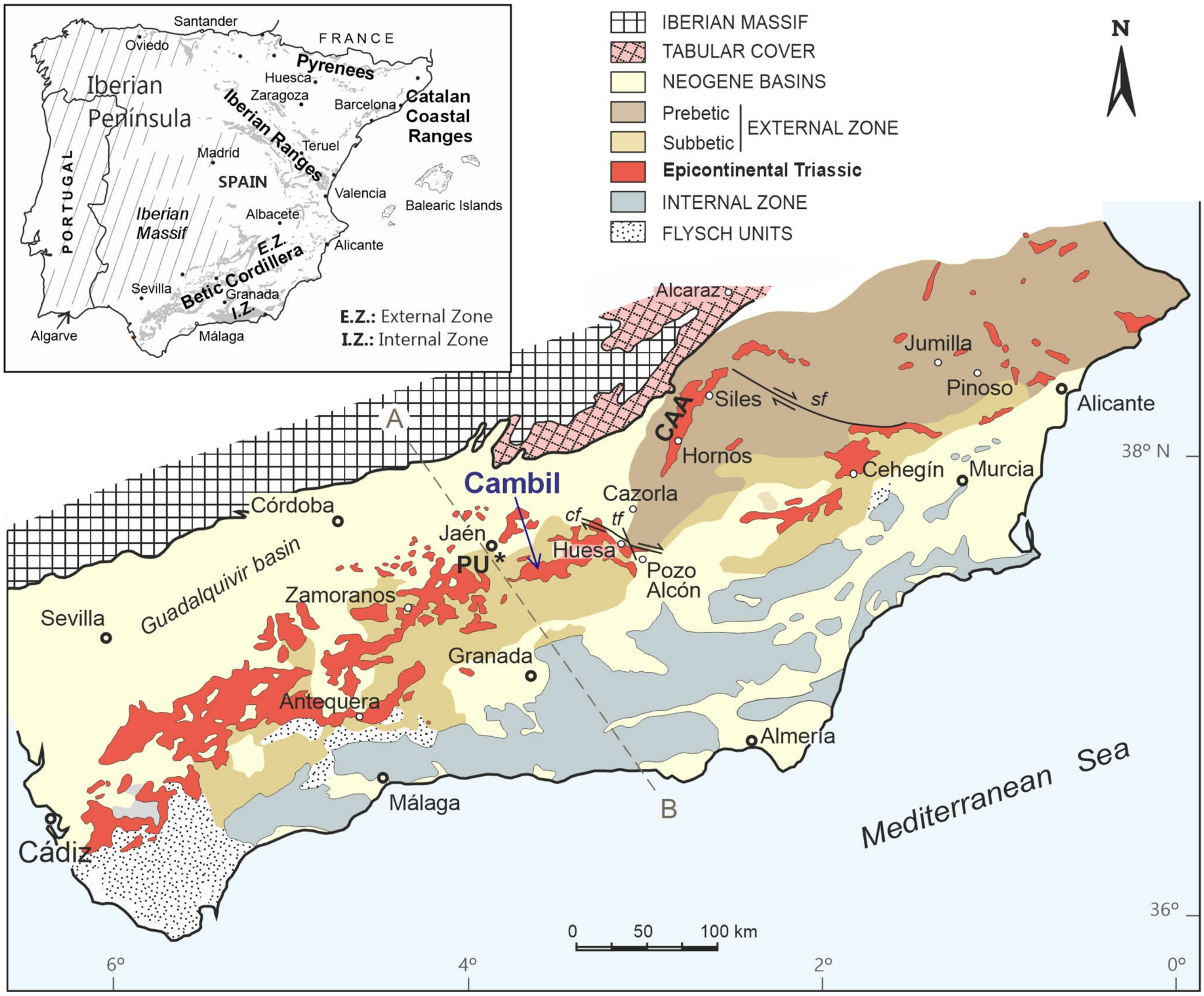

Fig. 1 Geological context of the Epicontinental Triassic showing the different tectonic domains in the Betic Cordillera (southern Spain). These Triassic outcrops comprise disrupted sections of Buntsandstein, Keuper, and Muschelkalk facies (Pérez-López et al., 2021). The study zone, Cambil, is situated in the central sector of the Betic Cordillera. *Legend:* **CAA**, Cazorla-Alcaraz Arc; **PU**, blocks of Prebetic units (Sierras de Bedmar, Pegalajar, Aznatín, Castillo de Jaén); **cf**, Collejares fault; **tf**, Tiscar fault; **sf**, Socovos fault. Regional structural cross-section A-B is in Fig. 3

characteristics: The External Zone and Internal Zone (e.g. Azéma et al., 1979), the latter corresponding to the so-called Alboran Domain (e.g., Balanyá & García-Dueñas, 1987; Martínez-Martínez & Azañón, 1997). The External Zone formed part of the southern and southeastern edge of the Variscan Massif, which contains deposits of the Iberian paleomargin, and presents Mesozoic and Cenozoic sediments (Vera, 2001).

In the External Zone, two major tectonic domains or assemblages can be discerned: The Subbetic domain and the Prebetic domain. In both domains, deposited sediments were mainly marine, although in the Prebetic domain, facies are generally shallower, or even continental, because of their position closer to the Variscan Massif. In the central sector of the Cordillera, the Subbetic is subdivided into Internal Subbetic, Median Subbetic and External Subbetic, which is closest to the Prebetic (García-Dueñas, 1967; Fonboté, 1970; Vera & Martín-Algarra, 2004). Furthermore, within the Subbetic, to the north of the External Subbetic, the Intermediate Domain (Ruiz-Ortiz, 1980, 1981) is distinguished, characterized as the most subsident sector of the South Iberian Paleomargin, reaching the greatest Jurassic and Cretaceous thicknesses in the entire basin (Vera & Martín-Algarra, 2004).

In the External Zone, rocks of Triassic age, given their stratigraphic position, their considerable thickness and their lithological characteristics, constitute the main level of detachment of the tectonic units formed during

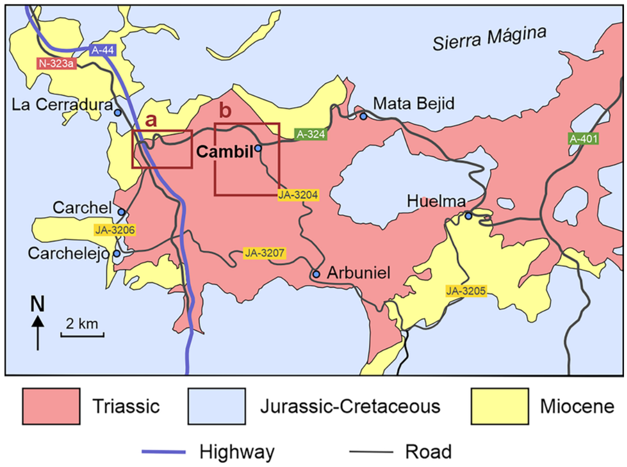

Fig. 2 Geographical location of the two mapped study areas: **a** Oasis Hotel area; **b** Cambil area. The outcrop of the materials that constitute the "Trías de Cambil" is indicated as "Triassic materials", surrounded by Mesozoic tectonic units of the Subbetic domain —modified after data from geological maps of Huelma (Díaz de Neira et al., 1992), Valdepeñas de Jaén (Enrile-Albir et al., 1996), Torres (Álvaro-López et al., 1992), and Jaén (Roldán García et al., 1992)

the Alpine orogeny (Fig. 3). This resulted in the formation of extensive and continuous highly deformed Triassic outcrops (Fig. 1). Within the outcrops of the External Zone, different tectonic units of Triassic materials are of disputed origin: "Trias of the Guadalquivir units", "Antequera Trias", or "Cambil Trias" (e.g. Fallot, 1927; García-Rossel, 1972; Roldán-García and Cortés, 1988; Vera & Martín-Algarra, 2004).

Among the Neogene basins, it should be noted that the Gualdalquivir Basin, located to the N and NW of the Subbetic domain (Vera & Martín-Algarra, 2004), harbors the "Guadalquivir units". During the early Miocene, the Guadalquivir Basin may have constituted a submerged basin in which, by gravitational sliding, materials of Subbetic origin were inserted between formations of Miocene age, forming olistostromes and nappes (García-Rossel, 1972; García-Hernández, et al. 1980; Martínez del Olmo et al., 1999; Martínez del Olmo, 2019). However, according to the interpretation of Pérez-Valera et al. (2017), supported by structural and geophysical data, the origin of the "Guadalquivir units" would be purely tectonic.

The study area of the present work is near the town of Cambil (Jaén, S Spain), within the Subbetic domain, and includes part of the so-called "Trías de Cambil", where materials of different lithologies of the Epicontinental Triassic facies crop out (Figs. 1 and 3). Cambil has long been a site of reference for Triassic rocks. Indeed, from the sixteenth century until the beginning of the twentieth century, it held great interest owing to its mining resources (Cubillo Cobo, 2020), and later for its structural geology, as a tectonic unit of uncertain origin. Fontboté (1964) defined the "Cambil nappe" and attributed it a southern origin. Shortly thereafter, García Dueñas (1969) described it as a detachment unit integrated in the base of the Median Subbetic Domain. Because its geological features and facies make it comparable to Triassic tectonic units such as the "Trías de Antequera" of Subbetic origin (Vera, 1969), this particular zone holds clues of regional interest.

More detailed studies of the Cambil lithofacies, especially in terms of breccias and blocks, relate these Triassic

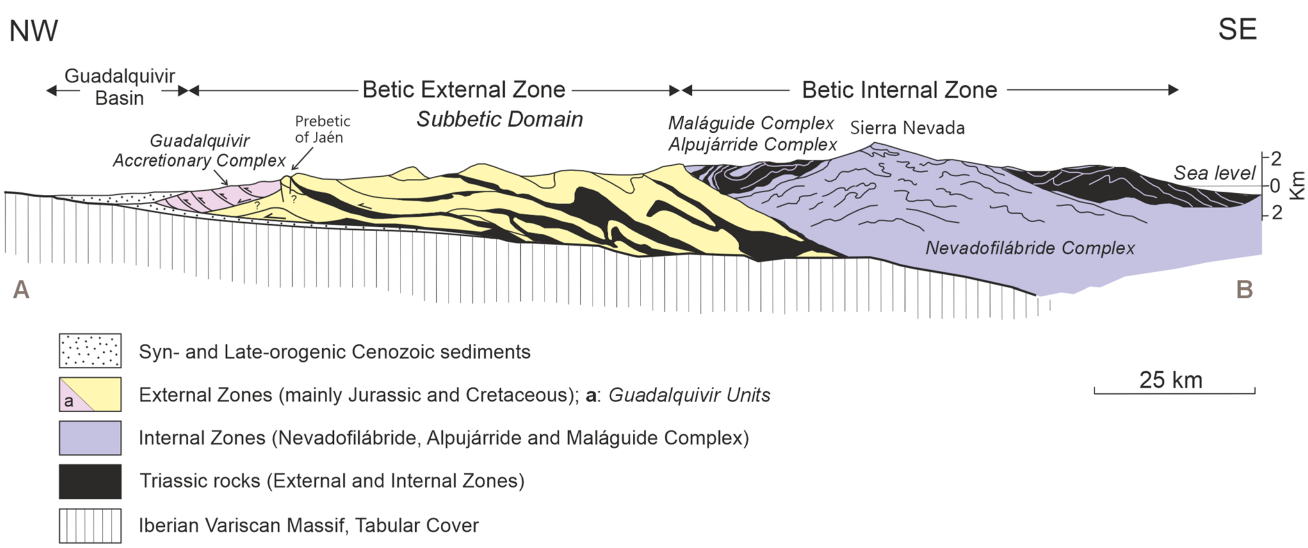

Fig. 3 Schematic regional structural cross-section (A-B, Fig. 1) of the Betic central sector, showing the Triassic materials as the main detachment level of the tectonic units (modified from Pérez-López & Pérez-Valera, 2007; Vera, 2001). Structure of the Guadalquivir Accretionary Complex after Pérez-Valera et al. (2017)

outcrops of complex structure to olistostromic units (Oligocene–Miocene) containing elements of Triassic origin and materials of Jurassic to Early Miocene age, the clayey matrix being dated as Langhian (Roldán-García et al., 1992). South of Cambil, towards Arbuniel, they are described as very deformed Triassic outcrops or materials of "anomalous aspect" related to the Triassic but including Jurassic, Cretaceous and Cenozoic fragments that constitute a megabreccia of the late Oligocene-Aquitanian (Enrile-Albir et al., 1996).

3 Material and methods

This study relies on laboratory and field work. After reviewing satellite images (Google Earth) and field research in several stages, a geological map was made to identify and characterize several Triassic units. The mapped study area comprises nearly 14 km^2. To identify some of the carbonate outcrops, a study of 47 thin-section was conducted using a petrographic microscope at the department of Stratigraphy and Paleontology of the University of Granada.

This research is supported by hundreds of photos taken in the field at different scales, proving useful to compare facies from diverse points of the study area and interpret contacts between units. In addition to the field photos, measurements of strike and dip direction of many beds and faults were recorded, and several lutite samples were taken (washed through 63–500-1000 µm sieves) to look for microfossils.

To distinguish the Keuper detritic-evaporite facies from the middle Muschelkalk facies, the $\delta^{34}S$ values contained in the gypsum served as reference (Ortí et al., 2022). The sulfur and oxygen isotope composition of the gypsum samples ($\delta^{34}S$, $\delta^{18}O$) analyzed here (3 samples) were determined at the Scientific and Technological Centers (CCiTUB) of the *Universitat de Barcelona* (Spain).

4 Triassic stratigraphy

Different Triassic lithofacies crop out in the Betic Cordillera due to the extensive and varied sub-basins that developed in southern Iberia during the rifting phase of the Pangea breakup. The main Triassic lithotypes can be distinguished as continental, epicontinental and alpine (Pérez-López & Pérez-Valera, 2007). In the External Zone of the cordillera, where the studied Cambil sector is located, the epicontinental type of Germanic facies crops out widely, showing the classic facies of Buntsandstein (Anisian), Muschelkalk (Anisian-Ladinian) and Keuper (Carnian-Norian). Above them in this stratigraphic succession (Fig. 4) lie Rhaetian carbonates defined as the Zamoranos Fm (Pérez-López et al., 2012). The most significant features of these facies, used to

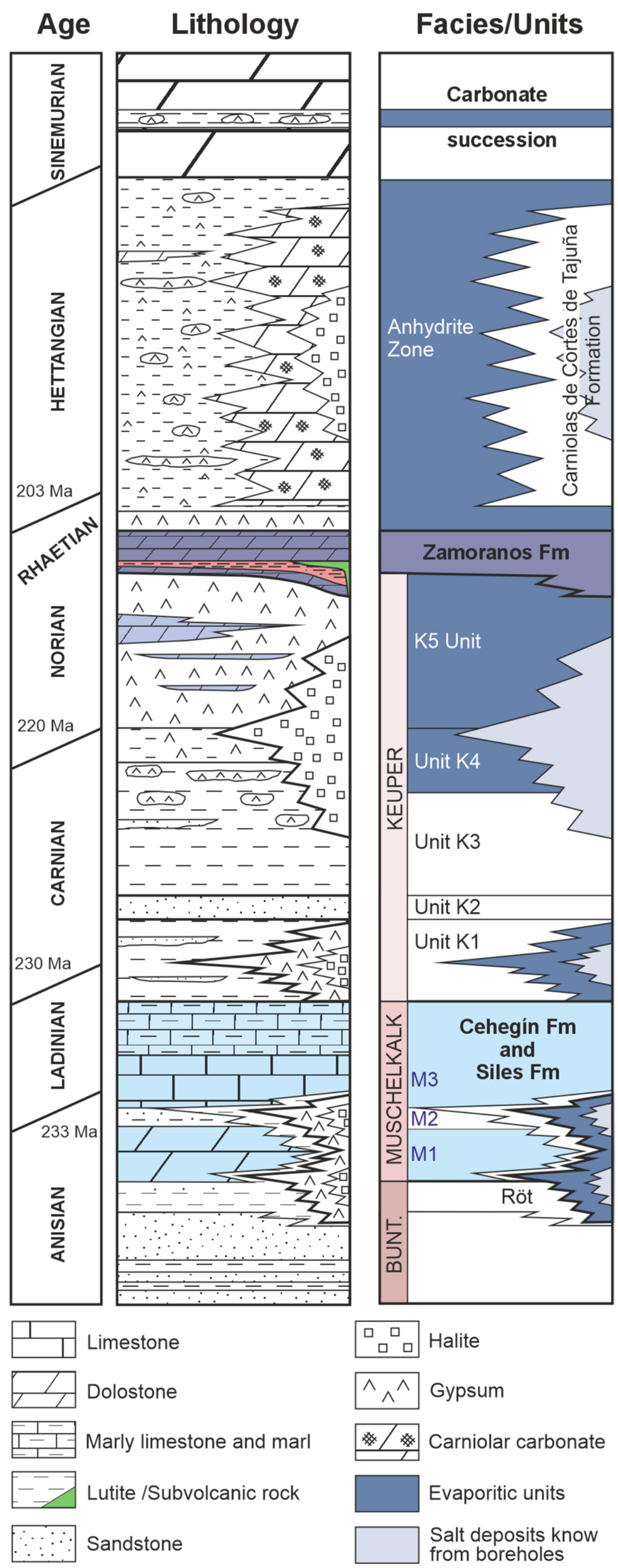

Fig. 4 Stratigraphy of the Triassic–Jurassic transition in the Betic External Zones (modified from Pérez-López et al., 2012). Salt deposits known from boreholes and associated with different evaporite units (Ortí, 1990). The Anhydrite Zone corresponds to the Carniolar Cortes de Tajuña Formation in the Iberian Range (Morillo-Velarde and Meléndez-Hevia, 1979; Ortí, et al., 2017). Without scale

identify the different units in the Cambil sector, are highlighted below.

The prevailing deposits are those having Muschelkalk, shallow marine, epicontinental facies. Two different formations were defined in view of their paleogeographic origin: The Siles Fm occupies the most proximal sectors of the Iberian Palaeomargin, while the Cehegín Fm is present in more distal areas (Pérez-Valera & Pérez-López, 2008) (Fig. 5). The two formations are correlated, sharing a Ladinian age based on ammonoid biostratigraphy (Pérez-Valera et al., 2016). From a lithological point of view, the Siles and Cehegín formations present carbonates and marl limestones; but the Cehegín Fm is thicker, with several massive limestone or dolomite banks and deeper facies than the Siles Fm, which presents very thin beds and abundant bivalves of the *Enantiostreon flabellum* (Schmidt) together with other species such as *Costatoria goldfussi* (Alberti) or *Bakevellia costata* (Schlotheim) (Pérez-López et al., 1991; Pérez-Valera & Pérez-López, 2008). In addition, the Siles Fm carbonates feature *Glossifungites* ichnofacies containing *Diplocraterion* and *Rhizocorallium* burrows (Rodríguez-Tovar et al., 2007). The Cehegín Fm is associated with the Subbetic domain, whereas the Siles Fm stems from a paleogeographic domain closer to the continent, most likely the Prebetic domain (Fig. 5).

Both Muschelkalk formations are overlain by a thick detrital succession of Keuper facies ("Keuper Group of Jaen"). In the Prebetic domain they consist of red lutites and sandstones with some gypsum, especially in the upper part. The Keuper facies of the Subbetic domain are much thicker, having different facies and variegated colors. Carbonate beds, marl and gypsum are more abundant than in the Prebetic domain. Toward the upper part, laminated gray gypsum predominates (K5 unit).

Deposited above the Keuper facies sediments, the carbonates of the Zamoranos Fm are characterized by the Ferruginous Detrital Member with hematite mineralizations, in some outcrops showing intercalations of volcanogenic materials. Another diagnostic feature of this formation is the presence of the coprolite *Parafavreina thoronetensis* (Bronnimann et al., 1972), recognized in the carbonate thin section of the middle-upper part of the succession. This carbonate formation, very characteristic of the Subbetic domain Triassic, has been assigned a Rhaetian age (Pérez-López et al., 2012). Towards the Prebetic domain it presents shallower sediments (tidal facies), without iron mineralization, therefore it is similar to the Imon Fm defined in the Iberian Range (Gómez & Goy, 2005).

It is noteworthy that in this epicontinental Triassic, and in the rest of the Iberian Peninsula (Ortí et al., 2017), up to six evaporitic episodes alternated with carbonatic and

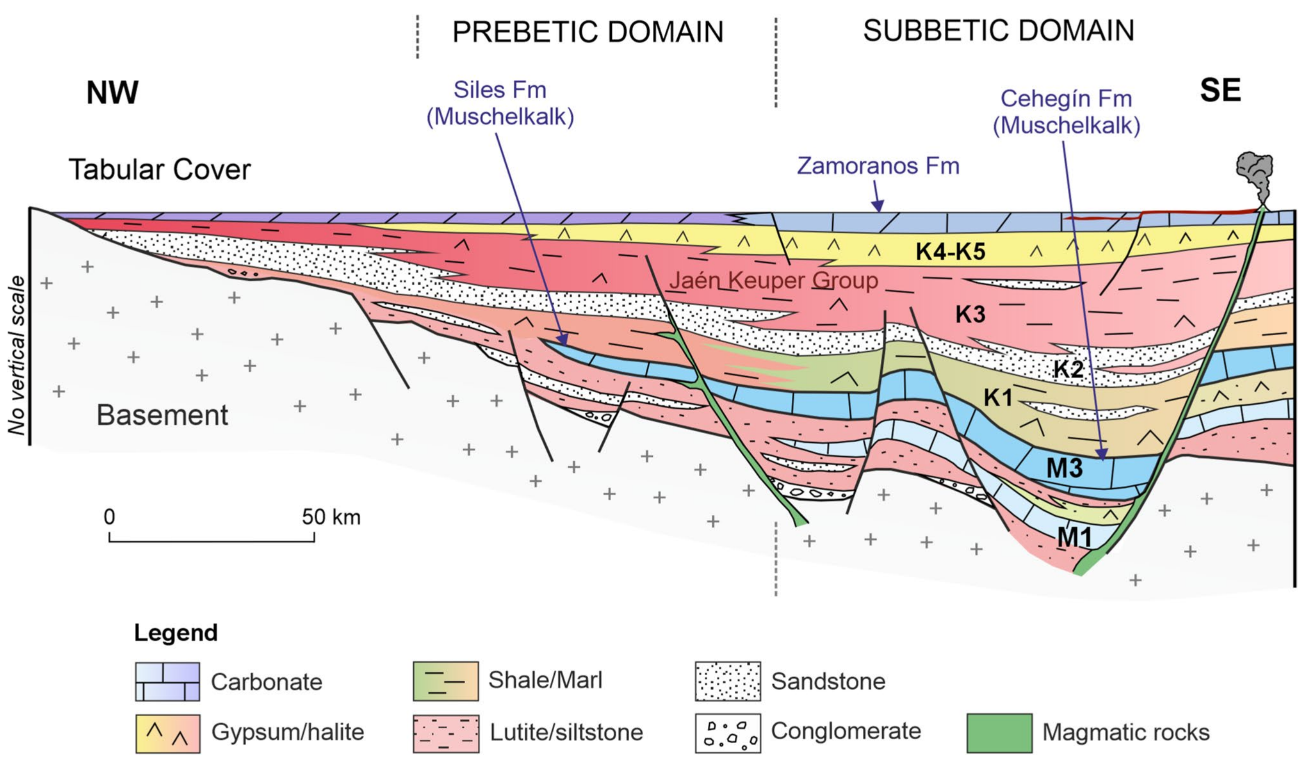

Fig. 5 Stratigraphic framework in the paleogeographical context of the Triassic basin, where it is possible to correlate the main lithostratigraphic units in several domains controlled by the rifting phase (modified from Pérez-Valera & Pérez-López, 2008; and López-Gómez, et al., 2019)

siliciclastic episodes between the Anisian and the early Hettangian (Fig. 4). At the subsurface, the presence of thick successions of halite is important (e.g. Suárez-Alba, 2007). The alternation of competent units, mainly carbonates and sandstones, and evaporite units with clays, cause the plastic behavior of Triassic materials in response to tectonic deformation, hence the development of very peculiar structures (Pérez-Valera et al., 2011).

5 Results

5.1 Lithological units

The field study conducted to identify and map the different units allows us to highlight the most significant features of the area´s structural geology (Figs. 6, 7 and 8). Outcrops of lithological units corresponding to well-known Triassic formations —also identified in other sectors of the Betic Cordillera— have been recognized. In addition, there are outcrops of other units that are more difficult to identify, due to two main reasons. Firstly, intense tectonic activity has caused most of the contacts between units to be faulted, and in some cases, the deformation is so severe that the units have been transformed into breccias. Secondly, the identification of some highly deformed outcrops is further complicated by the fact that several Triassic units exhibit very similar lithofacies, making them difficult to distinguish. The facies similarity is particularly evident in detrital successions and in dolomitic or gypsiferous sections. Despite these challenges, two distinct areas can be distinguished from both cartographic and stratigraphic perspectives:

a) A continuous stratigraphic succession, over 200 m thick, located in the central sector of the Cambil area (Fig. 7), and separated from other Triassic units by mechanical contacts. This succession is overturned, beginning with red lutites and sandstones, which are conformably overlain by carbonates that clearly belong to the Siles Fm. This detrital succession closely resembles the Arroyo Molinos Fm, defined by Pérez-Valera (2005) for the Buntsandstein in the Siles sector (Jaén). The carbonate succession of the Siles Fm, overlying the Arroyo Molinos Fm, is approximately 30 m thick and is characterized by marly limestones, often heavily bioturbated and containing the characteristic bivalves: *Enantiostreon flabellum, Costatoria goldfussi* (Alberti) and *Bakevellia costata* (Schlotheim) (Fig. 9a, b). The overall features of this formation are closely comparable to those described for the Siles Fm by Pérez-Valera (2005) and Pérez-Valera and Pérez-López (2008). Conformably overlying the Siles Formation are red lutites, clays, and sandstones (Fig. 9c). The predominance of red coloration in these materials, along with the scarcity of carbonate and evaporite beds, supports the interpretation that this Triassic succession is similar to the Keuper units described in the Hornos-Siles sector (Jaén) of the Prebetic Domain (Pérez-Valera, 2005). In fact, three lithostratigraphic units (K1, K2, and K3) have been distinguished and mapped within this detrital succession (Fig. 7).

b) A broad area marked by limited continuity in the stratigraphic successions of Triassic units gives rise to a cartographic pattern characterized by dispersed blocks of varying lithologies (detrital, carbonate, gypsum, ophitic) embedded within a matrix of highly brecciated clay-evaporite formations (Figs. 6, 7). Within this complex unit, the following formations can be distinguished:

- Carbonate sections of Muschelkalk facies of the Cehegín Fm: The Cehegín Formation exhibits very thick sections (> 100 m) east of Oasis Hotel (Fig. 6), with typical successions comprising three massive basal banks and thinly bedded marly limestones in the upper part (Fig. 9d). In other sectors of the study area, its identification is less evident: Carbonate successions are often incomplete, and sometimes only massive carbonate blocks are exposed, likely marking the base of the formation. The stratigraphic features and fossil content (bivalves, nautiloids; Pérez-Valera & Pérez-López, 2008) are distinctive.

- Variegate detrital successions, although often highly deformed and cropping out discontinuously, are common. Their lithological features and special relationship with the Cehegín Fm suggest they correspond to Keuper facies (likely K1 unit) of the Subbetic domain (Pérez-Valera, 2005). The presence of thick, laminated gray gypsum beds (K5 unit) further supports their assignment to the Keuper facies (Fig. 9e) of the so-called "Jaén Keuper Group" (Pérez-López, 1998).

- Isolated carbonate blocks, mostly embedded within brecciated materials, are interpreted as belonging to the Zamoranos Fm based on: a) the occurrence of iron mineralization or red mineralized conglomerates (Fig. 9f); and b) specific carbonate microfacies features, such as the presence of the coprolite *Parafavreina thoronetensis* or pyroclastic grains typical of this formation.

- Extensive outcrops of highly brecciated Keuper facies are prominent, although locally some less-deformed beds or intercalated layers can be observed within the breccias (Fig. 10). These lithofacies typically display red, green, and ochre hues; the breccias consist of angular clasts of lutite, gypsum, sandstone, and carbonate, embedded in a clayey matrix (Fig. 10c, d). In some cases, these breccias are cemented by calcium carbonate or calcium sulfate (Fig. 10e).

- Numerous decametric-scale carbonate blocks are present, though their stratigraphic attribution remains uncertain. Many are considered part of the Zamoranos Fm, which commonly appears as scattered blocks enclosed within brecciated Keuper facies materials. In some localities, these carbonate blocks are associated with banded white gypsum of

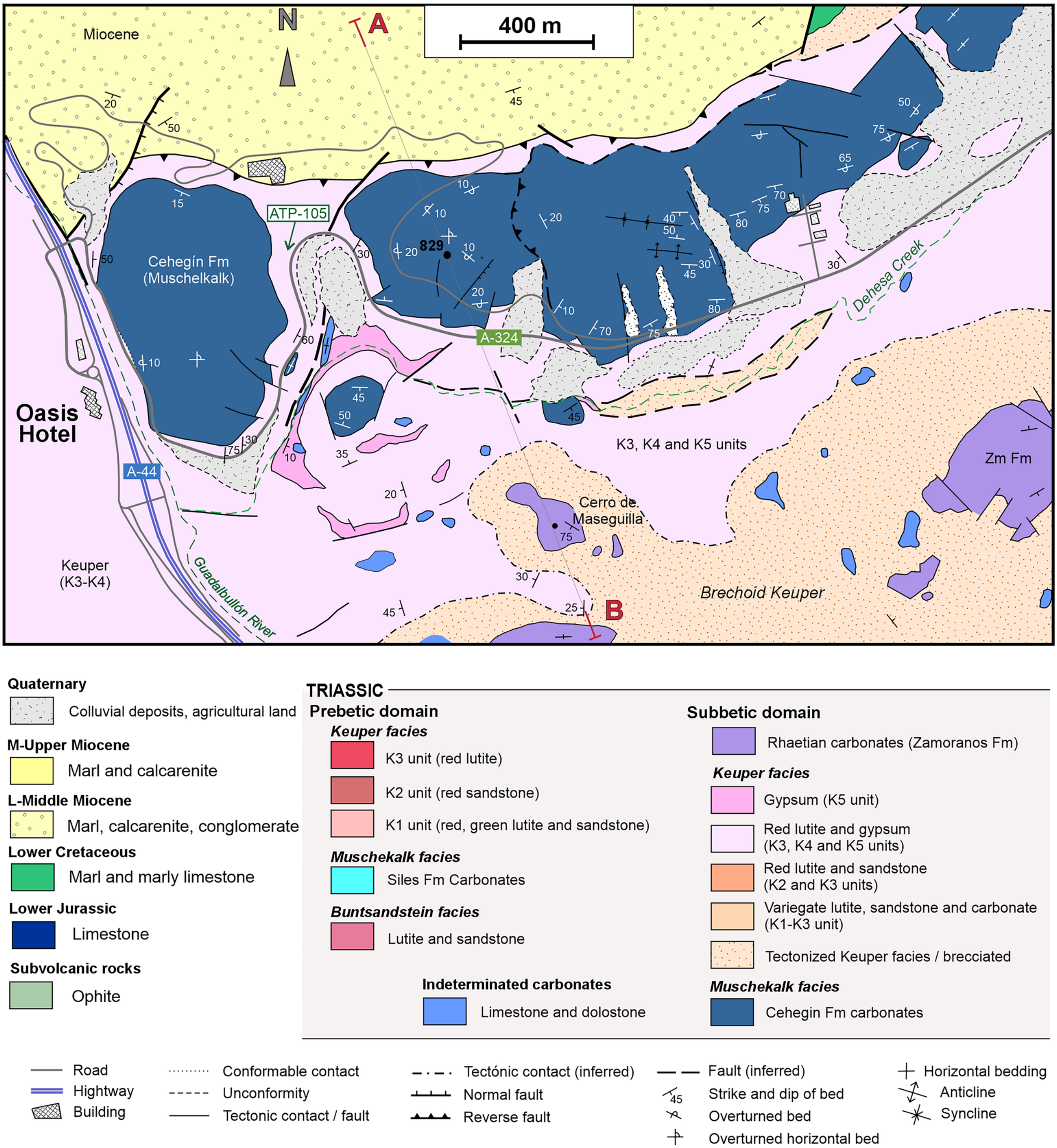

Fig. 6 Geological map of the Oasis Hotel area, 4 km west of Cambil village (see location in Fig. 2, (**a**). The geological cross-section A-B is indicated (see fig. 8)

the K5 unit, potentially correlating with the K5d member of the K4-K5 unit of the Jaén Keuper Group (Pérez-López, 1991, 1998).

- Subvolcanic rocks (ophites) crop out in the central part of the sector, associated with the Keuper detrital materials. These subvolcanic bodies are occasionally found intercalated among the red detrital successions of the Subbetic domain, mostly showing mechanical contacts. However, in some locations, intrusions into sandstone beds attributed to the Subbetic can be observed. With the materials of the Prebetic, it shows a mechanical contact that cuts across

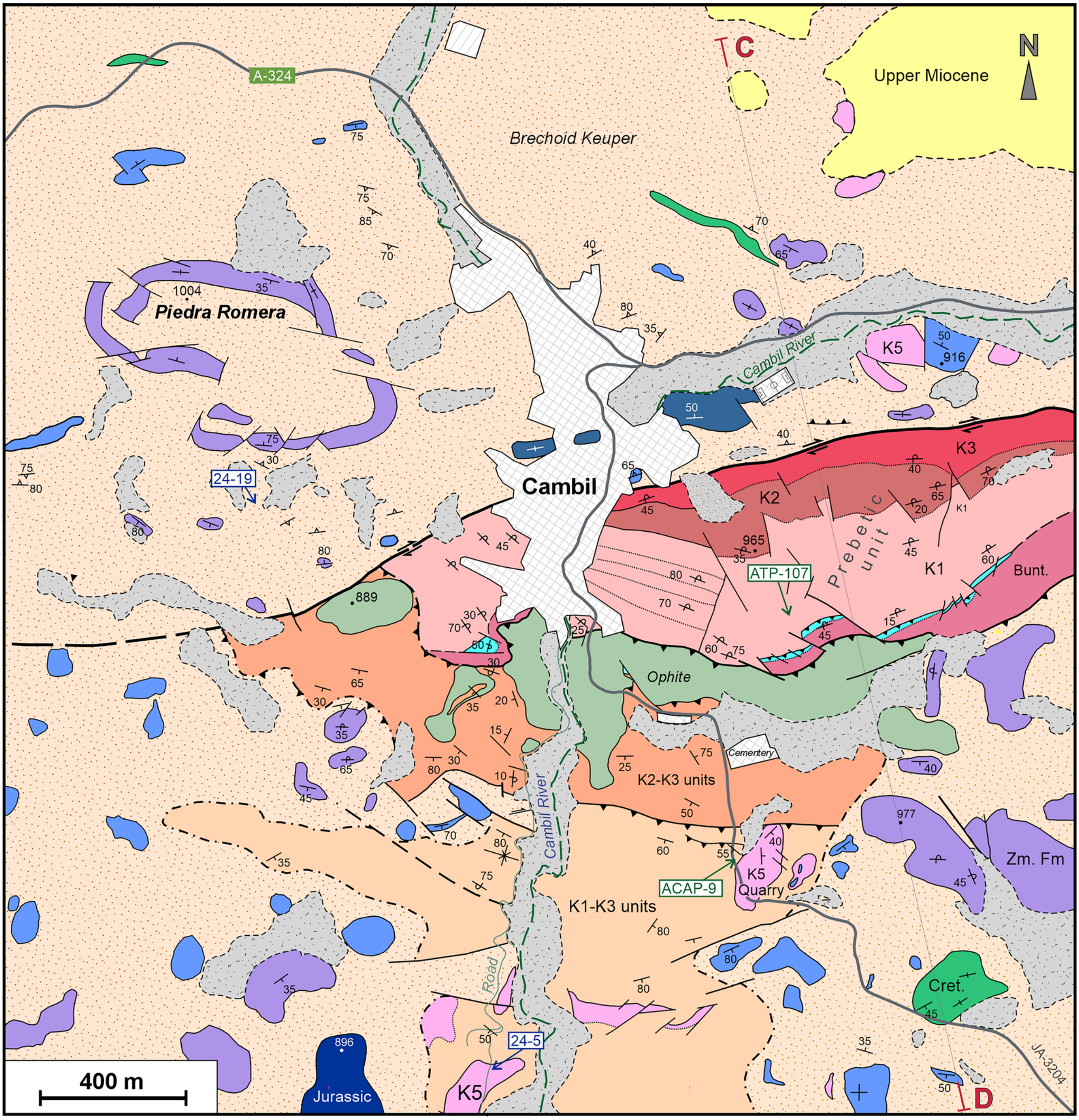

Fig. 7 Geological map of central Cambil Triassic (see location in Fig. 2, (**b**). Isotope samples are indicated in blue (24–5, 24–19) and pollen samples in green (ACAP-9, ATP-107). The geological cross-section C-D is indicated (see Fig. 8). Legend as in Fig. 6

the different Prebetic units: Siles Formation, K3–K2, and the Buntsandstein.

Non-Triassic materials are also present within the study zone. Specifically, four outcrops of Cretaceous limestones and marly limestones, and one outcrop of Jurassic carbonates, are identified as isolated blocks or packages enclosed within the Triassic formations (Figs. 6 and 7). Their lithological and structural characteristics are consistent with typical Subbetic units.

Both study areas display Miocene outcrops, although these are likewise affected by faulting: Serravallian-Tortonian deposits in the Cambil area, and Burdigalian-lower Langhian deposits near the Oasis Hotel (Roldán-García et al., 1992). In Cambil, an unconformity separates the Triassic materials from the overlying Miocene carbonates and

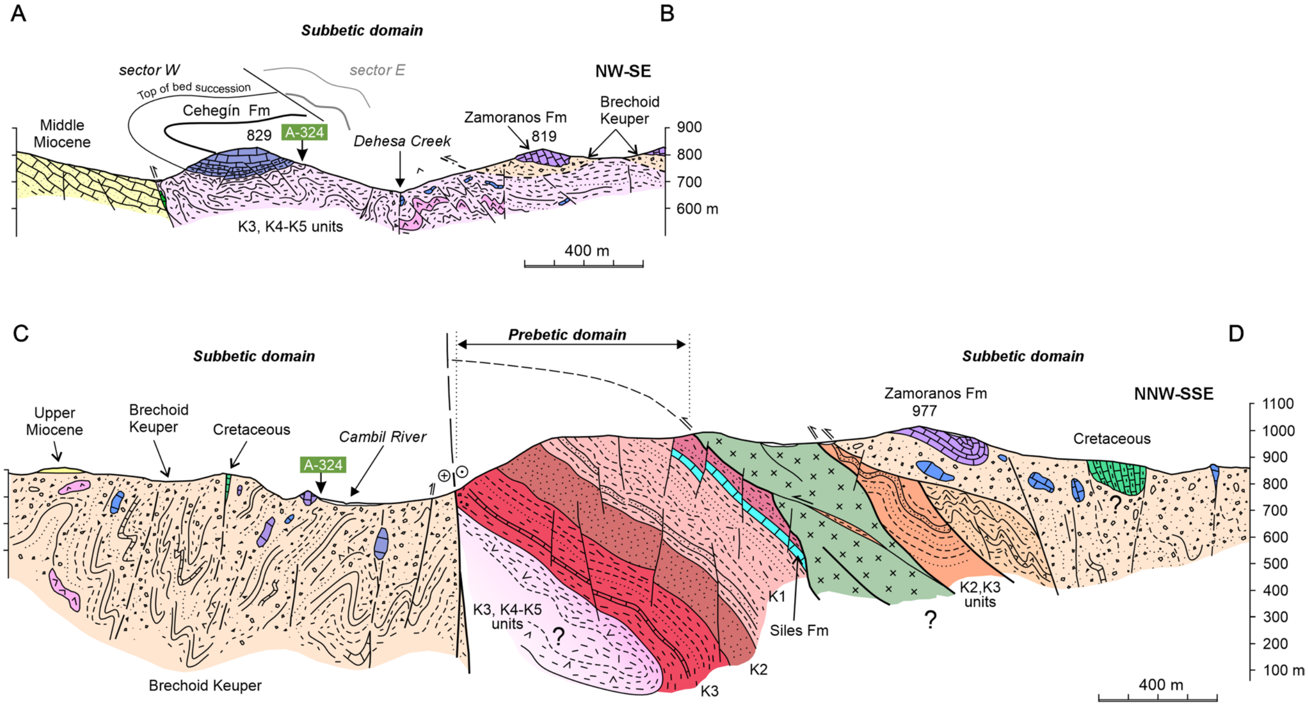

Fig. 8 Geological cross-sections of the Oasis Hotel (A-B) and Cambil (C-D) areas (Figs. 6 and 7). In both cross-sections, legend as in Fig. 6

marls (Figs. 7 and 8), whereas near the Oasis Hotel the Miocene deposits are in mechanical contact with the Triassic rocks (Figs. 6 and 8). In several localities to the north of this area, the Miocene beds dip towards the Triassic outcrops. In this area, the Burdigalian–Langhian Miocene deposits are older than those of the Upper Miocene in the Cambil area and show a geometry suggesting that the Triassic rocks were emplaced above them. Although the contact is largely covered and affected by some normal faults, the observed structural configuration indicates a possible reverse fault relationship between both units.

5.2 Age of detrital-evaporite units

Our identification of the carbonate units is based on stratigraphic and biostratigraphic criteria, lithofacies characteristics, fossil content, and microfacies (determined by means of the petrographic microscope). This allowed us to distinguish the Cehegín and Siles formations of Ladinian age as opposed to the Zamoranos Fm of Rhaetian age (Pérez-Valera & Pérez-López, 2008; Pérez-López et al., 2012; Pérez-Valera, 2016).

The differentiation of the detrital-evaporitic units is complicated by the fact that these lithofacies are present in both the Keuper and middle Muschelkalk successions (Fig. 4), in some cases being very similar (García-Ávila et al., 2024). In the present work, to ensure their attribution to the Keuper facies, the Sulfur and Oxygen isotopes of three gypsum samples ($\delta^{34}S$, $\delta^{18}O$) selected in the Cambil sector were analyzed (Fig. 7). Two of them (24–5 and 24–19) show respective $\delta^{34}S$ values of 15.3‰ and 14.4‰. They were obtained within the limits of the Cambil map (Fig. 7), in the "Piedra Romera" mountain and in the eastern sector adjacent to the K5 gypsum quarry. The third sample (24–6) corresponds to gypsum from the extreme southern sector of the Cambil map, with a $\delta^{34}S$ value of 17.3‰, much higher than the other two samples. Therefore, following Ortí et al., (2022, 2024), the whole evaporitic detritic outcrop around the "Piedra Romera" mountain can be assigned to the Keuper, as well as the gypsum outcrops to the south of the study area. However, the sample with higher values indicates that a middle Muschelkalk gypsiferous unit could crop out beyond the Cambil map area (125 m south of sample 24–5). Although no additional samples could be analyzed, the limited isotopic data provided support the assignment of the gypsums within the mapped area and illustrate the potential of these methods for this type of study, especially when absolute dating is not available.

In this same sector of Cambil we found a sample of lutite (ATP-107), in the red succession of the Prebetic, with an assemblage of pollen indicating a Ladinian-Carnian age: *Aratrisporites* cf. *major* Mädler, 1964, *Ovalipollis ovalis* (Krutzsch) Scheuring, 1970, *Duplicisporites granulatus* (Leschik) Scheuring, 1970, and *Duplicisporites scurrilis* Scheuring, 1970 (Pérez-López, 1993). Similarly, in a sample of lutite (ACAP-9) from this same area, east of the gypsum

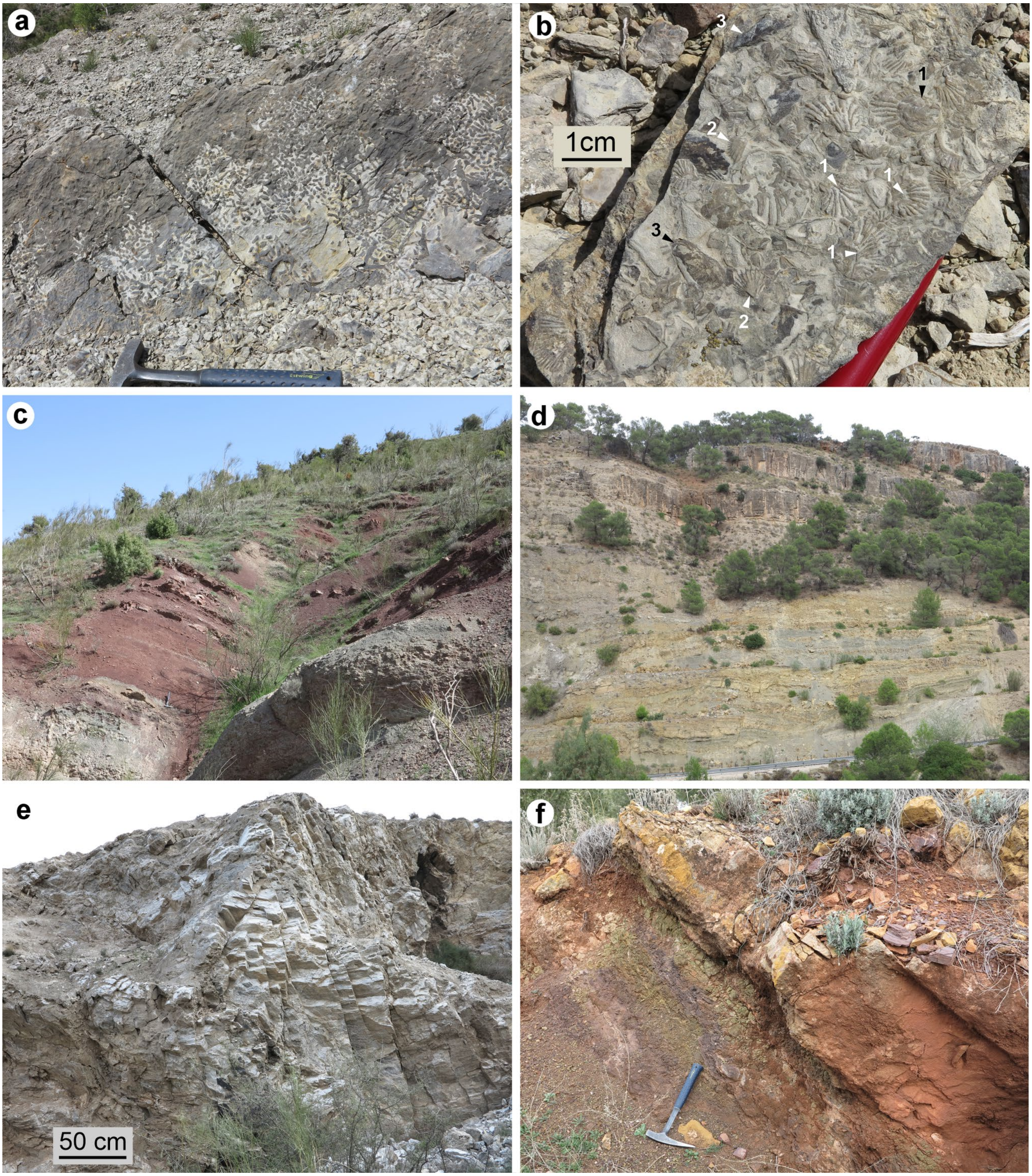

Fig. 9 Significant facies of the Cambil Triassic. **a** Typical bioturbation of the Siles Fm carbonate (Diplocaterion). **b** *Enantiostreon flabellum* (1), *Costatoria goldfussi* (2) and *Bakevellia costata* (3) of the marly limestones of the Siles Fm upper part **c** Outcrop of red lutites and sandstones (K1 unit) assigned to the Prebetic domain. **d** Overturned carbonate section of the Cehegín Fm. **e** Deformed gypsum of the Subbetic domain (K5 unit), very fractured (NW–SE). **f** Overturned section of Zamoranos Fm; note detrital deposits including volcanic pyroclasts

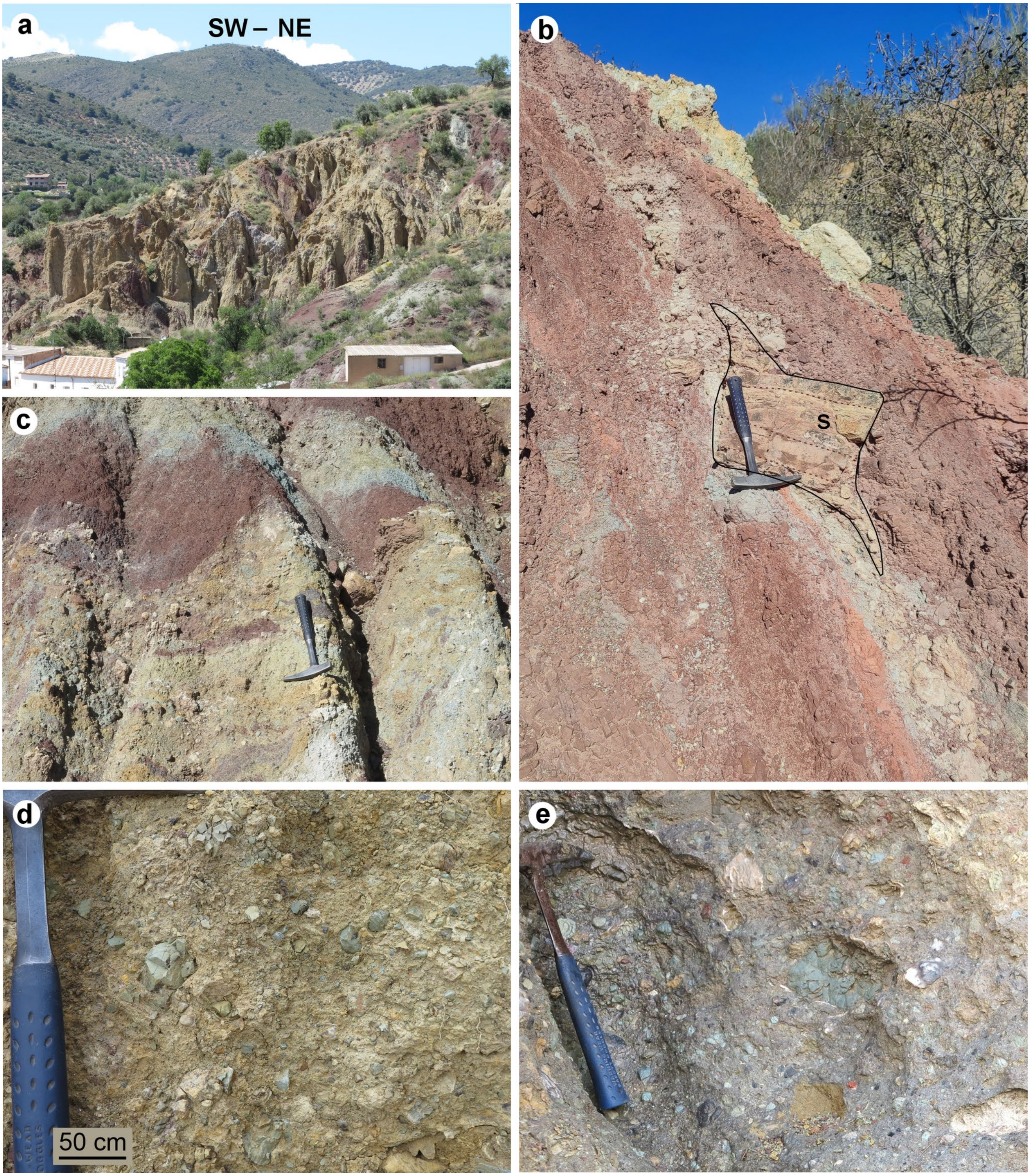

Fig. 10 Triassic brecchoid material. **a** Keuper facies outcrop (N Cambil) showing bedding successions and more or less brecciated bands. **b** Detail of Keuper detrital units with moderate deformation showing a subvertical fabric where more competent lithologies (s: sandstone) are stretching, brecciated and rotated in a more plastic clay-rich matrix (N of Cambil). **c-d** Detail of the brecciated Keuper facies with abundant clayey matrix (SW Cambil). **e** Brecciated Keuper facies with pebbles of different nature and gypsiferous matrix (NW Cambil)

quarry, an assemblage showed the presence of *Ovalipollis ova*lis (Krutzsch) Scheuring, 1970, *Duplicisporites granulatus* (Leschik) Scheuring, 1970, and *Praecirculina granifer* Klaus, 1960 (Pérez-López, 1991), which correspond to the Ladinian-Carnian age.

Just around the Oasis Hotel (Fig. 6) no data on the S isotope of the gypsum could be obtained, but in a trench of A-324 road, a sample of lutite (ATP-105) contained a pollen assemblage characteristic of the middle-upper Carnian, with the presence of *Patinasporites densus* Leschik, 1955 and *Partitisporites quadruplicis* (Scheuring) Van der Eem, 1983 (personal communications of N. Solé de Porta, 1993), for which reason it is attributed to the upper Keuper facies and not to the middle Muschelkalk. This finding is of great interest: the fact that this area features a large outcrop of the upper Muschelkalk (Cehegín Fm), with overturned stratification (Fig. 9d), serves to confirm that it is in contact with the Keuper units, not with the middle Muschelkalk. It likewise signals that the red shales and gypsum could correspond to the upper Keuper units (K3 to K5 units).

5.3 Structure features of Cambil's Triassic units

A most remarkable aspect of Cambil is the presence of Triassic units pertaining to two different paleogeographic domains, as described in Sect. 5.1. On the one hand, there is a stratigraphic succession resembling the more proximal successions of the South Iberian Paleomargin, related to the Prebetic Domain (Fig. 5). On the other hand, the remainder of the materials in the studied zone show affinities with successions that were initially deposited in more distal areas of the South Iberian Paleomargin, associated with the Subbetic Domain. Notwithstanding, both Triassic units are located in the same area, separated by mechanical contacts (see geological map in Fig. 7).

Detailed observations around the contacts between the two Triassic units reveal differences in structural style depending on the sector. The southern contact exhibits a band several hundred meters wide, oriented east–west, with an average southward dip of 30º. This structure corresponds to a thrust zone where Triassic units with Subbetic affinity lie structurally above the Prebetic Triassic succession (Fig. 8). These thrust faults cut through the materials of the Prebetic succession, including the Buntsandstein units as well as the Muschelkalk and Keuper, which were laterally transported afterwards by dextral strike-slip faults. This thrust is most likely responsible for the inversion of the Prebetic stratigraphic succession (Fig. 11a). Throughout the area, minor thrust structures are observed, with planes dipping southeast (approximately to N150E). Additionally, in the contact zone, a unit of strongly deformed subvolcanic rocks (ophites) is found, with frequent fault planes affecting the Prebetic units (Arroyo Molinos and Siles Formations, Fig. 7). Structurally above the ophites there are several meters of detrital breccias with carnioles and carbonate blocks (i.e., Zamoranos Fm). Small thrust structures are also present (Fig. 11b).

The northern contact exhibits a different structural style. This contact features a fault zone with a steep, almost vertical dip between the red clays of unit K3 of the Prebetic Triassic and a zone of clastic breccias with ochre carnioles (Fig. 11c). This zone is aligned east–west, and some discrete fault planes can be identified, although kinematic indicators (striate or slickenside) are scarce (Fig. 11d). When present, they are oblique, almost horizontal. To the north of this limit, most recognizable contacts within the Subbetic Triassic unit show subvertical dips, such as the blocks of the Cehegín Fm that crop out in the village of Cambil (Fig. 11e).

Another significant aspect of the Cambil Triassic is the widespread occurrence of large brecciated bodies, bands or beds. The vast extent of breccia facies, covering a substantial part of the study zone, is noteworthy (Figs. 6, 7). The breccias consist of clasts ranging from centimeters to decameters in size, of various lithologies (carbonates, lutites, gypsum, sandstones…), embedded in a marly-clay matrix (Fig. 10). Occasionally, the breccias are cemented by calcium carbonate or even calcium sulfate, giving them the appearance of gypsum breccias. No sedimentary structures, e.g. stratification or internal arrangement, are observed. A detailed examination of the detrital breccias reveals that many are fractured clayey-sandy formations, showing multiple fracture planes, the sandstone beds being entirely fractured and brecciated within a matrix comprising the lutite beds. In these cases, a rough but visible subvertical banding is generated, with an overall east–west orientation.

The megablocks (carbonates and gypsum) within this breccia complex mostly show steep or inverted dips, having elongation consistent with the E-W banding observed in the breccia matrix (Fig. 11f). Still, there are examples −such as the extensive outcrop of the Cehegín Fm east of Oasis Hotel (Fig. 6), entirely overturned− that present subhorizontal beds whose tops face downward.

Lastly, minor structures affecting all units are found throughout the area, involving even Plio-Quaternary alluvial deposits. They include high-angle reverse faults with steep striations. The average strike is east–west, dipping both to the north and south. Displacements range from centimeters to meters, and some may be considered out-of-sequence, disturbing the thrust plane (Fig. 11b). Small folds with east–west axes and broad radii are also observed, affecting the brecciated units.

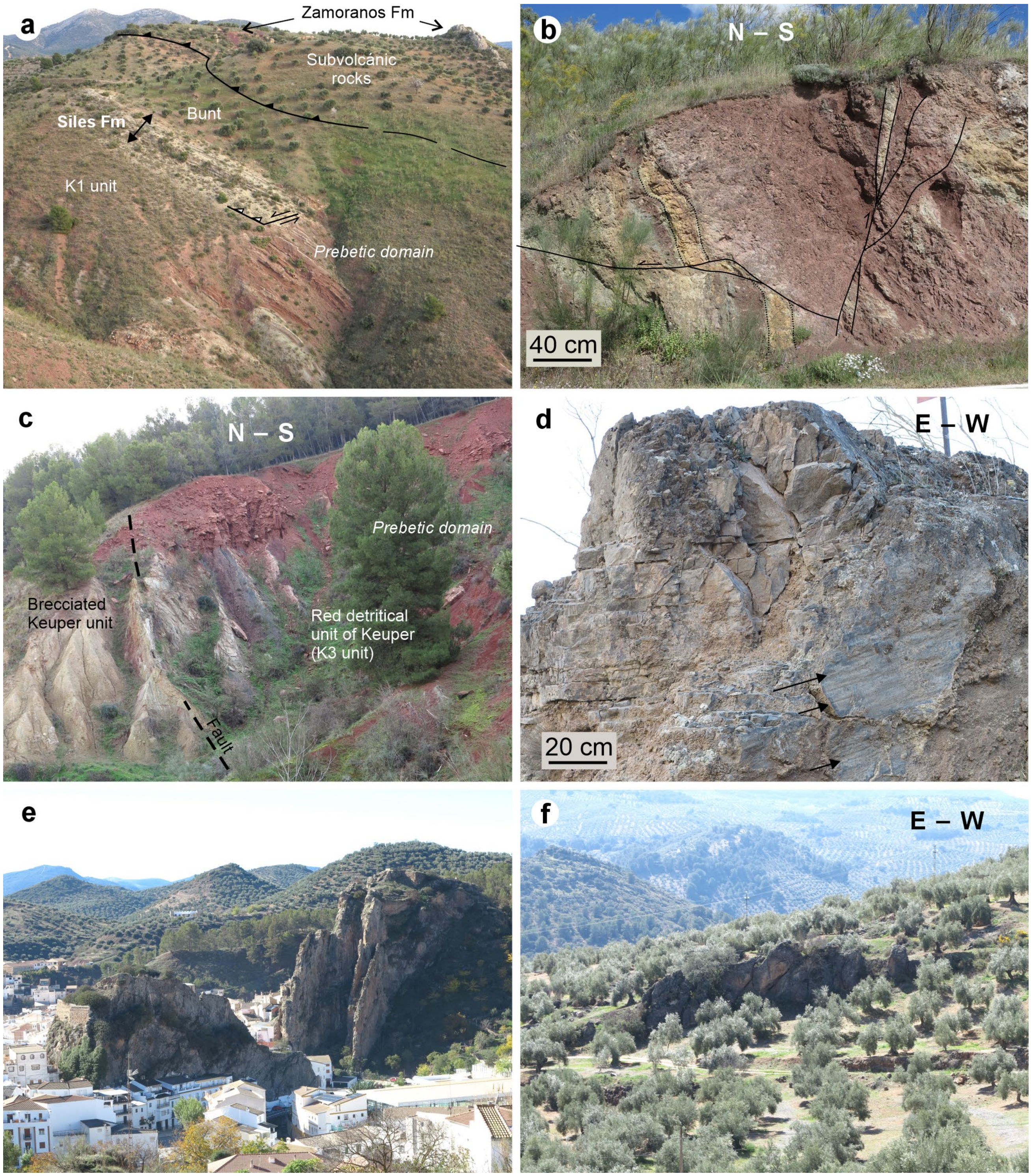

Fig. 11 Significant features for tectonics. **a** Field view of the Triassic Prebetic sequence in the southeast of Cambil formed by an overturned succession of the Siles Fm with Keuper and Buntsandstein facies, revealing that the Siles Fm carbonate beds moved northward along a subhorizontal fault, overlapping the Keuper facies below. **b** In the Cambil-Arbuniel road cuts, a small thrust is visible affecting K2-K3 detrital succession near the main thrust of Subbetic unit over Prebetic units. Also, near vertical reverse faults cut the low angle thrust in an opposite vergence. **c** Panoramic view to the east of Cambil, showing the contact between the brecciated Keuper facies unit of the Subbetic domain and the red detrital Keuper unit of the Prebetic domain by means of a subvertical fault. **d** Strike-slip fault plane where slickenline lineations (080/30º) around the relative displacement can be seen (SW of Cambil). **e** Vertical carbonate beds of the Cehegín Fm cropping out among the houses in Cambil, more or less parallel to the strike-slip fault found east of the village (Fig. 9a). **f** Carbonate block, with south-dipping beds, which is bounded by faults that orient the block from E to W

6 Interpretation and discussion

Based on our study of the stratigraphy and structural features of the Cambil Triassic, two units with distinct stratigraphic characteristics stand out. Their paleogeographic origins can be interpreted through comparison with other sectors of the Betic Cordillera. The so-called "Prebetic Triassic" crops out extensively in the Cazorla-Alcaraz Arc (CAA) sector (Fig. 1), between the towns of Hornos and Siles (Jaén), extending to the Alcaraz area (Albacete). The southernmost outcrops of these materials are found at the southern end of the CAA, in the Pozo Alcón area (Pérez-Valera et al., 2006) and in the Guadiana Menor corridor (Huesa section: Pérez-Valera, 2005; Rodríguez-Tovar & Pérez-Valera, 2008; Rodríguez-Tovar et al., 2007), while the Cambil outcrop described in this work represents the first record of the "Prebetic Triassic" outside the CAA domain. Conversely, the surrounding materials display all the characteristics of the Subbetic units, which are widely exposed from the province of Alicante to the province of Sevilla (Pérez-López & Pérez-Valera, 2007; Pérez-Valera & Pérez-López, 2008).

Considering the above, the Cambil Triassic presents two Triassic units which —in a cross-section of the eastern Betic Cordillera, from Alcaraz (Albacete) to Cehegín (Murcia)— would be separated by at least 80 to 100 km, the distance remaining after tectonic shortening (see Fig. 1 for location). Together with the characteristics of the contact between the two units, this suggests major tectonic displacements, likely due to thrust systems (nappes) and/or strike-slip zones that transported the units from east to west. A similar situation has been described in the Pozo Alcón sector (southern end of the CAA), where two units of different paleogeographic affinities coexist (Pérez-Valera et al., 2006). In this case of Pozo Alcón sector, the contact between the two units is considered to correspond to a strike-slip zone. However, the nature of the contact in Cambil appears more complex. The steeply dipping northern contact is better explained by a broad E-W shear zone, while the southern contact shows a significant thrust of the Subbetic Triassic over the Prebetic Triassic. Field relationship suggests that the north strike-slip shear zone affect to the thrust (Figs. 7, 8). This lateral displacement may have transported Prebetic units from the Cazorla sector, located more than 50 km east of Cambil. Nevertheless, this shear phase may also have had a transpressive character, ultimately resulting in NE-directed tectonic transport in the southernmost units of the Cambil sector. The presence of evaporitic levels, particularly those composed of anhydrite and halite, has played a key role in the tectonic behavior of these structural units, acting as ductile detachment horizons. This tectonic influence of salt has favored the development of complex structures and the formation of brecciated units, reflecting plastic flow processes during the evolution of the orogen.

North of the study zone, along the boundary between the mountain front of the Sierras de Jaén and the Guadalquivir foreland basin, Pérez-Valera et al. (2017) describe similar structures as thrust and dextral strike-slip shear zones. Here, the Subbetic units overlap the Prebetic ones towards the west-northwest, along the southern part of the Cazorla-Alcaraz Arc, through the Betic Floor Thrust (Guezou et al., 1991), while dextral shear zones (Collejares Fault zone) transfer the deformation towards a transpressive accretionary complex at the southern margin of the Guadalquivir Basin. The conjunction of overlapping plus strike-slip displacements would result in blocks of Prebetic units (Sierras de Bedmar, Pegalajar, Aznatín, Castillo de Jaén) being disconnected from their main Prebetic domain, leading to the complex juxtaposition of Prebetic and Subbetic domains.

Another question to address is the origin of the brecciated facies surrounding the Prebetic Triassic of Cambil, whose megablocks have Subbetic affinities. The extensive clayey detrital outcrops with angular clasts of different compositions, showing gradation in the degree of brecciation, can be interpreted as deformed units in a plastic-brittle context due to salt-induced and tectonic causes. These deformations result in complex fault rock fabrics that can be encompassed as cataclasites sensu lato (Marshak & Mitra, 1988). Locally, these units exhibit banded development with varying degrees of deformation, ranging from completely brecciated zones to areas of deformed but intact beds (Fig. 10). They could be the result of heterogeneous stretching of different parts of a clay-rich detrital succession, giving rise to the formation of banded cataclasites. In many sectors, these brecciated materials contain decametric blocks of carbonates, gypsum, or sandstones, interpreted as more competent materials that are fractured and embedded in the finer-grained clayey materials, or even in a gypsum matrix, tectonized within a broad fault zone. The presence of subvertical faults that separate different lithological bodies within the brecciated materials, where rocks of various ages are mixed, further supports their tectonic origin (Fig. 11a, c). Additionally, no sedimentary structures or clast arrangements suggestive of sedimentary or redepositional processes were observed. The clayey matrix of the breccias, when washed and sieved, yielded no microfaunal evidence of marine deposition.

Triassic brecciated units similar to those described in the Cambil Triassic have been studied at many other locations in the Betic Cordillera, and interpreted as having a tectonic origin. These units are linked to major tectonic features, such as strike-slip fault zones, e.g. the Socovos Fault and the Tíscar and Collejares Faults (Pérez-Valera et al., 2022), or complex tectonic scenarios such as the Antequera area ("Triassic of Antequera," Sanz de Galdeano, 2008) or even smaller structures of this type (Pérez-Valera et al., 2011). They also appear in the thrust structures of the Guadalquivir units, forming accretionary frontal systems (Pérez-Valera et al., 2017). A diapiric origin —salt migration and deformation— can likewise generate brecciated units, mainly gypsiferous breccias as observed in diapirs in the eastern Prebetic (Jumilla or Pinoso), where units are considered parautochthonous and tectonic displacements are limited (Rondeel and van der Haag, 1986; de Ruig, 1995). However, in the above setting diapiric cartographic features are missing; and the orientation of the main structures (thrust and strike-slip faults), following the regional grain, suggests that any diapiric fabrics, if they existed, were obliterated.

Although the role of salt tectonics in the evolution of the passive stage of the South Iberian Paleomargin is widely accepted (Escosa et al., 2018; Martínez del Olmo et al., 2015; Pérez-Valera et al., 2017), other studies have proposed deformation mechanisms and salt tectonic processes in the External Zone of the Betic Cordillera (Flinch & Soto, 2022; Pedrera et al., 2020; Pérez-López & Pérez-Valera, 2003), following tectonic inversion. However, the detailed study of the Triassic lithostratigraphic units and their paleogeographic affinity, as well as the origin of the salts, may be the key to understand these outcrops of Triassic materials, which are not going to be the direct result of saline tectonic processes. In the case of the Triassic units in Cambil, salt tectonics alone cannot account for the existence of two units that are separated by over 100 km from their original position. Even the emplacement of allochthonous salt sheets on present-day margins cannot explain the mixing of Triassic units, as described in this work, due to the smaller size of the salt sheets (e.g. Dooley et al., 2012) and the absence of significant Triassic salt deposits in the Prebetic Domain (Pérez-Valera, 2005) (see Fig. 5). This would make very difficult their migration to deeper and more distal areas of the basin, such as the Subbetic domain, as suggested the emplacement of allochthonous salt sheets (Hudec & Jackson, 2006).

Regarding the age of the structures, calcarenites and marls of Burdigalian-Lower Langhian age were affected by the emplacement of Triassic materials, as observed in the Oasis Hotel area (Fig. 6). The Triassic rocks could have displaced and overlain the middle Miocene materials during their emplacement, although these contacts are not currently visible (covered by debris). In contrast, in the Cambil area, Serravallian-Tortonian materials were deposited on top the already-emplaced Triassic rocks, later affected by minor structures (Fig. 7).

Finally, the minor structures present throughout the region, e.g. the high-angle east–west trending reverse faults and small-scale folds, are likely the result of a final stage of compression in a general north–south direction (Galindo-Zaldívar et al., 1993; Ruiz-Constán et al., 2011). These compressional features even affect Pleistocene deposits, indicating recent tectonic activity, which may have further masked the structural complexity of the region.

7 Conclusions

A combined structural and stratigraphic analysis of the various units cropping out in the External Zone of the Betic Cordillera, including the apparently chaotic Triassic materials, provides insights into the structural and tectonic origins of many regional outcrops. The identification of distinctive lithostratigraphic units —from two different paleogeographic contexts— leads us to interpret the Triassic of Cambil as a chapter of a highly deformed tectonic complex, where thrusting and strike-slip fault zone deformation would explain the juxtaposition of two Triassic sets, one hundred km apart in origin. Consequently, many of the breccias present in the Triassic materials can be interpreted as true tectonic cataclasites. The banded fabric observed can be explained as the result of dragging and stretching of the original Mesozoic beds during their displacement along the main faults, while only salt tectonics processes cannot explain this largely allochthonous Triassic units emplacement.

Additionally, many of the supposedly olistostromic units of the Miocene in the Betic Cordillera, previously interpreted in outcrops containing abundant Triassic brecciated materials, could in fact result from dynamics similar to those observed by the town of Cambil. These processes, related to fault zones, could give rise to various types of tectonic breccias and cataclasites, although salt tectonics processes in the passive margin stage may have contributed to the development of clay and evaporite-rich brecciated material. Therefore, many outcrops within the Betic Cordillera, previously categorized under the so-called chaotic Subbetic complex, should be revisited and studied in detail, with particular attention to the orientation of fabrics and minor structures if major contacts are not evident. At any rate, such units should not be immediately attributed to olistostromic processes unless clear evidence of material re-sedimentation is found, yet it may have occurred during the tectonic evolution of the Betic Cordillera.

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Data availability All data generated or analyzed during this study are included in the manuscript. There are no additional data available elsewhere.

Declarations

Conflict of interest There are no direct or indirect conflicts of interest between the authors and the work being submitted for publication in the journal.

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