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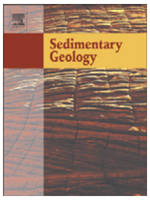

Record of epicontinental platform evolution and volcanic activity during a major rifting phase: The Late Triassic Zamoranos Formation (Betic Cordillera, S Spain)

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ABSTRACT

The study of the Late Triassic Zamoranos Formation and the comparison to coeval carbonate units provides new insights into the evolution and palaeogeography of carbonate platforms during major rifting phases in the Earth's history. The platform carbonates of the Zamoranos Formation record the last major transgression during the Triassic, and document the initial phase of the CAMP volcanism in the external Zone of the Betic Cordillera. New palynological data from the lower part of the Zamoranos Formation indicate a Middle Norian age. The entire succession is built up by limestones, dolomites, and ferruginous red detrital deposits with volcaniclastic breccias. The carbonates are interpreted as tidal and shallow marine sediments, deposited under arid conditions. The red detrital deposits appear in coastal environments in relation to a volcanic event, which triggered hydrothermal processes in these deposits and started the massive magmatic event associated with the Central Atlantic Magmatic Province (CAMP). The Zamoranos Formation was also recognized in the SW part of the Valencia Triassic and is correlated to the Imón Formation (Iberian Ranges), to the Isábena Formation (Pyrenees) and to other carbonate units of the W Tethys realm (Aquitaine, Tunisian Atlas, West Carpathians). These units indicate that an extensive epicontinental platform developed during the Late Triassic.

1. Introduction

The present study focuses on key sections of the Norian Zamoranos Formation located in the south and south-eastern of the Iberian Peninsula (Betic Cordillera, Spain), between the cities of Cádiz and Alicante. This study contributes to the understanding of the spatio-temporal carbonate-platform evolution and the Late Triassic palaeogeography of Western Europe. Correlation to coeval epicontinental carbonate units of the Alpine facies in the Betic Cordillera (Delgado et al., 1981; Delgado et al., 2004) and in the Northern Calcareous Alps (e.g., Fruth and Scherreiks, 1982; Reijmer and Everaars, 1991; Vörös, 2000) remains difficult. However, the inner platform deposits of the Zamoranos Formation document the evolution of an extensive platform setting during Norian times and may serve as an example to interpret and understand similar settings that record major rifting phases.

The classical Germanic Triassic units Buntsandstein, Muschelkalk, and Keuper were recognized in the Betic External Zone at the end of the 19th century (Bertrand and Kilian, 1989). Many authors described the Triassic rocks of the Betic Cordillera, comparing them to the Germanic facies (e.g., Blumenthal, 1927; Schmidt, 1935; Fonboté, 1964; Hirsch, 1972; Busnardo, 1975). However, an upper carbonate unit was later identified above the Keuper units in the External Zone of the Betic Cordillera. This carbonate unit has been defined as the Zamoranos Formation of Norian age (Pérez-López et al., 1992). The correlation with carbonate units of epicontinental platforms of the Iberian Peninsula and the Germanic realm of Central Europe has been attempted in previous studies (Goy and Yébenes, 1977; Pérez-López et al., 1992; López-Gómez et al., 1998; Arnal et al., 2002; Pérez-López and Pérez-Valera, 2007).

The detailed study of the Zamoranos Formation is crucial to understand the Late Triassic platform evolution, which is a recent matter of debate (Hesselbo et al., 2007). The main knowledge of Norian carbonates in the Tethys realm s.l. derives from studies on carbonates of Alpine facies (e.g. Fruth and Scherreiks, 1982; Haas, 2002; Marzoli et al., 2004; Berra et al., 2010). Thus, the study of the Zamoranos Formation provides new data on climate, eustatism, and tectonics in a

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marginal setting, documenting the major transgression during the Norian. Furthermore, volcanic rocks of the Zamoranos Formation document the volcanic activity during this transgression phase at the end of the Norian.

The present paper aims to characterize the different members of the Zamoranos Formation to studying the evolution of the sedimentary environments in order to understand the origin of the volcanogenic rocks. Finally, the results identify the controlling factors of the platform evolution and contribute to the discussion on global events during Norian times.

2. Geological setting

The Betic Cordillera is formed by two large geological zones: the External Zone and the Internal Zone (Fig. 1). During Alpine orogeny, today's sediments covering the External Zones were part of the southern margin of the Iberian Plate (Fig. 2). This margin was subdivided into various palaeogeographical domains, today constituting two main tectonic zones (Vera, 2001; Vera and Martín-Algarra, 2004): the Subbetic Zone and the Prebetic Zone. The Prebetic, palaeogeographically closer to the Variscan massif, displays mainly marine sediments shallower than the Subbetic. In both domains, five units have been assigned to the Keuper (Pérez-López, 1991, 1998), corresponding to the formations defined by Ortí (1973, 1974) in the Valencia region (E Spain), and two formations to the Muschelkalk (Pérez-Valera, 2005; Pérez-Valera and Pérez-López, 2008). The Norian Zamoranos Formation overlies these Triassic units (Fig. 3). Due to diapirism and the alpine deformation (Fig. 4), its today's position between shale and evaporite beds (K5 unit and Anhydrite Zone of Ortí, 1987) resulted distinct blocks of decametre size (20–60 m) limited by tectonic contacts (Fig. 5). In the External Zones, Upper Triassic units form part of a thrust–fault zone (e.g., Azañón et al., 2002). This deformation history is documented in outcrops, a megabreccia of gypsum and lutite with intercalated carbonate blocks of the Zamoranos Formation.

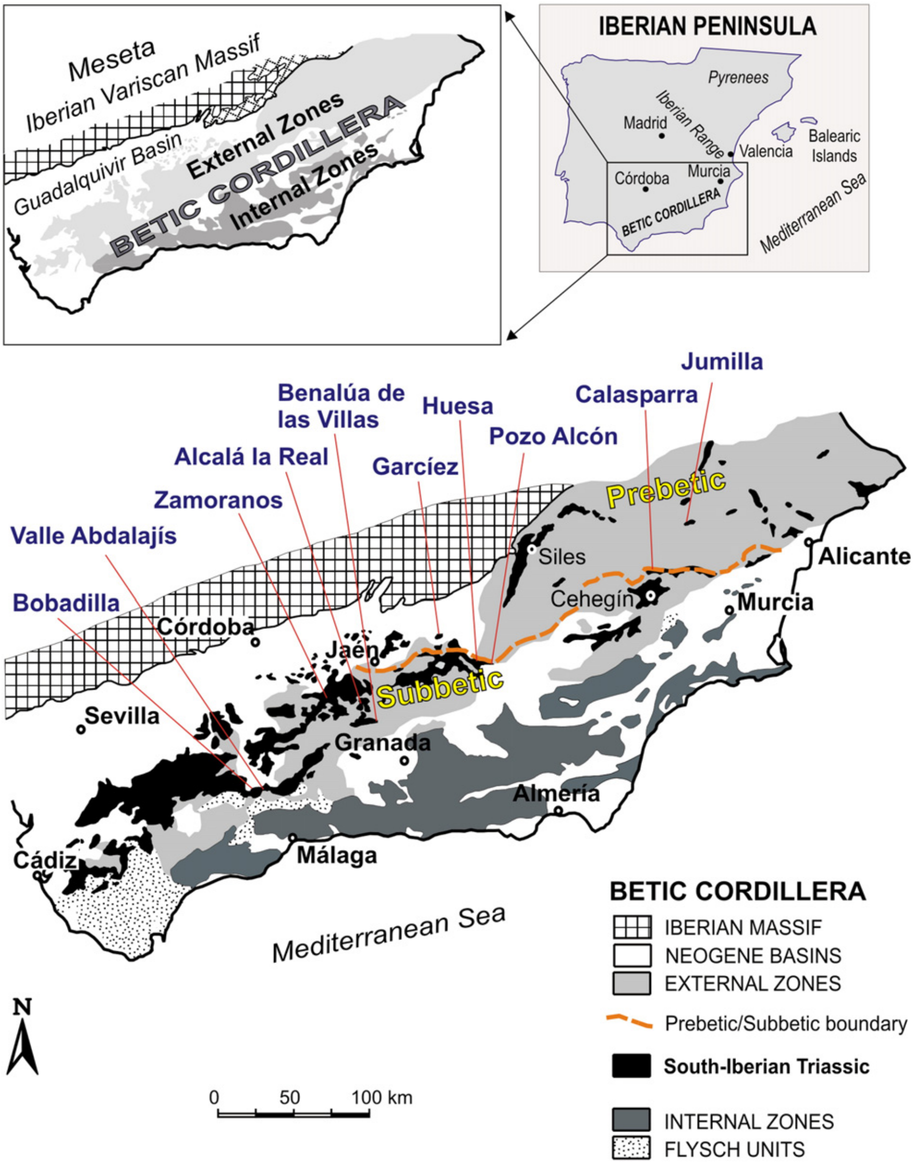

Fig. 1. Geological map showing the different tectonic units in the Betic Cordillera (S Spain). The South-Iberian Triassic outcrops expose sedimentary rocks of the Southern Iberian Palaeomargin (see Fig. 2) and are composed of disrupted sections of Buntsandstein, Keuper, and Muschelkalk facies. Location of the studied sections exposing the Zamoranos Formation is indicated (modified from Pérez-Valera and Pérez-López, 2008).

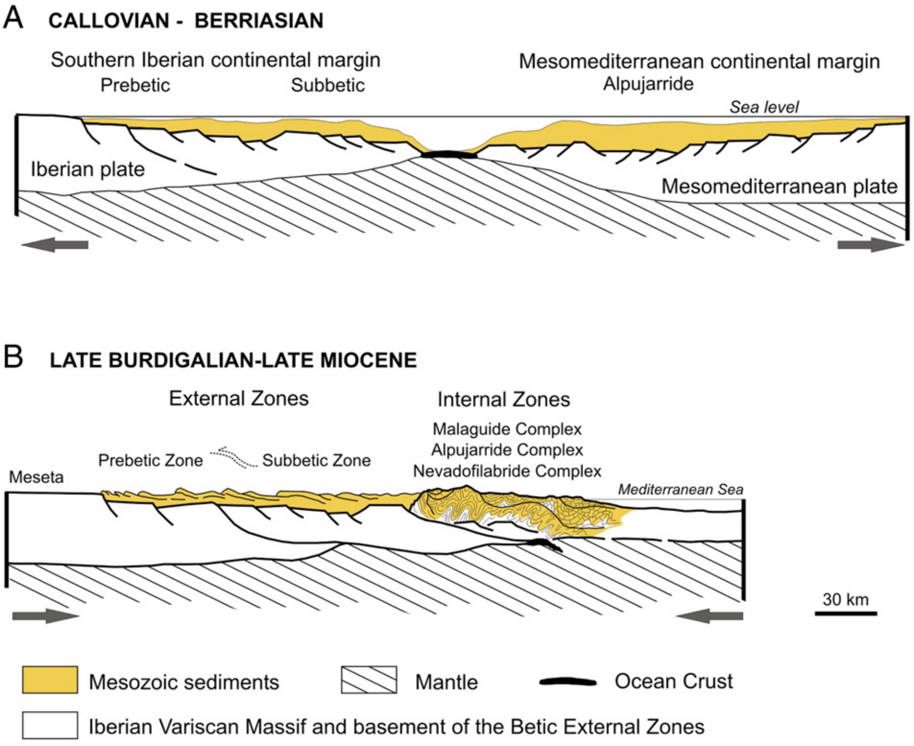

Fig. 2. Geotectonic setting of the different palaeogeographic domains in the Betic Cordillera. A) Development of the southern Iberian continental palaeomargin during the Jurassic–Cretaceous. B) Tectonic units of the Betic Cordillera after the alpine orogeny.
Figure from Pérez-Valera and Pérez-López (2008) and Vera (2001).

The Internal Zones, which extend across the southernmost part of the Betic Cordillera, represent the most intensely deformed region of the cordillera, frequently showing metamorphism. They comprise a complex of imbricated units, usually called Frontal Units, and numerous units that have been classified as three large tectonic complexes (Sanz de Galdeano, 1997; Vera, 2004,). From bottom to top, these complexes are: the Nevado–Filabride Complex, the Alpujarride Complex, and the Malaguide Complex. Triassic rocks of these complexes are composed of thick units of unclear stratigraphic position (Pérez-López and Pérez-Valera, 2007).

In the Betic Cordillera, well-exposed outcrops of Triassic–Jurassic successions have not been found due to tectonics and, in general, the fossil record of the Triassic rocks in the Iberian Peninsula is quite poor with generally bad fossil preservation (Márquez-Aliaga, 1985). Thus, the lack of an unequivocal age determination of the Zamoranos Formation has led to the correlation to Muschelkalk deposits in the past (Busnardo, 1975; López Chicano and Fernández, 1988). The definition of this formation is based on age determinations made some years ago (Pérez-López, 1991; Pérez-López et al., 1992). First palynological studies on the Zamoranos Formation (Pérez-López et al., 1992) suggested a Norian age on the basis of the presence of *Classopollis* sp. and *Granuloperculatipollis rudis*. This age was supported by findings of age-diagnostic Middle Norian to Late Norian foraminifera (*Earlandia tintinniformis* and *Glomospira* cf. *sinensis*) and coprolite assemblages (*Parafavreina thoronetensis* and *Palaxius salataensis*). Late Triassic bivalves such as *Chlamys* cf. *valoniensis* have also been found. New palynological data from the Calasparra and Alcalá la Real sections confirm a Middle Norian age, identified by a palynomorph association of *Corollina* spp., *Chasmatosporites* spp., *Ovalipollis* sp., *Granuloperculatipollis rudis*, and *Perinopollenites elatoides*. The dating of these carbonates, well exposed in the Jumilla section (N Murcia), is crucial to resolve its stratigraphic position.

3. Materials and methods

The present study focuses on the most representative stratigraphic sections of the Zamoranos Formation (Fig. 1): Bobadilla, Valle de Abdalajís in Málaga province; Zamoranos, Alcalá la Real and Benalúa de las Villas in Granada province; Huesa and Pozo Alcón in Jaén province; Calasparra and Jumilla in Murcia province. More than 20 outcrops were examined and 10 stratigraphic sections were selected for detailed analysis of their lithology, sedimentary structures, biofacies, and microfacies .

More than 120 thin sections of carbonates, 28 of conglomerates and 18 of volcanic rocks were examined. Alizarin Red S was used to stain the thin sections and to distinguish calcite from dolomite. The dolomite microfacies were studied with a light diffuser (Delgado, 1977) to identify different grain types.

Five samples from different shale units were studied with respect to the sedimentary organic-matter content and age-diagnostic palynomorphs. These samples were taken from the few unweathered lutite beds recognized in the Calasparra, Alcalá la Real and Garcíez sections. All samples were prepared using standard palynological processing techniques, including HCl (33%) and HF (73%) treatment for the dissolution of carbonates and silicates, and saturated $ZnCl_2$ solution ($D \approx 2.2$ g/ml) for density separation. Residues were sieved at 15-μm mesh size. Slides were mounted in Eukitt, a commercial resin-based mounting medium.

Finally, clay and mineralized sediments were studied by X-ray technique using X-Powder software (Martin, 2004) to determine the mineralogy and quantitative composition of these specific sediments.

4. Stratigraphy, facies and depositional environments

The Zamoranos Formation consists of limestones and dolomites with a red detrital intercalation characterized by its iron mineralization

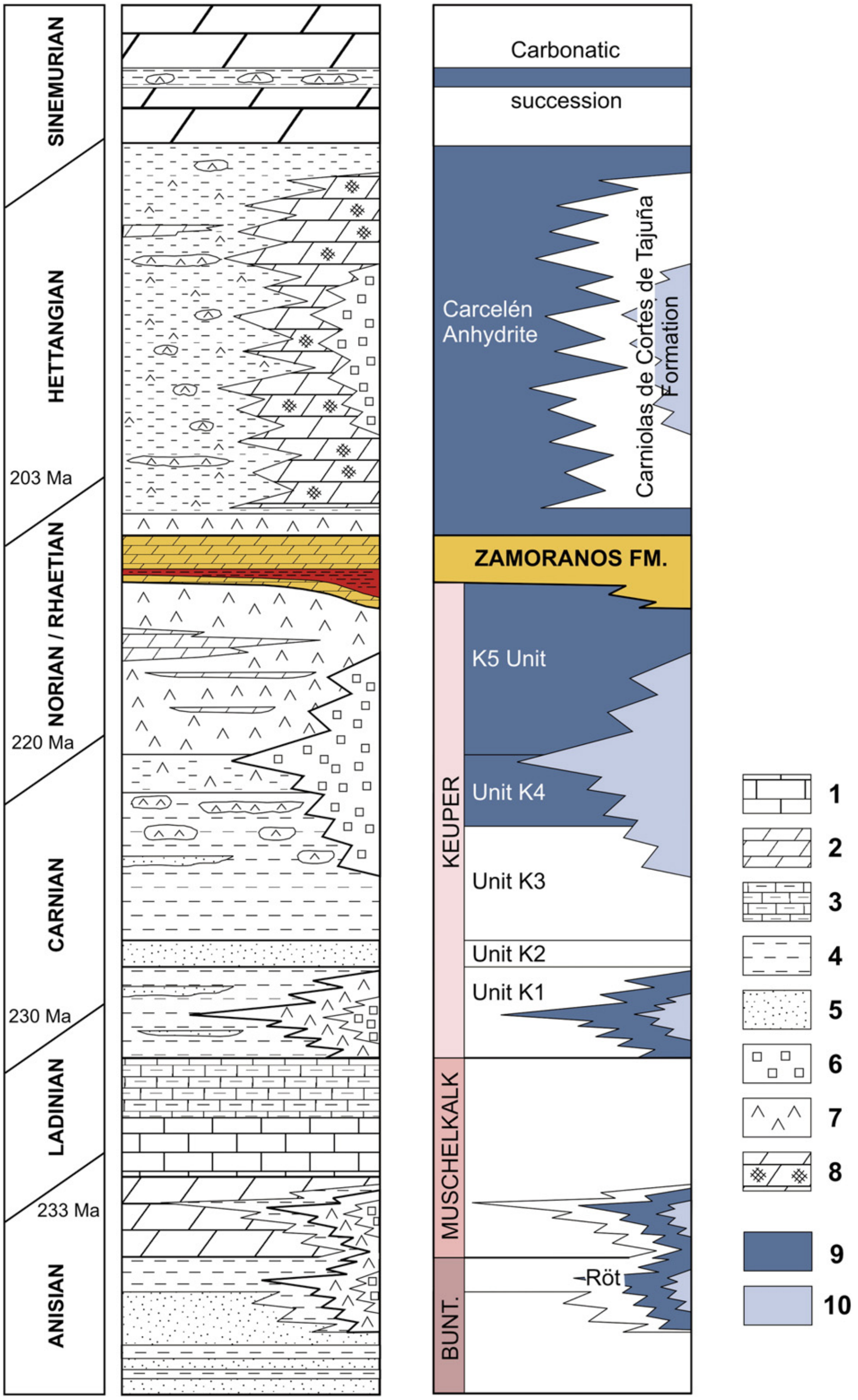

Fig. 3. Stratigraphy of the Triassic–Jurassic transition in the Betic External Zones and in the SW Valencia region (modified from Pérez-López et al., 1996). Legend: 1: Limestone; 2: Dolomite; 3: Marly limestone and marl; 4: Lutite; 5: Sandstone; 6: Halite; 7: Gypsum; 8: Carniolar carbonate; 9: Evaporitic units; 10: Salt deposits known from boreholes and associated with different evaporite units (Ortí, 1990). The Carcelén Anhydrite unit (Ortí, 1987) corresponds to the Carniolar Cortes de Tajuña Formation in the Iberian Range (Morillo-Velarde and Meléndez-Hevia, 1979; Ortí, 1990). Without scale.

that was exploited in the past (Fig. 6). Generally, the dolomite beds occur in the upper part of the stratigraphic succession, although in some outcrops the entire succession consists of dolomites. The thickness of this formation is between 20 m and 65 m.

In most outcrops of the Zamonaros Formation, three members of very different thicknesses can be distinguished (Figs. 6 and 7): (1) the Carniolar Limestone Member, (2) the Ferruginous Detrital Member, and (3) the Limestone and Laminated Dolomite Member. The facies and depositional environment of these members are summarized in Table 1.

The base of the carniolar member is a tectonic contact and locally this member overlies gypsum and red clay of the Keuper

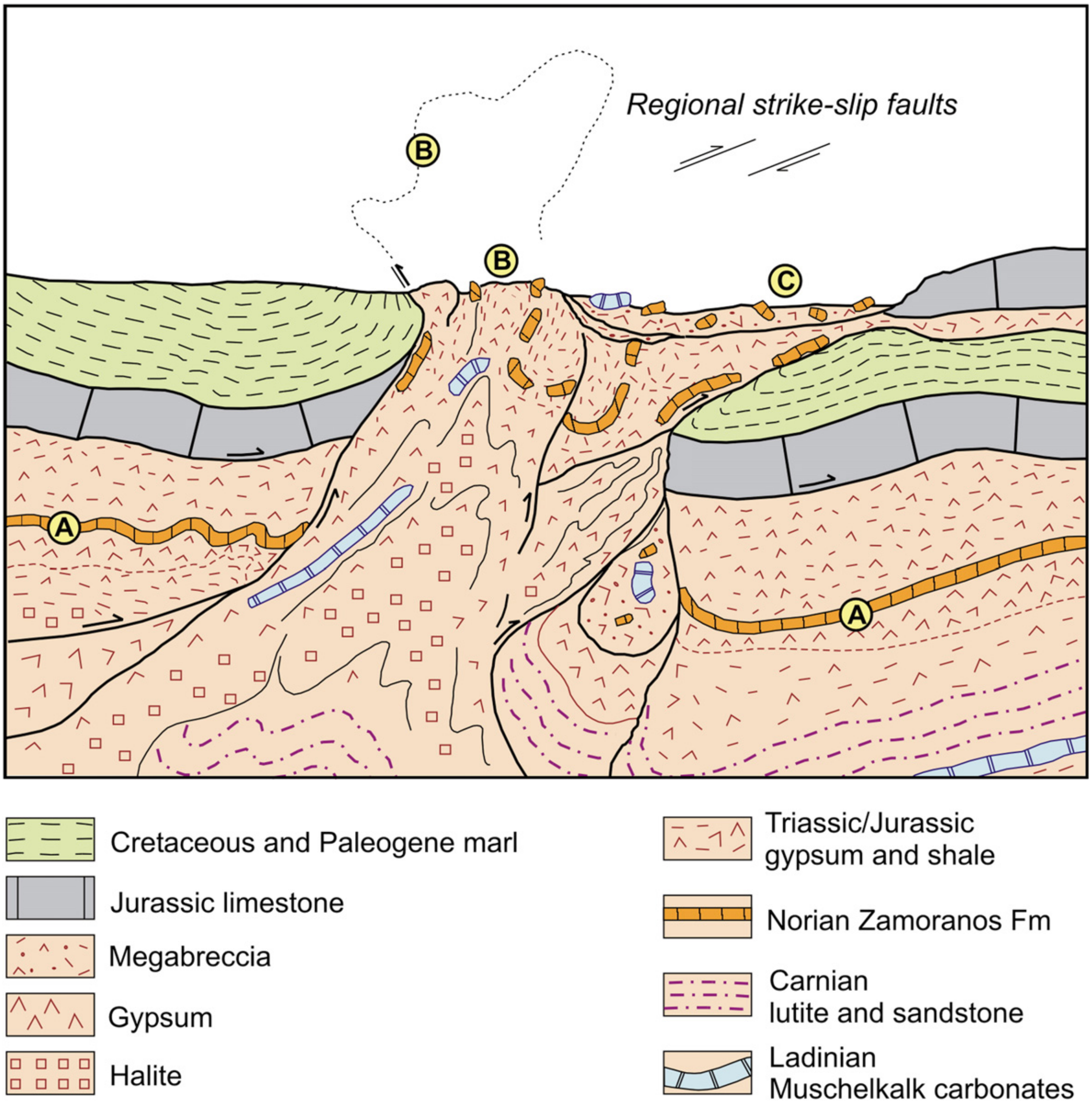

Fig. 4. Sketch showing the tectonic setting of the Zamoranos Formation exposed in outcrops. (A) Original stratigraphic position. (B) The carbonate beds are broken due to tectonics and diapirism and show strong boudinage in the Upper Triassic/Jurassic units. (C) Blocks of the Zamoranos Formation belong to a megabreccia, interpreted as a cap-rock or reworked deposits. The origin of halite is shown in the Fig. 3.

facies. The upper boundary is distinct and in some cases marked by an irregular surface due to dissolution (Palaeokarst). Laminated carbonates with vugs (Flügel, 2004) are interpreted as tidal deposits (Fig. 8A, B). In places, these carbonates are bioclastic or oolitic, documenting a very shallow marine environment, which emerged and underwent karstification before the deposition of the next member.

The Ferruginous Detrital Member is the most typical of the Zamoranos Formation due to its red color and to its siliciclastic nature (Fig. 8A). The lithological succession is highly variable in different outcrops, but consists mainly of lutite though locally of sandstone with cross-lamination interpreted as fluvial deposit. Thin gypsum and oolite carbonate beds are rare but sedimentologically significant (Fig. 8C) because they indicate the marine influence in this member deposition. Iron oxide mineralization is associated with these deposits, locally forming ores (Fig. 8D). These iron-rich ores are hematite or magnetite (Fenoll-Hach-Alí and García-Rossell, 1974). There is a notable presence of distinct volcanogenic beds (Pérez-López et al., 2010) consisting of conglomerates or breccias with highly variable volcanic contents (Pérez-López and Morata-Céspedes, 1993) and high concentrations of iron oxides. The details of these volcanogenic beds are described below. X-ray analysis of the red lutites, which constitute the main lithology of this member, shows diffractograms that are similar to the red clays of Keuper facies (Pérez-López and Pérez-Valera, 2011), although with some peculiar minerals the most significant being quartz, illite, calcite, hematite, montdorite (K, Fe, Mg silicate), and wiserite (Manganese Borate hydrate). Therefore Fe, Mg, Mn, K, and B are common in these sediments. This member is interpreted as a coastal sedimentary series displaying a distal ephemeral fluvial system. The hematite, magnetite, and the high content of Mn, Mg, Fe, and B in the clays indicate hydrothermal processes. The presence of boron points to local volcanic activity as a source of this element (Warren, 1999).

The upper member, the Limestone and Laminated Dolomite Member reaches 60 m, although the general thickness is 20 or

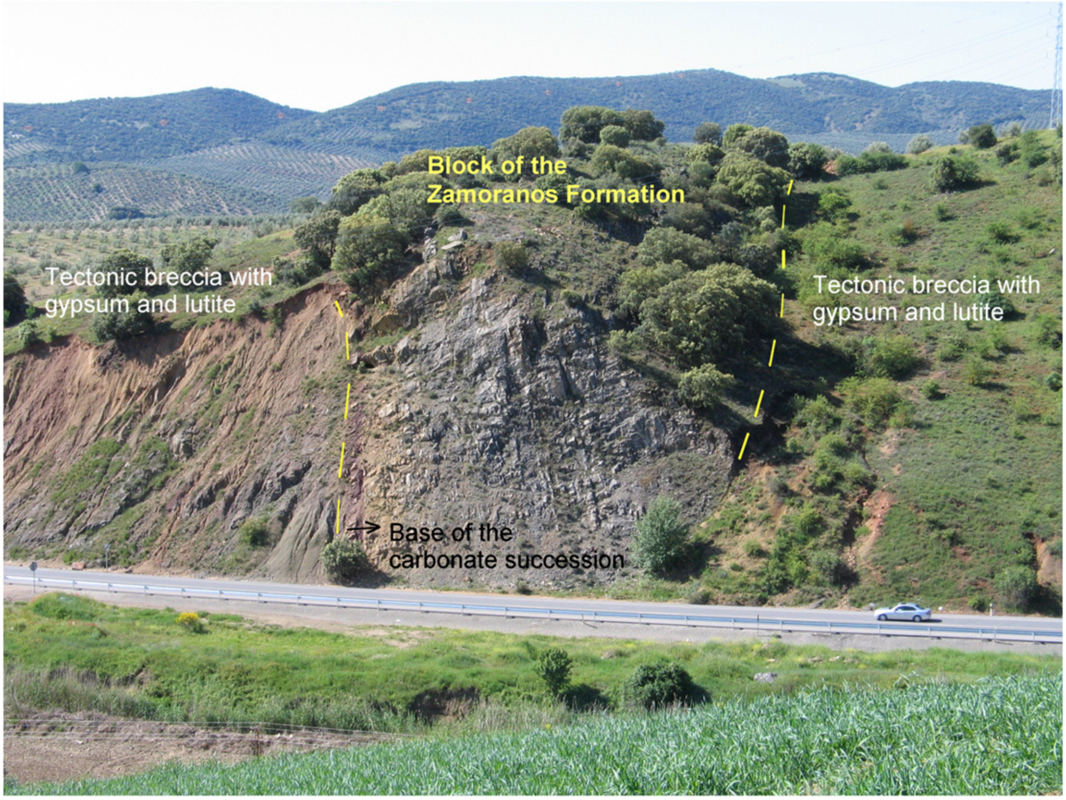

Fig. 5. Outcrops of the Zamoranos Formation are generally isolated blocks limited by tectonic contacts (dashed line). At sites exposing carbonate beds, a tectonic breccia with gypsum and lutite appears (Alcalá la Real section). The stratigraphic log of this outcrop is shown in Fig. 7.

25 m (Figs. 6 and 7). It consists mainly of bedded limestone and dolomite showing lateral facies changes.. In the Alcalá la Real and Benalúa de las Villas sections, carbonate beds with hummocky-cross lamination are recognized (Fig. 9A) and interpreted as tempestite beds. Occasionally, above these latter facies, thin-bedded marly limestones appear, showing a thinning-upward sequence

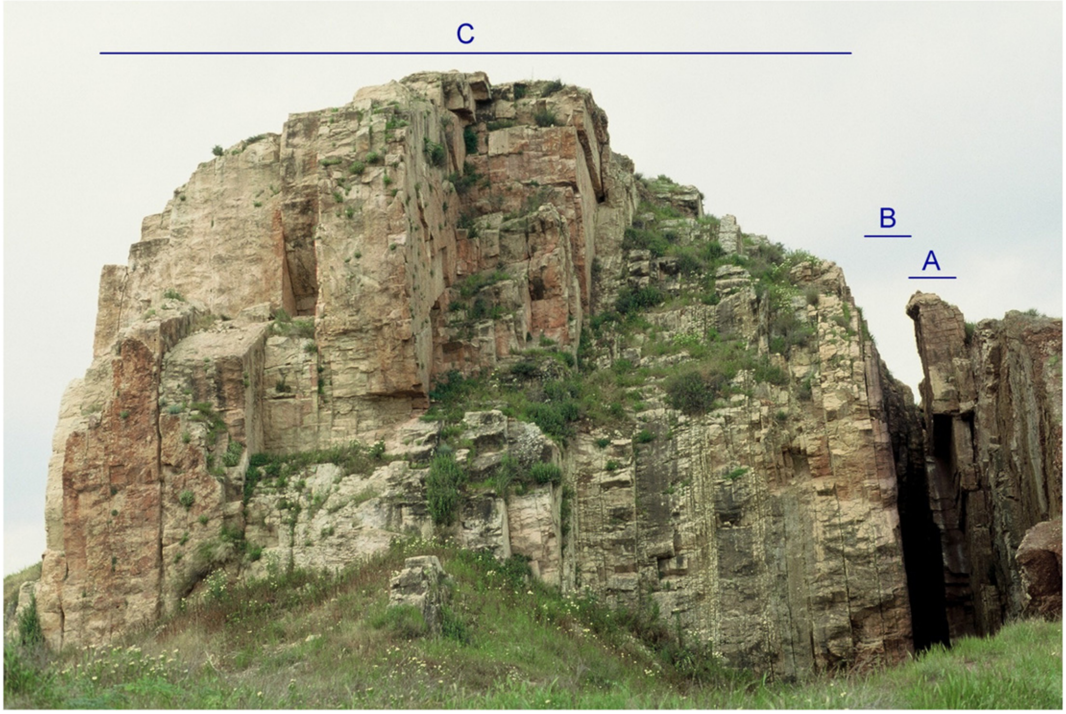

Fig. 6. Outcrop of the Zamoranos Formation (E Jaén) showing the three different members: (A) Carniolar Limestone Member; (B) Ferruginous Detrital Member (exploited in this section); (C) Limestone and Laminated Dolomite Member.

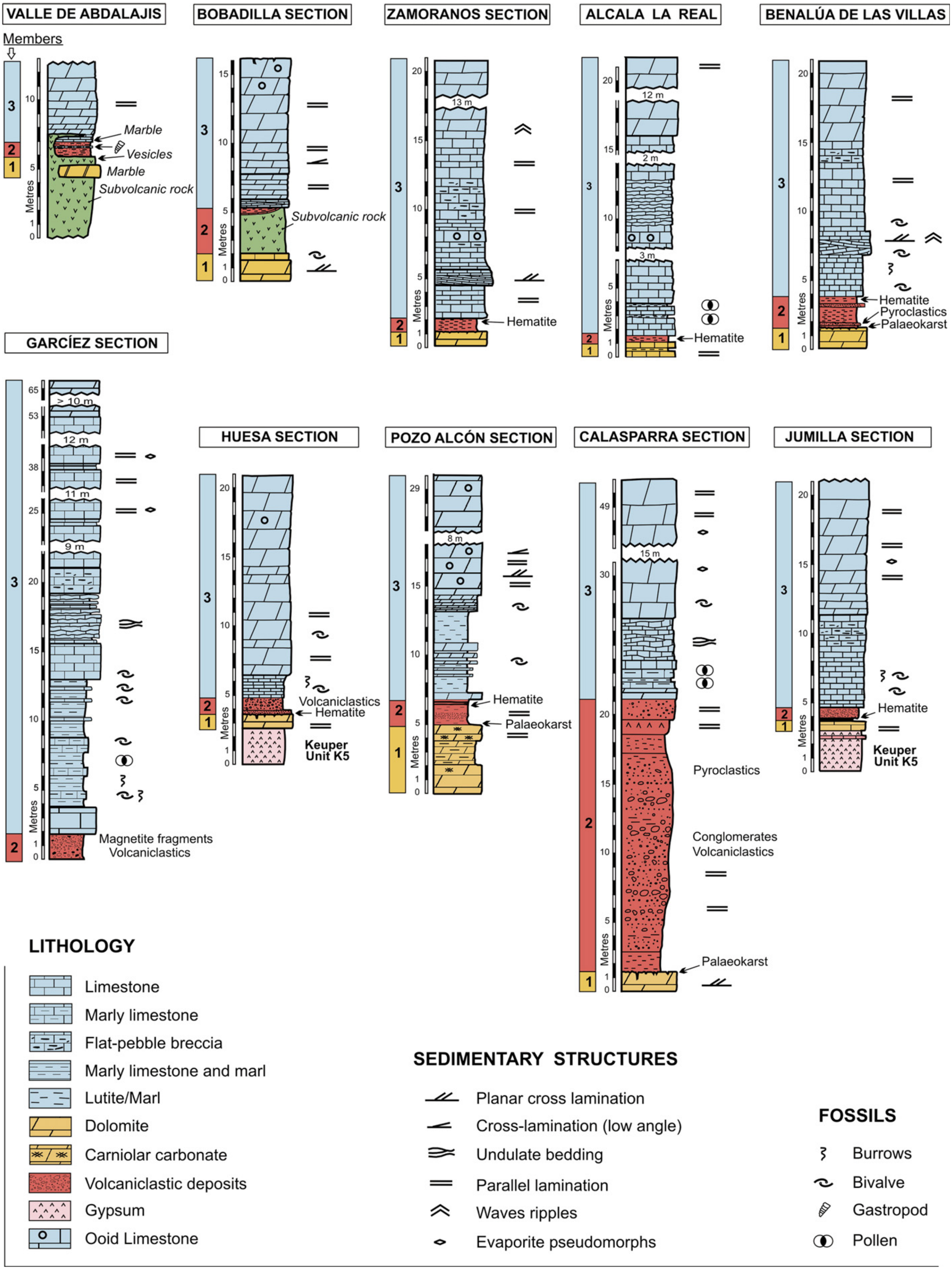

Fig. 7. Stratigraphy, lithology, fossils content, and sedimentary structures of the main sections exposing the Zamoranos Formation (for the locations see Fig. 1).

Table 1
Facies and environments of the Zamoranos Formation Members.

Member Thickness	Lithofacies	Microfacies, components and mineralogy	Sedimentary structures Feature of beds	Depositional environment
Carniolar limestone 0.5–2 m	Ochre or dark-yellow carniolar limestone	Mainly mudstones. Pack-/grainstones with bioclasts or ooides. Recrystallised facies.	Parallel/ondulated laminations, vugs Massive beds, irregular top surface.	Tidal flat, restricted subtidal zone
Ferruginous detrital 0.3–20 m	–Red siliciclastics: Lutite, sandstone and conglomerate –Limestones –Gypsum –Conglomerate and breccias with volcanic fragments	–Iron oxides mineralization (Hematites, Magnetite) –Mud-/wackestones with gastropods and oolitic packstones –Megacrystaline gypsum with red lutite –Volcanic rock fragments and iron oxides	–Cross-lamination and carbonated crust –Thin beds –Laminated beds –Variable thickness beds	–Distal ephemeral fluvial system and mud flat –Restricted subtidal zone or lagoon. –Coastal shabka or playa lake –Fluvial and pyroclastic deposits
Limestone and Laminated Dolomite 20–25 m to 60 m	–Gray/ochre limestone/ dolomite –Thin-bedded limestone and marl –Dolomite	–Mud and dolosparstone, Oolitic or bioclastic grainstone to packstone, with quartz and magnetite fragments in the lowest beds. Bioclasts of bivalves, crinoids, and gastropods –Mudstones and wackestones with bivalve shells –Dolomicrite, locally with coproliths (*Parafavreina thoronetensis*)	–Massive bed,locally planar cross-lamination or hummocky-cross lamination. Laminated limestones with flat pebbles –Massive or nodular structures, bioturbation –Lamination and evaporite pseudomorphs	–Lagoon with shoals, and tempestite deposits; Tidal flat; Tidal channel or tidal bar deposits. –Restricted lagoon –Tidal flat with protected tidal ponds

(Fig. 9B) and undulating and nodular structures (Fig. 9C) with bioturbation (*Planolites*) and bivalve shells. Upsection, gray laminated mudstones with pseudomorphs of evaporite minerals are plentiful, while in some sections, above of the thin-bedded marly limestone, laminated limestones with cm-sized flat pebbles abound (Fig. 9D, E, F). Mudstones and dolosparstone (Wright, 1992) are common, although oolitic or bioclastic grainstones and packstones are frequent in this member (Fig. 10). The distribution of microfacies grain types is highly variable (Fig. 11) in the sections studied. Quartz or magnetite fragments are present, but they invariably occur in the lowest beds of this member. Moreover, bivalve fragments appear in the lower part of many sections. In the Benalúa de las Villas, Garcíez, Calasparra, and Jumilla sections, mudstones and wackestones are more frequent in the upper part of this member,, locally with coprolites (Fig. 10E) such as *Parafavreina thoronetensis*, Bronnimann, Caron and Zaninetti (Bronnimann et al., 1972). The Bobadilla and Pozo Alcón sections are characterized by ooidal grainstones (Fig. 10F), in the middle and in the upper part, which occasionally display isopachous cement.

These facies are interpreted as lagoon and tidal deposits. Quartz, magnetite fragments and bivalve bioclasts are characteristic of the first transgressive deposits of this carbonate member. Bioclasts are more abundant in the lower beds. In some sections, bioclastic grainstones become ooidal grainstones at the beginning of the regression stage. This facies evolution is similar to that of the Bahamas platform during the Pliocene–Pleistocene. Beach and Ginsburg (1980) and Caracuel et al. (1995) recognized a general shallowing-upward trend of coralgal, skeletal grain-rich facies evolving to ooid- and peloid-rich facies. The muddy limestones with flat-pebbles, locally laminated, are interpreted as lag deposits in tidal channels and on tidal flats (Flügel, 2004). The gray limestone with pseudomorphs of evaporite minerals indicates arid to semiarid conditions in these coastal environments (sabkhas). The laminated dolomite is interpreted as microbial mats. Arnal et al. (2002) interpreted similar carbonates with millimeter-thick lamination and evaporite pseudomorphs as sabkha deposits. Oolitic carbonates displaying cross lamination are interpreted to represent tidal-bar shoal or shoal deposits. When showing strongly micritised bioclasts, these sediments are deposited in a shallow-marine warm-water environment (Leonard et al., 1981; Fürsich et al., 2003). The presence of aggregate and micritised ooids may be interpreted as stabilized sand-flat deposits sensu Carney and Boardman (1996), who described such carbonates from the Joulters Cays (Bahamas). In the stabilized sand flat the water is very shallow (<1 m) and the bottom, colonized by algae and sea grass, is burrowed.

The facies evolution of the upper member follows a characteristic pattern. The lower part is normally built up by bioclastic carbonates then, locally, oolitic beds appear, and finally in the upper part the thin-laminated carbonates are dominated by intraclasts or flat pebbles. The upper dolomite displays a mesocrystalline texture and stromatolitic laminations. Therefore, this facies evolution records a regression stage, although the tidal deposits occur in different formations.

In conclusion, these sediments represent low-energy, shallow-water tidal and lagoonal environments of a carbonate ramp in the

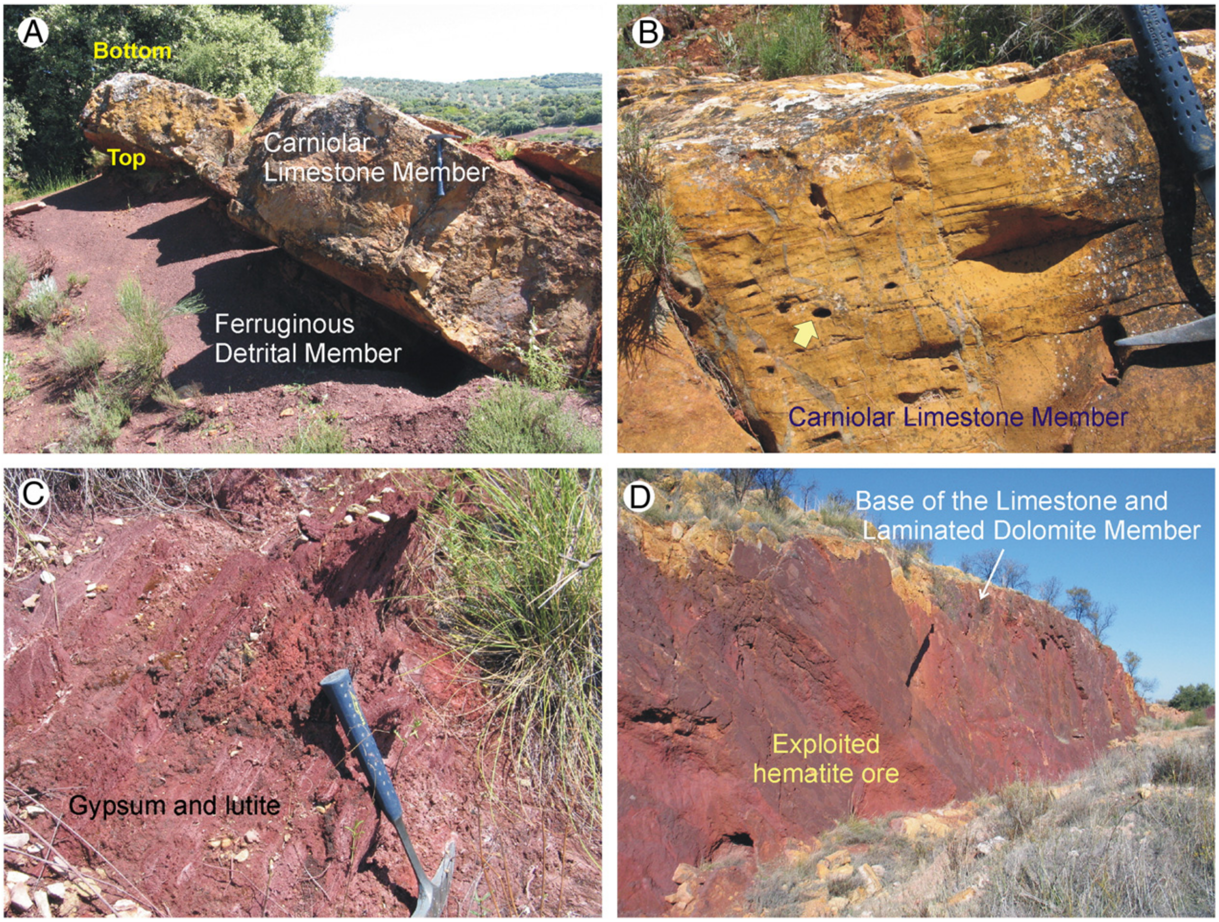

Fig. 8. Lithofacies of the Carniolar Limestone Member and the Ferruginous Detrital Member. A) Outcrop of the Benalúa de la Villas section exposing the Carniolar Limestone Member with a maximal thickness of 1.5 m. Its ochre or dark yellow color is characteristic of the basal beds. The stratigraphy is overturned in this outcrop. The stratigraphic position of the Ferruginous Detrital Member is on top of the red lutite and sandstone (2 m thick). B) Detail of a carniolar bed with lamination, pseudomorph evaporite (yellow arrow), lowest member of the Zamoranos Formation. C) Laminated gypsum with red clay in the upper part of the Ferruginous Detrital Member of the Calasparra section. D) Outcrop of the Ferruginous Detrital Member with traces of exploited hematite ore. The mineralization occurs at the base of the first yellow bed of the Limestone and Laminated Dolomite Member.

epicontinental platform setting. The lower energy, mainly in the upper part of successions, suggests the presence of small islands or bars (Pratt and James, 1986). Arnal et al. (2002) discuss the role of tides and waves in the Upper Triassic carbonates of the NE Iberian Peninsula. These authors emphasize the importance of tidal currents in these environments, as recognized in the Zamoranos Formation, although wave currents and storms are also significant.

5. Volcanic rocks and volcaniclastic deposits

The Zamoranos Formation is identified in the field by the iron oxides that appear in the Ferruginous Detrital Member (Fig. 8D). Hematite and magnetite are the main minerals of iron which occur in the middle and upper part of this member. In the locality of Garcíez, magnetite is present and has been considered of hydrothermal origin (Fenoll-Hach-Alí and García-Rossell, 1974). Evidently, the origin of this iron ore suggests volcanic activity. In fact, this member is also characterized by volcaniclastic beds and subvolcanic rock body, although the latter is rare. In the Bobadilla section, a sill with ophitic texture occurs and, in the Abdalajís section, subvolcanic rocks with vesicles were recognized (Fig. 12A).

The study of these volcanic rocks and fragments of the volcaniclastic deposits is difficult because its minerals underwent strong diagenetic alteration (Pérez-López and Morata-Céspedes, 1993). Chemical analysis of this volcanic material reveals a composition of sub-alkaline basalts to basaltic andesites (Pérez-López et al., 2010).

The most frequent volcanogenic rocks are volcaniclastics (Table 2). Volcaniclastic deposits exposed in the Huesa and Jumilla sections display volcanic rock fragments with phenocrysts or microcrystalline texture with very small vesicles and clasts of glass and are interpreted as hydroclastites. These deposits were formed when extruding lava came into contact with water (Fisher and Schmincke, 1994). The rapid chilling and quenching fragmented the lava, most probably in a coastal flooded area.

In the Garcíez section, breccias display angular fragments of volcanic rocks in a glassy matrix (Fig. 12B). These may be autoclastites produced by autobrecciation of lava (Fisher and Smith, 1991). When the lava flows and the upper surface cools and develops a brittle crust, the crust breaks and produces clasts.

In the Calasparra section, some of these volcanic breccias display graded beds and rounded carbonate fragments, which are interpreted as reworked sediments (Fig. 12C). Their origin is unknown, these breccias probably being reworked pyroclastic deposits (Pérez-López and Morata-Céspedes, 1993).

Other prominent volcaniclastic deposits consist of partially cemented thin greenish-yellow beds (Fig. 12D) formed by clay to

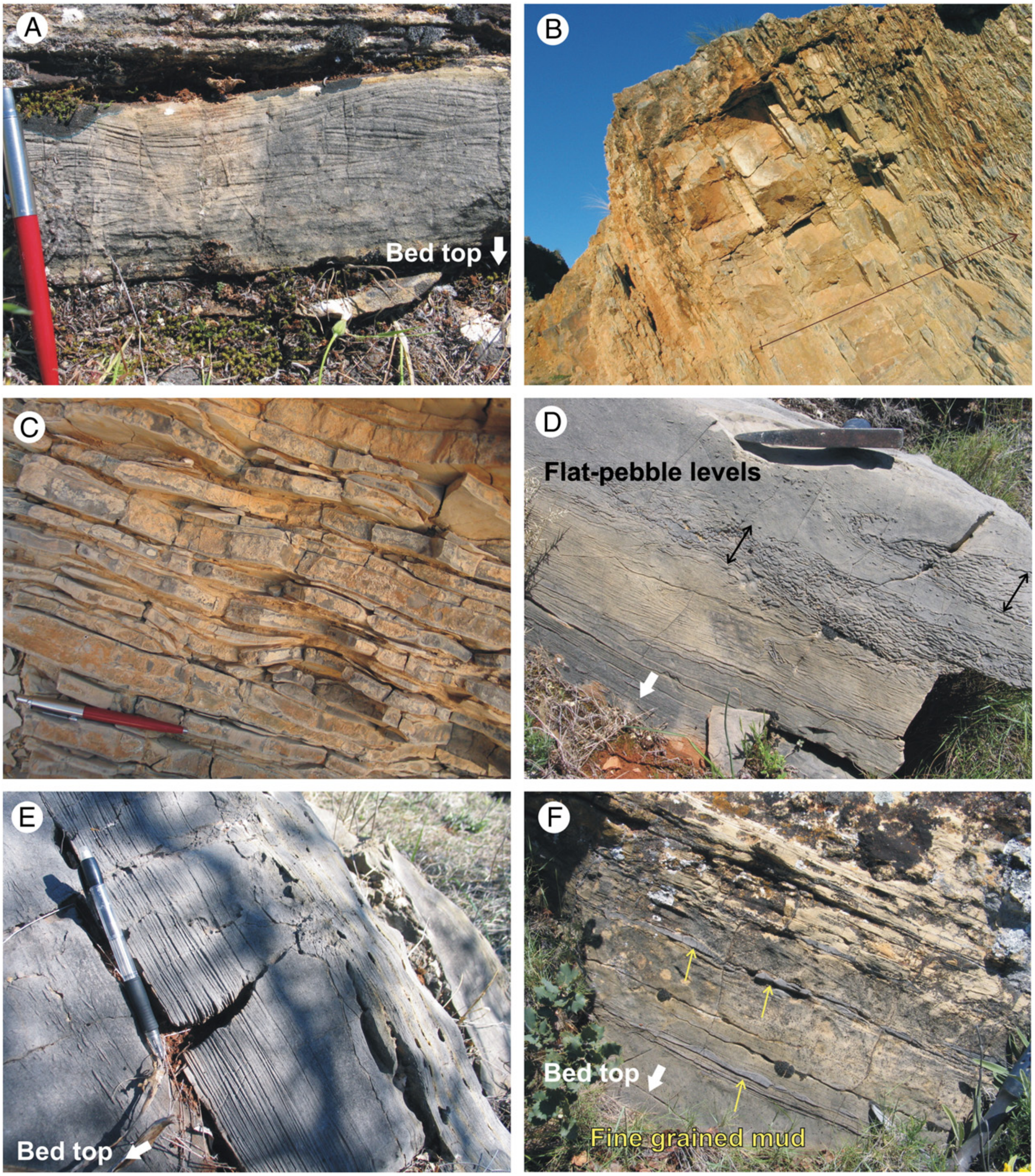

Fig. 9. Lithofacies and sedimentary structures of the Limestone and Laminated Dolomite Member. The stratigraphy is overturned in the photographs A, D, E and F. A) Storm wave ripples interpreted as hummocky-cross lamination. B) Thinning-upward sequence with sediments deposited under low-energy conditions at the top, corresponding to the deeper deposits of this member. C) Detail of the thin-bedded marly limestone with undulating structure probably related to bed forms of storm waves. D) Limestones with flat-pebbles interpreted as intertidal deposits. E) Laminated limestone of a high-energy tidal flat setting. F) Laminated limestone documenting variations in grain size and erosion/deposition according to the water flow of a tidal flat.

coarse sand-size grain of altered volcanic fragments, partly glass fragments and small quartz crystals. It is possible to distinguish two beds which are interpreted as pyroclastic-fall because they are very extensive and relatively thin (3 to 40 cm thick). The quartz grains likely derive from underlying unconsolidated to partly consolidated Keuper sandstones, as occurs in mafic volcaniclastic deposits in flood basalt provinces (Ross et al., 2005).

In any case, the presence of these volcaniclastics, which are intercalated in the Ferruginous Detrital Member, implies a volcanic event during the deposition of the Zamoranos Formation.

6. Discussion

6.1. Depositional environment, climate and relative sea-level changes

The Zamoranos Formation is composed of coastal and shallow marine deposits, with changes recorded in relative sea level. This differs from Triassic carbonate successions of the Betic Internal Zones, where the thick carbonate units reveal less unequivocal eustatic signatures (Delgado et al., 2004; Martin-Rojas et al., 2010).

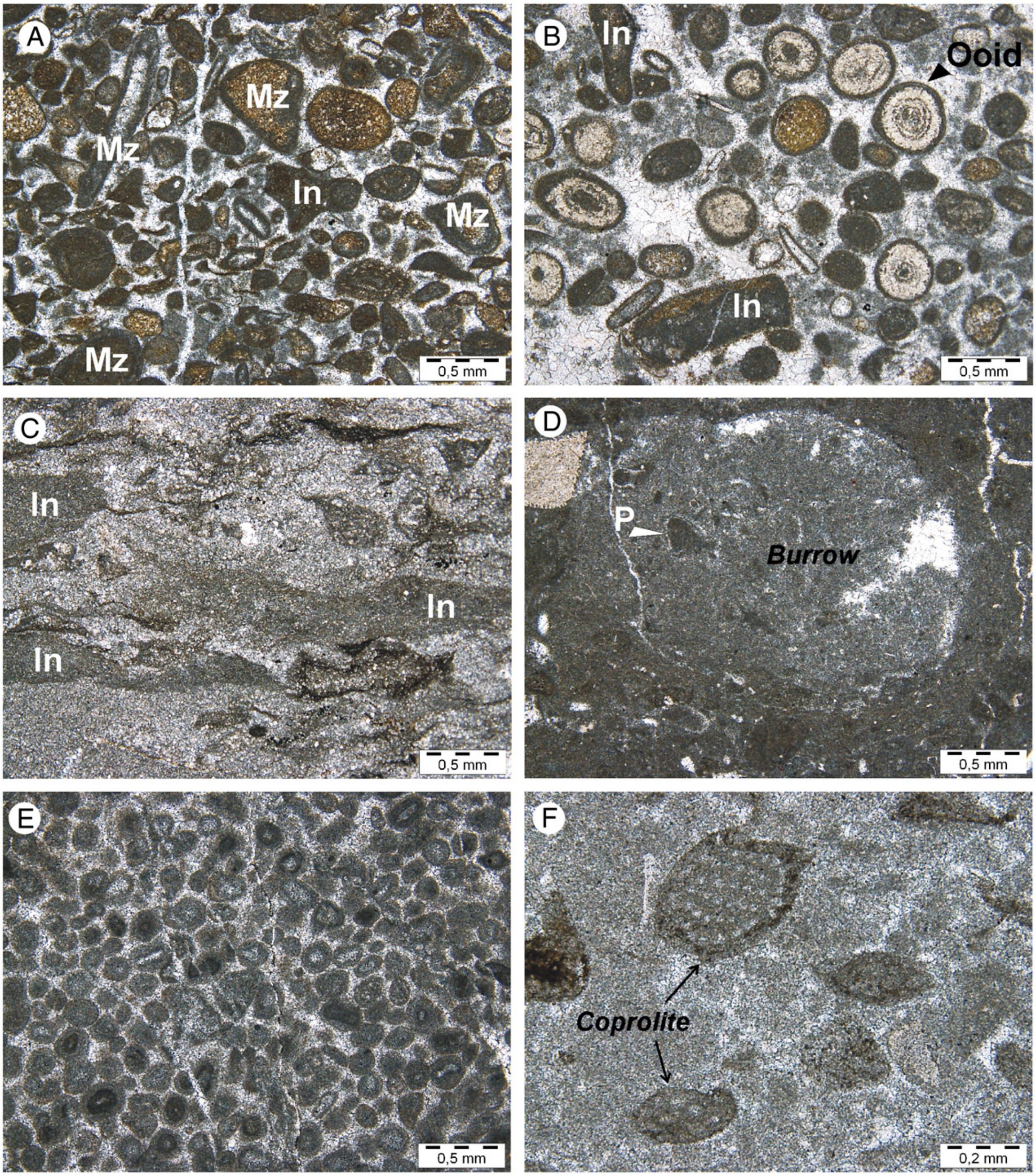

Fig. 10. Microfacies of the Limestone and Laminated Dolomite Member. A) Grainstone composed of coated grains with intraclasts (In), peloids and strongly micritized bioclasts (Mz). The content of micritic matrix varies in each sample. B) Ooidal grainstone with intraclasts (In) and bioclasts, showing micritized grains (predominantly ooids). C) Mudstone composed of reworked laminated muddy sediment forming intraclasts which are partially consolidated (In). D) Mudstone with burrows filled with micrite and single peloids (P). E) Ooidal grainstone interpreted as sand deposits of shoal bars. F) Wackestone with coprolites (*Parafavreina thoronetensis*) interpreted as deposit of a restricted environment.

In the External zones, following the transgression of the Middle Triassic, the carbonates of the Zamoranos Formation mark the next major transgression over the Keuper deposits. However, the relative sea-level rise began during the red shale deposition of the Keuper facies (Unit K3) (Pérez-López, 1996).

The carbonates of the Carniolar Limestone Member represent the first marine deposits during this relative sea-level rise (Fig. 13). After the deposition of these carbonates, a relative sea-level fall is documented in the sedimentary series and a palaeokarst developed. The intercalated Ferruginous Detrital Member represents the lowstand systems tract. This latter member suggests that the platform was unstable probably due to volcanism/tectonics. A fall in relative sea-level resulted in deposition of continental siliciclastics associated to a rifting phase. This red member documents an interruption of the lower carbonate deposition, this being interpreted as a local abrupt environmental change related to tectonics, volcanism, and consequently to the changes in relative sea level. Upsection, the evolution of the carbonate facies displays a sequential pattern (transgression–regression cycle), with bioclastic rudstones deposited during the transgressive stage. Coastal barriers or longshore sediments and

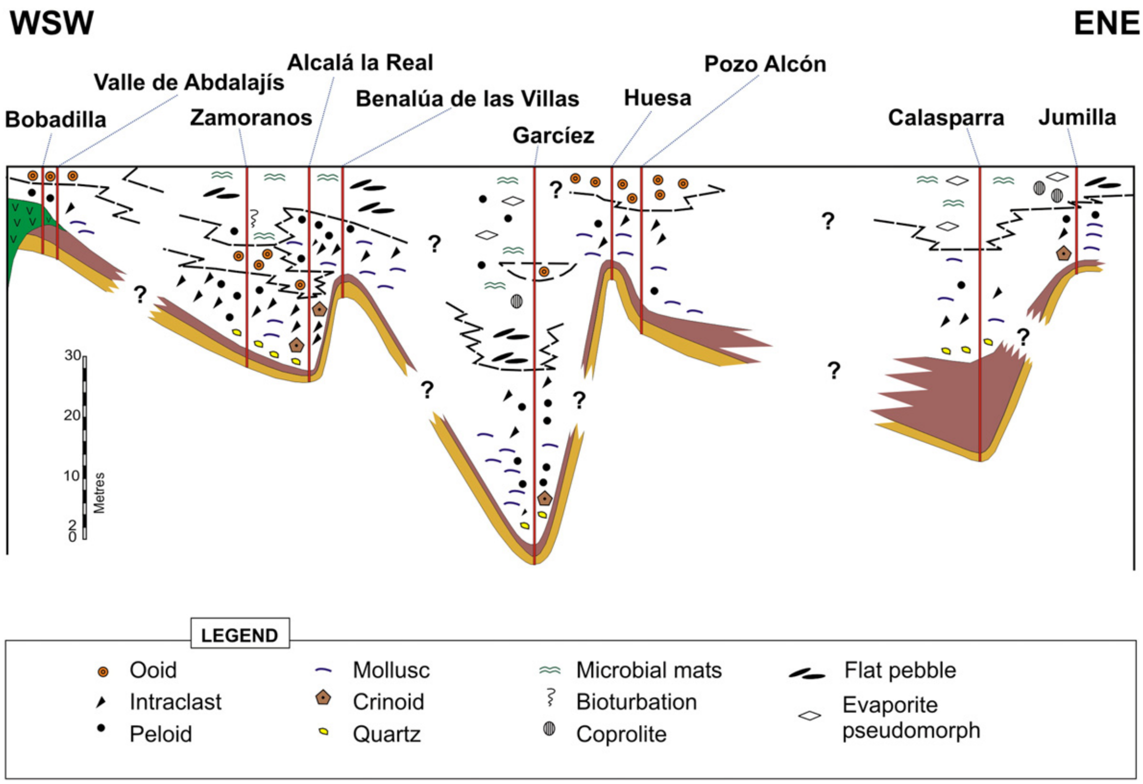

Fig. 11. Distribution of sedimentary structures and grains recorded in the Limestone and Laminated Dolomite Member. The position of the sections is relative, without horizontal scale. For location of the sections see Fig. 1.

shoals occurred during transgression. Then, the regression stage began with a prominent progradation of tidal flats and carbonate sabkhas. The maximum flooding zone is probably documented in the middle part of the Limestone and Laminated Dolomite Member, recognized by tempestite beds in the Benalúa de las Villas section and nodular thin-bedded limestones in the Garcíez section.

This carbonate series terminates with laminated dolomite interpreted as supratidal deposits. These are characterized by stromatolites and evaporites, which prograded over lagoon deposits. Gypsum and lutite of the Carcelén Anhydrite Unit overlie the dolomite of the Zamoranos Formation (Pérez-López et al., 1996). Previous conditions, typical of the Keuper sediments, were established. The sediments described above indicate a dry climate and arid to semi-arid coastal to playa settings in the Western Tethys during the Norian, although, by contrast, the basal beds of the basinal shales of the Northern Calcareous Alps show evidence of a wet climate (Berra et al., 2010; Bonis et al., 2010). Berra et al. (2010) point out that the end of the Norian depositional system records a major relative sea-level fall and a transition from a dry to a wet climate. The top of the Zamoranos Formation displays a relative sea-level fall. Upsection, evaporites and coastal shales are recognized in the Imón Formation (Gómez and Goy, 2005) althought there is no evidence of a wet climate. Evaporites occur below, above and inside of this formation, locally with abundant oolite facies.

6.2. Rifting phases and volcanism

During the Lower Triassic, the break-up of Pangaea produced grabens, which host large amounts of detritic materials (e.g. Lucas, 1998). During the Middle Triassic, the westward expansion of the Tethys flooded continental areas and locally covered the Palaeozoic relief, with several transgression–regression cycles occurring until the end of the Triassic (Aigner and Bachmann, 1998; Lucas, 1998). Extension, subsidence and sedimentation prior to the Middle Triassic can be interpreted as fault-related synrift events according to the model proposed by Allen and Allen (2005).

The most expansive stages took place during the Ladinian and Norian, leading to the deposition of carbonates on almost every European epicontinental platform. However, different thicknesses and facies variations indicate that sedimentation was influenced by local or regional tectonic movements, besides relative sea-level changes. The Tethys Sea successively prograded over the eastern margin of the plate during at least five major transgression–regression cycles (López-Gómez et al., 2002). The last cycle, in S and SE of Iberia, corresponds to the deposition of the Zamoranos Formation carbonates (Fig. 13), which broadly covered the Iberian Massif during the Late Triassic.

Keuper lutites contain several subvolcanic rocks and sills of basalts of uncertain age in the Iberian Peninsula (Lago and Pocovi, 1984; Bastida et al., 1989). In the Cordillera Bética, Morata-Céspedes (1993) identified sills in lutites (unit K3) of Carnian age (Pérez-López, 1991). Volcanic rocks of the Zamoranos Formation document one volcanic event because they are intercalated in the Ferruginous Detrital Member of this formation of Norian age. Variations in facies and thickness of the Ferruginous Detrital Member (Fig. 11) are interpreted to reflect a revival of the rifting phase and its related volcanic activity. Chemical analysis of the volcanic material reveals a composition of sub-alkaline basalts to basaltic andesites, and their Th/Yb vs. Ta/Yb ratios are indicative of the calc-alkaline series (Pérez-López et al., 2010). Variations concurrent with increasing Th content imply that the magmas arising from a subcontinental upper mantle assimilated continental crust in their ascent to the surface. Similar geochemical patterns have been described for other Mesozoic magmas in the Subbetic Zone, mainly those emplaced in the Carnian units underlying the Zamoranos Formation, associated with a rifting phase (Morata et al., 1997; Puga et al., 2010).

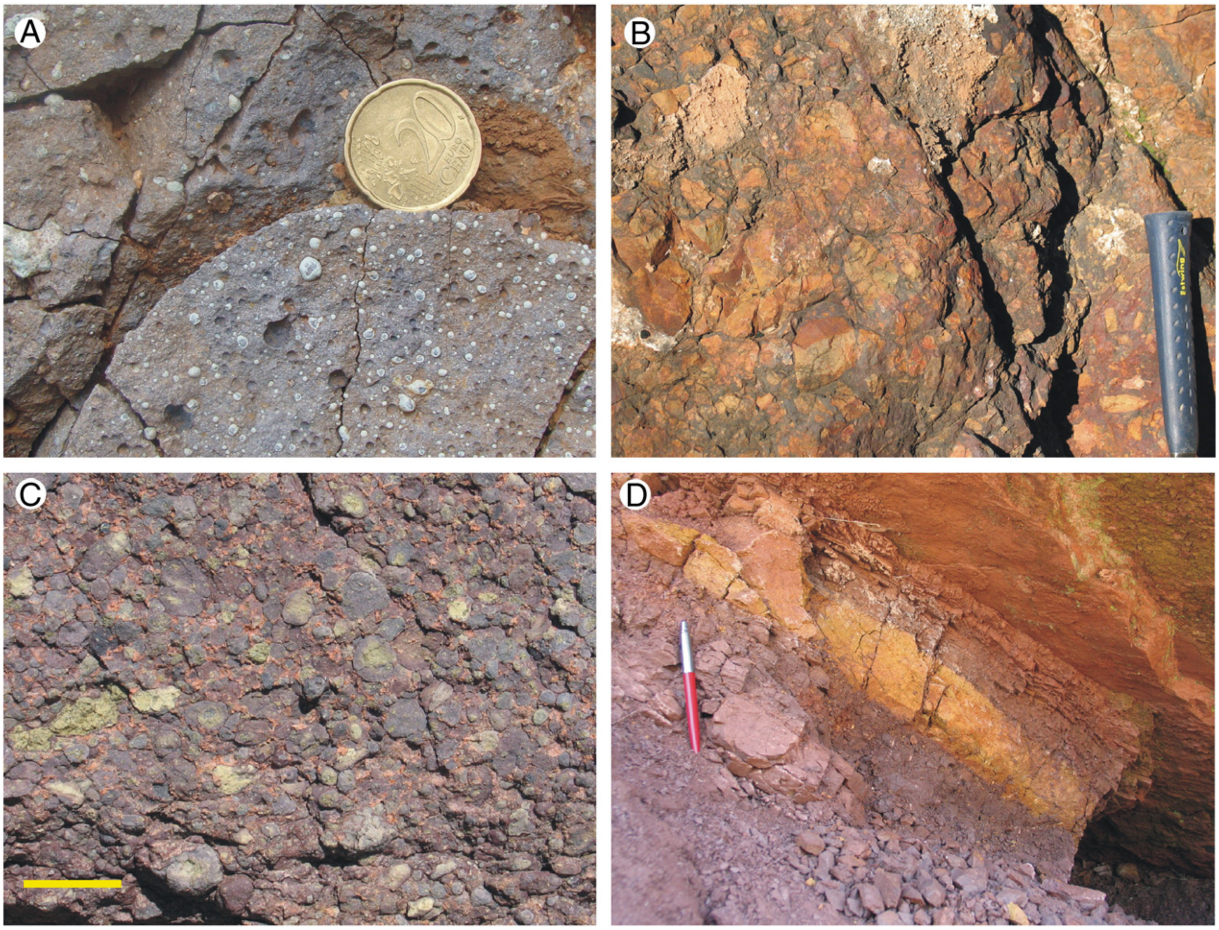

Fig. 12. Volcanogenic rocks of the Ferruginous Detrital Member. A) Microcrystalline and glassy volcanic rock with vacuoles, Abdadalajís Section. B) Flow breccia with angular blocks of volcanic rock in glassy matrix. C) Conglomerate comprising volcanic material reworked by currents (yellow bar is 3 cm long). D) Yellow bed of pyroclastic sand-size grain deposits in the lowest part of this member (overturned section, Benalúa de las Villas).

Volcanic deposits of the Zamoranos Formation extend from the province of Málaga to the provinces of Albacete and Valencia, and their coeval stratigraphic position indicates significant volcanic activity in the southern and south-eastern of the Iberian platform during the Norian. This study thus indicates that the rifting phase that began elsewhere during the early Triassic extended into the

Table 2
Volcanogenic rocks of the Ferruginous Detrital Member (Zamoranos Formation).

Type	Main bed feature	Clast nature	Petrographic characteristics	Origin/Categorie	Localities
Volcanic rock	Irregular large body of green rock	_	Ophitic texture Vesicles	Subvolcanic and volcanic rock (Sub-alkaline basalt to basaltic andesite)	Bobadilla Abdalajís
Volcaniclastic deposits	Breccia bed	Volcanic clasts	Angular fragments of volcanic rock in a glassy matrix	Autoclastite	Garcíez
	Breccia bed	Volcanic clasts	Volcanic rock fragments with phenocrysts or microcrystalline texture, and clasts of glass, partly with vacuoles	Hydroclastite (Fragmented lava)	Huesa Jumilla
	Graded bed	Volcanic and carbonate clasts	Conglomerate with rounded carbonate fragments	Fluvial volcaniclastic conglomerate	Calasparra
	Partially cemented thin greenish-yellow bed	Volcanic fragments with significant alterations	Sandstone made up of clay to coarse sand-size grains of altered volcanic rock fragments, partly glass fragments and small quartz crystals	Pyroclastic deposit	Benalúa de las Villas

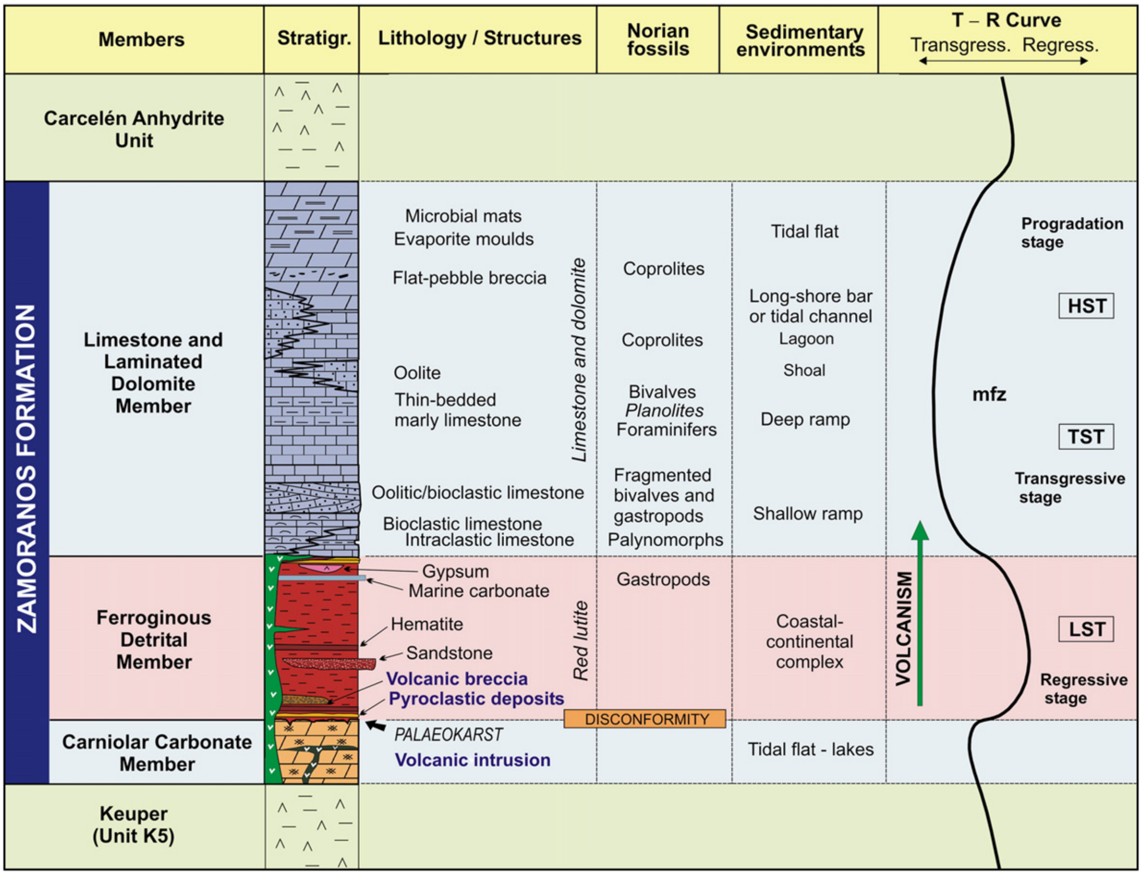

Fig. 13. Stratigraphy, lithofacies, fossil content and sedimentary environments of the Late Triassic Zamoranos Formation. Interpretation of relative sea-level changes marks a major transgressive–regressive cycle. Abbreviations of the depositional cycle: HST — Highstand Systems Tract, mfz — maximum flooding zone, TST — Transgressive Systems Tract, LST — Lowstand Systems Tract.

Norian in the Subbetic domain. This corroborates the hypotheses of several authors who postulated that the rifting and break-up of Pangaea started during the Early Triassic and continued and intensified at the beginning of the Norian (Ziegler, 1982, 1988; Veevers, 1994; Withjack et al., 1998; Golonka and Ford, 2000; Golonka and Kiessling, 2002; Veevers, 2004). In conclusion, the volcanic activity recorded in the Zamoranos Formation implies that the massive magmatic event associated with the Central Atlantic Magmatic Province (CAMP), which is mostly contemporaneous with the Jurassic–Triassic boundary (e.g., Verati et al., 2007), is first documented in the External Zone during the Late Triassic. Relative sea-level changes are controlled by tectonics, resulting in the different extent of flooding of coastal areas of the W Tethys realm.

6.3. Correlation with other carbonate units: an epicontinental platform

The correlation of the Zamoranos Formation to other carbonate formations of Late Triassic age is shown in Table 3. In the Iberian Ranges, Catalan Coastal Ranges and Ebro Depression, Upper Triassic carbonates are known as the Imón Formation (Goy et al., 1976; Goy and Yébenes, 1977), in the southern Pyrenees as the Isábena Formation (Calvet and Anglada, 1987). Pérez-López et al. (1992) correlated the Zamoranos Formation with the Imón Formation of the Iberian Ranges and Pérez-López et al. (1996) studied its extension to the SW part of the Valencia Triassic. López-Gómez et al. (1998, 2002) and Arnal et al. (2002) pointed out that the Imón Formation, which is built up by dolomites, and the Isábena Formation, which consists of limestones, represents the most prominent units of the Late Norian in NE Iberia (Fig. 14), corresponding to the Zamoranos Formation in the Betic Cordillera (S Iberia). In the Betic Cordillera, carbonate units have also been reported to occur at the top of the Triassic successions of the Maláguide Complex, which belongs to the Internal Zones (e.g. Roep, 1972; Martín-Algarra et al., 1995a). Moreover, this formation is similar to the Norian carbonates described by Boutet et al. (1982) in the Balearic Islands, to dolomie de Carcans (Curnelle, 1983) and to the Boutenac Formation (Peybernès et al., 1988) of the northern Pyrenees. In the literature, several carbonate units are considered similar to the Zamoranos Formation (Table 3). Tomašových (2004) suggested that the Fatric intra-platform setting was more restricted from the open ocean than intra-shelf habitats in the Eastern or Southern Alps at the end of the Triassic. As in the Betic Cordillera, the facies of each carbonate unit show different environments of a broad platform connected to the Tethys Ocean (e.g. Iannace and Zamparelli, 2002). The Zamoranos Formation was connected to the extensive platform of the Alpujárride Domain (to the E Betic Basin), which consists of dolomite with gypsum beds and reaches a thickness of more than 300 m in Almería (SE Spain). The Norian–Rhaetian carbonate units described above can be correlated with Alpine platform deposits in Western and Central Europe, showing reef and lagoon facies (Hauptdolomit and Dachstein Limestone Formation) connected to the Tethys Ocean. The connection of the Norian Betic carbonate platform to the Tethys Ocean is evident from the influence of the Tethysian bioprovince (Martín-Algarra, 1987; López-López et al., 1988; Martín-Algarra et al., 1995b; Pérez-López and Pérez-Valera, 2007). The Norian and Rhaetian stages correspond to the global reef bloom (Flügel, 2002), although in these marginal carbonate units reefs do not occur. Reef build-ups appear only in the thickest units, in the areas closer to the open-platform environments (Table 3,

Table 3
Coeval Norian carbonate platforms of the W Tethys realm discussed in the present study.

Unit name	Lithology thickness	Age	Location	Depositional environments	References
Zamoranos Formation	Limestone and dolomite with red siliciclastic intercalation 20–65 m	Mid to Late Norian	External zone of the Betic Cordillera	Tidal flats, shallow platform and sabkha deposits	Pérez-López et al., 1992 and present paper
Imón Formation	Dolomites 30–50 m	Late Norian–Rhaetian	Iberian Range Catalan Coastal Ranges	Tidal flats, shallow platform and sabkha deposits	Goy et al., 1976; Goy and Yébenes, 1977; López-Gómez et al., 1998; Arnal et al., 2002
Isábena Formation	Limestone and dolomite 20–35 m	Late Norian–Rhaetian	Southern Pyrenees	Tidal flats, shallow platform and sabkha deposits	Calvet and Anglada, 1987; López-Gómez et al., 1998; Arnal et al., 2002
Maláguide Complex	Dolomite 10–40 m	Rhaetian	Internal Zone of the Betic Cordillera	Tidal flats, lagoon and sabkha deposits	Roep, 1972; Martín-Algarra et al., 1995a
Dolomie de Carcans	Dolomites 30 m	Rhaetian	Aquitaine basin	Shallow platform	Curnelle, 1983
Fkirine	Oolitic limestone 15–25 m	Rhaetian	Tunisian Atlas	Shallow platform	Kamoun et al., 2001
Fatra Formation	Limestone, marls (corals) 30–40 m	Rhaetian	Western Carpathians	Peritidal–shallow subtidal intraplatform lagoonal storm-dominated carbonate environment	Tomašových, 2004
Alpujárride Complex[a]	Dolomite and gypsum beds 300 m	Norian–Rhaetian	Internal Zone of the Betic Cordillera	Tidal flats, lagoon and reefs	Delgado et al., 1981; Pérez-López and Pérez-Valera, 2007
Hauptdolomit[a]	Dolomite, limestone 2000–2500 m	Norian	Southern Alps, Central and Northern Austroalpine Transdanubian Range, Western Carpathians and Southern Apennines	Restricted inner lagoonal platform: tidal flats, lagoons	Fruth and Scherreiks, 1982; Haas, 2002; Berra et al., 2010
Dachstein Limestone Fm.[a]	Oncoidal limestone Reefal limestone 200–250 m	Norian–Rhaetian	Northern Calcareous Alps Austria/Hungary	Shallow water limestone and reef complexes	Haas,Tardy-Filácz, 2004 Fruth and Scherreiks, 1982

[a] Thick carbonate units with reefal and deeper facies correlate with the thin Norian–Rhaetian carbonates which were deposited on epicontinental platforms

units*). In the Betic Cordillera, biostromes developed in the Internal Zone, only in some Alpujarride units (Martín and Delgado, 1980; Delgado et al., 1981; Braga and Martín, 1987), not in the Zamoranos Formation dominated by tidal and very shallow deposits.

The shallow carbonate facies in all these formations are very similar, showing lateral facies variations from peritidal flats/islands with microbial mats, skeletal and oolitic banks/shoals or small barriers to restricted lagoons. In the Zamoranos Formation, in general, the subtidal and intertidal facies predominate in the lower part of the successions, which passes upsection into the supratidal facies. This facies succession was also recognized by Arnal et al. (2002) in the Imón and Isábena formations, documenting the evolution of a shallow epicontinental platform (Irwin, 1965; Tucker and Wright, 1990) in the S, E, and NE of Iberia. The significant spatial facies variations indicate the different environments that developed within the platform setting characteristic of shallow epicontinental seas, similar to the Ladinian epicontinental platform (Pérez-Valera and Pérez-López, 2008).

The Norian–Rhaetian carbonates, which correspond to the Zamoranos Formation, indicate the development of an extensive epicontinental platform in the western Tethys realm, succeeding the Muschelkalk facies (Fig. 15). However, during the Norian–Rhaetian these carbonates covered coastal deposits over broad areas and much more spacious than the Muschelkalk carbonates without onlapping all former coastal areas. In the Germanic realm, the Norian sediments are represented by marine sandstones and shales of less thickness (Aigner and Bachmann, 1998). The sedimentological features detected in the Zamoranos Formation, the intraplate setting and the low subsidence rates, which are recorded by the Imón and Isábena formations (Arnal et al., 2002), support the interpretation of a more pronounced transgressive stage than the Ladinian transgression, which overlaps to the W of the Iberian plate (López-Gómez et al., 1998).

The intercalated red member (Ferruginous Detrital Member) of the Zamoranos Formation with volcanogenic breccias is comparable to the ferruginous breccia of the Graus Tremp in the Pyrenees (Delmas et al., 1971) and to the volcaniclastic conglomerates described from Poza de la Sal (Burgos) by Salvany (1990). However, these may correspond to different phases of volcanism because they occur in different stratigraphic positions. For example, the Isábena Formation is limited at the top by a volcanic ferruginous breccia (Ramón, 1989), while the volcaniclastic deposits of the Zamoranos Formation occur near the basal boundary. Kamoun et al. (2001) studied Norian volcanic flows which are situated below of the Rhaetian carbonate platform (Fkirine Formation). Therefore, tectonics appear to be the controlling the factor of the Norian–Rhaetian platform

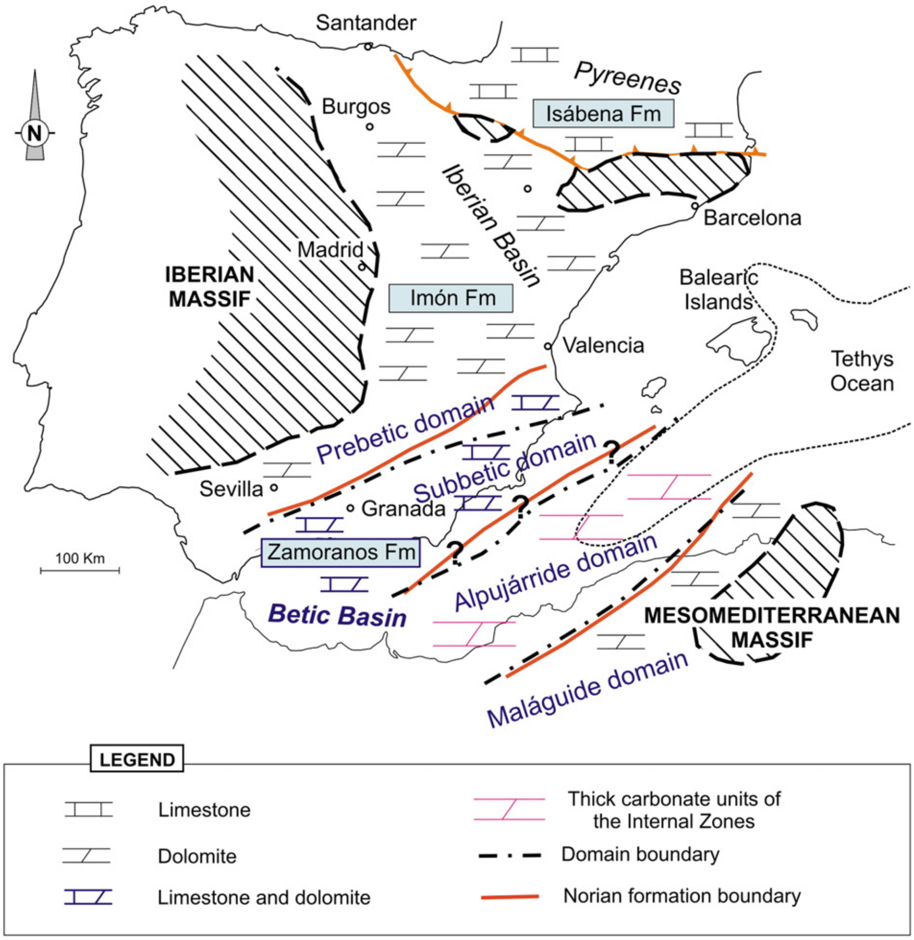

Fig. 14. Distribution of the Upper Triassic formations in the Iberian Peninsula (modified from Arnal et al., 2002).

evolution. The rifting tectonics determines different subsidence in this epicontinental platform setting. This has been corroborated by studying the deposition time of the different Late Triassic units. The Imón and the Isábena formations are of Latest Norian s.s. to Lower Rhaetian s.l. (López-Gómez et al., 1998, 2002; Arnal et al., 2002), and thus older than the Zamoranos Formation.

7. Conclusions

The Zamoranos Formation represents a tidal shallow-marine carbonate succession of Norian age which is confirmed in the present study by a palynomorph association of *Corollina* spp., *Chasmatosporites* spp., *Ovalipollis* sp., *Granuloperculatipollis rudis*, and *Perinopollenites elatoides.*

The Zamoranos Formation displays a significant lateral facies change characteristic of shallow epicontinental platforms. The lower calcarenitic deposits, representing the transgression stage, pass upwards into tidal laminites with flat-pebble breccias. The correlation of this formation and its resemblance to the Imón and Isábena formations and other Late Triassic carbonate units, suggest the development of an extensive epicontinental carbonate platform at the western margin of the Tethys realm. Their sedimentary facies indicate broad tidal flats and very shallow marine environments which can be traced to the Alpine domain. Some Hauptdolomit sections of the Central Alps display similar tidal facies. The abundant ooidal facies, the presence of red shales, the gypsums and the hypersaline dolomites that appear in the Zamoranos and Isabena formations indicate warm and arid conditions during the Late Triassic in the Iberian area.

During Norian times, these platform deposits were interconnected to the deeper intra-platform basins of the Tethys Sea. The Zamoranos Formation, and the equivalent formations, record the last transgressive stage of the Triassic. They were deposited in a similar palaeogeographic position to the Ladinian platforms with Muschelkalk facies although in a more extensive area. The transgression flooded the emerging zones in the east (Iberian Massif and S European Central Massif), although sedimentation was controlled by tectonics, as recorded by local intercalations of red coastal deposits.

The volcaniclastic breccias and iron mineralizations (hematite, magnetite) of the Ferruginous Detrital Member of the Zamoranos Formation indicate a volcanic event and active tectonics, locally influencing the basin subsidence and the environment conditions. In this context, together with the intraplate setting, the development of this epicontinental platform is interpreted as being related to a rifting phase. The volcanic activity recorded in the Norian Zamoranos Formation, and the volcanism of Carnian age, indicate that the rifting phase started during the Early Triassic and continued in Late Triassic times. Probably, the Norian volcanism was the initial phase of the CAMP event in the Betic basin.

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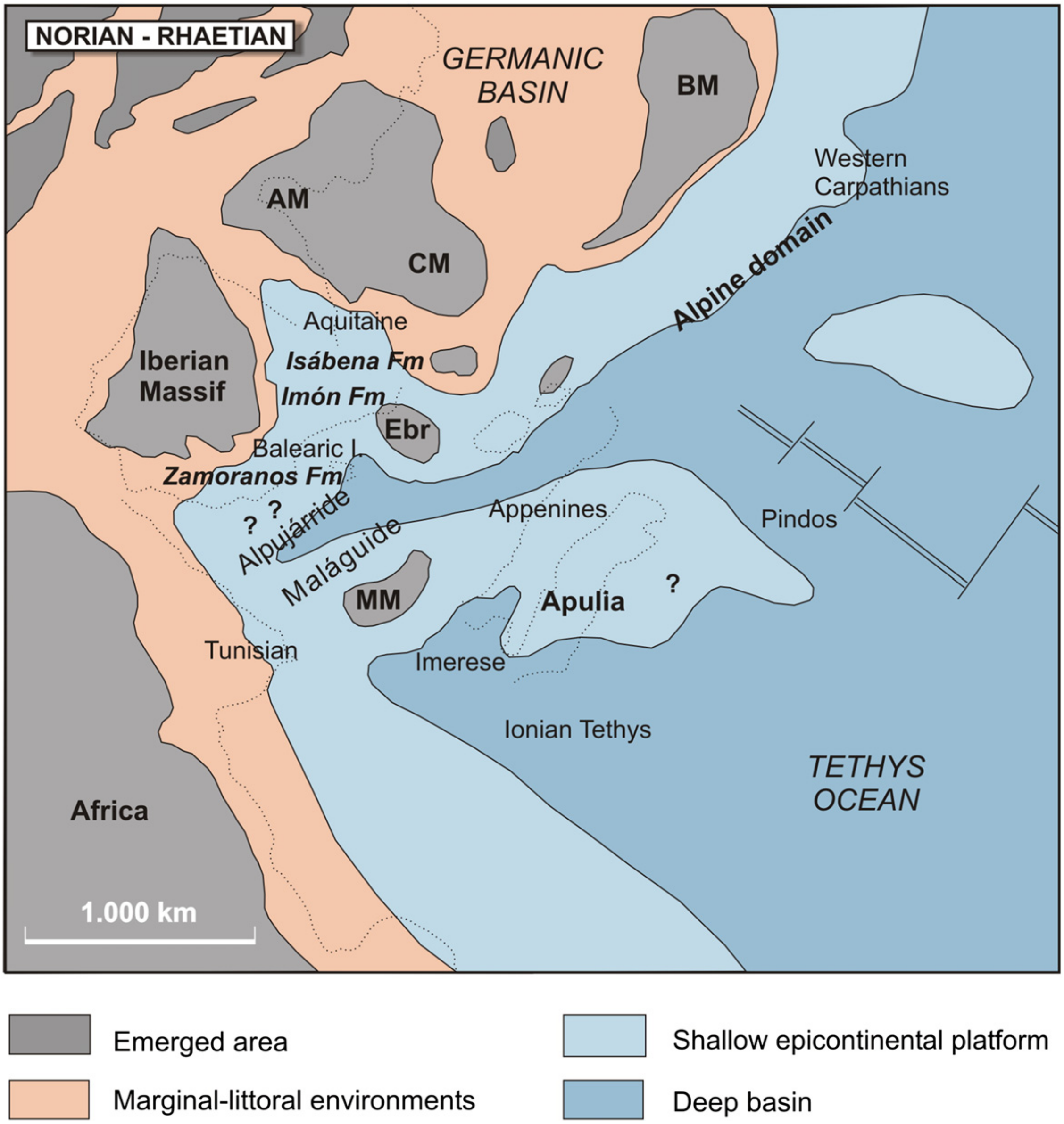

Fig. 15. Palaeogeographic reconstruction of the westernmost Tethyan realm for the Late Triassic. The depositional areas of the Zamoranos, Imón and Isábena formations building epicontinental carbonate platforms are indicated. These platforms were connected to the open sea by slopes or reef build-ups. The palaeogeographic reconstruction is based on data of Márquez-Aliaga et al. (1986), Decourt et al. (1993), López-Gómez et al. (1998), Iannace and Zamparelli (2002), Martín-Algarra and Vera (2004), Ciarapica (2007), Pérez-López and Pérez-Valera (2007), and this study. Legend: AM: Armorican Massif; BM: Bohemian Massif; CM: Central Massif; Ebr: Ebro Massif; MM: Mesomediterranean Massif.

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