# Stratigraphy and evolution of the Galve sub-basin (Spain) in the middle Tithonian–early Barremian: implications for the setting and age of some dinosaur fossil sites

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**ABSTRACT**

A review of the stratigraphy of the Galve sub-basin (western Maestrazgo Basin, eastern Spain) around the Jurassic-Cretaceous transition is presented here, based on new data acquired after extensive geological mapping and logging complemented with facies analysis, new biostratigraphic data and a revision of the published information available. The results obtained are relevant for a more detailed understanding of the tecto-sedimentary evolution of the studied basin during the transition between two stages of rift evolution (i.e., syn-rift sequences 1 and 2). In addition, new information on the age and setting of numerous dinosaur fossil- and track-sites found across the Galve sub-basin and in the northern part of the nearby Penyagolosa sub-basin is provided here. Two new lithostratigraphic units are defined and characterized, the Aguilar del Alfambra and the Galve formations. The previous stratigraphic framework considered only two lithostratigraphic units (the Villar del Arzobispo and El Castellar formations) bounded by a single regional unconformity, and this resulted in significant misinterpretations. The whitish limestones, red lutites and cross-bedded sandstones of the Aguilar del Alfambra Formation were deposited in transitional environments, ranging from coastal lutitic plains to restricted lagoons. Of particular interest are the laminated micritic-peloidal limestones with abundant fenestral porosity (supratidal ponds to intertidal flats), which preserve common dinosaur footprints. This unit is bounded by widespread unconformities and is of very variable thickness (0–450 m), controlled by extensional tectonics operating at the climax of syn-rift sequence 1 during the latest Tithonian–middle Berriasian. The overlying Galve Formation is of variable thickness (from 0–100 m) and is also bounded by regional unconformities described in detail here. It consists of red lutites with cross-bedded and tabular-burrowed sandstones representing channel and overflow deposits in an alluvial floodplain. The sauropod dinosaur *Aragosaurus ischiaticus* found in this unit has a controversial age assignment. The age of the Galve Formation is poorly constrained from late Berriasian to Hauterivian, but new biostratigraphic data presented here, combined with the correlation with the nearby Penyagolosa and Salzedella sub-basins, suggest a possible equivalence to the upper Berriasian–lower Valanginian sequence deposited during the initial stage of syn-rift sequence 2.

**Highlights:**

- A revised stratigraphic framework for the Galve sub-basin of eastern Spain
- Characterization of the newly defined Aguilar del Alfambra and Galve formations
- The setting of the Tithonian–Hauterivian dinosaur fossil- and track sites revisited
- Implications for the tecto-sedimentary evolution of the western Maestrazgo Basin

**Keywords:** Jurassic, Cretaceous, Maestrazgo, Dinosaurs, Stratigraphy, Extensional tectonics

## 1. Introduction

The Iberian Rift System of eastern Spain formed part of the network of rifted basins that evolved on the northwestern Peri-Tethyan Platform during the break-up of Pangaea, and the opening of the Alpine Tethys and the North Atlantic. The Maestrazgo Basin forms part of the Iberian Rift System and developed during a rifting phase that commenced at the end of the Jurassic and lasted until mid-Albian times (Salas et al., 2001). The main objective of this work is to review the stratigraphy and tecto-sedimentary evolution of the western part of the Maestrazgo Basin (i.e., the Galve sub-basin) around the Jurassic-Cretaceous transition. Here we report on a revised stratigraphic framework, facies analysis and new biostratigraphic data, which allow a more complete understanding of the age and palaeoenvironmental setting of the numerous dinosaur fossil- and track sites found across the Galve sub-basin (e.g., Ruiz-Omeñaca et al., 2004).

When taking place in extensional basins developed in continental or marine coastal environments such as the Galve sub-basin studied here, discontinuous fault activity over space and time may result in rapid variations in thickness and facies, involving the development of local unconformities and stratigraphic gaps of variable amplitude. This, in turn, can make the correlation between the different sedimentary successions and fossil sites found across the basin challenging. A relevant example to illustrate these problems is provided by the discussion on the stratigraphic position and age of the first dinosaur to be described in Spain, the sauropod *Aragosaurus ischiaticus* Sanz, Buscalioni, Casanovas, Santafé, 1987 (**Fig. 1**). In Galve (the municipality where *Aragosaurus* was recovered), Diaz-Molina and Yébenes (1987) differentiated five lithostratigraphic units (units 1–5), bounded by significant sedimentary discontinuities. Unit 2 was developed around the Jurassic-Cretaceous transition, as indicated by the presence of the large benthic foraminifer *Anchispirocyclina lusitanica.* This unit was subsequently assigned to the Villar del Arzobispo Formation (e.g., Aurell & Meléndez, 1993). *Aragosaurus* was recovered in the overlying Unit 3 and was tentatively attributed to the Hauterivian by Diaz-Molina and Yébenes (1987). The latest Hauterivian–early Barremian age of Unit 4 was well constrained by the presence of the charophyte *Atopochara trivolvis triquetra* (Martín-Closas, 1989). Later on, Soria (1997) proposed that Units 3 and 4 would correspond to the upper Hauterivian–lower Barremian alluvial-lacustrine system represented by the lower and upper parts of the El Castellar Formation, respectively.

Canudo et al. (2012) characterized the unconformity between Units 2 and 3 in the Galve area by further logging and geological mapping, also providing new biostratigraphic data. Below this unconformity, the authors recovered the middle Berriasian charophyte *Globator maillardii incrassatus* in a marly level that was attributed to the uppermost part of the Villar del Arzobispo Formation, and they proposed that *Aragosaurus* was most probably Valanginian–Hauterivian in age (Fig. 1). More recently, Royo-Torres et al. (2014) have described an angular and erosive unconformity between Units 3 and 4 in Galve, but do not consider any significant discontinuity between Units 2 and 3. Therefore, according to Royo-Torres et al. (2014), Unit 3 would correspond to the upper part of the Villar del Arzobispo Formation, and the age of *Aragosaurus* would be thus older than previously considered, i.e. between the Tithonian and Berriasian, most likely Berriasian in age (Fig. 1).

The controversy about the age of *Aragosaurus* as detailed above rests upon the currently acceptance of the available stratigraphic framework for the Galve sub-basin at the Jurassic-Cretaceous transition (e.g., Soria, 1997; Salas et al., 2001), with the presence of two lithostratigraphic units: the Villar del Arzobispo Formation (Tithonian–middle Berriasian) and the El Castellar Formation (upper Hauterivian–lower Barremian). In accordance with this framework, there should be a single regional unconformity, located either at the bottom of Unit 3 (Canudo et al., 2012) or at the top of Unit 3 (Royo-Torres et al., 2014). The new data reported here show that this stratigraphic framework is not consistent. In fact, the angular unconformities described at the bottom and at the top of Unit 3 by Canudo et al. (2012) and Royo-Torres et al. (2014), respectively, both exist, and these justify the definition of a new lithostratigraphic unit bounded by regional unconformities (i.e., the Galve Formation, see Fig. 1). An additional unit developed as a result of extensional tectonic activity operating around the Tithonian–Berriasian transition is also defined here (i.e., the Aguilar del Alfambra Formation).

In summary, the purpose of this paper is: (1) to propose a revised stratigraphic framework for the Galve sub-basin around the Jurassic-Cretaceous transition; (2) to present new biostratigraphic and sedimentological data that provide precise information on the distribution, age and palaeoenvironments of the studied interval; (3) to present an updated report on the different dinosaur fossil sites found across the Galve and northwestern Penyagolosa sub-basins and (4) to discuss the impact of these results for a better understanding of the tecto-sedimentary evolution of the Galve sub-basin around the Jurassic-Cretaceous transition.

## 2. Geological setting and methods

The study area is located in the northeastern part of the Iberian Chain. The Iberian Chain developed as a result of the Alpine Palaeogene inversion of the Mesozoic Iberian Rift System. The Maestrazgo Basin is included in this rift system; it was produced by extensional tectonics that took place from the end of the Jurassic to mid-Albian times (e.g., Salas et al., 2001; Capote et al., 2002; Antolín-Tomás et al., 2007). The Maestrazgo Basin was divided into seven sub-basins bounded by areas with concentrations of major extensional faults. The results presented here are based on the analysis of 25 km wide x 50 km long area that covers the Galve sub-basin and the northern edge of the Penyagolosa sub-basin (**Fig. 2A**).

The Cenozoic compressional structure of the eastern part of the Iberian Chain, shows the superimposition of two orthogonal folding and thrusting structural trends striking around NNW–SSE and WSW–ENE, respectively (**Fig. 2B**). Both structural trends represent the rejuvenation and inversion of previous normal faults, essentially inherited from the Mesozoic extension and/or the post-Variscan fracturing (Guimerà & Salas, 1996; Liesa et al., 2004, 2006). During the Late Jurassic–Early Cretaceous rifting stage, differential subsidence in the Galve and northern Penyagolosa sub-basins was caused by the reactivation and the formation of these normal faults (Soria, 1997; Liesa et al., 2006). Significant tilting of blocks, low-angle angular unconformities and fan-shaped geometries of syn-rift deposits have been related to the listric geometry of the faulting (e.g., Salas, 1987; Liesa et al., 1996, 2006; Salas & Guimerà, 1997).

The stratigraphy of the Galve sub-basin is summarized in **Fig. 2C** and it comprises pre-, syn- and post-rift sequences in relation to the Late Jurassic–Early Cretaceous rifting stage. The pre-rift sequence consists of Upper Triassic lutites with gypsum (Keuper facies) followed by a 400–600 m thick Jurassic succession, deposited in shallow to relatively deep carbonate platforms (e.g., Aurell et al., 2003). The syn-rift series can be divided into two sequences (Liesa et al., 1996): the mid Tithonian–mid Berriasian syn-rift sequence 1 (Villar del Arzobispo and Aguilar del Alfambra formations, up to 650 m thick), and the mid Berriasian–mid Albian syn-rift sequence 2 (more than 1000 m thick in the depocentral areas). Syn-rift sequence 2 includes a dominantly continental-transitional series (*Weald* facies; Soria, 1997; Salas et al., 2001), incorporating in its lower part the Galve Formation defined here, followed by Aptian shallow carbonate platform facies (*Urgon* facies, e.g., Vennin & Aurell, 2001; Bover-Arnal, 2010; Peropadre et al., 2013). The post-rift sequence includes Albian continental sandstones (Utrillas Formation) and Upper Cretaceous shallow marine carbonates. The overlying Cenozoic terrigenous and lacustrine deposits are coeval with the Alpine basin inversion.

The revision of the stratigraphy of the middle Tithonian–lowermost Barremian units of the Galve sub-basin presented here is based on new data acquired after extensive geological mapping and logging in certain key reference localities (**Fig. 2B**), complemented with a review of the published information. The workflow relevant to this paper consisted of: (1) extensive review of the available data on the stratigraphy, sedimentology and palaeontology of the Galve and northwestern Penyagolosa sub-basins; (2) geological mapping based on fieldwork and an analysis of the high-resolution aerial imagery available at http://sigpac.mapa.es/fega/visor/; (3) production of detailed stratigraphic sections to a decimetre scale, including rock and palaeocurrent measurement in the field; (4) facies analysis (microfacies, petrography) and microfossil determination; and (5) the integration of different data sets.

## 3. Data and results: a revised stratigraphic framework for the Galve sub-basin

Two new lithostratigraphic units are defined, the Aguilar del Alfambra and the Galve formations (**Table 1**). The type locality of the Aguilar del Alfambra Formation is located west of the village of Aguilar del Alfambra. The type locality of the Galve Formation is located in the eastern limb of the Galve syncline, in the site of Pelejón (**Fig. 3**). The main lithological and facies distributions that characterize these two formations are shown in the six key logs studied in this work (**Fig. 4**). A summary of the key stratigraphic, sedimentological, palaeontological and structural observations across different areas of the Galve sub-basin and in the northwestern part of the Penyagolosa sub-basin is presented below.

The Galve and Aguilar del Alfambra formations have been proposed as independent lithostratigraphic units compared with other, potentially similar lithostratigraphic units defined in other areas of the basin, taking into account the recommendations of the *International Stratigraphic Guide* (Murphy & Salvador, 1999). In particular, this guide indicates that *the stratigraphic sequences of similar lithologic composition but separated by regional unconformities or major hiatuses should be mapped as separate lithostratigraphic units* (Murphy & Salvador, 1999, p. 260), and this is the case of the Aguilar del Alfambra and the Galve formations defined here.

### *3.1. Northwestern Galve sub-basin (1): the Galve syncline*

The Galve syncline is an N-S trending Alpine structure, exposing along more than 7 km the Upper Jurassic–Lower Cretaceous units across its western and eastern flanks. This continuous outcrop allows analysis of the sedimentary record at the northwestern margin of the Galve sub-basin. Around the village of Galve there are abundant fossil sites including Las Zabacheras, the recovery site of the sauropod *Aragosaurus ischiaticus* (see Canudo et al., 2012; Royo-Torres et al., 2014), and the Las Cerradicas tracksite (Pérez-Lorente et al., 1997). According to our stratigraphical proposal, the site of Las Zabacheras is located in the lower part of the Galve Formation and the Las Cerradicas tracksite in the upper levels of the Villar del Arzobispo Formation.

Geological mapping in the area located close to Galve (**Fig. 5**) reveals the existence of an erosive unconformity between the Villar del Arzobispo and Aguilar del Alfambra formations. Relevant field relationships can be seen southwest of Las Zabacheras, where a set of normal faults produced the tilting and erosion of the upper levels of the Villar del Arzobispo Formation. The Aguilar del Alfambra Formation consists of a 5–12 m-thick succession of light grey marlstones followed by a set of dm-thick, irregularly bedded limestones (ranging from mudstones to peloidal packstones, see Figs. 4 and 5). Discrete thickness changes observed in this unit are linked to synsedimentary fault activity, as observed west of the village of Galve (Fig. 5). Discontinuous dm-thick conglomeratic levels including rounded calcareous pebbles are found in different levels of the unit. The last marly level belonging to the Aguilar del Alfambra Formation has yielded the middle Berriasian charophyte *Globator maillardii incrassatus* near Las Zabacheras (Canudo et al., 2012) and west of the village of Galve (see 1a and 1b in Figs. 4 and 5).

The unconformity between the Aguilar del Alfambra and Galve formations corresponds to the unconformity previously described in Canudo et al. (2012). At Las Zabacheras, the Galve Formation consists of a 78 m-thick succession dominated by red lutites with interbedded burrowed and cross-bedded sandstones (Fig. 4). Laterally, the Galve Formation shows large isolated sandstone bodies with evidence of lateral accretion (i.e., point-bar geometries, see Fig. 5, west of the Galve village). There are also discontinuous levels with channel bases that host large oncolites up to 15 cm in diameter, some of them including freshwater bivalves in their cores (Royo-Torres et al., 2014). Between Las Zabacheras and Las Cerradicas there is thickness variation in the Galve Formation that is related to synsedimentary fault activity (Canudo et al., 2012). Near the top of the unit (see 2 in Figs. 4 and 5), above a silty-limestone level, Canudo et al. (2012) found the latest Berriasian–Hauterivian charophyte *Globator maillardii steinhauseri*.

The upper Hauterivian–lower Barremian El Castellar Formation generally starts with a calcrete level, which rests above different levels of the underlying Galve Formation, indicating the presence of a low-angle erosive unconformity that can be traced across the Galve syncline area (Royo-Torres et al., 2014). Around Las Zabacheras the formation is 25–30 m thick and consists of burrowed marls and irregularly bedded bioclastic wackestones-packstones.

The stratigraphic relationship described above can be observed across the Galve syncline, and the studied units are bounded by erosive unconformities, in many cases underlined by the presence of fossilized normal faults. However, the distribution of the Aguilar del Alfambra Formation is more irregular, and it is absent in the northern half of the eastern flank of the syncline. In this case, there is a major erosive unconformity between the Galve Formation and the underlying Villar del Arzobispo Formation, and the thickness of the Galve Formation reaches around 30–40 m.

### *3.2. Northwestern Galve sub-basin (2): the Pelejón-Abeja anticline*

Eastwards of the Galve syncline, there is an N–S trending anticline located between the logged localities at Pelejón and Abeja (Fig. 2.B). The thickness and facies reconstruction of this area is based on the physical correlation of the master beds identified in these two reference logs (Fig. 4) across the well-exposed outcrop **(Fig. 6)**. There are dramatic changes in thickness in the Aguilar del Alfambra and Galve formations along the western (Pelejón) and eastern (Abeja) flanks of this anticline.

Around Pelejón, the Aguilar del Alfambra Formation consists of marls and peloidal limestones (Fig. 4). The thickness variation of this formation across the western flank of the anticline (i.e., from 5 to 15 m) is related to synsedimentary fault activity. These faults have a nearly E–W trend, dipping to the south (see P1 in Fig. 6A, upper left). Some of these faults are fossilized by the erosive unconformity found at the base of the Aguilar del Alfambra Formation.

On the eastern flank of the anticline, the Aguilar del Alfambra Formation thickens up to the 105 m measured near Abeja (Figs. 4 and 6). The unit mainly consists of red lutites with discontinuous interbedded sandstones (up to 100 m in lateral continuity, see levels Aj1, Aj2 and Aj4 in Fig. 6), as well as continuous micritic to peloidal limestones with benthic foraminifera (levels Aj3, Aj5, Aj6 and Aj7 in Fig. 6). These limestones can be laminated (cryptalgal lamination), including levels with fenestral porosity and local dinosaur footprints (level Aj5).

In the area located in the hinge of the anticline, the thickness of the Aguilar del Alfambra Formation is progressively reduced to 40–70 m, and it is formed by a succession of lutites with abundant channelized sandy levels with conglomeratic bases (Fig. 6). The lower siliciclastic level Aj1 has been correlated up to this hinge area, and this level is in turn located above level P1 logged in Pelejón. Therefore, level P1 marks the onset of the deposition of the Aguilar del Alfambra Formation in the hinge area. In this area, the upper part of the formation includes a 2 m-thick carbonate level that may be equivalent to level Aj5 of Abeja.

In the type locality of Pelejón, the Galve Formation consists of a 65 m-thick succession dominated by red lutites with intervals of hydromorphic soils (Figs. 3, 4 and 6), with interbedded, cross-bedded and tabular, burrowed, dm- to m-thick sandstones. Towards the upper part of the succession, there is an up to 1 m-thick discontinuous level (see P5 in Figs. 4 and 6) that includes large, poorly rounded calcareous pebbles, some of them derived from the erosion of the underlying Aguilar del Alfambra Formation. In contrast, around Abeja the Galve Formation is very reduced in thickness, down to less than 10 m. The unit consists of a lower red lutitic interval with intercalations of dm-thick burrowed sandstones, followed by 1–2 m thick a conglomeratic level rich in carbonate pebbles.

The thickness distribution of the overlying El Castellar Formation is more regular around the Pelejón-Abeja anticline, ranging from 20 to 40 m; in its upper part it shows its typical aspect of alternating marls and burrowed bioclastic limestones. The lower part of the unit is more variable in thickness and lithology. In particular, near Pelejón the unit starts with an up to 10 m-thick level of channelized white sandstones (see grey level in Fig. 6B).

The normal faults mapped in the area can be grouped into two nearly orthogonal family sets with trends NNW-SSE and E-W, respectively. The NNW-SSE trending faults are dipping to the west and constitute the main extensional structures of the outcrop (faults 1 and 2 in Fig. 6A), defining half-graben structures in a W-E cross-section (Fig. 6B). Fault 1 was active during the deposition of the Aguilar del Alfambra Formation, controlling a wedge-shaped geometry open to the east (towards the fault) and the thinning of the initial fill (levels Aj1 to Aj3) towards the west. Fault 2 was activated later on during the deposition of the Galve Formation. This fault cut through the previously produced extensional structure and was responsible for the thicker record of the Galve Formation on its western fault block (the hangingwall), and for the local erosion of the Aguilar del Alfambra Formation and its footwall (near the fault plane), with the formation of a low-angle angular unconformity between the Aguilar de Alfambra and Galve formations. The nearly E-W trending faults are dipping towards the south and seem also to control the deposition of the Aguilar del Alfambra Formation. These faults are smaller and with more minor displacements than the NNW-SSE trending ones. The overlying Galve Formation is less affected by this set of faults, and even fossilizes some of them (see faults near Abeja, Fig. 6).

### *3.3. Central Galve sub-basin: Aguilar del Alfambra village and the Ababuj anticline*

Near the village of Aguilar del Alfambra and around the N-S trending Ababuj anticline (Fig. 2), there are continuous and clean outcrops that favour detailed stratigraphic and facies analysis. In these areas, there is a low-angle unconformity and a sharp lithological change between the Villar del Arzobispo and the Aguilar del Alfambra formations. This unconformity is well visible in the continuous outcrop located north of the village of Aguilar del Alfambra, with some normal faults involving tilting and erosion of the upper part of the Villar del Arzobispo Formation (**Fig. 7A**).

The Aguilar del Alfambra Formation shows an overall increase in thickness from north to south (Fig. 4): it is 240 m thick north of Aguilar del Alfambra village (Fig. 3), 345 m thick in the log measured west of the Ababuj anticline, and around 400 m thick in the log from Los Cerezos measured west of Allepuz. The unit consists of an alternation of red lutites and white to light grey limestones, with intercalations of discontinuous light grey sandstone levels. The proportion of these sandstones decreases to the south. The carbonates consist of well-bedded dm-thick lime mudstone to peloidal beds, with frequent cryptalgal lamination and fenestral porosity. These carbonate levels have yielded dinosaur track sites that have been described near Ababuj (Alcalá et al., 2012) and near Aguilar de Alfambra (Mampel et al., 2010-11; Herrero-Gascón & Pérez-Lorente, 2012).

In the logs measured near Aguilar del Alfambra and Ababuj, towards the middle-upper part of the unit (i.e., levels A4 and Ab4 in Figs. 4 and 7) there is a bioclastic level rich in vertebrates, plant debris and charophytes, mixed with marine fossils (oysters, benthic foraminifera, dasycladacean algae, echinoderms). This level contains abundant *Anchispirocyclina lusitanica* and was used a marker bed for correlation between logs. The micritic-laminated to peloidal carbonate levels found below and above this bioclastic level seem to be continuous at a regional scale and are also tentatively correlated (see discontinuous lines in Fig. 4).

In the outcrops studied near Aguilar del Alfambra village, the Galve Formation is absent and the El Castellar Formation rests unconformably upon the uppermost carbonate-laminated levels of the Aguilar del Alfambra Formation (A6 in Fig. 7A). In these areas, the El Castellar Formation consists of a lower member with 10 m-thick cross-bedded sandstones topped by 5 m-thick reddish-orange gypsiferous lutites. The upper member of the El Castellar Formation has its typical aspect and consists of an up to 40-m-thick alternation of ochre-coloured marls with root traces and skeletal limestones, with abundant charophytes and bivalves.

North of the village of Ababuj, close to the northern end of the Ababuj anticline, there is an erosive unconformity between the Aguilar del Alfambra and Galve formations (see levels Ab5 and Ab6 in **Fig. 7B**). The Galve Formation consists of a 51 m-thick succession of burrowed silty/micritic and marly levels with abundant root traces followed by red lutites with intercalations of cross-bedded and conglomeratic levels. A reddish conglomeratic level found towards the top of the Galve Formation has abundant calcareous pebbles, some of them with microbial covers giving rise to incipient oncolites. Above the Galve Formation, the lower member of the El Castellar Formation consists of a 20 m-thick interval with sandstones followed by grey marls (including the latest Hauterivian–earliest Barremian charophyte *A. t. triquetra*, see 1 in Fig. 7) and gypsiferous lutites. The upper member forms the more characteristic alternation of marls and burrowed skeletal limestones, with an overall thickness ranging from 30 to 40 m.

The distribution of the Aguilar del Alfambra and Galve formations has also been studied in the outcrops located along the eastern flank of the Ababuj anticline, west of Allepuz and Gúdar villages (Fig. 2). These outcrops represent the sedimentation in the depocentral area of the Galve sub-basin (Soria, 1997). The log analysed in Los Cerezos, northwest of Allepuz (Fig. 4), exposes 380 m of the Aguilar del Alfambra Formation. The boundary with the underlying Villar del Arzobispo Formation is covered in this log, although mapping of the area shows that the total thickness of the unit is around 400 m. Of particular interest in this log is the abundance of levels indicating marine influence (oolitic and skeletal levels with abundant oysters, gastropods, dasycladacean algae and foraminifera), which are concentrated towards the middle-upper part of the unit (Fig. 4). Remarkable new biostratigraphic data have been obtained in the Los Cerezos log, towards the top of the Aguilar del Alfambra Formation, consisting of the presence of the ostracod *Theriosynoecum fittoni*. This ostracod has been identified in a sediment sample from a dark-grey lutitic layer, which is rich in plant remains (meter 330 in the Los Cerezos log, see Fig. 4). The stratigraphic range of the species *Theriosynoecum fittoni* is lower Berriasian to Barremian (Schudack & Schudack, 2009), which confirms a Cretaceous age for the Aguilar Formation, at least in its upper part. The overlying Galve Formation is 80 m thick and consists of red lutites with interbedded burrowed and cross-bedded sandstones and conglomerates. The El Castellar Formation is 50 m thick and has a 10 m-thick lower member of sandstones and red lutites, locally including gypsum levels.

In the outcrops studied northwest of the village of Gúdar (see Caña Seca in Fig. 2), the Aguilar del Alfambra Formation is around 400 m thick. The overlying Galve Formation is formed by a 20–30 m thick succession of red lutites, including burrowed dm-thick sandstones and a conglomeratic level in its middle part. The El Castellar Formation is 60 m thick and has a lower level of discontinuous white sandstone up to 5 m thick, with cross-bedding and lateral accretion geometries. The rest of the unit is dominated by alternating brown-yellow marls and burrowed skeletal limestones, with two vertebrate fossil sites one found in the lower and in the other in the middle part of the unit (Gasca et al., 2012).

### *3.4. Northeastern Galve sub-basin: the Aliaga-Miravete anticline*

The western flank of the nearly N-S trending Aliaga-Miravete anticline allows the analysis of the Tithonian–lower Barremian units exposed in the northeastern part of the Galve sub-basin. The two key areas selected in this work for the characterization of the Aguilar el Alfambra, Galve and El Castellar formations are located east of Miravete de la Sierra village and 1 km south of Aliaga village (Molino Alto: Cuenca-Bescós et al., 2014), respectively.

In Miravete de la Sierra (**Fig. 8**), the Villar del Arzobispo Formation is poorly represented by a 10–20 m-thick succession of skeletal, peloidal and oolitic limestones alternating with m-thick marly intervals. The limestone levels contain frequent *Anchispirocyclina lusitanica*. The lower 12 m of the log studied by Soria et al. (1995) east of Miravete de la Sierra belong to this unit. The overlying Aguilar del Alfambra Formation forms a 165 m-thick succession with an alternation of m-thick red lutites and intervals of alternating whitish to light grey marls and dm-thick micritic to peloidal limestones with common cryptalgal lamination and fenestral porosity (Soria et al., 1995). Sandstone levels are scarcer compared to the outcrops located around Aguilar-Ababuj. In Miravete, the carbonate levels commonly include miliolids and ostracods. In the middle part of the succession there is a 1–2 m thick bioclastic and peloidal limestone interval, rich in dasycladacean algae and large benthic foraminifera, including abundant *Anchispirocyclina lusitanica* (see AL level in Fig. 8). The Galve Formation is absent around Miravete de la Sierra, and there is a significant erosive and angular unconformity between the Aguilar del Alfambra and the El Castellar formations (Fig. 8). The El Castellar Formation is around 60 m thick and includes a lower marly/lutitic level rich in gypsum (Meléndez et al., 2009).

South of Aliaga, on the west side of the road to Miravete de la Sierra, there is a complete exposure of the Aguilar del Alfambra, Galve and El Castellar formations **(Fig. 9).** The Aguilar del Alfambra Formation has a thickness of around 200 m, and it contains larger proportion of lutitic intervals compared to Miravete. The Galve Formation is up to 90 m thick in Molino Alto, and consists of red lutites with intercalations of cross-bedded sandstones and conglomeratic levels with abundant calcareous clasts (**Fig. 10**). The sedimentation of this conglomerate-rich succession was related to the activity of NNW–SSE normal faults that resulted in the formation of isolated half-grabens, with faulted blocks tilted eastwards (Fig. 9; see Liesa et al., 2006). These faults were also active during the deposition of the El Castellar Formation. As a whole, there is an increase in the thickness of the upper, carbonate-dominated member of the El Castellar Formation towards the NW (from 40 to 80 m, see Liesa et al., 2006).

The section logged in Molino Alto was extensively sampled for micropalaeontological analysis. Fifteen of these samples contain charophyte fructifications, including the four varieties of *Atopochara trivolvis* (Fig. 10). The samples studied from the Galve Formation have a poor charophyte content (less than 10 charophytes per 2 kg of samples) except sample SAL3, which was extensively studied (i.e., 50 kg of sample collected) for further characterization of the charophyte association. The presence of *Atopochara trivolvis horrida* in samples SAL1, 3, 4, 6 and 7 located indicates a Berriasian age for the lower and middle part of the Galve Formation (Martín-Closas, 2000). The charophyte association found in sample SAL3 is dominated by *Clavatoraxis* sp. and *Atopochara trivolvis horrida*, with the occasional presence of *Clavator grovesii grovesii* and *Atopochara trivolvis micranda*. *Clavatoraxis* sp. is of low biostratigraphic interest. *Clavator grovesii grovesii* was exclusively developed during the Berriasian (Martín-Closas, 2000). In terms of size and exposure, the vegetative structures of the *Atopochara trivolvis* found in the Galve Formation show intermediate morphologies between the *horrida* and *micranda* varieties, although the *horrida* variety is better represented, at least in sample SAL3. According to Riveline et al. (1996), *Atopochara trivolvis horrida* appears in the Berriasian, and the transition to the variety *Atopochara trivolvis micranda* occurs in the *Globator maillardii incrassatus* Zone (upper part of the middle Berriasian).

There is a discontinuity indicated by a sharp lithological change between the red-coloured Galve Formation and the light brown to ochre-coloured lutites, sandstone and limestones of the overlying El Castellar Formation (Fig. 9). In Molino Alto, the El Castellar Formation reaches a significant thickness of around 100 m (Meléndez et al., 2009) and consists of a lower lutitic and sandy member, and an upper member with marls and lutites (including gypsum levels) and burrowed skeletal limestones (Fig. 10). The eastward dipping faults controlling the half-graben formation in the previous stage (i.e., the Galve Formation) were also active during the deposition of the lower member of the El Castellar Formation. As a whole, however, the thickness of the upper, carbonate-dominated member of the El Castellar Formation increases towards the NW (from 40 to 80 m, see Liesa et al., 2006). This increase in thickness is well observed in the area mapped here south of Aliaga (Fig. 9) and has been related to the activity of the WSW-ENE trending, south-dipping major Aliaga normal fault located 1 km north of this outcrop (Liesa et al., 2006). The set of normal faults affecting mainly the upper member of the El Castellar Formation also constituted growth faults during the deposition of the El Castellar Formation.

The El Castellar Formation includes the fossil site of Molino Alto 1 in its middle part (see Fig. 10 for location), known for its fossil content including dinosaurs and mammals (Cuenca-Bescós et al., 2014). The presence of *Atopochara trivolvis triquetra* in samples SAL12 to SAL19 indicates an early Barremian age (Riveline et al., 1996) for the middle and upper part of the El Castellar Formation. The age attribution of the lower part of this unit, from the Valanginian to the Hauterivian, remains uncertain (Fig. 9).

### *3.5. Northwestern Penyagolosa sub-basin: a review*

The northwestern part of the Penyagolosa sub-basin was reviewed in order to achieve a further understanding of the lateral continuity of the two lithostratigraphic units defined in this work. The NW–SE trending Cedrillas fault area separates the Galve and Penyagolosa sub-basins (Fig. 2). Close to this faulted area, there is a continuous outcrop between the villages of Monteagudo del Castillo and Alcalá de la Selva. Further south, of particular interest for this review are the type localities of the El Castellar and Mora de Rubielos formations (Canerot et al., 1982; Salas, 1987).

The Villar del Arzobispo and Aguilar del Alfambra formations are well exposed south of the village of Monteagudo del Castillo (**Fig. 11**). Evidence for an erosive unconformity between the two units is provided by the presence of normal faults affecting the Villar del Arzobispo Formation, which are fossilized by the Aguilar del Alfambra Formation. The Aguilar del Alfambra Formation has a minimum thickness of 310 m and consists of an alternation of four 30–70 m-thick intervals of red lutites with channelized and cross-bedded sandstones, followed by four 10–30 m-thick intervals of white to pale grey marlstones and micritic-peloidal limestones (see levels M1–M4 in Fig. 11). These limestones are organized in dm-thick beds, with frequent cryptalgal lamination and fenestral porosity. In the uppermost level, M4, marine fossils are abundant, including a level with dm to m-thick oyster patch reefs. The outcrops located south of Monteagudo also allow the characterization of the boundary between the Aguilar del Alfambra and El Castellar formations (Fig. 11). In these areas, the El Castellar Formation consists of a 20 m-thick alternation of marls and skeletal limestones (bivalves, gastropods, charophytes) with vertical root traces. The Galve Formation is absent in this marginal area located between the Galve and Penyagolosa sub-basins.

The clear differentiation between the Villar del Arzobispo and Aguilar del Alfambra formations observed south of Monteagudo del Castillo can be traced southwards, along the wide Tithonian–Berriasian outcrops located east of El Castellar village (see Fig. 2). Of particular interest are the upper levels of the Tithonian–Berriasian successions exposed near El Castellar village, including micritic-peloidal laminated limestone levels with abundant dinosaur footprints (Alcalá et al., 2014). These levels have a characteristic fenestral porosity and are interbedded between red lutitic intervals and sandstones. Although this unit rich in dinosaur footprints has been attributed to the Villar del Arzobispo Formation (e.g., Alcalá et al., 2014), it actually fits well in its key lithological features and stratigraphic position to the Aguilar del Alfambra Formation defined in this work in the Galve sub-basin. The thickness of the Aguilar del Alfambra Formation exposed east of El Castellar village has been estimated to range around 400 m.

Near the village of El Castellar, there is a low-angle unconformity between the upper carbonate and sandy levels attributed here to the Aguilar del Alfambra Formation and the overlying El Castellar Formation (Gautier, 1981). This latter unit starts with a 10-20 m-thick interval of lutites with interbedded channelized ochre-coloured cross-bedded sandstones. The upper part of the unit consists of a 25 m-thick alternation of grey marls and burrowed skeletal limestones, including abundant ostracods, charophytes, bivalves, gastropods and fish teeth (Salas, 1987; Royo-Torres et al., 2014). This unit yielded *Atopochara trivolvis triquetra* both in the lower and upper intervals and was assigned to the latest Hauterivian–earliest Barremian (Martín-Closas, 1989; Martín-Closas et al., 2009).

The southernmost outcrops reviewed in this work, located around the village of Mora de Rubielos (Fig. 2), include the type locality of the Mora de Rubielos Formation (Canerot et al., 1982). This unit has a stratigraphic position similar to that of the Galve Formation, wedged between the upper Villar del Arzobispo Formation (equivalent to the Aguilar del Alfambra Formation defined in the Galve sub-basin) and El Castellar formations. The Mora de Rubielos Formation consists of an up to 150 m-thick alternation of sandstones and reddish lutites, also including conglomeratic levels with abundant calcareous pebbles (Canerot et al., 1982). The unit has been interpreted as deposited in alluvial plains within a setting of meandering rivers, as indicated by the frequent point-bar geometry in the sandstone levels (García-Ramos, 1985; Salas et al., 2001). The common presence of root traces, calcrete levels, plant debris and freshwater ostracods is coherent with this interpretation. This unit has a limited areal distribution in the northwestern part of the Penyagolosa sub-basin, south of the village of Cabra de Mora (see Fig. 2 for location; Gautier, 1981; Canerot et al., 1982). The age of the unit is open to discussion due to the absence of precise biostratigraphic markers. It has been dated to the Valanginian (Gautier, 1981; Canerot et al., 1982) or the upper Berriasian–lower Valanginian K1.1 sequence (Salas et al., 2001).

## 4. Sedimentological remarks

The results of the facies analysis carried out on the Aguilar del Alfambra and Galve formations are summarized below. The sedimentological analysis of the lacustrine system represented by the sandstones, gypsiferous clays, marls and skeletal limestones that characterize the El Castellar Formation was done by Meléndez et al. (2009).

### *4.1. Aguilar del Alfambra Formation*

The Aguilar del Alfambra Formation includes a wide variety of carbonate tidal flat-lagoon facies and siliciclastic tidal flat facies. These are stacked in alternating siliciclastic- and carbonate-dominated packages (Figs. 4 and **12**), but may also be laterally related at the outcrop scale (e.g., AJ5 and AJ6 reference levels in the Abeja section; Fig. 4).

Supra- to shallow subtidal carbonate facies encompass alternations of cm- to dm-thick bedded cryptalgal-peloidal laminites and peloidal packstones-grainstones, and marly to bioturbated silty limestones (Fig. 12A). The cryptalgal-peloidal laminites have ubiquitous fenestral porosity and show tepees, desiccation cracks (Fig. 12B, C), and local root traces; the intercalated peloidal packstones-grainstones include quartz silt and small skeletal grains (mainly miliolids, textulariids, gastropods, bivalves, ostracods, and occasional turtle bones), and present parallel and cross lamination and symmetric and asymmetric ripples, and local hummocky cross stratification, bioturbation (*Arenicolites*, *Thalassinoides*, root traces) and desiccation cracks. Marls and bioturbated silty limestones, with plant fragments, bioturbation (*Arenicolites*, *Thalassinoides* and root traces), local desiccation cracks, and small ostreid and serpulid patches, are likely to represent ponds in the tidal flat. These supra- to shallow subtidal facies have frequent dinosaur tracks (e.g., the Aguilar 1-4 and Ababuj track sites; Fig. 4), dm-thick levels rich in characean algae and cm-thick intraclastic breccias.

Bioturbated bioclastic wackestones-packstones and oolitic packstones-grainstones dominate in the southern areas (the Ababuj and Los Cerezos sections; Figs. 4 and 12D) and stack in dm-thick beds intercalated in siliciclastic and carbonate muddy tidal facies. They have a high variety of skeletal grains, reflecting more open marine, shallow-water (lagoon) areas located towards the south. The bioturbated bioclastic wackestones-packstones have traces of *Thalassinoides* and include fragmentary or complete gastropods and bivalves (including ostreids), ostracods, characean algae, miliolids, textulariids, as well as fragments of lituolids, ooids and dasycladacean algae. The oolitic packstones-grainstones contain ooids with well-developed micritic and sparitic laminae and skeletal grains (mainly dasycladacean algae, lituolids including *Anchispirocyclina lusitanica*, echinoderms, bivalves and gastropods). They correspond to oolitic banks formed in open lagoons or to wedge-shaped dm-thick washover deposits intercalated in tidal flat facies (Fig. 12D). The bioturbated bioclastic wackestones-packstones and oolitic washover deposits cover the dinosaur track levels (Fig. 4).

The dominant siliciclastic facies are massive or laminated red to grey lutites with occasional plant fragments and root traces (Figs. 4 and 12A). The vertical and lateral stacking of red to grey lutites and marly pond deposits represent siliciclastic muds deposited on muddy tidal flats lateral to carbonate tidal flats. The lutites are intercalated with sandy deposits including cross-bedded sandstones and laminated and/or bioturbated sandstones, and heterolithic (lutite-sandstone) alternations towards more open, shallow-marine areas (Fig. 4). Channels correspond to coarse to fine sandstones arranged in dm-to m-thick concave-plane or plane-convex lenticular beds, with planar and trough cross-bedding and frequent lateral accretion surfaces and mud drapes (Fig. 12E) that grade laterally into laminated and/or bioturbated sandstones or to heterolithic (lutite-sandstone) alternations. This observation, together with the variable palaeocurrent direction (NE, SW, NW-SE; Fig. 4), as well as the presence of lutite and lime mudstone intraclasts, plant fragments, bioclasts (gastropods, bivalves, including ostreids) and glauconite grains, reflect a marine influence and tidal-current action. The deposition of dm-thick tabular laminated and/or bioturbated fine to medium sandstones and that of cm-thick heterolithic (lutite-sandstone) alternations was also controlled by tidal action, as indicated by the presence of parallel lamination and symmetric, asymmetric ripples, traces of *Arenicolites*, lutite pebbles and ostreid fragments (Fig. 12F, G). The observed facies distribution (Fig. 4) and the sedimentary features of these deposits indicate siliciclastic facies representing tide-influenced fluvial channels in muddy tidal flats to muddy-sandy tidal flats to the SE. Local, dm-thick, poorly sorted conglomerates, including trunk fragments, dinosaur bones, lime mudstone intraclasts (cryptalgal-peloidal facies), bivalves and ostreids, are present at the base of cross-bedded sandstones or as isolated beds. They would represent basal lags of channels or high-energy flow events (floods, storms) on the tidal flats.

### *4.2. Galve Formation*

The Galve Formation represents deposition in a distal alluvial plain, in extensive floodplain areas and related fluvial channels. It is formed dominantly by fine-grained overbank deposits (red to ochrish lutites and occasional grey lutites and silty limestones) that intercalate with coarse-grained deposits including channels (cross-bedded sandstones), levee and crevasse splay deposits (laminated and/or bioturbated sandstones), and flash-flood deposits (poorly bedded conglomerates) (Figs. 4 and **13**).

The dominant red to ocherish, up to 7.5 m-thick massive lutites represent fine-grained floodplain facies oxidized under subaerial conditions (Fig. 13A, B, D). Occasional colour mottling and dm-thick intervals with vertical root traces reflect hydromorphic soil horizons. Local, more humid floodplain areas are also indicated by discrete dm- to m-thick grey lutites with frequent root traces and local edaphic carbonate nodules (Fig. 13D), while dm-thick sandy peloidal limestones with characean algae and plant remains, ripples and bioturbation would represent small ponds. The dm-thick bedded fine to medium sandstones with parallel lamination, ubiquitous bioturbation including *Taenidium* traces (Fig. 13C, D) and local cross-lamination, ripples and convolute bedding are interpreted as crevasse splays. Dinosaur tracks are also present (e.g., Corrales de Pelejón tracksite; Fig. 4).

The channel deposits correspond to few decametres wide and m-thick ribbon bodies of coarse-to-fine cross-bedded sandstones usually with gentle bank margins, and local conglomerates in their basalmost part (Fig. 13A, B, C). The ribbon bodies are isolated or offset stacked. Channel-fill sediments have lateral accretion surfaces reflecting the steady lateral migration of the channel (i.e., point-bar deposits; Figs. 4 and 13B), complex vertical stacking of planar- and trough cross-bedded sets, as well as simple trough cross-bedding. The orientation of the ribbon bodies is variable even between areas close to one another: e.g., the ribbon bodies are NE-SW oriented in Galve (Fig. 5), but NW-SE oriented in Pelejón (Fig. 13A). The palaeocurrents in cross-bedded sets reflect the fact that the location of source areas was variable, ranging from NW to NE (Fig. 4). Levee deposits are represented by wedge-shaped dm-thick massive to parallel-laminated sandstone beds that extend laterally a few decametres from the channel margin (Fig. 13B). Conglomerate flash-flood deposits form dm-thick lenticular levels with irregular erosive bases and crude horizontal and cross bedding that passes vertically to coarse and medium sandstones with pebbles. Conglomerates are clast-supported and formed by a coarse sandstone matrix and poorly sorted clasts (granules to pebbles up to 10 cm in diameter) with variable roundness and lithology (sandstone, mudstone, lime mudstone). Dinosaur bone remains and oncolitic coatings on clasts and freshwater bivalves are also present.

## 5. Discussion of results and implications

### *5.1. Age and equivalent units to the Aguilar del Alfambra and Galve formations*

The Villar del Arzobispo and the Aguilar del Alfambra formations together form a middle Tithonian–middle Berriasian long-term sequence (Aurell et al., 1994, 2003; Salas et al., 2001). This so-called J10 sequence represents the end of the sedimentation of the Jurassic supersequence in the Maestrazgo Basin (**Fig. 14**). However, the regional erosive unconformity described here between the Villar del Arzobispo and the Aguilar del Alfambra formations results in the differentiation between the J10.1 and J10.2 sequences in the Galve sub-basin. This unconformity represents a relative fall in sea level at the end of the Jurassic in the studied Galve sub-basin, indicated by the sharp transition from coastal to shallow marine environments (Villar del Arzobispo Formation; e.g., Díaz-Molina & Yébenes, 1987; Aurell et al., 1994) to carbonate and siliciclastic tidal flats (Aguilar del Alfambra Formation).

The unconformity between the Villar del Arzobispo and the Aguilar del Alfambra formations is located around the late Tithonian and has been tentatively correlated to the Major Cycle Boundary 146.2 of Haq (2014). The Villar del Arzobispo Formation contains *Anchispirocyclina lusitanica* at different stratigraphic intervals (e.g., Díaz-Molina & Yébenes, 1987; Bádenas et al., 2004; Aurell et al., 2010). This large benthic foraminifer, which ranges from the middle Tithonian to the earliest Berriasian (e.g., Hardenbol et al., 1998; see Fig. 14) is also found in some marine levels interfingered towards the middle and upper part of the overlying, newly defined, Aguilar del Alfambra Formation (Fig. 4). Other relevant biostratigraphic data come from around the village of Galve, where the uppermost levels of the Aguilar del Alfambra Formation contain the middle Berriasian charophyte *Globator maillardii incrassatus*. The presence of the ostracod *Theriosynoecum fittoni* in the Los Cerezos log also confirms a Cretaceous age for the Aguilar Formation, at least in its upper part. Accordingly, the Aguilar del Alfambra del Alfambra Formation was most probably deposited during the late Tithonian–middle Berriasian timespan.

The boundary between the Aguilar del Alfambra and Galve formations corresponds to a major unconformity described across the entire Maestrazgo Basin between the Jurassic and Cretaceous supersequences (see the boundary between the J10 and K1.1 sequences in Fig. 14). This major sequence boundary has traditionally been placed around the middle-late Berriasian transition (Salas & Casas, 1993; Aurell et al., 1994; Salas et al., 2001; Bádenas et al., 2004). The biostratigraphic data reported here indicate that, in the Galve sub-basin, the boundary between these two sequences is located towards the top of the middle Berriasian (Fig. 14).

In the Galve sub-basin, above this unconformity the sedimentation was irregular and discontinuous, with the local record of the terrigenous continental facies represented by the Galve Formation defined in this work. The onset of the deposition of this unit was well constrained by biostratigraphic data in the Molino Alto section and occurred around the middle-late Berriasian transition, at the top of the *Globator maillardii incrassatus* Zone. In addition, in Las Zabacheras the upper levels of the Galve Formation contain *Globator maillardii steinhauseri* (Canudo et al., 2012), which ranges from the late Berriasian to the Hauterivian (Fig. 13; Riveline et al., 1996). Above this unit, the El Castellar Formation corresponds to the uppermost Hauterivian–lowermost Barremian K1.4 sequence (Soria, 1997; Salas et al., 2001).

According to the available biostratigraphic data, the equivalence of the Galve Formation to any of the lowermost Cretaceous K1.1, K1.2 or K1.3 sequences defined by Salas (1987) and Salas et al. (2001) in the Maestrazgo Basin is an open question (Fig. 14). In the nearby Penyagolosa sub-basin, the Mora de Rubielos Formation has a similar lithology and stratigraphic position to the Galve Formation. Salas et al. (2001) attributed this formation to the K1.1 sequence. The sequences K1.2 and K1.3 are only recorded in the depocentral areas of the Maestrazgo Basin (i.e., the Salzedella sub-basin, Salas et al., 2001) and represent the deposition during the late Valanginian–early Hauterivian lowstand sea-level stage (Fig. 14, see Haq, 2014). Accordingly, the possible attribution of the Galve Formation to the upper Berriasian–lower Valanginian K1.1 sequence is tentatively proposed here (Fig. 14). This is coherent with the late Berriasian attribution of the lower and middle part of the Galve Formation in the Molino Alto section (Fig. 10). The presence of the K1.2 and K1.3 sequences either in the depocentral areas of the Galve sub-basin (not accessible in outcrop) and/or in the undated terrigenous successions locally found in the lower part of the El Castellar Formation, below the typical uppermost Hauterivian–lowermost Barremian lutitic-gypsum-carbonate successions (Aliaga-Miravete, see Fig. 10), cannot be ruled out.

### *5.2. Tecto-sedimentary evolution of the Galve sub-basin*

The tecto-sedimentary evolution of the Galve sub-basin is illustrated here by a reconstruction of the overall facies and thickness variation from the northwestern marginal areas of the basin (Galve) to the depocentral areas, represented by the Los Cerezos-Caña Seca outcrops (**Fig. 15**). The lowest datum is the erosive unconformity between the Villar del Arzobispo and Aguilar del

Alfambra formations, which occurred during the late Tithonian (Fig. 14). The Villar del Arzobispo Formation shows a relatively homogeneous thickness and facies distribution across most of the Galve sub-basin, ranging around 140–170 m (Aurell et al., 1994). This unit consists of an alternation of 10–40 m-thick intervals dominated by shallow marine carbonates (restricted lagoons to internal bars) and 20–50 m-thick lutitic and siliciclastic intervals deposited in transitional environments, from foreshore to coastal plains (e.g., Díaz-Molina & Yébenes, 1987; Aurell et al., 1994). As a whole, the overall facies distribution of the Villar del Arzobispo Formation indicates a long-term regressive evolution (Aurell et al., 1994; 2010), which is coherent with the long-term fall in sea level (Haq, 2014) around the middle-late Tithonian transition (see sequence J10.1 in Fig. 14). A significant decrease in the thickness of this unit to 10–20 m is only observed in the northeastern marginal area of the basin (i.e., between Aliaga and Miravete). This observation indicates that the structuration of the Galve sub-basin already started during the deposition of this unit, which would therefore represent the initial stage of syn-rift sequence 1.

The basin-wide unconformity found at the boundary between the Villar del Arzobispo and Aguilar del Alfambra formations was related to a significant increase in extensional fault activity around the Jurassic-Cretaceous transition, combined with the sea level fall at the end of the Tithonian (Haq, 1994). There is a dramatic thickness variation in the Aguilar del Alfambra Formation, from zero to more than 400 m in the depocentral areas located to the south (Fig. 15). This thickness variation indicates significant extensional tectonics operating in the Galve sub-basin in the latest Tithonian–middle Berriasian, which can be assigned to the climax stage of syn-rift sequence 1. Accumulation rates were very high in the depocentral areas (more than 100 m/Ma). The thickness distribution pattern indicates a combined role of the ENE-WSW trending normal faults (dipping to the south), laterally bounded by steeper NNW-SSE transfer faults during the sedimentation of the Aguilar del Alfambra Formation.

The facies distribution of the Aguilar del Alfambra Formation shows a long-term transgressive-regressive facies trend (Fig. 15). The unit is dominated by the alternation of lutites, sandstones and peloidal-micritic laminated limestones, deposited in tidal flat environments. The greater marine influence is indicated by the intercalation of skeletal-oolitic levels rich in large benthic foraminifera and dasycladacean algae, which are concentrated towards the upper part of the unit. The increase in the marine influence could be tentatively related to a sea level rise at the early-middle Berriasian transition (Haq, 2014; see the upper part of the J10.2 sequence in Fig. 14).

The boundary between the Aguilar del Alfambra and the Galve formations is an erosive unconformity, representing a major tectonic reactivation event all across the Galve sub-basin at the boundary between the Jurassic and Cretaceous syn-rift sequences 1 and 2, respectively. In some areas of the Galve sub-basin there is no large stratigraphic gap between the uppermost levels of syn-rift sequence 1 (Aguilar del Alfambra Formation) and the lowermost levels of syn-rift sequence 2 (Galve Formation). In other areas, however, the Galve Formation may be absent and the associated gap is significant and spans from the mid-Berriasian to the latest Hauterivian. Interestingly, our data indicate that there is no significant thickness and facies variation in the Villar del Arzobispo and Aguilar del Alfambra formations in the transition area between the Galve and the Penyagolosa sub-basins. In contrast, the Galve Formation is not recorded in this transition area, indicating that the extensional tectonics that gave rise to the separation between these two sedimentary realms took place during syn-rift sequence 2.

The deposition of the Cretaceous syn-rift sequence 2 was also controlled by an orthogonal system of two family sets of ENE-WSW and NNW-SSE trending faults (e.g., Liesa et al., 2006). However, the thickness distribution of the Galve Formation (from 0–90 m thick) follows a different pattern compared to the previous syn-rift stage controlling the sedimentation of the Aguilar del Alfambra Formation (Fig. 15). This indicates that not all the faults operating during syn-rift sequence 1 were reactivated during the development of syn-rift sequence 2. This is well illustrated in the area located around the limb of the Pelejón-Abeja anticline (Fig. 6).

The Galve Formation has been tentatively attributed here to the upper Berriasian–lower Valanginian K1.1 sequence (Fig. 14). The sea level lowstand during the late Berriasian–Valanginian (Haq, 2014), combined with the break-up and formation of isolated grabens and half-grabens across the Galve sub-basin at the onset of the Cretaceous syn-rift sequence (e.g., Liesa et al., 2006), explains the continental character (alluvial plain to palustrine, see Fig. 15) of the facies recorded in the Galve Formation.

During most of the Valanginian–Hauterivian lowstand sea-level stage, sedimentation is thought to be absent or scarcely recorded in the marginal areas of the Galve sub-basin accessible today in the available outcrop exposures. Sedimentation resumed all across the basin around the latest Hauterivian, within the setting of the extensive, shallow carbonate lacustrine-palustrine facies represented by the El Castellar Formation (Fig. 15). The change in the thickness distribution pattern observed between the Galve and El Castellar formations is related to the transition from an independent movement of faults to the movement of all the extensional faults as a whole, at a single detachment level. The interval with gypsum found in the lower part of the El Castellar Formation was caused by changes in the underground water flow associated with the interrelation and connection of the faults in the transition period. These changes were correlated with the transition from the initial rift stage to the climax rift stage of syn-rift sequence 2, which took place around the Hauterivian–Barremian transition (Liesa et al., 2006).

### *5.3. Review of the stratigraphic setting for the dinosaurs found in the Galve sub-basin*

The new stratigraphic framework presented here implies changes in the placement of many fossil sites yielding dinosaurs and other vertebrates that were traditionally considered as belonging either to the Tithonian–Berriasian Villar del Arzobispo Formation or to the Lower Cretaceous, within the lower part of the El Castellar Formation (Ruiz-Omeñaca et al., 2004; Canudo et al., 2012; Pereda Suberbiola et al., 2012; Royo-Torres et al., 2014). An updated list of the sites from the Villar del Arzobispo, Aguilar del Alfambra and Galve formations, as well as their geographical location, is provided in the **supplementary information** to this paper.

Concerning the Galve sub-basin, vertebrate fossils from the Villar del Arzobispo Formation are only known in outcrops of the Galve syncline. These include dinosaurs representing different groups (Sauropoda, Theropoda, Ornithopoda) as well as chelonians referred to *Plesiochelys* and *Tropidemys* (Ruiz-Omeñaca et al., 2004; Canudo et al., 2005; Pérez-García et al., 2013). The most significant discoveries are the skeleton of the sauropod *Galvesaurus herreroi* Barco et al. (2005) found in the lower half of the unit and an isolated megatheropod tooth (Canudo et al., 2006), probably found in the upper part of the Villar del Arzobispo Formation (Canudo et al., 2005). A level found towards the top of this unit also includes the tracksite of Las Cerradicas (Pérez-Lorente et al., 1997), one of the most significant Berriasian dinosaur track sites described worldwide. Las Cerradicas records the tracks of a spectrum of small and medium-sized ornithopods and small sauropods showing gregarious behaviour (Castanera et al., 2011, 2013).

The ichnites traditionally ascribed to the upper part of the Villar del Arzobispo Formation (e.g., Alcalá et al., 2012, 2014; Mampel et al., 2010-2011) are now placed in the newly defined Aguilar del Alfambra Formation. In fact, the carbonate beds found at different levels of this unit are particularly rich in dinosaur footprints. During the fieldwork and logging performed here, abundant dinosaur tracks and evidence of dinoturbation were found. These are indicated in the synthetic logs represented in Figure 4. A significant new finding is the La Puerta fossil site, consisting of an unpublished isolated large-sized dinosaur footprint with skin impressions (see image in the supplementary information). La Puerta is located near the limb of the Ababuj anticline, close to the track sites of Ababuj 1 and 4 described in Alcalá et al. (2012). The area located between Ababuj and Aguilar del Alfambra includes large theropod and sauropod tracks (Alcalá et al., 2012), as well as small ornithopod tracks and either sauropod or stegosaur tracks. This latter, inconsistent record comes from the El Rompido or Aguilar 3 tracksite, which was studied and published with these two different names by Herrero-Gascón and Pérez-Lorente (2012) and Mampel et al. (2010-2011), respectively. Further theropod and sauropod tracks have been identified in Miravete de la Sierra (Pérez-Lorente & Romero-Molina, 2001).

Bone remains from the Aguilar del Alfambra Formation are less frequent in the Galve sub-basin (Mampel et al., 2010-11; Alcalá et al., 2012). An isolated dinosaur vertebra was discovered at the top of a burrowed layer within the Las Cerradicas series in Galve (Canudo et al., 2012) and fragmentary dinosaur remains have been collected from the new site of La Peñuela in the municipality of Camarillas.

In addition to the Galve sub-basin, the Tithonian–Berriasian dinosaur fossil record from the northwestern part of the neighbouring Penyagolosa sub-basin is also remarkable. These fossil sites were traditionally placed within the upper part of the Villar del Arzobispo Formation (Cobos et al., 2010, 2014; Alcalá et al., 2014), equivalent to the newly defined Aguilar del Alfambra Formation (see supplementary information). Within the municipalities of El Castellar and Formiche Alto in this sector, several bonebeds (including skeletal remains of stegosaurids and megalosaurids) and tracksites have been identified. Noteworthy within the ichnological record is the description of *Deltapodus ibericus* and *Iberosauripus grandis*, associated with stegosaurs and theropods as their respective trackmakers (Cobos et al., 2010, 2014).

Fossil sites are scarce in the newly defined Galve Formation (see supplementary information), but they yielded a high diversity of vertebrates including Lissamphibia, Testudines, Squamata, Crocodylomorpha, Pterosauria, Stegosauria, Sauropoda, Theropoda, Dromaeosauridae and Mammalia (e.g. Díez et al., 1995; Ruiz-Omeñaca et al., 2004; Cuenca-Bescós et al., 2011). These vertebrates were previously attributed either to the upper part of the Villar del Arzobispo Formation or to the lower part of the El Castellar Formation (Ruiz-Omeñaca et al., 2004; Royo-Torres et al., 2014). All the published vertebrate fossil sites are located in the Galve area. Of particular interest is the fossil site of Piélago 0, which includes microvertebrates, dinosaur bones, plant remains as well as the palynological content that was first studied by Díez et al. (1995) and assigned to the Valanginian–Hauterivian. Also remarkable in the Galve Formation is the tracksite of Los Corrales del Pelejón. This outcrop, located in the middle part of the unit (between levels P4 and P5, see Figs. 4 and 6) includes ornithopod, theropod and possible sauropod tracks (Cuenca et al., 1993). Moreover, some dinosaur casts were discovered during the fieldwork in the Las Cerradicas series (see supplementary information).

The Galve Formation includes Las Zabacheras, the type-locality site of the sauropod *Aragosaurus ischiaticus* Sanz, Buscalioni, Casanovas, Santafé, 1987. As explained in the introductory section, there has been a discussion concerning the age and stratigraphic position of *Aragosaurus*, regarded either as Tithonian–Berriasian, most likely Berriasian in age (upper Villar del Arzobispo Formation, Royo-Torres et al., 2014) or as Valanginian–Hauterivian (lower El Castellar Formation, Canudo et al., 2012). The new data reported here indicate that *Aragosaurus* is located in the lower part of the Galve Formation. The most probable age assignment of this unit is late Berriasian–early Valanginian (see Figs. 1 and 14). This stratigraphic assignment was supported by the finding of the middle Berriasian charophyte *Globator maillardii incrassatus* by Canudo et al. (2012) in a level located almost 20 m below Las Zabacheras and is relevant emphasizing certain misinterpretations concerning the inclusion of *Aragosaurus* at the end of the Jurassic (e.g., McPhee et al., 2016, see the Tithonian–Berriasian age assignment of *Aragosaurus* in their Fig. 10 based on the work by Royo-Torres et al., 2014).

## 6. Concluding remarks

A revision of the stratigraphy, sedimentology and structural evolution of the Galve sub-basin (western Maestrazgo Basin) around the Jurassic-Cretaceous transition is presented here. The studied units record the transition from the middle Tithonian–middle Berriasian syn-rift sequence 1 to the initial stages of the evolution of the upper Berriasian–mid Albian syn-rift sequence 2. The definition and characterization of the Aguilar del Alfambra and Galve formations, located between the previously defined Villar del Arzobispo and El Castellar formations, provide key data for a better understanding of the evolution of the Galve sub-basin in this critical interval. The main findings of our study are summarized here:

1. In the Galve sub-basin and in the northernmost part of the Penyagolosa sub-basin, the use of the middle–upper Tithonian Villar del Arzobispo Formation should be restricted to an interval with a remarkably homogeneous thickness (140–170 m) and lithological distribution, deposited in coastal to shallow marine environments. A significant decrease in the thickness of this unit observed towards the northeastern marginal areas of the Galve sub-basin indicates that the onset of the structuration of this basin started at the mid Tithonian. Accordingly, the Villar del Arzobispo Formation has been related to the initial stage of syn-rift sequence 1.

2. The definition of a new lithostratigraphic unit, the Aguilar del Alfambra Formation, is here justified by the existence of a widespread late Tithonian unconformity, combined with the presence of a particular lithology consisting of an alternation of lutites, sandstones and peloidal-micritic laminated limestones, deposited in tidal flat environments. The thickness distribution of this unit is variable (from 0–400 m) and was controlled by intense normal fault activity around the Jurassic-Cretaceous transition, at the climax stage of syn-rift sequence 1. These faults formed an orthogonal system with ENE-WSW and NNW-SSE trends. The unit shows a long-term transgressive-regressive facies evolution, with the levels of greater marine influence yielding *Anchispirocyclina lusitanica.* The presence in the upper levels of the charophyte *Globator maillardii incrassatus* and of the ostracod *Theriosynoecum fittoni* indicates that the upper part of the unit extends into the lower and middle Berriasian.

3. The lower boundary of the newly defined Galve Formation (0–100 m thick) is also a widespread low-angle unconformity, developed close to the middle–late Berriasian transition. This unconformity is linked to the major tectonic reactivation event at the boundary between syn-rift sequences 1 and 2, which involved the differentiation between the Galve and the nearby Penyagolosa sub-basins*.* The Galve Formation consists of red lutites with intercalations of cross-bedded and tabular sandstones and conglomerates and some scarce carbonate-rich levels, deposited in alluvial plain environments. The lowstand of sea level during the late Berriasian–

Valanginian, combined with the break-up and formation of local and isolated grabens and half-grabens across the Galve sub-basin at the onset of syn-rift sequence 2, explains the irregular distribution of this unit and the continental character of the recorded facies. The stratigraphic gap associated with this discontinuity is variable. In the areas where the Galve Formation was not deposited, the El Castellar Formation rests directly over the Aguilar del Alfambra Formation, and this gap lasts, at least, from the late Berriasian through the Valanginian and most of the Hauterivian.

4. The available biostratigraphic data leaves a wide open interval for the deposition of the Galve Formation, from the end of the middle Berriasian to the onset of the late Hauterivian. Accordingly, the equivalence of this unit with any of the lowermost Cretaceous K1.1, K1.2 or K1.3 sequences previously defined in the Maestrazgo Basin remains uncertain. However, the new biostratigraphic data reported here from the Molino Alto section (Aliaga) indicate that the lower and middle part of the Galve Formation was deposited in this locality during the late Berriasian. These local data, combined with the correlation with the nearby sub-basins, give support to a possible attribution of the Galve Formation to the upper Berriasian–lower Valanginian K1.1 sequence. Therefore, this is also the most probable age range for the sauropod *Aragosaurus ischiaticus*. The younger upper Valanginian–Hauterivian K1.2 and K1.3 sequences could be present in the depocentral areas of the Galve sub-basin (not accessible in outcrop). They may even correspond to the undated terrigenous successions found locally (e.g., Molino Alto section) between the Galve Formation and the typical lutitic, gypsum and carbonate successions of the El Castellar Formation.

5. The shallow carbonate-lutitic lacustrine-palustrine facies represented by the El Castellar Formation across the entire Galve sub-basin were deposited during the latest Hauterivian–earliest Barremian, as indicated by the widespread presence of *Atopochara trivolvis triquetra*. Here we confirm previous interpretations, in which the homogeneous thickness distribution pattern observed in the El Castellar Formation is related to the transition from a stage with independent movement of faults (Galve Formation, initial syn-rift stage of sequence 2) to another stage characterized by the movement of all the extensional faults as a whole during the climax stage of syn-rift sequence 2 (El Castellar and the rest of the Barremian–Aptian units).

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**FIGURE CAPTIONS**

**Fig. 1.** Summary of the stratigraphy of the Galve area at the Jurassic-Cretaceous transition according to successive work. Unit 3 (or the Galve Formation) includes the Las Zabacheras fossil site, the recovery site of *Aragosaurus ischiaticus*.

**Fig. 2.** (A) Sedimentary basins and sub-basins in eastern Iberia during the Early Cretaceous, indicating in light green the location of the more subsiding domains; the Galve sub-basin is located at the western edge of the Maestrazgo Basin (modified from Salas et al., 2001). (B) Geological map of the study area including the Galve sub-basin and the northwestern edge of the Penyagolosa sub-basin; the main localities used for logging and mapping are squared. For the legend of colours, see the synthetic stratigraphic log (C). The two studied units (Aguilar del Alfambra and Galve formations) are indicated in light grey.

**Fig. 3.** Panoramic view of the type localities of the Aguilar del Alfambra Formation (upper photo) and Galve Formation (lower photo). See Figure 7A for the location of reference levels A1–A5 and Fig. A for the location of reference levels P2–P6.

**Fig. 4.** Summary of the facies distribution and biostratigraphic markers in the key sections logged in the northern (left) and in the southern (right) part of the Galve sub-basin. Notice the change of vertical scale from left to right.

**Fig. 5.** Photogeological sketch map based on fieldwork and analysis of the 1:3000 aerial photograph (available at http://sigpac.mapa.es/fega/visor/) of the outcrops located north and west of Galve village (see Fig. 2B for location). Numbers 1 and 2 correspond to samples including charophytes. The two images of charophyte fructifications of *Globator maillardii incrassatus* from sediment samples recovered near Las Zabacheras (in lateral view, 1a) and west Galve (in basal view, 1b) were captured with a camera adapted to Olympus SZX7 stereomicroscope. The lower insert shows a field view of the Aguilar del Alfambra Formation south of Las Zabacheras (see Galve section in Fig. 4 for location).

**Fig. 6.** (A) Photogeological sketch map based on fieldwork and analysis of the 1:3000 aerial photograph (available at http://sigpac.mapa.es/fega/visor/) of the outcrops located between Pelejón and Abeja sites (see Fig. 2B for location). (B) Geological section showing the distribution of the studied units from Pelejón to Abeja, including the system of synsedimentary faults. Main faults 1 and 2 are indicated. For details of the sections logged in Pelejón and Abeja, including levels P1–P6 and Aj1–Aj7 respectively, see Fig. 4 (left).

**Fig. 7.** Photogeological sketch map based on fieldwork and analysis of the 1:3000 aerial photograph (available at http://sigpac.mapa.es/fega/visor/) of the outcrops located west of Aguilar de Alfambra village (A) and north of Ababuj village (B). See Fig. 2B for location. For details of the sections logged in Aguilar and Ababuj, including levels A1–A6 and Ab1–Ab6 respectively, see Fig. 4 (right).

**Fig. 8.** Photogeological sketch map based on fieldwork and analysis of the 1:3000 aerial photograph (available at http://sigpac.mapa.es/fega/visor/) of the outcrops located near Miravete de la Sierra village (see Fig. 2B for location). The location of the log measured in Soria et al. (1995) in the Aguilar del Alfambra Formation east of Miravete is also indicated (see base and top).

**Fig. 9.** Photogeological sketch map based on fieldwork and analysis of the 1:3000 aerial photograph (available at http://sigpac.mapa.es/fega/visor/) of the outcrops located south of Aliaga village (see Fig. 2B for location). The section of Molino Alto (see Fig. 10) was logged south

of Aliaga (see base and top). The lower field view shows the boundary between the Galve and El Castellar formations in the area used for logging.

**Fig. 10.** The Molino Alto section (see Fig. 9 for location), indicating the location of sediment samples and the levels bearing charophytes. The right column shows scanning electron microscope photographs of some charophyte fructifications (*Atopochara trivolvis* varieties) selected from samples SAL 3, 9 and 13.

**Fig. 11.** Photogeological sketch map based on fieldwork and analysis of the 1:3000 aerial photograph (available at http://sigpac.mapa.es/fega/visor/) of the outcrops located south of Monteagudo del Castillo (see Fig. 2(B) for location).

**Fig. 12.** Field images of siliciclastic and carbonate facies of the Aguilar del Alfambra Formation. (A): Packages of siliciclastic- and carbonate-dominated facies in the Aguilar section. The carbonate-dominated package (20 m thick) corresponds to the A2 reference level in Fig. 4 and encompasses supra- to shallow subtidal cryptalgal-peloidal laminites and peloidal packstones-grainstones (locally dolomitized; see orange bed), and marly to bioturbated silty limestones. (B, C): Detailed view of cryptalgal-peloidal laminites and peloidal packstones-grainstones with tepees (B) and fenestral porosity (C). (D): Top of the Aguilar Formation in the Los Cerezos section, including open lagoon oolitic packstone-grainstone facies (oolitic banks and washover deposits). (E): Cross-bedded sandstones with mud drapes (see arrow), representing tide-influenced fluvial channels. (F, G): Muddy to muddy-sandy tidal flat facies, including laminated and/or bioturbated sandstones with traces of *Arenicolites* (F) and cm-thick heterolithic (lutite-sandstone) alternations with ripples (G).

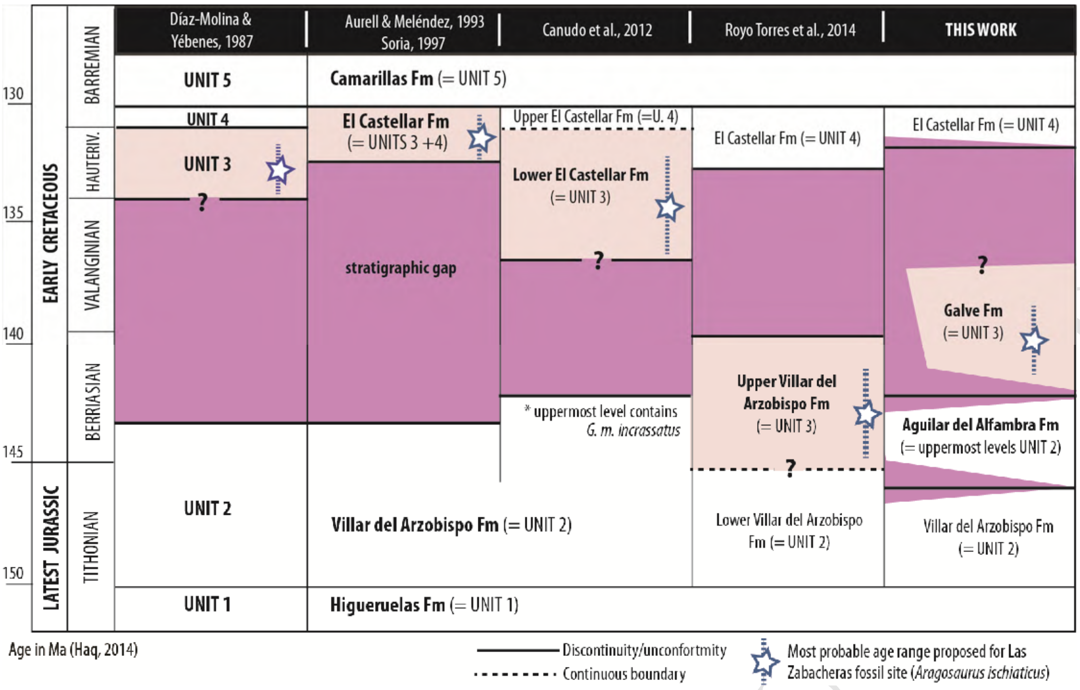
**Fig. 13.** Field images of the main facies of the Galve Formation. (A, B). Red to ochrish floodplain lutites with intercalated fluvial channels in the Pelejón section. Channels correspond to 2- to 3 m- thick ribbon bodies of cross-bedded sandstones that are isolated (see 1) or offset stacked (see 2 and 3). Note, in B, wedge-shaped sandstone beds extending laterally from the channel margin in 1 (levee) and lateral accretion surfaces (point bar) in 2. (C, D): Laminated and/or bioturbated sandstone beds (crevasse splay deposits) intercalated in fine-grained floodplain facies. Note, in C, *Taenidium* traces in crevasse splay deposits (see 1) and conglomerates at the base of a fluvial channel (see 2). Grey lutites and soil horizons in D reflect local, more humid floodplain areas.

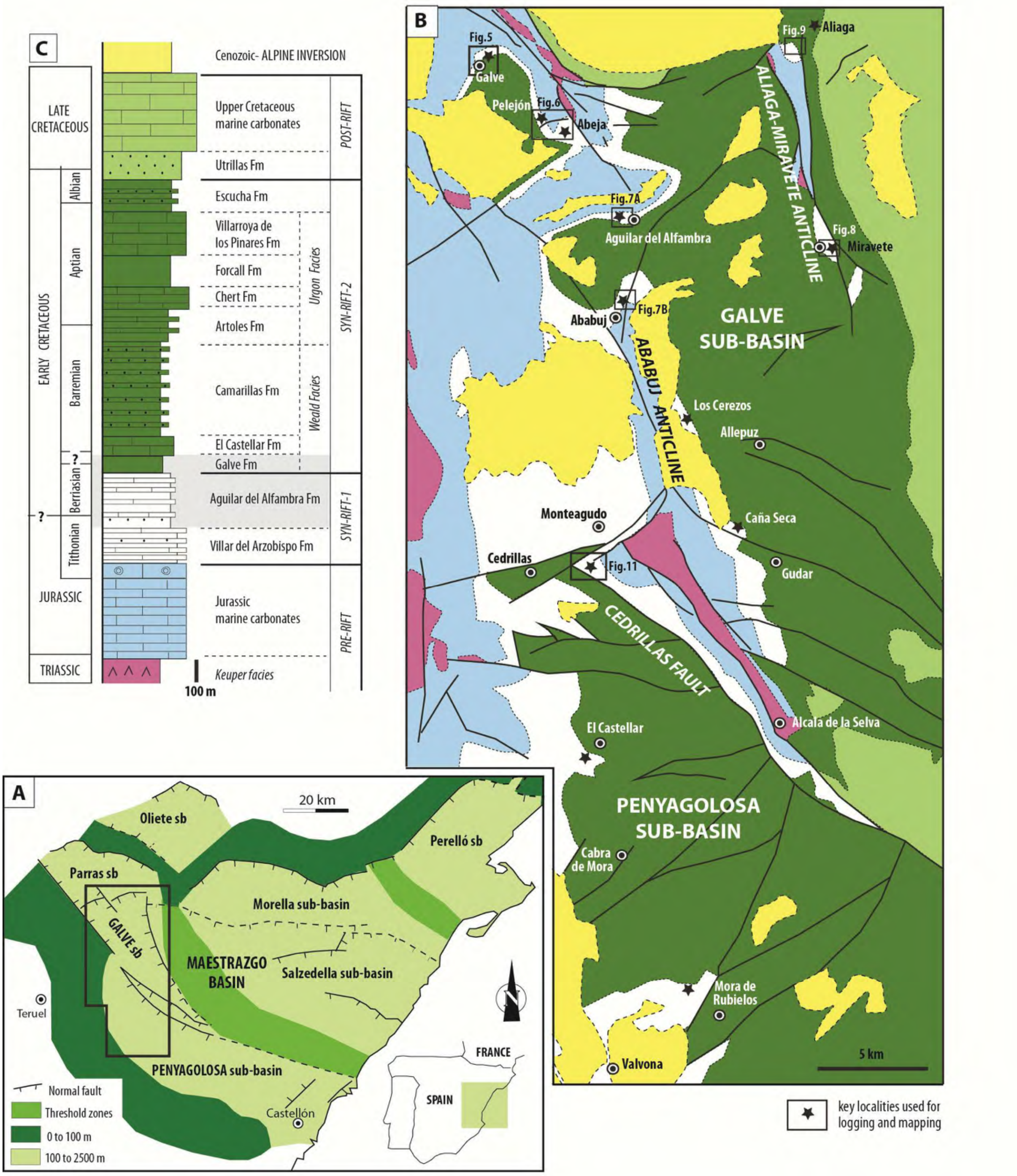
**Fig. 14.** Chrono- and biostratigraphy of the middle Tithonian-lower Barremian of the Galve sub-basin. Sea level curve and absolute ages according to Haq (2014).

**Fig. 15.** Overall facies and thickness distribution in the Aguilar del Alfambra, Galve and El Castellar formations across a NNW-SSE transect. See Fig. 2B for location of the reference localities indicated in the lower part.

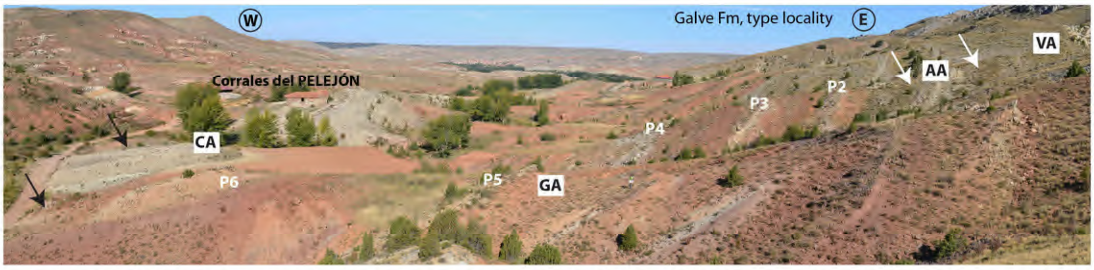
**Table 1.** Key aspects of the Aguilar del Alfambra and Galve formations defined in this work.

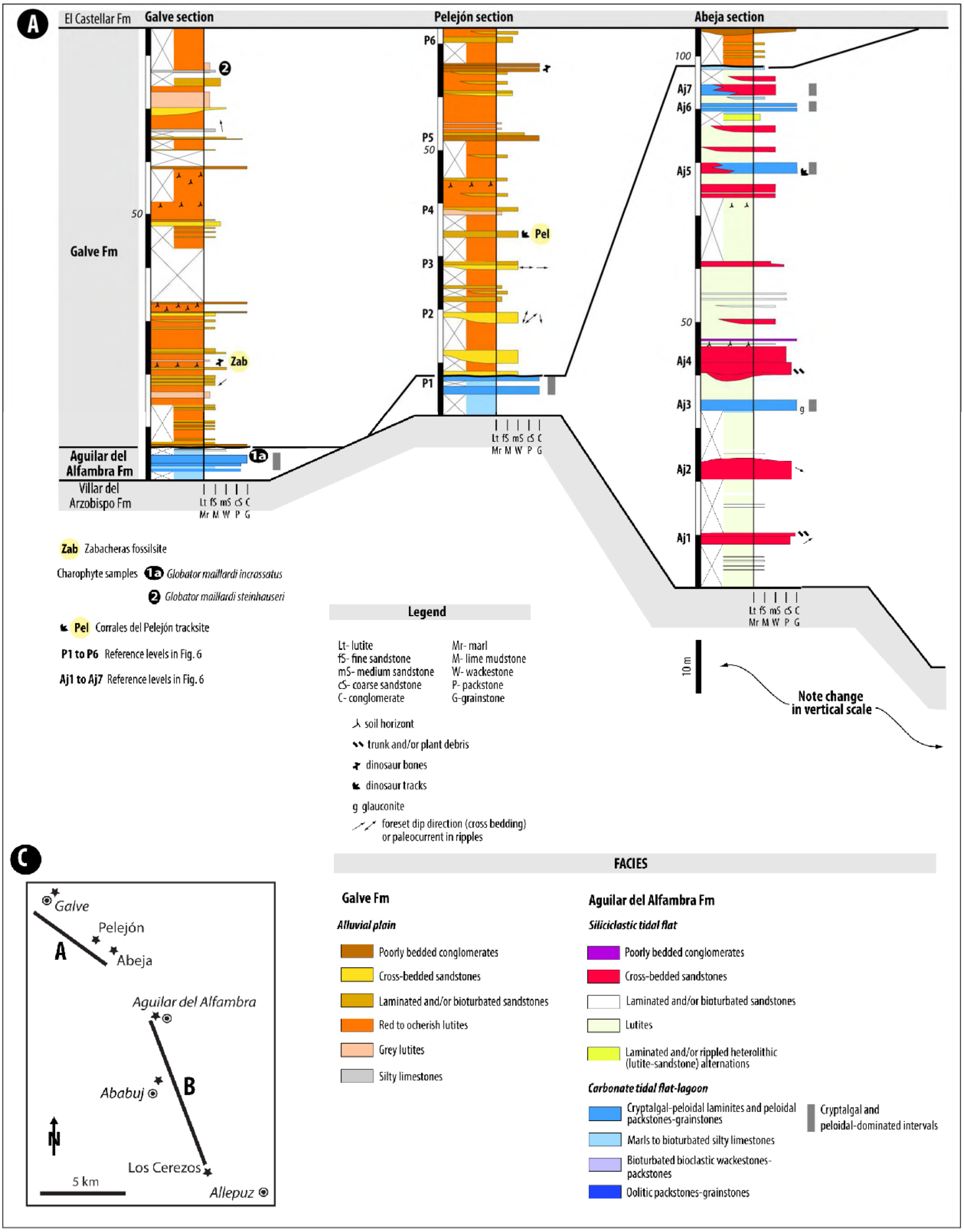
| | **Aguilar del Alfambra Formation** | **Galve Formation** |
|---|---|---|
| ***Main lithology*** | **Limestones and lutites:** White to pale grey laminated micritic and peloidal limestones, red lutites and cross-bedded sandstones. | **Lutites:** Red lutites and burrowed/cross-bedded sandstones. |
| ***Stratotype*** | West of the Aguilar del Alfambra village (see log A1 to A6 in Figs. 3, 4 and 7): *Bottom*: 40º 37’ 41.18” N / 0º 50’ 51.58” W; *Top*: 40º 37’ 36.14” N / 0º 50’ 55.35” W. | East of Pelejón (see log G1 to G5 in Figs. 3, 4 and 6): *Bottom*: 40º 37’ 41.18” N / 0º 50’ 51.58” W; *Top*: 40º 37’ 36.14” N / 0º 50’ 55.35” W. |
| ***Other type-locality*** | West of Allepuz (Los Cerezos). | South of Aliaga (Molino Alto). |
| ***Facies and thickness*** | Along the Galve syncline, the unit is represented by > 10 m-thick succession of white to pale grey marls and peloidal to micritic laminated limestones. Further south, the unit is thicker (100–450 m) and the carbonate levels have common fenestral porosity and abundant dinosaur footprints. These carbonates are found interbedded between red lutites. Sandstone levels are discontinuous, with channel bases and geometries of lateral accretion and mud drapes. Fossil content is concentrated in some levels, including vertebrates, fish toot, charophytes, ostracods, benthic foraminifera, dasycladacean algae, gastropods and bivalves (oysters). | The unit has a variable thickness (0–100 m), generally ranging from 40–70 m. It is dominated by red to ocherish lutites with some levels with root traces, and interbedded sandstones. Sandstones can be either tabular with abundant burrowing (arthropod burrows: *Taenidium*) and root traces, or lenticular, showing channel bases and point-bar geometries. Conglomeratic levels with abundant calcareous pebbles are also common. Carbonate-rich levels are scarce and include burrowed marls and micritic/peloidal limestones, as well as channelized levels including large oncolites. |
| ***Boundaries*** | *Lower boundary:* erosive unconformity with the Villar del Arzobispo Formation, which can fossilize synsedimentary normal faults.<br>*Upper boundary:* regional low-angle erosive unconformity with the overlying Galve or El Castellar formations. | *Lower boundary:* regional low-angle erosive unconformity with the underlying Aguilar del Alfambra or Villar del Arzobispo formations<br>*Upper boundary:* low-angle erosive unconformity with the El Castellar Fm. |
| ***Geographical distribution and lateral equivalences (Maestrazgo Basin)*** | The unit is found across the Galve sub-basin and in the northwestern part of the nearby Penyagolosa sub-basin. The lateral counterpart of the unit in the eastern part of this sub-basin and in the Salzedella sub-basin is the upper part of the Bovalar Formation (e.g., Montanejos, see Bádenas et al., 2004). It is also equivalent the algal-laminated limestones of the La Pleta Formation commonly found in the Morella and Perelló sub-basins (e.g., Salas et al., 2001). | The unit has an irregular distribution across the Galve sub-basin, reaching the maximum thickness in certain subsident areas like Galve (Zabacheras, Pelejón), south of Aliaga (Molino Alto section) or in the eastern flank of the Ababuj anticline (Los Cerezos). In other localities (e.g., Aguilar del Alfambra, Miravete) is not present. The Mora de Rubielos Formation defined in the nearby Penyagolosa sub-basin (Canérot et al., 1982; Salas et al., 2001) has a similar lithology and stratigraphic position. |
| ***Depositional environment*** | Lagoons, carbonate tidal flats and silicilastic tidal flats with tide-influenced fluvial channels. | Distal alluvial plain, extensive floodplain areas and related fluvial channels with overbank deposits. |
| ***Age range*** | Late Tithonian-Middle Berriasian | Late Berriasian-Hauterivian |

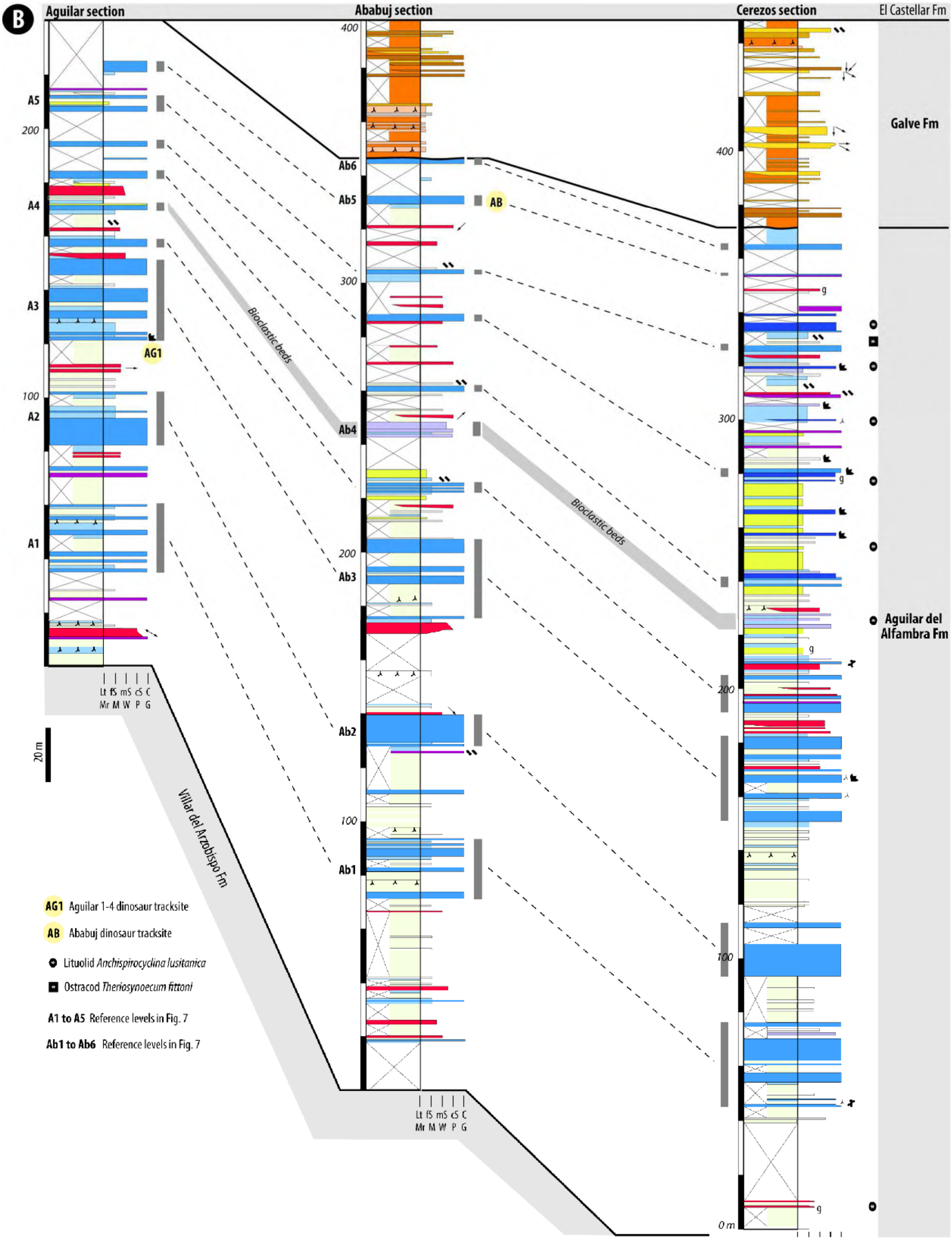

Díaz-Molina & Yébenes, 1987
Aurell & Meléndez, 1993 Soria, 1997
Canudo et al., 2012
Royo Torres et al., 2014
THIS WORK
BARREMIAN
HAUTERIV.
VALANGINIAN
BERRIASIAN
TITHONIAN
EARLY CRETACEOUS
LATEST JURASSIC
130
135
140
145
150
UNIT 5
Camarillas Fm (= UNIT 5)
UNIT 4
UNIT 3
El Castellar Fm (= UNITS 3 +4)
Upper El Castellar Fm (=U. 4)
Lower El Castellar Fm (= UNIT 3)
El Castellar Fm (= UNIT 4)
stratigraphic gap
Galve Fm (= UNIT 3)
* uppermost level contains G. m. incrassatus
Upper Villar del Arzobispo Fm (= UNIT 3)
Aguilar del Alfambra Fm (= uppermost levels UNIT 2)
UNIT 2
Villar del Arzobispo Fm (= UNIT 2)
Lower Villar del Arzobispo Fm (= UNIT 2)
Villar del Arzobispo Fm (= UNIT 2)
UNIT 1
Higueruelas Fm (= UNIT 1)
Age in Ma (Haq, 2014)
Discontinuity/unconformity
Continuous boundary
Most probable age range proposed for Las Zabacheras fossil site (Aragosaurus ischiaticus)

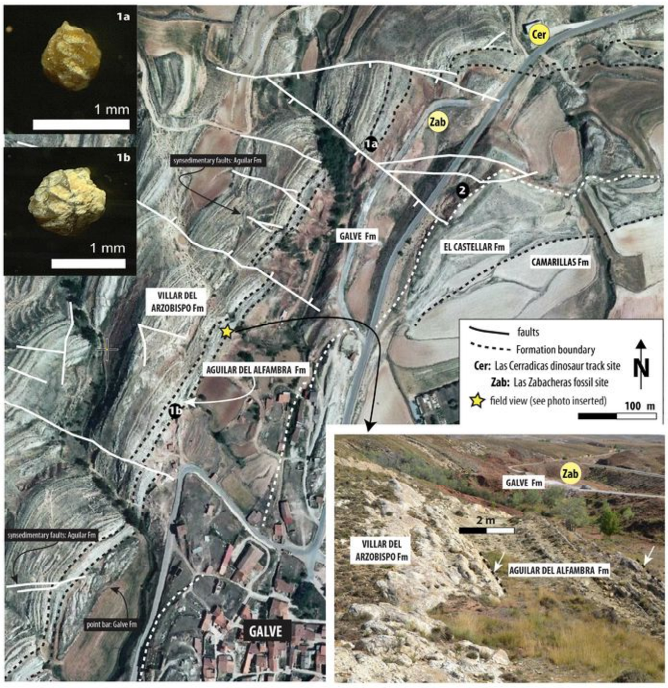

C
Cenozoic- ALPINE INVERSION
LATE CRETACEOUS
Upper Cretaceous marine carbonates
POST-RIFT
Utrillas Fm
Albian
Escucha Fm
Aptian
Villarroya de los Pinares Fm
Forcall Fm
Chert Fm
Artoles Fm
Urgon Facies
SYN-RIFT-2
EARLY CRETACEOUS
Barremian
Camarillas Fm
Weald Facies
El Castellar Fm
Galve Fm
Berriasian
Aguilar del Alfambra Fm
SYN-RIFT-1
Tithonian
Villar del Arzobispo Fm
JURASSIC
Jurassic marine carbonates
PRE-RIFT
TRIASSIC
Keuper facies
100 m
B
Fig.5
Galve
Pelejón
Fig.6
Abeja
Fig.9
Aliaga
ALIAGA-MIRAVETE ANTICLINE
Fig.7A
Aguilar del Alfambra
Fig.8
Miravete
Fig.7B
Ababuj
ABABUJ ANTICLINE
GALVE SUB-BASIN
Los Cerezos
Allepuz
Monteagudo
Caña Seca
Cedrillas
Fig.11
Gudar
CEDRILLAS FAULT
Alcala de la Selva
El Castellar
PENYAGOLOSA SUB-BASIN
Cabra de Mora
Mora de Rubielos
Valvona
5 km
key localities used for logging and mapping
A
20 km
Oliete sb
Perelló sb
Parras sb
GALVE sb
Morella sub-basin
MAESTRAZGO BASIN
Salzedella sub-basin
Teruel
PENYAGOLOSA sub-basin
Castellón
FRANCE
SPAIN
Normal fault
Threshold zones
0 to 100 m
100 to 2500 m

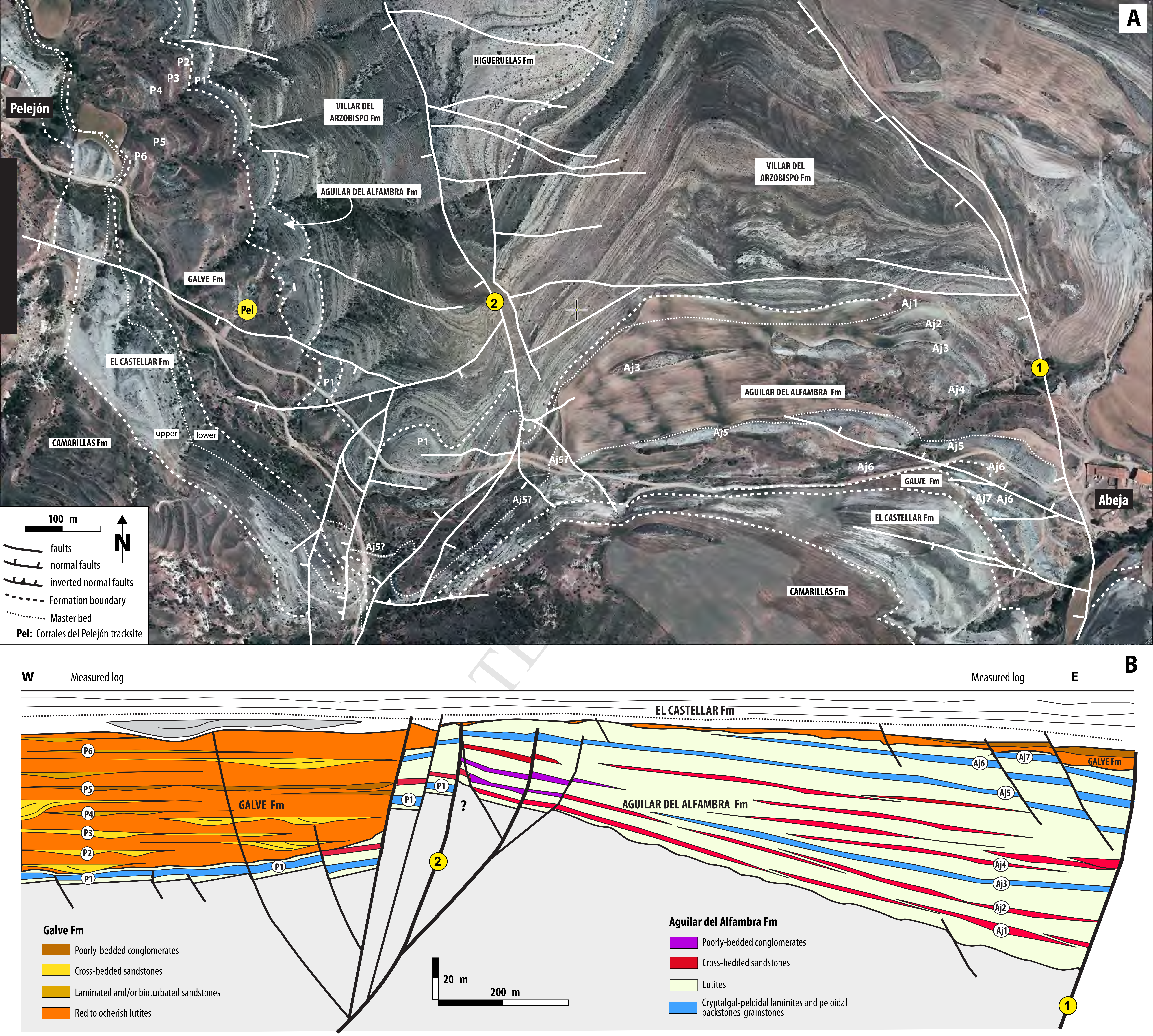

VA
N
A1
AGUILAR DEL ALFAMBRA
Aguilar del Alfambra Fm, type locality
S
A2
A3
A4
A5


W
Galve Fm, type locality
E
VA
AA
Corrales del PELEJÓN
P2
P3
P4
CA
P6
P5
GA

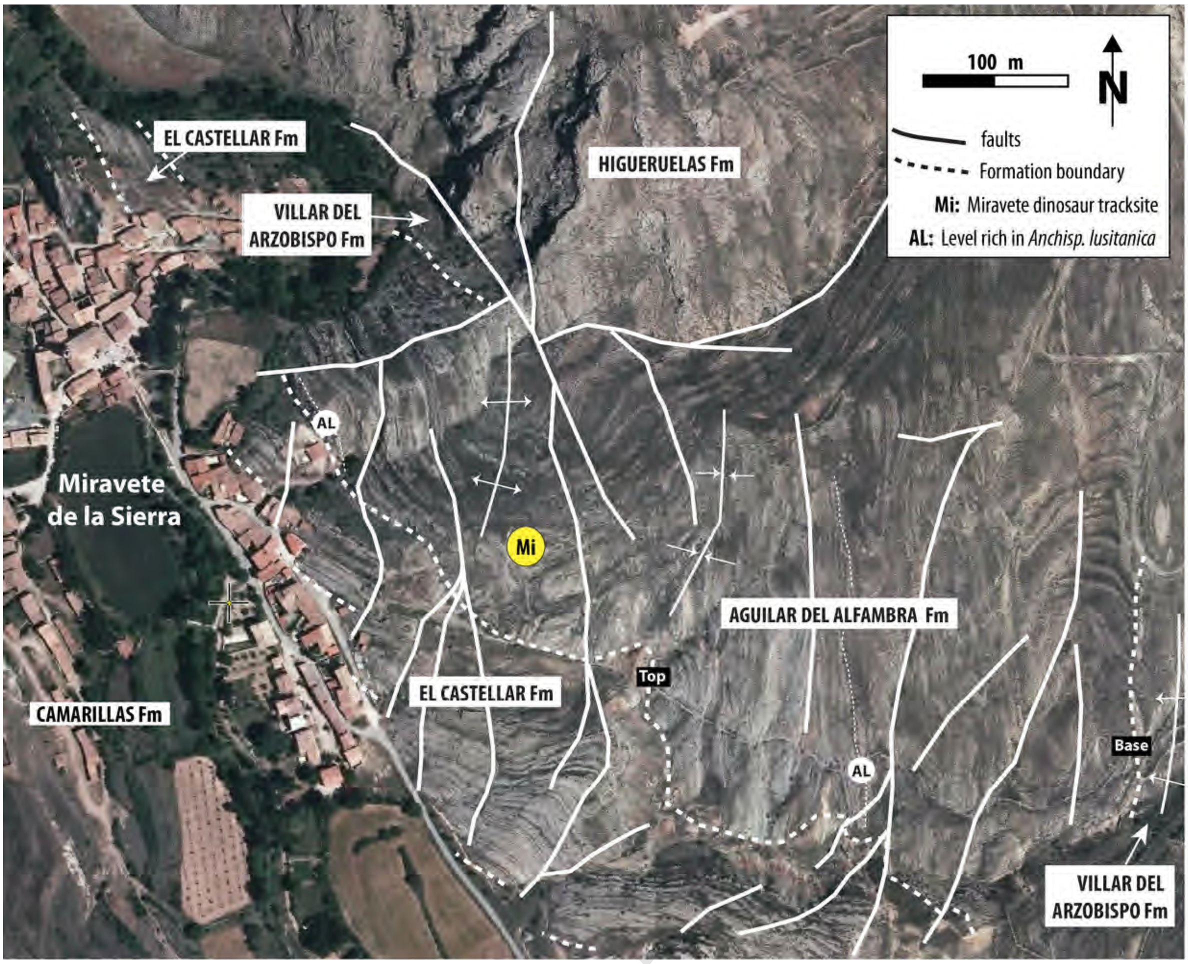

A
El Castellar Fm
Galve section
Pelejón section
Abeja section
Galve Fm
Aguilar del Alfambra Fm
Villar del Arzobispo Fm
Zab Zabacheras fossilsite
Charophyte samples 1a Globator maillardi incrassatus
2 Globator maillardi steinhauseri
Pel Corrales del Pelejón tracksite
P1 to P6 Reference levels in Fig. 6
Aj1 to Aj7 Reference levels in Fig. 6
Legend
Lt- lutite
fS- fine sandstone
mS- medium sandstone
cS- coarse sandstone
C- conglomerate
Mr- marl
M- lime mudstone
W- wackestone
P- packstone
G-grainstone
soil horizont
trunk and/or plant debris
dinosaur bones
dinosaur tracks
g glauconite
foreset dip direction (cross bedding) or paleocurrent in ripples
10 m
Note change in vertical scale
FACIES
Galve Fm
Alluvial plain
Poorly bedded conglomerates
Cross-bedded sandstones
Laminated and/or bioturbated sandstones
Red to ocherish lutites
Grey lutites
Silty limestones
Aguilar del Alfambra Fm
Siliciclastic tidal flat
Poorly bedded conglomerates
Cross-bedded sandstones
Laminated and/or bioturbated sandstones
Lutites
Laminated and/or rippled heterolithic (lutite-sandstone) alternations
Carbonate tidal flat-lagoon
Cryptalgal-peloidal laminites and peloidal packstones-grainstones
Marls to bioturbated silty limestones
Bioturbated bioclastic wackestones-packstones
Oolitic packstones-grainstones
Cryptalgal and peloidal-dominated intervals
C
Galve
Pelejón
Abeja
Aguilar del Alfambra
Ababuj
Los Cerezos
Allepuz
5 km
N

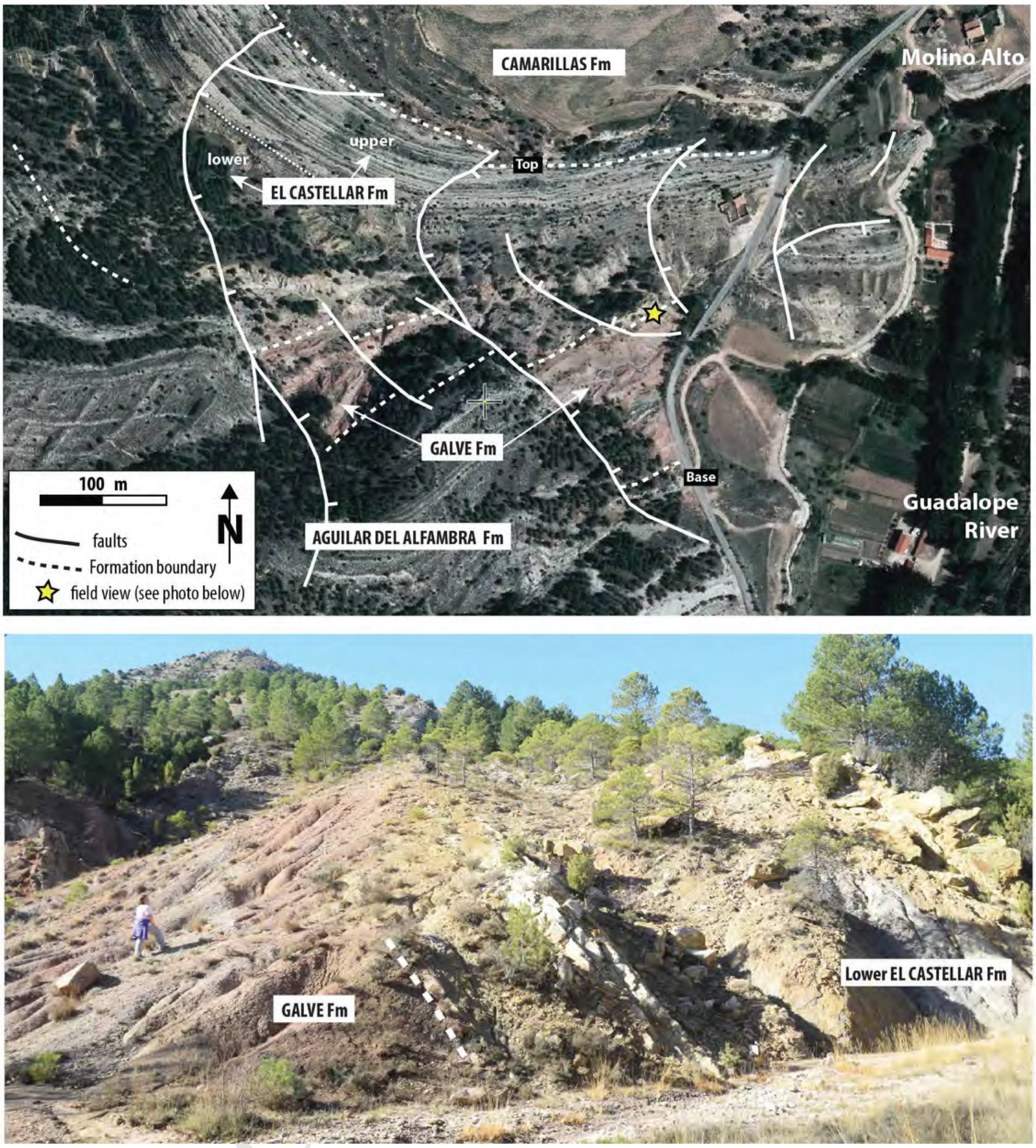

B
Aguilar section
Ababuj section
Cerezos section
El Castellar Fm
Galve Fm
Aguilar del Alfambra Fm
Villar del Arzobispo Fm
Bioclastic beds
Bioclastic beds
A1
A2
A3
A4
A5
Ab1
Ab2
Ab3
Ab4
Ab5
Ab6
AG1
AB
100
200
300
400
0 m
Lt fS mS cS C
Mr M W P G
20 m
AG1 Aguilar 1-4 dinosaur tracksite
AB Ababuj dinosaur tracksite
Lituolid Anchispirocyclina lusitanica
Ostracod Theriosynoecum fittoni
A1 to A5 Reference levels in Fig. 7
Ab1 to Ab6 Reference levels in Fig. 7


1a
1 mm
1b
1 mm
Cer
Zab
1a
2
synsedimentary faults: Aguilar Fm
GALVE Fm
EL CASTELLAR Fm
CAMARILLAS Fm
VILLAR DEL ARZOBISPO Fm
AGUILAR DEL ALFAMBRA Fm
1b
faults
Formation boundary
Cer: Las Cerradicas dinosaur track site
Zab: Las Zabacheras fossil site
field view (see photo inserted)
N
100 m
GALVE Fm
2 m
VILLAR DEL ARZOBISPO Fm
AGUILAR DEL ALFAMBRA Fm
synsedimentary faults: Aguilar Fm
point bar: Galve Fm
GALVE

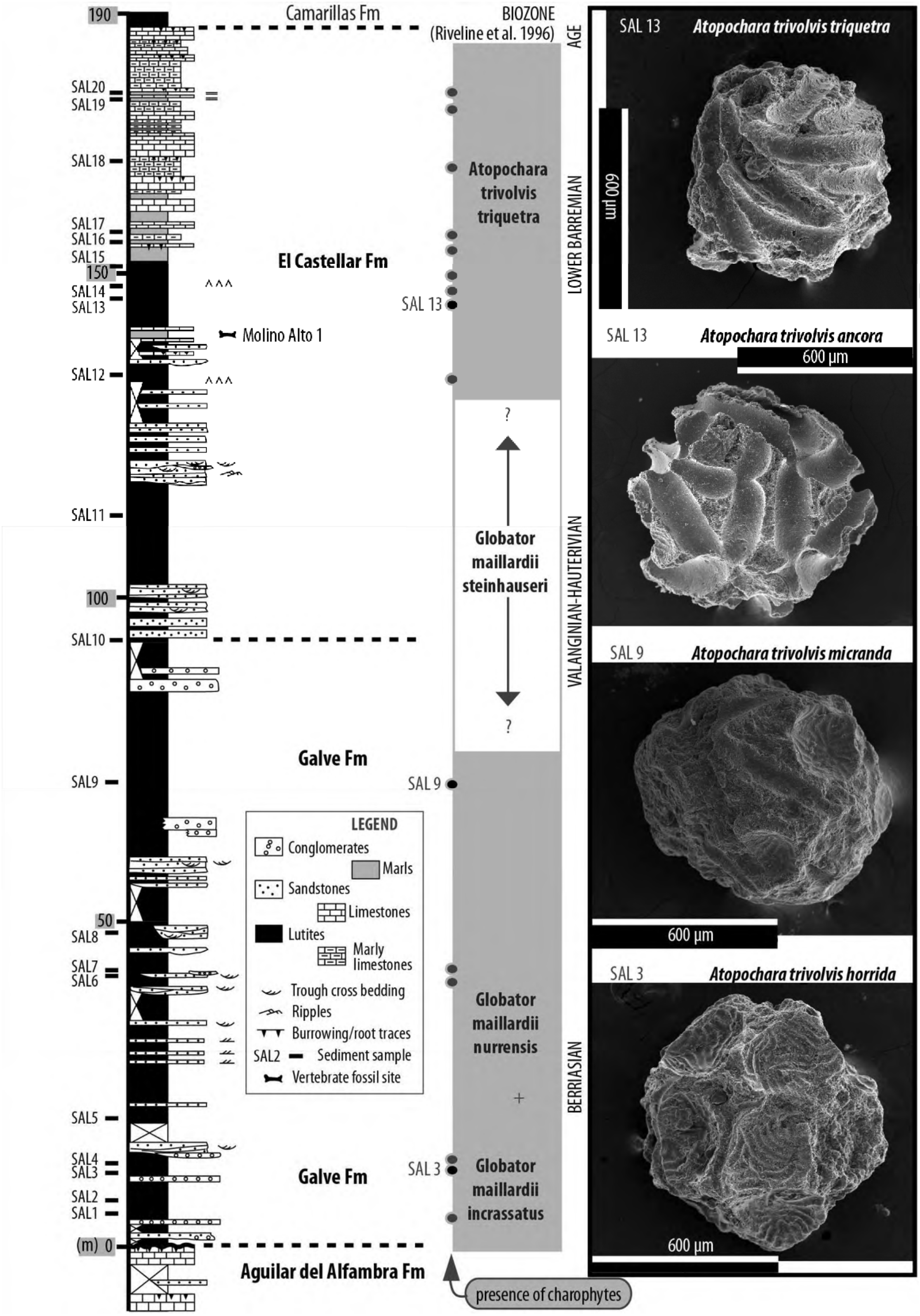

A
Pelejón
P1
P2
P3
P4
P5
P6
HIGUERUELAS Fm
VILLAR DEL ARZOBISPO Fm
VILLAR DEL ARZOBISPO Fm
AGUILAR DEL ALFAMBRA Fm
GALVE Fm
Pel
2
1
EL CASTELLAR Fm
CAMARILLAS Fm
upper
lower
Aj1
Aj2
Aj3
Aj3
Aj4
AGUILAR DEL ALFAMBRA Fm
Aj5
Aj5
Aj5?
Aj5?
Aj5?
Aj6
Aj6
Aj7 Aj6
GALVE Fm
EL CASTELLAR Fm
CAMARILLAS Fm
Abeja
100 m
N
faults
normal faults
inverted normal faults
Formation boundary
Master bed
Pel: Corrales del Pelejón tracksite
B
W
Measured log
Measured log
E
EL CASTELLAR Fm
GALVE Fm
AGUILAR DEL ALFAMBRA Fm
GALVE Fm
?
Aj1
Aj2
Aj3
Aj4
Aj5
Aj6
Aj7
20 m
200 m
Galve Fm
Poorly-bedded conglomerates
Cross-bedded sandstones
Laminated and/or bioturbated sandstones
Red to ocherish lutites
Aguilar del Alfambra Fm
Poorly-bedded conglomerates
Cross-bedded sandstones
Lutites
Cryptalgal-peloidal laminites and peloidal packstones-grainstones


A
HIGUERUELAS Fm
VILLAR DELARZOBISPO Fm
Aguilar del Alfambra
A1
A2
A3
AG1
AGUILAR DEL ALFAMBRA Fm
A4
A5
?
A6
EL CASTELLAR Fm
100 m
N
faults
Formation boundary
AG1: Aguilar 1-4 dinosaur tracksite
AB: Ababuj dinosaur tracksite
B
AB
EL CASTELLAR Fm
Ab6
Ab5
CAMARILLAS Fm
GALVE Fm
Ab4
AGUILAR DEL ALFAMBRA Fm
Ab3
Ab2
Ab5
1
Ab1
Ababuj Anticline
VILLAR DEL ARZOBISPO Fm
Continental MIOCENE

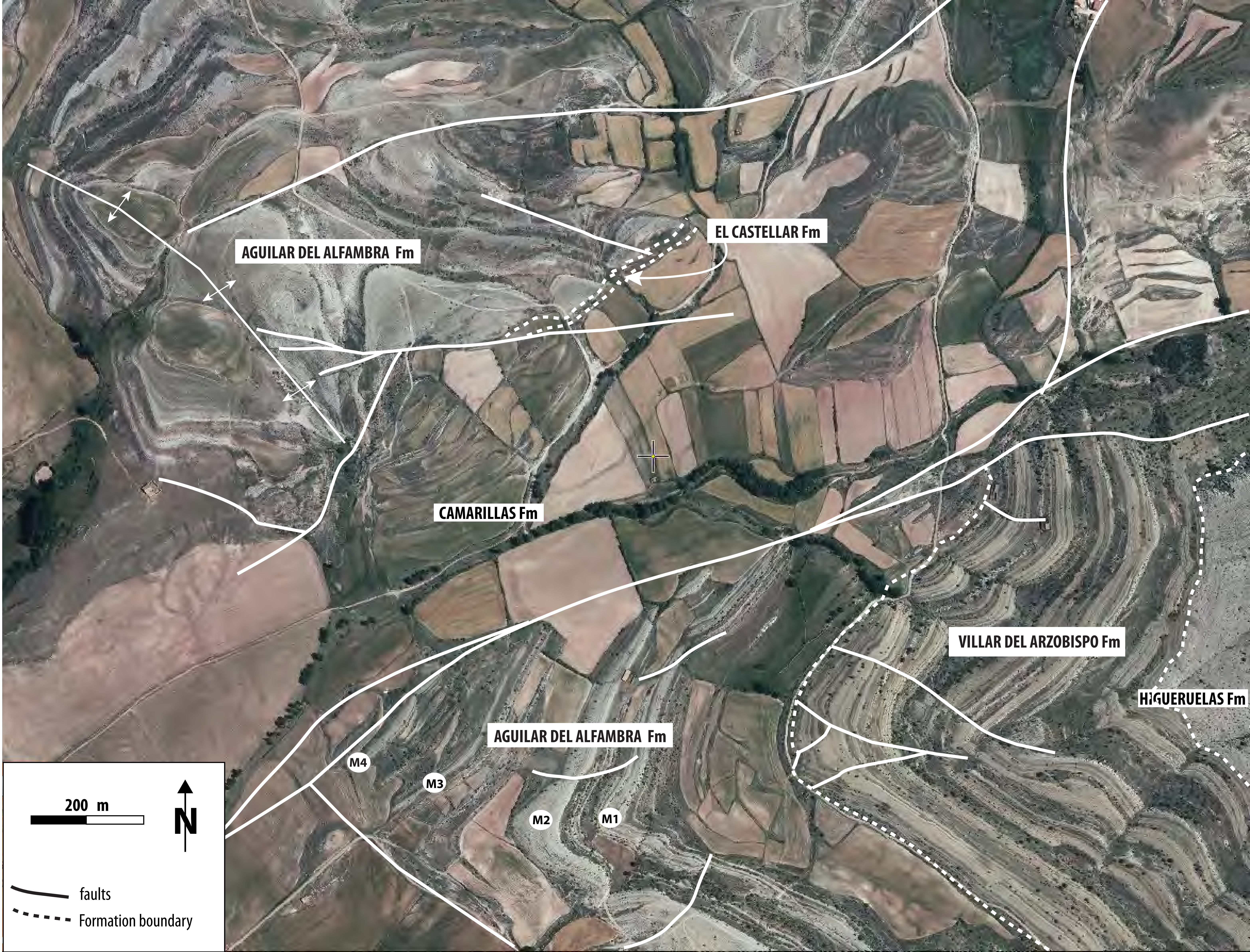

100 m
N
faults
Formation boundary
Mi: Miravete dinosaur tracksite
AL: Level rich in *Anchisp. lusitanica*
EL CASTELLAR Fm
VILLAR DEL ARZOBISPO Fm
HIGUERUELAS Fm
AL
Miravete de la Sierra
Mi
AGUILAR DEL ALFAMBRA Fm
Top
EL CASTELLAR Fm
CAMARILLAS Fm
AL
Base
VILLAR DEL ARZOBISPO Fm



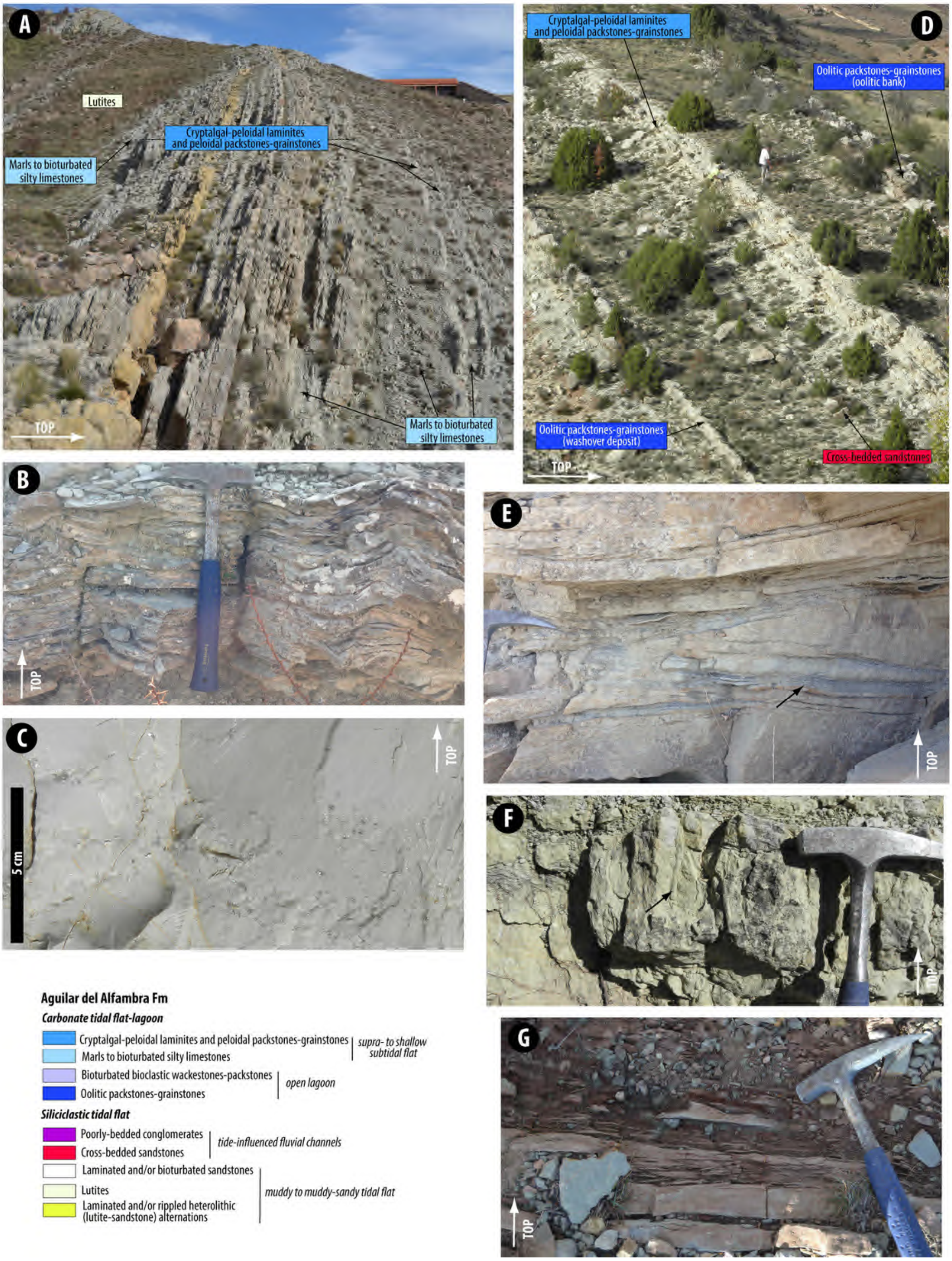
CAMARILLAS Fm
Molino Alto
upper
lower
Top
EL CASTELLAR Fm
GALVE Fm
Base
Guadalope River
100 m
N
faults
Formation boundary
field view (see photo below)
AGUILAR DEL ALFAMBRA Fm
GALVE Fm
Lower EL CASTELLAR Fm

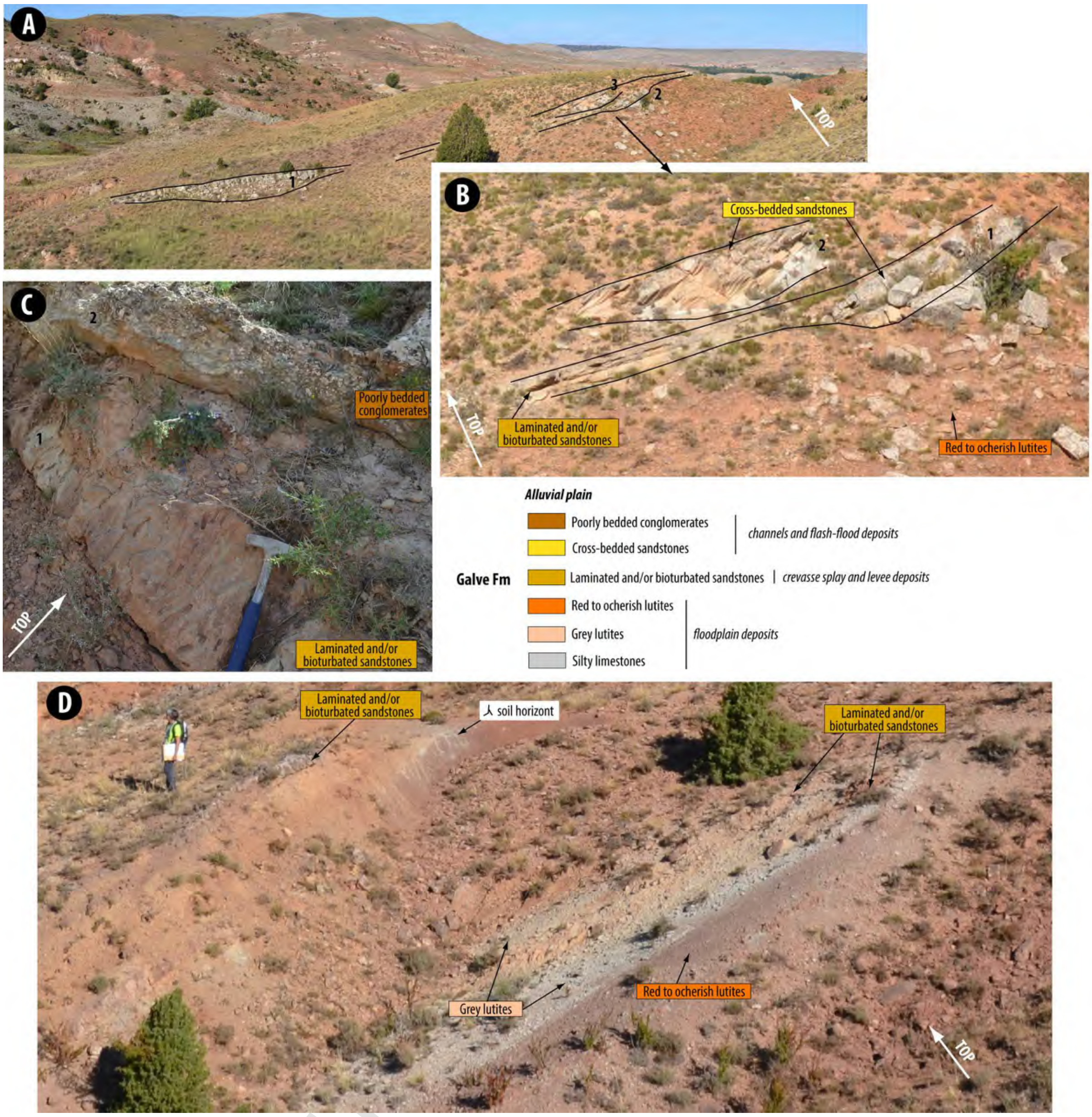


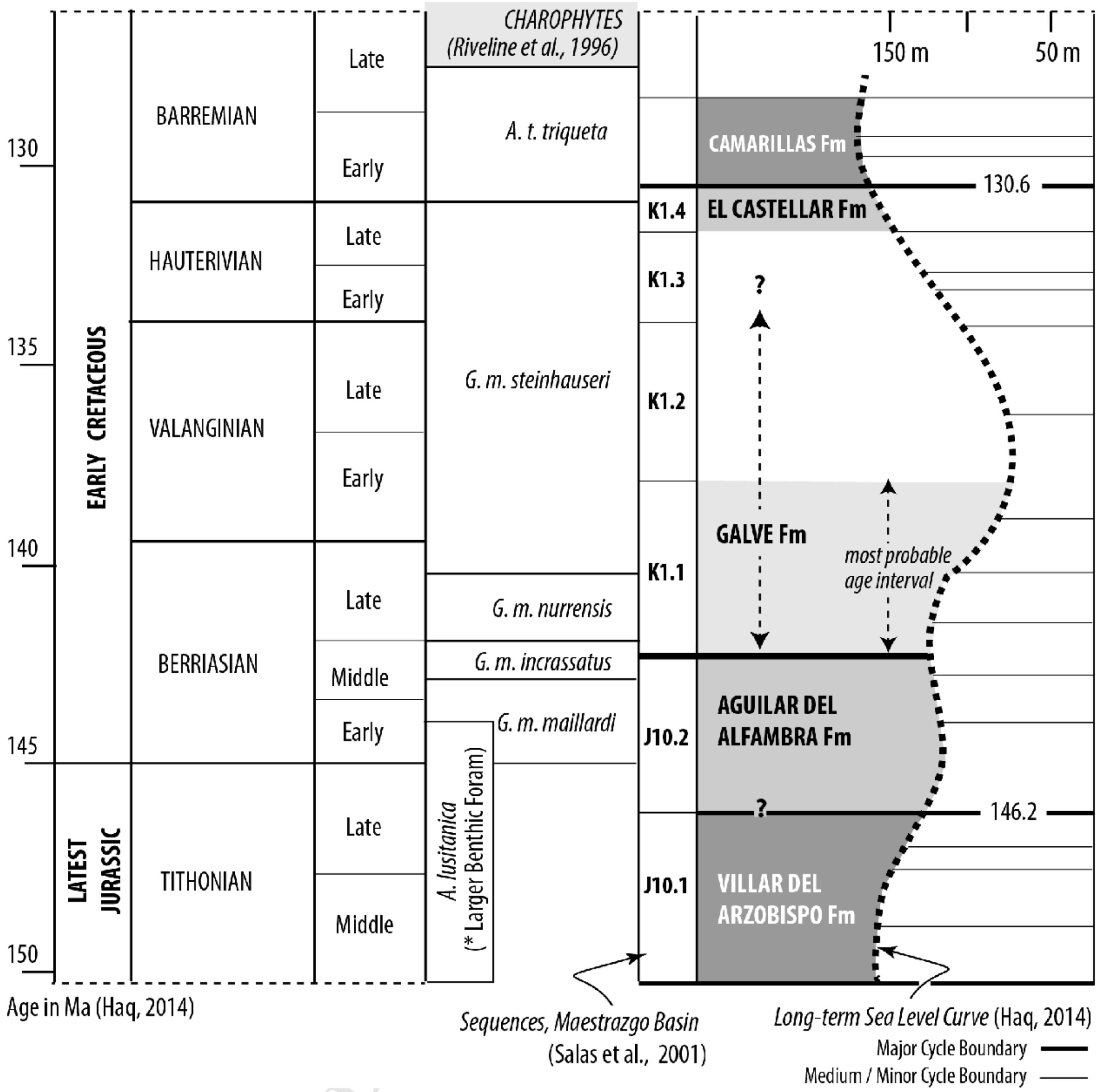
Camarillas Fm
BIOZONE
(Riveline et al. 1996)
AGE
190
SAL20
SAL19
SAL18
SAL17
SAL16
SAL15
150
SAL14
SAL13
SAL12
SAL11
100
SAL10
SAL9
50
SAL8
SAL7
SAL6
SAL5
SAL4
SAL3
SAL2
SAL1
(m) 0
Molino Alto 1
El Castellar Fm
Galve Fm
Galve Fm
Aguilar del Alfambra Fm
Atopochara trivolvis triquetra
Globator maillardii steinhauseri
Globator maillardii nurrensis
+
Globator maillardii incrassatus
SAL 13
SAL 9
SAL 3
LOWER BARREMIAN
VALANGINIAN-HAUTERIVIAN
BERRIASIAN
presence of charophytes
LEGEND
Conglomerates
Marls
Sandstones
Limestones
Lutites
Marly limestones
Trough cross bedding
Ripples
Burrowing/root traces
SAL2 Sediment sample
Vertebrate fossil site
SAL 13 Atopochara trivolvis triquetra
600 µm
SAL 13 Atopochara trivolvis ancora
600 µm
SAL 9 Atopochara trivolvis micranda
600 µm
SAL 3 Atopochara trivolvis horrida
600 µm

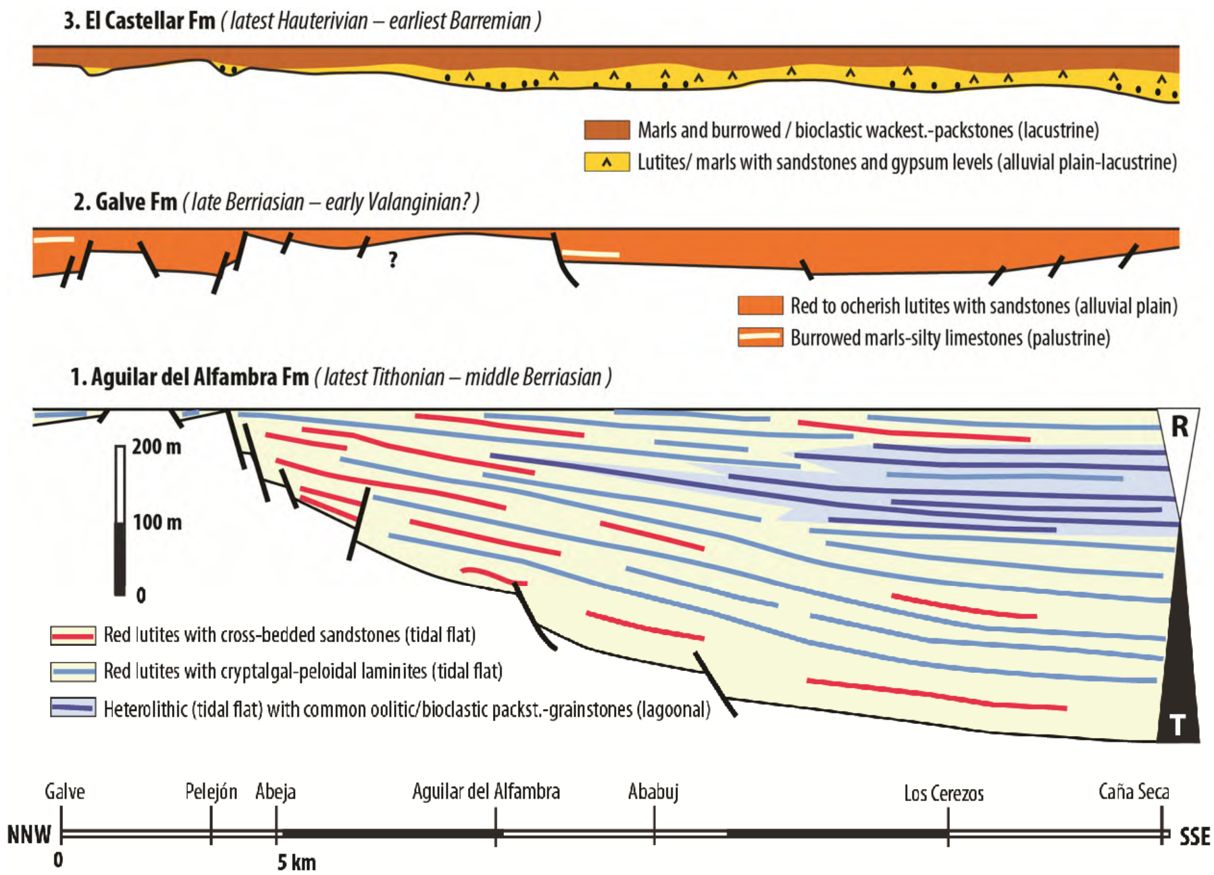


AGUILAR DEL ALFAMBRA Fm
EL CASTELLAR Fm
CAMARILLAS Fm
VILLAR DEL ARZOBISPO Fm
HIGUERUELAS Fm
AGUILAR DEL ALFAMBRA Fm
M4
M3
M2
M1
200 m
N
faults
Formation boundary


A
Lutites
Cryptalgal-peloidal laminites and peloidal packstones-grainstones
Marls to bioturbated silty limestones
Marls to bioturbated silty limestones
TOP
B
TOP
C
5 cm
TOP
D
Cryptalgal-peloidal laminites and peloidal packstones-grainstones
Oolitic packstones-grainstones (oolitic bank)
Oolitic packstones-grainstones (washover deposit)
Cross-bedded sandstones
TOP
E
TOP
F
TOP
G
TOP
Aguilar del Alfambra Fm
Carbonate tidal flat-lagoon
Cryptalgal-peloidal laminites and peloidal packstones-grainstones
Marls to bioturbated silty limestones
supra- to shallow subtidal flat
Bioturbated bioclastic wackestones-packstones
Oolitic packstones-grainstones
open lagoon
Siliciclastic tidal flat
Poorly-bedded conglomerates
Cross-bedded sandstones
tide-influenced fluvial channels
Laminated and/or bioturbated sandstones
Lutites
Laminated and/or rippled heterolithic (lutite-sandstone) alternations
muddy to muddy-sandy tidal flat


A
3
2
1
TOP
B
Cross-bedded sandstones
2
1
Laminated and/or bioturbated sandstones
Red to ocherish lutites
TOP
C
2
1
Poorly bedded conglomerates
Laminated and/or bioturbated sandstones
TOP
Alluvial plain
Galve Fm
Poorly bedded conglomerates
Cross-bedded sandstones
channels and flash-flood deposits
Laminated and/or bioturbated sandstones
crevasse splay and levee deposits
Red to ocherish lutites
Grey lutites
Silty limestones
floodplain deposits
D
Laminated and/or bioturbated sandstones
soil horizont
Laminated and/or bioturbated sandstones
Grey lutites
Red to ocherish lutites
TOP


CHAROPHYTES
(Riveline et al., 1996)
150 m
50 m
130
135
140
145
150
EARLY CRETACEOUS
LATEST JURASSIC
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
TITHONIAN
Late
Early
Middle
A. t. triqueta
G. m. steinhauseri
G. m. nurrensis
G. m. incrassatus
G. m. maillardi
A. lusitanica
(* Larger Benthic Foram)
K1.4
K1.3
K1.2
K1.1
J10.2
J10.1
CAMARILLAS Fm
EL CASTELLAR Fm
GALVE Fm
AGUILAR DEL ALFAMBRA Fm
VILLAR DEL ARZOBISPO Fm
130.6
146.2
most probable age interval
?
Age in Ma (Haq, 2014)
Sequences, Maestrazgo Basin
(Salas et al., 2001)
Long-term Sea Level Curve (Haq, 2014)
Major Cycle Boundary
Medium / Minor Cycle Boundary



3. El Castellar Fm ( latest Hauterivian – earliest Barremian )
Marls and burrowed / bioclastic wackest.-packstones (lacustrine)
Lutites/ marls with sandstones and gypsum levels (alluvial plain-lacustrine)
2. Galve Fm ( late Berriasian – early Valanginian? )
?
Red to ocherish lutites with sandstones (alluvial plain)
Burrowed marls-silty limestones (palustrine)
1. Aguilar del Alfambra Fm ( latest Tithonian – middle Berriasian )
200 m
100 m
0
R
T
Red lutites with cross-bedded sandstones (tidal flat)
Red lutites with cryptalgal-peloidal laminites (tidal flat)
Heterolithic (tidal flat) with common oolitic/bioclastic packst.-grainstones (lagoonal)
Galve
Pelejón
Abeja
Aguilar del Alfambra
Ababuj
Los Cerezos
Caña Seca
NNW
SSE
0
5 km