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TECTONO-SEDIMENTARY EVOLUTION AROUND THE JURASSIC-CRETACEOUS TRANSITION IN GALVE (AGUILAR DEL ALFAMBRA FORMATION, TERUEL, IBERIAN CHAIN)

Evolución tectono-sedimentaria en torno al límite Jurásico-Cretácico en Galve (Formación Aguilar del Alfambra, Teruel, Cordillera Ibérica)

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Abstract: *Extensive mapping and facies analysis in a 2 km continuous outcrop located west of Galve (Teruel) resulted in the identification of a set of synsedimentary normal faults. Fault activity after the sedimentation of the shallow marine to coastal deposits of the Tithonian Villar del Arzobispo Formation resulted in block tilting and the formation of a low-angle erosive unconformity with an associated gap probably ranging from the late Tithonian to the early Berriasian. The lower beds of the overlying mid-Berriasian Aguilar del Alfambra Formation locally onlap this erosive surface. Synsedimentary fault activity explains the sharp thickness changes observed within this formation. The Aguilar del Alfambra Formation was deposited in mixed terrigenous-carbonate tidal flat to restricted lagoon environments. The boundary between this formation and the overlying alluvial to fluvial terrigenous deposits of the Galve Formation is another erosive unconformity. This mid-late Berriasian unconformity is associated to successive conglomeratic beds. Synsedimentary fault activity at the onset of the sedimentation of the Galve Formation is indicated by the local incision of fluvial channels on the hanging walls of the faults. The reported data provides further understanding of the unconformities previously described at the lower and upper boundaries of the Aguilar del Alfambra Formation.*

Keywords: *synsedimentary tectonics, Berriasian, Galve, Aguilar del Alfambra Formation.*

Resumen: *Los resultados obtenidos en este trabajo están basados en el análisis cartográfico y de facies en un afloramiento continuo de 2 km de largo, que expone las formaciones Villar del Arzobispo, Aguilar del Alfambra y Galve al oeste de Galve (Teruel). Se ha identificado un conjunto de fallas normales que fueron activas durante la sedimentación de las unidades del tránsito Jurásico-Cretácico. En particular, se han documentado sucesivas etapas de erosión y sedimentación, que proporcionan una mayor comprensión del origen de las discontinuidades regionales descritas previamente en el límite inferior y superior de la Formación Aguilar del Alfambra en otras localidades de la subcuenca de Galve. La actividad de fallas normales tras la sedimentación de la plataforma carbonatada-siliciclástica somera de la Formación Villar del Arzobispo produjo un basculamiento de bloques y la formación de una superficie erosiva que tiene asociada una laguna estratigráfica que probablemente comprende desde el final del Titoniense al inicio del Berriasiense. Los niveles inferiores de la Formación Aguilar del Alfambra se superponen localmente en onlap sobre esta superficie irregular y erosiva. La actividad tectónica sinsedimentaria explica los cambios abruptos de espesor, de 4 a 14 m, observados dentro de esta formación. Se interpreta que la Formación Aguilar del Alfambra se depositó en una llanura de marea mixta terrígeno-carbonatada, con sedimentación episódica en ambientes de lagoon restringido. En torno al tránsito Berriasiense medio-superior hay una caída relativa mayor del nivel del mar, que marca el paso brusco a los depósitos terrígenos aluviales y fluviales de la Formación Galve. La presencia de sucesivos niveles conglomeráticos de cantos carbonatados poco redondeados se encuentra asociada a la superficie erosiva desarrollada en el límite entre las formaciones Aguilar del Alfambra y Galve. La actividad tectónica del inicio de la sedimentación de la Formación de Galve implica la incisión local de canales fluviales en los bloques hundidos de las fallas.*

Palabras clave: *tectónica sinsedimentaria, Berriasiense, Galve, Formación Aguilar del Alfambra.*

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Introduction

In rift settings, discontinuous fault activity favours the development of separate basins where a variety of sedimentary environments can develop, ranging from continental lakes to open marine shelves (Basilone and Sulli, 2016). The stratigraphic analysis of these subbasins, as well as the correlation between their sedimentary infills, often proves to be challenging, due to the frequent temporal and spatial discontinuities found in their stratigraphic record (*e.g.*, Gawthorpe *et al.*, 2000; Bosence, 2005). The uppermost Jurassic-lowermost Cretaceous sedimentary units recorded in the Galve Subbasin provide relevant examples of coastal to alluvial sedimentation controlled by normal fault activity (Aurell *et al.*, 2016).

The Galve syncline (Teruel province, eastern Iberian Chain) is a large N-S trending alpine structure, which offers an exceptional continuous exposure of the Upper Jurassic-Lower Cretaceous units. These units were deposited during the initial rift stage that gave rise to the Galve Subbasin, a NW-SE trending depositional trough located in the north-western marginal areas of the Maestrazgo Basin (Fig. 1A; Salas *et al.*, 2001; Liesa *et al.*, 2018).

The stratigraphic assignment of some of the units recorded in the Galve syncline has been controversial (*e.g.*, Diaz-Molina and Yébenes, 1987; Canudo *et al.*, 2012; Royo-Torres *et al.*, 2014; Aurell *et al.,* 2016). Their stratigraphic complexity is mainly derived from the existence of discontinuous fault activity over space and time during the latest Jurassic-

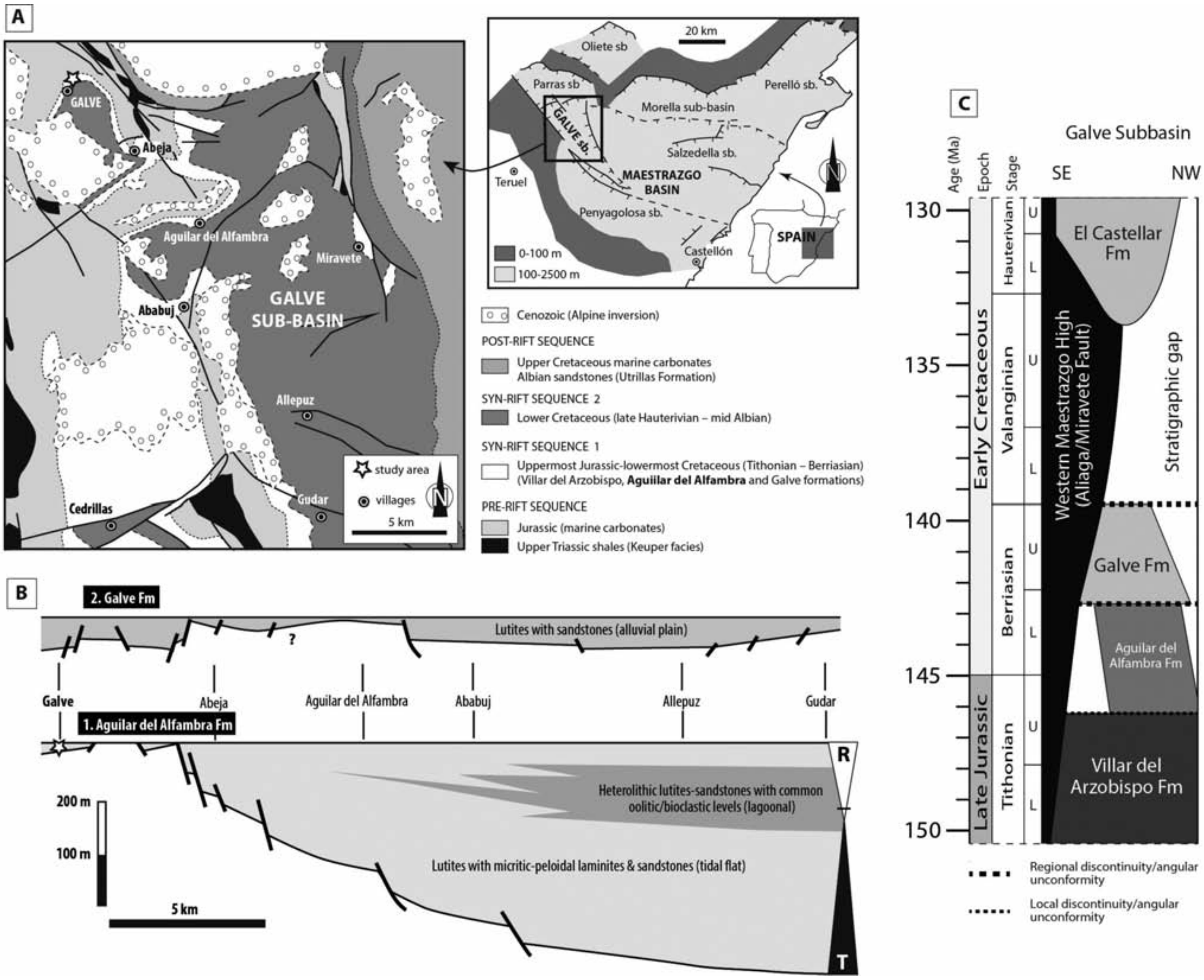

Fig. 1.- A. Location of the Galve Subbasin in the Maestrazgo Basin of the Eastern Iberian Peninsula. The geological map shows the sedimentary sequence distribution along the subbasin. B. Cross-section of the Aguilar del Alfambra Formation and the overlaying Galve Formation, showing their thickness variability and overall facies distribution in the Galve Subbasin (adapted from Aurell *et al.*, 2016). C. Chronostratigraphic distribution of the units concerning this study in the Galve Subbasin (Modified from Liesa *et al.*, 2018).

Early Cretaceous, which resulted in rapid variations in thickness and facies in different domains of the Galve Subbasin, involving the development of local unconformities and stratigraphic gaps of variable amplitude (*e.g.*, Liesa *et al.*, 1996, 2006). In a recent research, Aurell *et al.* (2016) have reconstructed the stratigraphy and tectono-sedimentary evolution of the Galve Subbasin during the Tithonian-early Barremian. The authors describe regional low-angle unconformities and significant lithological changes across the subbasin, and propose the definition of two new lithostratigraphic units (Fig. 1B, C): the upper Tithonian–mid Berriasian Aguilar del Alfambra Formation and the mid–upper Berriasian Galve Formation. These two units would be located between the previously defined Villar del Arzobispo and El Castellar formations and would represent the last tectono-sedimentary stage of the syn-rift sequence 1 (Liesa *et al.*, 2018).

The Tithonian–Barremian units exposed in the Galve syncline are well known in the relevant geological literature, mainly due to their richness in vertebrate sites (*e.g.*, Ruiz-Omeñaca *et al.*, 2004). Specifically, the sauropod *Aragosaurus ischiaticus* (the first dinosaur ever described in Spain) was recovered from this locality (Sanz *et al.,* 1987). Also relevant is the presence of well-preserved dinosaur tracks, like those of the Las Cerradicas tracksite (Pérez-Lorente *et al.*, 1997). A pioneering stratigraphic analysis in the Galve syncline was carried out by Diaz-Molina and Yébenes (1987), and an updated stratigraphy of the Galve Subbasin was proposed in Aurell *et al.* (2016) and Liesa *et al.* (2018).

The main purpose of the present paper is to present the research findings resulting from the detailed mapping and facies analysis of the Aguilar del Alfambra Formation, extending along a 2 km-long continuous outcrop located near the village of Galve, in the western limb of the Galve syncline. The reported data contribute to the better understanding of the tectono-sedimentary evolution of the Galve Subbasin around the Jurassic-Cretaceous transition.

Geological setting and methods

The study area is located in the western Maestrazgo Basin (Fig. 1A), which is included in the Mesozoic Iberian rift system that was the result of extensional tectonics that took place from the end of the Jurassic to the mid-Albian stage. The Maestrazgo Basin was divided into seven subbasins bounded by areas with concentrations of major extensional faults (Guimerà and Salas, 1996; Salas *et al.*, 2001; Capote *et al.*, 2002; Aurell *et al.*, 2016; Liesa *et al.*, 2017).

Synrift sedimentation in the Galve Subbasin was controlled by an ENE-WSW trending system of listric normal faults, limited laterally by a NNW-SSE trending system of transfer normal faults with subvertical fault planes (Liesa *et al.*, 2006). Both fault systems started acting synchronously during the late Hauterivian; until then, the ENE-WSW listric faults operated individually, giving rise to small, localised subbasins. Significant tilting of blocks, low-angle angular unconformities and fan-shaped geometries of the syn-rift deposits have been related to the listric geometry of the faulting (*e.g.*, Liesa *et al.*, 1996, 2006).

The stratigraphy of the Galve Subbasin comprises pre-, syn- and post-rift sequences (Fig. 1A). 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.*, 2018): the mid Tithonian–Berriasian syn-rift sequence 1 (Villar del Arzobispo, Aguilar del Alfambra and Galve formations, up to 700 m thick), and the late Hauterivian–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; *e.g.*, Soria, 1996), followed by Aptian shallow carbonate platform facies (Urgon facies, *e.g.*, Vennin and Aurell, 2001). 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 studied interval is included in the mid Tithonian-Berriasian syn-rift sequence 1 (Fig. 1C). The Villar del Arzobispo Formation has a relatively constant thickness of 150–170 m along the Galve subbasin. The unit includes *Anchispirocyclina lusitanica* (Diaz-Molina and Yébenes, 1987). This large benthic foraminifer existed throughout the Tithonian-earliest Berriasian, which indicates that the Villar del Arzobispo Formation developed most probably at the middle part of the Tithonian in the Galve subbasin (Aurell *et al.*, 2016). The upper Tithonian-mid Berriasian Aguilar del Alfambra Formation has significant thickness changes related to synsedimentary fault activity, with a maximum thickness of 380 m recorded in the southern areas of the Galve subbasin located around Allepuz (Fig. 1B; Aurell *et al.*, 2016). The unit shows an overall transgressive-regressive trend, with the transgressive peak indicated by oolitic/bioclastic limestones, also containing abundant *Anchispirocyclina lusitanica*. The sedimentary record of the Aguilar del Alfambra Formation around Galve is reduced, with up to 14 m-thick red and grey lutites, marls and limestones. A marly bed located towards the top of the unit includes the middle Berriasian charophyte *Globator maillardii incrassatus* (Canudo *et al.*, 2012). Considering the age of the underlying Villar del Arzobispo Formation (i.e., mid-Tithonian) it can be inferred that, near Galve, the unconformity found between the Villar del Arzobispo and the Aguilar del Alfambra formations has an associated stratigraphic gap which spans around the late Tithonian–early Berriasian (Aurell *et al.*, 2016).

The thickness of the Galve Formation varies significantly across the Galve Subbasin (from 50 to 80 m) and is dominated by red lutites with cross-bedded sandstones, originated in an alluvial plain (Fig. 1B) The upper boundary of the Galve Formation is a major unconformity with a large associated stratigraphic gap (Fig. 1C), spanning most of the Valanginian and Hauterivian (Aurell *et al.*, 2016).

The results presented here are based on new data acquired after extensive geological mapping and logging in a 2 km-long continuous outcrop located west of the Galve village, including the uppermost Villar del Arzobispo, the Aguilar del Alfambra and the lowermost Galve formations (Fig. 2). The workflow relevant to this paper consisted of: (1) geological

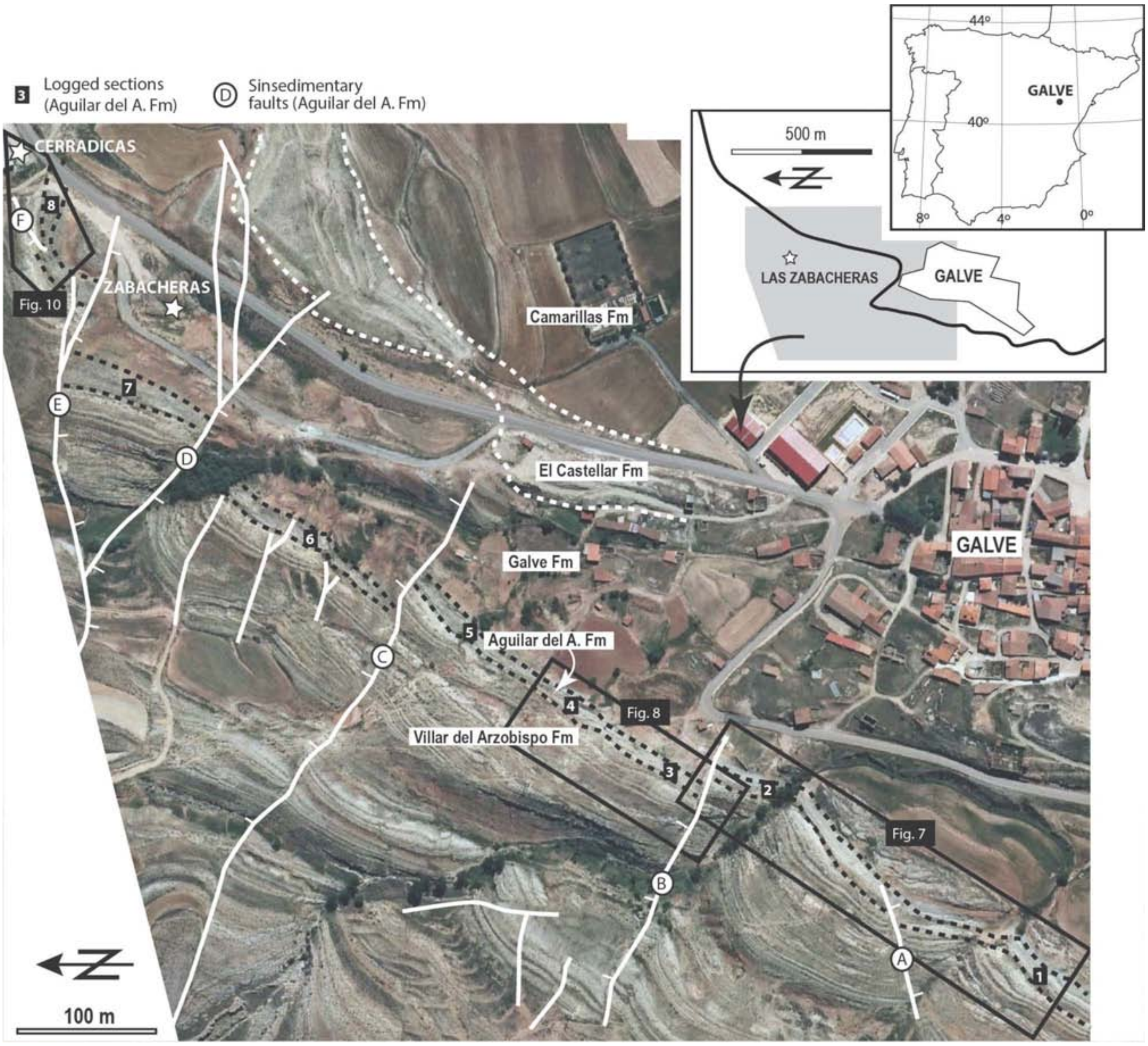

Fig. 2.- Photogeological map of the study area, showing the main synsedimentary faults affecting the Aguilar del Alfambra Formation and the location of the detailed views shown in figures 7, 8 and 10. The location of the eight logged sections, which provide the stratigraphic background of this study, is also indicated (adapted from Aurell *et al.*, 2016).

mapping based on fieldwork and the analysis of high-resolution aerial imagery obtained by a drone; (2) logging of eight detailed stratigraphic sections to a dm scale in the Aguilar del Alfambra Formation, including rock sampling for petrographic study in thin sections and analysis of carbonate content; (3) facies analysis (microfacies, petrography) and microfossil determination; and (4) integration of these data sets.

Overall distribution of stratigraphic units and synsedimentary faults in Galve

The study area in the western limb of the Galve syncline includes a number of normal faults that were active during the deposition of the Aguilar del Alfambra Formation (see *faults A–F* in Fig. 2). However, there is no significant evidence of differential subsidence or tilting of blocks linked to the activity of *faults A–F* during the deposition of the Villar del Arzobispo Formation. Accordingly, facies distribution in the Villar del Arzobispo Formation is very constant around the Galve syncline. There, this unit consists of four sequences, each one formed by a carbonate succession (10–30 m thick) of shallow marine skeletal-peloidal-oolitic burrowed limestones followed by a terrigenous succession (15-40 m thick) of red lutites and cross-bedded sandstones, representing coastal plain to shoreface sediments (Subias, 2015).

In the western limb of the Galve syncline, fault activity becomes evident after the deposition of the Villar del Arzobispo Formation. The thickness of the overlying Aguilar del Alfambra Formation along the study area is reduced (from 4 to 14 m). In addition, there are evidences of fault activity during its deposition, including block tilting and the existence of a local, low-angle erosive unconformity between the Villar del Arzobispo and the Aguilar del Alfambra formations (see detailed description below).

Local thickness variation in the Galve Formation near the Las Zabacheras fossil site (see Fig. 2) has also been re-

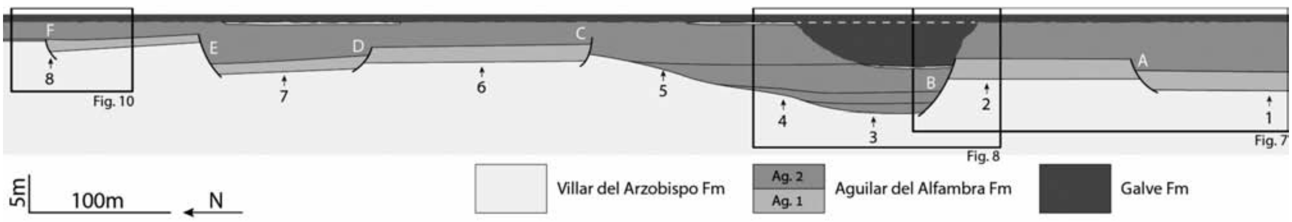

Fig. 3.- General stratigraphic section showing the overall distribution of the studied lithostratigraphic units, the main synsedimentary faults (A–F) and the location of the eight logged sections (1–8). The squared areas show the position of the outcrops depicted by figures 7, 8 and 10. The facies distribution in grey area between faults B and C is complex and the lithological sets Ag.1 and Ag.2 (see Fig. 4) have not been differentiated.

lated to synsedimentary fault activity (Canudo *et al.*, 2012; Aurell *et al.*, 2016). The lower boundary of the Galve Formation is a significant erosive unconformity, and in the central areas of the eastern limb of the syncline, the Galve Formation may even rest directly over the Villar del Arzobispo Formation, the Aguilar del Alfambra Formation being absent (see Fig. 1B). Evidences of this erosive unconformity at the boundary between the Aguilar del Alfambra and Galve formations are represented in the study area by the widespread presence of conglomeratic beds with abundant carbonate clasts accumulated both at the uppermost part of the Aguilar del Alfambra Formation and in the lower part of the Galve Formation. Some normal faults were active at the onset of the deposition of the Galve Formation (see detailed description below), while others were only active during the sedimentation of the Aguilar del Alfambra Formation and are fossilized by the Galve Formation (see *faults A* and *F* in Fig. 2).

Facies analysis

Description

The overall lthological distribution of the Aguilar del Alfambra Formation in the area of study, obtained after sedimentological analysis and physical correlation of logs 1–8 (see Fig. 2 for location), is summarised in a N-S trending synthetic section (Fig. 3). The observed thickness variation is related to synsedimentary activity of *faults A–F*.

As a whole, two main lithological sets are differentiated within the Aguilar del Alfambra Formation (Ag. 1 and Ag. 2 in Figs. 3 and 4). The lower set Ag. 1 is 2–4 m thick, and consists of greyish-to-reddish lutites with scarce and discontinuous peloidal limestone beds. These lutites present a progressive, northwards, thickness reduction. The upper set Ag. 2 is more variable in thickness (from 2 to 12 m) and is formed by an alternation of dm-thick greyish oolitic to peloidal limestone beds and cm- to dm-thick grey lutitic beds.

Three main lithofacies are distinguished within the Aguilar del Alfambra Formation (Fig. 5): lutites (Lu), limestones (Li) and conglomerates (Co). Lutitic lithofacies (Lu) include two subfacies: red lutites (Lu-1) with very low carbonate content (2–5%) and pale grey lutites (Lu-2) with a higher carbonate content (10–35%). Abundant mottling in these grey lutites evidences biological activity (*i.e.*, root traces).

Limestone lithofacies (Li) include three interfingered subfacies. Subfacies Li-1 (Fig. 5E,F) is integrated by peloidal packstones-grainstones forming dm- to m-thick, tabular to irregular, greyish beds with cm-thick, grey-to-reddish lutitic intercalations. Some beds show parallel and undulate lamination, symmetrical ripples and fe-

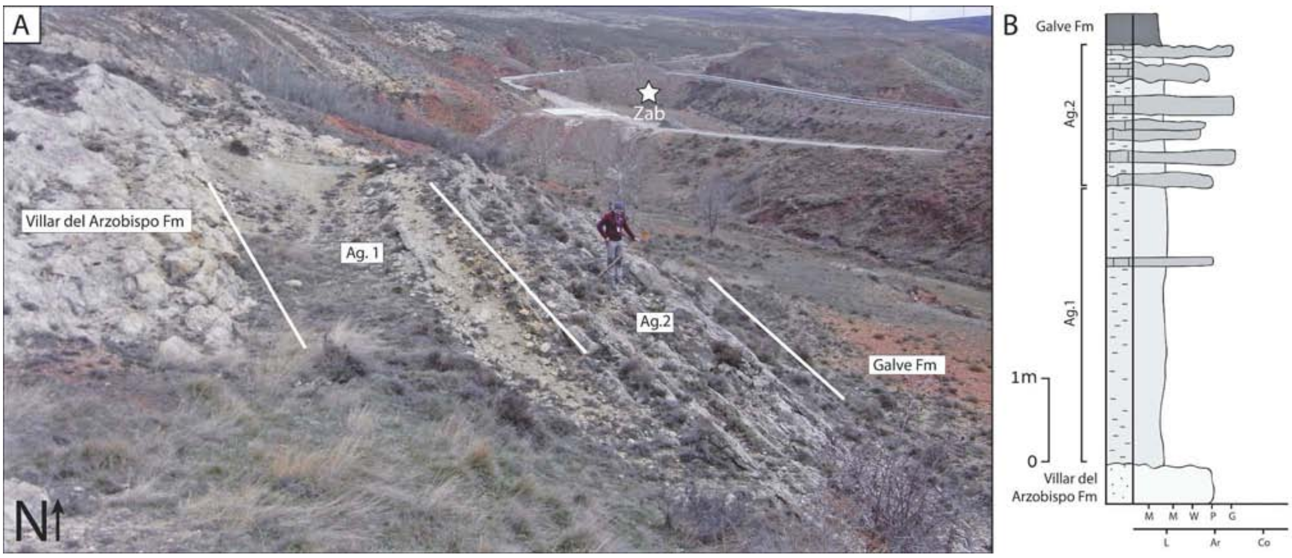

Fig. 4.- Field view of an outcrop of the Aguilar del Alfambra Formation (A) and stratigraphic log 5 (B), showing two distinct lithological sets; the lower one (Ag. 1) is mainly lutitic with occasional thin and irregular limestone beds; the upper one (Ag. 2) is composed of irregular limestone beds interbedded with grey lutites. The location of the Las Zabacheras (Zab) fossil site is indicated in the background.

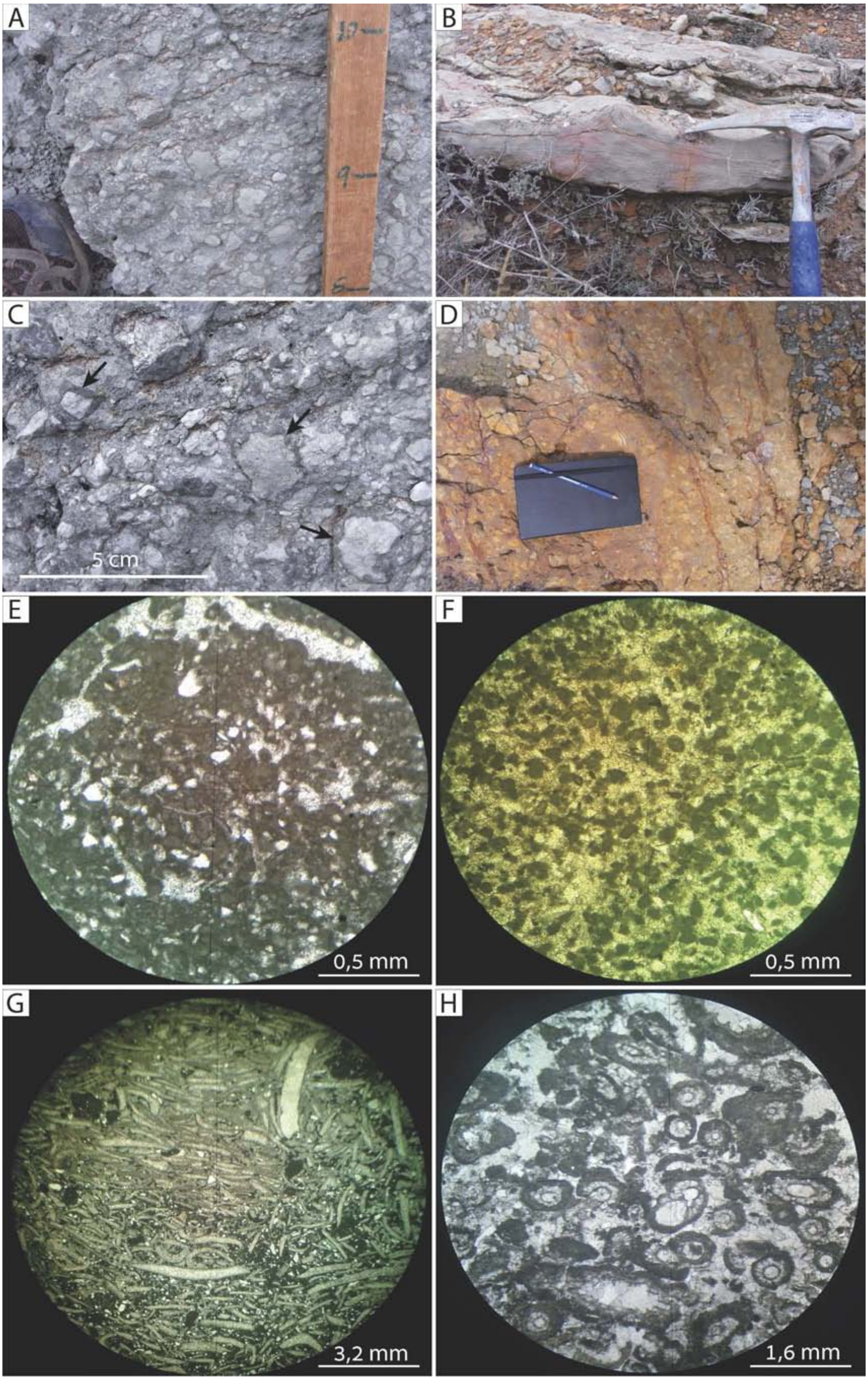

Fig. 5.- A. Conglomerate bed in facies Co1, showing angular clasts embedded in a grey carbonate matrix. B. Carbonate laminites (Li-1) typical of the Aguilar del Alfambra Formation, showing a tepee desiccation structure. C. Detail of the Co1 conglomerate bed showing micritic envelopes around the clasts (see arrows). D. Conglomerate bed in facies Co2, showing subangular to subrounded clasts in an orange, siliciclastic matrix. E. Peloidal packstones (Li-1) with fenestral porosity and quartz grains. F. Peloidal grainstones with quartz grains (Li-1). G. Bioclastic packstones (Li-2) composed of fragmented bivalve shells. H. Bioclastic grainstones composed of charophyte stems (Li-3).

nestral porosity. Other beds show evidences of intense bioturbation (uneven distribution of micritic matrix, irregular bedding surfaces, vertical galleries). In general, the packstones show poorer grain sorting than the grainstones. Fossil content is scarce and of low diversity, and is mainly composed of fragmented gastropod and bivalve shells, benthic foraminifera (miliolids) and serpulids. Subfacies Li-2 (Fig. 5G) is composed of bioclastic packstones-grainstones containing abundant remains of bivalves, gastropods and benthic foraminifera (up to 65%), and also peloids (up to 30%), forming dm-thick tabular, grey beds, with cm-thick grey lutitic intercalations. Subfacies Li-3 (Fig. 5H) consists of bioclastic grainstones with abundant charopyte stems (up to 50%) forming cm- to dm-thick, tabular, grey beds. All three subfacies present variable proportions of quartz silt (less than 15%).

The conglomeratic lithofacies (Co) are concentrated in the upper part of the Aguilar del Alfambra Formation and includes two subfacies. The Co-1 subfacies is formed by subrounded-to subangular carbonate clasts embedded in a grey carbonate matrix. Individual clasts can be surrounded by algal laminae (Fig. 5A,C). Laterally discontinuous beds of Co-1 conglomerates appear interbedded in the aforementioned Li-1 subfacies. The Co-2 subfacies is a poorly sorted breccia, with subangular limestone clasts included in an orange, sandy matrix (Fig. 5D). This facies appears at the topmost part of the Ag. 2 set (see Fig. 4) of the Aguilar del Alfambra Formation in some of the logged sections.

Interpretation

The depositional environment of the Aguilar del Alfambra Formation in the Galve area has been interpreted as a restricted lagoon-tidal flat with episodic storm activity and continentally derived clastic input (Fig. 6). The reconstructed model is coherent with the sedimentary model proposed in Aurell *et al.* (2016) for this unit in the overall Galve Subbasin.

The more interior facies belt corresponds to the lutitic lithofacies Lu-1 and Lu-2, which would be deposited in a supratidal to upper intertidal tidal flat, characterized by land-derived input of siliciclastic clay and silt. These lithofacies progressively grade into the limestone (Li) lithofacies, which have been interpreted as deposited in a lower intertidal to shallow subtidal lagoon environment. Some limestone beds (subfacies Li-1) show parallel and undulate lamination, symmetrical ripples, fenestral porosity and tepee structures, diagnostic of intertidal environments. The fossil content of these lithofacies (bivalves, gastropods and miliolids) is coherent with the proposed interpretation. The presence of grain-supported peloidal and skeletal beds (subfacies Li-2) interbedded among the laminated facies indicates the existence of high-energy events, most probably storm-driven.

The scarcity and low diversity of fossil debris in most beds of the limestone subfacies Li-1 indicate some restricted environment. Poor communication with open waters could have led to conditions of hypersalinity. Other beds, however, show copious evidence of biological activity, which points to the existence of episodes of communication with oxygenated water during which the development of benthic communities could have taken place. Subfacies Li-2 is characterized by local accumulation of fragmented bivalve shells, gastropods and benthic foraminifera, and was possibly caused by storm episodes. Subfacies Li-3 represents fresh or brackish water ponds located in the supratidal-upper intertidal zone. The communication between these ponds and the lagoon could not have been permanent, as this would not have allowed the development of the conditions necessary for charophytes to thrive. It is also possible that the existence of moderate-to-large-sized freshwater courses coming from the continent, coupled with the absence of strong currents inside the lagoon, gave rise to the development of estuarine conditions, which allowed the development of charophytes.

Some beds of the conglomerate facies Co-1 are also interbedded in the limestone facies Li-1 and Li-2. The con-

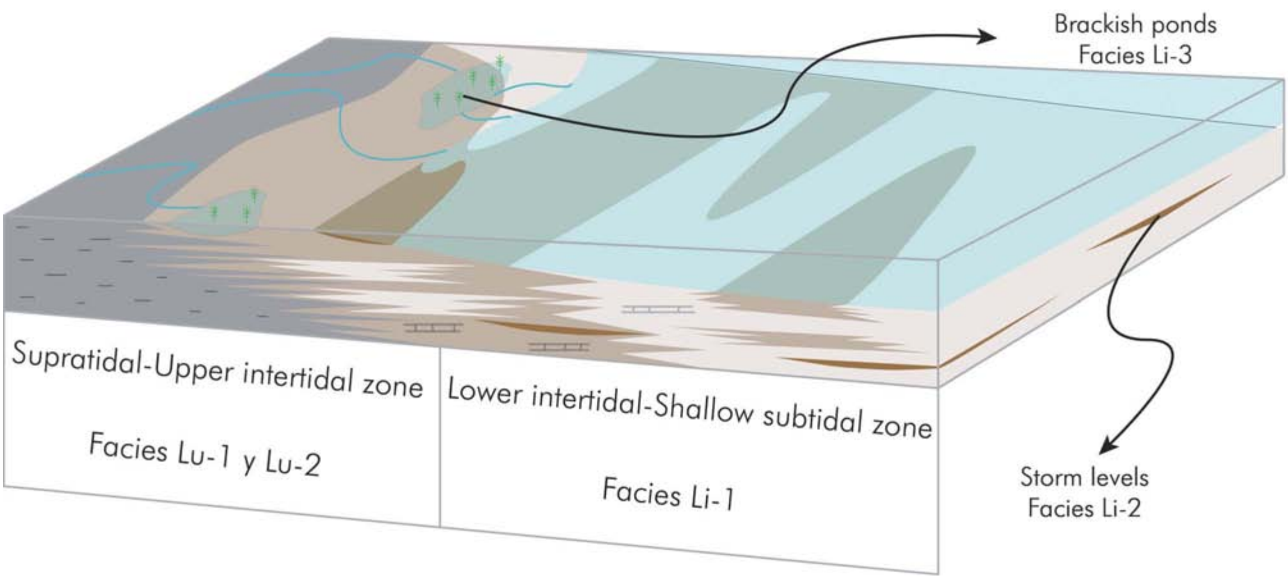

Fig. 6.- Paleoenvironmental interpretation for the Aguilar del Alfambra Formation in the study area.

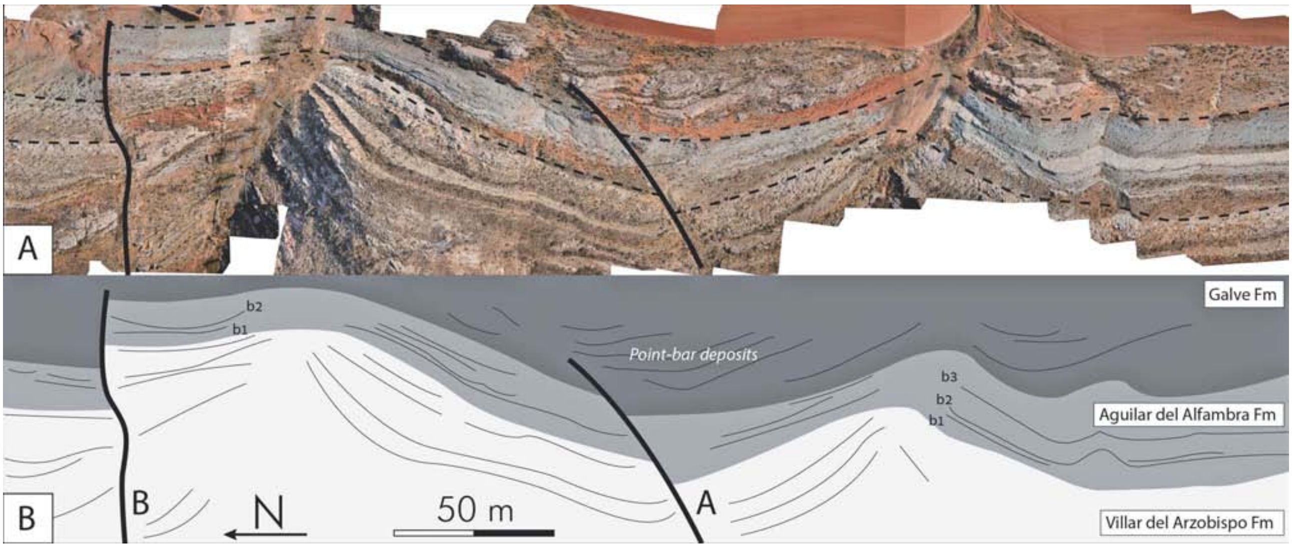

Fig. 7.- Drone image and mapping around synsedimentary *fault A* (see Figs. 2 and 3 for location). Three competent b1, b2 and b3 beds have been identified in the hanging wall block of the fault. In the footwall block, the upper level has been eroded away, and only the two lower beds b1 and b2 are identifiable. Point bar deposits can be observed at the base of the Galve Formation in the central part of the image. Note that the drone photograph provides an oblique view of the bedding, and thicknesses are exaggerated.

glomerate (Co) facies present subangular clasts, which are evidence for a very short transport. They are likely to have been also caused by storm episodes, which reworked and resedimented the semiconsolidated muddy substrate. Wave activity originated after earthquakes offers an alternative explanation for the origin of these conglomeratic beds (*i.e.*, tsunamites; *e.g.*, Navarrete *et al.*, 2014).

Synsedimentary fault activity around the Jurassic-Cretaceous transition

The deposition of the Aguilar del Alfambra Formation in the studied area was controlled by a set of ENE-WSW master faults (*A-F* in Fig. 2), some of which were active up until the onset of the deposition of the El Castellar Formation. In order to describe the influence of tectonics during the deposition of the Aguilar del Alfambra Formation, the activity of each master fault has been studied individually.

The synsedimentary activity of *fault A* led to a differential erosion of the upper levels of the Aguilar del Alfambra Formation in the footwall block (Fig. 7). Three local lithological sets have been differentiated in this specific segment using drone aerial imagery (Fig. 7) in order to analyze the influence of erosion associated to the movement of *fault A*. The lower local set is integrated by the basal lutitic set found at the base of the formation in this area (Ag. 1, Fig. 3), and is topped by two competent limestone beds (b1 and b2 in Fig. 7). The middle local set comprises an alternation of grey lutites and irregular limestone beds topped by a third competent limestone bed (b3 in Fig. 7). The upper local set consists of an alternation of grey lutites and irregular limestone beds. At the hanging wall of the fault, all three local sets are present, while only the lower local set and the lutitic portion of the middle local set are preserved at the footwall.

During the deposition of the Aguilar del Alfambra Formation, the hanging wall block of master *fault B* contained a small syntectonic basin in which the unconformities located at the base and top of the Aguilar del Alfambra Formation can be clearly observed (Figs. 8 and 9). An ochre sandstone bed (Vi2 in Fig. 8) with abundant skeletal remains (bivalves, gastropods) and plant debris and interbedded with lutites is found at the uppermost part of the Villar del Arzobispo Formation. This bed is cut by a prominent erosive surface found at the base of the Aguilar del Alfambra Formation. The lowermost limestone beds of the Aguilar del Alfambra Formation onlap this erosive surface. The upper erosive surface between the Aguilar del Alfambra and Galve formations is underlined by the presence of conglomeratic beds (C1 in Fig. 9). This erosive surface incised the upper levels of the Aguilar del Alfambra Formation, generating a channel-like geometry. The lower area of the incision is also associated to a conglomerate bed (C2 in Fig. 9).

The tectono-sedimentary evolution in relation to *fault B* is shown in successive stages (Fig. 9). *Stage 1* depicts the situation previous to the onset of the fault activity. Beds Vi1 and Vi2 correspond to the whitish sandstone and ochre bioclastic sandstone beds located at the top of the Villar del Arzobispo Formation. The initial fault activity (*stage 2*) resulted in the formation of a half graben, involving the coeval erosion of the topmost levels of the Villar del Arzobispo Formation and the onlapping deposition of the basal levels of the Aguilar del Alfambra Formation. During this stage, sedimentation alternated with erosional stages that gave rise to thin and laterally discontinuous intraformational conglomeratic beds. After the deposition of the Aguilar del Alfambra Formation, an erosional *stage 3* was followed by the onset of the deposition of the continental siliciclastic facies characterizing the Galve Formation. This erosional surface is associated to a relatively thick and laterally continuous conglomerate bed (C1 in Fig. 9) in facies Co-1. The initial deposits of the Galve Formation consist of dark reddish lutites with interbedded dm-thick sandstone beds showing abundant *Taenidium* traces, interpreted as crevasse splay deposits (Aurell *et al.*, 2016). The erosion of the topmost levels of the Aguilar del Alfambra Formation increased near *fault B* (*stage 4*), generating a channel-like erosional scar, possibly due to the incision of a water course favoured by the continued activity of the fault. This scar is associated to a conglomerate bed (C2 in Fig. 9) in facies Co-2. The presence of a channelled water course is coherent with the presence of point bar deposits on an equivalent stratigraphical position less than 100 m to the south of this location, around *fault A* (see Fig. 2; Aurell *et al.*, 2016). Displacement at *fault B* progressed (*stage 5*), furtherly offsetting the preserved levels of the Aguilar del Alfambra Formation. The upper levels of the Galve Formation eventually fossilized the fault.

Between *faults C* and *D*, the Aguilar del Alfambra Formation presents a slight northwards reduction in thickness, from 4.5 m near *fault C* to 3.5 m near *fault D* (Fig. 2). The poor conditions of the outcrop did not allow to establish if the observed small lateral thickness variation was due to synsedimentary tectonics or erosion following postsedimentary rotation of blocks. The Aguilar del Alfambra Formation fossilizes some smaller scale normal faults affecting the Villar del Arzobispo Formation (between master *faults C* and *D* in Fig. 2).

The thickness of the Aguilar del Alfambra Formation increases from 7 m near *fault D* to 12 m near *fault E*. The observed thickness increase can be related to block tilting related to these faults. North of *fault E* (towards the uplifted block) the Aguilar del Alfambra Formation has a significant thickness reduction, down to 2.4 m (Fig. 2).

The activity of the small *fault F* was also coeval to the sedimentation of the Aguilar del Alfambra Formation (Fig. 10). This activity led to the formation of a small half graben, filled up by a 2.1 m thick succession of lutites (subfacies Lu-2), including intercalations of peloidal limestones (subfacies Li-1). The fault is fossilized by the first continuous limestone bed (subfacies Li-1) of the upper part of the Aguilar del Alfambra Formation, indicating a short-living stage of activity of *fault F*.

Concluding remarks: tectono-sedimentary evolution

Extensive mapping and facies analysis has been carried out in a 2 km-long continuous outcrop exposing the uppermost Villar del Arzobispo, Aguilar del Alfambra and lowermost Galve formations west of the village of Galve (Teruel). The obtained data resulted in the identification of a set of normal faults that were active around the Jurassic-Cretaceous transition. In particular, a set of alternating erosion and sedimentation stages has

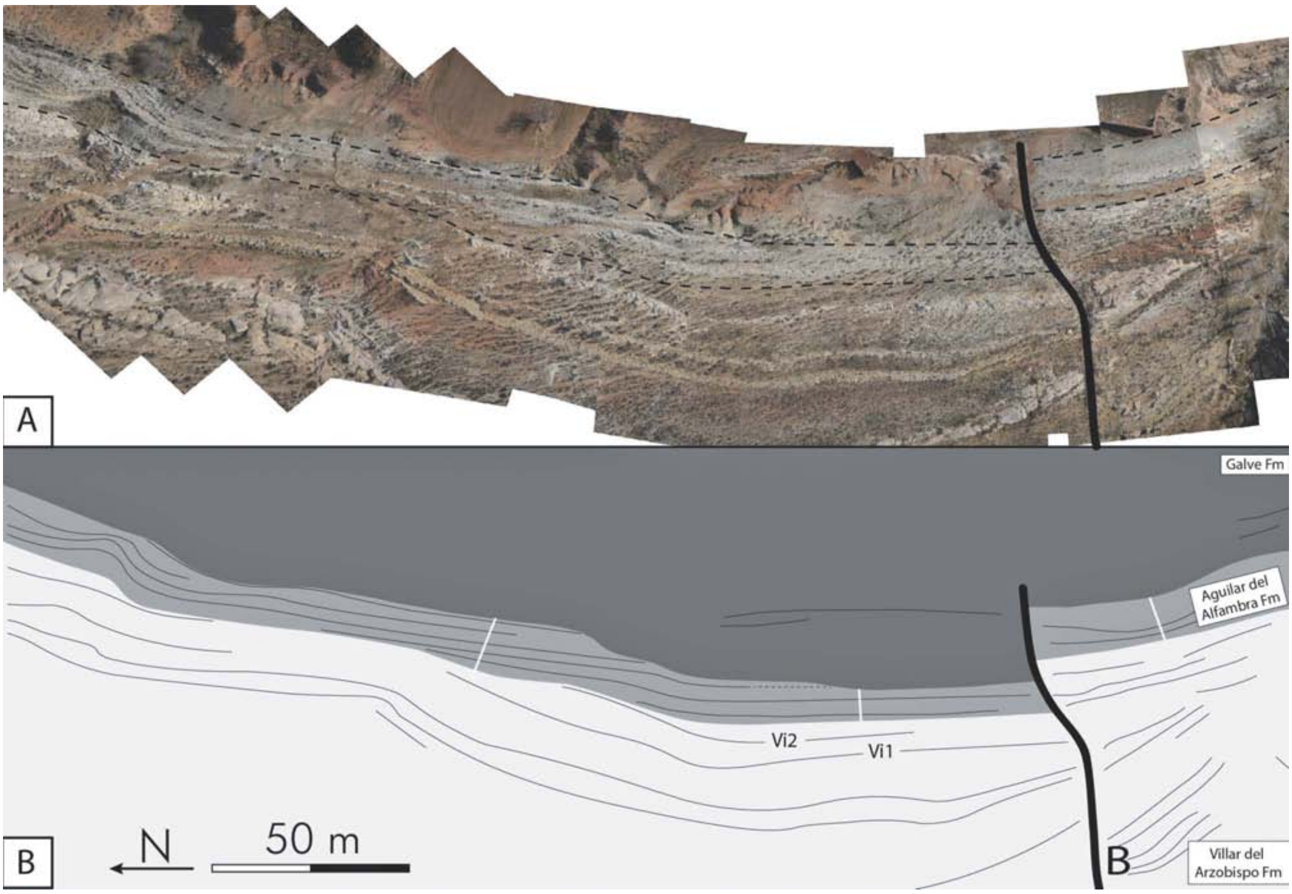

Fig. 8.- Drone image and mapping showing a small syntectonic graben developed on the hanging wall block of *fault B* (see Figs. 2 and 3 for location). The base of the Aguilar del Alfambra Formation is erosive, and truncates the two beds Vi1 and Vi2 located at the top of the underlying Villar del Arzobispo Formation. The lower levels of the Aguilar del Alfambra Formation onlap over this erosive surface. Near *fault B*, the base of the Galve Formation forms a channel-like erosive scar, which incises the topmost levels of the Aguilar del Alfambra Formation.

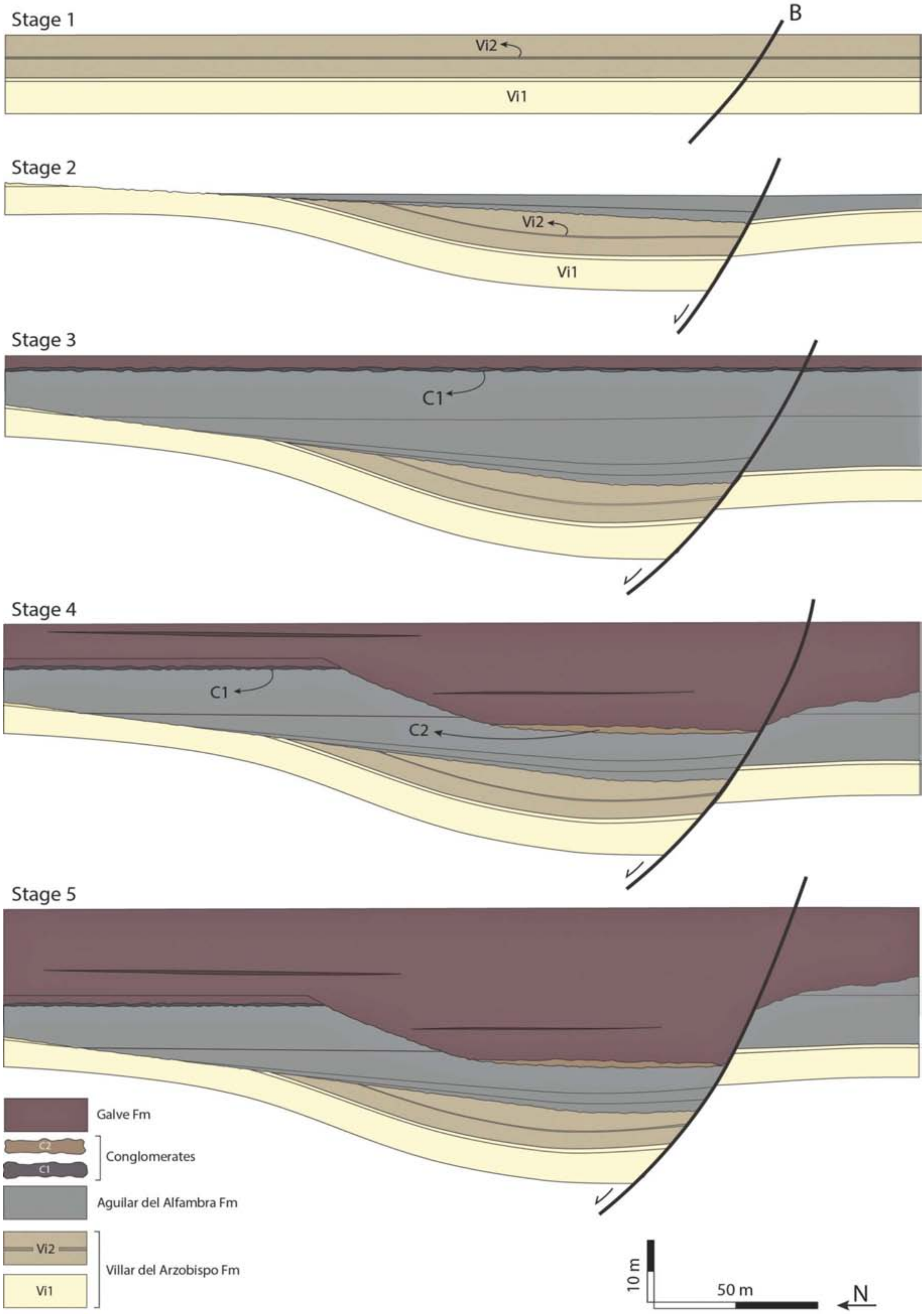

Fig. 9.- Evolution of the syntectonic basin depicted in Figure 8. A. Deposition of sandstone and lutite beds at the top of the Villar del Arzobispo Formation. Two competent beds, Vi1 and Vi2, can be identified. B. *Fault B* becomes active, generating a small basin adjacent to the fault plane. The topmost levels of the Villar del Arzobispo Formation are eroded away, and the basal levels of the Aguilar del Alfambra Formation onlap over the erosive surface. C. A second erosive stage takes place coevally to the deposition of the basal levels of the Galve Formation. A grey conglomerate bed (C1) is associated to the erosive surface (see Fig. 5A,C). D. A fluvial incision (possibly related to the nearby point-bar deposits visible in Fig. 7) eroded the upper levels of the Aguilar del Alfambra Formation, generating a channel-like erosive scar associated to an orange bed of conglomerates (C2) (see Fig. 5). E. *Fault B* remains active during the deposition of the Galve Formation.

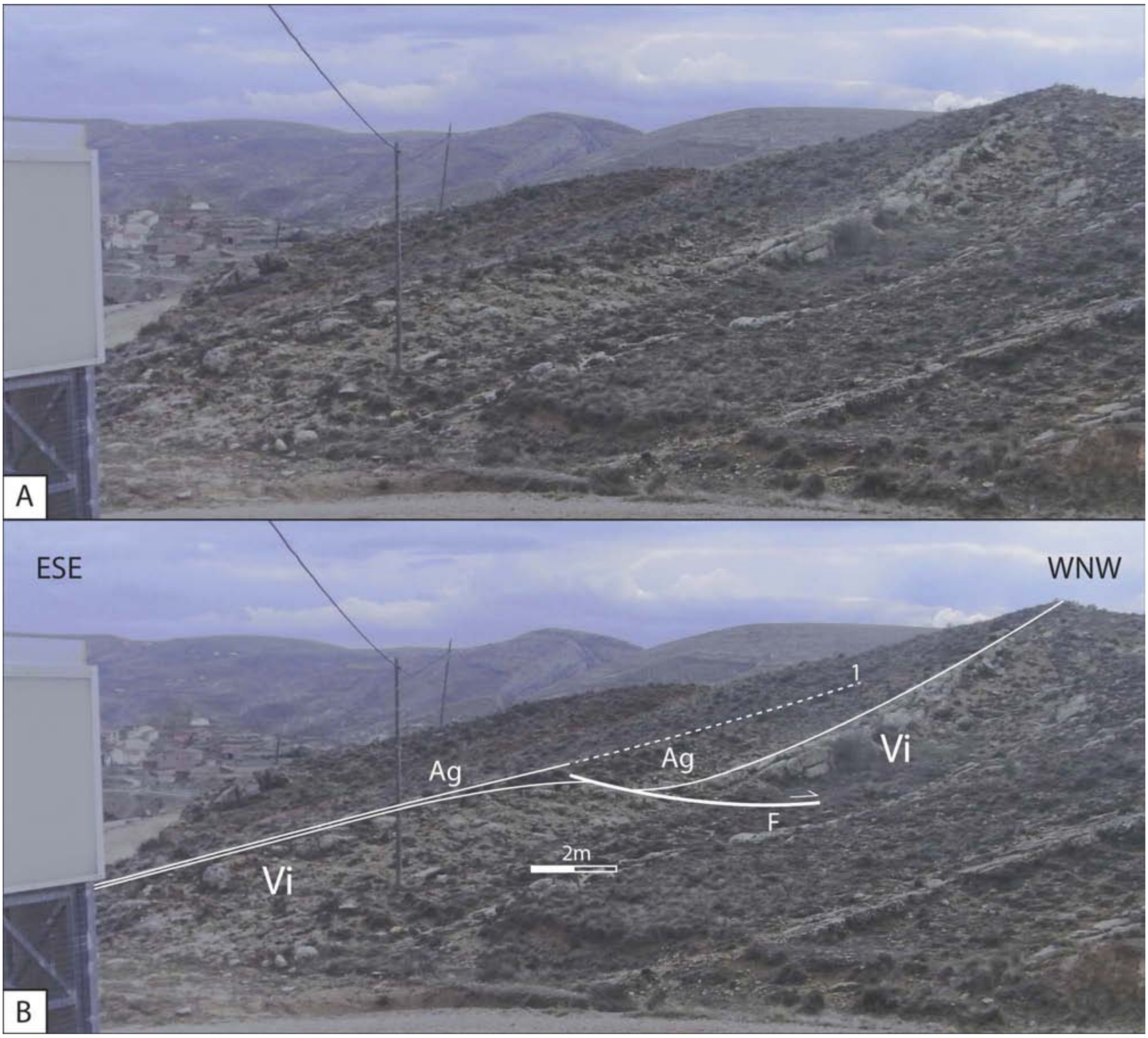

Fig. 10.- Small syntectonic basin at the northern part of the study area (see Figs. 2 and 3 for location), generated on the hanging wall block of *fault F*. The basin infill is integrated by grey lutites of the lower lithologic set (as per Fig. 4) of the Aguilar del Alfambra Formation (Ag. 1). The basin is fossilized by the first limestone bed of the upper set of the formation (Ag. 2).

been documented. The reported data provides further understanding of the unconformities previously described at the lower and upper boundaries of the Aguilar del Alfambra Formation in other localities of the Galve subbasin.

Fault activity after the sedimentation of the shallow platform to coastal carbonates and siliciclastics of the uppermost Jurassic Villar del Arzobispo Formation resulted in block tilting and erosion. As a result, a low-angle erosive unconformity developed between the mid-Tithonian Villar del Arzobispo Formation and the mid-Berriasian Aguilar del Alfambra Formation. This unconformity has an associated gap probably ranging from the late Tithonian to the early Berriasian.

The lower levels of the Aguilar del Alfambra Formation locally onlap this irregular and erosive surface. Synsedimentary fault activity explains the abrupt thickness changes observed within this 4–14 m-thick formation, deposited in a mixed terrigenous-carbonate tidal flat to restricted lagoon environments.

Around the mid-late Berriasian transition there is a major relative sea-level fall, associated with the abrupt setting of the alluvial to fluvial terrigenous deposits of the Galve Formation. Several conglomeratic beds mostly formed by poorly rounded carbonatic clasts underline the erosive surface between the Aguilar del Alfambra and Galve formations. Synsedimentary fault activity was still present at the onset of the sedimentation of the Galve Formation, as indicated by the local incision of fluvial channels on the hanging walls of the faults.

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