

The Iberian Middle Jurassic carbonate-platform system: Synthesis of the palaeogeographic elements of its eastern margin (Spain)

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Abstract

During the Middle Jurassic, the domain of the Iberian and Catalan Coastal ranges of eastern Spain was occupied by a system of fault-controlled carbonate platforms that flanked the Iberian Massif to the East. This platform system marked the transition between the shelves of the Alpine Tethys and the Central Atlantic Ocean. The palaeogeographic reconstruction of the Iberian Middle Jurassic platform system is based on more than 199 surface sections and 37 wells. From southwest to northeast, eight main palaeogeographic elements with associated characteristic facies are recognized. These represent a system of horsts and grabens. In the southwest, the Internal Castilian Platform is characterized by the frequently dolomitized oolitic and restricted facies of the Yemeda Formation. To the northeast, the NW-trending open-marine carbonate environments of the External Castilian and Aragonese platforms were separated by the fault-controlled El Maestrazgo High that is characterized mainly by the dolomitized Raffles Formation. The External Castilian and Aragonese platforms consist from bottom to top of the microfilament mudstones to wackestones of the El Pedregal Formation, the bioclastic and oolitic grainstones to packstones of the Moscardon Formation, and the Domeño Formation, that reflects a return to an open-marine low-energy wackestone to mudstone facies, locally containing patches of oolitic grainstones. The highly subsiding Tortosa Platform, represented by the Sant Blai, Cardo and La Tossa formations, is bounded by the dolomitic facies deposited on the El Maestrazgo and the Tarragona highs, and by the Catalan Massif where no Middle Jurassic deposits have been recorded. The open-marine facies and condensed sections of the Beceite Strait separated the Aragonese and Tortosa platforms. A regional stratigraphical gap spanning the upper Callovian Lamberti Zone to the lower Oxfordian Cordatum Zone is evident. A system of northwest- and northeast-trending normal faults controlled thickness and facies distribution. Data from the Iberian carbonate-platform system indicate that expanded sections were not necessarily associated with open-marine environments. Condensed and expanded sections are developed in open and restricted-marine facies, even on such palaeogeographic highs as the El Maestrazgo High. Restricted and shallow-marine environments occasionally developed in parts of the External Castilian Platform.

Keywords: Middle Jurassic; Carbonate platforms; Stratigraphy; Palaeoenvironments; Palaeogeography; Spain

1. Introduction

Regional Middle Jurassic palaeogeographic reconstructions of the early opening stage of the Central Atlantic Ocean and the Alpine Tethys indicate that the East-Iberian area was occupied by a carbonate-plat-

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form system, the facies development and subsidence patterns of which were controlled by active faults (Fig. 1; Ziegler, 1990; Bassoullet et al., 1993; Enay et al., 1993; Thierry, 2000; Vera, 2001, 2004; Vera et al., 2001; Stampfli and Borel, 2004).

In the fold-and-thrust belts of the Iberian and Catalan Coastal ranges of Spain, which evolved by Paleogene inversion of Mesozoic rifted basins (Salas et al., 2001), Middle Jurassic carbonates are exposed under outstanding outcrop conditions over a distance of more than 500 km. In the context of our studies, we

analysed in these areas 199 Middle Jurassic surface sections and data from 37 boreholes (Fig. 2). This permitted us to develop a detailed reconstruction of the palaeogeographic elements of the East-Iberian Middle Jurassic carbonate-platform system. In the Iberian Range, Middle Jurassic carbonates, formerly attributed to the “middle portion” of the Chelva Formation (Gómez and Goy, 1979), were recently subdivided into several lithostratigraphic units (Gómez and Fernández-López, 2004a,b) on the basis of their distinct facies development that can be related

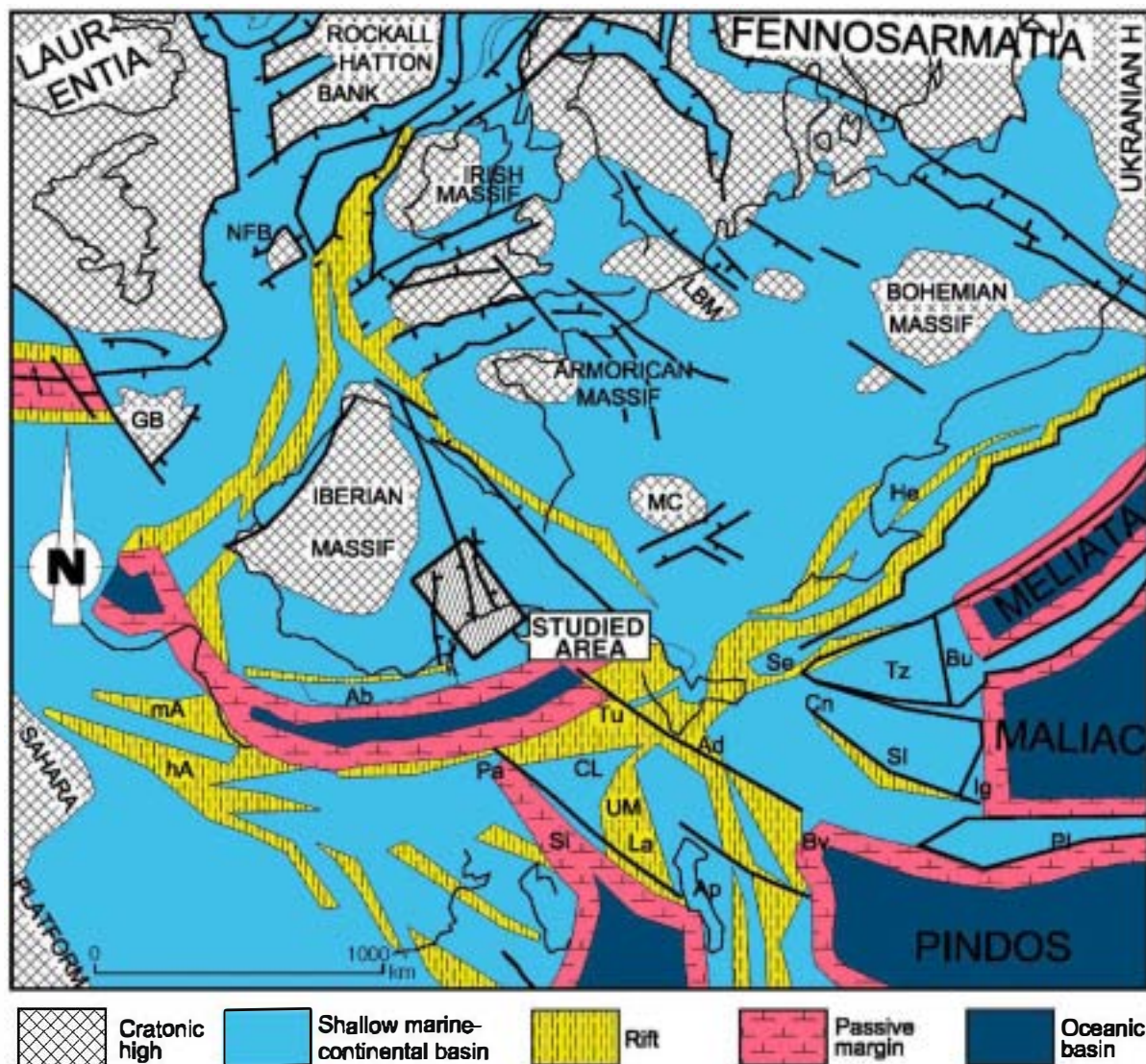
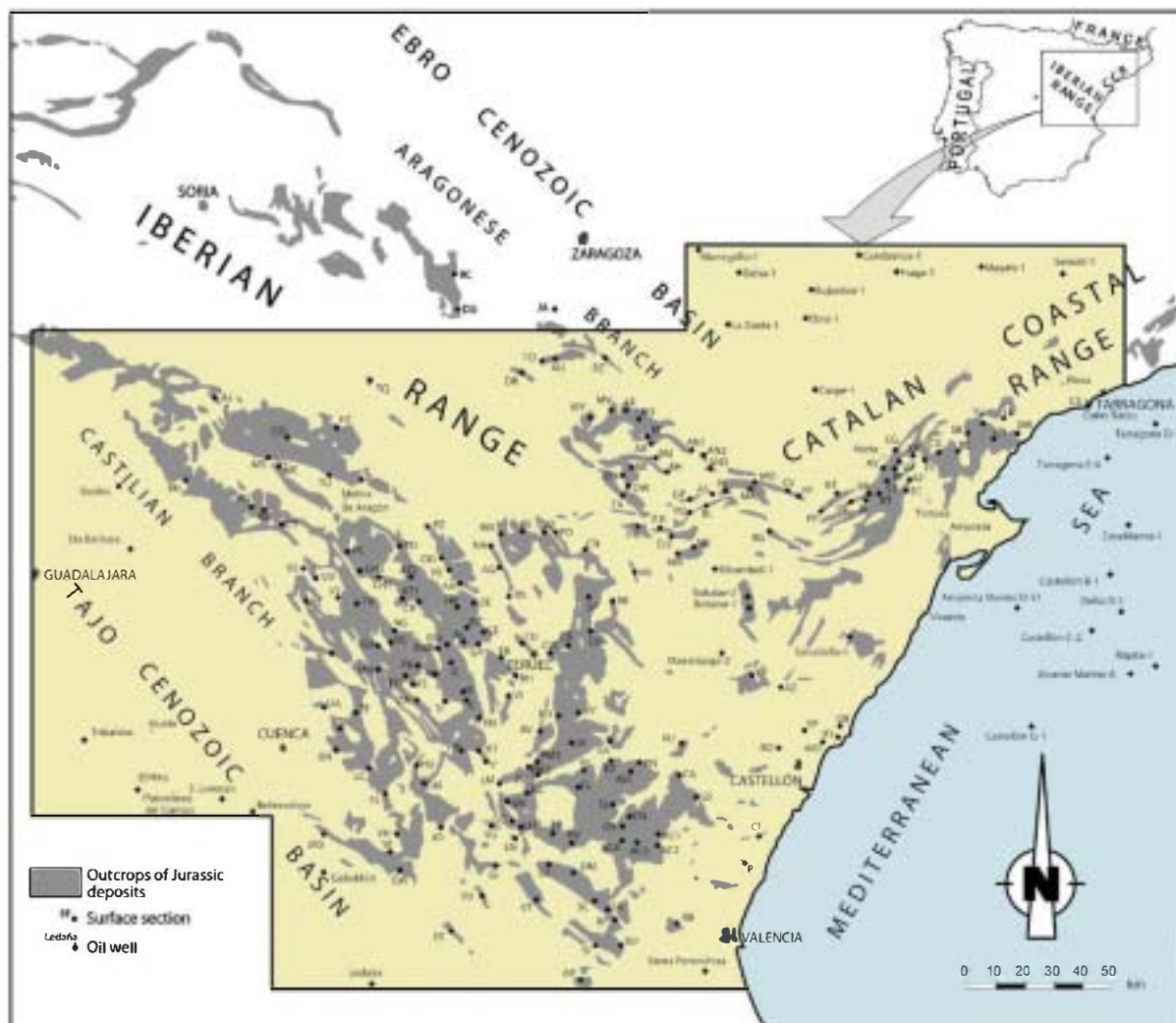


Fig. 1. Middle Jurassic palaeogeography of the Western Tethys and the Proto-Atlantic Ocean (Ziegler, 1990; Stampfli and Borel, 2004; modified) and location of the studied area. Ab: Alboran. Ad: Aetia s. str. Ap: Apulia s. str. Bu: Bucovinian. CL: Campania Lucania. Cn: Carnic-julian. GB: Grand Bank. hA: High Atlas. He: Helvetic rim basin. Ig: Igal trough. La: Lagonegro. LBM: London-Brabant Massif. mA: Middle Atlas. MC: Massif Central High. NFB: East Newfoundland Basin. Pa: Panonnides. Pl: Pelagonian. Se: Sesia (western Austroalpine). Si: Sicanian. Sl: Slavonia. Tu: Tuscan. Tz: Tizia. UM: Umbria-Marches.

to their palaeogeographic setting (Fig. 3). In the Catalan Coastal Range, Cadillac et al. (1981) and Fernández-López et al. (1996, 1998) had analysed the lithostratigraphy of Middle Jurassic deposits. Detailed palaeontological studies of these deposits, containing ammonites, allowed for a high-resolution biostratigraphic subdivision of this sequence at the scale of zones, subzones and horizons (Hinkelbein, 1975; Gómez, 1979; Fernández-López, 1985; Meléndez, 1989). In this study, biostratigraphical data are referred to the standard zones of ammonites.

During the Middle Jurassic, the so-called Iberian Basin was occupied by a complex system of epicontinental carbonate platforms that in many cases were tectonically controlled. Up-thrown blocks formed palaeogeographic highs that were characterized by shallow-water depositional environments. Areas between these highs were largely dominated by open-marine

environments, under which low-energy fossil-rich ammonite-bearing facies developed, suggesting that they were partly connected to the open ocean (Aurell et al., 2002, 2003; Fernández-López and Gómez, 2004). From southwest to northeast, eight main palaeogeographic elements can be recognized that were associated with characteristic facies, and that represent a horst and graben system (Fig. 4). In the southwestern area, the Internal Castilian Platform was attached to the Iberian Massif. To the northeast, the fault-controlled El Maestrazgo High separated the NW-trending open-marine External Castilian and Aragonese carbonate platforms. The highly subsident Tortosa Platform was delimited to the north by the Tarragona High and the Catalan Massif, that are devoid of Middle Jurassic deposits, and to the south by the El Maestrazgo High. The Beceite Strait formed a transitional area between the Aragonese and the Tortosa platforms.



The main objective of our study was to synthesize the palaeogeography and facies distribution on the eastern margin of the Iberian carbonate-platform system. The different fault-bounded platforms show characteristic facies variations, ranging from restricted and shallow-marine to open and deep-marine environments that are associated with condensed and expanded sections (Gómez and Fernández-López, 1994; 2004a,b; Fernández-López and Gómez, 2004).

2. Internal Castilian Platform

The Middle Jurassic Internal Castilian carbonate platform flanks the Iberian Massif to the east (Fig. 4). It is characterized by the high-energy oolitic bars and associated low-energy, restricted shallow-marine facies of the Yemeda Formation. Owing to successive post-Jurassic erosional events, the transition between these carbonates and a continental facies is no longer preserved.

This lithostratigraphic unit consists of oolitic grainstones to packstones, sometimes including ooids and/or bioclasts, which are interbedded with calcareous mudstones to wackestones that can be the dominant facies in some areas. These carbonates, which are stratified into thick beds, are locally partial or entirely dolomitized. The unit often contains grainstone to packstone bodies which display a well preserved bar morphology,

showing planar and through cross-bedding, wave ripples, bioclastic rills and bioturbation. Locally, low angle planar cross-lamination, algal laminae and fenestral porosity occur. Common are thickening- and coarsening-upward sequences generated by the migration of oolitic bars over low-energy restricted mudstones to wackestones. Similarly, successions of calcareous oolitic and bioclastic grainstones are common. Thickness of the Yemeda Formation in the type section (YE in Fig. 2; Gaibar-Puertas and Geyer, 1967, 1969; Viallard, 1973) attains about 250 m, marking a subsident area that defines the Enguñanos Depocentre (Fig. 4; Fernández-López and Gómez, 2004; Gómez and Fernández-López, 2004a). Another reference section is the Embalse de Contreras section, where this unit exceeds a thickness of 225 m. Partial sections from Buenache de la Sierra and La Toba have been described by Viallard (1973) and Morillo-Velarde and Meléndez-Hevia (1981). The most fossiliferous deposits of this restricted internal platform area contain occasional remains of benthic organisms such as bivalves, echinoids, calcareous algae, bryozoans, brachiopods, foraminifers and gastropods. Ammonites and belemnites are very scarce or absent in the whole unit. Yet, in the Yemeda section, where micritic low-energy restricted facies dominate, exceptionally Bajocian stephanoceratids in its lower and middle part, and *Procerites*,

Fig. 2. Outcrops of the Jurassic sediments in the Iberian Range and in the Catalan Coastal Range, showing the sections and wells studied in this work. Abbreviations of the surface sections: AA: Aras de Alpuente. AC1: Alcublas-1. AC2: Alcublas-2. AC3: Alcublas-3. AC4: Alcublas-V. AF: Alfara. AG: Aguatón. AH: Almohaja-N. AJ: Arcos de Jalon. AL: Albarracín. AN1: Andorra-1. AN2: Andorra-2. AN3: Andorra-3. AO: Alcotas. AP: Arroyo Picastre. AR: Ariño. AS: Alcorisa-E. AT1: Alustante-S. AT2: Alustante-E. AU: Aguilon. AV: Barranco del Avellanar. AZ: Adzaneta-NE. BB: Ababuj. BC: Bañeraio de Cardo. BD: Barranco de la Cedrilla. BE: Barranco de las Estacas. BG: Río Bergantes. BH: Barranco de la Hontanilla. BI: Barranco de Milles. BL: Barranco de Valdecastillo. BM: Barranco Moro. BN: Buenache de la Sierra. BO: Barranco Las Enmitas. BP: Barranco del Sapo. BS: La Buena Fuente del Sistol. BT: Beceite. BU: Buñol. BV: Barranco del Vall. BZ: Belchite. C: Barranco La Canaleja. CA: Caudiel. CB: Corbalán-E. CD: Cedrillas. CE: Cella. CG: Coll de l'Argila. CI: Chilches. CL: La Cerredilla. CM: Campillos-Paravientos. CN: Canales. CÑ: Cañada Vellida. CO: Codes. CR: Bronchales. CS: Cap de Salou. CT: Villar de Cobeta. CU: Concud. CV: La Cañada de Verich. CW: Corbalán-W. CH1: Alcoroches-W. CH2: Alcoroches-NW. D: Molino Romedanos. DG: La Almunia de Doña Godina. DM: Domeño. DR: Aladren. EB: Embalse San Blas. EC: Coll del Caragol. EG: En Grillo. EH: Embalse de Hijar. EJI: Ejulve-SW. EJ2: Ejulve-S. ER1: El Coscojar. ER2: Entrambasaguas. ET: Embalse de Contreras. EZ: El Cabezo. FN: Frias de Albarracín-N. FS: Frias de Albarracín-S. FW: Frias de Albarracín-W. FZ: Fuentelsaz. G: Rambla La Gotera. GA: Gea de Albarracín. GC: Graja de Campalbo. GE: Embalse del Generalísimo. GI: Aliagülla. GP: Embalse de Gallipuen. GS: Gaibiel-S. GU: Guadalaviar. GW: Enguñanos-NW. HP: Hoya del Peral. HR: Barranco del Chorrillo. HT: Hontanar. HU: Huerquina. HV: Chelva. IL: Cillas. JA: Jaulín. JO: Henarejos. JV: Javalambre. LC: La Cierva. LD: Lidón. LE: Lecera. LH: Las Higuieruelas. LM: La Olmeda. LO: Coscollola. LV: Les Voltes. LL: Llaberia. M: Moscardón. MA: Mas Nueva. MC: Masia de la Sisca. MD: Masada del Diablo. ME: Maranchon-SE. MG: Monteagudo de las Salinas. MI: Miravete. ML: Molinos. MN: Montoro. MO: Montornes. MR: Mas Riudoms. MS: Maranchon-S. MT: Masada Toyuela. MU: Montes Universales. MV: Moneva-E. MY: Moyuela. NA: Bueña. NE: Alcaine. NG: Noguera. NJ: Montanejos. OE: Miravet. OG: Ojos Negros. ON: Obón-N. OS: Oset. OW: Obón-W. P: Sagunto. PA: Palomar de Arroyos. PC: Puerto del Caballo. PD: Pancrudo. PE: Peracense. PI: Espina. PJ: Pajaroncillo. PL: Pinilla de Molina. PM1: Arcos de las Salinas. PM2: La Puebla de San Miguel-2. PM3: La Puebla de San Miguel-3. PN: Pina de Montalgrao. PP: Río Pena. PT: Peralejos de las Truchas. PZ: El Pedregal. RB: Ribarroja. RC: Ricla. RE: Rubielos de la Cerida-E. RF: Rafales. RG: Ribagorça. RJ: Torrijas. RN: Renales. RO: Revolcadero-Cucutas. RR: Barranco del Grevolar. RS: Rambla del Salto. RT: Carlades-L'Embaronat. RV: Riodeva. RW: Rubielos de la Cerida-W. SA: Sarrion. SB: Sant Blai. SC: Sot de Chera. SE: Santa Eulalia. SI: Siete Aguas-NE. SL: Salada. SM: Santa Cruz de Moya. SN: Sinarcas-N. SP: Sierra de El Pobo. SR: Serretilla. ST: Río de Estrets. SU: Sierra de la Bicuerca. TA: Torre las Arcas. TB: La Toba-S. TD: Tordalelgo. TE: La Toba-E. TI: Toril. TJ: Tuejar. TL: Tejadillos. TM: Torron. TO: Tosos. TQ: La Tranquera. TR: Checa-SW. TT: Beteta. TU: Turmiel. TV: Tivissa. TY: Tivenys. UA: Uña. US: Chuvellus. V: Vallanca. VB: Vistabella del Maestrazgo-E. VC: Villar del Cobo. VD: Poveda de la Sierra. VF: Fordenchana. VH: Villar del Humo. VI: Vilhel. VN: Vandellos. VS: Valsalobre. VT: Villar de Tejas. XP: Xerta-Pauls. YE: Yemeda. YU: Talayuelas. ZA: Zafra.

reineckeids and hecticoceratinae of Bathonian and Callovian age in its upper part have been found (Gaibar-Puertas and Geyer, 1967, 1969; and unpublished data of the authors).

High-energy facies belts, reflecting the action of waves, tides and storms, characterize the shallow-water Middle Jurassic Internal Castilian carbonate platform. It corresponds to a belt of bars and channels and is characterized by high rates of carbonate production and accumulation. Oolitic and bioclastic grainstone bars system is associated with washover and beach facies. Low energy micritic facies were deposited between these high-energy bars and in extensive lagoons, as well as tidal flat deposits. In the southern parts of the Castilian Platform, the Montes Universales Fault marks the boundary between its internal and external areas. In the northern parts of the Castilian Platform, the boundary between internal and external areas is more transitional, delineating a northwestern-trending belt of fine-grained limestones, oolitic, bioclastic and oncolitic packstones to grainstones and dolomitic deposits that are organized into shallowing-upward sequences. South of La Mancha Fault, the oolitic facies continues southward, but its chronostratigraphic attribution is still uncertain in these areas. The Montes Universales and La Mancha faults delineate a rapidly subsiding area that corresponds to the Enguianes Depocentre in which tectonically controlled subsidence rates were fully compensated by sedimentation rates, as evidenced by the persistence of shallow-water restricted facies during most of Middle Jurassic.

3. External Castilian and Aragonese platforms

On the External Castilian and Aragonese carbonate platforms, which outcrop in the Iberian Range, most of the Middle Jurassic is represented by open-marine facies that commonly contain ammonites, allowing for a high-resolution biostratigraphic zonation (Hinkelbein, 1975; Fernández-López, 1985; Fernández-López and Gómez, 1978; Meléndez, 1989). Three lithostratigraphic units are recognized, that can be followed over the entire Iberian Range, and which permit a detailed reconstruction of the palaeogeographic and palaeotectonic evolution of these platforms. From bottom to top, these are the El Pedregal, Moscardón and Domeño formations.

3.1. El Pedregal Formation

The El Pedregal Formation consists of lime mudstones and wackestones containing bioclasts, mainly

bivalves (microfilaments), echinoderms and pellets. These may contain interbedded marls, sometimes bioclastic, which in the upper part of this unit locally constitutes an alternation of marls and limestones. Chert nodules are common in limestones. In the basal parts of this formation, interbedded horizons consisting of limestones containing ferruginous and/or phosphatic ooids are common (Geyer et al., 1974). These are associated with the stratigraphical gap that is located at the base of the El Pedregal Formation. On the Aragonese Platform, ferruginous and/or phosphatic ooids are also common in the uppermost levels of this unit (Mouterde et al., 1978; Fernández-López, 1985; Gómez and Fernández-López, 1994). In the NW External Castilian Platform, peritidal dolomitic limestones and mudstones, showing microbial laminae and mudcracks (Fernández-López, 1997), as well as oolitic grainstones, are interbedded in the lower part of the sections (Fig. 5). Mounds formed by volcanic rocks occur on the SE External Castilian Platform (Figs. 4 and 5; Gautier, 1968, 1974; Gómez et al., 1976; Gómez, 1979, 1985a,b; Ortí and Vaquer, 1980; Fernández-López et al., 1985; Martínez González et al., 1997, 1998; Cortés, 2001). In the NW and Central Castilian platforms, sponge build-ups and marls are common in the upper part of the El Pedregal Formation (Fig. 5; Fernández-López et al., 1978; Fernández-López, 1985; Gómez, 1985a,b, 1991; Friebe, 1995). *Zoophycos* and *Thalassinoides* are common, and occasionally bioclastic rills, ferruginous crusts, and remobilization surfaces are recognized. These ichnofossils are widely represented in external platform facies of the Middle Jurassic deposits, ranging from restricted and shallow to open and deep environments (Fernández-López, 1997; Olivero, 2003; Knaust and Hauschke, 2004).

The El Pedregal Formation is generally organized into shallowing-upward sequences, usually composed of a lower marly and an upper calcareous part, which is bioturbated and, on occasions, contains build-ups of sponges and algae or dolomitic facies. The tops of many of these sequences are marked by hardgrounds, which are characterized by borings, ferruginous crusts, glauconitic, phosphatic and bioclastic carbonates, as well as reworked fossils (reelaborated and resedimented fossils in Fernández-López, 1991).

The thickness of the El Pedregal Formation reaches more than 150 m in the Pozuel and Casinos depocentres (Fig. 4). On the Central External Castilian Platform the thickness of this unit varies between 60 and 80 m. On the Aragonese Platform, remarkable thickness variations are observed, ranging between 8 m in the Andorra-I section and 45 m in the Ricla section (Fig. 2).

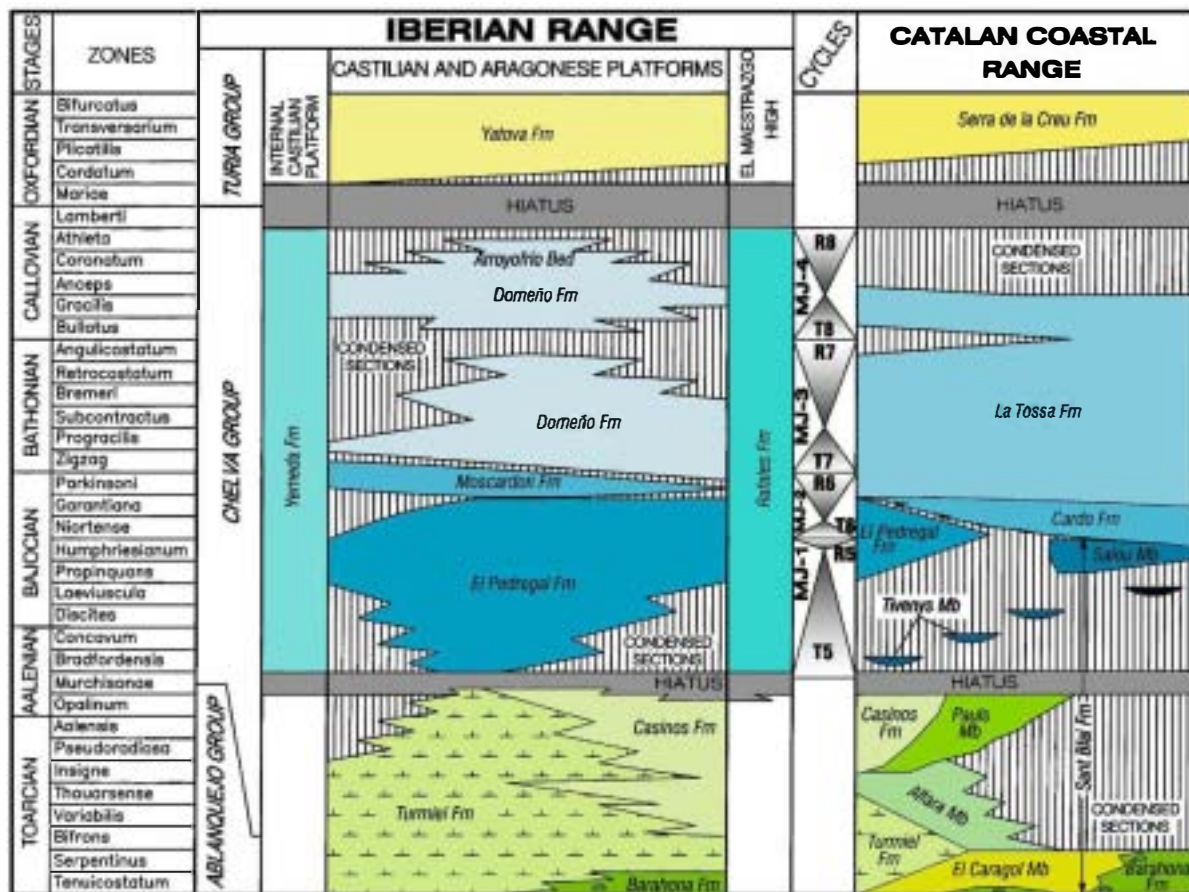


Fig. 3. Middle Jurassic lithostratigraphic units and the shallowing and deepening cycles of the Iberian and Catalan Coastal ranges, referred to the chronostratigraphical units.

Remains of ammonites, belemnites and benthic organisms, such as bivalves, brachiopods, echinoderms, serpulids, gastropods, bryozoans, sponges and calcareous algae, are abundant in some levels. The base of the El Pedregal Formation coincides with the upper part of the Aalenian Murchisonae Zone, although Aalenian and lower Bajocian deposits are usually included in condensed sections, whilst its top is slightly diachronous at a regional scale. It corresponds to the Bajocian Nirtense and Garantiana zones (Figs. 3 and 5).

The El Pedregal Formation was deposited on an external platform, dominated by low-energy, open-marine, normal salinity, shallow-water environments, occasionally affected by storms. Microbial laminae, mud-cracks and karstification surfaces indicate local, occasional emersion in mudstones related to deposition in confined shallow-marine environments (Fernández-López and Gómez, 1990b). In the upper part of the El Pedregal Formation, facies, taphonomy and palaeobiological evidence (Fernández-López and Gómez, 2004) indicate depth increasing and, presumably, facil-

itation of connections with open-sea Atlantic and Western Tethys waters.

3.2. Moscardon Formation

The Moscardon Formation consists mainly of bioclastic grainstones to packstones on which crinoids, corals and intraclasts are sometimes abundant. Bioclastic wackestones and mudstones are locally represented. The unit, which commonly forms steep escarpments, is usually bedded in layers which may surpass 3 m in thickness. Chert nodules as well as *Zoophycos* and *Thalassinoides* are locally common. Among the sedimentary structures, planar and festoon cross-lamination, ripples, bioclastic rills, and sedimentary bodies showing bar morphology are common. On the Aragonese Platform, the Moscardon Formation consists of calcareous packstones to boundstones forming sponge build-ups (Fig. 5; Fernández-López and Aurell, 1988). These lithologies and structures are generally organized into shallowing-upward sequences with a lower part of cal-

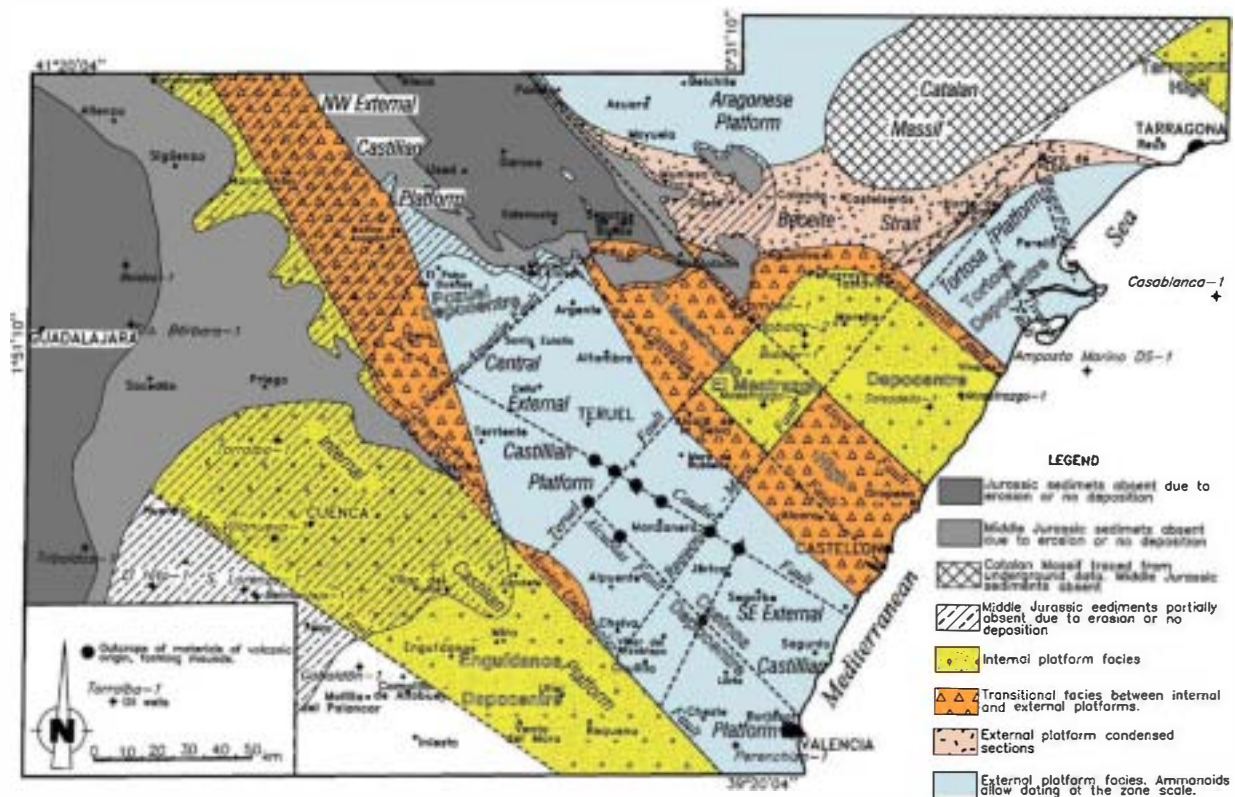


Fig. 4. Palaeogeographic reconstruction of the different platforms in the eastern margin of the Iberian platform system during Middle Jurassic. From southwest to northeast the Internal Castilian Platform, the External Castilian Platform, divided into the NW, Central and SE External Castilian platforms, the El Maestrazgo High, the Aragonese Platform and the Tortosa Platform, linked by the Bécete Strait, the Tarragona High and the Catalan Massif.

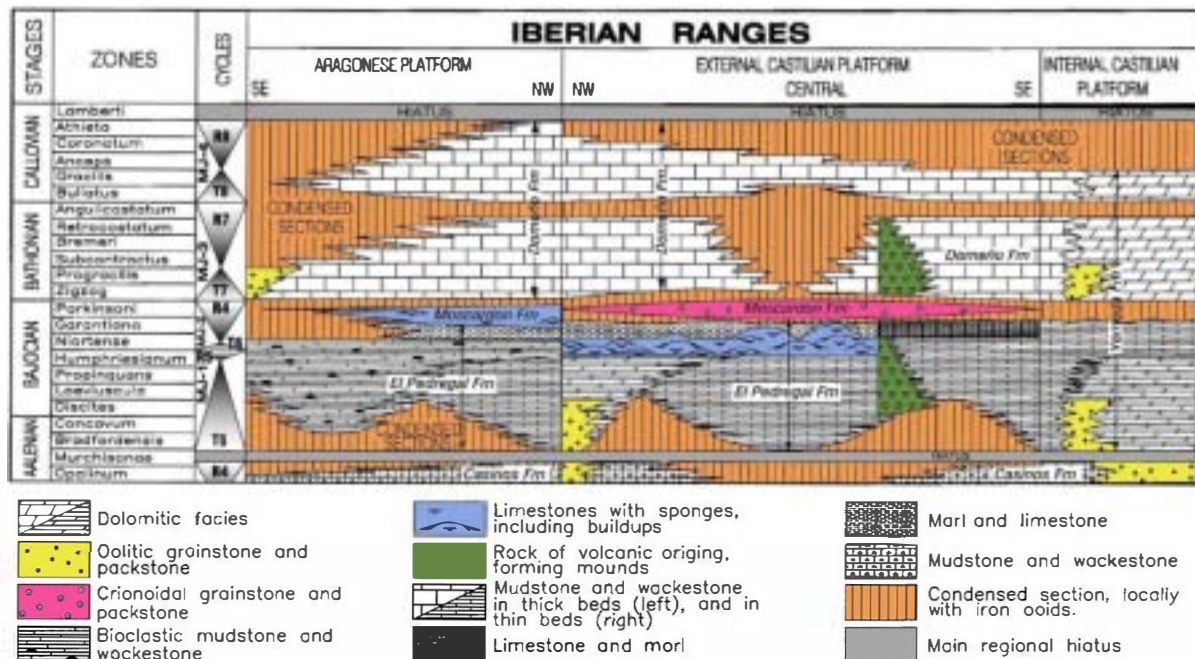


Fig. 5. Chronostratigraphic correlation chart showing the facies distribution on the Aragonese and Castilian platforms.

careous mudstones to wackestones, which can be absent or replaced by a basal reworked level, and an upper part consisting of calcareous grainstones to packstones. Other, locally developed, sequence types are filling sequences. Their lower parts consist of calcareous packstones to wackestones that contain large bioclasts and reworked fossils, sometimes phosphatic and imbricated whereas their upper parts are made of calcareous wackestones to mudstones which can show ripple laminations. The thickness of the Moscardón Formation varies on the Central External Castilian Platform between 3 and 25 m (Fernández-López, 1985), decreases towards its SE parts where it is represented by a few meters of calcareous wackestones to packstones containing calcareous ooids, and finally pinches out near the Mediterranean coast. On the Aragonese Platform, the thickness of these bioclastic facies, containing crinoids and sponges, reaches 23 m in Ricla and 17 m in the Belchite sections (Sequeiros et al., 1978; Fernández-López and Aurell, 1988). Laterally the Moscardón Formation pinches out towards the southeast (about 2 m in the Obón-W section, Fig. 2) and is missing on the El Maestrazgo High.

The Moscardón Formation commonly contains diverse and abundant macrofossils indicative of open-marine environments, such as ammonites, belemnites and sponges. Echinoderms, calcareous algae, bryozoans, bivalves, brachiopods, serpulids, and gastropods are also abundant. The unit is bounded by stratigraphic discontinuities. The oldest sediments correspond to the Bajocian Garantiana Zone, as seen in the Moscardón and in the Ricla sections. However, the lowest deposits of this unit can belong to the Bathonian Zigzag Zone, as in the Puebla de San Miguel section (Fernández-López, 1985). The age of the top of this unit varies from the Bajocian Parkinsoni Zone up to the Bathonian Zigzag Zone (Fernández-López, 1985).

The Moscardón Formation was deposited under open-marine, normal salinity, high-energy and very shallow conditions providing for high carbonate production and deposition rates during a brief episode. The External Castilian Platform was dominated by wave action and the progradation of high-energy facies over the low-energy, open-marine shallow facies of the El Pedregal Formation. On the Aragonese Platform, development of the Moscardón Formation was conditioned by the growth of sponge mud-mounds, similar to those recorded on the Castilian Platform in the El Pedregal Formation. Towards the end of the Moscardón Formation the sea bottom relief of the external platform areas was largely infilled, giving rise to a brief phase of widespread shallowing of the Iberian platform system.

3.3. Domeño Formation

The Domeño Formation is generally composed of well-stratified wackestones of microfilaments, locally packstones and mudstones, commonly with pellets, that are interbedded with marly limestones and calcareous marls. In the southeastern part of the External Castilian Platform, it contains mounds formed by volcanic rocks (Gautier, 1968, 1974). In some localities of the External Castilian and the Aragonese platforms, lenticular bodies of grainstones, containing calcareous ooids, are overlying the uppermost carbonates of the Moscardón Formation (e.g. Rambla del Salto, Aguaton, Obón-W and Andorra-I sections, respectively, Fig. 2). The Domeño Formation locally contains chert nodules, and *Thalassinoides* and *Zoophycos* are common. In the Iberian Range, the top of the Middle Jurassic series is generally associated with ferruginous crusts and ferruginous ooids, formally defined as the Arroyofrio Bed (Gómez and Goy, 1979), which marks a regional stratigraphical gap.

The Domeño Formation is organized into upward-shallowing and -thickening sequences which are characterized by a basal level that includes reworked fossils, an intermediate part of marly limestones, marls and limestones, and an upper part of limestones with irregular bedding that is capped by ferruginous crusts and borings. The Domeño Formation attains a thickness of 45 m at the type section and more in other outcrops of the SE External Castilian Platform (e.g. Chelva, Alcuéblas, Ribarroja and Sagunto sections, Fig. 2). In the Central External Castilian Platform, its thickness is usually smaller than a dozen meters. In the NW External Castilian Platform, its thickness is of the order of 100 m, where it constitutes the main sediments filling the Pozuel Depocentre. On the Aragonese Platform, there are expanded sections which surpass a thickness of 100 m (e.g. Ricla and Aguilon), and which grade into condensed sections thinner than 15 m, such as in the Andorra, La Cañada de Verich, Barranco de las Estacas and Obón sections (Fig. 2, Sequeiros and Meléndez, 1987; Aurell et al., 1994).

Open-marine bivalves, brachiopods, echinoderms, serpulids, ammonites, belemnites and gastropods are common. The base of the Domeño Formation is diachronous at the zone scale, varying in age from the Bathonian Zigzag Zone (e.g. in the Domeño section) up to the Bathonian Progracilis Zone. The limestones with ferruginous ooids of this formation vary in age from Bathonian to Oxfordian. The upper Callovian Lamberti Zone and the lower Oxfordian Mariae Zone have so far not been identified. The top of the Domeño Formation,

generally corresponds to the Arroyofrio Bed, which represents condensed sections (Figs. 3 and 5) and includes a hiatus of regional extent.

The sediments of the Domeño Formation were deposited on an open-marine, normal salinity, external carbonate platform, the palaeogeographic configuration of which was varied during early Bathonian to middle Oxfordian times. During the Bathonian and Callovian, the thermal subsidence of this external platform was overprinted by synsedimentary faulting controlling differential subsidence of individual blocks (Salas et al., 2001). During late Callovian and early Oxfordian, the External Castilian and Aragonese platforms became extremely shallow and uniform. The top of the Domeño Formation reflects a phase of widespread homogenisation and emersion of these platforms and is associated with a hiatus that is recorded in the entire studied area.

4. El Maestrazgo High

During Middle Jurassic, the El Maestrazgo area formed a high that was flanked by the open-marine External Castilian, Aragonese and Tortosa platforms. This high was transected by a complex array of NW- and NE-trending synsedimentary faults (Vinaros, Ateca, Castellon, Caudiel, Teruel, and Requena-Mora faults in Fig. 4), which delimited a series of tectonically active blocks (Canerot, 1974; Burrollet and Winnock, 1977; Cadillac et al., 1981; Canerot et al., 1985a,b; Fernández-López et al., 1996, 1998; Gómez and Fernández-López, 2004a,b).

On the El Maestrazgo High, restricted marine, commonly dolomitic carbonates, forming 20–40 m thick condensed sections, were deposited. However, oil wells drilled in this area indicate that on some subsiding fault blocks up to 100–250 m thick expanded dolomitic sections were deposited, thus forming the so-called El Maestrazgo Depocentre (Fig. 4). The Raffles Formation (Gómez and Fernández-López, 2004a,b) includes the restricted carbonate facies, and the transition between internal and external facies, that are associated with the El Maestrazgo High.

4.1. Raffles Formation

The Raffles Formation is generally composed of massive, crystalline dolomitic limestones. These pass laterally into higher energy facies consisting of bioclastic grainstones to packstones with calcareous ooids (e.g. in the Ejulve sections), as well as into calcareous

mudstones containing rare macrofossils (Barranco de las Ermitas and Adzaneta sections). Bioturbation textures and structures and bioclastic rills are common. The most common sequences are upward-thickening and -shallowing, showing hardgrounds with borings that can be filled with ferruginous crusts and glauconite. In some areas where dolomitization does not affect the whole Middle Jurassic sequence (e.g. in the Raffles section), the restricted facies of the Raffles Formation grade into the open-marine bioclastic wackestones of the Domeño Formation that contains ammonites. The unit reaches a thickness of 26 m in the Raffles section, where the lower contact is fault-controlled, and about 25 m in the Barranco de las Ermitas and in the Adzaneta sections (Canerot et al., 1985b). These condensed sections pass laterally into 100–250 m thick dolomitic sections, identified in oil wells (Bobalar-1 and 2, Maestrazgo-2 and Salsadella-1 wells in Fig. 2; Lanaja, 1987; Fernández-López et al., 1996, 1998).

In areas where this unit is not dolomitized, remains of benthic organisms, such as bivalves, echinoids, calcareous algae, sponges, bryozoans, brachiopods and gastropods, are common. In contrast, remains of nektonic organisms, such as ammonites and belemnites, indicative of open-marine conditions, are very rare or absent. However, in the lowermost part of the Raffles section (Fig. 2), the occurrence of sonninids and stephanoceratids indicates an early Bajocian age, whilst in its upper part parkinsonids suggest a late Bajocian age. At the transition between restricted and open-marine facies, as seen in the upper part of the Raffles Formation type section, this unit is covered by the ammonite-bearing carbonates of the Domeño Formation, that permit to identify Bathonian and Callovian zones. The Raffles Formation was deposited in a restricted shallow-marine environment that was characterized by intense production and accumulation of carbonates. Bars and channel belts characterize high-energy facies, whereas low-energy facies are represented by dolostones with local muddy limestones.

5. Tortosa Platform

On the Tortosa Platform, expanded Middle Jurassic sections surpassing 350 m in thickness are composed of open-marine external platform facies and testify to its rapid subsidence (Fig. 6; Fernández-López et al., 1996, 1998; Gómez and Fernández-López, 2004b). Although thickening- and shallowing-upward sequences predominate, some deepening sequences occur locally during

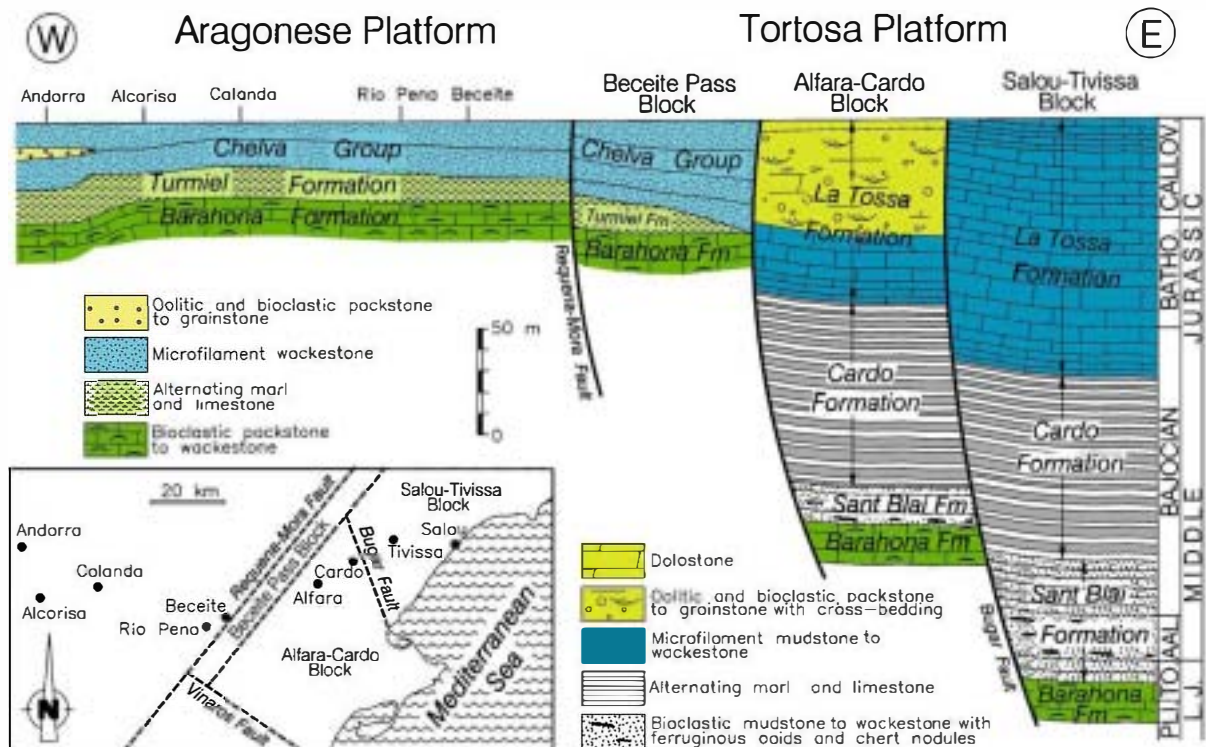


Fig. 6. Reconstructed cross-section of the distribution of the Middle Jurassic deposits in the Aragonese and Tortosa platforms. Several fault-controlled blocks in the strongly subsident Tortosa Platform, and the drastic change in thickness and facies between both platforms can be observed. Source data from Fernández-López et al. (1996, 1998).

early Bajocian. Palaeogeographic differentiation of the Tortosa Platform commenced during early Toarcian. Open-marine condensed sections developed during middle and late Toarcian, Aalenian, middle and late Callovian and early Oxfordian. By contrast, Bajocian, Bathonian and lower Callovian stages correspond to expanded sections. The Tortosa Platform can be traced into offshore areas through the Amposta Marino D-S1 and Casablanca-1 wells (Fig. 4; Lanaja, 1987; Maldonado López et al., 1986; Fernández-López et al., 1996).

Stratigraphical gaps corresponding to a part of the Aalenian Murchisonae Zone and the Callovian Lamberti Zone, recorded both in the Iberian and Catalan Coastal ranges, reflect two peaks of regional shallowing that affected the entire Iberian platform system (Figs. 3 and 5). On the Tortosa Platform, maximum sedimentation rates were recorded during the Bajocian Garantiana Zone, which corresponds to expanded sections that exceed 60 m in thickness. However, as indicated by the colonization of the platform by ammonite populations, maximum water depths were reached during the Bajocian Niortense and Garantiana zones (Fernández-López and Mouterde, 1985;

Fernández-López, 1995; Fernández-López and Meléndez, 1996). Among the ammonoid assemblages, taxa characteristic for neritic NW European platforms are common, whereas phylloceratids and lycoceratids characteristic of oceanic Tethyan environments are very rare or missing. During the Bajocian Garantiana Zone, the Tortosa Platform was colonized by Mediterranean elements, like juvenile phylloceratids; however, these represent less than 0.1% of the total population.

The Middle Jurassic series of the Tortosa Platform consists from bottom to top of the Sant Blai Formation, which includes the Tivenys and the Salou members, the Cardo Formation, and the La Tossa Formation (Figs. 3 and 6).

5.1. Sant Blai Formation

The Sant Blai Formation is composed of bioclastic mudstones to wackestones and interbedded marls and marly limestones with occasional levels containing ferruginous and/or phosphatic ooids. This lithostratigraphic unit, which is topped by a hard ferruginous surface, is characterized by metric scale thickening- and

coarsening-upward sequences, except for some thinning- and fining-upward sequences that occur in the upper parts of the Tivissa, Vandellos and Llaberia sections (Fig. 2). *Zoophycos*, *Thalassinoides* and *Rhizocorallium* are abundant whilst ammonites, belemnites, bivalves, brachiopods, crinoids, serpulids, gastropods, ahermatypic corals and bryozoans are common. Above the Aalenian Murchisonae Zone discontinuity, the Tivenys and Salou members of the Sant Blai Formation can be distinguished.

The Tivenys Member is made up of wackestones to packstones, which commonly contain a variable proportion of ferruginous and/or phosphatic ooids and pisoids. Ooids are irregular and complex, showing evidence of several phases of reworking. Remains of echinoderms, microfilaments, ammonites, bivalves, brachiopods, foraminifers, sponges, belemnites, ostracods, gastropods and bryozoans, as well as wood and bone fragments are present. *Thalassinoides* and *Rhizocorallium* are common. Although the thickness of the Tivenys Member is less than 2 m, it is a characteristic unit on the Tortosa Platform. The Tivenys Member extends from the Aalenian Bradfordensis Zone to the Bajocian Propinquans Zone. Biofacies identified in these deposits are indicative of open-marine environments with ammonoid assemblages supporting relatively free communications with open-sea waters. The lateral distribution of these deposits is very discontinuous and indicative of episodic sedimentation with firm- to hardgrounds prevailing. Local occurrences of mud-cracks are indicative of temporary subaerial exposure. Such environmental conditions are confirmed by several taphonomic criteria, such as concretionary internal moulds without septa, internal moulds with ellipsoidal abrasion facets and annular abrasion furrows observed on ammonites, which are indicative of shallow, subtidal to intertidal environments (Fernández-López and Meléndez, 1994; Fernández-López et al., 1998).

The Salou Member consists of mudstones and interbedded marls. Except for ammonites and some bivalves (*Bositra*), macrofossils are rare, although *Zoophycos* are abundant. This 15–45 m thick member is organized into aggradational, thickening- and shallowing-upward sequences, but shows in its upper parts several deepening sequences in the Tivissa area. Its age spans the Bajocian Propinquans and Humphriesianum zones, although its upper and lower boundaries are slightly diachronous. The Salou Member was deposited below wave-base on a low-energy, open-marine platform that was dominated by soft to firm, well-oxygenated bottom conditions.

5.2. Cardo Formation

The Cardo Formation is composed of alternating mudstones and marls, which tend to be more calcareous upwards (Fig. 6). Ammonites and bivalves (*Bositra*) are abundant whereas belemnites, brachiopods and benthic bivalves are less frequent. Some carbonized plant remains have been observed in several levels. Nevertheless, encrusting benthic organisms are virtually absent. The layers, which do not show evidence for early cementation, such as hardgrounds or borings, normally extend over several hundred meters. Marls and limestones are organized into shallowing- and thickening-upward sequences, although the basal parts of this unit locally show thinning-upward sequences.

The Cardo Formation overlies in most cases a hardground with ferruginous crusts that marks the top of the Sant Blai Formation. The Cardo Formation attains a maximum thickness of 100 m in the Tivenys and Cardo sections. To the north and west of this area, its thickness decreases to less than 1 m in the Engrillo, Rio de Estrets and Barranco del Avellanar sections.

The base of the Cardo Formation is diachronous at the scale of zones. In the Cardo, Tivissa, Vandellos, Llaberia and Cap Salou sections, its basal parts correspond to the Bajocian Humphriesianum Zone, whereas in the Tivenys, Xerta-Pauls, Mont Caro and Alfara sections its first layers belong to the Bajocian Nior tense Zone (Fig. 2). The top of the Cardo Formation corresponds to the Bajocian Parkinsoni Zone.

NW Europe ammonoids dominated the assemblages of the Cardo Formation, whereas Tethyan representatives such as phylloceratids and lycoceratids are very scarce (less than 0.1% of the total; Fernández-López, 1983; Fernández-López and Mouterde, 1985; Fernández-López and Meléndez, 1996). The Cardo Formation was deposited under open-marine conditions on a strongly subsiding and faulted external platform, which had open connections to the NW Europe domain. By contrast, and as indicated by the small amount of characteristic Tethyan taxa, communication with the Tethys domain was very poor. On the Tortosa Platform, maximum water depths were reached during Middle Jurassic and were associated with episodes of strongest subsidence. On the Tortosa Platform, taphonomic and palaeobiological evidence of its ammonoid colonization during the Bajocian Polygyralis Subzone of the Nior tense Zone indicates the establishment of maximum water depths and its free communication with the NW European domain (Fernández-López, 1997; Fernández-López and Gómez, 2004). Subsidence was only partly compensated by high sedimentation rates that amounted

during the Garantiana Zone up to 100 m of sediments per million years.

5.3. La Tossa Formation

In the area of the Tivissa section, the La Tossa Formation can be subdivided into a lower part, consisting of microfilament mudstones to wackestones, containing thin marl interbeds, a middle part composed of mudstones and marly limestones, and an upper part formed by bioclastic mudstones and wackestones. The carbonates of these three units are generally organized into thickening- and coarsening-upward sequences, except for the middle unit in which locally fining- and thinning-upward sequences are recognized. Ammonites and bivalves (*Bositra*), as well as *Zoophycos* and *Thalassinoides*, are abundant. The lower part of this formation, which is in the order of 30 to 35 m thick, is laterally quite continuous. However, the middle and upper parts, which reach a thickness of 90 m in the Tivissa section (Fig. 6), show significant lateral facies variations. In the area of the Tivenys and Alfara-Cardo sections, they grade into thick bedded oolitic packstones to grainstones with cross-bedding and bar geometry, and in the Xerta and Pauls sections into a 90 m thick dolomitic facies.

The La Tossa Formation was deposited during the late Bajocian, Bathonian and Callovian. Its transitional boundary with the Cardo Formation is slightly diachronous. Whereas in the Xerta, Pauls, Alfara and Coll del Caragol sections the lowermost beds contain ammonites of the Bajocian Garantiana Zone; they contain ammonites of the Parkinsoni Zone in the area of the Tivenys, Cardo, Tivissa and Vandellos sections. The Bathonian deposits are 40 m thick in the Tivissa and Vandellos sections, and the late Bathonian, which is rarely recorded on the Castilian and Aragonese platforms, is represented in these areas by biostratigraphically complete and expanded sections. In the about 45 m thick Callovian deposits of the Tivissa section, at least the *Bullatus*, *Gracilis*, *Anceps* and *Coronatum* zones have been identified. The top of the Middle Jurassic series is marked by a hardground, characterized by reworked fossils, glauconite and locally by ferruginous crusts.

6. Tarragona High

The stratigraphic successions described for the Tortosa Platform, on which Middle Jurassic deposits attain a total thickness of 350 m, dramatically change to the north, where stratigraphical equivalent sediments are

represented by a much thinner dolomitic facies, or are missing altogether (Robles Orozco, 1974; Esteban and Robles, 1979; Anadón et al., 1982). These dolomitic facies were deposited on a high area, referred to as the Tarragona High (Salas and Casas, 1993). During the Bathonian, an oolitic and dolomitic high-energy belt of shallow proximal facies developed between the Tortosa and Aragonese platforms, which prograded over the low-energy open-marine external platform sediments of the Cardo Formation.

7. Catalan Massif

This palaeogeographic element has been defined on the basis of wells that had penetrated the entire Cenozoic succession of the Ebro Basin and bottomed in Mesozoic strata. No Middle Jurassic sediments were encountered by the oil wells Fraga-1, Mayals-1, Senant-1, Ebro-1 and Caspe-1 (Fig. 2; Stoeckinger, 1976; Lanaja, 1987), either owing to their non-deposition or erosion in the area of the postulated Catalan Massif (Canerot et al., 1985a,b; Fernández-López et al., 1996). Due to post-Jurassic tectonic deformation and erosion, it is difficult to precisely define the outlines of the Catalan Massif, the southeastern margin of which may have been controlled by the Requena-Mora Fault (Fig. 4).

8. Beceite Strait

The Tortosa and the Aragonese platforms were connected via the Beceite Strait (Fernández-López et al., 1996, 1998) that is located between the positive areas of the Catalan Massif and the El Maestrazgo High (Fig. 4). Condensed sections of the Chelva Group, not exceeding 40 m in thickness, characterize the Beceite Strait. These consist mainly of bioclastic wackestones to packstones that were deposited on an open-marine external platform. The open-marine facies and condensed sections of the Beceite Strait are the lateral equivalents of the expanded open-marine, external platform successions of the Aragonese and Tortosa platforms (Fig. 6), although stratigraphical features show more affinities with the Aragonese Platform.

9. Structural control on palaeogeographic elements of the eastern margin of the Iberian platform system

During the Middle Jurassic, the East-Iberian carbonate platform was affected by tensional tectonics and minor volcanic activity that can be related to the final rifting phase that preceded the opening of the oceanic Alpine Tethys (Ziegler, 1990; Salas et al., 2001; Stamp-

fli and Borel, 2004). Correspondingly, this carbonate platform was dissected into a system of differentially subsiding fault and in some cases tilted blocks, each of which followed a relatively independent evolution (Fernández-López and Gómez, 1990a). On these fault-bounded blocks, carbonate platforms formed under diverse depositional environments giving rise to successions that laterally varied substantially, both in terms of thickness and facies development. For instance, Aalenian and lower Bajocian deposits are represented on most platforms, which corresponded to relatively slowly subsiding areas, by thin condensed sections. On the Central External Castilian Platform, however, Aalenian and lower Bajocian deposits are represented by expanded sections, suggesting that this area represented a downthrown block that subsided more rapidly than adjacent blocks. In several cases, changes in subsidence rates can also be observed on the same block. For instance, on the Central External Castilian Platform, Aalenian and lower Bajocian deposits form normal sections, showing average sedimentation rates, to expanded sections, whereas most of the Bathonian and Callovian deposits represent condensed sections, reflecting a slowing down of the subsidence rate of this block. By contrast, on the Tortosa Platform, upper Aalenian and lower Bajocian condensed sections, give way to expanded upper Bajocian to lower Callovian sections, being the upper Bajocian sections the thickest ones of the entire Middle Jurassic platform system.

Despite these strong lateral and temporal variations, some features remained common to all platforms. The regionally most extensive features observed on the Iberian platform system, are the stratigraphical gaps that are recorded in part of the Aalenian Murchisonae Zone and in the Callovian Lamberti Zone. Moreover, the presence of condensed sections at the base of the Bathonian and Callovian is another stratigraphic feature that virtually occurs in the entire area, although the time interval covered by them strongly varies between the different platforms. Further features that can be traced all over the different platforms are, at a stage-scale, the timing of maximum relative water depth of the successive deepening–shallowing cycles. In external platform areas, maximum water depths were attained during the Bajocian Humphriesianum and Niortense zones, the Bathonian Progracilis Zone and the Callovian Gracilis Zone, as indicated by the colonization of the platforms by ammonites and the taphonomical features observed in the fossil assemblages (Fernández-López, 1997; Fernández-López and Gómez, 2004). However, subsidence maximums, indicated by the distribution of depocentres, are markedly diachronous from one platform to

another (Fernández-López et al., 1996, 1998). Maximum sedimentation rates were reached on the Tortosa Platform during the Bajocian Garantiana Biochron.

The different fault-bounded elements of the Iberian platform system show characteristic variations in terms of relative thickness (e.g. condensed versus expanded sections) that are associated with changes in the palaeoenvironmental conditions (e.g. restricted versus open-marine and shallow versus deep-water environments, respectively), as shown in Fig. 7. Condensed sections, that developed under restricted environments, are represented by dolomitic sediments, for instance on the El Maestrazgo and the Tarragona highs. By contrast, the Enguidanos Depocentre, located within the Internal Castilian Platform, and the El Maestrazgo Depocentre, represent expanded sections composed of restricted facies that accumulated on relatively rapidly subsiding blocks. Deposits representative of such restricted environments on internal platforms are the mudstones and oolitic grainstones of the Yemeda Formation, and the mainly dolomitic deposits of the Raffles Formation on the El Maestrazgo High. Detailed biostratigraphic dating of such restricted deposits is extremely difficult, owing to the scarcity of ammonites. On platforms, which developed mainly under open-marine conditions, a high-resolution biostratigraphic zonation, based on ammonites, has been achieved. Examples of such external platforms are the External Castilian, Aragonese and Tortosa platforms. Differential subsidence of these fault-bounded platforms conditioned their development. For example, the Pozuel Depocentre, located on the NW External Castilian Platform, was mainly filled-in

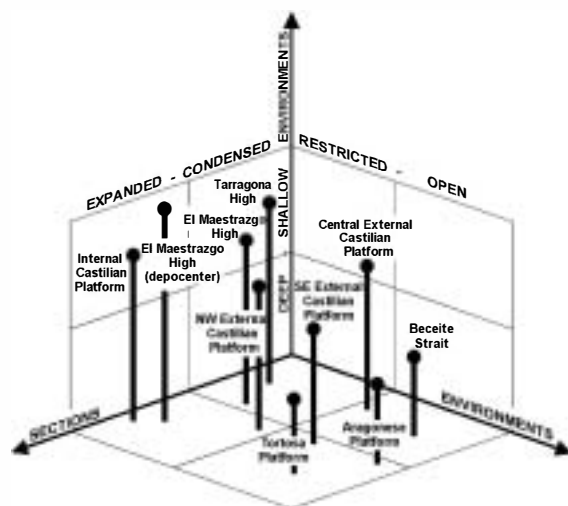


Fig. 7. Plot of palaeogeographic elements mentioned in this work, in terms of condensed to expanded sections, restricted to open-marine environments and deep to shallow environments.

during the Bathonian and Callovian by the carbonates of the Domeño Formation. By contrast, the Casinos Depocentre, located on the SE External Castilian Platform, was filled-in during the Bajocian by the carbonates of El Pedregal Formation. The Tortosa Platform represents an example of an extremely rapidly subsiding external platform that is characterized by highly expanded sections. In this area, more than 350 m of Middle Jurassic sediments accumulated. Maximum sedimentation rates were recorded during the upper Bajocian Garantiana Zone, when up to 60 m of alternating pelagic marls and limestones were deposited, although subsidence rates reached a maximum during the Nior-tense Zone. Condensed sections, which were deposited on external platforms, are represented for example by the less than 40 m thick Middle Jurassic deposits of the Beceite Strait that connects the Tortosa and Aragonese platforms between the El Maestrazgo High and the Catalan Massif. Condensed external platform sections are also present on the Castilian Platform where they are associated with volcanic mounds, providing for a sea floor relief (Fernández-López et al., 1985; Cortés, 2001). Deposits of restricted environments are recorded, locally and occasionally, in external platform areas. For example, some lower Bajocian deposits of the El Pedregal Formation, filling the Pozuel Depocentre that is located on the NW External Castilian Platform, are composed of peritidal dolomitic limestones and mudstones showing microbial laminae and mud-cracks. These restricted facies, and associated open-marine facies, find their lateral time equivalents in open-marine deposits which grade into the Internal Castilian Platform facies.

Based on the above, we conclude that during the Middle Jurassic syn-depositional extensional faults controlled subsidence patterns of the main palaeogeographic elements along the eastern margin of the Iberian platform system. The different platforms can be categorized in terms of their sediment thickness (expanded versus condensed sections) and palaeoenvironmental setting (restricted versus open environments). Open-marine, normal salinity, environments were developed in external platform areas, whereas restricted environments characterized internal platform areas, although occasionally they occur in proximal areas on the shallow parts of external platforms.

10. Conclusions

The study of 199 surface sections under outstanding outcrop conditions along more than 500 km, and 37 wells, has allowed a detailed reconstruction of the

palaeogeographic elements along the eastern margin of the Middle Jurassic Iberian carbonate-platform system. Around the El Maestrazgo High, three main platforms can be recognized, namely the Castilian, Aragonese and Tortosa platforms. Attached to the Iberian Massif, the Internal Castilian Platform, dominated by restricted facies and commonly expanded sections, was bounded by the Montes Universales and La Mancha faults. The External Castilian Platform was dominated by open-marine facies, locally containing interbedded restricted facies in some proximal and shallow areas, and commonly normal to expanded sections. The Northwestern, Central and Southeastern External Castilian platforms are separated by a northeast-trending fault system, involving the Noguera-Aguaton, Teruel and Requena-Mora faults. The fault-bounded El Maestrazgo High, that was characterized by condensed to expanded sections of restricted environments, separated the Castilian and the Aragonese and Tortosa platforms. Open-marine environments dominated these external platforms. Whereas expanded sections are common on the Tortosa Platform, the Aragonese Platform contains condensed as well as expanded sections. A connection between the Aragonese and Tortosa platforms was established via the Beceite Strait, located between the Catalan Massif and the El Maestrazgo High. The Tarragona High, characterized by restricted facies, delimited the Tortosa Platform to the north. Along the eastern margin of the Iberian carbonate-platform system, expanded sections were not necessarily associated with open-marine environments. On these external and internal platforms, condensed and expanded sections developed, even on palaeogeographic highs, such as the El Maestrazgo High. Open-marine environments dominated external platforms, whereas restricted environments characterized internal platforms and occasionally occur in the shallow parts of external platforms.

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