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Thrust sequence and syntectonic sedimentation in a piggy-back basin: the Oligo-Aquitanian Mula–Pliego Basin (Internal Betic Zone, SE Spain)

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Abstract – The Oligo-Aquitanian deposits of the Mula–Pliego basin consist of a marine carbonate platform assemblage (bottom), transitioning into a turbidite wedge (top). This evolution was controlled by tectonics in a piggy-back basin by means of three main mechanisms: first, a flexural tectonic event created the basin; later on, blind-fault-propagation folds deformed it progressively from south to north; finally a tectonic event destroyed the basin. ***To cite this article: M. Martín-Martín, A. Martín-Algarra, C. R. Geoscience 334 (2002) 363–370.*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

sedimentary evolution / Oligo-Aquitanian / piggy-back basin / geodynamic evolution / fault-propagation fold

Résumé – Séquence de chevauchements et de sédimentation syntectonique dans un bassin transporté (*piggy-back*) : le bassin oligo-aquitanien de Mula–Pliego (Zone interne bétique, Sud-Est de l'Espagne). Les dépôts oligo-aquitaniens du bassin de Mula–Pliego débutent par un ensemble carbonaté marin et passent progressivement vers le haut à un « coin » turbiditique ; ils ont été contrôlés par la tectonique, dans un bassin de type transporté (*piggy-back*). L'évolution tectonique résulte de trois mécanismes principaux : d'abord, une tectonique flexurale, ensuite, une succession de plis de propagation de la déformation du sud vers le nord et, finalement, un ultime événement tectonique, qui détruit le bassin. ***Pour citer cet article : M. Martín-Martín, A. Martín-Algarra, C. R. Geoscience 334 (2002) 363–370.*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

évolution sédimentaire / Oligo-Aquitanien / bassin transporté / évolution géodynamique / plis de propagation chevauchants

Version abrégée

1. Introduction

Le basin de Mula–Pliego, localisé dans la province de Murcie (Sud-Est de l'Espagne), montre des matériaux mésozoïques et tertiaires appartenant aux unités malaguides des zones internes bétiques (Fig. 1). Les dépôts oligo-aquitaniens ont rempli un bassin transporté (*piggy-back*), sensu [16], en même temps que leurs unités étaient déplacées et que les unités les plus basses enregistraient le métamorphisme alpin [8].

Le bassin présente les structures suivantes :
– anticlinaux de La Sabina (Fig. 2, section 3), Palomeque (Fig. 2, section 2), Calvillo (Fig. 2, section 2), Castillo (Fig. 2, section 4), Marinas (Fig. 2, section 4) et Herrero (Fig. 2, section 4) ;
– le chevauchement de Manzanete (Fig. 2, section 4) ;
– deux systèmes de fractures (Figs. 2 et 3) : N150–170E et nord–sud [10].

Les anticlinaux peuvent être classés [2, 24] parmi les plis asymétriques à flanc renversé et chevauchant vers le nord-ouest, mis à part celui de l'Herrero, qui rétrochevauche vers le sud-est. Généralement, ces chevauchements frontaux

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disparaissent latéralement en passant à des discordances progressives (Figs. 1 et 2, sections 2 et 3).

2. Stratigraphie séquentielle et évolution géodynamique

On distingue deux formations sédimentaires pendant l'Oligocène et l'Aquitanien (Figs. 1 et 2, sections 1, 2 et 3) [9]. Au sud, la formation Bosque, transgressive, en discordance progressive sur la série sous-jacente, est constituée par des dépôts marins peu profonds, calcarénites, conglomérats calcaires et marnes (autour de 1000 m d'épaisseur dans la zone de La Sabina), constituant un système d'éventail deltaïque, alimenté depuis le sud par du matériel résultant de l'érosion du Mésozoïque et du Tertiaire sous-jacent (Fig. 3, colonnes I et II). Ce type de dépôts est usuellement connu dans des bassins syntectoniques, proches des limites actives de la dépression, où une érosion rapide résulte de la montée des reliefs.

Dans le reste du bassin, la formation Río Pliego est formée de lutites rouges, grès et conglomérats polygéniques (Fig. 3, colonnes III, IV et V). Il s'agit d'un système turbiditique, alimenté depuis le nord par l'érosion des terrains paléozoïques et triasiques [6, 11]. On constate un passage latéral de faciès entre les deux formations [9].

En fonction des faits cartographiques, sédimentaires et biostratigraphiques disponibles dans ce bassin [9, 11, 14, 22], nous avons divisé la série sédimentaire en quatre séquences de dépôt mineures.

La **première séquence**, d'âge Oligocène supérieur, correspond à la partie basse de la formation Bosque. Sont représentés des calcaires à lépidocyclines, *Solenomeris* et algues rouges, ainsi que des conglomérats à galets calcaires arrondis et des marnes. Ces dépôts transgressifs peuvent s'interpréter comme la réponse à un accroissement de volume du bassin par montée du niveau de la mer. À leur base, ces matériaux montrent un dispositif de discordance progressive (Fig. 2, section 2) qui atteste une tectonique flexurale contemporaine. À ce moment, le dépocentre est localisé près des reliefs en formation, dans les secteurs d'El Bosque et de La Sabina.

La **deuxième séquence**, d'âge Oligocène terminal à Aquitanien basal, correspond au sommet de la formation Bosque et à la base de la formation Río Pliego, avec passage latéral de faciès de l'une à l'autre formation. La formation Bosque, épaisse d'environ 100 m seulement, est représentée par des marnes qui, dans un contexte régressif, passent à des calcaires dans la zone de La Sabina (Couche Sabina : Fig. 3, colonnes I et II). La formation Río Pliego (environ 180 m pour l'intervalle de temps considéré) constitue une succession grano- et strato-croissante, passant des lutites (faciès b, deTM [5]) à des grès (faciès b, deSM et cSM) jusqu'à, finalement, des conglomérats. Pendant cette période, une importante lacune (Éocène supérieur et Oligocène) affecte les secteurs de La Sabina et de Palomeque. En même temps, l'aire de La Sabina montre une sédimentation marine peu profonde. Les dépocentres étaient alors localisés dans la partie centrale du bassin.

Les zones à lacunes stratigraphiques et à sédiments marins peu profonds de type récifal ont été attribuées dans d'autres études antérieures [20, 21] à des zones antiformes, tandis que les dépôts profonds correspondraient à des zones synformes. Certains auteurs considèrent de telles antiformes comme des plis de propagation de chevauchements aveugles [24].

La **troisième séquence**, d'âge Aquitanien, épaisse d'environ 100 m, constitue également une succession strato- et grano-croissante. Elle est formée par des lutites (faciès b, dMS), grès (b, deSM et cSM) et des conglomérats poligéniques (GyS, G, gG et mG) turbiditiques de la formation Río Pliego (Fig. 3, colonnes III, IV et V), alimentés depuis le nord-ouest ou le nord et en progradation vers le sud (Figs. 1 et 3, colonnes III, IV et V). De nouvelles zones hautes sont alors apparues successivement à Calvillo, Castillo et Marinas. En relation avec ces dernières apparaissent des discontinuités et des lacunes, au moins de l'Oligocène moyen à l'Aquitanien inférieur. Le volume du bassin diminue pendant cette séquence.

La **quatrième séquence**, d'âge Aquitanien, épaisse de 30 m (Fig. 3, colonnes III, IV et V), est formée de lutites rouges (faciès b, deTM) et de grès (b, dMS). La sédimentation, plus réduite, fut reléguée dans les zones synclinales de la partie nord du bassin. À la fin de cette période, un événement tectonique, lié à la mise en place des unités malaguides couronnant la pile tectonique des zones internes bétiques [6], détruisit le bassin, avant que ne s'en crée un nouveau (formation El Niño : [9]).

3. Discussion et conclusions

La Fig. 4 montre l'interprétation de l'évolution du bassin en trois étapes successives.

3.1. Étape flexurale à sédimentation marine carbonatée

Embrassant la période de la première séquence (Oligocène supérieur), elle est caractérisée par l'installation d'un éventail deltaïque, alimenté depuis le sud à partir de l'émergence de reliefs. Pendant cette période, se produisait une flexure dans le bassin.

3.2. Étape tectonique à sédimentation marine mixte, carbonatée et terrigène

Elle correspond à la deuxième séquence (Oligocène terminal–Aquitanien basal). Pendant cette période, la sédimentation a présenté deux types de faciès : au sud et à la base, un ensemble carbonaté ; au nord et au toit, un ensemble turbiditique. En même temps, une tectonique de propagation de chevauchements aveugles peut être invoquée pour justifier l'apparition de hauts structuraux (antiformes de La Sabina et Palomeque), les changements latéraux des faciès et les discordances progressives, ainsi que le déplacement des dépocentres (synformes) du sud vers le nord (Fig. 4). Cette interprétation paraît en accord avec les modèles proposés dans d'autres régions [3, 4, 20, 24].

3.3. Étape tectonique à sédimentation marine terrigène

Elle représente la fin du développement du bassin transporté, pendant le dépôt de la troisième et la quatrième séquences (Fig. 4), avant la disparition du bassin rattachée à la mise en place des unités malaguides au sommet de la pile tectonique des Zones internes bétiques [6]. La sédimentation fut alors contrôlée par la tectonique, un ensemble turbiditique dans des zones subsidentes (synformes) apparaissant durant l'Aquitanien. Les zones élevées (antiformes), situées chaque fois plus au nord, sont celles de Calvillo, El Castillo et Marinas.

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1. Introduction

The Mula–Pliego Basin is located in the province of Murcia (SE Spain, Fig. 1). In this area, Mesozoic and Tertiary deposits belonging to the Malaguide units (the upper and non-metamorphosed complex of the Internal Betic Zone) are widely outcropping (Fig. 1). The deposition of the Oligocene to Aquitanian sediments in the Malaguide domain took place within piggy-back basins (sensu [16]); at the same time, the tectonic transport on the top of the orogenic wedge accounted, and the lower units of the Internal Betic Zones were affected by the Alpine metamorphism [8].

Several recent studies on piggy-back basins [4, 15, 17, 20, 23] provided a useful methodology for understanding the evolution of the Mula–Pliego Oligo-Aquitanian basin. So, this paper proposes a model for the geodynamic evolution of a pre-collisional syntectonic basin.

2. Structural framework

The Mula–Pliego Basin is bounded to the north with the External Betic Zone [10], and to the south, by the Sierra Espuña Massif [10] (an antiformal stack, sensu [2]). In the upper part, it consists of two folded nappes (Figs. 1 and 2) forming the Espuña Fold [7]: the Morrón de Totana Unit, footwall; and the Perona Unit, hanging-wall. The thrust contact of the upper unit involves Early Oligocene materials, but is sealed by Late Oligocene sediments, in which the contact consists of a progressive unconformity.

At the Mula–Pliego Basin, several folding and thrusting structures (structural culminations) can be recognised (Figs. 1 and 2). According to the nomenclature proposed by [2, 24], they consist mainly of asymmetric folds with one steep or overturned limb (usually the northern one) adjacent to thrust faults (Fig. 2, sections 2 and 4).

The detachment level of these thrusts is the Palaeozoic–Triassic boundary, although thrust surfaces usually propagate northwards through the Cretaceous and the Palaeocene (Fig. 2, sections 2 and 3). The following structures have been distinguished:

– the Sabina, Palomeque, Calvillo, Castillo and Marinas anticlines (Fig. 2);
– the Herrero anticline (Fig. 2, section 4), the only thrust-fold system that shows the fault limb located to the south;
– the Manzanete thrust (Fig. 2, section 4);
– two fault systems that have been recognised throughout the area (Figs. 2 and 3).

The main fault system is N150–170E oriented, while the system shows faults oriented roughly north–south to N10E. These systems consist of normal faults with a major strike-slip component [10].

Related to each anticline, thrust-faults usually appear; these present minor slips and change laterally into successive stratigraphic unconformities (see Fig. 2, sections 2 and 3).

Shear sigmoid structures, striations and fold axes were measured in order to determine the displacement direction of thrusting. They are indicated in Fig. 1.

3. Sequence stratigraphy and geodynamic evolution

The first regional evidence of thrusting in the area was found at the end of the Lower Oligocene, when the Perona Unit thrusted onto the Morron de Totana unit and a new basin was created to be filled from the Late Oligocene to the Late Aquitanian [12, 13].

Studies were made following the methodology described in previous works [4, 15, 23]. The relative sea-level changes and the relationships (onlapping) of the sedimentary bodies (usually transgressive) with previous sediments were analysed. Also, sedimentological studies in the siliciclastic turbiditic deposits have been made following Guibaudo's methodology [5].

Two laterally related formations have been distinguished [9] (see Figs. 1 and 2, sections 1, 2 and 3). In the southern part of the basin, the Bosque Formation is formed by shallow marine limestones, calcarenites, calcareous conglomerates and yellowish marls (reaching about 1000 m in thickness in the Sabina area), which represent a fan delta system fed from the south, from Sierra Espuña – type Mesozoic and Tertiary rocks –, and which showed a distal northwards transition toward a basin (Fig. 3, columns I and II). These kinds of deposits are commonly described in syntectonic basins, related to active boundaries where a

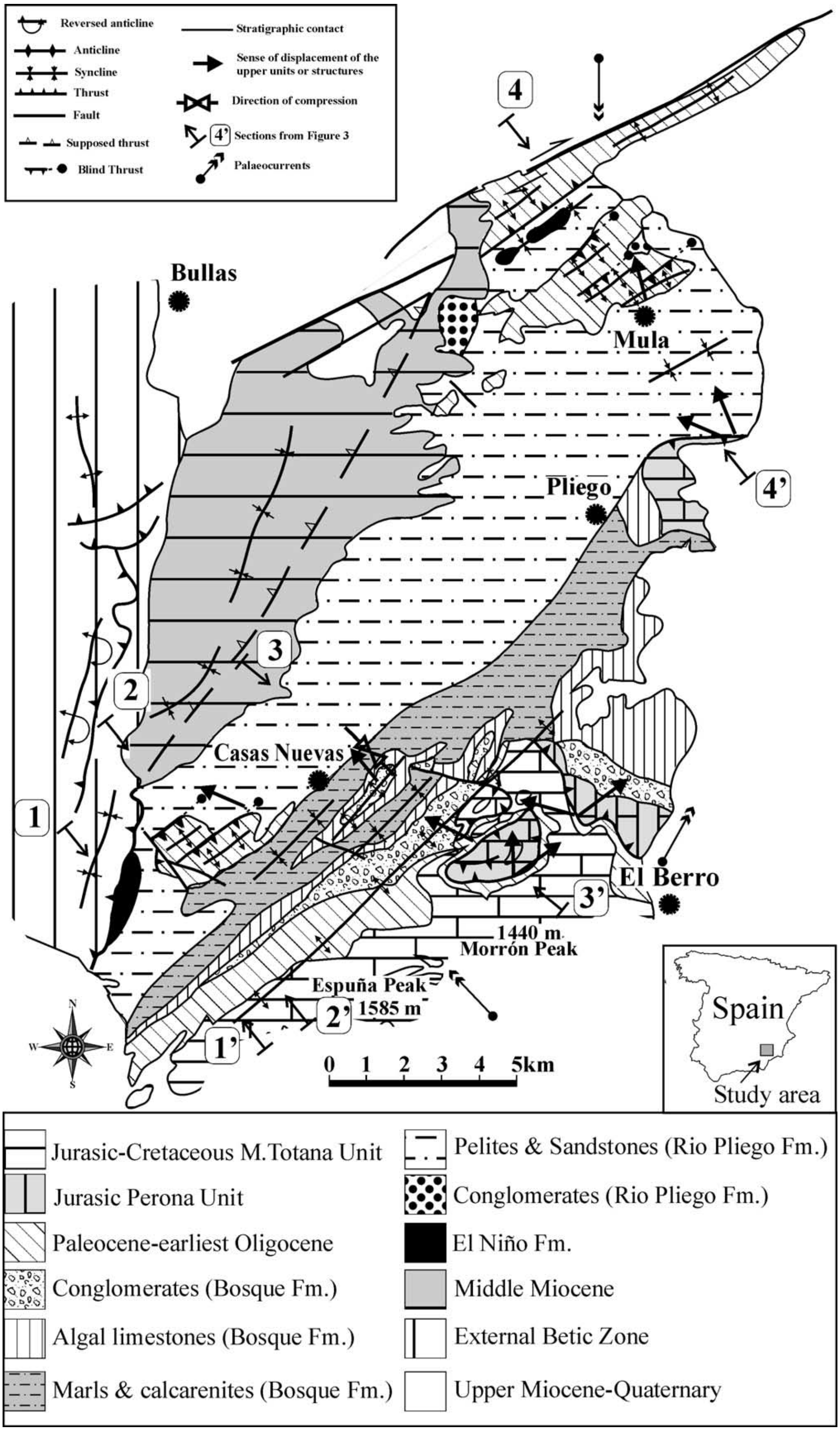

Figure 1. Geological map of the Mula–Pliego Basin with location of cross-sections of Fig. 2.

Figure 1. Carte géologique du bassin de Mula–Pliego, avec localisation des coupes de la Fig. 2.

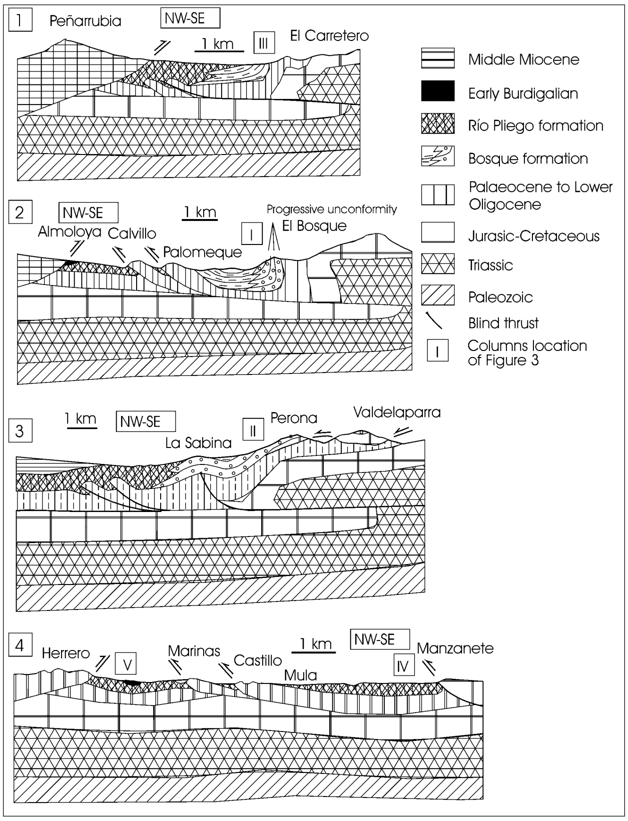

Figure 2. Cross-sections through the area (location in Fig. 1) and location of stratigraphic columns of Fig. 3.

Figure 2. Coupes à travers le secteur étudié (localisation sur la Fig. 1) et localisation des colonnes stratigraphiques de la Fig. 3.

rapid erosion of the hanging wall block takes place and deposition flows into fan-delta systems.

In the central and northern part the Río Pliego Formation appears, which consists of reddish lutites and polygenic sandstones and conglomerates (Fig. 3, columns III, IV and V), belonging to a turbiditic system fed from the north [11]. A lateral change from one to the other formation occurs, but opposite source areas were pointed out [9]. The Bosque Formation is transgressive on Mesozoic and older Tertiary deposits located to the southeast on the Sierra Espuña proper, which in turn forms its source area. The bottom part of this formation forms an onlapping dispositive with a progressive unconformity. On another hand, the Río Pliego Formation is located to the north, and its source area appears to consist mainly of Palaeozoic and Triassic rocks according to the petrographic composition of its sandstones and conglomerates [6].

This sedimentary cover is organised as a carbonate platform assemblage to the south and at the bottom, and a syntectonic turbidite wedge (sensu [19]), to the north and to the top, in good agreement with previous models proposed [1, 16, 18, 19] for piggy-back basins.

According to cartographic, sedimentologic and biostratigraphic data [9, 11, 14, 22], four minor sequences have been separated in the Late Oligocene–Aquitanian depositional megasequence.

The **first sequence**, Upper Oligocene in age, corresponds to the lower part of the Bosque Formation. The facies consist of Lepidocyclina, *Solenomeris* and algal-rich limestones, rounded calcareous conglomerates and marls, deposited in a fan-delta system related to a shallow sea, located close to emerging reliefs in the southern boundary of the basin. This transgressive level can be interpreted as the response to increased accommodation of the basin during a relative sea-level rise (Fig. 3, columns I and II). These overlie Earliest Tertiary and Mesozoic sediments by means of an angular unconformity (Fig. 1). This progressive unconformity is the only evidence of tectonics at this moment, suggesting a general flexure with an increase in the accommodation (Fig. 2, section 2). During deposition of this sequence, the depocentre was located in the Bosque–Sabina area, where measured sections are thicker.

The **second sequence**, late Upper Oligocene to Earliest Aquitanian in age and related to the end of deposition of Bosque Formation (carbonate assemblage) and to the beginning of the Río Pliego Formation (syntectonic turbidite wedge), while a lateral change of facies is recognized between both. For this time interval, the Bosque Formation is only about 100 m thick and it is mainly made up of marls forming, in the Sabina area, a regressive succession. This marls gradually change upwards into limestones rich in algal and *Solenomeris* rodoliths (Sabina Bed) indicative of shallow marine environments (Fig. 3, columns I and II). The Río Pliego Formation, 180 m thick for this time interval, forms an upwardly coarsening and thickening succession (Fig. 3, columns III and IV) changing from lutites (facies b, deTM [5]) to sandstones (facies b, deSM and cSM) and finally, to conglomerates (xG, mG, GyS, S and lS). The above evolution can be interpreted as increasing tectonics. Within this sequence in the southern and central part of the basin, there is an important gap related to the erosion of uplifting areas in the Sabina and Palomeque. In the Palomeque area also, a gap affects the Late Eocene–Late Oligocene; at the same time, in the Sabina area, shallow marine sedimentation was occurring. Depocentres are located in the central part of the basin.

Distribution of the shallow-water, deep-water deposits and sedimentary gaps in the basin indicates the birth of incipient tectonic structures. Deep-water deposits are located in the synclines and carbonates bearing reefal biostromes, and sedimentary gaps are located on the rising anticlines, as found in the Pyrenean Belt during the Eocene [20, 21]. From these observations (depocentre migration, lateral change of

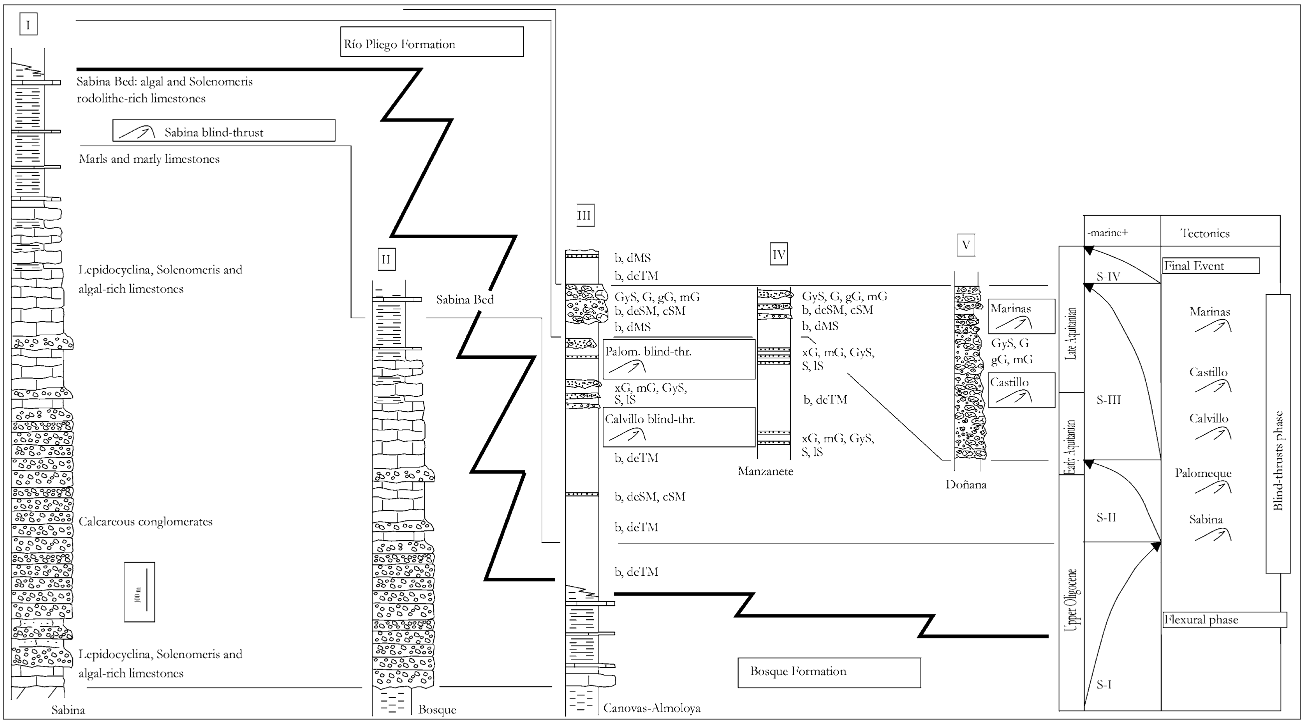

Figure 3. Stratigraphic columns (located in Fig. 2) with defined sequences, formations, tectonic phases and relative sea-level changes in the Late Oligocene to Late Aquitanian deposits of the Mula–Pliego Basin.

Figure 3. Colonnes stratigraphiques (localisation sur la Fig. 2) figurant les séquences et formations définies, les phases tectoniques et les changements du niveau de la mer, de l'Oligocène terminal à l'Aquitanien terminal dans le bassin de Mula–Pliego.

facies, progressive unconformities and formation of shallow and deep successive areas) we propose a blind-thrust-anticline and syncline system, in good agreement with [24]: the Sabina anticline and correlative syncline, first, and Palomeque anticline and correlative syncline, later.

The **third sequence** is Early to Late Aquitanian in age, 100 m thick and also forms an upwardly coarsening and thickening succession. It is composed of lutites (facies b, dMS), sandstones (b, deSM and cSM) and polygenic conglomerates (GyS, G, gG and mG) belonging to the Río Pliego Formation (Fig. 3, columns III, IV and V). These terrigenous sediments came from a northwestern or northern area, now absent in outcrop, but deduced from the cartographic location of the conglomerates, grain-size analysis and palaeocurrent directions ascertained from clast imbrication and sole marks in turbidites (Figs. 1 and 3, columns III, IV and V). The development of this sequence seems to be associated with a relative sea-level fall during a period of increased tectonic activity, as shown by the sedimentary evolution of the sequence, in the form of a coarsening upward succession. Newly uplifting areas can be deduced at this period in the Calvillo, Castillo and Marinas areas (chronologically in this order), being related to unconformities with associated sedimentary gaps (at least, the Middle Oligocene to Early Oligocene). In the same way as the previous sequence, it could constitute a blind-thrust anticline-syncline [24]. During this sequence accommodation, decreased and detrital deposits prograded from north to south in the northern part of the basin.

The **fourth sequence**, Latest Aquitanian in age and 30 m thick (Fig. 3, columns III, IV and V), consists of reddish lutites (facies b, deTM) and sandstones (b, dMS) located only in the synclines of the northern part. During this period a tectonic event (final emplacement of the Malaguide) domain over the lower Betic Units [6] destroyed the Upper Oligocene–Aquitanian basin, developing a new basin (El Niño Formation) [9].

4. Discussion and conclusion

Although relative sea-level changes took place during the Oligo-Aquitanian in the Mula–Pliego Basin, these were probably related to a variation in basin morphology and migration of depocentres due to tectonic processes. Fig. 4 shows the interpretation for this

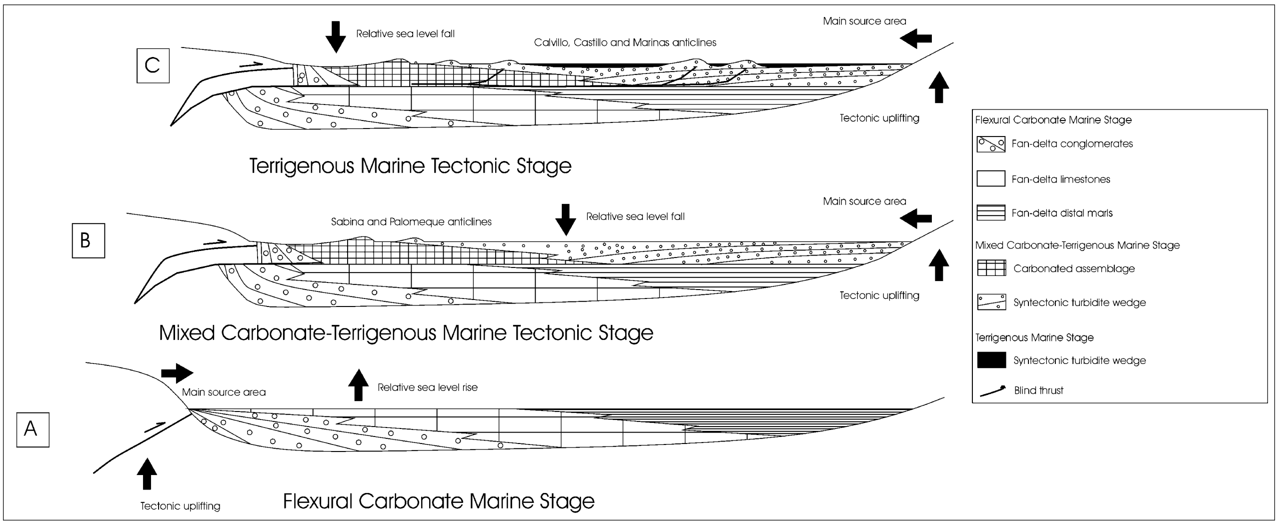

Figure 4. Synthetic basin evolution. **A**: flexural carbonate marine stage, **B**: mixed carbonate-terrigenous marine tectonic stage, **C**: terrigenous marine tectonic stage.

Figure 4. Évolution synthétique du bassin. **A** : stade flexural à dépôts marins carbonatés. **B** : stade tectonique à dépôts marins mixtes, carbonatés et terrigènes. **C** : stade tectonique à dépôts marins terrigènes.

geodynamic evolution by means of three successive stages.

4.1. Flexural carbonate marine stage

This is represented by the first sequence (Upper Oligocene), and was characterised by the installation of a fan-delta system fed from the south to the erosion of the uplifting reliefs of the Sierra Espuña. This was associated with a relative sea-level rise and with the development of a progressive unconformity due to a general flexural behaviour of the basin basement dating to the first stage of the former piggy-back basin (Fig. 4).

4.2. Mixed carbonate and terrigenous marine stage

This coincides with the second sequence from the late Upper Oligocene to the Earliest Aquitanian. Sedimentation gave rise to a piggy-back basin that followed the initial flexural basin, associated with a relative sea-level fall. Two different depositional areas took place: to the south and at the beginning of the stage, a carbonate assemblage; to the north and at the top, a syntectonic turbidite wedge. At the same time, blind thrusts can be proposed to originate the structural culminations, and variation in depocentres, from south to north (Fig. 4). This interpretation is in good agreement with models proposed for other areas [3, 4, 20, 24].

Therefore, from time to time, the sedimentation area shifted towards an external position, with the uplifting and subsiding areas being consecutively located in the Sabina anticline and following syncline and in the Palomeque anticline and correlative syncline (Fig. 3).

4.3. Terrigenous marine tectonic stage

This occurred at the end of the piggy-back basin stage (Fig. 4) during deposition of the third and fourth sequences, while the Malaguide domain was reaching the top of the nappe stacking [6]. Sedimentation was controlled mainly by tectonics, and a thick syntectonic turbiditic wedge was formed during the Aquitanian, related to subsident areas located on deepening synclines. At the same time uplifting areas (structural culmination), coinciding with anticlines, show sedimentary gaps and take place in the northern area, indicating that blind thrusts could be reaching the northern boundary of the basin. During this period, the uplifting and subsiding areas were located: first. at Calvillo anticline and following syncline, and later, at Castillo de Mula anticline and correlative syncline. Finally, during the end of third sequence, the uplifting and subsiding areas were, respectively, at Marinas anticline and following syncline.

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