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A Liassic isolated platform controlled by tectonics: South Iberian Margin, southeast Spain

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Abstract – The middle and upper members of the Gavilán Formation near Vélez-Rubio (Almería Province, southeast Spain) are interpreted as carbonate platform deposits. The studied outcrops form geologically part of the External Zones of the Betic Cordillera (South Iberian Palaeomargin). A genetic unit limited by intra-Sinemurian and intra-Upper-Carixian sedimentary breaks is defined. The evolution of the parasequence sets in the area, and the development of deeper sedimentation in its northern outcrops, suggest that this platform was isolated with regard to the South Iberian Margin. Three distinct parasequence sets are proposed: progradational parasequence set (only locally present), retrogradational parasequence set (middle member of the Gavilán Formation) and aggradational parasequence set (basically composed of the upper member of the Gavilán Formation). Sedimentary features (such as neptunian dykes, sharp lithological changes, thickness variations), the presence of palaeofaults and the subsidence history all lead to the conclusion of a significant regional tectonic influence in the genetic unit evolution. Normal extensional faulting has been proposed as a major control on sedimentation on this isolated platform. This regional factor has completely distorted the effect of the eustatic fluctuations for this period of time.

1. Introduction

Mainly based on the Mitchum, Vail & Thomson (1977) definition of the depositional sequence, many authors have attempted to apply sequential methodology to recognize these units in the stratigraphic record. Based on the postulate that sequence stratigraphy reflects global changes in sea-level (Vail, Mitchum & Thomson, 1977), sequence boundaries are proposed as elements for world-wide correlations (Haq, Hardenbol & Vail, 1988). However, apart from eustasy, other factors may have affected the evolution of these genetic units (see, e.g. Aurell, 1991; Posamentier & Allen, 1993), such as local tectonics, widely studied by various authors (e.g. Pedley & Grasso, 1991; Aurell & Meléndez, 1993; Frostick & Steel, 1993; Rosales, Fernández-Mendiola & García-Mondejar, 1994; Rey, 1995*a*,*b*; Aguado & Rey, 1997).

The aim of this paper is to document an example of tectonic control associated with sequence formation on a carbonate platform. For this purpose we have studied Lower Jurassic succession to the north of Vélez-Rubio (southeast Spain; Fig. 1a). These outcrops are geologically included in the External Zones of the Betic Cordilleras. During Mesozoic time these sediments constituted a sedimentary covering of the southern continental margin of the Iberian plate. Three major tectono-palaeogeographic complexes can be distinguished (García-Hernández *et al.* 1980): the Prebetic Zone, the Intermediate Units and the Subbetic Zone. These complexes became differentiated during the Upper Carixian, when the homogeneity of the basin was broken (see, e.g. García-Hernández *et al.* 1980; Vera, 1988), with the transition from a pre-rifting phase to a synrifting one. This event caused palaeogeographic differentiation into troughs and swells in the South Iberian Palaeomargin.

Before Upper Carixian time, the External Zones of the Betic Cordillera formed part of a vast carbonate platform (Vera, 1988). However, this platform was by no means uniform and was divided into two separate smaller platforms as the result of an intra-Sinemurian tectonic event, which was registered as a sedimentary break (Andreo *et al.* 1991; Rey, 1993). The northern platform remained connected to the South Iberian continental margin and was separated from an isolated platform by a seaway where hemipelagic facies were deposited (Fig. 1b). This isolated platform is the subject of this study and was composed of a series of independent banks in an area of irregular palaeotopography.

This paper focuses on the evolution of the isolated second platform (Fig. 1b), which was controlled by both regional tectonics and eustasy. In this area, a genetic unit limited by two sedimentary breaks, intra-Sinemurian and intra-Upper-Carixian, has been identified. The terms 'depositional sequence' and 'sequence boundary', with eustatic relationships (Vail, Mitchum & Thomson, 1977), have not been used. As an alternative, the terms 'genetic unit' and 'sedimentary break' are used in the sense of Vera (1994). The stacking pattern and lateral evolution of the parasequence sets forming this unit are analysed.

The relative position of the localities is different to their actual position. In a palinspastic reconstruction, Marrajo (Fig. 1a) and equivalent outcrops, along with the Lias and Dogger facies (Rey, 1993, 1995*a*), were located north of the Gabar outcrop, and never south of the Gigante outcrop (Fig. 1a).

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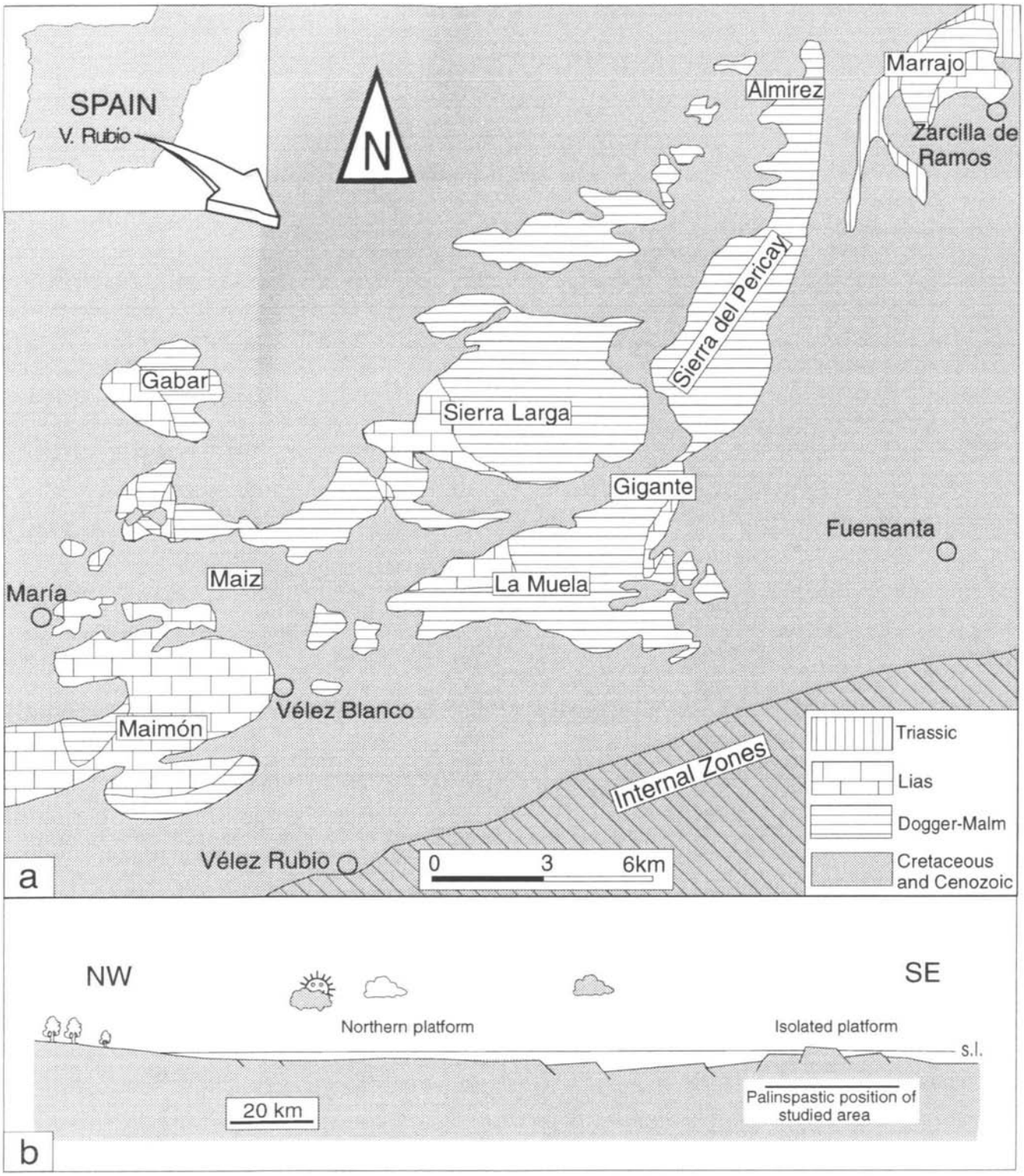


Figure 1. (a) Schematic geological map showing the studied localities and the exposed Lias carbonates (after Rey *et al.* 1990). (b) Sketch of the palinspastic reconstruction of the Southern Iberian palaeomargin of the Betic Cordillera just after the intra-Sinemurian sedimentary break.

2. Stratigraphy

2.a. Stratigraphic setting

In the External Zones of the Betic Cordillera, especially in the studied area, the infra-Domerian carbonates belong to the Gavilán Formation. This lithostratigraphic unit is made up of three members, which are referred to as the lower, middle and upper member respectively (Fig. 2).

The lower member (M.1), sometimes over 500–600 m thick, is mainly composed of dolomitic cryptalgal laminites. The lithology is uniform all over the studied region, suggesting that the member has been deposited

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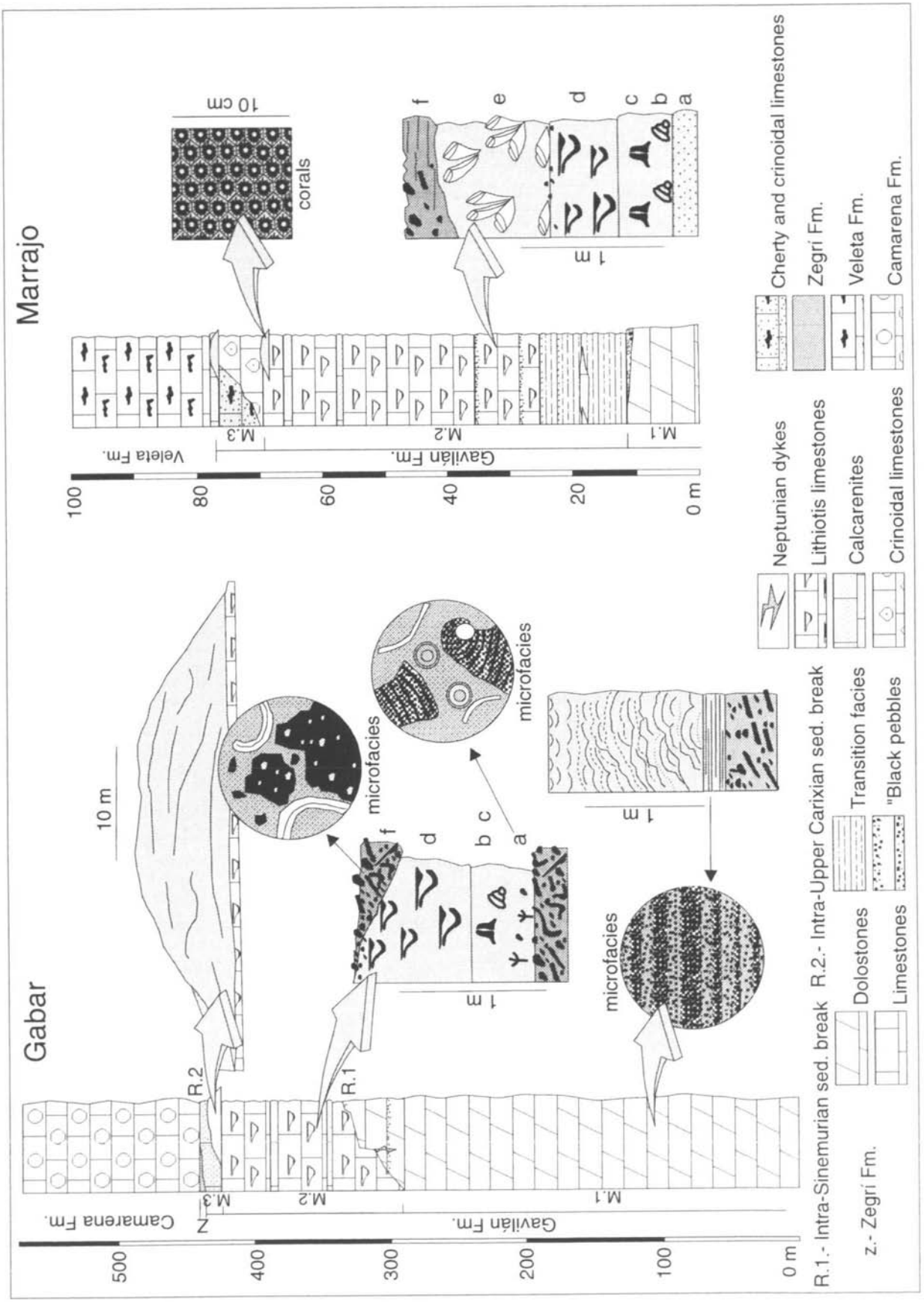


Figure 2. Stratigraphic columns of the Gavilán Formation (after Andreo *et al.* 1991). Monte del Gabar section showing details of cryptalgal sheets in the lower member and of metre-scale cycles in the *Lithiotis* limestones of the middle member. The mud mound in the upper part of the middle member is also shown. Circles represent details from thin sections. Diagram of Monte del Marrajo shows details of metre-scale cycles in the middle member and coral biolitite.

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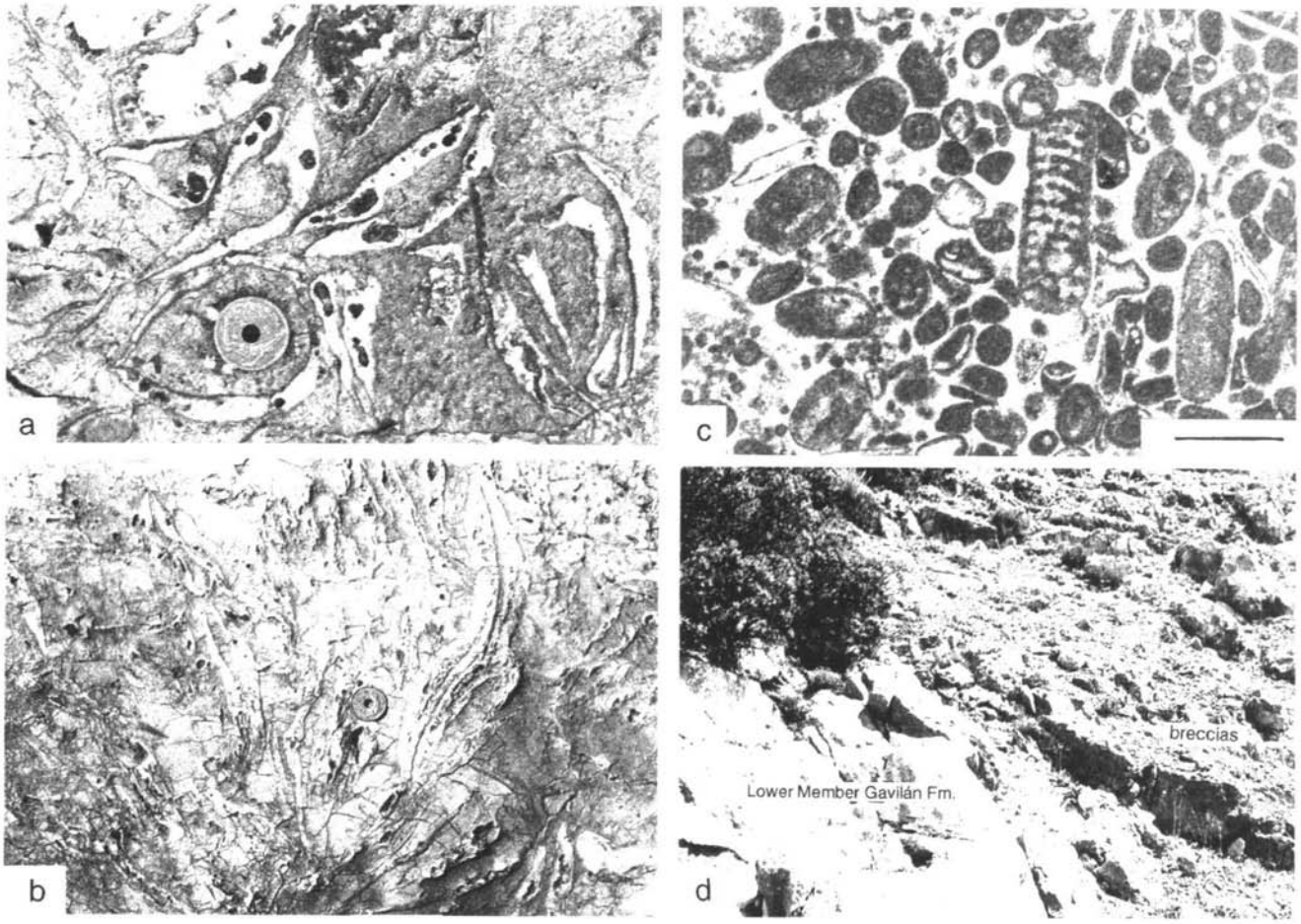


Figure 3. (a), (b) and (c) correspond to facies of the middle member of the Gavilán Formation *(Lithiotis* limestones). (a) *Gervilleioperna* facies (Gabar). (b) *Lithioperna* facies (Marrajo). (c) Grainstone of ooids, peloids and benthonic foraminifera (lituolids) (Gigante). Scale bar is 0.6 mm. (d) Palaeofault observed in the contact between the two lower members of the Gavilán Formation (Gabar).

under homogeneous sedimentary conditions. Rey *et al.* (1990) described small-scale cycles 2 m thick in this member. From bottom to top, it comprises calcarenites, cryptalgal laminites, stromatolitic domes and 'tepee-like' calcilutites (Fig. 2).

The middle member (M.2) is separated from the lower one by an intra-Sinemurian sedimentary break (Andreo *et al.* 1991; Rey, 1993). It is composed of strata with remarkable lateral facies variations involving micrite limestone, *Lithiotis* limestone, oolitic limestone and also, just north of the study area, cherty limestone. Collectively these indicate that after the intra-Sinemurian sedimentary break, another sedimentary regime prevailed in the platform. The depositional thickness ranges from 0 to 150 m.

An upper calcarenite member (M.3) composed of a crinoidal grainstone, sometimes with nodular chert, is not always present, and its thickness never exceeds 20 m.

The Zegrí Formation locally overlies the Gavilán Formation, from which it is separated by the intra-Upper-Carixian sedimentary break (Andreo *et al.* 1991; Rey, 1993). The Zegrí Formation is composed of alternating marls and marly limestones, dated by means of ammonites as Upper Liassic (Domerian–Toarcian: Rey, 1993). In other areas of the Cordillera, equivalent lithologies have been deposited under pelagic conditions (Vera, 1984).

In the studied sector, however, a significant gap is associated with the intra-Upper-Carixian sedimentary break. Consequently, the Zegrí Formation is generally missing, and the Gavilán Formation is overlain by oolitic limestones of the Camarena Formation (Dogger, Fig. 2). In Monte del Marrajo, cherty limestones of the Veleta Formation (Dogger) directly overlie the Gavilán Formation (Fig. 2).

2.b. The middle and upper members of the Gavilán Formation (M.2, M.3)

2.b.1. Field data

This study is restricted to the middle and upper members of the Gavilán Formation. The boundary between the lower and middle member tends to be sharp. However, in Monte del Marrajo and Sierra Larga a gradual change of facies takes place and cryptalgal laminites, typical of the lower member, are locally intercalated in the middle member (transitional facies). The laminites are thin

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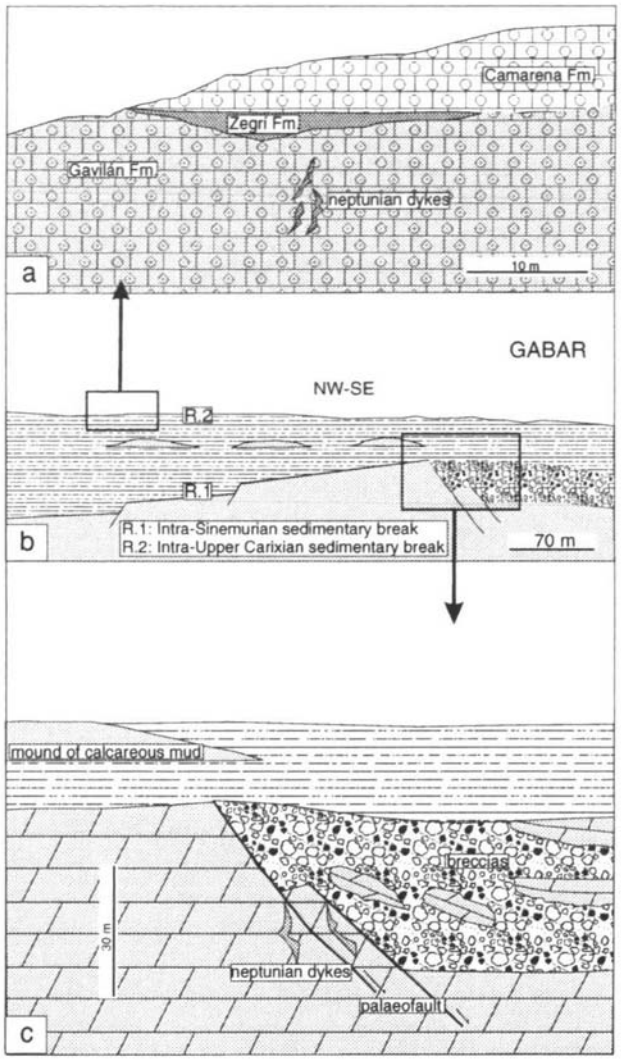


Figure 4. Generalized stratigraphic section (b) and details (a, c) showing the geometric relations between the Lias–Dogger genetic units at Monte del Gabar. (c) Palaeofault observed at the lower boundary of the J-2 unit (from Andreo *et al.* 1991).

layers, rarely exceed 20 to 30 cm in thickness, and are present within the small-scale cycles that are described below.

At Monte del Gabar, the lower member is affected by faults with throws exceeding 50 m (Figs 3, 4). Neptunian dyke systems, metres in height and tens of centimetres in width, penetrate the upper part of the lower member of the Gavilán Formation. Dyke walls display irregular and sharp fracture geometry. The fillings are reddish or yellow coloured micrites, and can sometimes include 'black pebbles' and clasts derived from the lower member of the Gavilán Formation. The middle member overlies a downfaulted block. Locally, covering this irregular surface, a polygenic breccia with angular clasts derived from laminite facies, 'black pebbles' and reddish-coloured micritic clasts, with thicknesses exceeding 30 m, can be distinguished (Figs 3, 4). Downlap morphologies are observed at the bottom. The *Lithiotis* limestones are onlapping both lower member and breccias.

In the northwestern Gabar outcrops, the middle member consists of approximately 100 m of mainly *Lithiotis* limestone, within which three genera of bivalves can be distinguished: (i) *Mytilus*: small shells with triangular sections; (ii) *Gervilleioperna*: centimetre-size shells with asymmetric morphology. One valve is fixed to the substrate, and is large, thick and convex. The free valve is flat and smaller and thinner than the fixed valve (Fig. 3a); (iii) *Lithioperna*: large organisms (over 10 cm) with very thick subrectangular shells. The inner cavity is small. Both isolated individuals and colonies occur (Fig. 3b).

In the middle member, six types of facies can be identified (B. Andreo, unpub. Lic. thesis, Univ. Granada, 1990; Rey *et al.* 1990; Rey, 1993). They occur in metre-scale cycles (Fig. 2), described here from bottom to top:

(a) *Calcarenitic facies*: Packstone to grainstone of ooids, peloids and bioclasts, with a rich association of benthonic foraminifera (lituolids) and remains of *Paleodasycladus mediterraneus* (PIA) (Fig. 3c). This facies is especially abundant in Gigante and Marrajo, but is poorly represented in Gabar. In adjoining areas, it occasionally displays herring-bone cross-stratification (B. Andreo, unpub. Lic. thesis, Univ. Granada, 1990).

(b) *Gastropod facies*: Basically gastropod packstone–wackestone. The gastropods are generally small (1–3 cm), but sometimes reach almost a decimetre.

(c) *Mytilus facies*: Usually thin micritic or fine calcarenitic layers with *Mytilus*. This facies, representing the lowest appearances of the *Lithiotis* limestones in most metre-scale cycles, can also contain gastropods.

(d) *Gervilleioperna facies*: Beds with a general thickness of several decimetres. They are usually composed of a monospecific assemblage of *Gervilleioperna*.

(e) *Lithioperna facies*: *Lithioperna* shells usually lie horizontally in accumulations with bioclasts and scant micrite sediment. Locally, they show evidence of slight reworking, which gave rise to rudstone and floatstone layers. The shells are sometimes lying at an angle which tends to increase upward, until they reach a perpendicular position with regard to the bottom of the deposit. This facies is well developed at Monte del Marrajo (Fig. 2), whereas at Monte del Gabar it only appears locally in the southern part.

(f) *Breccia facies with 'black pebbles'*: Calcareous breccia mainly consisting of 'black pebbles'. These are dark angular limestone clasts. Reddish-coloured clasts also occur.

In the *Lithiotis* limestones (middle member), the metre-scale cycles thicken upwards, with thicknesses varying between 1.5 and 2.5 m. Two basic types of small-scale cycles can be differentiated (Rey *et al.* 1990), constituted from bottom to top by facies a–b–c–d–e–f or by a–b–c–d–f (Fig. 2).

In Gabar area, at the top of the middle member, a continuous level of mud mounds overlies (Fig. 2) a layer rich in black pebbles. These mounds can reach 10 m in height and 40 m in extension. In the southeastern outcrops, the *Lithiotis* facies are almost absent, and mud mounds or the

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upper member of the Gavilán Formation lie directly on the lower member. Mud mounds are essentially made of massive grey micritic limestones. The skeletal elements preserved in the mound core (*Lithiotis*) are not abundant enough to form an interlocking framework. It consists of mudstone–wackestone with foraminifers (lituolids). Dense micrites commonly exhibit faint laminations and probable cyanobacterial remains. The flanking beds are made up of well-bedded fine-grained calcarenite strata. These flanking beds dip away from the massive core at low angles (less than 30°).

In other sections of the studied area, at Muela, Gigante and Sierra Larga, notable differences are found with respect to the above described Gabar and Marrajo sectors. At a few places (Muela and locally in Sierra Larga, Fig. 1a), the middle and upper members of the Gavilán Formation are absent and oolitic limestones of the Camarena Formation lie directly on the lower member of the Gavilán Formation (Fig. 5). In the Gigante outcrops (Fig. 1a), the *Lithiotis* limestones reach a thickness of 120 m. This member usually appears well stratified, and several different types of metre-scale cycles, often ending in removed levels, can be observed. It is usual to find insertions of oolitic and crinoid-rich grainstones, even showing cross-bedding and forming thinning-upward cycles (Fig. 5). In the Maimón area (Fig. 1a), a lag occurs directly on the lower member, in a layer with reworked bivalve fragments (B. Andreo, unpub. Lic. thesis, Univ. Granada, 1990).

North of Vélez-Rubio, the upper member (M.3) is only exposed at Monte del Gabar, Monte del Marrajo and locally in the Gigante. This member is up to 20 m thick and is formed by calcarenites composed mainly of crinoidal grainstone with well-developed syntaxial rim cements. Associated bioclasts are molluscs and agglutinated foraminifers.

In the Marrajo area (Fig. 2), this third member has particular characteristics that can vary in the different sectors. There are sometimes coral colonies in the upper part of the calcarenites which are rich in crinoids and bentonic foraminifers. In the southeast Marrajo outcrops, these calcarenites pass laterally over a short distance into wackestone with crinoid fragments, chert nodules and sponge spicules, that reach a thickness of some 50–60 m.

2.b.2. Interpretation

Facies interpretations and sedimentary models are based on recent stratigraphic studies (Rey *et al.* 1990; Andreo *et al.* 1991; Rey, 1993). In the calcarenitic facies of the middle member of the Gavilán Formation, the presence of cross-stratification, as well as the absence of a matrix, point to deposition in high-energy environments within the platform. The Gigante section contains fining-upward levels of this facies with an eroded base. These correspond to tidal channel infills.

The textures of the gastropod and *Mytilus* facies indicate low-energy depositional environments, in the inner platform zone (Rey *et al.* 1990). The *Gervilleioperna* facies display occasional floatstone and rudstone layers explainable as small patch reefs or as lag associated with tidal channels, depending on whether shells maintain life positions or not. At times, these shells appear suspended in a micritic matrix, a fact attributable to a low-energy environment, possibly a lagoon. The *Lithioperna* must have formed parts of small patch reefs in high-energy areas of the platform, where they co-existed with corals. Given the increase in this type of *Lithiotis* limestones vertically within the small-scale cycles, it would seem that *Lithioperna* adapted better than *Gervilleioperna* to a rise in sedimentation rate (Rey *et al.* 1990). The breccia facies with 'black pebbles' tend to be associated with hardened levels linked to edaphic phenomena in high-tidal areas (Strasser & Davaud, 1983; Vera & Jiménez de Cisneros, 1993). Usually the facies is separated from the *Lithioperna* or the *Gervilleioperna* facies by an erosive surface. In this case, it is considered as lag fill-in of tidal channels in intertidal domains.

The facies types of the middle member of the Gavilán Formation are organized in metre-scale shallowing-upward cycles, ending in brief emergence, as indicated by the presence at the top of the black pebbles, hardened surfaces and even edaphic levels. They could have been conditioned by climatic factors, possibly connected with Milankovitch's astronomical cycles (fourth order; 0.1 Ma; see, e.g. Tucker & Wright, 1990). They are superposed on one of the third-order parasequence sets which are discussed in Section 3.

Mud mounds, like most low-energy facies, are formed in quiet water environments. An inner–outer platform transitional zone can be inferred from the fossil content and the sedimentological criteria reported in the encasing facies.

Comparing calcarenites of the upper member of the Gavilán Formation with those in other Alpine cordilleras (Arnaud-Vanneau *et al.* 1992; Hunt & Tucker, 1993) leads to the interpretation that they are deposits of an outer carbonate platform, under shallow and turbulent waters. In the Marrajo area, the wackestone with crinoid fragments, chert nodules and sponge spicules was most probably deposited in a deep part of the outer platform, in relatively quiet waters below the storm wave base level.

3. Sequential analysis

The J-2 genetic unit is bounded at its base and top by the intra-Sinemurian and intra-Upper-Carixian sedimentary breaks, respectively.

A palinspastic reconstruction of an isolated platform north of Vélez-Rubio is given in Figure 5. Three parasequence sets, in the sense of Van Wagoner *et al.* (1988), can be identified.

3.a. Progradational parasequence set ('lowstand systems tract')

In carbonate environments, relative sea-level changes exert a strong control over sediment production and dispersal.

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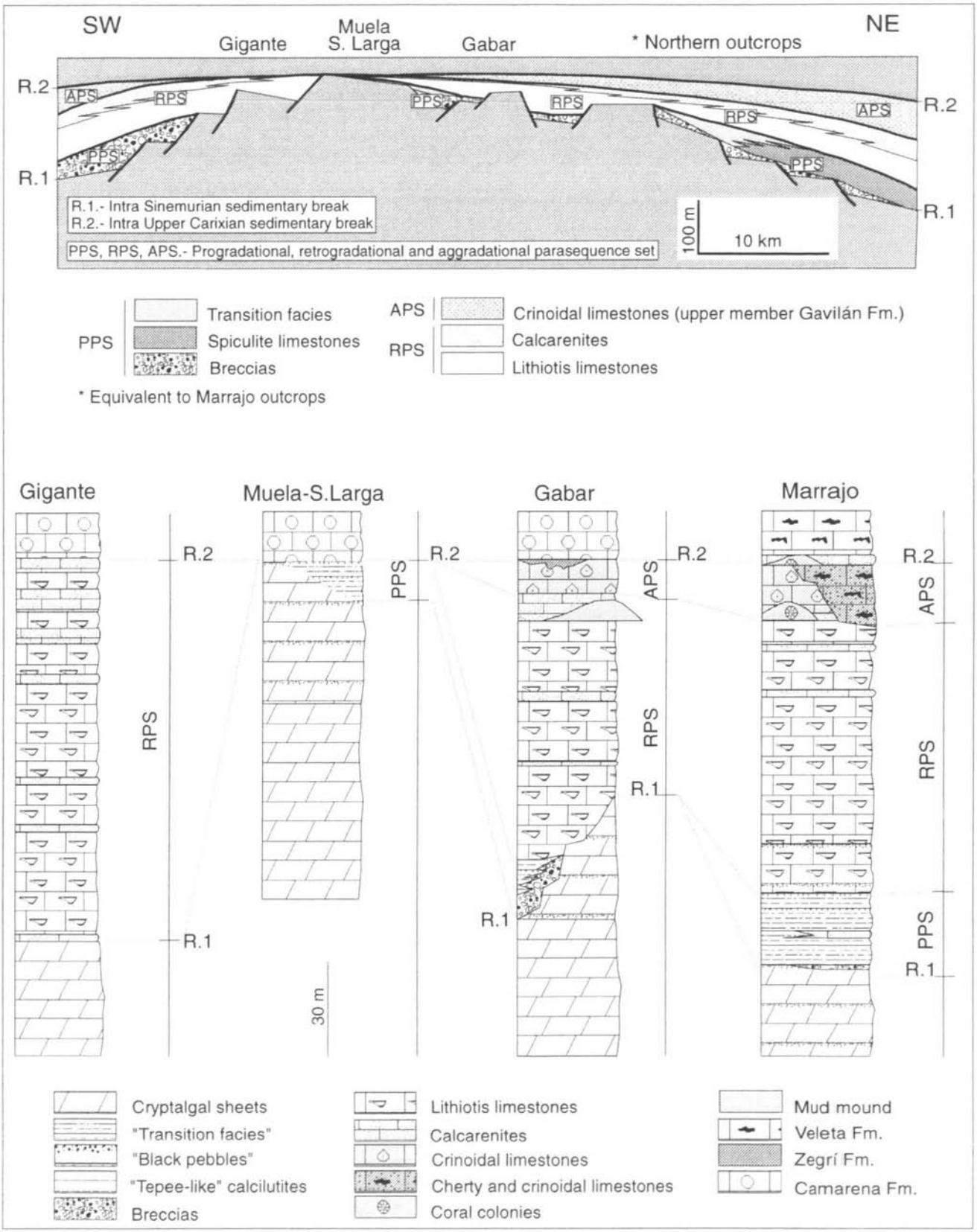


Figure 5. A model for the evolution of the Lias isolated platform in the Vélez-Rubio area (from Rey, 1993). Palinspastic reconstructions indicate that the localities mentioned were located as shown in the section. The aim is only to propose a model with approximate distances and directions.

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Reduced sedimentation and subaerial exposure foster the retreat of shelf edges and slopes by erosion and slope failure during lowstands. As a result, thick mechanical reworking deposits may form (see, e.g. Sarg, 1988; Hunt & Tucker, 1993; Handford & Loucks, 1993).

This parasequence set is only locally represented in the sector studied (PPS in Fig. 5), which is interpreted as the result of deposition on an irregular relief, controlled by tectonics. It only appears locally in Sierra Larga and in Gabar, but is somewhat better represented in Monte del Marrajo, where it is considered to be the margin of the isolated platform. It is composed of the transition facies between the lower and middle members of the Gavilán Formation, and locally of reworked facies (breccias). The identification of the strata as belonging to this parasequence set is justified as follows:

(a) Their position in the genetic unit: they are the first levels above the intra-Sinemurian sedimentary break (lower boundary of the genetic unit).

(b) Morphology: discontinuity morphologies are characteristics of this systems tract in carbonatic platforms (see, e.g. Sarg, 1988; Arnaud-Vanneau *et al.* 1992; Handford & Loucks, 1993).

(c) Structures: downlap structures, which are characteristic of periods of progradation (Van Wagoner *et al.* 1988), have been observed associated with the breccias (lower part) in the southeastern Gabar outcrops (see Fig. 4).

(d) Facies: may be associated with redeposition (breccias in the southeastern Gabar outcrop), common in this parasequence set (see, e.g. Sarg, 1988; Hunt & Tucker, 1993; Handford & Loucks, 1993).

(e) Facies associations: there are calcarenitic facies, characteristic of open environments (outer platform), associated in the same small-scale cycles with cryptalgal laminites (commonly found in inside sectors of inner platforms). These associations are compatible with small platforms, developed during lowstand periods (Arnaud-Vanneau *et al.* 1992).

(f) Correlation with other sectors: downlap structures have been recorded for equivalent parasequence sets in nearby areas (Sierra de Ponce sector: Rey, 1993).

3.b. Retrogradational parasequence set ('transgressive systems tract')

This usually rests directly on the preceding genetic unit (J-1: Rey, 1993). Locally in the Maimón area, a transgressive lag occurs in a layer with reworked bivalve fragments. This parasequence set consists of the *Lithiotis* limestones of the middle member of the Gavilán Formation (RPS in Fig. 5). Their identification is justified as follows:

(a) The position in the genetic unit: above the previous parasequence set.

(b) Body morphology: onlap morphology has been observed in the Gabar area (Fig. 3), which is characteristic of periods of retrogradation (Van Wagoner *et al.* 1988).

(c) Facies associations: the vertical evolution of the parasequence set reveals generally confined *Lithiotis* facies that are substituted by calcarenites characteristic of outer, high-energy platform conditions, suggesting retrogradation phenomena (see, e.g. Sarg, 1988; Handford & Loucks, 1993).

(d) Correlation with other sectors: in the Sierra de Ponce, east of the study area, Rey (1993) recognized retrogradational features, which agree with the proposed stacking pattern of this parasequence set on the isolated platform.

3.c. Aggradational parasequence set ('highstand systems tract')

This unit is composed of the calcarenites of the upper member of the Gavilán Formation. It is poorly developed north of Vélez-Rubio and can be wholly absent in places (APS in Fig. 5). The identification of this parasequence set is justified as follows:

(a) The position in the genetic unit: over the above parasequence set and prior to the intra-Upper-Carixian sedimentary break (upper boundary of the genetic unit).

(b) Absence of vertical facies changes: indicates equilibrium between the accommodation space and deposition rate (bodies do not migrate laterally, increasing instead vertically), common in this parasequence set (see, e.g. Sarg, 1988; Arnaud-Vanneau *et al.* 1992; Handford & Loucks, 1993).

(c) Facies interpretation: the upper member of the Gavilán Formation has been deposited in open, high-energy areas of the platform. In other alpine domains, equivalent calcarenites are very common during aggradational parasequence sets of highstand periods (see, e.g. Arnaud-Vanneau *et al.* 1992; Hunt & Tucker, 1993; Handford & Loucks, 1993).

(d) Absence of elemental sequences: indicates lack of lateral zoning, which suggests larger platforms, characteristic of this parasequence set (Hunt & Tucker, 1993).

(e) Correlation with other sectors: correlatable lithologies in nearby areas have been described as belonging to a highstand systems tract (Sierra de Ponce: Rey, 1993).

4. Tectonics

Sequence stratigraphic models of passive continental margins consider the subsidence history as a linear and continuous process across the basin (Posamentier, Jervey & Vail, 1988). As a consequence, variations in the accommodation are considered to be produced by superimposed eustatic fluctuations. However, a tectonic mechanism may have the potential to explain the increasing or reducing accommodation space (see, e.g. Aurell, 1991; Pedley & Grasso, 1991; Aurell & Meléndez, 1993; Frostick & Steel, 1993; Graciansky *et al.* 1993; Loup, 1993). In the Digne area (southeast France), the early and middle Jurassic stratigraphic succession has been subdivided into 37 third order depositional sequences (Graciansky *et al.* 1993). They can be grouped into four transgressive–

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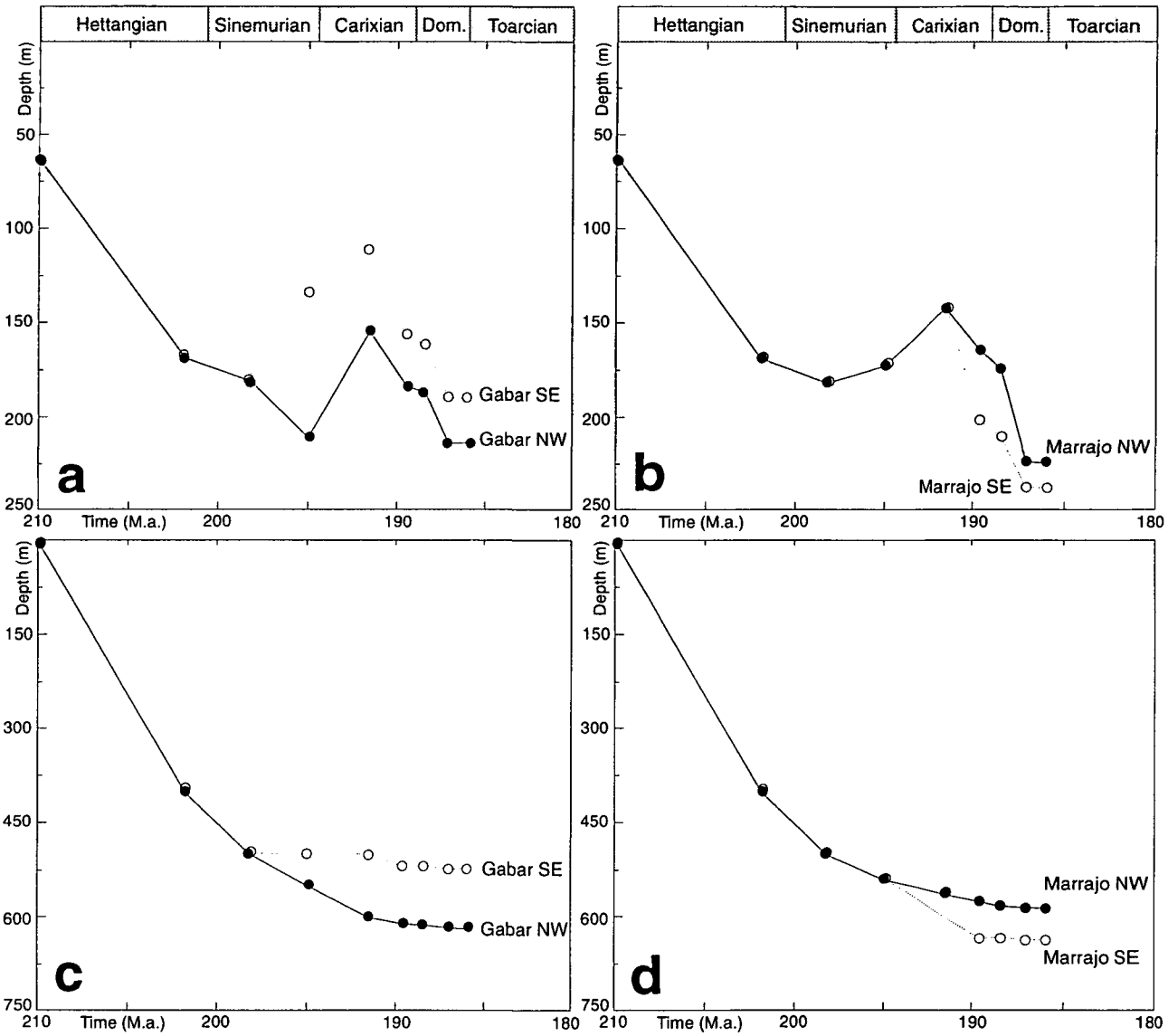


Figure 6. Backstripped subsidence plots. (a) Tectonic subsidence curves of the southeast and northwest Gabar sections. (b) Tectonic subsidence curves of the southeast and northwest Marrajo sections. (c) Total thickness of the southeast and northwest Gabar sections. (d) Total thickness of the southeast and northwest Marrajo sections. See text for discussion.

regressive cycles controlled by the successive phases of extension and subsidence that are related to Tethyan rifting. The episodes of extension and block faulting are coeval with second-order regressions. Each extensional episode has been followed by regional subsidence that appears to be the cause of the transgressive phases. Thus, the important role of the regional or local tectonics cannot be ignored.

4.a. Field data

The evidence for tectonically controlled Liassic sedimentation north of Vélez-Rubio is based on the following criteria:

(i) The sudden changes in thickness in the middle member of the Gavilán Formation across the different outcrops reflect asymmetry in basin subsidence. In the Vélez-Rubio area, the thickness of the J-2 genetic unit changes laterally over short distances (see Figs 5, 6c, d).

(ii) The substantial lateral changes of facies between the northwest–southeast Gabar successions also suggest the presence of a highly uneven palaeorelief after the intra-Sinemurian sedimentary break, with restricted low-energy environments close to others of higher energy. In the upper member at Marrajo, prior to the intra-Upper-Carixian sedimentary break, there are also abrupt lateral facies changes interpretable as being due to local synsedimentary tectonics.

(iii) Numerous faults can be observed or inferred: at Monte del Gabar, fractures affecting the lower member are synsedimentary normal faults with throws exceeding 50 m (Figs 4, 5). The movement of these palaeofaults, as well as of others related to the intra-Sinemurian sedimentary break (R.1), caused a very irregular relief in the

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platform. This occurrence affected not only the thickness of the middle member, but also the facies distribution within the platform. The *Lithiotis* associations are different on either side of the palaeofaults in Gabar, reflecting more-or-less confined sedimentary environments.

(iv) The occurrence of sedimentary break, which involved increased erosion on the uplifted components of fault blocks. Redeposited facies have been described in the Gabar (Fig. 4).

(v) Neptunian dykes: the rectilinear geometry of many of these structures as well as their relation to the sedimentary breaks lead us to associate them directly with palaeofaults or palaeodiaclases (Rey, 1995*b*).

4.b. Geohistorical analysis

Geohistorical analysis based on field data has allowed us to determine the subsidence rates. To ascertain solely the value of the tectonic subsidence, calculations were made to eliminate the effect of the sediment load, the water column and the eustatic variations that presumably occurred from time to time. This technique is known as backstripping (see Allen & Allen, 1990), and to carry it out, a series of corrections must be included, such as material compactness, palaeobathymetry and eustasy.

For decompaction analysis, the porosity must be known (both on the surface and at depth), as well as the depth at which each group of materials occurred for the different time intervals (the loss of porosity as a function of depth). In this sector, the surface porosity can be calculated by petrographic methods. Nevertheless, the first difficulty appears when making estimates on the porosity at depth since that can only be determined by boring and then only when downhole electrical logs are carried out (sonic, neutron or density), data that are unavailable for this region. To this must be added the fact that it is impossible to determine the overlying lithological column that the various sediments withstood at each point in time. On one hand, the thickness of the different lithostratigraphic units varies considerably for the Mesozoic and Cenozoic in the distinct outcrops. To these synsedimentary difficulties must be added the emplacement tectonics: the Betic Cordilleras have a very complex structure in which it is not easy to recognize the superposition of thrusts (which would increase the thickness) undergone by rocks now visible at the surface.

All these limitations discourage carrying out the decompaction analysis, as they have for other authors as well (P. A. Ruiz-Ortiz, unpub. data, 1990; Rey, 1993; Rey, 1995*a*). Nevertheless, the subsidence curves obtained with 'complete' or 'partial' corrections are still very similar. The amplitude of the curves may change but their overall shape is preserved (Loup, 1993).

Figure 6 shows the subsidence curves for the sectors considered in this work. They were obtained after applying the correction of Bond & Kominz (1984) to the preliminary data given in Table 1. According to these authors, the tectonic subsidence (Yd) can be expressed as

$$\mathrm{Yd} = \Phi\left\{S\left(\frac{\rho m - \rho s}{\rho m - \rho w}\right) - slv\left(\frac{\rho w}{\rho m - \rho w}\right)\right\} + (\mathrm{Wd} - \mathrm{slv})$$

where Φ = basement (function) response (using the local Airy isostatic model, the value of Φ is equal to unity); S = accumulated sediment thickness (not decompacted and determined from the base of the Gavilán Formation); ρm = mantle density taking the value 3.33 gr/cm^3; ρs = density of sedimentary cover taking the value 2.71 gr/cm^3; ρw = density of sea-water taking the value 1.03 gr/cm^3; slv = eustatic variations with respect to reference level (position of sea-level in the Upper Carixian); the eustatic curve of Haq, Hardenbol & Vail (1988) has been used; Wd = palaeowaterdepth, estimated from the analysis of the different facies.

The geohistorical analysis, and particularly the backstripping (in spite of its limitations in this region), reveal quite significant mechanical subsidence for the Lower Liassic. Due to possible errors in constructing the tectonic geohistory curves (e.g. compactation, sea-level changes, depositional water depth), the curves obtained have no quantitative value; in spite of that, they do offer qualitative information. Thus, the subsidence graphs show different behaviour for the time interval located between the intra-Sinemurian break and the intra-upper Carixian break in the sectors considered.

The Marrajo and Gabar areas (Fig. 6a, b) are of interest because of the completely different and more complex subsidence pattern exhibiting two main rapid phases: the first in the Sinemurian, and the second during the Upper Carixian.

For the intra-Sinemurian break, in the Gabar outcrops, the salient feature is the opposite trend of the curves, with negative (uplift) and positive subsidence in the southeast and northwest sectors, respectively (Fig. 6a). These variations, caused by tilting of blocks, are higher than the eustatic changes proposed by Haq, Hardenbol & Vail (1988) for this interval of time.

For the intra-Upper-Carixian sedimentary break, abrupt changes in mechanical subsidence rates have been calculated in the Marrajo outcrops (Fig. 6b).

The comparison between the positions of the sedimentary breaks recognized in a basin and those proposed as of global origin (see Exxon curves; Haq, Hardenbol & Vail, 1988) can yield some idea of the interplay of the eustasy and subsidence, creating accommodation. This tool has been used in the Iberian Chain (Spain) by Aurell (1991) and Aurell & Meléndez (1993), and in the Venetian Alps (Italy) by Zempolich (1993), among others.

The eustatic role in the lower boundary of the genetic unit would be denoted by the 'possible coincidence' between the Intra-Sinemurian sedimentary break recorded north of Vélez-Rubio and those proposed in the Exxon curves (UAB-3.1 and UAB-3.2 boundary third-order cycles) (unfortunately, the biostratigraphical control is not sufficiently precise; see Rey *et al.* 1990). However, tectonic reactivation of basement faults, occur-

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Table 1. Parameters for geohistory analysis

Age (Ma)	S (m)	Slv (m)	Wd (m)	Yd
Northwest Gabar				
211	0	–40	5	62.4
202	400	–44.5	1	171.66
198	500	–30.5	1	178.26
195	550	–16.5	40	210.67
191	600	8.3	5	153.3
189	610	2.5	20	179.29
188	610	0	20	182.87
187	612	–5.5	40	211.29
186	612	–5.5	40	211.29
Southeast Gabar				
211	0	–40	5	62.4
202	400	–44.5	1	171.66
198	500	–30.5	1	178.26
195	500	–16.5	–20	137.32
191	500	8.3	–10	111.59
189	520	2.5	20	155.26
188	520	0	20	158.84
187	522	–5.5	40	187.26
186	522	–5.5	40	187.26
Northwest Marrajo				
211	0	–40	5	62.4
202	400	–44.5	1	171.66
198	500	–30.5	1	178.26
195	540	–16.5	5	173
191	560	8.3	5	142.62
189	570	2.5	20	168.61
188	580	0	20	174.86
187	581	–5.5	60	223.02
186	581	–5.5	60	223.02
Southeast Marrajo				
211	0	–40	5	62.4
202	400	–44.5	1	171.66
198	500	–30.5	1	178.26
195	540	–16.5	5	173
191	560	8.3	5	142.62
189	630	2.5	40	204.62
188	630	0	40	208.2
187	631	–5.5	60	236.37
186	631	–5.5	60	236.37

S – accumulated sediment thickness; Slv – eustatic fluctuations in relation to a reference level (Upper Carixian); Wd – palaeowaterdepth; Yd – correction to obtain the tectonic subsidence (see text).

ring during the Sinemurian, implies a predominant role of tectonic subsidence in creating the larger accommodation space (see Fig. 6a).

The intra-Upper-Carixian sedimentary break, which represents the transition from shallow platform lithofacies to pelagic lithofacies, can be correlated with UAB-3 and UAB-4 second-order cycles in the Exxon curves. However, mechanical subsidence is present as well (see Fig. 6b). If this phenomenon were more pronounced in the intra-Upper-Carixian sedimentary break, then some sectors of this isolated platform could have emerged while others were submerged to great depth, thereby favouring the creation of troughs and pelagic swells that are typical of the post-Carixian Jurassic period in the External Zones of the Betic Cordilleras (García-Hernández *et al.* 1980).

Analysis of these graphs reveals the fundamental role of regional tectonics in the palaeogeographic evolution of this domain. As the tectonic factor could have been more important than the eustatic changes, it seems inappropriate to consider the middle and upper members of the Gavilán Formation together as a depositional sequence in the sense of Vail, Mitchum & Thomson (1977); Posamentier, Jervey & Vail (1988); Sarg (1988); Van Wagoner *et al.* (1988); Haq (1991) or Vail *et al.* (1991). It has recently been found, based on different examples in the External Zones of the Betic Cordilleras, that the local or regional tectonic regime has controlled the history and limits of the distinct genetic units in this region (Rey, 1995*a*,*b*).

5. Conclusions

The middle and upper members of the Gavilán Formation near Vélez-Rubio are interpreted as carbonate platform deposits. The evolution of the parasequence sets in the area (progradations northwards) and the development of deeper sedimentation in its northern outcrops (Rey, 1993), suggest that this platform was isolated with regard to the South Iberian Margin. Three parasequence sets can be identified from bottom to top (Fig. 5):

(i) Progradational parasequence set, basically composed of the transitional facies between the lower and middle member. It is only locally present.

(ii) Retrogradational parasequence set, consisting of the middle member, the *Lithiotis* limestones. An uneven palaeorelief at its base indicates a discontinuous deposit.

(iii) Aggradational parasequence set, basically composed of the crinoidal limestones of the upper member. The thickness of this parasequence set increases towards the outer parts of the platform.

Regional tectonics played an important role in the control of the distribution of the parasequence sets. The presence of palaeofaults affecting the lower member of the Gavilán Formation, the sudden thickness and facies variations in the middle and upper member, the presence of neptunian dykes, redeposition and geohistorical analysis demonstrate that the tectonically induced palaeorelief was probably more important in the evolution of this platform than eustasy.

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