Int J Earth Sci (Geol Rundsch) (2006) 95: 815–826
DOI 10.1007/s00531-005-0061-7

ORIGINAL PAPER

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Tectonic framework and extensional pattern of the Malaguide Complex from Sierra Espuña (Internal Betic Zone) during Jurassic–Cretaceous: implications for the Westernmost Tethys geodynamic evolution

Received: 15 June 2005 / Accepted: 11 November 2005 / Published online: 13 January 2006

Abstract Mapping, lithostratigraphic, biostratigraphic and structural detailed analyses in Sierra Espuña area (Internal Betic Zone, SE Spain) have allowed us to reconstruct the Jurassic–Cretaceous evolution of the Westernmost Mesomediterranean Microplate palaeomargin and, by correlation with other sectors (Northern Rift, central and western Internal Betic Zone), to propose a geodynamic evolution for the Westernmost Tethys. Extension began from Late Toarcian, when listric normal faults activated; these faults are arranged in three categories: large-scale faults, separating hectometric cortical blocks; main faults, dividing the former blocks into some kilometre-length blocks; and secondary faults, affecting the kilometric blocks. This fault ensemble, actually outcropping, in the Sierra Espuña area, broke the palaeomargin allowing the westerly Tethyan Oceanic aperture with an extension at about 17.2%. Extension was not homogeneous in time, being the Late Toarcian to the Dogger–Malm boundary the period when blocks underwent the greatest movement (rifting phase), leading to the drowning of the area (8.2% extension). During the Malm (drifting phase) extension followed (5.7%), while during the Cretaceous a change to pelagic facies is recorded with an extension of about 3.3% (*post-drift* stage). This evolution in the Westernmost Tethys seems to be related to areas out of the limit of significant crustal extension in the hanging wall block of the main cortical low-angle fault of the rifting.

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Keywords Westernmost Tethys oceanic opening · Jurassic–Cretaceous · Normal fault categories · Extensional rates · Palaeomargin

Introduction

After the Hercynian orogeny, the western part of the present Mediterranean region was part of a coherent continental block called Pangea, comprising Africa, Europe and North America (Channell et al. 1979; Winterer and Bosellini 1981) with the oceanic regions being constrained to the eastern region (palaeo-Tethys). Starting from the Triassic, the Central Atlantic Ocean began to open, and the western Mediterranean region was fragmented by rifting and transform faulting, giving rise to the Western Tethyan Ocean, and several new lithospheric plates (Biju-Duval et al. 1977). One of these lithospheric plates was the Mesomediterranean Microplate (Guerrera et al. 1993), comprising the internal zones of the Betic–Rif, Tellian, Kabylian, Calabria–Peloritani and Southern Apennine chains, built up after the alpine compressive Tertiary phase related to the Mediterranean opening. In the Westernmost Tethys a complicate palaeogeography with junction of two oceanic branches occurs (Guerrera et al. 2005). These branches (Nevado-Filábride Ocean to the North and Maghrebian Flysch Basin to the South) would separate three continental margins (S-Iberian, N-African and W-Mesomediterranean Microplate margin, respectively).

The evolution of the Westernmost Tethyan area is closely related to the Betic–Rif Cordillera (Fig. 1). This mountain belt has classically been divided into Internal and External Zones separated by the western Tethyan (Nevado-Filábride Ocean of Guerrera et al. 2005) oceanic aperture since Early Jurassic (Martín-Algarra 1987). The External Zones belong to the South Iberian Palaeomargin (Vera 1988) and consist of post-Palaeozoic non-metamorphic rocks. On the contrary, the Internal Betic–Rif Zone is nowadays built up by the

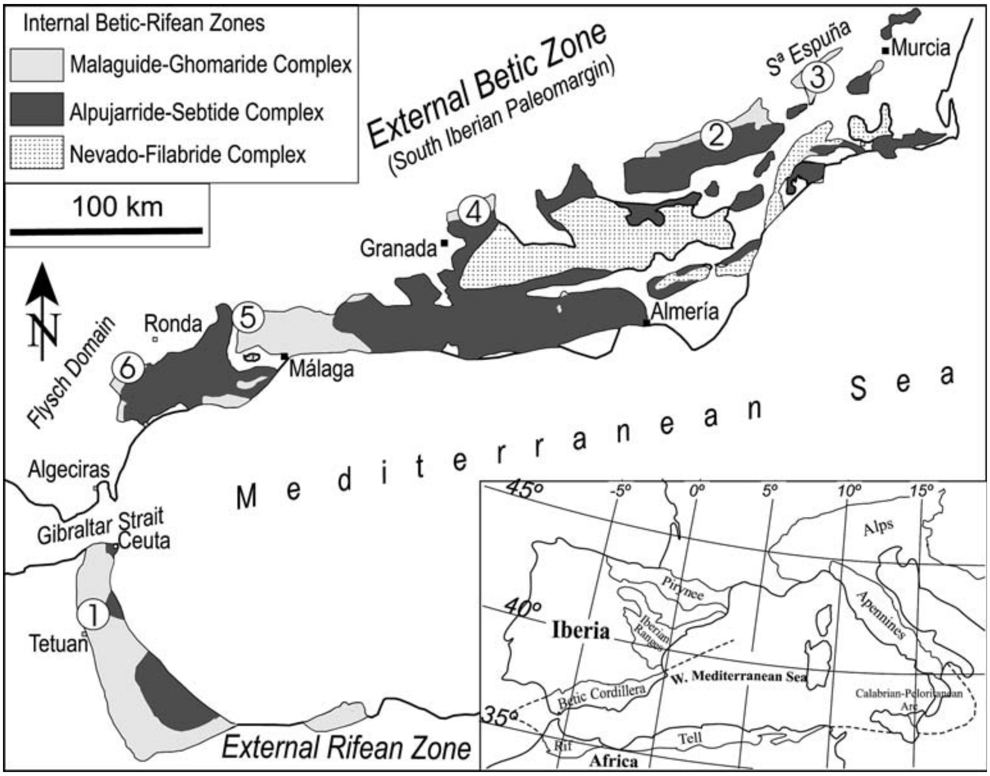

Fig. 1 Geologial sketch of the Western Mediterranean Alpine Chains (*lower*) and geological map from the Betic–Rifean Internal Zones (*upper*) with the location of the six areas correlated in Fig. 8: *1* Ghomaride from Northern Rif, *2* Vélez Rubio, *3* Sierra Espuña, *4* Sierra Arana, *5* Turón-Ardales, *6* Convento-Nieves (Robledo like units)

stacking of three complexes, called from bottom to top: Nevadofilabride, Alpujarride–Sebtide and Malaguide–Ghomaride (Martín-Algarra 1987). The Nevadofilabride and Alpujarride units are composed mainly of Palaeozoic and Triassic metamorphic rocks, while the Malaguide–Ghomaride Complex includes very low-grade Palaeozoic metamorphic rocks and a Meso-cenozoic sedimentary cover. In general, the scarcity of Jurassic non-metamorphosed successions, and the intense poliphasic tectonics have hampered a detailed description of the geodynamic evolution of the Jurassic in the Internal Zones.

The Malaguide–Ghomaride is the uppermost (and, consequently, the most internal) complex of the Internal Zones (coming from the south-eastern part of the Western Tethys). This Complex outcrops mainly from the Malaga Province (westward) to the Murcia Province (eastward) in the Betics and in the northern Rif (Morocco; Maaté 1996). Contrary to the Alpujarride and Nevadofilabride units, the Malaguide–Ghomaride Complex includes post-Triassic sedimentary covers, and thus can be considered the clue for recognizing the Mesozoic evolution of the Internal Betic Zone. The Sierra Espuña area, in the Murcia Province (southern Spain), is probably the most extensive, less deformed and best exposed Jurassic–Cretaceous outcrop belonging to the Malaguide–Ghomaride Complex in the Internal Betic–Rif Chain.

Studies of Mesozoic rifting on carbonate platforms usually focus on facies association (Wilson 1975; Schlager 1981; Kendall and Schlager 1981; Read 1985; James and Mountjoy 1983; McIlreath and James 1984; Santantonio 1993, 1994; Zempolich 1993), on the analysis of syntectonic deposits, or on subsidence (Wintered and Bosellini 1981; Martire 1996; Boutakiout and Elmi 1996; Hanne et al. 2003; Ruiz-Ortiz et al. 2004). Recently, papers on geometric and analogical model of rifting faulting (Dula 1991; Darros de Matos 1993; Withjack and Peterson 1993) based on seismic data have also been published. Nevertheless, deformational-pattern analyses on Jurassic outcropping are scarce in the literature.

In the present paper, we analyse the Jurassic–Cretaceous outcropping from the Sierra Espuña area, improving the stratigraphic, biostratigraphic and structural framework, in order to clarify, for the first time, the complete geodynamic evolution and the stretching deformational pattern of this passive margin, and to provide a correlation with other Malaguide–Ghomaride successions from the Internal Betic–Rif Zone, providing a regional model for the Jurassic–Cretaceous geodynamic evolution of the western Tethyan oceanic opening.

Geographical and geological settings

The Sierra Espuña area, located in the Murcia Province (Fig. 2a), belongs to the Malaguide Complex (Internal Betic Zone). The Malaguide units outcropping in the study area bounds tectonically with the Alpujarride Complex to the SE, and with the External Betic Zones (Subbetic) to the NW. Two Malaguide tectonic units

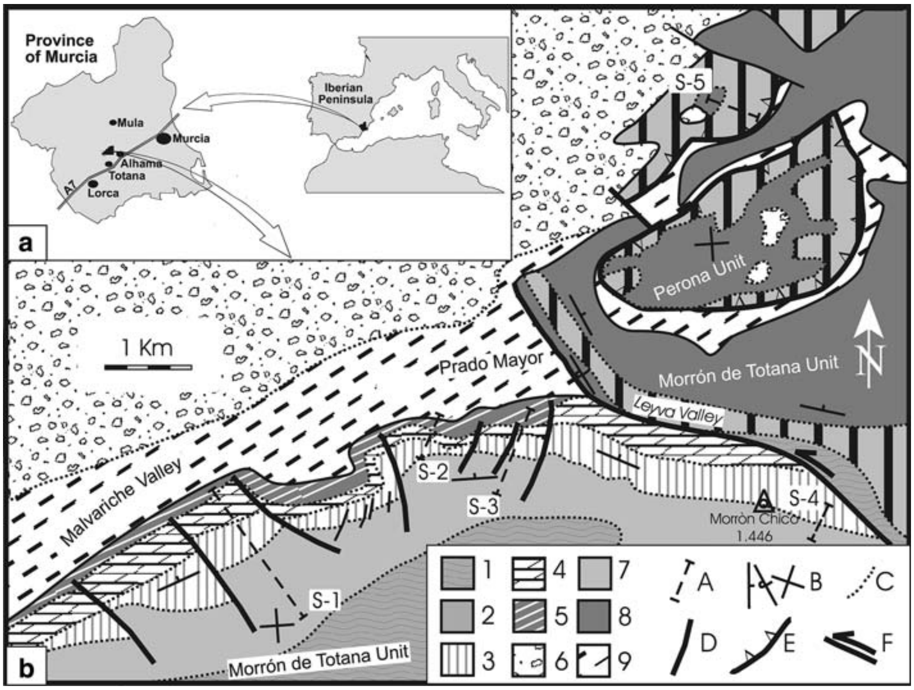

Fig. 2 Geographical (*upper*) and geological (*lower*) maps with the location of the five studied sections in Sierra España: Malvariche (S-1), Tres Carrascas (S-2), Prado Mayor (S-3), Morrón Chico (S-4) and Perona (S-5). Key: Morrón de Totana Unit (*1* Triassic, *2* Liassic, *3*Dogger, *4* Malm, *5* Cretaceous. *6* Paleogene); Perona Unit (*7* Dolomitic Liassic, *8* Calcareous Liassic), *9* Late Oligocene–Aquitanian post-thrusting; *A* Jurassic studied section (S-1 to S-5), *B* Bedding, *C* Stratigraphic contact, *D* Listric fault, *E* Thrust, *F* Strike–slip fault

(Fig. 2b) have been defined in Sierra Espuña (Martín-Martín and Martín-Algarra 1997): Morrón de Totana unit (lower) and Perona unit (upper). Both units include a Jurassic to Tertiary sedimentary cover, although in the Perona Unit only outcrops of Liassic p.p. and Tertiary sediments with a reduced extension are recognized. In the Morrón de Totana unit, the Jurassic to Tertiary succession is well exposed, outcropping with lateral continuity along more than 10 km (Fig. 3) over a Palaeozoic to Triassic succession, especially from the Prado Mayor area, in the E, to the Malvariche Valley area, in the W. The structural analysis shows a first-folding phase antiformal (Fig. 4; Espuña fold from Lonergan 1991) affecting the whole succession (Martín-Martín and Martín-Algarra 1997). The northern limb of this fold reveals the bedding of continuous Jurassic to Tertiary successions with a sub-vertical disposition (Fig. 3), favouring structural analysis by maps and

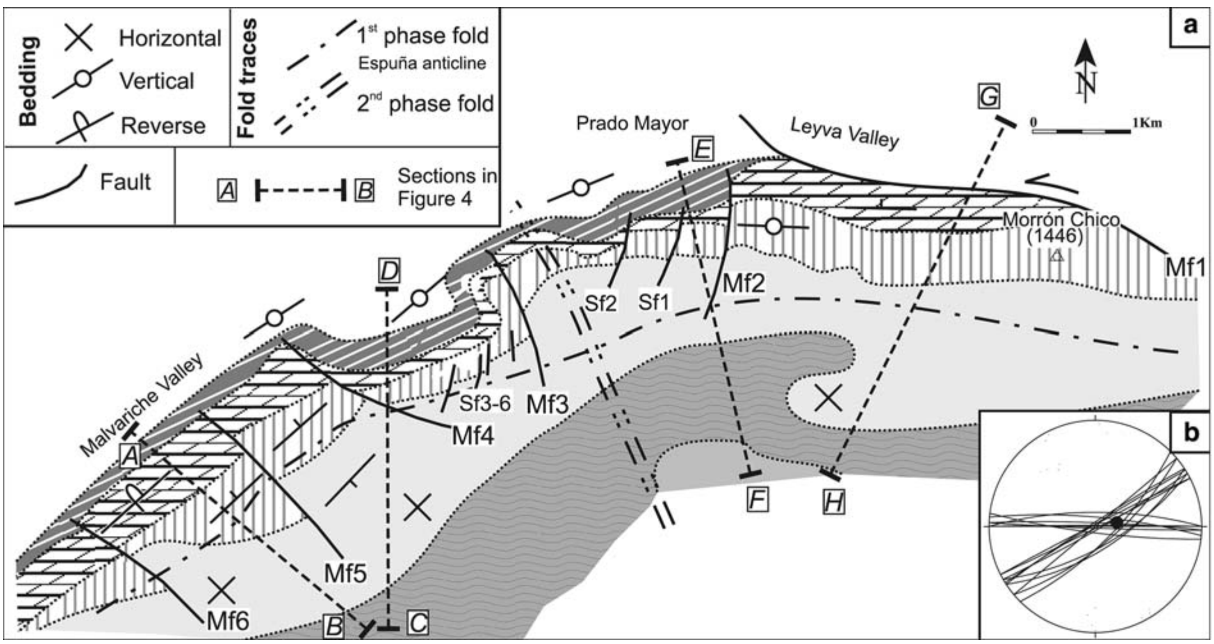

Fig. 3 **a** Detailed geological map from the Morrón Chico to Malvariche areas with location of geological sections from Fig. 4. **b** Stereoplot of bedding showing the second phase fold axes. *Hatches* as Fig. 2

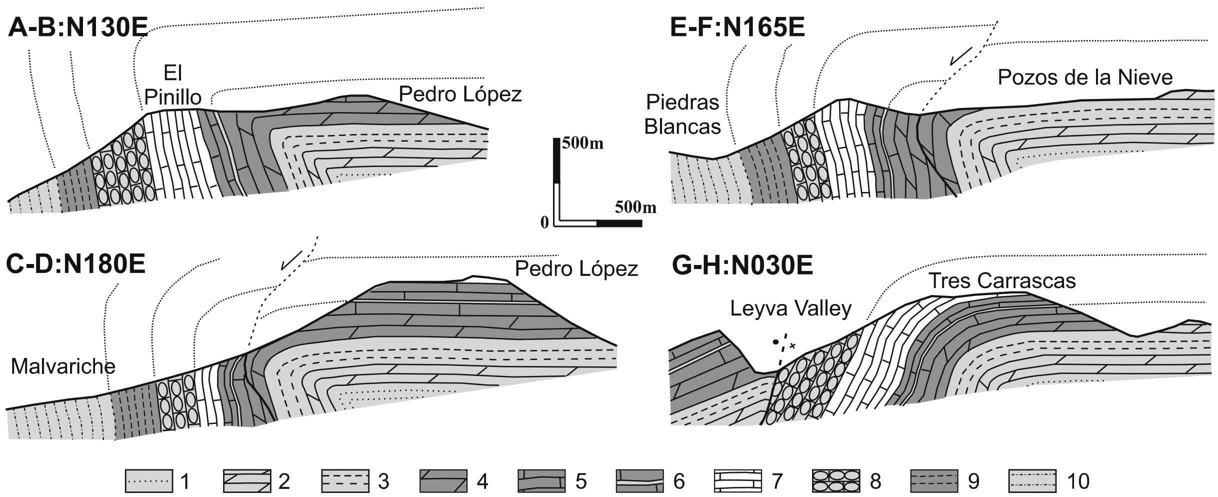

Fig. 4 Geological cross sections. Key: *1* middle Triassic sandstones, *2* middle Triassic limestones and dolostones, *3* late Triassic clays with gypsum, *4* early Liassic dolostones, *5* Liassic limestones, *6* Domerian Fe-rich level, *7* Dogger limestones, *8* Malm nodular limestones, *9* Cretaceous, *10* Tertiary

aerial photos. An open, sub-vertical axis syncline affecting the entire study area constitutes a second-phase fold, producing a Type 2 interference pattern (Ramsay and Hubbert 1987). Both folding phases have been ascribed to lower Miocene by Martín-Martín and Martín-Algarra (1997).

In this area, the structural features and five stratigraphic sections (spaced 2–5 km from each other in a W–E direction) were analysed. Except for the pioneer work by Fallot (1929), the main papers on the Mesozoic of Sierra Espuña are from the 1960s and 1970s (Peyre and Peyre 1960; Mac Gillavry et al. 1963; Navarro and Trigueros 1963; Paquet 1962, 1969; Geyer and Hinkelbein 1971, 1974; Kampschuur et al. 1974; Seyfried 1978 among others). Recent studies have been made on the biostratigraphy and the palaeogeographic evolution of the Jurassic–Cretaceous series of Sierra Espuña (Caracuel et al. 2001, 2005; Martín-Rojas et al. 2002).

Remarks on the palaeoenvironmental evolution of the Malaguide Complex in Sierra Espuña

Five more-or-less complete stratigraphic Jurassic sections were studied in Sierra Espuña: Malvariche (S-1), Tres Carrascas (S-2), Prado Mayor (S-3), Morrón Chico (S-4) and Perona (S-5) from Figs. 2, 5 to 6. The sections homogeneously cover the Jurassic from the Sierra Espuña area, enabling us to propose a synthetic stratigraphic column (Fig. 5). Biostratigraphy and facies analysis were approached using more than 140 thin sections and more than 500 ammonite specimens.

Lower Jurassic

Over the thick Triassic succession, after a gradual passage, the Jurassic appears. The lower part of the Jurassic succession is composed of dolostones and oo-oncolitic, evolving to crinoidal limestones, showing decametric thickening and coarsening upward parasequences. Microfacies are mainly grainstones to packstones (occasionally rudstones) with oolites, pisolites, oncolites and benthic micro- and macrofauna. This lower part of the succession is interpreted as restricted inner-shelf deposits of oolitic shoals, near algal and/or crinoidal meadows.

The upper part of the Lower Jurassic succession is built up by 2–12 m of alternating yellowish marly/silty limestones, occasionally slightly nodular, with levels of ferruginous oolites and/or decimetric Fe–Mn oncoids; these being constituted by concentric laminae around the nucleus. This level is constrained between two unconformity surfaces, the lower one presenting Neptunian dykes. This upper part of the successions is, unlike the lower one, rich in well-preserved macrofauna. The ammonite assemblages enable the characterization of discrete and discontinuous horizons within the Domerian (Lavinianum, Algovianum and Emaciatum Zones) to the bottom, and the Toarcian (Polymorphum, Sepentinum, Bifrons, Gradata and Reynesi Zones) to the top (Caracuel et al. 2005).

This interval appears to record the platform break-up, leading to an open shelf-depositional environment with variable depth, water chemistry and hydrodynamics, due to the intricate bottom topography (block faulting and tilting), allowing the dated level to specify the timing of this break-up.

Middle Jurassic

The Middle Jurassic, some 140 m thick, is composed of well-stratified micritic/crinoidal limestones with abundant chert in nodules and ribbons, increasing toward the upper part. At the base, the micritic/crinoidal limestones alternate with thick oolitic limestones levels, which

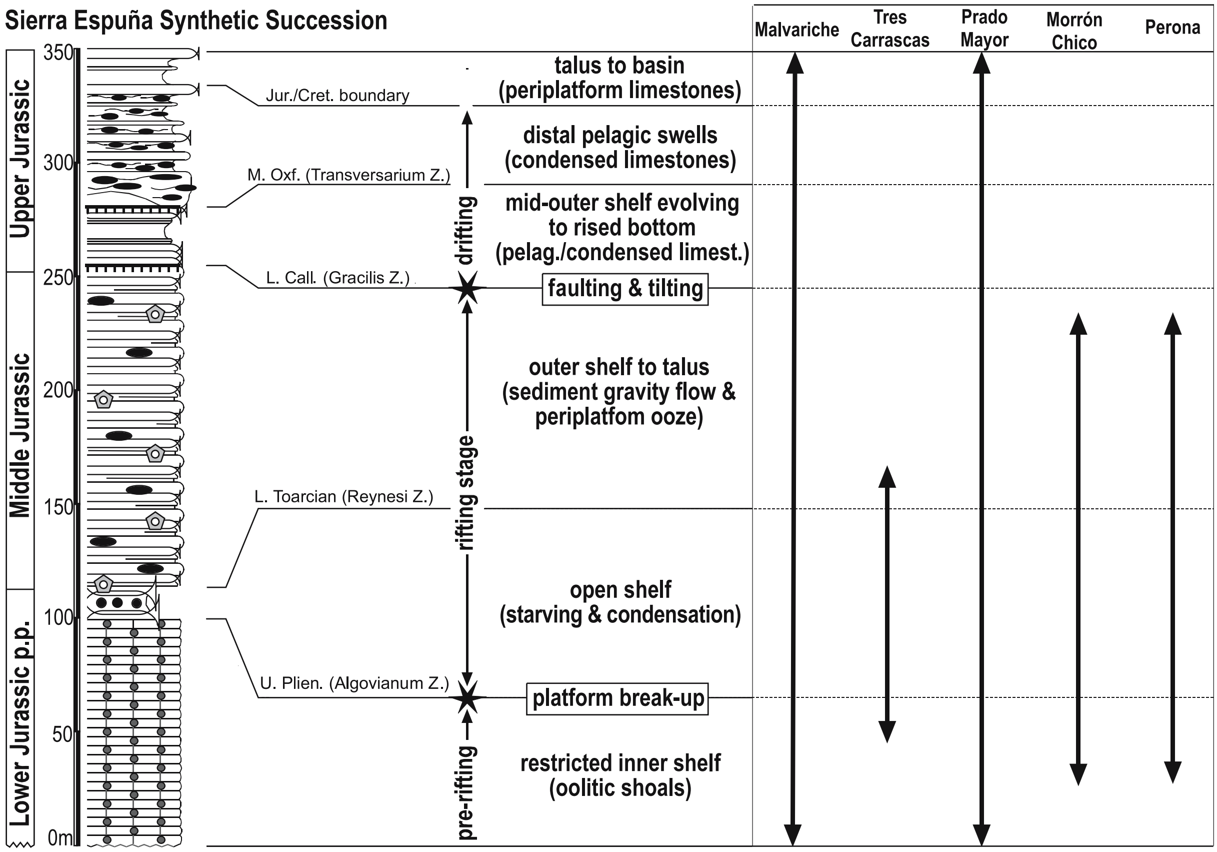

Fig. 5 Synthetic Jurassic stratigraphic, biostratigraphic and palaeoenvironmental reconstruction from succession at Sierra Espuña

resemble those of the Lower Jurassic. Toward the upper part, some levels composed of micritic limestone show incipient nodularization, with abundant trace fossils, developing two multiple hardgrounds at the top, with accumulations of glauconite or ferruginous crusts and faunal concentrations (ammonites and occasionally oriented belemnites).

This level is composed of hierarchized, upwardly thickening and coarsening parasequences, with stacking of upwardly thicker parasequences. Microfacies range from wackestones to packstones (occasionally crinoidal grainstones) with crinoids, along with thin-shelled bivalves (filaments), radiolaria, benthic and planktonic foraminifera, and diverse macroinvertebrate fragments. Apart from disarticulated crinoid knuckles, benthic macrofauna are almost absent in the Middle Jurassic, in contrast to the situation in the Lower Jurassic. Planktonic macrofauna is also scarce, but in the top of some levels, especially toward the upper part, cephalopods are widespread (ammonites and belemnites).

In these levels, better developed in the Malvariche section, ammonite assemblages were collected, enabling the recognition of the Lower Bajocian, based on the record of a specimen of *Skirroceras* sp. The Middle Jurassic succession ended with a multiple Fe–Mn crusts dated as Lower Callovian (Gracilis Zone: Caracuel et al. 2005).

As in other western Tethyan palaeomargins, during the Dogger, widespread pelagic or hemipelagic sediments (gravity flows and periplatform ooze), enriched in chert were deposited, originating from siliceous planktonic organisms (radiolaria) due to the drowning of the area.

Upper Jurassic

The succession is composed of 80–90 m of finely stratified marls and marly limestones evolving to stratified limestones stacked in upwardly thickening parasequences. Next, massive nodular limestones alternate with stratified limestones and marls, arranged in upwardly thinning parasequences. Textures and microfacies are highly variable, ranging from pelloidal mudstones to intraclastic packstones (occasionally crinoidal grainstones) with *Globuligerina* (at the base), filaments, *Saccocoma*, radiolaria, *Globochaete*, *Stomiosphaera*, *Cadosina* and calpionellids.

Over the multiple Fe–Mn crusts dated as Lower Callovian (Gracilis Zone) an interval of marly limestones and marls crops out, composed of finely stratified, and texturally mudstones to wackestones rich in *Globuligerina*, dated with ammonites as Middle Oxfordian (Transversarium Zone) to the Lower Kimmeridgian.

Upwards, appear slightly nodular marly limestones (upwardly thickening parasequences) with irregular massive breccioid banks, and then slightly nodular marly limestones organized in upwardly thinning parasequences, dated with ammonites as uppermost Kimmeridgian. These slightly nodular marly limestones stacked in upwardly thinning parasequences continues, and then changes to upwardly thickening parasequences; the facies change gradually to alternating marly/calcareous nodular limestones, often breccioid. The upper part of the succession is composed of encrinitic levels and marly intervals with microfacies enriched in hyaline calpionellids which characterize the Upper Tithonian.

During the Malm, the depositional environment for the Malaguide in Sierra Espuña is a mid-outer shelf that rises in some areas, becoming a distal pelagic swell with sedimentation of condensed ammonitico rosso, and related facies. In the study area, the condensed sedimentation linked to this raised sea-bottom started gradually from the Middle Oxfordian.

Cretaceous

The succession at the end of the Jurassic evolved into a basin environment in the Lower Berriasian (probably from the uppermost Tithonian) with deposition of periplatform limestones and basin marls. A sandy glauconite-rich level from the Albian appears, and the marly sediments follow up to the Senonian, where scaglia-like deposits are present.

Therefore, the main unconformity surfaces related to the main change of facies found in the studied successions can be summarized as follows:

- Change from shallow limestones to an open-shelf depositional environment of variable depth, water chemistry and ferric oolites with neptunian dyke development, before the Domerian (Lavinianum, Zone) in age (Fig. 6).
- Change to micritic/crinoidal limestones with abundant chert in nodules and ribbons, after Toarcian (Reynesi Zone) in age.
- Development of marl and marly limestones which evolve to stratified limestones and massive nodular limestones, late Middle Jurassic in age (Lower Callovian: Gracilis Zone).
- Change to a basin with deposition of periplatform limestones together with local sedimentation by planktonic microfossils, in the Lower Berriasian (probably from the uppermost Tithonian).

Tectonic features of the study area

The structural analysis was focused on the Morrón de Totana Unit (Fig. 3), from the Valle de Malvariche to Morrón Chico area. It has comprised mapping of synsedimentary Jurassic–Cretaceous faults and variations in thickness undergone by the materials during the action of the faults, measurement of direction and dipping along the trace of the listric faults and the study of their kinematics. The outcrops studied are on the verticalized to reversal limb of an antiformal fold (Lonergan 1991; Sanz de Galdeano et al. 2001), affecting a continuous Palaeozoic to Tertiary succession (Martín-Martín and Martín-Algarra 1997). In this area, several main faults (Mf) separating kilometric blocks and minor faults (secondary faults, Sf) can be distinguished. This distinction has been made on the basis of the amount of stratigraphic succession affected by the faults and the fault length. Thus, the Mf practically affect the entire Jurassic–Cretaceous succession, while the Sf usually

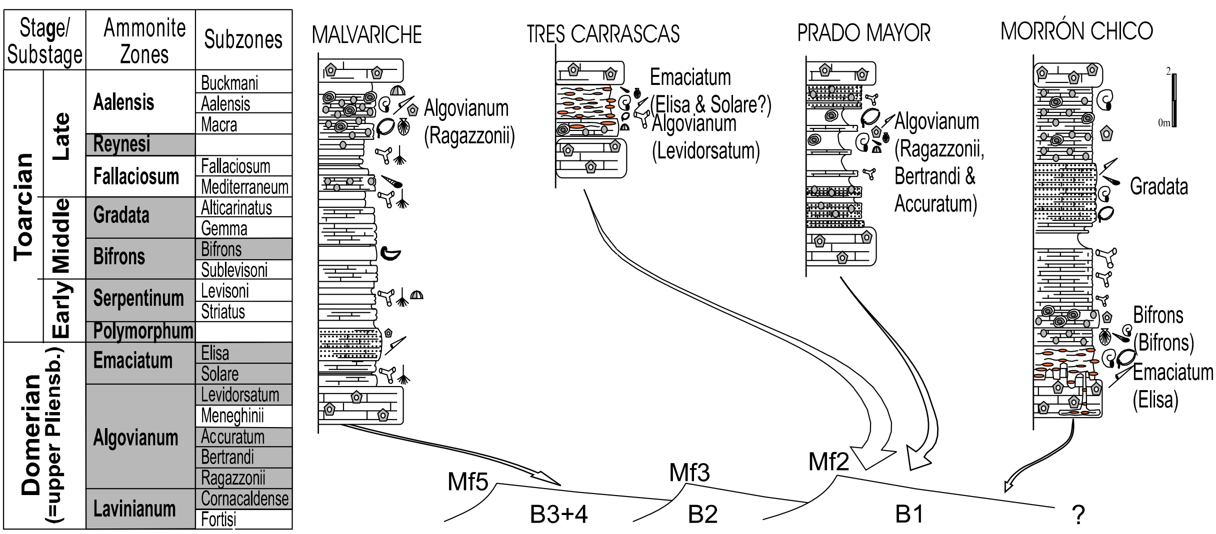

Fig. 6 Detailed successions in the four Domerian–Toarcian sections studied; interval of alternating yellowish marly/silty limestones, occasionally slightly nodular, with levels of ferruginous oolites and/or decimetric oncoids. Recognized zones and subzones are shaded in the chronostratigraphic chart. B1, B2 and B3 + 4 refer to the blocks after the actuation of the Mf (location in Fig. 7)

partially affect the succession, showing minor lengths. There are six Mf called (from E to W) Mf1–Mf6 (Fig. 3). These faults divide the zone into six blocks (named B1–B6 from E to W) 1–2 km wide, with the only exception being B1, which is about 3 km wide (Fig. 3). The Mf2–Mf6 faults are normal, measuring 2–3 km long, and affect the entire Jurassic and Cretaceous succession, being sealed by the Tertiary. Meanwhile, Mf1 is a reverse fault affecting the Triassic to Tertiary succession; it is probably a Jurassic main normal fault inverted into a reverse fault during the Tertiary after the tectonic inversion. The five main normal faults affecting the Jurassic and Cretaceous succession can be divided into four westwardly oriented (Mf2, Mf4, Mf5 and Mf6), and one eastwardly oriented (Mf3).

Secondary faults, about 200–500 m long, can also be distinguished, being westwardly oriented (Fig. 3). These minor faults break the blocks with minor displacement. Six evident Sf have been mapped, called (from E to W) Sf1–Sf6. The Sf1 and Sf2 affect the entire Jurassic to Cretaceous succession of B2, while the Sf3–Sf6 affect only the Liassic of B3.

According to the stratigraphic data presented earlier, together with previous palaeogeographic data (Martín-Martín 1996), continental areas seem to be located eastward, respecting the present coordinates. Therefore, if fracturation uplifted the present east area, the westwardly dipping faults can be considered synthetic, while eastwardly oriented ones must necessarily be antithetic. These faults are relict from the Mesozoic geodynamic evolution, as deduced from the Tertiary sealing (Fig. 3).

In addition to the above data, other evidence of synsedimentary tectonics can be gathered from the Sierra Espuña area outcropping. The data can be divided into direct evidences (neptunian dykes related to jointing, and faults sealed by upper bed) and indirect evidences (slumping, rotated beds, significant thickness changes (see Fig. 7) and lateral distribution of facies).

Deformational pattern: fault activation and subsidence

A prior treatment was made in order to obtain a cross section reflecting the original geometry preceding the Tertiary compressional alpine tectonics. We used the Prado Mayor-Morrón Chico sector as a reference area (central-eastern part), and therefore the western part of the study area was rotated until the azimuth of the bedding was parallel to the one in the reference area, using the axis of the second-phase fold as rotation axis (Fig. 3), giving a total length of 10.43 km. We consider that the direction for the cross-section obtained is

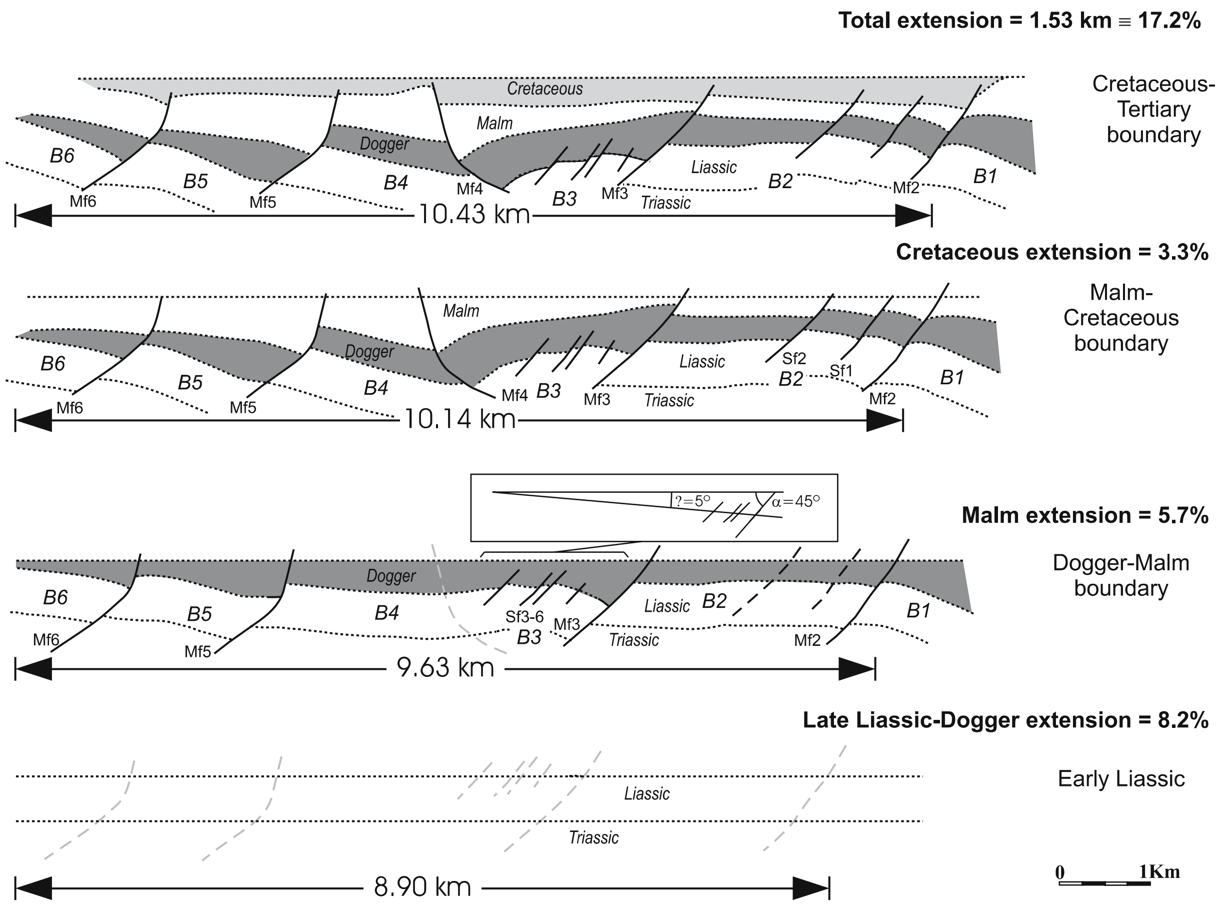

Fig. 7 Restored cross section from Malvariche to Prado Mayor area for the Cretaceous–Tertiary boundary and following deformational evolutionary analysis for the Cretaceous period, Malm period, and Late Liassic–Dogger period

approximately perpendicular to the Mf affecting the region during the Mesozoic and, consequently, it is appropriate to calculate the amount of extension. In the southern part of this western sector, the bedding shows a northerly dipping disposition, and thus we rotated this part to verticality, using as rotation axis the Espuña Fold axis. The resulting cross-section is sub-perpendicular to the fault planes, that is, sub-parallel to the transport direction during the action of these faults. After that, the section was restored until the roof surface of the Cretaceous interval became horizontal, following the constraints generally used for section balancing (Elliot 1983; Gibbs 1983; Davinson 1986; Ramsay and Hubbert 1987). Three other evolutive sections were obtained by restoring the rotation caused by the normal faults, in order to reconstruct the geodynamic evolution of the margin during the Jurassic times. The length obtained for the Early Liassic times was of 8.90 km.

This Jurassic geodynamic evolution of the study area can be summarized as follows (Fig. 7):

Early Liassic

The stratigraphic thicknesses and facies distribution during this period are quite similar (about 450 m) in all blocks, indicating a period with no tectonics.

Late Liassic–Dogger

After the Early Liassic period, the first active faults were Mf2, Mf3, Mf5 and Mf6, separating and tilting the blocks B1, B2, the ensemble B3 + B4, B5 and B6. Secondary faults, Sf3–Sf6, were active only during this period. These tilted blocks were more subsident in the internal part of each block, producing wedge-shaped sedimentary bodies (see Fig. 6), as deduced from their thicker successions these having mean values of 100 m (external part) to 150 m (internal part) thick. The resulting extension during this period was 730 m (8.2%) from an initial length of 8.90 km.

The amount of stretching can be estimated (Allen and Allen 1990) if the dips of the faults and bedding are known, when successive fault blocks have been tilted back at a constant angle (α), and the bedding or basement-fill surface dips into the fault plane at a constant angle (θ). The rotation of fault blocks gives the amount of stretching of the brittle upper crust, calculated by the following mathematic relation:

$$e(\%) = \left[\frac{\sin(\alpha + \theta)}{\sin \alpha} - 1\right] \times 100;$$

$$e(\%) = \left[\frac{\sin(45 + 5)}{\sin 45} - 1\right] \times 100; \quad e(\%) = 8.5(\%)$$

This approach was possible only in this period, since the angles of the fault blocks (α) and bedding (θ) were determined for Sf (Sf 3–6). In this case, α was equal to 45° and θ a medium value from 5°, giving an extension of 8.5%, this being close to the 8.2% calculated by the quantitative geometric analysis.

Malm

The previous active faults, Mf2, Mf3, Mf5 and Mf6, remained active, and Mf4 began to activate, separating and tilting the blocks B3 and B4, probably related to the roll-over of the block during the previous period or a new faulting and tilting phase. Also, new Sf (Sf1 and Sf2) were activated, affecting B2. During this period, B2 and B6 showed less subsidence than other blocks, and no tilting was detected. B3 showed subsidence related to the activation from Mf4 in the western part of the block. B4 and B5 showed thicker successions in the internal part of each block (wedge-shaped sedimentary bodies). The blocks had thicknesses ranging from 80 to 125 m (in the most subsident part of the block). Extension during this period reached 510 m (5.7%) for an initial length of 9.63 km.

Cretaceous

The extension follows during the Cretaceous. In this period the previous faults were also active, especially Mf2, Mf3 and Mf6, tilting B2, B3 and B6. B4 and B5 showed less subsidence than other blocks and no tilting was evidenced, since the thicknesses were equal and constant in the above blocks (about 70 m). Nevertheless, B1, B2 and B6 are tilted and thicknesses reached about 150 m in the internal part of the blocks. Extension during this period reached 290 m (3.3%) from an initial length of 10.14 km.

Finally, during the entire study period (Jurassic and Cretaceous) length varied 1.53 km, i.e., from 8.90 to 10.43 km, providing an extension of 17.2%. The most active period was the late Liassic to the Dogger–Malm boundary, when all the Mf were active (except for Mf4, which was active only from the Malm). During this stage, after the drowning of the platform, the stratigraphic thicknesses increased from 600 m (less subsident part of the block) to 750 m (more subsident part of the block).

Westernmost Tethys tectonic framework

Figure 8a shows the late Liassic to Malm synthetic succession of the Sierra Espuña area, correlated with four other Malaguide successions from the Betic Cordillera located in Fig. 1 [Vélez Rubio, Sierra Arana, Turón-Ardales and Convento-Nieves (Robledo-like units) successions] from Martín-Algarra (1987), and another synthetic succession from the Ghomaride Complex in the northern Rif (Fig. 1) from Maaté (1996).

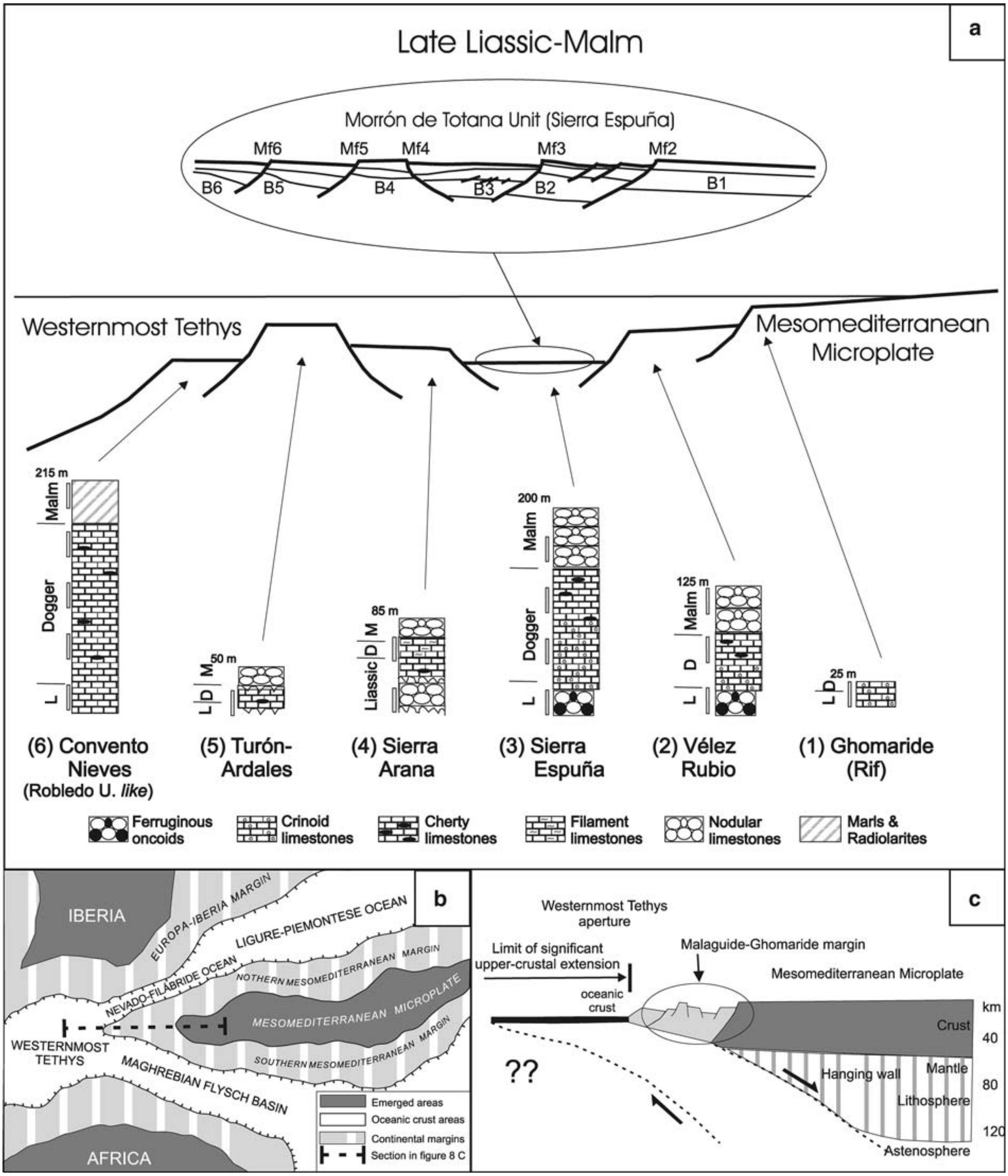

Fig. 8 **a** Correlation with other sections from the Internal Betic–Rifean Zones and cross-section with subsidence model for the Westernmost Tethys for the late Liassic–Malm period. **b** Schematic palaeogeographic map of the Westermost Tethys at the lower Cretaceous (after Guerrera et al. 2005). **c** Tectonic model for the Western Mesomediterranean Microplate margin

This correlation supports the explanation of the tectonic pattern previously deduced from the Jurassic and Cretaceous in the Morrón de Totana in the context of the entire Betic–Rif Cordillera. The successions considered above are representative of the westernmost palaeomargin of the Mesomediterranean Microplate (at present, responsible of the Internal Betic–Rif Zone after the Burdigalian compressive tectonics: Guerrera et al. 1993, 2005) located during the Jurassic in a southwestern position of the Tethyan Ocean.

The columns of these successions were translated (projected) into the same transversal to make an interpretative synthetic geological section. The columns were positioned according to the proximality–distality, taking into account the lithofacies, the stratigraphic series and the palaeogeographic models proposed by Martín-Algarra (1987) and Maaté (1996). These models are based on the presence or absence of a Palaeozoic basement, on the Palaeozoic and Triassic sedimentary successions, as well as the Jurassic–Cretaceous facies (pelagic–neritic character and thickness). As can be deduced from Fig. 8a Convento–Nieves can be considered to be the thickest succession (215 m for the Late Liassic–Malm series) and the Ghomaride succession the thinnest (about 25 m). The presence of radiolarites in the Convento–Nieves also indicates a distal position (basinal) for this succession, while the Ghomaride succession must be located according to their nerithic facies in a proximal position near to the emerged lands (Mesomediterranean Microplate). The other successions considered, must be located between the above two, with the Sierra Espuña series the thickest among them (200 m). The period when the entire succession showed the greatest thickness was the Late Liassic–Dogger, when faults should be more active.

The thickness variation for the succession considered indicates great differences in the subsidence rates for each sector, suggesting a narrow and swell submarine topography. This distinctive topography can be interpreted as being caused by fault activity separating and tilting different blocks to create the Tethyan Ocean westward during the Jurassic, according to Schlager (1981), Kendall and Schlager (1981) and Santantonio (1993).

As a result, for the westward opening of the Tethyan ocean, three kinds of faults were active: large-scale faults (Lf) separating hectometric cortical blocks, allowing great differences in the thickness of the successions (first-order fragmentation); and Mf and Sf, allowing the second-order fragmentation of each palaeogeographic block into kilometric blocks. All the faults (Lf, Mf and Sf) seem to be listric, since the blocks show wedge-shaped sedimentary bodies.

Discussion

The analyses made on the Morrón de Totana Unit indicate an extension for the entire Jurassic–Cretaceous period at about 17.2%, although the cortical extensional models generally indicate an extension of 25% (McKenzie 1978), at about the 100% (Wernicke 1985; Debelmas and Mascle 1991; Houseman and England 1986) of the initial length.

Nevertheless, extension rates are quite different according to the position considered in the rifting zone. The Wernicke's model (1985) proposes a zonation of rifting areas according to the extensional rates. It consists of an asymmetric model with a main low-angle normal fault where the hanging wall is also faulted by high-angle normal faults. These cortical faults produce large blocks (large fault block) with minor rotations, creating emergent (ranges) and subsident (basins) contiguous areas. These blocks, at about 10–15 km long, are located according to Wernicke (1985) out of the "*limit of significant crustal extension*" where faults are usually highly dipping with a minor capacity of stretching. In another way, the bottom wall is faulted by minor low-angle faults, giving greater extension, with high, rotated blocks in the "*significant crustal extension area*" (during the drifting phase), where the crust becomes thinned and where magmatic and metamorphic processes take place.

The fact that the extension rates established in the Morrón de Totana Unit are lower than those of the current model could be related to the different extension capacity from the large-scale compartmentalization (Lf) to the second-order fragmentation (Mf and Sf), higher in the first case and lower in the second one. Therefore, the Lf separating palaeogeographic crustal blocks were responsible for larger extensions, while second-order fragmentation, located into palaeogeographic blocks, was responsible for minor extension rates of close to 17%. Moreover, the general framework of the western Tethys (Malaguide–Ghomaride Domain) appears to be related to areas outside the "*limit of significant crustal extension*" in the hanging wall of the main low-angle fault of the rifting (Fig. 8b), since neither magmatic nor metamorphic processes have been recognised in the Sierra Espuña area, either here or in previous work in the Betic–Rif Chains (Sanz de Galdeano 1997 and references therein). This implies that the main cortical normal low-angle fault should be palaeogeographically located in a western position in the opening of the Tethyan but with an eastern dipping, according to the current coordinates (Fig. 8b).

Models for the temporal evolution of passive margins (National Research Council 1979; Winterer and Bosellini 1981) divide the history into several phases: first a pre-rift quiet period, followed by a "*rifting and transforming*" faulting phase with drowning of the area; later, a "*drifting*" phase when continental crust and oceanic crust accretion separate with rapid tectonic subsidence and opening of the ocean; finally, a post-drift phase with thermal subsidence when oceanographic effects, such as sea-level changes, oxygenation and current regimens, dominate over the effects of the tectonics.

The dating of these phases is difficult since they are usually hetero-chrones in widespread basins (Winterer and Bosellini 1981; Vera 1988), but the bounds of these phases usually coincide with unconformities and changes in sedimentary facies. The change from the pre-rift to rifting phase, and from the rifting to drifting stage coincides with erosive surfaces, the second one being called the "*break-up unconformity*" (Falvey 1974). Finally, the change from the drifting to post-drifting phase usually coincides with a less marked unconformity where a change to pelagic and/or siliceous rocks becomes widespread.

In the study area (a part of the western Tethys) the extensional evolution can also be divided into four stages according to the fault activation, subsidence-rate variation, the occurrence of unconformity surfaces and the facies evolution. Also, the biostratigraphic and stratigraphic study enables the dating of the unconformity surfaces related to the changes among the different tectonic phases of the oceanic opening:

- *Pre-rifting phase*: the Triassic to Early Liassic quiet period took place before the Domerian (Algovianum Zone), when a relative sea-level fall occurred, evidenced by an important unconformity with palaeokarst developing
- *Rifting phase*: this can be divided in two stages: first, the *platform break-up* (faulting and transforming) and drowning of the area until the Toarcian (Reynesi Zone), where a notable change in the sedimentary facies to ferro-manganese oolites and pelagic faunas took place; second, the Late Liassic–Dogger stage with *subsidence developing* with high variability from block to block.
- *Drifting phase*: the unconformity surface related to the rifting-to-drifting change (''*break-up unconformity*'' according to Falvey 1974) must be Dogger–Malm boundary in age (Lower Callovian: Gracilis Zone), where a homogenisation of the subsidence rates recorded are related to another unconformity.
- *Post-drift phase*: the change from drift to post-drifting must be Jurassic to Cretaceous boundary in age (Lower Berriasian, probably from the uppermost Tithonian), related to minor subsidence rates (thermal subsidence) in all the blocks and developing of pelagic and siliceous rocks.

Conclusions

The study of the Malvariche-Prado Mayor area has allowed us to analyse the structural extensional pattern of the Sierra Espuña Malaguide Complex. This analysis, included in a general frame, gives three kinds of listric faults for the westward opening of the Tethyan ocean: macro-scale faults separating hectametric cortical blocks (Lf); and Mf and Sf separating kilometric and hectametric blocks, respectively (second-order fragmentation). This extensional analysis shows a variation of length from 8.90 to 10.43 km for the entire Jurassic to Cretaceous period, providing an extension at about 17.2%. The most active period was the late Liassic to the Dogger–Malm boundary when the extension was at about 730 m (8.2%) from an initial length of 8.90 km

Furthermore, the stratigraphic and biostratigraphic study made in the area has enabled the recognition of four main unconformity surfaces related to changes in sedimentary facies: Domerian late Liassic (Algovianum Zone), Toarcian late Liassic (Reynesi Zone), Dogger–Malm boundary (Lower Callovian: Gracilis Zone) and Lower Berriasian (probably already from the uppermost Tithonian). These surfaces could be related to the boundary of the four stages of the western Tethys extensional evolution: Triassic to Early Liassic pre-rifting phase, rifting and transforming phase at the beginning of the late Liassic, late Liassic–Dogger rifting phase, Malm drifting phase and Cretaceous post-drift phase with thermal subsidence.

The picture of this part of the western Tethys seems to be related to areas outside the ''*limit of significant crustal extension*'' in the hanging wall of the main low-angle fault of the rifting, taking into account the structural architecture and the extensional percentage found. Therefore, the main cortical normal low-angle fault, where cortical thinning is greatest, should be palaeogeographically located in a western position in the Tethyan opening with an eastern dipping, according to the present coordinates.

Acknowledgements This research was economically co-financed by the research projects BTE2001-3020, BTE2001-3029, BTE2003-01113 and CGL2005-03887 (Spanish Ministry of Education and Science) and Research Groups and project of the Generalitat Valenciana in the CTMA department (IGA) from the Alicante University, and Junta de Andalucía (RNM-178). We also thank constructive criticism and accurate reviews by Dr. Guerrera and Dr. Sanz de Galdeano. The English revision effectuated by Dr. David Nesbitt to the manuscript is also acknowledged.

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