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Oligocene-early Miocene transgressive cover of the Betic-Rif Internal Zone. Revision of its geologic significance

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Key words: Oligocene, early Miocene, Ciudad Granada group, Viñuela group, nappe emplacement, extensional events, Internal Betic Cordillera, Internal Rif

ABSTRACT

The Oligocene-early Miocene sedimentation in the Betic-Rif Internal Zone (BRIZ) occurred during the same time interval as the main tectonic events that are classically considered responsible for the structuring of this zone. Therefore, its paleogeographic and tectonic significance has been the subject of much controversy. The sedimentation developed in two successive groups of formations: the Ciudad Granada group of late Oligocene–Aquitanian in age and the Viñuela group of Burdigalian p.p. in age. The former consists of reddish marls containing clastic intercalations of Malaguide origin, while the Viñuela group is made up of siliceous-intercalated marlstones and lime-poor pelites, with a basal coarse-grained clastic material inherited from both the Malaguide and Alpujarride complexes. An overview of all the outcrops of the BRIZ leads to the conclusion that the two groups are closely related both geographically and tectonically. The paleogeographic, tectonic, stratigraphic and sedimentary relationships suggest that there was no nappe stacking stage between the two groups in the BRIZ. The transition from Ciudad Granada to Viñuela seems to have been the result of a transtensive tectonic event probably related to the westward migration of the BRIZ and to the opening of the Algero-Provençal and Alboran basins. This tectonic disturbance would have caused a severe subsidence in the downfaulted blocks, thus deepening the deposition zones; at the same time, the rapid uplifting of upfaulted blocks would have uncovered Alpujarride units, thus comprising the basement and the source of detritics for the Viñuela group.

RESUME

Les séries tertiaires assurant la couverture transgressive de la zone interne bético-rifaine (BRIZ) sont incluses dans le même intervalle d'âge, Oligocène-Miocène inférieur, que les événements tectoniques responsables, pour certains auteurs, de la structuration majeure de la dite zone. C'est pourquoi, l'interprétation tectono-sédimentaire de ces séries suscitait de vives controverses. Stratigraphiquement, deux groupes sédimentaires sont distingués : le groupe Ciudad Granada d'âge Oligocène supérieur–Aquitanien et le groupe Viñuela d'âge Burdigalien p.p. Le plus ancien contient de pélites rougeâtres et des coulées détritiques d'origine "Malaguide", alors que le groupe Viñuela se compose de marnes, localement siliceuses, et de décharges conglomératiques à éléments hérités à partir des complexes Malaguide et Alpujarride. La révision générale des affleurements dans toute la BRIZ permet de conclure que les deux groupes appartenaient initialement aux mêmes dépocentres, sans que le puisse constater de phase de structuration en nappes pendant la période qui séparait leur dépôt. Le passage de Ciudad Granada à Viñuela semble dû à un événement tectonique transtensif, lié probablement à la dérive vers l'ouest de la BRIZ et à l'ouverture conséquente des bassins Algéro-Provençal et d'Alboran. Cette perturbation tectonique aurait généré un système de horsts et de grabens très contrastés. Des zones à forte subsidence étaient alors juxtaposées à des horsts exposant les unités Alpujarrides. Ces dernières peuvent servir à la fois de substratum et de source de matériel clastique pour le groupe Viñuela.

Introduction

The Betic Cordillera and Rif constitute the western extremity of the peri-Mediterranean Alpine chain. Their common internal zone (henceforth BRIZ, Fig. 1), formed part of the Mesomediterranean block (Durand-Delga & Fontboté 1980), i.e., the so-called Alkapeca (Alboran-Kabylian-Peloritani-Calabrian domain, Bouillin et al. 1986). During the Jurassic times, this continental domain was located N of Africa from which it detached since the Cretaceous, resulting then in a northward-deriving microplate between Africa and Eurasia (e.g., synthesis by Andeweg, 2002). During the Oligocene, the domain was fragmented by the rifting of the Algero-Provencal basin (western Mediterranean), so that its WSW-migrating part (the Alboran block, Andrieux et al. 1971) become wedged between the

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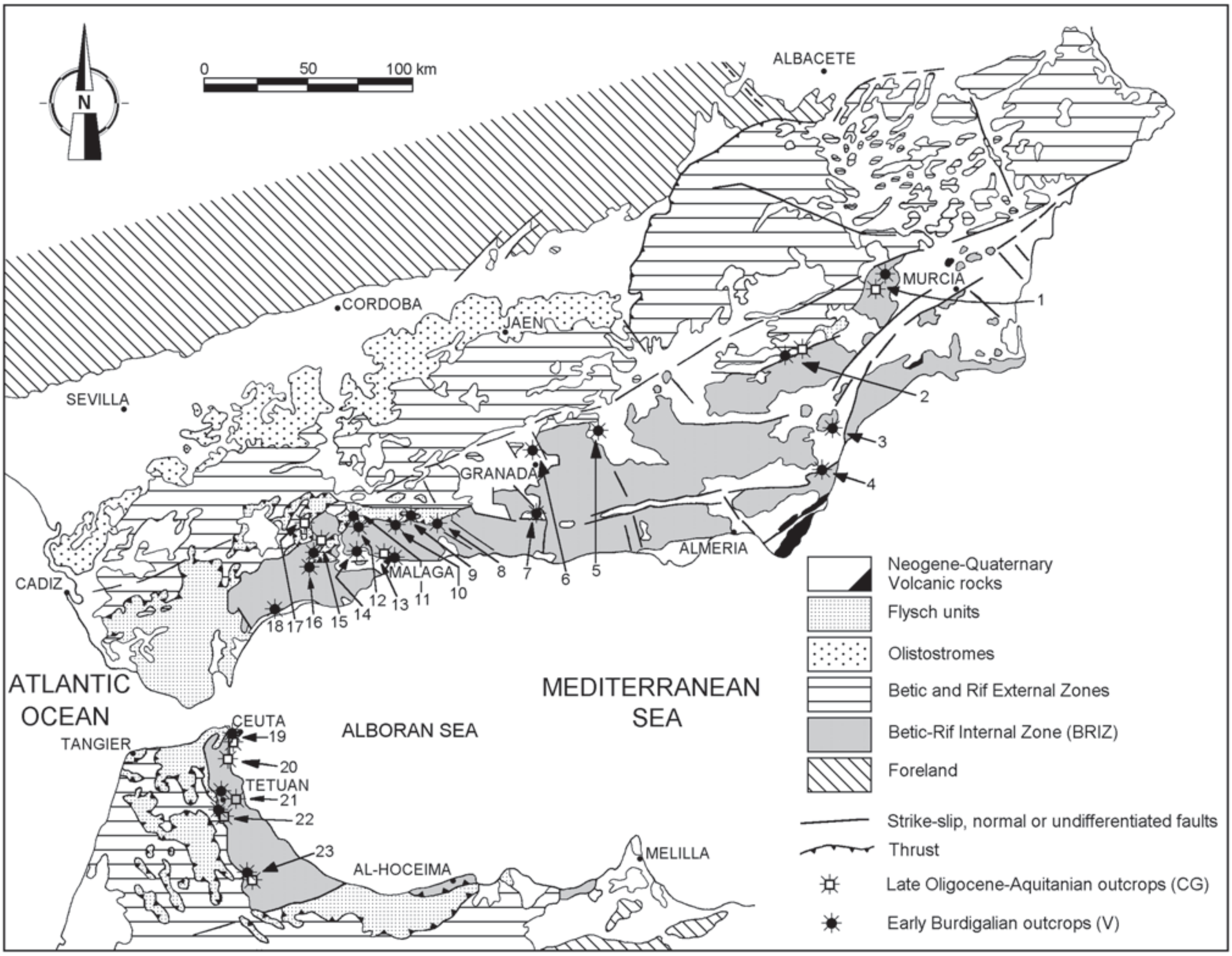

Fig. 1. General scheme of the Betic-Rif orogen and geographic location of the Oligocene-early Miocene transgressive formations over the BRIZ (CG: Ciudad Granada group; V: Viñuela group).
1. Sierra Espuña sector; 2. Chirivel sector; 3. Southern Sierra Almagro; 4. Northern Sierra Cabrera; 5. South-western Guadix basin; 6. North-eastern Granada basin; 7. South-eastern Granada basin; 8. La Viñuela sector; 9. Colmenar sector; 10. Casabermeja; 11. Cortijo Cherino; 12. Northern Almogía; 13. Malaga sector; 14. Northern Cártama; 15. Alozaina-Tolox sector; 16. Guaro sector; 17. Ardales sector; 18. San Pedro de Alcántara sector; 19. Ceuta-Fnideq sector; 20. Zem sector; 21. Tetuan-Sidi Abdeslam sector; 22. Tamezzakht sector; 23. Talembote sector

Iberian block and the African plate, thus forming the Gibraltar Arc. Finally, the westward prolongation of the Mediterranean rifting thinned the axial zone of the BRIZ. The resulting deep internal trough originated the Alboran Sea (Sanz de Galdeano 1990; Comas et al. 1992).

Three main tectonically stacked complexes can be distinguished in the BRIZ. These are from bottom to top: the Nevado-Filabrides (not present in the Rif), the Alpujarrides (i.e, Rifian Sebtides) and the Malaguides (Rifian Ghomarides). Originally, the complexes that today occupy the highest tectonic positions were located in more southerly positions (Durand-Delga 1980; Wildi 1983). In addition, the Dorsal is usually identified as occupying a distinct domain extending south of the Malaguide. Tectonic movements and the linked nappe emplacement initially had a north mean direction (NW, N or NE). Subsequently, during the westward migration of the BRIZ, important W and WSW displacements occurred in the Rif (Frizon de Lamotte et al. 1991), while movements in the Betic Cordillera were towards the W-NW (Kirker & Platt 1998; Luján et al. 2000; among others). Some units locally underwent severe backthrusting and rotations.

During the Cretaceous to early Miocene, the Maghrebian Flysch trough developed between these domains and the African plate (Durand-Delga 1972). The paleogeographic transition between the calcareous Dorsal and the Flysch trough corresponded to the Predorsalian and the Mauretanian zones, re-

Table 1. Transgressive formations of the Oligocene–early Miocene over the BRIZ and group assigned in this paper. Sector numbers correspond to those in Fig. 1.

Sector	Formation (authors)	Group
	BETIC CORDILLERA	
1. Sierra Espuña	El Niño Fm. (Martín-Martín 1996) Oligo-Aquitanian of the "zone limite" (Paquet 1969) or Río Pliego Fm. (Martín-Martín 1996) Bosque Fm. (Martín-Martín 1996)	Viñuela Ciudad Granada Ciudad Granada
2. Chirivel	Espejos Fm. (Soediono 1971) Fuentes Fm. (Soediono 1971) Ciudad Granada Fm. (Mac Gillavry 1963) Frac Fm. (Soediono 1971) Cortijo del Perro Malo Fm. (Soediono 1971)	Viñuela Viñuela Ciudad Granada Ciudad Granada Ciudad Granada
3. SE Sierra Almagro	Fuente Álamo Fm. (Völk 1967)	Viñuela
4. N Sierra Cabrera	Fuente Álamo Fm. (Völk 1967)	Viñuela
5. SW Guadix Basin	Los Alamillos Fm. (Rodríguez-Fernández 1982)	Viñuela
6. NE Granada Basin	Los Alamillos Fm. (Rodríguez-Fernández 1982)	Viñuela
7. SE Granada Basin	Base del Tramo de Murchas (González Donoso 1977-78)	Viñuela
8. La Viñuela	Viñuela Fm. (Vera 1969)	Viñuela
9. Colmenar	Majiaza Complex pro-part (Peyre 1974)	Viñuela
10. Casabermeja	Upper Oligocene of the "Bético de Málaga" pro-part (Didon et al. 1961)	Viñuela
11. Cortijo Cherino	Burdigalian sediments (Peyre 1974)	Viñuela
12. N Almogía	Burdigalian sediments (Peyre 1974)	Viñuela
13. Malaga	Viñuela group (Serrano et al. 1995) Ciudad Granada group (Serrano et al. 1995)	Viñuela Ciudad Granada
14. N Cártama	Viñuela group (Sanz de Galdeano et al. 1993)	Viñuela
15. Alozaina-Tolox	Las Millanas Fm. (Bourgois et al. 1972a) Alozaina Fm. (Bourgois et al. 1972b)	Viñuela Ciudad Granada
16. Guaro	Viñuela group (this work)	Viñuela
17. Ardales	Pantano de Andrade Fm. (Bourgois 1978)	Ciudad Granada
18. San Pedro de Alcántara	San Pedro de Alcántara Fm. (Didon et al. 1973)	Viñuela
	RIF	
19. Ceuta-Fnideq	Burdigalian sediments (El Kadiri et al. 2000) Fnideq Fm. (Durand-Delga et al. 1964)	Viñuela Ciudad Granada
20. Zem-Zem	Fnideq Fm. (Durand-Delga et al. 1964)	Ciudad Granada
21.Tetuan-Sidi Abdeslam	Sidi Abdeslam Fm. (Durand-Delga et al. 1964) Boujarrah section (Maaté et al. 1995) Fnideq Fm. (Durand-Delga et al. 1964)	Viñuela Viñuela Ciudad Granada
22. Tamezzakht	Oligo-Early Miocene sediments (El Kadiri et al. 2006)	------
23. Talembote	Viñuela group (El Kadiri et al. 2001) Ciudad Granada group (El Kadiri et al. 2001)	Viñuela Ciudad Granada

spectively (e.g., Durand-Delga 1980). Due to the shortening between the BRIZ and the External Betic and Rif zones, Predorsalian and Mauretanian deposits were stacked, forming in the Betics the Campo de Gibraltar Flysch nappes (Fig. 1).

The tectonic complexity evidenced in the BRIZ, provoked discrepancies about the timing of the metamorphism and the nappe emplacement. De Jong (1991 1992) first proposed the early and middle Eocene, and then (De Jong 1993) the latest Oligocene–early Miocene age for the Alpujarride/Nevado-Filabride overthrusting during an extensional regime. Chalouan et al. (2001) and Chalouan & Michard (2004) showed that initially the metamorphism occurred in the context of a double subduction process, mainly during the middle Oligocene and the earliest Miocene, while Zeck (2004) indicated that the exhumation of the metamorphic rocks began as early as the Aquitanian-Burdigalian transition (during the time interval 22–18 Ma) and rapidly occurred as a consequence of tectonic extrusion and concomitant extensional events. Extensional tectonics continued up to the Tortonian and thinned the former nappe edifice (García-Dueñas et al. 1992; Crespo-Blanc et al. 1993). As a complement to this debate, observations in the next section will indicate that the tectono-sedimentary significance of the late Oligocene and early Miocene formations that transgressively rest upon the Malaguide and/or Alpujarride basement, remains a crucial issue when deciphering the structuring phases of the BRIZ.

The aim of this paper is to provide a comprehensive review of the transgressive formations outcropping in the BRIZ. Special emphasis is laid on their stratigraphic, sedimentologic and paleoenvironmental features.

Previous studies and interpretations

Oligocene–early Miocene sediments outcrop in many points of the BRIZ (Table 1). In the eastern part of the Betic Cordillera, Soediono (1971) formally defined these deposits in the Vélez Rubio corridor, and differentiated the Ciudad Granada group (including the Ciudad Granada Fm., Frac and Cortijo del Perro Malo formations, Fm.), the Fuente Fm. and the Espejos Fm., all stacking in a single stratigraphic column. Based on planktonic foraminifera, González Donoso et al. (1988) assigned the Ciudad Granada Fm. to the early-middle Aquitanian (without ruling out the possibility that the basal levels belong to the late Oligocene) and dated the group of Fuente-Espejos formations as covering the interval early Burdigalian-early late Burdigalian.

Many authors (e.g., MacGillavry et al. 1963; Geel 1973; Hermes 1978) interpreted the basal conglomerates of the

Fuente Fm. as being the oldest levels reworking detrital remains of Alpujarride origin and having been separated from the underlying Ciudad Granada Fm. by a tectonic phase. These authors concluded that the deposition of Ciudad Granada and equivalent groups occurred prior the overthrusting of the Malaguide over the Alpujarride Complex.

On the contrary, Rivière et al. (1980) reported Alpujarride-derived detritics in sediments equivalent to those of the Ciudad Granada Fm., in the Sierra Espuña sector (Oligo-Aquitanian at the "zone limite de Río Pliego" by Paquet 1969, or Río Pliego formation by Jerez 1979), which are conformably overlain by sediments equivalent to the Fuente Fm.. These authors thus concluded that the Oligo-Aquitanian deposits in Río Pliego postdated the Malaguide/Alpujarride thrusting.

In the western Betic Cordillera, Vera (1969) described sediments attributed to the Aquitanian-Burdigalian, termed La Viñuela Fm.. Boullin et al. (1973) reported that this formation transgressively covers both the Malaguide and the Alpujarride, and thus postdates the nappe emplacement of the BRIZ. They also described this formation as being tectonically covered by Flysch units in the Colmenar sector. Concerning the Alozaina area (Malaga province), Bourgois et al. (1972a, 1972b, 1973) placed a tectonically-induced unconformity (post-Aquitanian phase) between the Oligo-Aquitanian Alozaina Fm., and the Burdigalian Las Millanas Fm., a result that they completed by a second phase (post-Burdigalian phase) responsible for the overlying flysch-bearing olistostromes. Based on a regional correlation, Rivière et al. (1980) concluded that only the western sectors of the Betic Cordillera were affected by the post-Aquitanian phase. González Donoso et al. (1982) assigned the La Viñuela Fm. precisely to the early Burdigalian, and correlated it with the Fuente Fm. and with many other sediments covering Malaguide (Casabermeja, Almogía, Alozaina; González Donoso et al. 1981) and Alpujarride rocks (Granada basin, the base of the "tramo de Murchas"; González Donoso 1977–78). Rodríguez-Fernández (1982) correlated the Alamillos Fm. that crops out near La Peza (east of the Guadix basin) with early Burdigalian formations.

Lateral equivalent of the Alozaina Fm. have been described from the Ardales (Pantano de Andrade Fm.; Bourgois 1978) and the Malaga sectors (Serrano et al. 1995). As for La Viñuela Fm., lateral equivalents were reported from Sierra Bermeja (San Pedro de Alcantara Fm.: Didon et al. 1973; Aguado et al. 1990); the area of Colmenar (Majiaza complex; Peyre 1974), Cártama (Sanz de Galdeano et al. 1993); and from the Malaga area (Serrano et al. 1995).

In the Rif, Durand-Delga et al. (1964) ascribed the Fnidek Fm. to the late Oligocene–Aquitanian transgressive cover of the Ghomaride terranes. Ben Yaich et al. (1986) characterized early Burdigalian strata trapped in the Ghomaride-Dorsal thrust front (Oued El Gharraq section, northern Calcareous Chain), that subsequently proved to be identical to the Sidi Abdeslam Fm. defined by Feinberg et al. (1990) east of Tetuan. Additional outcrops pertaining to both formations were found north of Tetuan by Maaté et al. (1995) and in the Ceuta area by El Kadiri et al. (2000). In neither case stratigraphic relations between the two formations could be observed. El Kadiri et al. (2001) described in the Talembote sector (north of Chauen) lateral equivalents of the Tertiary formations defined in the western internal Betics by Bourgois et al. (references cited): Alozaina Fm., Las Millanas Fm., and the Flysch olistostrome. These Talembote formations appear to be stacked in a single stratigraphic succession, with ravinement surfaces and/or chaotic breccia in between. These authors showed that the tobacco-brown pelites of the Sidi Abdeslam Fm., classically assigned to the early Burdigalian Viñuela group, should rather correspond to a regional equivalent of the overlying Bourgois's olistostrome. Martín-Algarra (1987) proposed to extend the term "Ciudad Granada group" (Soediono 1971) to all the late Oligocene–Aquitanian transgressive formations over the Malaguide basement. This author considered these formations as recording the last sedimentary episode in the Malaguide domain, prior to the major nappe emplacement. Martín-Algarra (1987) also regarded all the early Burdigalian formations as post-nappe strata transgressively covering both the Malaguide and Alpujarride units, and suggested that they should be classified as "Viñuela group".

Based on a stratigraphic review at the Gibraltar Arc scale, Olivier (1984) concluded that the major nappe emplacement in the BRIZ (in considering, at least, the Malaguide and the calcareous Dorsal) occurred during the Oligocene. Subsequently, the displacement of the BRIZ towards the WSW during the early Burdigalian resulted in the whole BRIZ overthrusting the Predorsal and the neighbouring flysch areas. However, Mäkel (1985) reported that the tectonic superposition, which started by the late Oligocene near the suture between the Nevado-Filabride and the Alpujarride, migrated towards the Malaguide and the Dorsal, respectively. The latter event would have occurred during the early Miocene as a result of mantle diapirism that uplifted the Alboran region (Weijermars, 1991).

On the contrary, Lonergan (1991, 1993), Durand-Delga et al. (1993), Lonergan & Mangé-Rajetzky (1994) all assumed the early Oligocene–Miocene sediments to be posterior to nappe stacking of the BRIZ. Similarly, Platt & Vissers (1989) regarded these sediments as post-orogenic, but deposited in a basin that evolved from the late Eocene-Oligocene and received clastic material from both the Internal and the External Zones. Martín-Martín (1996) and Martín-Martín & Martín-Algarra (1997) indicated that the Oligocene tectonics represents only an early phase of a long-lasting nappe emplacement process that continued until the latest Aquitanian. For Guerrera et al. (1993) the formations of the Ciudad Granada group predated the final nappe stacking phase in the BRIZ. Finally, Martín-Algarra et al. (2000) argued that this group predates the tectono-metamorphic event, as well as the final nappe emplacement processes and the exhumation of the metamorphic units of the Betic-Rifian orogen. These authors attribute the metamorphic and granitic pebbles found in Ciudad Granada-type formations to a Calabride Hercynian basement similar to the Malaguide.

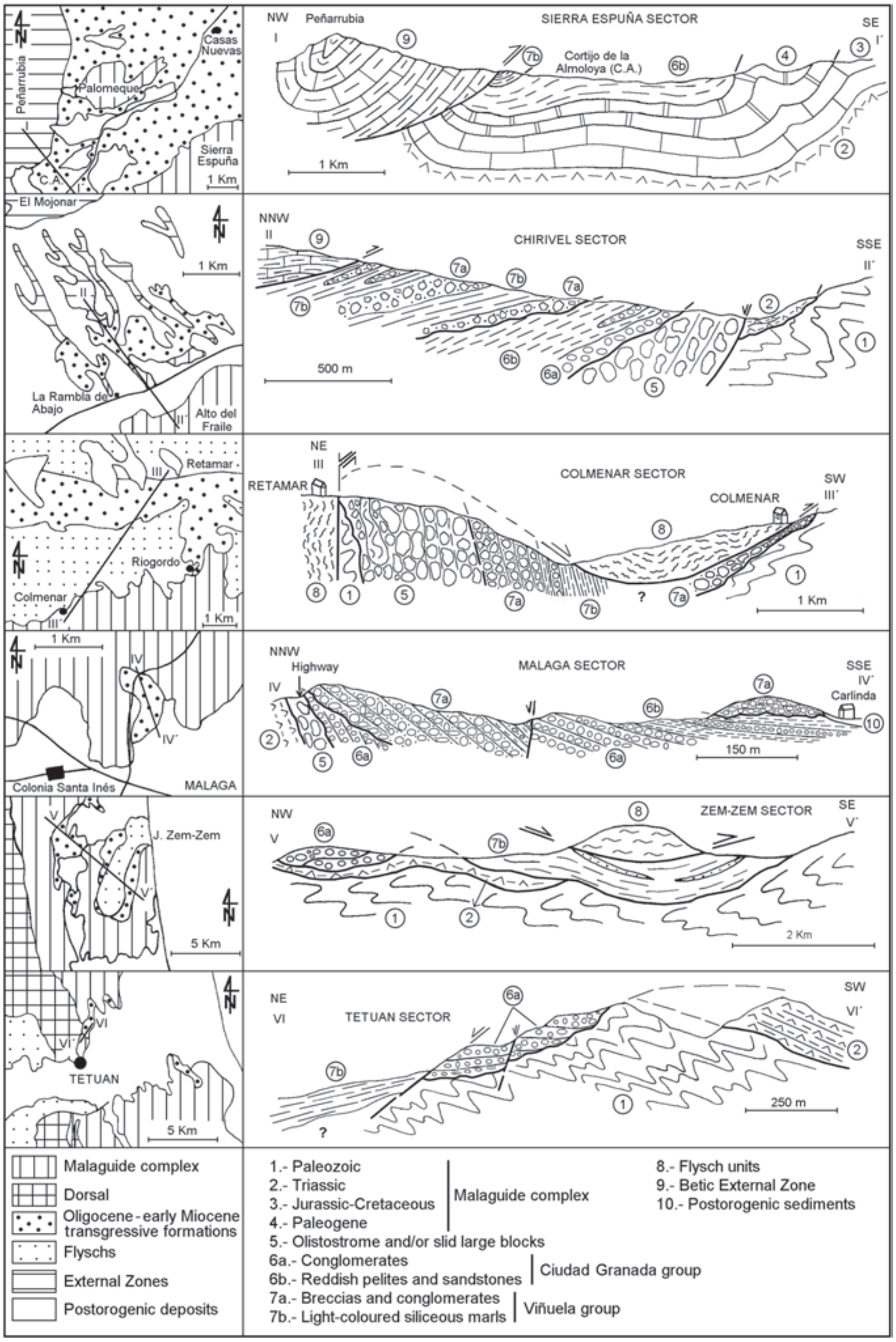

Fig. 2. Cross sections through the BRIZ implying Oligocene-early Miocene transgressive cover. 1-4: Malaguide (1: Paleozoic; 2: Triassic; 3: Jurassic-Cretaceous; 4: Paleogene); 5: Olistostrome and/or detached large blocks; 6: Ciudad Granada group (6a: Conglomerates; 6b: Reddish pelites and sandstones); 7: Viñuela group (7a: Breccias and conglomerates; 7b: Light-coloured siliceous marls); 8: Flysch units; 9: Betic External Zone; 10: Postorogenic sediments.

1. Location of outcrops

Ciudad Granada and Viñuela groups crop out widely throughout the BRIZ, mostly in the vicinity of frontal bands bounding flysch units. Nevertheless, significant outcrops of these formations also appear in axial troughs within internal areas of the BRIZ. The best examples can be taken around the northern (Cartama, Malaga), western (Alozaina, Tolox), and southern (Guaro-Monda) borders of the Malaga basin (localities 14, 15 and 16, respectively, in Fig. 1). Further outcrops are evidenced at the edge of the Vera basin (localities 3 and 4 in Fig. 1), at the junction of the Alpujarras corridor with the Granada basin (Murchas, Loc. 7 in Fig. 1), as well as at the edge of the Alboran Sea (San Pedro de Alcantara, Loc. 18 in Fig. 1).

The outcrops of the Ciudad Granada and Viñuela groups in the Rif are distributed in a fairly similar way, with both

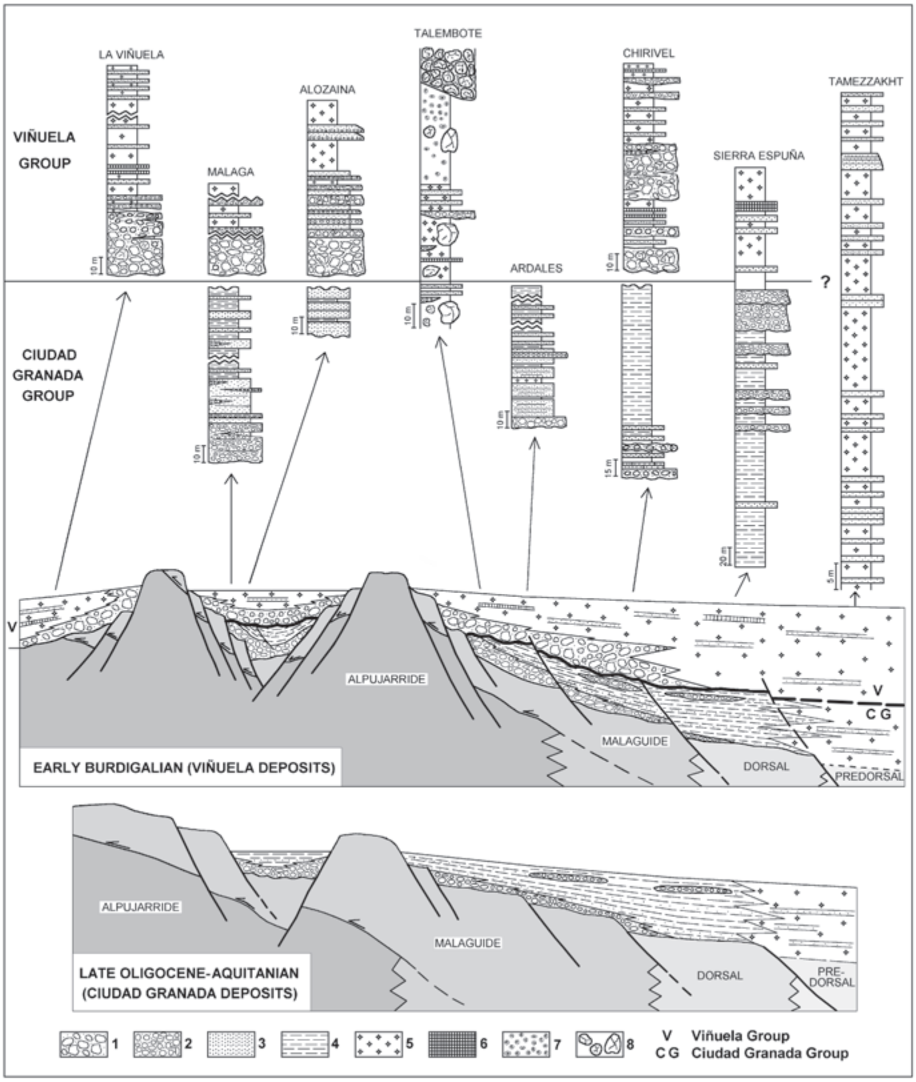

Fig. 3. Tectono-sedimentary framework of the transgressive formations of the Oligocene-early Miocene over the BRIZ. 1. Breccias; 2. Conglomerates; 3. Sandstones; 4. Reddish pelites; 5.Light-coloured siliceous marls; 6. Silexites; 7. Dusty brown pelites with a nodular appearance; 8. Large blocks.
Representative sequences compiled from González Donoso et al. 1982 (La Viñuela), El Kadiri et al. 2001 (Talembote), González Donoso et al. 1988 (Chirivel), Martín-Martín 1996 (Sierra Espuña), El Kadiri et al. 2006 (Tamezzakht), and this work.

groups appearing in peripheral areas of the BRIZ and in internal troughs.

Fig. 2 shows that Ciudad Granada and Viñuela-type formations may be involved in different tectonic settings. Generally, the outcrops are located on the borders of collapsed areas, where they are either covered by post-orogenic sediments or overthrust by the External Zones (Fig. 2, cross-section I-I' and II-II') or even by Flysch units (Fig. 2, cross-sections III-III' and V-V'). These formations would extend considerably beneath their tectonic or sedimentary covers. The Colmenar corridor provides a good example of this (Fig. 2, cross section III-III'): it is bounded to the south by the Malaguide, above which small, localised outcrops of Viñuela (between Colmenar and Casabermeja, Loc. 10 in Fig. 1) are generally overthrust by flysch units. Some 2-5 km further north, the Viñuela-type sediments (Majiaza complex, Loc. 9 in Fig. 1) reappear beneath flysch units. Northwards, the BRIZ appears in contact with flysch by a transcurrent fault where the rock formations are brecciated and involved in vertical slices.

Despite the large Tertiary outcrops, there is little opportunity to see clearly how Ciudad Granada- and Viñuela-type formations stack in a stratigraphic succession. This is either because the Viñuela formations cover the Ciudad Granada formations over extensive areas, or because they separately overly the Paleozoic basement. This explains why the outcropping areas of the Viñuela group are, on the whole, larger and more numerous than those of the Ciudad Granada group. However, in areas where only the Viñuela group appears, Ciudad Granada-type formations are likely to lie beneath them in the inner basin areas.

4. Stratigraphic sequences

Stratigraphic descriptions, in varying degrees of detail, of the different formations comprising the Ciudad Granada and

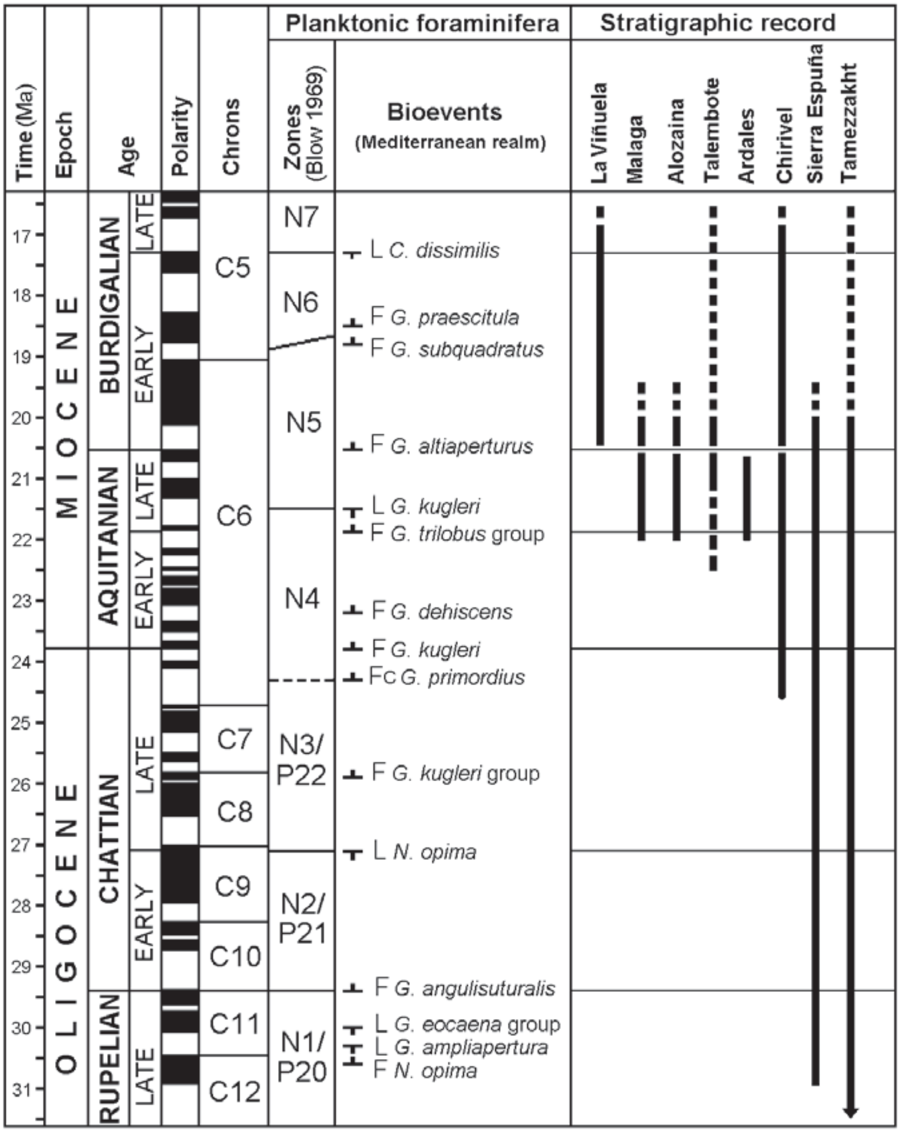

Fig. 4. Sedimentation chronology of the formations of the Ciudad Granada and Viñuela groups in representative sequences, determined by mean of planktonic foraminifera. F: first occurrence. Fc: first common occurrence. L: last occurrence.

Viñuela groups can be found in the above-mentioned studies. In the present study, we focus on the stratigraphic features required to characterize each group, in order to reconstruct their depositional setting (Fig. 3).

Ciudad Granada group

The Ciudad Granada successions generally start with quartz-dominated, yellow puddingstones, that may laterally evolve into either brownish to grey chaotic conglomerates or sandstones. Upwards, these basal levels give way to greyish-brown or reddish monotonous pelites, which are the most characteristic facies of these formations. Sandy turbiditic beds and conglomerates, made up of Malaguide-derived detritics (Fig. 3), commonly intercalate within this pelitic interval.

In many places (Sierra Espuña, Loc. 1; Chirivel, Loc. 2; Malaga, Loc. 13; Tetuan, Loc. 21; see Fig. 1), polymictic conglomerates occur at the top of this sequence. These conglomerates rework a mixture of metamorphic, granitic, or basalt pebbles, partly supplied from Malaguide and Alpujarride sources, and partly from unknown origins (Martín-Algarra et al. 2000, El Kadiri et al. 2001, 2006). The conglomeratic erosive bases may rip up red clayey clasts from Triassic strata or from Palaeozoic schists. In Sierra Espuña, the polymictic conglomerates alternate with reddish pelites, which conformably and gradually change upwards to grey and greenish mudstones of the Viñuela-type El Niño formation (Martín-Martín 1996). In Chirivel, conglomerate lenses lie at the top of the Ciudad Granada formation (the *black conglomerate* of Soediono 1971). In Malaga, (Loc. 13 in Fig. 1) equivalent conglomerates directly rest on Ciudad Granada reddish pelites, while their upper levels alternate with Viñuela-type light-coloured marls.

Viñuela group

The Viñuela formations normally consist of two well-contrasted members: **i**) a conglomeratic lower member reworking pebbles from both the Malaguide and Alpujarride basements, and **ii**) an upper member dominated by light-coloured siliceous marls with silexites and turbiditic intercalations (Fig. 3).

In the type area (La Viñuela, Loc. 8 in Fig. 1), the coarse-grained lower member exhibits a fining-upward trend and may rests directly on a Malaguide or Alpujarride basement. Its chaotic basal levels may consist of metric to decimetric boulders. These clastic facies, with a very reduced or absent muddy matrix, strongly recall grain-flow facies R1/R3 and S1/S3 of Lowe (1982). They are well known to be triggered from over steepened faulted continental slopes, and to be efficient over short distances only. Upwards, the fine-grained matrix supporting pebbles contains microfauna, mainly planktonic foraminifera, suggesting an open marine environment. The top of this member contains intercalations of light-coloured marls showing the transition towards the upper member.

In the outcrops lying far from the basin edges, the lower member is usually thinner and the pebbles become smaller and more rounded. Thus, it resembles the conglomerates found at the top of the Ciudad Granada. The attribution of these intermediate conglomerates to either group may be proposed based only on the nature of the intercalated pelites. The light-coloured marls of the upper member of Viñuela-type formations are typically rich in biogenic silica, which sometimes develops as silexite beds (Sierra Espuña; Cortijo Cherino, Loc. 11 in Fig. 1). Turbiditic intercalations made up of micaceous marly sandstones (Didon 1969) may also appear, recalling the silici-clastic facies widespread in the Predorsal and the Mauretanian flysch units. The stratigraphical position of the silexites with respect to the turbidites varies from one sequence to another. At La Viñuela, the lower part of the marly member is more siliceous, while the upper part contains a higher proportion of turbidites and these develop into thicker beds. However, in Sierra Espuña, the turbidites are more common towards the bottom, and the silexites lie rather at the top of the series (Martín-Martín 1996).

In Tamezzakht (Loc. 22 in Fig. 1; Predorsal domain), there are no facies characteristic of Ciudad Granada. All the late Oligocene–early Miocene sedimentation develops entirely into facies of light-coloured marls with sandy-micaceous turbidites similar to those of the Viñuela group (Fig. 3). Nevertheless, the siliceous nature of the sedimentation seems to be restricted mainly to the early Burdigalian.

Stratigraphical setting

Ciudad Granada-type formations unconformably rest over Malaguide or Dorsal rocks (Fig. 3). The lower levels in these areas commonly consist of a chaotic interval that recalls coeval olistostromes described by Serrano et al. (1995) and El Kadiri et al. (2001).

Outcrops where Ciudad Granada- and Viñuela-type sequences stack in a single stratigraphic succession are confined mostly to the border of depocenters (e.g., Malaga basin, Talembote). Here, the normal faults preceding the onset of the Viñuela group, first tilted Ciudad Granada strata, which resulted in an angular and/or erosional unconformity of varying degree, in between (Fig. 3). Basinwards, this contact progressively evolves into a parallel conformity preserving discrete erosional features (Cortijo de la Almoloya in Sierra Espuña, Fig. 2 cross section I-I'; Rambla de Frac in the Chirivel sector). A good example of these vertical and lateral stratigraphic relationships can be found close to the city of Malaga: the unconformity between Ciudad Granada and the Viñuela basal conglomerates is clearly angular at the edge of the outcrop (at km 239.5 on the highway). However, towards the centre of the outcrop (e.g. 1.5 km SE), their separating contact becomes an erosional surface lying between quite parallel layers (Fig.2 cross section IV-IV').

In the Rifian Talembote sequence (Loc. 23 in Fig. 1), green pelites with Viñuela-type silexites succeed Ciudad Granada-type marly sandstones, through an erosion surface, which may be sealed by coarse-grained breccias (facies R1 of Lowe 1982) and olistostromes. However, in the Tamezzakht Predorsalian sequence (El Kadiri et al. 2005, 2006), the late Oligocene–earliest Miocene levels appears in sedimentary continuity with the underlying Paleogene sediments.

5. Biostratigraphy and Chronostratigraphy

The sedimentation chronology of the Ciudad Granada and Viñuela formations is determined on the basis of assemblages of planktonic foraminifera present in representative sections (Fig. 4). The most significant biostratigraphic events in the Mediterranean domain are correlated with the magnetostratigraphy and with absolute ages, following Berggren et al. (1995).

The sedimentation timing of Ciudad Granada-type formations

Most authors state that the sedimentation of Ciudad Granada-type formations synchronously began by the Oligocene-Aquitanian boundary. However, detailed biostratigraphic analyses reveals that the onset of these formations is diachronous from the bordering units of the BRIZ (e.g. Predorsal) to its inner areas. In the internal troughs of the BRIZ (Alozaina, Malaga), the basal levels of the Ciudad Granada formations contain assemblages of planktonic foraminifera that are characteristic of the Aquitanian. The presence in these levels of *G. woodi* (see taxonomic appendix) and the first representative specimens of the *G. trilobus* group (*G. inmaturus* and *G. quadrilobatus*) points to the late Aquitanian.

In Chirivel, the Ciudad Granada sequences were deposited on a Malaguide basement, probably located in the vicinity of

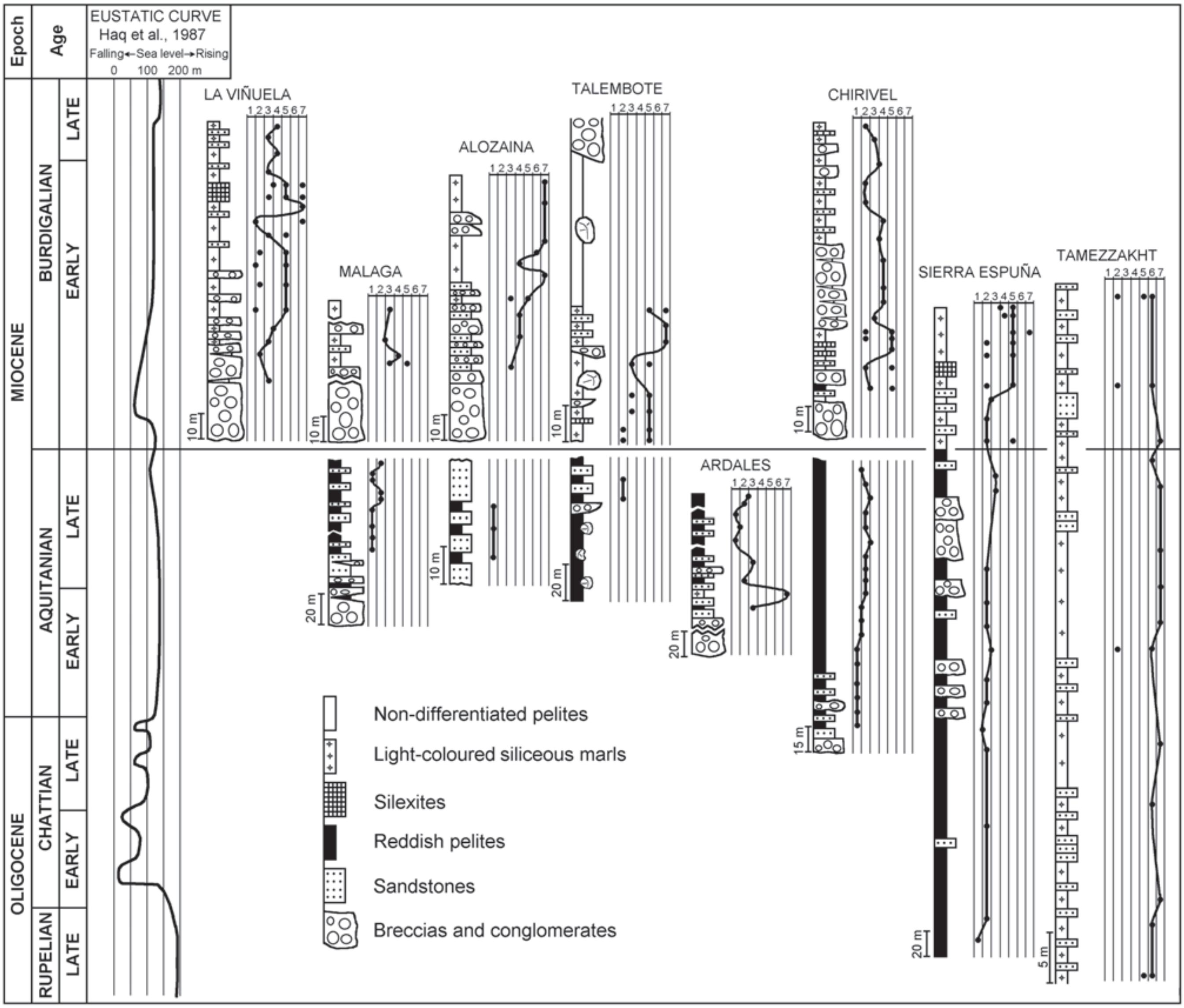

Fig. 5. Environmental characterization of the sedimentation of the Ciudad Granada and Viñuela groups in representative sequences, reconstructed based on assemblages of organisms within pelitic sediments. 1-7: faunal assemblages (see text for description). Dotted lines: principal assemblages; isolated dots: subsidiary assemblages.

the calcareous Dorsal. In this sector, *G. primordius* and *G. kugleri* appear from the base levels, which indicate that the deposition began close to the Oligocene-Aquitanian boundary. The Talembote sequence in the Rif and Pantano Andrade Fm., Ardales area, in the Betics) could have been deposited in equivalent paleogeographic settings. In both areas, planktonic assemblages have confirmed the late Aquitanian age of the sediments, but it has not yet been possible to date the basal levels.

The Sierra Espuña sequences were deposited on a Dorsal basement, where Ciudad Granada sedimentation began very early. The presence of *G.* gr. *eocaena* and *N. opima* in the basal deposits suggests they may belong to the highest part of Blow's P20/N1 zone of the latest Rupelian.

The Tamezakht sequence, deposited in a Predorsal area close to the Dorsal, shows a sedimentary continuity between the Oligo-Aquitanian deposits and the underlying Paleogene sequence. Middle Oligocene, hemipelagic, yellow marls alternated with thin distal turbidites and change upwards to Viñuela-type, light-coloured marls. The transitional interval between the two facies contains an assemblage with *N. opima, G. increbescens, G. eocaena* and *G. corpulenta* that is characteristic of the N21 zone of the late Rupelian.

Sedimentation timing of the Viñuela-type facies

The basal breccia of Viñuela-type formations rarely contains fauna. The only exception observed in the present study was in the type section (La Viñuela), where the finest breccia matrix yielded an early Burdigalian planktonic assemblage with *G. altiaperturus, G. trilobus* and *C. dissimilis* (upper part of the N5 zone). Identical assemblages are found in the first levels of light-coloured marls that are intercalated at the top of the breccias as well as in the Malaga intermediate conglomerates lying between Ciudad Granada and Viñuela Fms (Serrano et al. 1995). The absence of *G. subquadratus* from all these levels reveals that the onset of the Viñuela group occurred by the beginning of the early Burdigalian.

In Sierra Espuña, the uppermost levels of reddish pelites of the Ciudad Granada-type Fm. contain *G.* gr. *trilobus*, whereas *G. altiaperturus* appears in the first few metres of the light-coloured siliceous marls of the Viñuela-type Fm. Thus, in this area the passage between these formations also occurs close to the Aquitanian/Burdigalian boundary.

In agreement with the above data, the biostratigraphy of planktonic foraminifera fails to reveal any significant stratigraphic gap between the uppermost deposits of the Ciudad Granada formations and the immediately overlying Viñuela levels.

It should be emphasized that, although the Viñuela siliceous light-coloured marls clearly contrast with the Ciudad Granada red pelites, the corresponding facies change does not occur so sharply, since these facies can alternate during a transitional interval (e.g., Chirivel, Ardales). As mentioned above, in the Predorsal domains, Viñuela-type facies appears precociously by the end of the middle Oligocene and lasts during the Aquitanian–early Burdigalian interval, with no apparent internal stratigraphic hiatus or discontinuity. The breccias and polymictic conglomerates can no longer be used as "breaking levels" between the studied groups, since they may intercalate within both the upper part of the reddish pelites and the lower part of the overlying siliceous marls.

Therefore, the data appear to indicate that a sedimentary transition occurred from Ciudad Granada- to Viñuela-type deposits, and that this transition roughly coincides with the Aquitanian-Burdigalian boundary.

The stratigraphic top of the Viñuela formations is not visible, either because it eroded or was hidden below Flysch nappes or post-nappe formations. The most complete sequences have been recognized in La Viñuela and Chirivel successions. Their uppermost levels are characterized by the disappearance of the *C. dissimilis* group, concurrently with the abundance of the *G. trilobus* group bearing an enveloping final chamber (*G. bisphaericus*) and *Globoquadrina* (*G. dehiscens, G. baroemoenensis* and *G. globosa*). This assemblage suggests that deposition of the Viñuela formation continued at least until the beginning of the N7 zone of the late Burdigalian. The end of Viñuela sedimentation could also be marked by the oldest post-Viñuela deposits. In the Chirivel area (Fm. Maiz, Hermes 1978) and in Sierra Espuña (Fm. Bernabeles, Lonergan 1991; Martín-Martín 1996), the basal sediments of these formations yielded planktonic foraminifera that still correspond to the N7 zone of the late Burdigalian (dating by F. Serrano in Martín-Martín 1996).

6. Depositional environment

The depositional environment of Ciudad Granada and Viñuela-type sequences can be interpreted based on the micro paleontological content of their pelite levels from representative sections. This includes the proportions of planktonic foraminifera (P) with respect to the total foraminifera (F), the abundance of radiolaria (R) and that of agglutinated foraminifera (A). According to data from present-day depositional environments by Phleger (1951), Parker (1954), Van Andel and Veevers (1967), Reiss et al. (1974), Berger (1974), Berger et al. (1978) and Gibson (1989), seven major assemblages can be distinguished:

1. Assemblages dominated by benthic foraminifera ($P/F < 0.33$), represented mainly by calcareous forms. These taphocenoses generally accumulate at depths of less than 200 m and characterize shelf environments.
2. Assemblages that are rich both in planktonic and benthic foraminifera (P/F: 0.33–0.66), with the latter being dominated by carbonate-shelled forms. These assemblages tend to accumulate at depths of 200–500 m and do characterize outer-shelf, upper-bathyal environments and depth-equivalent environments.
3. Assemblages dominated by planktonic foraminifera (P/F: 0.66–0.90). These usually accumulate in bathyal environments and in their bathymetric equivalents (200–2000 m).
4. Assemblages comprised almost entirely of planktonic foraminifera ($P/F > 0.90$), generally formed between 1000 m water depth and the calcite compensation depth.
6. Assemblages rich in radiolaria ($P/R < 0.33$), in which planktonic foraminifera frequently, though not always, prevail over benthic calcareous foraminifera. These assemblages correspond to environments similar to those of the previous class, or to deeper ones. Such assemblages are currently found at pelagic depths at low latitudes of the Pacific and Indian Oceans (Jenkins 1978). High concentrations of radiolarians have also been reported in areas of volcanic activity, where biosiliceous productivity could be increased, thus favouring the dissolution of carbonates.
6. Assemblages dominated by agglutinated foraminifera ($A/F > 0.5$) with varying proportions of planktonic components (foraminifera and radiolaria) and deep calcareous benthic components. These normally correspond to deep deposits, below the lysocline, where carbonates have been totally or partially dissolved. The possibility should also be considered that these may correspond to deposits above the lysocline, in which carbonates dissolve during sediment diagenesis.

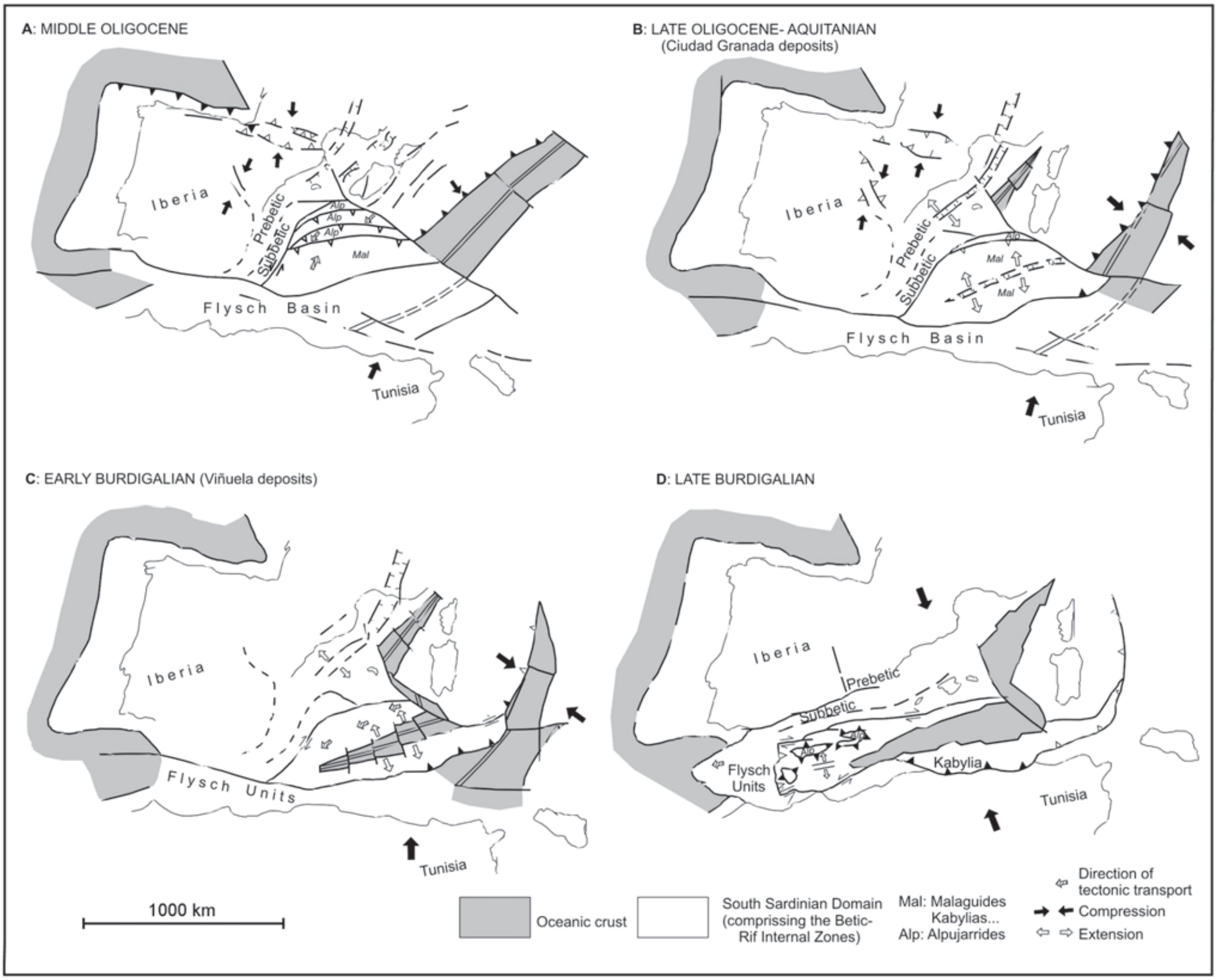

Fig. 6. Geotectonic framework during sedimentation of the transgressive formations of the Oligocene–early Miocene over the BRIZ.

7. Azoic pelitic levels that are not associated with any particular bathymetric environment. However, the sediments studied appear to be related mainly to levels containing the assemblages 6.

The results (Fig. 5) show that the pelites of the Ciudad Granada-type formations were primarily deposited in shelf and upper bathyal environments. The lower part of the more complete stratigraphic sequences (Sierra Espuña, Chirivel, and Malaga) reveals a relatively clear deepening trend, irrespective of the age at which these deposits began. This leads suggests that sedimentation is mainly influenced by tectonics, a result supported by the fact that the late Oligocene was an epoch with a relatively low eustatic level (Chart 2, De Graciansky et al. 1998). In the upper levels, which immediately underlie Viñuela-type pelites (Tamezzakht, Sierra Espuña), or where the top of the Ciudad Granada sequence has undergone only slight erosion (Chirivel), we note a slight shallowing-trend, which might be related to the final-Aquitanian eustatic fall. The BRIZ also reveals a tendency towards deeper environments from the inner troughs toward the Predorsal. Thus, the deposits in the Malaga and Alozaina sectors mainly present shelf assemblages (type 1), with few levels of the type 2 assemblages (outer shelf or upper bathyal). In Chirivel, which could be representative of the inner zone of the Malaguide, the lower part of the sequence contains type 1 assemblages, while type 2 assemblages predominate at the upper part (as in Talembote), with occasional examples of intermediate assemblages between type 2 and type 3. In Ardales, the only outcropping series contains assemblages of types 1, 2 and 3. In the Sierra Espuña sequences, which could represent deposits in dorsal areas, there is a predominance of type 2 assemblages, with few levels of type 3 assemblages. Finally, the Tamezzakht Oligo-Aquitanian sequence, with Viñuela-type facies deposited in the Predorsal domain, shows signs of the carbonate dissolution. Microfauna are very rare in these sediments and mainly consist of agglutinated foraminifera, sometimes accompanied by radiolarian and planktonic or calcareous benthic foraminifera (assemblages types 6 and 7). These deposits reveal environmental conditions similar to those of the Flysch trough. It is possible that in these deep areas, narrow troughs the lysocline could be notably shallower than present-day levels (3500-4000 m).

Nevertheless, the paleogeography would be somewhat more complex than the simple model described above. In the Sierra Espuña sector, for example, the Río Pliego Fm. (Ciudad Granada type) evolves laterally to the Bosque Fm.. According to Martín-Martín (1996), the latter formation consists of shallow-water carbonate-shelf deposits featuring the development of a delta fan.

On the whole, the Viñuela-type pelites suggest depositional environments much deeper than those of Ciudad Granada-type formations. Taking into account that the Aquitanian eustatic peak was higher than that of the Burdigalian times, and the Aquitanian- Burdigalian transition was characterized by a low eustatic level (Chart 1, De Graciansky et al. 1998), this early Burdigalian deeper facies should be related to an extensional tectonic pulse (Alonso Chaves and Rodríguez Vidal 1998) that created the Viñuela depocenters. In general terms, irrespective of the studied sector, the Viñuela sequences contain types 2–7 assemblages. In sequences where the highest chronostratigraphic levels are observed (La Viñuela and Chirivel), the top of the sequence offers evidence of a shallowing trend, but remains characteristics of bathyal environments.

7. Geotectonic framework

The first alpine phase affecting the BRIZ occurred in the late Cretaceous in the Nevado-Filabrides (Puga 1980) and probably also affected the Alpujarrides. During the Eocene (De Jong 1991, 1992) or from the Eocene to the late Oligocene, an important metamorphic event developed in the Nevado-Filabrides (Puga et al. 2002), and this could have occurred contemporarily with the Alpujarride metamorphism. Coevally, a less significant deformation took place in the Malaguides, leading the Paleogene sequences to rest on a Mesozoic basement through a low-angle unconformity resulting in variable stratigraphic hiatuses (Serrano et al. 1995). The Sierra Espuña sequence, where the Paleogene marine series is fairly complete, bears the record of a middle Oligocene folding phase (Martín-Martín 1996). This deformation could be related to the thrusting of the Malaguide over the Alpujarride. Close to the Flysch basin, these deformations are imperceptible, since in the Predorsal and in the Flysch trough, the Oligocene sequences show no internal unconformity. Nevertheless, in all these domains, there is a notable increase in detrital sedimentation during the Oligocene, this being particularly accentuated in the early Miocene. This change in sedimentation input appears to be linked to an uplifting/erosion double process controlled by the Oligocene tectonics.

The onset of Ciudad Granada-type formations occurred by the end of the middle Oligocene (Sierra Espuña), and more commonly in the late Oligocene–Aquitanian transition. They unconformably rest on the Malaguide complex or on the Dorsal (see Fig. 2), but we have never found these formations directly on the Alpujarride-type units in the BRIZ. On the contrary, Viñuela-type formations may rest on both Malaguide and Alpujarride units, sometimes sealing the thrust front between. According to Alonso Chaves & Rodríguez Vidal (1998), this contact shows an extensional movement in the area type of La Viñuela, induced by "the first Neogene rifting phase in the Betic Cordilleras". In both cases, the Viñuela basement clearly shows that the overthrusting of the Malaguide over the Alpujarride occurred before the beginning of the Burdigalian, but not necessarily at the end of the Aquitanian (i.e. it could have been earlier). Moreover, the close relationships between the Ciudad Granada and Viñuela formations with regard to the outcrop distribution, on one hand, and their vertical stacking in an apparent sedimentary continuity on the other, lead us to conclude that there was no nappe stacking stage during the transitional time span between. However, as above mentioned, their entire paleogeographic setting was the subject of major vertical displacements related to extensional tectonics.

Consequently, we propose that at the end of the middle Oligocene, and before the beginning of Ciudad Granada sedimentation, there had already occurred the double nappe stacking of the Alpujarride over the Nevado-Filabride, and the Malaguide over the Alpujarride. As a result, their ante-Oligocene domains ceased to act as differentiated paleogeographic settings. On the contrary, the regions located further south, from the Dorsal to the Flyschs trough, were moderately affected by Oligocene tectogenesis, and their paleogeographic domains persisted during the late Oligocene and the early Miocene.

By the end of the middle Oligocene, an extensional process began, concurrently with the westward migration of the BRIZ. Consequently, upfaulted Malaguide blocks (Zeck 2004) actively eroded, when adjacent larges areas underwent subsidence beneath a thick sedimentary pile. To the south, from the Dorsal to the Mauretanian domain, flysch deposits register a clear tendency to deepening (the Tamezzakht Oligo-Miocene formation in the Predorsal, the Algeciras-Béni Ider units in the Mauretanian flysch realm), but the Malaguide-derived sandy-micaceous turbidites continue to feature detrital materials. Further south, the Massylian and Numidian flyschs are mainly composed of a clastic material from Sahara sources (Durand-Delga 1980; Hoyez 1976).

At the beginning of this transtensional process (Fig. 6A) the BRIZ was located approximately south of Sardinia (Sanz de Galdeano 1990, 1997; Andeweg 2002). The progressive opening of the Algero-Provençal basin and the formation of a new oceanic crust displaced the BRIZ to the west. By the late Aquitanian, the extensional tectonics thinned the continental crust of the central sector of the BRIZ. This progressively resulted in the opening of the Alboran area: it was at this time that Ciudad Granada-type sedimentation began in the internal troughs of the BRIZ.

By the Aquitanian-Burdigalian transition, the extension process must have been accentuated to such the point that the previously downfaulted blocks underwent severe subsidence. This was the environment in which Ciudad Granada-type formations evolved into Viñuela-type formations (Fig. 6C). The most notable aspects of this turning event are as follows:

- Extensional pulses and deepening of the Ciudad Granada depocenters, which explains the transgressive character of Viñuela with respect to Ciudad Granada facies. This event was not necessarily sudden and synchronous as evidenced by : **i**) the gradual passage between these two facies groups, and **ii**) the recurrent coarse-grained detritics intercalated within both the upper and the base levels of the Ciudad Granada and Viñuela sequences, respectively.
- Fault-related tilting of the Ciudad Granada-type formations mostly at the edges of the basins, which explains the progressive low-angle unconformities.
- The Viñuela basal breccias showing both a basinward and upward fining. Its lenticular shape, with convex-up geometry close to the basin edges, indicates rock falls from steep escarpments (e.g., Cook & Mullins, 1983). These coarse-grained flows may transform into high-density turbidity currents (namely facies F4/F5 and F7/F8 of Mutti, 1992) that eroded part of the underlying Ciudad Granada deposits, which would explain the erosional surfaces that may locally separate these two groups.
- Extensional detachment along the Malaguide/Alpujarride thrust front locally exposing Alpujarride rocks. The latter was later partly transgressively covered by Viñuela deposits and partly upfaulted to act as new detrital sources. This depositional setting explains why the Viñuela formations can be deposited on both Malaguide and Alpujarride complexes, and even can seal the nappe contact (e.g. La Viñuela locality).
- Thermal anomaly, that in the Algero-Provençal basin fuelled the whole ocean-crust-related extensional process, also affected the axial trough of the BRIZ (Alboran protobasin), thus generating tholeitic basaltic dykes (traditionally termed diabases), which date from the Aquitanian (22–23 Ma, Torres Roldán et al. 1986). The basaltic dykes, located in the Malaga region from Fuengirola to Velez-Malaga, are observed in both the lower part of the Malaguide sequence and the overthrust Alpujarride unit. They were also found within Aquitanian coastal Rifian outcrops. Data from these dykes show that the Malaguide/Alpujarride nappe pile formed before the Aquitanian. The formation of these dykes is consistent with the opening up of the Alboran Sea (see Rehault et al. 1984, Comas et al. 1999), in a transtensive-dominated tectonic regime, although the external BRIZ fringe coevally played the role of a compressive to transpressive front. Platt & Whitehouse (1999) indicated that extension would have started at approximately 27 Ma, and a phase of rapid lithospheric extension and subsidence of the Alboran Domain occurred during the late Aquitanian–early Burdigalian. In accordance with these authors, Sánchez-Rodríguez & Gebauer (2000) suggested an age of about 20–18 Ma for the exhumation of Ronda peridotites area (Malaga) while Zeck (2004) indicated a rapid exhumation of the Alpujarride in the area of Malaga between 22 and 18 Ma. In deeper areas the crystalline networks of metamorphic minerals could have remained open until the pressure and the temperature had sufficiently decreased. Thus, in lower-lying complexes, such as the Nevado-Filabride, middle Miocene metamorphism (15 ± 0.6 Ma) has been recorded (López Sánchez-Vizcaíno et al. 2001).

When the extensional pulses of the latest Aquitanian attenuated, early Burdigalian light-coloured marls relayed the coarse-grained detritics. However, in many places, small-scale turbiditic flows still intercalate within the dilated marly sequences, and may reflect distal reverberations of the intermittent Mediterranean extensional regime. Regionally, the latter resulted in deepening the Malaguide and flysch depocenters to such a point that the biosiliceous signal became generalized. As shown by Lorenz (1984), the cryptocrystalline matrix of the early to middle Burdigalian silexites mainly consists of volcanic ash, a facies that recalls the late Jurassic supra-ophiolitic tufaceous cherts of the Coast Ranges (USA, e.g., Pessagno, 1977). In both cases, this kind of deposit was commonly paired with a drastic CCD-shallowing. A similar scenario would have occurred precisely during the early-middle Burdigalian transition, easily explaining why many early to middle Burdigalian levels contain very little calcareous microfauna (an additional role of diagenesis dissolution cannot be discounted).

While the BRIZ was migrating, its frontal areas began to collide with neighbouring domains from the beginning of the late Burdigalian (Fig. 6D). The presence of Subbetic clastics at the top of the Viñuela-type Espejos Fm. (Chirivel area, González Donoso et al. 1988) suggests that these two zones were already brought nearer at this time. This collision progressively produced the large-scale nappe pile: Malaguide (Ghomaride) / Dorsal / Predorsal / Flysch units. In the western part of the Betic-Rif orogen, the Flysch units overthrust more external zones concurrently with backthrusting processes, responsible for their superposition onto the BRIZ (e.g., “Neonumidian” olistostromes of Bourgois, 1978). This tectonic setting can be observed in the Malaga basin, in the Colmenar corridor (Fig. 2, cross-section III–III’), and in Morocco, north of Tetuan (Jebel Zem-Zem; Fig. 2, cross-section V-V’). The Dorsal and the Malaguide also underwent either overthrusting or backthrusting, depending on the points.

The Gibraltar Arc was formed during this process, while severe deformations resulted both at the BRIZ edges and in the External Zones. During the Burdigalian, the northern edge of the BRIZ was the subject of a strong dextral transpression, along which certain units were left behind the BRIZ (Sierra Espuña, Chirivel, Sierra Arana, and Ardales). As a consequence, some of these backward units underwent considerable clockwise rotation (Parés et al. 1992; Allerton et al. 1993). If these latter units were relocated in their former paleogeographic situation, the whole northern set of outcrops of the Ciudad Granada group would be situated on the southern or western border of the BRIZ. These considerations lead us to conclude that the sedimentation in the more northern sectors began only after the transtensive pulse of the Aquitanian-Burdigalian boundary (see Fig. 3). The huge tectonic instability on the northern border of the BRIZ triggered large-scale olistostromes and tectonic breccia (Espejos Fm. in Chirivel, Majiaza complex in Colmenar, Loma del Castillo in Ardales).

At present, the Sierra Espuña outcrops are also located on the northern (visible) border of the BRIZ, but they show two peculiarities: **i**) the transition between Ciudad Granada and Viñuela-type formations was gradual and took place in pelitic sedimentation no significant hiatus evident; **ii**) there is no sign of large olistostromic deposits associated with Viñuela-type formations. This sector probably remained stable and far from the olistostromic areas, but we should also consider that in the late Burdigalian it would be overthrust by the Subbetics (External Betic Zone), covering thus most Viñuela-type sediments (see Fig. 2 cross section I-I').

The collision between the BRIZ and the External Zones results in the disappearance of the Viñuela depositional basins, so that during the remaining times of the late Burdigalian, sedimentation in the BRIZ was restricted to the eastern Betic sector.

Conclusions

Biostratigraphic analyses and the regional review of the facies evolution and the stacking pattern of the Oligocene-early Miocene sedimentation on the Betic-Rif internal zone lead us to reach the following conclusions:

- Ciudad Granada and Viñuela groups outcrop throughout the BRIZ, along both the borders and the central depocenter areas. The variability of stacking pattern and facies evolution between these depositional zones reflects a common paleogeography and complementary tectonic histories.
- Deposition of the Ciudad Granada group diachronously started from the end of the middle Oligocene in the Dorsal domain and lasted until the late Aquitanian in the internal axial troughs of the BRIZ. The sedimentation took place in shelf and upper bathyal marine environments, and bears the record of a tectonically controlled deepening trend.
- The tectonically induced facies change of Ciudad Granada reddish yellows marls into the Viñuela marlstones and pelites, should rather be ascribed to a late Aquitanian-early Burdigalian transtensive phase induced by the Alboran basin opening. This phase resulted in deepening the depocenters, which explains why the shelf–upper bathyal Ciudad Granada deposits evolved into the Viñuela pelagic marls. Moreover, the volcanic ash-bearing silexites (i.e, tufaceous cherty facies) indicate submarine volcanic activity that resulted at least in the causally linked biosiliceous productivity and CCD-shallowing (among other environmental stresses). On the contrary, in horst settings, the exhumed Alpujarride rocks play the role of detrital sources.
- However, the Ciudad Granada–Viñuela sedimentary change did neither occur suddenly nor synchronously throughout the whole BRIZ. Thus, both facies alternate during the late Aquitanian–earliest Burdigalian in the Dorsal domain, and as early as the late middle Oligocene in the Predorsal domain where the Viñuela facies developed. Later, the Viñuela silexite-intercalated marlstones became a monotonous and widespread facies throughout all the BRIZ depocenters during the early Burdigalian times.
- Field evidence, such as the conformity between Ciudad Granada and Viñuela deposits far from the faulted borders, synsedimentary normal faults, and the Viñuela transgressive base levels sealing the Malaguide/Alpujarride thrust front, implies that no nappe-emplacement phase occurred during the transition from Ciudad Granada to Viñuela Fms. This suspected paroxysmal tectonics could have already occurred during the middle Oligocene, as satisfactorily supported by the sudden Malaguide-derived siliciclastic input, since the middle Oligocene, in both the Dorsal and the flysch domain (e.g., El Kadiri et al. 2005, 2006).

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Taxonomic appendix (formal names)

***C.* gr. *dissimilis*:** group of *Catapsydrax dissimilis* (Cushman & Bermúdez), including:

Catapsydrax dissimilis (Cushman & Bermúdez), 1937
Catapsydrax unicavus Bolli, Loeblich & Tappan, 1957

***G. angulisuturalis*:** *Globigerina angulisuturalis* Bolli, 1957

***G.* gr. *eocaena*:** group of *Globigerina eocaena* Guembel, including:

Globigerina corpulenta Subbotina, 1953
Globigerina eocaena Guembel, 1868
Globigerina gortani (Borsetti), 1959

***G.* gr. *ampliapertura*:** group of *Globigerina ampliapertura* Bolli, including:

Globigerina ampliapertura Bolli, 1957
Globigerina increbescens Bandy, 1949
G. woodi*: *Globigerina woodi Jenkins, 1960
G. subquadratus*: *Globigerinoides subquadratus Brönnimann, 1954
G. altiapertus*: *Globigerinoides altiapertus Bolli, 1957
G. primordius*: *Globigerinoides primordius Blow & Banner, 1962
***G.* gr. *trilobus*:** group of *Globigerinoides trilobus* (Reuss), including:
Globigerinoides inmaturus LeRoy, 1939
Globigerinoides quadrilobatus (d'Orbigny), 1846; lectotype: Banner & Blow, 1970
Globigerinoides trilobus (Reuss), 1850
Globigerinoides bisphaericus Todd, 1954
***G. praescitula*:** *Globorotalia praescitula* Blow, 1959
***G.* gr. *kugleri*:** group of *Globorotalia kugleri* Bolli, including:
Globorotalia kugleri Bolli, 1957
Globorotalia pseudokugleri Blow, 1969
***G. dehiscens*:** *Globoquadrina dehiscens* (Chapman, Parr & Collins), 1934
***G. baroemoenensis*:** *Globoquadrina baroemoenensis* (LeRoy), 1939
***G. globosa*:** *Globoquadrina globosa* Bolli, 1957
***N. opima*:** *Neogloboquadrina opima* (Bolli), 1957

REFERENCES

AGUADO, R., FEINBERG, H., DURAND-DELGA, M., MARTÍN-ALGARRA, A., ESTERAS, M. & DIDON, J. 1990: Nuevos datos sobre la edad de las formaciones miocenas transgresivas sobre las Zonas Internas béticas: la Formación de San Pedro de Alcántara (Provincia de Málaga). Rev. Soc. Geol. España 3, 79–85.

ALLERTON, S., LONERGAN, L., PLATT, J.P., PLATZMANN, E.S. & MCCLELLAND, E. 1993: Paleomagnetic rotation in the eastern Betic Cordillera, southern Spain. Earth Planet. Sci. Lett. 119, 225–241.

ALONSO CHAVES, F.M. & RODRÍGUEZ VIDAL, J. 1998: Subsidence tectonique et sédimentation synrift associée au *rifting* du domaine d'Alboran au Miocène inférieur (Chaîne bétique, Espagne). C.R. Acad. Sci. (Paris) 326, 51–56.

ANDEWEG, B. 2002: Cenozoic tectonic evolution of the Iberian Peninsula. Causes and effects of changing stress fields. PhD Thesis, Univ. Amsterdam, 178 pp.

ANDRIEUX, J., FONTBOTÉ, J.M. & MATTAUER, M. 1971: Sur un modèle explicatif de l'Arc de Gibraltar. Earth Planet. Sci. Lett. 12, 191–198.

BEN YAICH, A., MAATÉ, A., FEINGBERG, H., MAGNÉ, J. & DURAND-DELGA, M. 1986: Implication de niveaux du Miocène inférieur dans les rétrochevauchements de la Dorsale rifaine (Maroc), signification à l'échelle de l'Arc de Gibraltar. C.R. Acad. Sci. (Paris) 302, 587–592.

BERGER, W.H. 1974: Deep-sea sedimentation. In : BURK CA. & DRAKE CL. (Eds): Continental margins, 213–241, Springer-Verlag, New York.

BERGER, W.H. & WINTERER, E.L. 1978: Pelagic sedimentation, pelagic sediments. In: FAIRBRIDGE, R.W. & BOURGEOIS, J. (Eds): The Encyclopedia of Sedimentology, 544–558, Downden, Hutchinson Ross, Stroudsburg.

BERGGREN, W.A., KENT, D.V., SWISHER, C.C. & AUBRY, M.P. 1995: A revised geochronology and chronostratigraphy. In: BERGGREN, W.A., KENT, D.V., AUBRY, M.P. & HARDENBOL, J. (Eds): Geochronology Time Scales and Global Stratigraphic Correlation. SEPM Spec. Publ. 54, 129–212.

BLOW, W.H. 1969: Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: BRÖNNIMANN, P., & RENZ, H.H. (Eds.), Proc. First Int. Conf. Planktonic Microfossils, 199–422, Geneva, 1967, Leiden (E.J. Brill).

BOUILLIN, J.P., DURAND-DELGA, M. & OLIVIER, P. 1986: Betic-Rifain and Tyrrhenian Arcs: distinctive features, genesis and development stages. In: WEZEL, F.C. (Ed.): The origin of arcs, 281–304, Elsevier, Amsterdam.

BOULIN, J., BOURGOIS, J., CHAUVE, J., DURAND-DELGA, M., MAGNE, J., MATHIS, V., PEYRE, Y., RIVIÈRE, M. & VERA, J.A. 1973: Age miocène inférieur de la Formation de la Viñuela, discordante sur les nappes internes bétiques (Province de Málaga, Espagne). C.R. Acad. Sci. (Paris) 276, 1245–1248.

BOURGOIS, J. 1978: La transversale de Ronda, Cordillères Bétiques, Espagne. Données géologiques pour un modèle d'évolution de l'Arc de Gibraltar. Thesis. Annales Scientifiques de l'Universite de Besancon, Géologie 30.

BOURGOIS, J., CHAUVE, P., MAGNE, J., MONNOT, J., PEYRE, Y., RIGO, E. & RIVIÈRE, M. 1972: La formation de las Millanas. Série burdigalienne transgressive sur les Zones Internes des Cordillères bétiques occidentales (région d'Alozaina-Tolox, province de Malaga, Espagne). C.R. Acad. Sci. (Paris) 275, 169–172.

BOURGOIS, J., CHAUVE, P., MAGNE, J., MONNOT, J., PEYRE, Y., RIGO, E. & RIVIÈRE, M. 1972: La formation d'Alozaina. Série d'âge oligocène et aquitanien transgressive sur le Bétique de Malaga (région d'Alozaina-Tolox, province de Malaga, Espagne). C.R. Acad. Sci. (Paris) 275, 531–534.

BOURGOIS, J., CHAUVE, P. & PEYRE, Y. 1973: Trame de l'histoire post-aquitanienne des Cordillères bétiques occidentales. C.R. Acad. Sci. (Paris) 276, 1393–1396.

CHALOUAN, A., MICHARD, A., FEINBERG, H., MONTIGNY, R. & SADDIQI, O. 2001: The Rif mountains building (Morocco): a new tectonic scenario. Bull. Soc. géol. France 172, 603–616.

CHALOUAN, A. & MICHARD, A. 2004: the Alpine Rif Belt (Morocco): a case of Mountain building in a Subduction-subduction-transform fault triple junction. Pure and applied Geophysics 161, 489–519.

COMAS, M.C., GARCÍA-DUEÑAS, V. & JURADO, M.J. 1992: Neogene tectonic evolution of the Alboran Sea from MCS data. Geo-Marine Letters 12, 157–164.

COMAS, M.C., PLATT, J.P., SOTO, J.I. & WATTS, A.B. 1999: The origin and tectonic history of the Alboran Basin: insights from Leg 161 results. In: ZAHN, R., COMAS, M.C. & KLAUS A. (Eds.): Proc. ODP, Sci. Results, 161: College Station, TX (Ocean Drilling Program), 555–580.

COOK, H.E. & MULLINS, H.T. 1983: Basin margin environment. In: SCHOLLE, P.A, BEBOUT, D.G. & MOORE, C.H. (Eds): Carbonate depositional environments, AAPG Memoir 33, 540–617.

CRESPO-BLANC, A., OROZCO, M. & GARCÍA-DUEÑAS, V. 1993: Extension versus compression during the Miocene tectonic evolution of the Betic Chain. Late folding of normal fault systems. Tectonics 13, 78-88.

DE GRACIANSKY, P.C., HARDENBOL, J., JACQUIN, TH. & VAIL, P.R. 1998: Cenozoic Sequence Chronostratigraphy. In: DE GRACIANSKY, P.C. (Ed.): Mesozoic and Cenozoic Sequence Chronostratigraphic Framework of European Basins. SEPM Spec. Publ. 60.

DE JONG, K. 1991. Tectono-metamorphic studies and radiometric dating in the Betic Cordilleras (SE Spain), with implications for the dynamics of extension and compression in the western Mediterranean area. Thesis Univ. Amsterdam, 204 pp.

DE JONG, K. 1992: A new Geodynamic Model for the Betic Cordilleras based on P-T-t path and Structural data from the Eastern Betic. Física de la Tierra 4, 77–107, Ed. Complutense, Madrid.

DE JONG, K. 1993: Redefinition of the deformation scheme of the Mulhacen Complex and implications for the relative timing of the overthrusting of the Alpujarride Complex in the Betic Zone (SE Spain). Geol. Mijnbouw 71, 317–326.

DIDON, J. 1969: Etude géologique du Campo de Gibraltar (Espagne méridionale). Thèse Univ. Paris. 539 p.

DIDON, J., DURAND-DELGA, M. & KORNPROBST, J. 1973: Homologies géologiques entre les deux rives du détroit de Gibraltar. Bull. Soc. géol. France 15, 77–105.

Durand-Delga, M. 1972. La courbure de Gibraltar, extrémité occidentale des chaînes alpines, unit l'Europe et l'Afrique. Eclogae geol. Helv. 65, 267–278.

Durand-Delga M. 1980: La Méditerranée occidentale: étapes de sa genèse et problèmes structuraux liés à celle-ci. Livre Jubiliaire à la Mémoire de P. Lucas, Soc. géol. France, Mém. hors sér. 10, 1830–1980.

Durand-Delga, M. & Fontboté, J.M. 1980: Le cadre structurale de la Méditerranée occidentale. 26th Congrès Géol Intern Paris, Géologie des Chaînes Alpines issues de la Tethys. Mem. B.R.G.M. 15, 67-85.

Durand-Delga, M., Leikine, M. & Magné, J. 1964: Au sujet du Nummulitique lié à la zone paléozoïque du Rif interne (Maroc). C.R. Acad. Sci. (Paris) 259, 1167–1170.

Durand-Delga M., Feinberg, H., Magné, J., Olivier, P. & Anglada, R. 1993: Les formations oligo-miocènes discordantes sur les Malaguides et les Alpujarrides et leurs implications dans l'évolution géodynamique des Cordillères bétiques (Espagne) et de la Méditerranée d'Alboran. C.R. Acad. Sci. (Paris) 317, 679–687.

El Kadiri, K., Chalouan, A., El Mrihi, A., Hlila, R., López-Garrido, A.C., Sanz de Galdeano, C. & Serrano, F. 2000: Descubrimiento del Burdigaliense (formación Viñuela) en la cobertera Gomáride de Ceuta (Rif septentrional). Geogaceta 28, 43–46.

El Kadiri, K., Chalouan, A., El Mrihi, A., Hlila, R., López-Garrido, A., Sanz de Galdeano, C., Serrano, F. & Kerzazi, K. 2001: Les formations sédimentaires olistolitiques de l'Oligocène supérieur-Miocène inférieur dans l'unité ghomaride des Béni Hozmar (secteur de Talembote, Rif septentrional, Maroc). Eclogae geol. Helv. 94, 313–320.

El Kadiri, K, Hlila, H, Sanz-De-Galdeano, C, López-Garrido, C.A, Chalouan, A, Serrano, F, Guerra-Merchán, A. & Liemlahi, H. 2006: Regional correlations across the Internides/Externides front (northwestern Rif Belt, Morocco) during the Late Cretaceous-Early Burdigalian times: paleogeographical and paleotectonic implications. In: Moratti, G. & Chalouan, A. (Eds): Tectonics of the Western Mediterranean and North Africa. Geological Society, London, Special Publication 262 (in press).

Feinberg, H., Maaté, A., Bouhdadi, S., Durand-Delga, M., Maate, M., Magné, J. & Olivier, Ph. 1990: Signification des dépôts de l'Oligocène supérieur-Miocène inférieur du Rif interne (Maroc), dans l'évolution géodynamique de l'Arc de Gibraltar. C.R. Acad. Sci. (Paris) 310, 1487–1495.

Frizon de Lamotte, D., Andrieux, J. & Guézou, J.C. 1991 : Cinematique des chevauchements néogènes dans l'Arc Bético-Rifain: Discussion sur les modèles Géodynamiques. Bull. Soc. géol. France 162, 4, 611–626

García-Dueñas, V., Balanyá, J.C. & Martínez Martínez, J.M. 1992: Miocene extensional detachments in the outcropping basement of the northern Alboran basin (Betics) and their implications. Geo-Marine Letters 12, 2/3, 88–95

Geel, T. 1973: The Geology of the Betic of Malaga, the Subbetic, and the zone between these two units in the Vélez Rubio Area (Southern Spain). Gua Papers of Geology 5, 1–181.

Gibson, T.G. 1989: Planktonic benthonic foraminiferal ratios: modern patterns and Tertiary applicability. Marine Micropaleontology 15, 29–52.

González Donoso, J.M. 1977–78: Los materiales miocénicos de la Depresión de Granada. Cuad. Geol. Univ. Granada 8–9, 191–204.

González Donoso, J.M., Linares, D. & Molina, E. 1981: Nuevos datos acerca de la edad de los materiales miocénicos transgresivos sobre las Zonas Internas de las Cordilleras Béticas en la provincia de Málaga. Bol. R. Soc. Esp. Hist. Nat. (Geol.) 79, 103–113.

González Donoso, J.M., Linares, D., Molina, E. & Serrano, F. 1988: El Mioceno inferior de Chirivel (Almería): bioestratigrafía, cronoestratigrafía y significado tectosedimentario de las formaciones Ciudad Granada y Fuente-Espejos. Rev. Soc. Geol. España 1, 53–71.

González Donoso, J.M., Linares, D., Molina, E., Serrano, F. & Vera, J.A. 1982: Sobre la edad de la formación de la Viñuela (Cordilleras Béticas, provincia de Málaga). Bol. R. Soc. Esp. Hist. Nat. (Geol.) 80, 255–275.

Guerrera, F., Martín-Algarra, A. & Perrone, V. 1993: Late Oligocene-Miocene syn-/late orogenic successions in Western and Central Mediterranean Chains from the Betic Cordillera to the Southern Apennines. Terra Nova 5, 525–544.

Haq, B. U., Hardenbol, J., & Vail, P. R. 1987: Chronology of fluctuating sea levels since the Triassic. Science 253, 1156–1167.

Hermes, J.J. 1978: The stratigraphy of the Subbetic and Southern Prebetic of the Vélez Rubio – Caravaca area and its bearing on transcurrent faulting in the Betic Cordilleras of Southern Spain. Kon. Neder. Ak. Wet. 81, 1–54

Hoyez, B. 1976: Dispersion du matériel quartzeux dans les formations aquitaniennes de Tunisie septentrionale et d'Algérie Nord-Orientale. Bull. Soc. géol. France 17, 1147–1156.

Jenkins, H.C. 1978: Pelagic environments. In: Reading, H.C. (Ed): Sedimentary environments and facies, 314–371, Blackwell, Oxford.

Jerez, L. 1979: Contribución a una nueva síntesis de las Cordilleras Béticas. Bol. Geol. y Min. España 90, 503–555.

Kirker, A.J. & Platt, J. 1998: Unidirectional slip vectors in the Western Betic Cordillera: implications for the formation of the Gibraltar arc. J. Struct. Geol. 155, 193–207.

Lonergan, L. 1991: The structural evolution of the Sierra Espuña, Betic Cordillera, SE Spain. Unpublished Thesis, Univ. Oxford, 154 pp.

Lonergan, L. 1993: Timing and kinematics of deformation in the Malaguide Complex, Internal Zone of the Betic Cordillera, S. Spain. Tectonics 12, 460–475.

Lonergan, L. & Mange-Rajetzky, A. 1994: Evidence for Internal Zone unroofing from foreland basin sediments, Betic Cordillera, SE Spain. J. Geol. Soc. London 151, 515–529.

López Sánchez-Vizcaíno, V., Rubatto, D., Gómez-Pugnaire, M.T., Trommsdorff, V. & Müntener, O. 2001: Middle Miocene high-pressure metamorphism and fast exhumation of the Nevado-Filábride Complex, SE Spain. Terra Nova 13, 327–332.

Lorenz, c. 1984: Les silexites et les tuffites du Burdigalien, marqueurs volcano-sédimentaires – corrélations dans le domaine de la Méditerranée occidentale. Bull. Soc. géol. France 26, 1203–1210

Lowe, D.R. 1982: Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. J. Sediment. Petrol. 52, 279–297.

Luján, M., Balanyá, J.C., Crespo-Blanc, A. 2000: Contrational and extensional tectonics in Flysch and Penibetic units (Gibraltar Arc, SW Spain): new constraints on emplacement mechanisms. C.R. Acad. Sci. Paris 330, 631–637.

Maaté, A., Martín-Algarra, A., Martín-Pérez, J.A., Serrano, F., Martín-Martín, M., Aguado, R. & El Hajjaji, K. 1995: Le Burdigalien inférieur de Boujarrah (Rif septentrional, Maroc) et la signification paléotectonique des séries miocènes transgressives sur les zones internes bético-rifaines. C.R. Acad. Sci. (Paris) 320, 15–22.

MacGillavry, H.G., Geel, T., Roep, TB. & Soediono, H. 1963: Further notes on the geology of the Betic of Malaga, the Subbetic and the zone between these two units, in the region of Velez-Rubio (Southern Spain). Geol. Rundsch. 53, 233–256.

Mäkel, G.H. 1985: The geology of the Malaguide Complex and its bearing on the geodynamic evolution of the Betic-Rif orogen (southern Spain and northern Morocco). GUA Papers of Geology 22, 264 pp.

Martín-Algarra, A. 1987: Evolución geológica alpina del contacto entre las Zonas Internas y las Zonas Externas de la Cordillera Bética. Thesis Univ. Granada, 1171 pp.

Martín-Algarra, A., Messina, A., Perrone, V., Russo, S., Maaté, A. & Martín-Martín, M. 2000: A Lost Realm in the Internal Domains of the Betic-Rif Orogen (Spain and Morocco): Evidence from Conglomerates and Consequences for Alpine Geodynamic Evolution. J. Geol. 108, 447–467.

Martín-Martín, M. 1996: El Terciario del dominio Maláguide en Sierra Espuña (Cordillera Bética oriental, SE de España). Estratigrafía y evolución paleogeográfica. Thesis Univ. Granada, 297 pp.

Martín-Martín, M. & Martín-Algarra, A. 1997: La estructura del área de Sierra Espuña (Contacto Zonas Internas-Externas, Sector oriental de la Cordillera Bética). Estudios Geológicos 53, 237–248.

Mutti, E. 1992: Turbidite sandstones. Agip, Spec. Pub. Milano-Instituto di Geologia, 275 pp.

Olivier, Ph. 1984: Evolution de la limite entre Zones Internes et Zones Externes dans l'Arc de Gibraltar (Maroc-Espagne). Thesis Univ. Paul Sabatier, Toulouse, 229 pp.

Paquet, J. 1969: Étude géologique de l'Ouest de la province de Murcie (Espagne). Mém. Soc. géol. France 48 (111), 1–260.
Parés, J.M., Pascual, J.O., Garcés, M., Dueñas, V. & Balanya, J.C. 1992: Resultados paleomagnéticos del Jurásico de Sierra Harana. In: Osete, M.L. & Calvo, M.(Eds.): Física de la Tierra. Paleomagnetismo y tectónica en las Cordilleras Béticas 4, 205–213, Complutense, Madrid.
Parker, F.L. 1954: Distribution of foraminifera in the north-eastern Gulf of Mexico. Harvard Univ. Mus. Comp. Zool. Bull. 111, 454–588.
Pessagno, E. A. Jr, 1977: Upper Jurassic radiolarian and radiolarian biostratigraphy of the California Coast Ranges: Micropaleontology 23, 56–113.
Peyre, Y. 1974: Géologie d'Antequera et de sa région (Cordillères bétiques, Espagne). Lab. Géol. Méditerranéenne, Thesis Univ. Paris, 528 pp.
Phleger, F.B. 1951: Foraminiferal distribution I, Ecology of foraminifera, northwest Gulf of Mexico. Geol. Soc. Amer. Mem. 46, 1–88.
Platt, J.P. & Vissers, R.L.M. 1989: Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alboran Sea and Gibraltar arc. Geology 17, 540–543.
Platt, J.P. , Whitehouse, M.J. 1999: Early Miocene high-temperature metamorphism and rapid exhumation in the Betic Cordillera (Spain): evidence from U-Pb zircon ages. Earth Planet. Sci. Lett. 171, 591–605.
Puga, E. 1980: Hypothèses sur la genèse des magmatismes calcoalcalins, intraorogénique et postorogénique alpins, dans les Cordillères bétiques. Bull. Soc. géol. France 22, 243–250.
Puga, E., Díaz de Federico, A. & Nieto, J.M. 2002: Tectonostratigraphic subdivision and petrological characterisation of the deepest complexes of the Betic zone: a review. Geodinamica Acta 15, 23–43.
Rehault, J.P., Mascle, J. & Boillot, G. 1984: Evolution géodynamique de la Méditerranée depuis l'Oligocène. Mem. Soc. Geol. Ital. 27, 85–96.
Reiss, Z., Halics, E. & Pereils, L. 1974: Planktonic foraminiferida from recent sediments in the Gulf of Elat. Israel J. Earth-Sci. 23, 69–105.
Riviére, M., Bourgois, J. & Feinberg, H. 1980: Evolution de la zone bétique au Miocène inférieur: asynchronisme tectonique entre l'Est et l'Ouest (Cordillères bétiques, Espagne). C.R. Somm. Soc. géol. France 1, 21–24.
Rodríguez-Fernández, J. 1982: El Mioceno del sector central de las Cordilleras Béticas. Thesis Univ. Granada, 224 pp.
Sánchez-Rodríguez, L., Gebauer, D. 2000: Mesozoic formation of pyroxenites and gabbros in the Ronda area (southern Spain), followed by Early Miocene subduction metamorphism and emplacement into the middle crust: U-Pb sensitive high-resolution ion microprobe dating of zircon. Tectonophysics 316, 19–44.
Sanz de Galdeano, C. 1990: Geologic evolution of the Betic Cordilleras in the Western Mediterranean, Miocene to the present. Tectonophysics 172, 107–119.
Sanz de Galdeano, C. 1997: La Zona Interna Bético-Rifeña. Monográfica Tierras del Sur. Univ. de Granada, 316 pp.
Sanz de Galdeano, C., Serrano, F., López-Garrido, AC. & Martín-Pérez, J.A. 1993: Paleogeography of the Late Aquitanian-Early Burdigalian Basin in the western Betic Internal Zone. Geobios 26, 43–55.
Serrano, F., Sanz de Galdeano, C., Delgado, F., López-Garrido, AC. & Martín-Algarra, A. 1995: The Mesozoic and Cenozoic of the Malaguide complex in the Málaga area: a Paleogene olistostrome-type chaotic complex (Betic Cordillera, Spain). Geol. en Mijnbouw 74, 105–116.
Soediono, H. 1971: Geological investigations in the Chirivel area, province of Almeria, Southeastern Spain. Thesis Univ. Amsterdam, 144 pp.
Torres Roldán, R., Poli, G. & Peccerillo, A. 1986: An Early Miocene arc tholeitic magmatic dik event from the Alboran Sea – Evidence for precollisional subduction and back-arc crustal extension in the westernmost Mediterranean. Geol. Rundsch. 75, 219–234.
Van Andel, Th. & Veevers, J.J. 1967: Morphology and sediments of the Timor Sea. Aust. Bur. Min. Resour., Geol. Geophys. Bull. 83, 1–73.
Vera, J.A. 1969: Estudio geológico de la zona Subbética en la transversal de Loja y sectores adyacentes. Mem. Inst. Geo. Min. Esp. 72, 1–191.
Völk, H.R. 1967: Zur Geologie und Stratigraphie des Neogens-Beckens von Vera, Südost-Spanien. Thesis Univ. Amsterdam, 160 pp.
Weijermars, R. 199: Geology and tectonics of the Betic zone, SE Spain. Earth Sci. Rev. 31, 153–236.
Wildi, W. 1983: La chaîne tello-rifaine (Algérie, Maroc, Tunisie): structure, stratigraphie et évolution du Trias au Miocène. Rev. Géol. Dyn. Geogr. Phys. 24, 201–297
Zeck, H.P. 2004: Rapid exhumation in the Alpine belt of the Betic-Rif (W Mediterranean): Tectonic Extrusion. Pure appl. Geophysics 161, 477–487.

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