The Western Mediterranean extensional basins and the Alpine orogen

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ABSTRACT

The western Mediterranean late Oligocene–Miocene basins (Alboran, Valencia and Provençal basins) are a coherent system of interrelated troughs. In all basins normal faults and thermal subsidence migrated toward the east progressively moving to the Miocene-to-Pleistocene Algerian and Tyrrhenian basins. All those troughs appear elements of the back-arc opening related to the eastward roll-back of the W-directed Apennines–Maghrebides subduction zone, similarly to western Pacific back-arc settings.

These late Oligocene–early Miocene basins nucleated both within the Betic cordillera (e.g. Alboran sea) and in its foreland (Valencia and Provençal troughs). The N40–70° direction of grabens is oblique to the coexisting N60–80°-trending orogen and shows its structural independence from the orogenic roots. Thus, as the extension cross-cuts the orogen and developed also well outside the thrust belt front, the westernmost basins of the Mediterranean had to develop independently from the Alps-Betics orogen. Therefore, the Alboran extension, considered a classic example of a basin generated by the collapse of an orogen, cannot be ascribed to the detachment or annihilation of the lithospheric root. In contrast with the eastward migrating extensional basins, the Betic-Balearic thrust front was migrating westward producing interference or inversion structures.

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Western Mediterranean basins

Extensional basins associated with convergent settings have been commonly associated with collapse of the orogens, attributed to detachment of the lithospheric roots or convective removal of the lithosphere (e.g. Platt and Vissers, 1989). The western Mediterranean is a laboratory where geological evidence can elucidate the relationships between extension and compression, since several basins formed within or close to active orogenic belts.

The Alboran sea opened mainly during the early Miocene (Comas *et al.*, 1992). Extension and subsidence migrated generally eastward within it (Docherty and Banda, 1995). The Valencia and Provençal opened maximally during the same period of time, but there is evidence that the extension started during the late Oligocene (Roca and Desegaulx, 1992; Gueguen, 1995; Sàbat *et al.*, 1997). The extension in those basins also migrated eastward (Roca and Desegaulx, 1992). In the Alicante area (Geel, 1995), and in Andalusia (de Larouzière *et al.* 1988) it is possible to follow the normal faults of the Valencia and Alboran basins to meet within the Betic Cordillera (Fig. 1). This is very important in establishing that these basins are linked genetically. Therefore, the extensional domain of the Alboran sea should be considered as a prolongation of the Oligo-Miocene rift system of the Liguro-Provençal basin and the Valencia trough. These extensional processes initiated contemporaneously in the foreland of the Alpine–Betic belt (Provençal basin and Valencia trough) and in the belt itself (Alboran sea), indicating independent origin of the extension with respect to the orogen (Fig. 1). A few crustal-scale sections across the Provençal-Alboran rift system and the Betic Cordillera at the late Oligocene – early Miocene stage were performed in order to verify this observation (Fig. 2). Present day sections were drawn using seismic reflection profiles and seismic refraction data (Torné *et al.*, 1992; Torrés *et al.*, 1993 ; Watts *et al.*, 1993; Gueguen, 1995, and references therein) and then retrodeformed using an area-balancing method. The amount of Neogene extension presently recorded in the Valencia and Provençal basins was removed. This reconstruction had to fit two constraints: (i) the amount of hor-

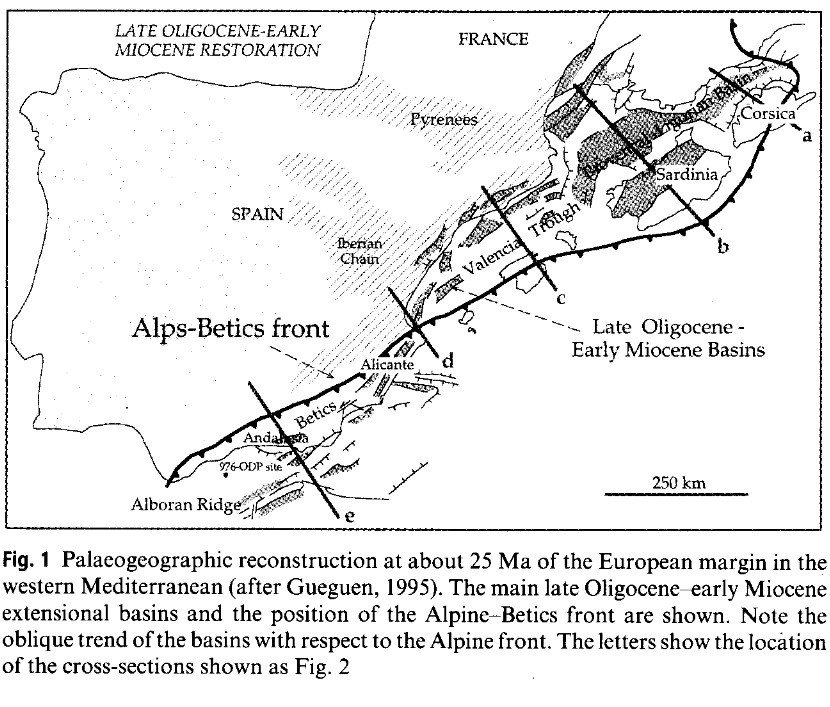

Fig. 1 Palaeogeographic reconstruction at about 25 Ma of the European margin in the western Mediterranean (after Gueguen, 1995). The main late Oligocene–early Miocene extensional basins and the position of the Alpine–Betics front are shown. Note the oblique trend of the basins with respect to the Alpine front. The letters show the location of the cross-sections shown as Fig. 2

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izontal movement cannot be higher than that given by the kinematic reconstructions; (ii) the balanced section should reach an initial crustal thickness of about 30 km on the margin of the basins. The sections show how, during the late Oligocene – early Miocene, the distance between the Alpine–Betic front and the extensional system varied from NE to SW. The distance appears to be at its maximum in the Sardinia foreland (about 65 km, Fig. 2b). In the Valencia trough early Middle Miocene normal faults and thrusts coexist in the eastern margin (Maillard *et al.*, 1992). The two fronts (eastern margin of the rift system and western front of the thrust belt) meet at the southern tip of the Valencia trough (Fig. 2d) where interference figures can be observed. The Betic thrust belt migrated WNW during the Miocene, whereas the extension wave propagated ESE. Extension and compression trended obliquely and migrated in opposing directions suggesting that the two tectonic waves were generated by independent geodynamic factors. This unusual tectonic relationship should have generated particular tectonic settings in which extension and compression may have in some places coexisted and cross-cut each other during their opposite migrations. NW-verging Betic thrusts and folds should have inverted or cross-cut Valencia rift-related normal faults in one side, whereas ESE-migrating normal faults should have inverted or cross-cut thrusts and folds. On the Balearic margin Middle Langhian thrusts are cross-cut by mainly SE-dipping Serravallian to Tortonian normal faults (Sàbat *et al.*, 1997). To the south-west, the Miocene Betic compression inverted, cross-cut and coexisted more intensively with the late Oligocene to early Miocene normal faults connecting the Valencia rift to the Alboran basin, e.g. uplifting the Neogene basins of the Sierra Nevada.

The Valencia-Provençal rift interferes with the Rhone–Rhine grabens system in the Gulf of Lyon. The two systems are here considered separately because the Rhone graben is mainly older (Eocene–Oligocene) and it is N0–10° trending with respect to the late Oligocene–Miocene N40–70° trending Valencia-Provençal system. In NE Corsica Jolivet *et al.* (1990) documented post-Alpine extension of probably early Miocene age. However, as there are no age constraints for this extension, it could have a wider late Eocene to late Miocene time span (Jolivet *et al.*, 1990). Therefore, it could be associated with both the earlier Rhone rift system and/or the later Provençal-Tyrrhenian eastward propagating back-arc rift system which jumped from the western to the eastern margin of Corsica. It is noteworthy that the greatest distance of the Valencia-Provençal rift from the Alpine–Betic front is at the intersection with the Rhone rift system.

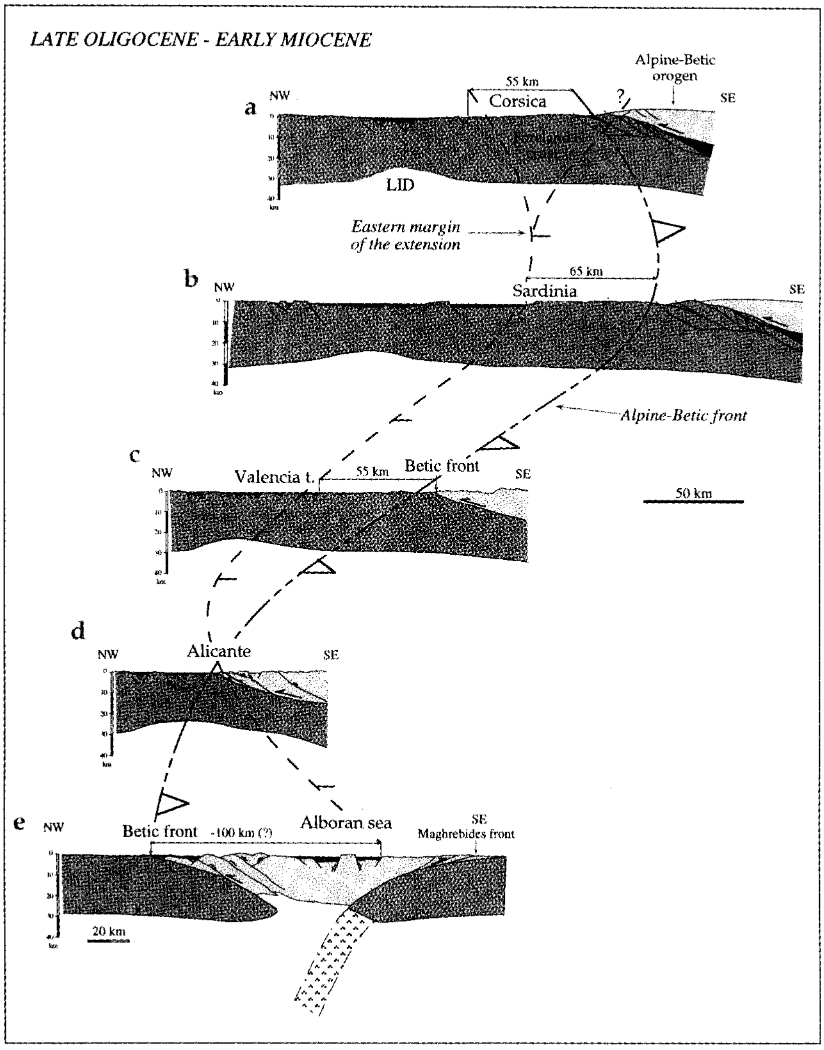

Fig. 2 Restored crustal sections illustrating the variation of distance between the Alpine–Betic front and the extensional system (location on Fig. 1). The late Oligocene–early Miocene extension is located at variable distances in the foreland of the Alpine–Betic orogen in the Provençal and Valencia basins (a-b-c). Then it interacts with the Betic orogen at the southern tip of the Valencia trough, in the Alicante area (d), continuing obliquely toward the south-west into the Alboran sea into the core of the Betics (e). Main data base for profile: a, MS47 (Gueguen, 1995) and Fournier *et al.* (1991); b, ECORS-Golfe du Lion and MS40 (Gueguen, 1995); c, Valsis 821 (Torrès *et al.*, 1993); d, Valsis 818 (Torné *et al.*, 1992); e, Conrad (Watts *et al.*, 1993)

Western Mediterranean orogens

The Betic cordillera is the northern part of two main orogenic systems of the western Mediterranean basin that interfere in the Alboran region. The first belt, on the northern side of the basin, is the Alpine–Betic orogen, which can be followed from the Betics of southern Spain, through the Baleares, into Alpine Corsica and the Western Alps, after Corsica-Sardinia rotation (Vigliotti and Langenheim, 1995). Figure 1 shows the palaeogeography of the Betic-Balearic-Alpine front at the end of the Oligocene – early Miocene, after the Oligocene extension of the Liguro-Provençal margins, before the oceanization of the basin (Gueguen, 1995). This reconstruction juxtaposes the foot of the continental slope as shown on seismic reflection profiles and fits the margin morphology considering the Corsica-Sardinia block as almost rigid (Vigliotti and Langenheim, 1995). In so-doing it minimizes the problems of the Provençal basin reconstruction and establishes good correlation of geological features between the Sardinian block, on one side, and Iberia and Europe on the other.

The Alps-Betic orogenic belt comprises large slices of basement rocks of Cretaceous–Miocene age with thrusting and elevated topography. The roughly NE–SW-trending segment of both the Betics and the Alps was formed in a context of right lateral transpression due to the oblique motion of the Iberian–European plate with respect to the hangingwall plate. No back-arc extension related to the Alpine belt is observed.

The second orogenic system, located on the southern side of the western Mediterranean, is the Maghrebides-Apennines belt. This late Oligocene to Pleistocene belt is continuous from Morocco throughout northern Africa, Sicily and the entire Apennines mountains, and it shows low topographic elevation, rapidly subsiding and deep foredeeps, mainly sedimentary cover involved in the thrust belt and the constant presence of the back-arc basin to the west, migrating in association with the accretionary wedge toward the east (or SE, or NE). The back-arc extension appears to be responsible for the progressive and coherent formation of the Provençal, Valencia, Alboran, Algerian and Tyrrhenian basins. The extension is younger moving from west, late Oligocene-early Miocene, to east, late Miocene–Pliocene–Pleistocene (Réhault *et al.*, 1984). The entire northern African belt and its Sicilian continuation are induced by right-lateral transpression (Channell *et al.*, 1990), whereas left-lateral transtension has been proposed along the same trend in the back-arc setting just to the north of the African margin (Doglioni, 1991). Left lateral movements along NE–SW-trending faults have been described in SE Spain (e.g. the Carbonera fault; de Larouzière *et al.*, 1988), and left-lateral transtensive evidence has been found at Site 976 in the Alboran Sea (Comas *et al.*, 1996).

The Gibraltar arc, where Alps and Apennines orogenic systems meet, is often simplified in tectonic maps as a single and regular arc. Maghrebides and Betics belts can be distinguished further.

(i) The Betic cordillera exhibits deep crustal sections where high-grade metamorphic rocks have been uplifted. The Betic arc may be followed also in Morocco where the basement crops out (e.g. the Beni Boussera peridotite). The Rif-Maghrebides mountains are instead mainly characterized by slices of sedimentary cover. Slices of metamorphic basement in the internal parts of the Apennines and Maghrebides, even bearing HP/LT mineral assemblages (e.g. W-Tuscany, Calabria, N-Morocco and Kabylie), are interpreted as relicts of the Alpine – Betic orogen. Deep crustal rocks and shallow rocks are typical, respectively, for orogens related to E- or NE-directed and W-directed subduction zones (Doglioni, 1992).

(ii) The Betics have a shallow long-lived foredeep characterized by low subsidence rates, in contrast with the Rif-Maghrebides foredeep which appears short-lived and with fast subsidence rates. The Gibraltar arc appears therefore to be mainly composed of Betic material which generated an arc similar to some extent to the western Alps arc, but close to the southwestern tip line of the orogen. In Morocco the Betics seem to have interfered with the Rif-Maghrebides belt that is generally younger (mainly Miocene in age in the western part, and rejuvenating toward the east). A similar interference can be seen at the transition between the western Alps and the northern Apennines which is the specular counterpart of the Betics-Rif link (Fig. 3) since they both belong to the two opposite subduction zones (Alps-Betics and Maghrebides-Apennines).

The early Miocene reconstruction of the western Mediterranean (Fig. 3) shows that the Alpine–Betic system reached the continental collision stage, making the subduction process more difficult. This situation favoured the inversion of the subduction, with the initiation of the Apennines–Maghrebides system at the front of the back-thrust belt of the Alps-Betics where there was still Tethyan oceanic crust to the east of the orogen. Then the roll-back of this W-directed subduction induced the back-arc opening of the Provençal-Valencia-Alboran basins which recorded the same age and migration polarity of the subduction.

Discussion

Interpretation of the thinning of the Betic Cordillera in the Alboran sea as being due to slab detachment or delamination of the Alpine slab is debatable for the following reasons:

1 The Alboran sea is part of the western Mediterranean late Tertiary to Quaternary basin system which is oblique to the Alpine–Betic orogen. The Provençal and Valencia basins formed in the foreland of the Alpine–Betic thrust belt, well outside its orogenic roots, whereas the Alboran basin developed within the belt.

2 All those basins show an eastward migration in age, from the late Oligocene (Provençal, Valencia and Alboran) in the western side to the Pleistocene (eastern Tyrrhenian), coeval with the eastward retreat of the W-directed Apennines subduction zone, suggesting a common driving mechanism.

3 The extensional features of the Valencia–Alboran basins trend N40–70°, obliquely to the largely coeval N60–80°-trending thrusts and folds of the Betics.

4 During the Miocene, the Betic thrust belt migrated 'westward', counter to the E-propagating extension (Fig. 3). This observation invalidates the hypothesis that the Alboran sea might have resulted from a back-arc extension related to the Gibraltar arc, because such an extension typically has the same migration polarity of the accretionary wedge.

5 The Alboran extension has a dominant ENE trend, apart from internal transfer zones, in contrast with the back-arc trends that are usually radial behind the arc. The Alboran trend does not follow the Gibraltar arc; moreover the extension cross-cuts obliquely the orogen up to its foreland in the Valencia trough. This is also inconsistent with a back-arc origin of the extension as related to the Betics.

6 Extensional collapse is intrinsic to the elevated topography of the orogens. Therefore, there should be some extensional features associated with this type of origin within the Betics, but they shouldn't be considered the reason for the entire Alboran-Valencia basins due to the aforementioned arguments.

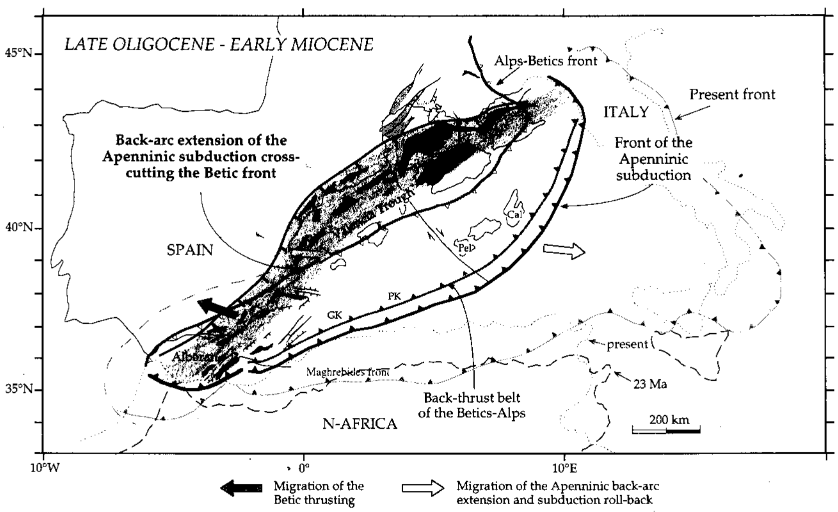

Fig. 3 Palaeoreconstruction of the western Mediterranean showing the extensional system in grey (Provençal-Valencia-Alboran) considered as the back-arc basin of the W- to NW-directed Apennines-Maghrebides subduction. In south-east Spain the ESE propagating extensional wave of the Valencia–Alboran system is oblique to the coeval WNW propagating Betics front. The back-arc extensional features are located both in the foreland (Sardinia–Valencia) and in the core of the Betics (Alboran), suggesting independent origins. Note the 'eastward' vergence of both the Apenninic trench and the back-arc extensional wave. Attempt of palaeogeographic relocation of Alpine metamorphic rocks: GK, Grande Kabylie; PK, Petite Kabylie; Pel, Peloritani; Cal, Calabria.

The main extension responsible for the opening of the Alboran-Valencia rift system seems not related to the dynamics of the orogen itself because it is oblique to it and presents a different polarity. It should be considered rather as a mainly independent process which can be regionally correlated to the back-arc extension of the 'eastward' retreating Neogene Apenninic subduction, even if the extensional system started while the Betics–Alps collisional subduction was still active.

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