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Tectonic adaptation of the External Zones around the curved core of an orogen: the Gibraltar Arc

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Abstract—There is no real curvature in the External Zones of the Arc of Gibraltar. These External Zones are made up by the juxtaposition of segments with NNW–SSE- or E–W-trending structures. Juxtaposition does not result from late tectonics nor from a paleogeographic layout, but only from Miocene tectonics.

During and after the late Burdigalian, relative motion between Europe and Africa was essentially a N–S convergence which accounts for the E–W structural trends. The NNW–SSE trends are the result of offset of the two main plates along sinistral strike-slip fault zones that cross-cut the previously mobile block of the Internal Zones and that shifted southward through time. To explain the sharp juxtaposition of different trending structures, two tectonic stages must be considered in each area of the External Rif. During the first one the rocks behaved plastically while during the second they could only move as a block.

The Internal Zones (Alboran block) slid independently between Europe and Africa only until early Burdigalian. After this time, they were locked in the main plates and broken together with them to allow further displacements.

INTRODUCTION

AT THE western end of the Mediterranean Sea, the Gibraltar Arc links the two branches of an alpine belt which constitute the main geological features in that area; namely the Betic Cordillera of southern Spain and the Rif-Tell chain of North Africa. These two branches trend approximately E–W but swing to a N–S trend to link across the Arc. The inner part of the arc is constituted by the Internal Zones, made up of different units that are common to both branches (Durand Delga 1972). The Calcareous chain underlines the external margin of the Internal Zones, which is surrounded by the Flyschs Domain and then the External Zones (Fig. 1). To the North of the eastern part of the Betic Cordillera, the Flyschs Domain is lacking. There, the Internal

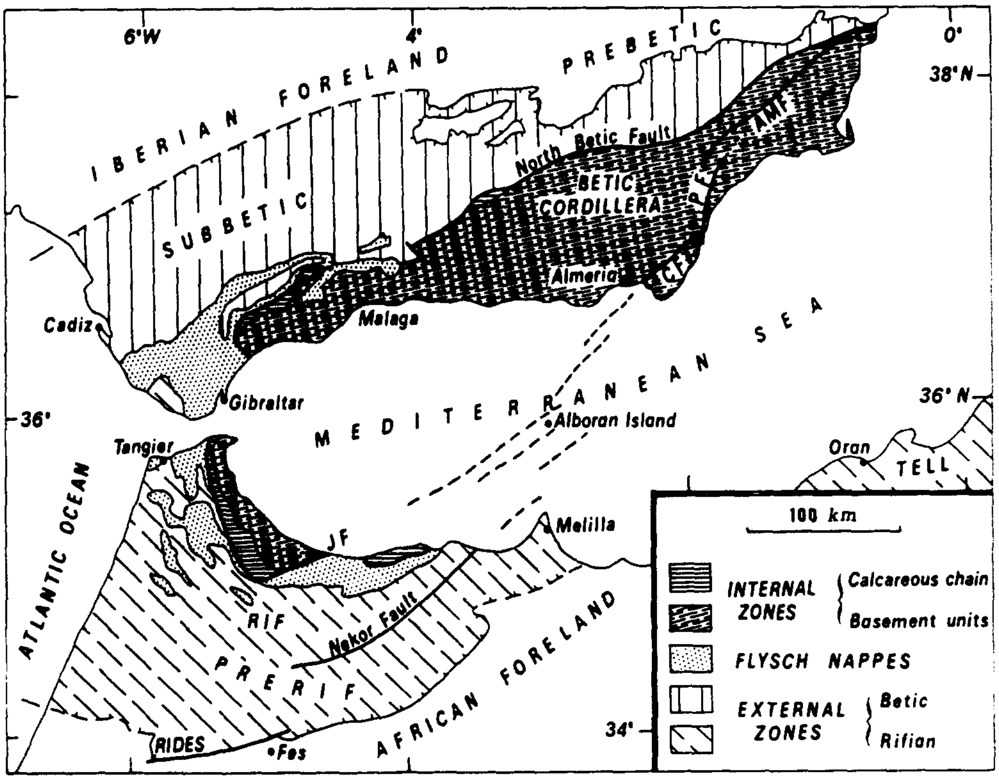

Fig. 1. Structural sketch map of the Gibraltar arc area. JF, Jebha Fault; CF, Carboneras Fault; PF, Palomares Fault; AMF, Alhama de Murcia Fault.

Zones lie adjacent to the External Betic Zones, separated from them by the North Betic Fault. Flysch units, however, crop out in the western part of the Betic Cordillera and are generally considered as a continuation of the North African Flysch nappes. These Flysch nappes, and the Internal units, swing through an angle of 180° in the Gibraltar area. Their curvature could result either from a tectonic rotation of originally linear E–W-trending units (Durand Delga 1980) or from a paleogeographic disposition, only slightly accentuated by the tectonics (Dercourt *et al.* 1985).

The External Zones are present all around the Arc of Gibraltar. However, according to sedimentological and structural evidence, the External Betic and Rifian Zones are very different and belong to two different continental margins, considered to be separated from each other by an important fault zone presently concealed under the Flysch nappes outcropping between Cadiz and Gibraltar (Durand Delga 1980). The structures of the External Betic Zones, which trend ENE–WSW over the entire length of the Cordillera, are not related to the N–S-trending structures of the adjacent northern part of the Rifian External Zones to the west of Gibraltar. The only possible curvature in the External Zones occurs in the Rif. There, the main cartographic and structural features trend N–S near the Straits of Gibraltar and E–W in the eastern Rif, apparently curving through a right angle. Most authors (Durand Delga 1980, Wildi 1983, Dercourt *et al.* 1985) agree that this curvature of the External Zones is due to the rotation, during Tertiary times, of an E–W-trending linear margin, although it has been proposed that the margin was already curved as early as the Cretaceous (Frizon de Lamotte 1985).

Many models have been proposed for the evolution of the western Mediterranean region. As there is no indication of subduction, the models generally account for the construction of the Gibraltar Arc by calling on the WSW offset of an intermediate (Alboran) block along major strike-slip faults during the N–S convergence of the European and African plates (e.g. Andrieux *et al.* 1971, Tapponnier 1977, Leblanc & Olivier 1984). In these models, the External Zones are not considered important and are generally neglected. In fact, a thorough study of the geometry of the structures of the External Zones and of the timing of tectonic events provides data that lead to a new interpretation of the tectonic evolution of the Gibraltar Arc during the Miocene.

DATA AND OBSERVATIONS

Geometry of the structures in the Rifian External Zones

In all previous models, the main structural directions of the External Rifian Zones, such as the azimuths of the fold axes and of the thrust contacts, are assumed to change their trend gradually from N–S to E–W. Detailed observations of the structures contradict such an approximative description. As can be seen in Fig. 2, the External domain where the structures are N–S to NNW–SSE in azimuth covers the whole western Rif, from Tangier to Fes in latitude, including the externalmost Prerifian Rides to the south. By contrast, the eastern Rif domain is exclusively occupied by structures that trend E–W to ENE–WSW. The transition between these two domains is nearly always abrupt. The External Rifian Zones can, therefore, be mapped out as two structural

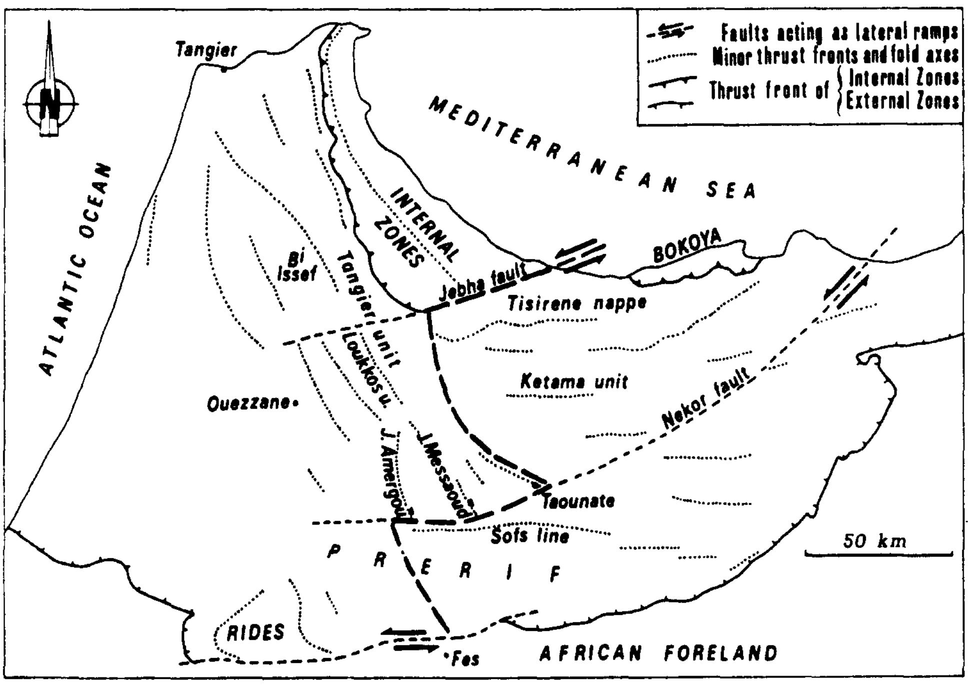

Fig. 2. Main structural trends of the Rifian chain. The thick broken line separates two domains with different structural trends.

domains which are juxtaposed. The thick broken line of Fig. 2 roughly underlines the boundary between these two domains.

The northern part of this boundary, the Jebha Fault, separates the eastern External Rif, here constituted by the Tisirene Cretaceous flysch nappe, from the Internal Rifian Zones. To the south, the boundary is NW–SE in orientation, approximately following the contact zone between the Tangier and Ketama units up to the Taounate area. The Tangier unit is probably the slightly displaced Upper Cretaceous cover of the Lower Cretaceous Ketama unit. The boundary between these two units does not correspond to an important fault. The Taounate area is the only site where some intermediate structural trends can be observed. From there, the boundary trends nearly E–W, corresponding to the western extension of the Nekor Fault (Leblanc 1980), that separates the Jbels Messaoud and Amergou ridges to the north from the Sofs Line to the south. The name "Sofs" describes individual Jurassic calcareous bodies, kilometric at most in size and spaced a few kilometers apart, that are extrusive in their Cretaceous and Miocene cover (Bulundwe 1987). Their E–W-trending alignment reveals a continuous underlying fault, the strike of which is parallel to the structures of the Cretaceous rocks in that area. Beyond the Jbel Amergou, the precise location of the boundary is not clearly defined because it is buried under the Tertiary deposits of the external Prerif which were emplaced as gravity slides. Hence the boundary drawn on Fig. 2 is very approximate, but has to be located to the east of the Prerifian Rides which definitely have clear NNW–SSE structural trends.

Comparison between paleogeographic and structural trends

Recent sedimentological studies have demonstrated that the NNW–SSE structures of the western Rif are not inherited from a pre-tectonic paleogeographical disposition as they transect the E–W trends of the paleogeographical zones. For example, the NNW–SSE ridge including the Jbels Amergou, Areschkou and Aoudiyar (50 km west of Taounate) shows progressively deeper sedimentary facies northward, for the Middle Jurassic deposits (Bulundwe 1987), the Tithonian (Suter 1966a) and also the Lower Cretaceous (Suter 1966b). Similarly, the Cenomanian–Turonian layers of the Loukkos structural unit were deposited in shallower water in the southern part of the unit than in the north (Kuhnt *et al.* 1986). The most convincing data were provided by a paleobathymetric interpretation of the Foraminiferal assemblages and by sedimentological observations in the Upper Cretaceous sequences (Kuhnt 1987). In the whole western External Rif, the presently exposed rocks of this age correspond to progressively deeper facies from south to north. This E–W direction of the paleogeographic lines is most probably related to the original arrangement of the African continental margin, at least until the end of the Mesozoic. Thus the NNW–SSE structural trends of the western External Rif were not foreshadowed in the paleogeographic disposition of the sedimentary packages. Furthermore, the tectonics retained that paleogeographic disposition, without generating large rotations.

Dating of tectonic events

Stratigraphic data indicate Miocene ages for the main phases of deformation in the External Rif (Leblanc 1979, Wildi 1983). But these phases are not contemporaneous all over the External Rif. The main offset along the major strike-slip faults was progressively younger from north to south. It was Burdigalian in age for the Jebha Fault (Olivier 1981), early Tortonian for the Nekor Fault (Leblanc 1980) and latest Miocene for the southern border fault of the Prerifian Rides (Vidal & Faugères 1975). In the same way, these strike-slip faults divide the External Rif into domains, the main structures of which become younger to the south. The boundary between the domains with different structural trends also separates adjacent regions where the structures in the west are younger than in the east. Thus, the Prerifian deformation and gravity sliding, which is Tortonian in age both in the southeastern Rif and the Ouezzane areas, pre-dates the latest Miocene uplift of the Rides (Morley 1986). Likewise, the construction of the E–W-trending pile of nappes bounded by the Jebha Fault to the north, pre-dates its westward thrusting over the NNW–SSE structures of the more western units (Lespinasse 1975). On the other hand, an age difference between the thrusting in the two areas divided by the Oued Loukkos Line (the western extension of the Jebha Fault) has never been considered. Such a hypothesis is plausible, however, as it would account for the involvement of Langhian deposits in the southern thrust sheets and not in the northern ones where the only post-Burdigalian outcrop, the Langhian deposits of Beni Issef (Didon & Feinberg 1979), seems to post-date thrusting.

NEW MODEL FOR THE EXTERNAL RIF

Since the beginning of the Miocene, relative motion of the European and African plates has been essentially N–S convergence (Savostin *et al.* 1986). The E–W structures of the eastern part of the External Rif that trend roughly perpendicular to the maximum compressive stress are naturally expected, but the NNW–SSE structures of the western part are not so easy to account for. The available stratigraphic data indicate that structures with parallel trends are not necessarily of the same age, whereas NNW–SSE and E–W structures have developed simultaneously. It must, therefore, be assumed that the same stress field resulted in entirely different trends for the structures of separate but neighbouring parts of the External Rif. Plotting of the boundary between areas of distinctive structural trend suggests that it is linked to the major strike-slip faults (Fig. 2). That link does not, however, correspond to a mere juxtaposition of terrains with pre-existent different structural trends by a late movement along the faults, as the indentations of the boundary seem to result from a dextral offset, whereas the faults have been shown to be sinistral (Leblanc 1980, Olivier 1981). The NNW–SSE structures must result from an abrupt reorientation of the N–S principal stress. A model must also account for the juxtaposition of different trending structures along NNW–SSE lines that are not important faults, like the contact between the Ketama and the Tangier units in the central Rif.

To explain these features, we have to assume that the mechanical behaviour of rocks changed fundamentally during deformation. Two stages must be distinguished in each area. During the first stage, the weakly deformed rocks were still plastic and they underwent their main deformation. During the second stage, the deformed rocks were more rigid and less able to warp, but they could however move as a whole block towards the WSW along large-scale strike-slip fractures. It was this last movement that induced the ENE–WSW compressive stress responsible for the plastic NNW–SSE structures of the western Rif.

The tectonic history of the external Rif can then be summarized as follows.

During the late Burdigalian, the Internal Rifian Zones had already reached the rigid stage when the more southern zones (Tisirene Flysch nappe, Ketama unit) were about to undergo an E–W plastic deformation due to N–S stress (Fig. 3). At the same time, the rigid block of the Internal Zones was broken along the Jebha Fault and its northern part shifted westward, compressing the northernmost External Zones and inducing NNW–SSE plastic structures.

The rigid block then increased in size by accretion of the newly deformed areas and the tectonic process continued in more external zones. Deformation along E–W trends spread in the southeastern part of the chain. Meanwhile a westward displacement of the northern part of the new rigid block, broken along the Nekor strike-slip fault, gave rise to NNW–SSE structures in the central area of the western Rif.

Finally, a new tectonic stage induced the NNW–SSE structures of the Prerifian Rides during the westward movement of the northern limb of the sinistral fault bordering them to the south.

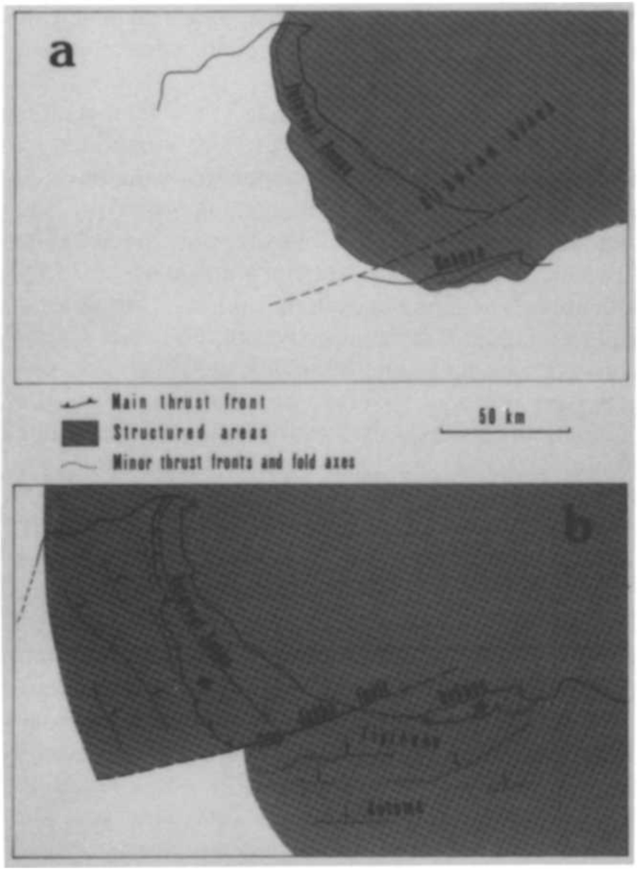

Fig. 3. Burdigalian tectonics in the Rif. (a) Relationship of Internal Zones and more southerly structures before the offset along the Jebha Fault; (b) after this offset. Arrows indicate directions of displacements.

MODEL FOR THE MIOCENE EVOLUTION OF THE GIBRALTAR ARC

In order to extend the model to the whole western end of the Mediterranean, we must first introduce some new observations.

Complementary data concerning the Internal Zones and the Betic Cordillera

The above model for the evolution of the External Rifian Zones involves some modifications of our previous ideas about the Alboran mobile block (Leblanc & Olivier 1984). It appears that the Jebha Fault was never the border of an Alboran block that included all the Betic and Rifian Internal Zones, since the Jebha Fault, which separates the Bokoya massif from the other internal units, cuts through the Internal Zones (Fig. 3). The same applies to the Nekor Fault. These two Moroccan faults, together with the faults of Carboneras, Palomares and Alhama de Murcia in southeastern Spain (Fig. 1), are probably part of a trans-Alboran-block shear zone documented by De Larouzière *et al.* (1988), who demonstrated the great importance of that shear zone as a boundary between two regions with different crustal structure.

Another observation concerns the curvature of the units of the Flyschs Domain and of the Internal Zones in the Gibraltar Arc area. Unlike the curvature of the External Zones, this curvature is not only a structural feature but corresponds also to a bend of the paleogeographic trends (Durand Delga 1980). This is well emphasized by the Calcareous chain, a narrow and very elongated curved unit with unique Mesozoic deposits generally accepted as originating on the continental shelf of the Alboran block (Bouillin *et al.* 1986). This difference between the structures of the Internal and External Zones of the Gibraltar Arc suggests an important change during their tectogenesis.

A study of the stress field orientation in the Betic

Cordillera (De Larouzière *et al.* 1988) sheds light on the nature of this change. This study pointed out that no further dextral displacement was allowed after the beginning of Tortonian time along the main 070° strike-slip faults that had previously been active along the northern margin of the Internal Betic Zones. In fact, the main strike-slip movements between Spain and the Alboran block probably stopped earlier, as Upper Burdigalian deposits seal the boundary fault between Internal and External Betic Zones (Durand Delga 1980). Thus the available data show that, from late Burdigalian, there was no further strike-slip motion of the Alboran block with respect to Spain. In contrast, on the Moroccan side deformed zones were still moving along strike-slip faults toward WSW, shortening the external units of the western Rif. This asymmetry is not taken into account in previous models.

The new model

The above facts require a new model (Fig. 4), the important characteristic of which is that the convergence of the European and African plates caused the previously mobile Alboran block to be definitely locked during Burdigalian time. Thus, the classical concept of an independent block displaced to the WSW relative to the two main plates only holds true until the early Burdigalian. An important change occurred at that time, Europe and Africa being united with the Alboran block in the western Mediterranean area. The persistent stress resulted immediately in large scale thrusting in the Betic Cordillera, Algeria, and probably Morocco, and also in a break-up of the newly united European and African plate along the Jebha–Carboneras transcurrent fault system that cut through the former boundaries of the plates. The stresses were relieved afterwards, on the one hand by renewed folding and thrusting in the Betic and Rifian External Zones, and on the other hand by a sinistral sliding displacement between a northern and a southern block, the boundary of which was shifting in a discontinuous manner towards the African foreland through time.

CONCLUSION

Two successive stages can be pointed out for the tectogenesis of the Gibraltar Arc. The structures of the Internal Zones were created at the first stage which ended during Burdigalian. The main tectonic event that characterizes this first stage is the westward displacement, relative to the European and African plates, of a small intermediate crustal block, the Alboran block. The transition between the two stages occurred when the whole system became locked owing to the convergent movement of Europe and Africa. During the second stage, the margins of the major plates (i.e. the External Zones) were crushed around the more rigid Alboran block (Internal Zones). In fact it was the offset of the plates along major strike-slip faults that cross-cut

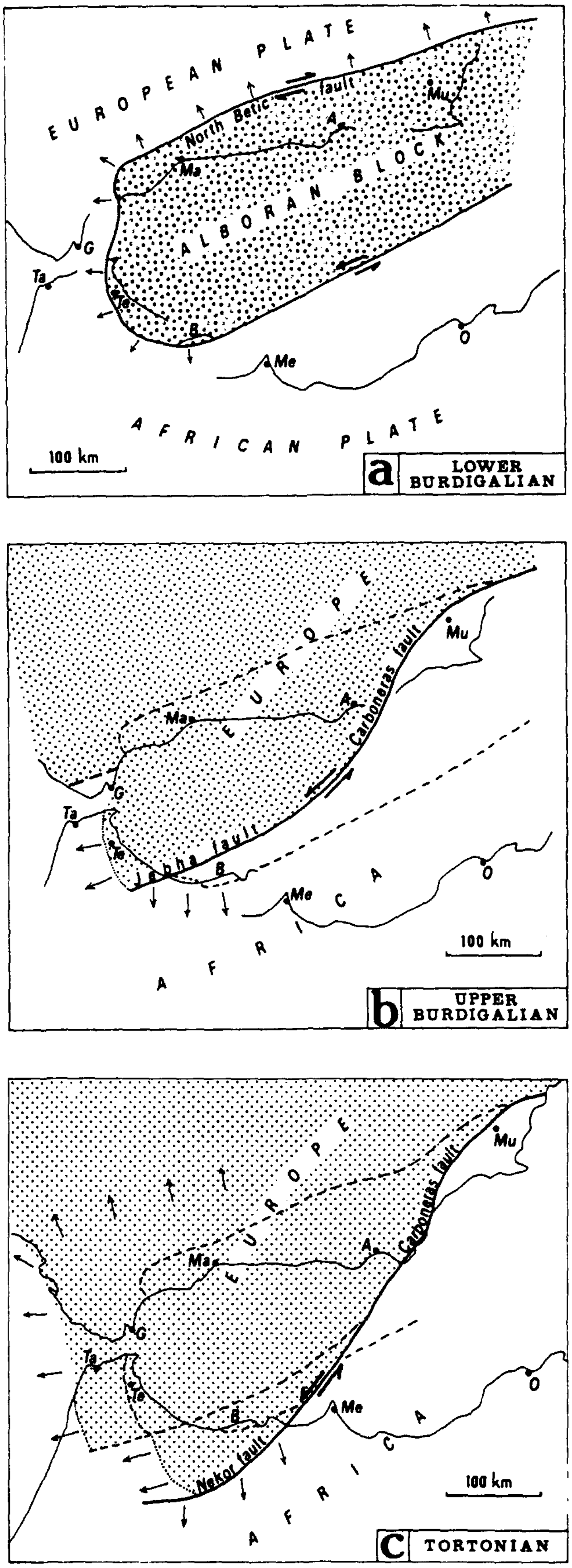

Fig. 4. Three stages of the Miocene structural evolution of the western end of the Mediterranean: (a) Lower Burdigalian, (b) Upper Burdigalian, (c) Tortonian times. A, Almeria; B, Bokoya massif; G, Gibraltar; Ma, Malaga; Me, Melilla; Mu, Murcia; O, Oran; Ta, Tangier; Te, Tetouan. Thin arrows indicate vergence of the structures. Note that the eastern part of Africa, from Melilla to Oran, is conventionally supposed to be fixed.

the Internal Zones, which created the NNW–SSE-trending structures of the western External Rif, structures which have been mistaken for a large curvature of the External Zones.

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