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THE E-W SEGMENTS OF THE CONTACT BETWEEN THE EXTERNAL AND INTERNAL ZONES OF THE BETIC AND RIF CORDILLERAS AND THE E-W CORRIDORS OF THE INTERNAL ZONE (A COMBINED EXPLANATION)

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ABSTRACT

The contact between the Internal Betic-Rif Zone and the corresponding external zones is not regular, some sections having a NNE-SSW direction and others approximately E-W. These latter coincide with some of the corridors of the Internal Zone, and have continuity with those within this zone. A model which relates the two features is proposed, in which the corridors originally corresponds to faults or fault zones which are the eastern continuation of the transcurrent contacts, by means of which the Internal Zone advanced westwardly more easily on its collision with the External Betic Zone. This means that the Internal Zone is divided into various cortical segments and advanced towards the west.

The proposal of the model includes a discussion of the Alpujarras and Colmenar corridors, which continue each other, and provides values for the displacement of the zone of faults. With this model, both the transcurrent E-W faults of the Internal Zone, as well as at least part of the extensional movements affecting this zone, remain subordinate to the shifting of the Internal Zone towards the west.

Key words: *Betic Cordillera, Internal Betic Zone, Neogene.*

RESUMEN

El contacto entre la Zona Interna Bético-Rifeña y las correspondientes zonas externas no es regular. Muestra unos sectores de dirección NNE-SSW y otros que son aproximadamente E-W; estos últimos coinciden con algunos de los corredores de la Zona Interna y están en continuidad con los que existen dentro de la misma. Se propone un modelo en el que se relacionan genéticamente ambos rasgos, de manera que los corredores corresponden originalmente a fallas o zonas de fallas que son la continuación de los contactos transcurrentes más occidentales, por medio de los cuales la Zona Interna ha logrado avanzar con más facilidad hacia el W en su choque con la Zona Externa Bética. Esto significa que la Zona Interna está dividida en varios segmentos corticales y que el avance de la misma se hizo fundamentalmente hacia el W.

En la propuesta del modelo se discuten los corredores de las Alpujarras y de Colmenar, situados en continuidad mutua, y se dan los valores de desplazamiento del conjunto de las fallas. Con este modelo, tanto las fallas transcurrentes E-W de la Zona Interna, como al menos parte de los movimientos extensionales ocurridos en la misma, quedan subordinados a la traslación de la Zona Interna Bético-Rifeña hacia el W.

Palabras clave: *Cordillera Bética, Zona Interna Bética, Neógeno.*

Introduction

Numerous articles treat the emplacement of the Betic-Rif internal Zone (Internal Zone) in its current position. In general, two fundamental types of models are proposed: A) those which indicate that the Internal Zone was deformed and metamorphosed practically in the same place as it is found at present, and afterwards rose, sliding gravitationally to deform the Betic and Rif External zones and create the Gibraltar Arc (Weijermars, 1987; Doblas and Oyarzun, 1989; Platt and Vissers, 1989); and B) those which assume a major shift of the Internal Zone towards the W, after having been deformed and metamorphosed itself in more easterly sectors of the western Mediterranean (Andrieux *et al.*,

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1971; Durand Delga, 1980; Durand Delga and Fontboté, 1980; Wildi, 1983; Sanz de Galdeano, 1983 and 1990a; Sanz de Galdeano and Vera, 1992; etc.). This movement would be partially connected to the formation of oceanic basins in the western Mediterranean (especially with the Argelo-Provençal) which gave rise to, among other features, the eastward displacement of Corsica and Sardinia and the southward displacement of Kabylias. This phenomenon would be tectonically parallel (but not contemporary) with the eastward expulsion of the Apennines and particularly the Calabrian Arc, coeval with the formation of the Tyrrhenian Sea. The expulsion of the Betic-Rif Zone could also be connected with the process of subduction proposed by Boillot *et al.* (1984), among other authors. Vissers *et al.* (1995) support the first model, but recognizing a «westward motion, particularly at the western end of the region» (Alboran Domain). Docherty and Banda (1995) indicate that «while the deformation front of the Alboran Domain migrated westwards, subsidence in the Alboran Sea basin propagated in the opposite direction, east/southeastward».

Many arguments have favoured the westward movement of the Internal Zone (see Sanz de Galdeano, 1992 and in press), but to date no special consideration has been given a) to the meaning of the irregularities of the contact between the Internal and External zones in the Betic and Rif cordilleras and b) nor has there been any attempt to provide an overall explanation for the origin and significance of the corridors running E-W to N70E in the Internal Zone. Moreover, never has a joint treatment of the segments oriented E-W to N70E of the contact between the Internal and External Zones and the corridors been considered, and this omission has hindered the understanding of some of the movements caused in the displacement of the Betic Zone.

The aim of the present work is to propose an overall explanation of both features, and thereby deduce the tectonic and palaeogeographic consequences.

General geological setting

The Betic and Rif Cordilleras from the two most westerly alpine chains of the western Mediterranean. In both chains we can identify, the Internal Zone, common to both, and the external zones (fig. 1), distinct to each cordillera. In fact, the Betic External Zone corresponds to the Mesozoic and Tertiary cover of the Iberian Massif; the Rif External Zone covering the NW end of the African shield.

The Betic External Zone is formed by the Subbetic and the Prebetic, the latter lying closer to the Iberian Massif. The External Rif Zone is divided into IntraRif, MesoRif and PreRif (which is positioned closest to the Atlas).

The Internal Zone is comprised of three tectonically superimposed complexes which, from the lowest upwards, are the Nevado-Filabride, the Alpujarride and the Malaguide. The first two, made up fundamentally of metamorphic rocks of alpine age, were Palaeozoic and Triassic sediments. The Malaguide, having little or no metamorphism, is composed of Palaeozoic basement and a Mesozoic and Tertiary cover, which, although it presents numerous interruptions, is much more complete than those of the other two lower complexes. The palaeogeographic origin of the Betic-Rif Zone must have been situated in the western Mediterranean, to the E of its present-day position.

Within the Betic Zone, we can also distinguish the Dorsal domain or complex, generally related to the Malaguide, although its palaeogeographical meaning is still under discussion.

Also noteworthy is the presence of tectonic units formed from the Flysch Basin, which developed to the north of the Rif and Tell external zones, currently extending as far as Calabria, in Italy, and to the south of the Betic, Rif, Kabylias and Calabrian internal zones. This basin was destroyed when the internal zones were expelled from the western Mediterranean and some of its units were dragged westwardly, in front of the Betic-Rif Internal Zone, outcropping presently in the Campo de Gibraltar and in the NW Rif.

The Betic-Rif Internal Zone, which began to move west at the end of the Oligocene, collided with the Subbetic at the end of the Early Burdigalian (Hermes, 1985; Martín Algarra, 1987). From that time, especially during the rest of the Burdigalian and part of the Langhian, and with less intensity during the rest of the Langhian until the beginnings of the Tortonian, the Internal Zone followed a westerly advance, dragging along the Flyschs units. This process progressively deformed and disorganized the Subbetic, rotating numerous units and forming important olistostromic units in its path (Sanz de Galdeano and Vera, 1992; Pérez López and Sanz de Galdeano, 1994). In this process the present contact between the Internal Zone and the External Zone of both chains was formed.

Geometry of the contact between the Internal and External Zones in the Betic Cordillera. The corridors and the E-W to N70E alignments of the Internal Zone

In the Betic Cordillera this contact presents a general direction of N65-70 from Alicante to the area of Ardales in the province of Málaga. More to the west, the direction of the contact is almost N-S

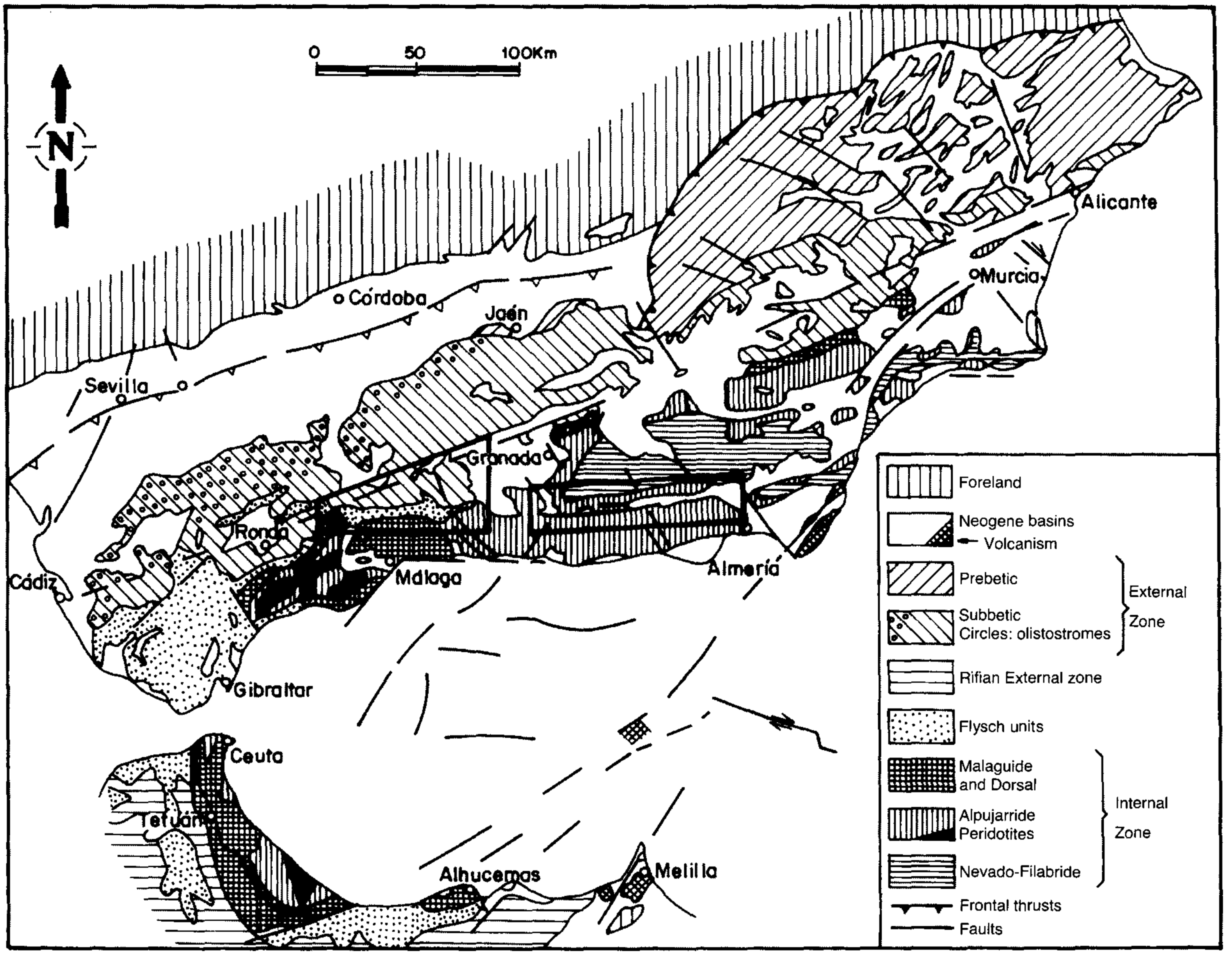

Fig. 1.—General scheme of the Betic Cordillera and the Rif. The polygons represent the position of figures 3 and 4.

from Ceuta to Charafate; from this location to Yebha, it becomes approximately N65E, and in Bocoyas is almost E-W. However, this contact, in detail, has irregularities in direction and length (figs. 1 and 2) which are described below. In addition, in the Internal Zone or in the contact with the External Zone, there are various corridors, elongated depressions, in an E-W to N70E direction: 1) Vélez Rubio, 2) Bajo Segura, 3) Almanzora, 4) Colmenar and 5) Alpujarras (between these latter two lies the corridor situated to the south of the Granada basin, from Zafarraya to Jayena). Finally, the coastline of Almería to Málaga, followed by the Málaga Basin, should also be considered.

Principal features of the corridors and of the contact between the External and Internal Zones

From the proximities of Alicante to near Mula (province of Murcia), the contact between the Internal and External Betic zones is hidden under Upper Neogene and Quaternary sediments, but the scattered outcrops of the Alpujarride and of the Malaguide complexes indicate that this contact occurs near the Crevillente Fault (or Cádiz-Alicante Zone of faults described by Sanz de Galdeano, 1983) (fig. 1), approximately in a N70E direction. This area, although it is not considered morphologically as a corridor, corresponds to the N70E sectors of the contact between the External and Internal zones.

In the area of Mula-Sierra Espuña, the contact takes a NE-SW direction, though it is partially masked by Middle Miocene sediments, which in turn are partially overthrust towards the ESE by a Subbetic unit (Paquet, 1969; Lonergan, 1993; Allerton *et al.*, 1993). In this area, within the Subbetic, there are overthrusts towards the E; in the Sierra Espuña (Malaguide and Alpujarride complexes) the vergences are towards the SE.

More westerly, the Vélez Rubio Corridor, situated to the N of the Sierra de las Estancias and with a

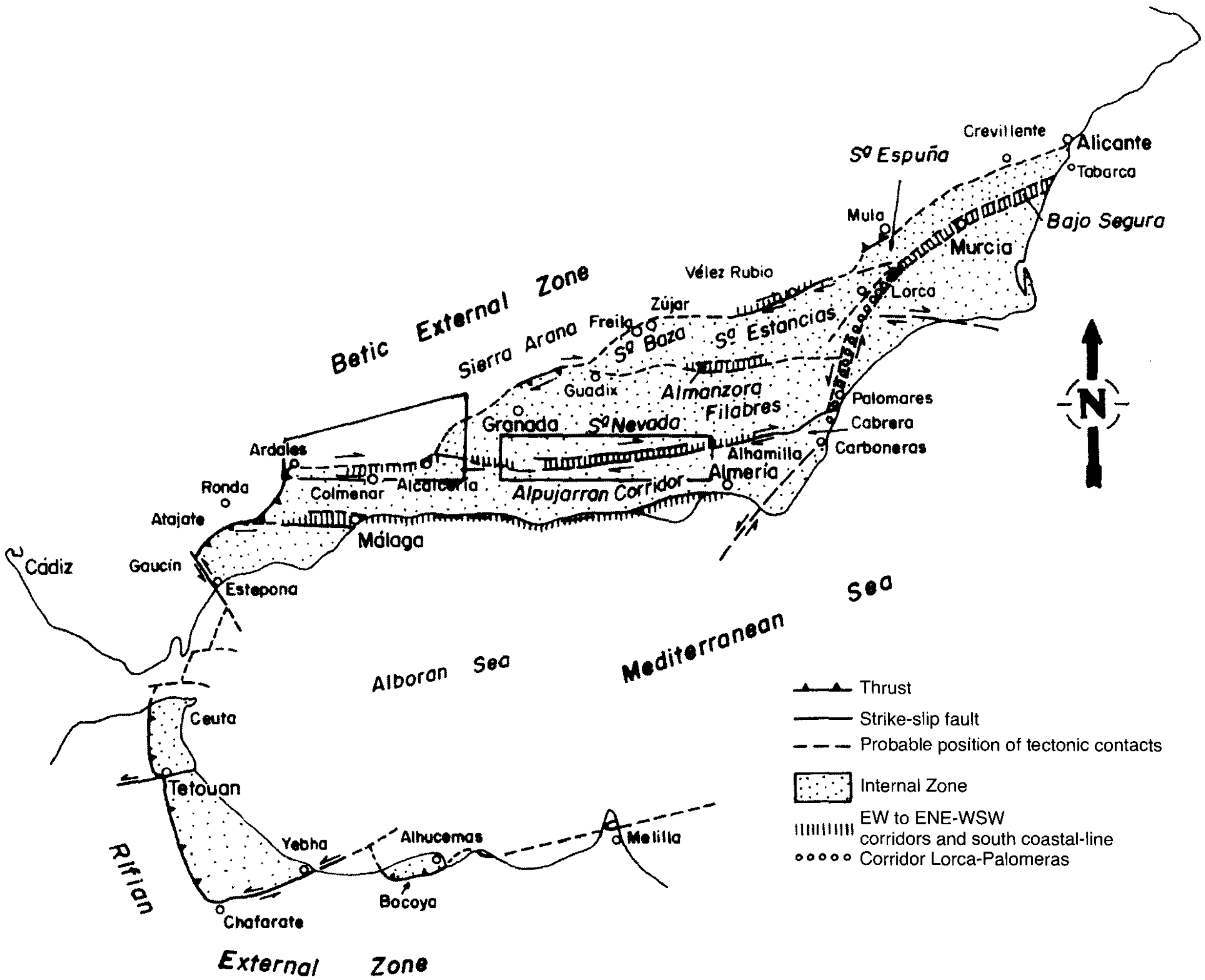

Fig. 2.—Scheme of the contact between the Internal and External Zones in the Betic Cordillera and the corridors present in the latter. The polygons represent the position of figures 3 and 4.

general N70E direction, developed directly in the contact between the Internal and External zones. This is a rectilinear contact with no visible superposition of the Internal Zone over the External. In fact, in a great part of the corridor the relief of the Subbetic clearly dominates the Internal Zone, the former overthrusting the latter, as indicated by Vissers *et al.* (1995). This appear as a dextral transcurrent contact. The vergences in the N of the Sierra de las Estancias (Malaguide and Alpujarride complexes) are also towards the S and SE.

Towards the E of this corridor the Bajo Segura Depression also lies in a N60-70E direction, with the Sierra Espuña Block in the middle of both corridors (fig. 2). Equally, the corridor of the Bajo Segura can be considered as the prolongation towards the ENE, in a NNE-SSW direction, of the Lorca-Palomares (fig. 2) formed during the Late Miocene, and with a remarkable change in direction between the two. The author put forward the hypothesis that the Bajo Segura corridor formed contemporary with the Vélez Rubio corridor, and was used in the Late Miocene as the NE prolongation of the Lorca-Palomares Basin (and faults).

Towards the W, the Vélez Rubio corridor is covered by the Upper Neogene and Quaternary sediments of the Guadix-Baza Basin. The Alpujarride outcrops existing between the localities of Zújar and Freila in this basin assure the continuity of the Internal Zone up to these localities. More westerly, the presence of outcrops of the Subbetic indicates an inflexion of the contact in a roughly NNE-SSW direction, under the Neogene deposits.

The place where this inflexion apparently ends, near the Sierra Arana, is the geometric prolongation of the Almanzora Corridor, which appears more to the E, completely in the Internal Zone. Thus, there is a possible alignment between the Almanzora Corridor and the contact between the Internal and External zones in the area of the Sierra Arana. Here, this contact has a N75E direction, and the Internal Zone overthrusts the External locally, but the principal movement is right lateral (Balanyá, 1982). There are retrovergent structures and, as in the Malaguide in the Sierra Espuña, the units of the Dorsal have rotated some 180° (Parés *et al.*, 1992). The morphological continuity between the Almanzora Corridor and the E of Sierra Arana-NW of the Sierra Nevada is interrupted by the Sierra de Baza, although the contact between the Nevado-Filabride and the Alpujarride, just to the S of this latter range, marks a line of continuity. In summary, the continuation of the faults of the Almanzora Corridor towards the W is probable, but not certain.

In the Granada Basin, another flexion of the contact appears, but as in the Guadix-Baza Basin it is almost completely hidden by Neogene and Quaternary sediments. This contact reappears near Alhama de Granada (fig. 4), where it takes a NE-SW direction until reaching a point called Alcaicería. From the Alcaicería and towards the west the contact follows an E-W direction for some 75 km. This direction is not readily visible because of the unconformable sediments over the Malaguide (from the end of the Aquitanian to the Early Burdigalian) and the allochtonous units of the Flysches of the Campo de Gibraltar apparently place the contact somewhat more to the S. Nevertheless, some Malaguide remains, with a Palaeozoic basement, to the N of Casabermeja as well as some Alpujarride and Malaguide outcrops from the S of the Sierra de Huma-Chorro indicate that the contact is close to the relief of the External Zone. All of those made up the Colmenar Corridor.

In this corridor, the relief of the External Zone clearly dominates over that of the Internal; here the Internal Zone does not overthrust the External, but the opposite occurs at many points.

The easterly prolongation of the Colmenar Corridor corresponds to the southern part of the Granada Basin (a depressed area situated from Zafarraya to Jayena). More to the E lies the extremely long corridor of the Alpujarras, which continues in the northern slopes of the Sierras of Alhamilla and Cabrera (province of Almería). Only the sector of Herrero Peak (fig. 3) interrupts the corridors, though several faults pass from the south of the Granada Basin to the Alpujarras Corridor.

To the W of the Colmenar Corridor, in Ardales (Málaga province), the contact takes a NNE-SSW direction, and the Internal Zone overthrusts the External, until reaching the sector to the south of Ronda (area of Atajate), where the contact has an E-W direction. This small sector of the contact, with an E-W direction, follows the line of the Almería to Málaga coast and of the Málaga Basin. In this sector near Atajate, no fault is clearly visible in the Internal Zone, but a major dextral flexion is evident.

From Atajate, the contact veers in a NNE-SSW direction, reaching Gaucin. From there, towards Estepona, its direction is completely different, being NW-SE, coinciding with a strike-slip fault with a sinistral displacement.

In Morocco the E-W corridor of Tetouan is found together with the ENE-WSW segment of the contact between the Internal and the External Zone, from Charafate to Yebha (fig. 2), although this segment does not correspond to a depressed relief.

The example of the Alpujarras Corridor and its continuation in that of Colmenar

The Alpujarras Corridor (Sanz de Galdeano *et al.*, 1985) is a long depression to the south of the Sierra Nevada, which geologically is extended more to the E and to the W. This corridor is filled by Neogene deposits over a substratum in which the three complexes of the Internal Betic Zone are represented.

There are two basic models to explain the formation and evolution of the Alpujarras Corridor.

The first model was published by Sanz de Galdeano *et al.* (1985 and 1986) and Rodríguez Fernández *et al.* (1990). According to this model, the corridor of the Alpujarras owes its formation and subsequent evolution to E-W right lateral strike-slip faults. These faults run along both the N and S edge of the corridor and even affect its interior. Especially concentrated towards the N, these faults correspond in detail to anastomosed faults, with segments of several kilometers. The total displacement estimated by the previous authors is several dozen kilometers, but without objective proofs of that value. To this horizontal displacement, the vertical ones must be added, which are also significant and are, from the Late Miocene, the most important movements. In some places the displacement can exceed 2,000 m.

These E-W strike-slip faults extend all along the corridor, continuing to the E through the sierras of Alhamilla and Cabrera, and to the W contact with the External Zone in the sector of Alcaicería-Zafarraya (figs. 1 to 4). In general, they facilitate the displacement of the Internal Zone towards the W.

The second model is supported by Galindo Zaldívar (1986), and more particularly by Mayoral *et al.*

(1994 and 1995). This model explains some of the deformations in the area of the Alpujarras Corridor as formed by major extensions which affect the complexes of the Internal Zone and even the Neogene deposits of the interior of the corridor.

The strike-slip faults described in the first model correspond to a transfer type connecting the extensional displacement occurring between the units affected and therefore would be shallow faults.

According to Crespo *et al.* (1993) and Mayoral *et al.* (1994) the extensions present, the following chronology with regard to the formation and evolution of the corridor: firstly, an extensional phase occurred which caused the upper units to move to the NNW with respect to the lower ones. This happened during the Late Burdigalian-Early Langhian. A second phase produced an extension in an approximately WSW direction, in such a way that the upper units moved with a westerly component. Over this period, the corridor neither existed nor was even prefigured. Only since the Late Miocene, when the region was subjected to compressions of an approximately NNW-SSE to N-S direction, did the anticlinal structures of the Sierra Nevada and the Sierra de Contraviesa and Gador form (fig. 3), while at the same time, the area in between was structured as a syncline. At this moment the corridor began to be formed.

Discussion of the models of the Alpujarras Corridor

The deposits which filled the Alpujarras Corridor are from the Late Langhian, Serravallian and Late Miocene. According the form of the lithosomes of these sediments it can be deduced that the basin being filled was an asymmetrical graben deeper towards the N and E. The unconformities and part of the deformations found indicate that the sediments are clearly syntectonic (Rodríguez Fernández *et al.*, 1990).

However, although the sedimentary analysis is useful, the discussion is centered on the geometric data. The points under dispute are: a) whether the structure of the corridor is that of a pinched syncline or not; b) the type of faults; c) whether these faults are merely epidermal, facilitating only the extension between the units, or deeper; and finally d) the importance of the possible movements produced by the faults. In this last part the effects of these movements in the External Zone will be discussed.

a) Structure of the Alpujarras Corridor

In the north of the corridor, the Sierra Nevada as a whole has an antiform structure, and on its southern slope, the Nevado-Filabride rocks dip toward the south, as is generally the case with the Alpujarride units which appear over the Nevado-Filabride on the southern side of the Sierra Nevada. Overall, the Neogene deposits of the corridor also dip towards the S, though they present a multitude of faults which cause a change in direction and dip locally.

However, the Alpujarride units which form the southern border of the Alpujarride Corridor do not generally dip towards the north. If we begin with the eastern sector (near Alhama de Almería) (fig. 3), the Sierra de Gador is clearly cut by a major E-W fault, with an impressive escarpment which is practically vertical for several hundred metres in height, at some points linked to thermal sources. There, neither the Gador Unit nor the Neogene sediments dip to the N and therefore do not form the southern limb of the proposed synclinal. The Neogene sediments (in this area from the Late Miocene) dip only to the N in the areas closest to the fault, but do not correspond to a limb of a syncline; rather they are adaptated to the fault movement as a drag fold. The fault shows clear dextral horizontal and vertical striations.

Farther to the W, in the sector of Capitan Hill, between Padules and Alcolea, with the Sierra de Gador to the south, the Neogene and Quaternary deposits, apart from being cut by many faults, do not dip to the N, with the exception of the most modern alluvial cones. In this sector, where the corridor itself is quite narrow, both the Neogene sediments (from the Serravallian) and the Alpujarride units are cut by clearly recognizable E-W vertical or reverse faults, with visible horizontal striations. Here no limb to complete the syncline from the south of the Sierra Nevada exists.

To the south of Ugijar, Cherin and Cadiar, the strike-slip faults are easily visible and the Neogene sediments, being clearly cut by these vertical faults, dip to the S. To the W of Cadiar, the Neogene deposits are less abundant and are pinched in vertical faults and the Alpujarride units do not form a synclinal. Between Orgiva and Lanjarón, there are few sediments of the Late Miocene not affected by faults, which do not adapt to a synclinal structure.

In conclusion, the Alpujarras Corridor does not correspond to a synclinal structure.

b) Type of faults in the Alpujarras Corridor

A second question is the types of faults that exist in the Alpujarras Corridor. Campos *et al.* (1986), García-Dueñas *et al.* (1992) and Galindo Zaldívar

(1993) point out that the present contacts between the units are extensional surfaces which generally take advantage of previously thrusting surfaces. These authors indicate that these extensions are so important that at many points entire units have laminated, or at least markedly thinned. The present-day contact between the Alpujarride and Nevado-Filabride is one of these extensional surfaces.

It is a clear error to deny the existence of relative movements between units, subsequent to the stacking of the units. In addition, in many cases, these movements must have an extensional character, although sometimes the extensive or compressive character can be disputed (Sanz de Galdeano, 1995). The question remains as to whether the set of faults discussed here from the Alpujarras Corridor corresponds to this type or whether, on the contrary, they are independent surfaces of the strike-slip type, more or less vertical in origin.

Faults which dip little and even run horizontally in some areas affect Neogene sediments in the sector between Ugijar and Yator; these faults tend to sink towards the N, where the dipping is most accentuated (even vertical). In addition to these, vertical or practically vertical faults which were not originally horizontal exist all along the corridor and in its interior. It would be a coincidence for a set of horizontal (or almost horizontal) faults to go uniformly vertical for some 90 km (especially considering their continuation to the E and to the W of the corridor). Moreover, these faults often affect formations which are practically horizontal, so that it is geometrically impossible for the fault surface to have undergone more than a small rotation. Other morphological and tectonic features contradict the idea that the faults have rotated appreciably and thereby increased the degree of dipping.

A study of the features accompanying these faults, in particular the striations and structures of the fault breccia, shows that they correspond to dextral strike-slip faults. At the same time they are practically vertical, though occasionally they change their dip acquiring the geometry of reverse or normal faults. Nevertheless, at some points there are true reverse faults as well as normal faults and, in addition, the surfaces separating units have interacted in different ways.

c) Depth reached by the faults

The question under discussion is whether these faults hardly penetrate in depth, or whether they in fact cut through the Alpujarride and the Nevado-Filabride complexes and therefore do not end in their most superficial units.

The faults clearly cut through the Neogene formations of the corridor, as well as the Alpujarride units, appearing at many points profusely mixing rocks from the Alpujarride units with various Neogene sediments. This is found both to the E and to the W of Ugijar. In other sectors, e.g. to the E of Orgiva and S of the Sierra de Mecina, there is a vertical contact between an Alpujarride lower units of the Lujar-Gador type and another upper unit of the Murtas type (see legend of fig. 3), which also include schists which possibly belong to another upper unit, in the fault zone. Therefore, this situation does not correspond to faults using earlier thrusting surfaces. In addition, the Nevado-Filabride is cut by vertical faults. This can be seen along the N border of the corridor and even in its interior, e.g. to the SE of Yegen, where a fault affecting the Neogene sediments incorporate tectonized blocks of the Nevado-Filabride.

In the eastward continuation of the corridor, to the N of Sierra Alhamilla, the same faults, also vertical, deeply affect the Nevado-Filabride Complex and show several associated mineralizations linked to deep hydrothermal fluids (e.g. in Lucainena de las Torres) laying in the Nevado-Filabride itself, as well as in the Alpujarride Complex and in the (Lower?) Tortonian sediments.

In the Alpujarras Corridor itself, many thermal springs and other springs called *agrias* (soured) indicate deep drainage of the waters. Moreover, the vertical displacement of the faults, generally exceeding 1,000 m and much more at some points, seems to indicate that the faults must necessarily reach greater depths.

The present geometry of these faults does not adapt to the surfaces of recognized units, but rather cuts through these surfaces, although, more deeply, there must be a basal surface where the faults dissipate. Conversely, nothing contradicts the possibility that, at a certain moment, they may have acted as transfer faults in some of the relative movements between units in order to facilitate the displacements. However, these are neither epidermal nor generally adapted to the surfaces which separate the units recognizable at present.

d) Displacement values of the faults

This is a controversial topic because of the lack of valid references which would permit valuations.

Sanz de Galdeano *et al.* (1985) favour a displacement of several dozen km, based on the total length of the faults and on the width of the trituration bands. However, as indicated above, this represents

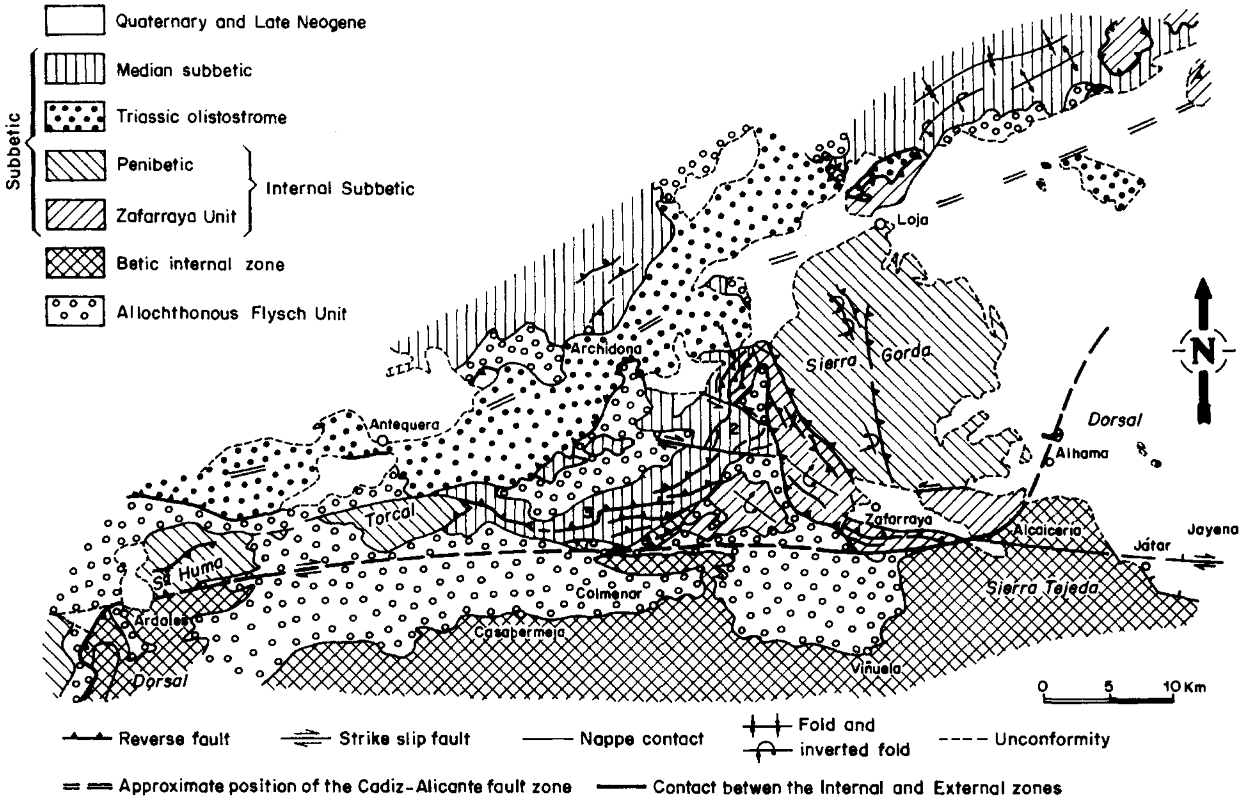

Fig. 4.—Simplified geological scheme of the External zone to the north of the Colmenar Corridor. The total displacement that occurred in the corridor can be calculated from the position of the Dorsal at both ends (see fig. 5). 1: Gibalto, 2: Sierra de San Jorge, 3: Alta Cadena. The position of the figure can be seen in figures 1 and 2.

a mere valuation. The problem is that the E-W fault direction roughly coincides with the general direction of the structure of the units, and thus we do not find transverse displacements which provide objective displacement values.

In their hypothesis that the structure of the corridor is a synclinal, Mayoral *et al.* (1994 and 1995), thought that there was continuity in the Gador Unit situated to the S and to the N of the corridor in the sector of Laujar de Andarax. In this case, the displacement, if it existed, would be minimal (but it is necessary to point out in this area the existence of faults separating both sides of the corridor).

An analysis of the Alpujarride units on each side of the corridor (the analysis of the Nevado-Filabride is not useful as it appears only on the northern border of the corridor) indicates: On the southern border, the Gador-Lujar nappe outcrops at both ends of the corridor (fig. 3), with thick series of Middle-Upper Triassic carbonates, especially well preserved in the sierras of Gador and Lujar. In addition, there are some units which duplicate Gador (called Alcázar or Escalate) and those of the Murtas nappe. On the northern border, the Gador-Lujar nappe is represented, although the thick series of carbonates is well preserved only in the Laujar sector. Along the rest of the Northern border this nappe appears quite thinned by tectonic and erosive processes. In addition, there are outcrops from the upper units.

If the sector of Laujar is correlated with that of the Sierra de Lujar, where similar stratigraphic sequences exist, the dextral displacement would be in the order of 50 km. Similarly, the correlation could be made with points situated between Lujar and Gador or with more westerly sectors. That is to say, the comparison of the Alpujarride units situated on both borders of the corridor is not useful for establishing the displacement value.

Finally, should be examined occurrences at the ends of the Alpujarras Corridor. To the east, it continues in the sierras of Alhamilla and Cabrera, but there we find the same limitation in identifying the displacement. It is surprising that in very close sectors such as Sierra Cabrera and the SE border of the Sierra de los Filabres, the upper Nevado-Filabride unit (the Bedar-Macael unit) is quite unevenly developed. In this way, major metagranite outcrops

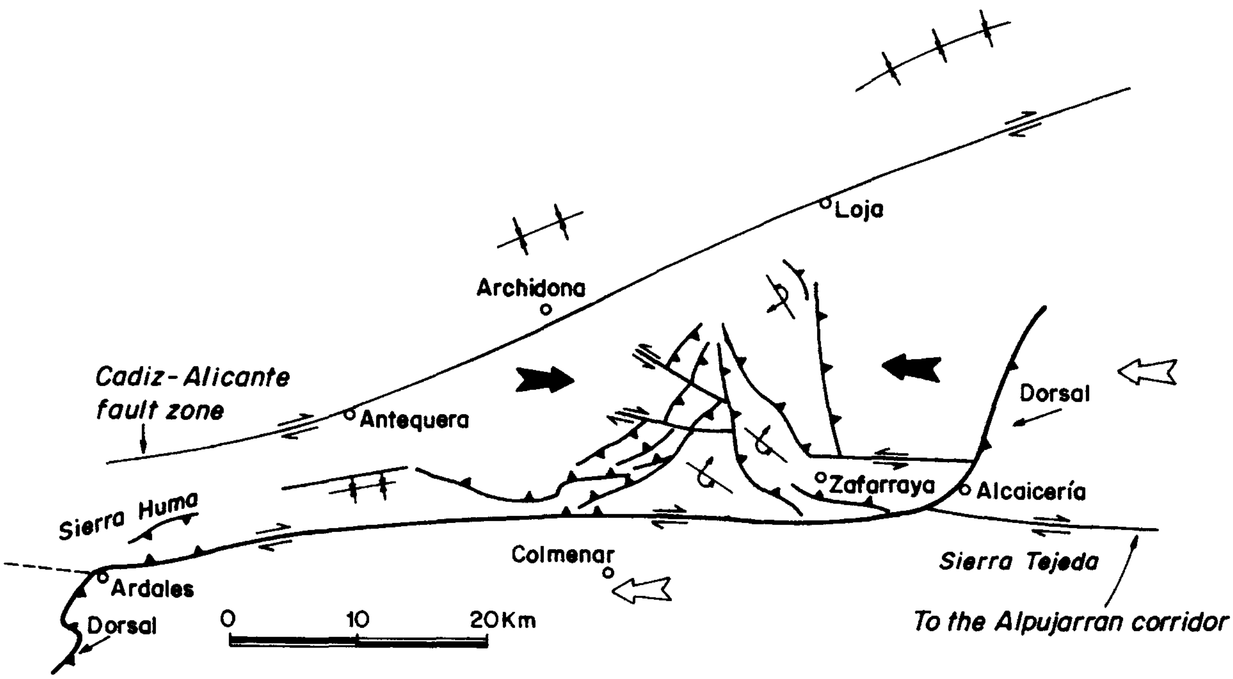

Fig. 5.—Simplified tectonic interpretation of the External Zone to the north of the Colmenar Corridor. The blank arrows indicate the direction of the displacement of the Internal Zone; the black arrows correspond to the direction of the principal compression undergone by the Subbetic in the sector between Archidona, Zafarraya and Loja. Thick lines delineate the contact between the Internal and External Zones. The position of the figure is equivalent to that of figure 4.

appear in the Filabres, while in Cabrera these are completely absent, a situation which might be explained directly by a possible lateral movement between the two sectors. In either case, no displacement values can be obtained.

Towards the west, the faults of the corridor clearly continue into the Lecrin Valley, with dextral drags in the Sierra de Albuñuelas (Sanz de Galdeano, 1990b). These faults are less clearly exposed, though sufficiently visible, in the intermediate sector (that of Herrero Peak) between the Lecrin Valley and the S of the Granada Basin. These traces clearly continue in the southern border of the basin (sector of Jayena-Jatar) and extend through the north of the Sierra Tejeda. From there, at the Alcaicería, the principal faults continue westward coinciding with the contact between the Internal and External Zones for some 75 km. This contact runs along the southern borders of the sierras of Zafarraya, Alta Cadena, Torcal de Antequera, Huma-El Chorro and Ardales. In this E-W sector between Ardales in the west and Alcaicería to east, no remains of the Dorsal (the complex related to the Malaguide) appear, although it is visible just to the W of Ardales, with the unit of the Sierra de las Nieves, and to the E in the spa of Alhama de Granada.

The proposal now presented to explain the formation of this sector of the contact (the Colmenar Corridor) is the following: the Internal Zone advanced westwardly colliding with the External Zone. Then, the Internal Zone broke and its southern part advanced more than the northern part. The value of the relative displacement would be some 75 km. This value is the length of this E-W sector, elements of the Dorsal appearing only at its ends.

Toward the East, the difference in displacement between the north and south parts in which the Internal Zone broke, must have resulted in combined movements of strike-slip faults and movements (commonly appearing in the literature as extensional) which reused earlier surfaces between units, or the appearance of some new ones.

In summary, the displacement values in the corridors of the Alpujarras and Colmenar seems to be of several dozen km, with a maximum of some 75 km, which was reached in the western part in the E-W segment of contact between the Internal and External Zones. Values of 40-50 km can be taken as reliable in the Alpujarras sector.

To support the last interpretation it is useful to discuss the structures in the External Zone which might be associated with the Colmenar Corridor.

It would be logical to assume that, in the part of the External Zone which is adjacent to the Colmenar Corridor, there are deformations produced by the transcurrent movement with respect to the Internal Zone and other deformations caused by the direct push that the Internal Zone must have exerted on the northern border of the Colmenar Corridor from the east (figs. 4 and 5).

We find in this sector that the Sierra Gorda of Loja, belonging to the Internal Subbetic (or Penibetic), does not show N60-70E folds as in the other Subbetic sectors of the central part of the Cordillera; instead, a large reverse fault appears, almost N-S, crossing Sierra Gorda (apart from other lesser, nearly parallel faults) and some reverse folds of NW-SE direction, all verging towards the W (López Chicano, 1989; Platzman, 1994). Similar vergence of faults and folds appears in the Zafarraya unit, which overthrusts that of the Sierra Gorda (some of these faults show very recent normal movements). The structure of the Sierra del Gibalto (1 in fig. 4) to Alta Cadena (3 in fig. 4) is consistent with the previous ones, in particular the two conjugate strike-slip faults which moved the Sierra de San Jorge (2 in fig. 4). These faults, together with dragged and inverted folds, are due to the roughly E-W compression to which this sector was subjected. Similarly, the arc form of this entire group of Gibalto to Alta Cadena is consistent with the same compression. The tectonic interpretation is shown in figure 5. Moreover, the palaeomagnetic data shows that the Sierra Gorda did not rotate clockwise, contrary to what occurs in other Subbetic areas which are not situated in such a special position.

In the interpretation of the author, the area of the Internal Zone which was left behind push strongly against the External Zone and thereby caused deformations different from those existing in the other Subbetic sectors, excepting the area situated directly W of the Sierra Espuña, where the situation is comparable. We should note that these features are incompatible with the interpretations which explain the emplacement of the Betic-Rif Internal Zone from the Alboran Sea as a radial thrust (Weijermars, 1987; Doblas and Oyarzun, 1989; Platt and Vissers, 1989).

Model proposed for the Alpujarra and Ardales-Colmenar corridors. Extension of the model to the whole Betic-Rif Internal Zone

In the Alpujarras and Colmenar corridors

During the westerly advance of the Internal Zone a differential displacement of two blocks took place, coinciding with the present-day position of the Alpujarras and Colmenar corridors. Related to this displacement and within the Internal Zone itself, movements of basically two types occurred: a) relative movements between different complexes and units which form the Internal Zone, so that the upper units shifted towards the W relative to the lower ones; b) in some places, the relative movement could not be accommodated by the displacement of the unit surfaces, resulting in a complex fault zone. Therefore, movements between units and transcurrent displacements combined in these corridors, provoking that the cortical segment of the Internal Zone nearest the Alboran moved more westward than that situated to the N, which was slowed down by the External Zone.

The extensional movements, consistent with the model proposed, moved the upper units in a westerly direction while those moving northwards were not congruent. In fact, the author have not observed such northward movements at any point in the Alpujarras Corridor or in any of its eastern or western prolongations.

General model

The model proposed for the movements of the Betic-Rif Internal Zone, with respect to the features described here, is the following.

The Betic-Rif Internal Zone was displaced progressively towards the W owing to the extension and opening of the Argelo-Provençal Basin. Because of this movement, the Internal Zone collided laterally with the External Zone, which was enormously deformed, and the contact was dextral transpressive. However, the resistance of the External Betic Zone (especially the Subbetic) was uneven and progressively minor towards the south. As the External Rif Zone also opposed the displacement of the Internal Zone, the area of lesser resistance was that situated between the two external zones, that of the present-day Gibraltar Arc. That is, since the resistance of the external zones was not uniform, the Internal Zone broke into various segments (figs. 1, 2 and 5). As a whole, these advanced further in the central part, coinciding with the contact area between Iberia and Africa, where there was less resistance.

In the sectors where the Internal Zone was cut into blocks which moved at different rates, two principal features coincide. First, a) the contact between the Internal and External Zones has an E-W to N70E direction. In these areas, there is usually no overthrusting of the Internal zone over the External one, but the contrary may occur; the general geometry is of a dextral strike-slip fault, with local features of a reverse fault. Second, b) in the Internal

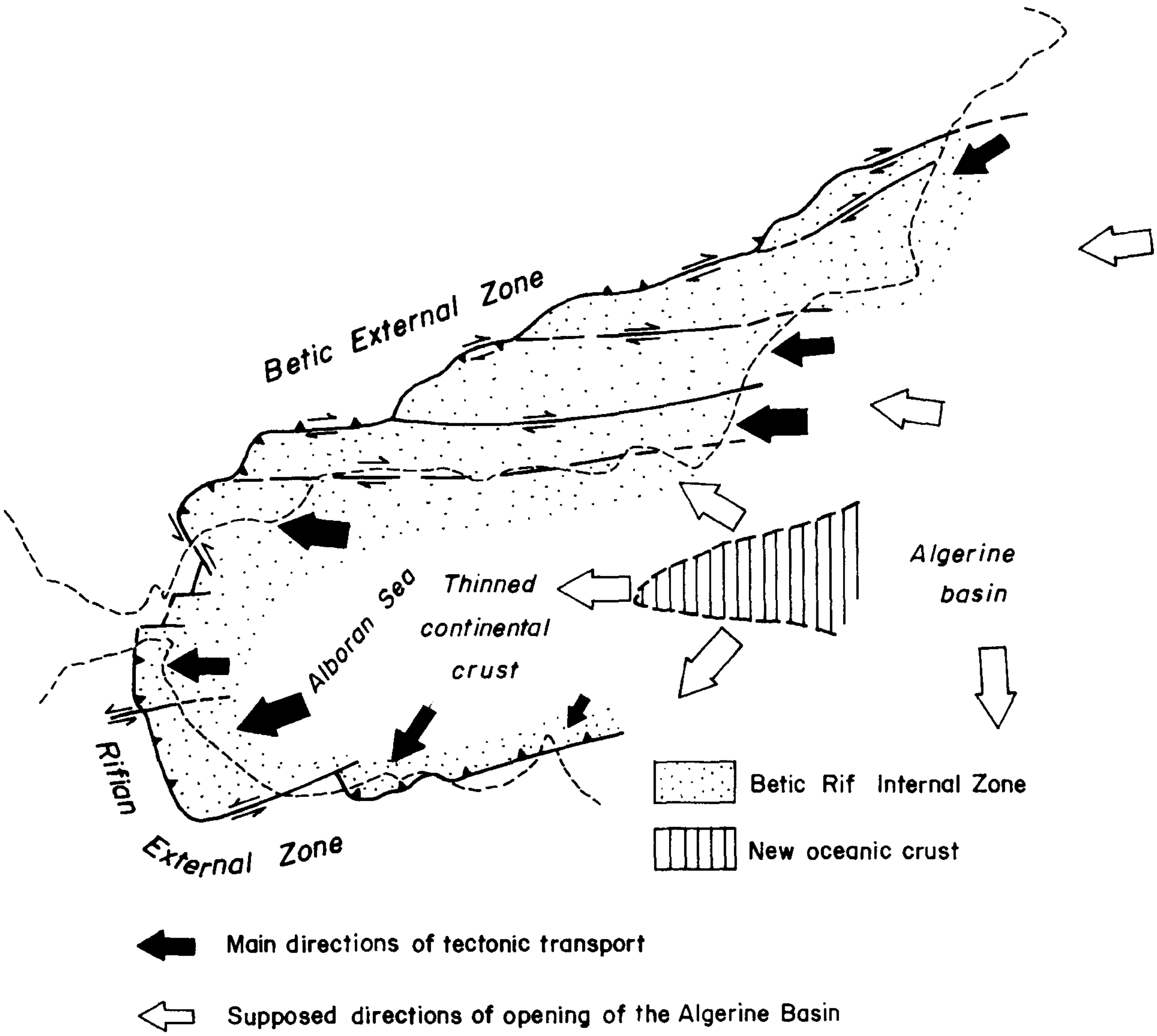

Fig. 6.—General scheme showing the relative movements of the Betic-Rif Internal Zone with respect to the External and the relative movements between cortical segments of the Internal Zone. The blank arrows indicate the presumed direction of the opening of the Argeline Basin, situated behind the Betic-Rif Internal Zone; the black arrows mark the direction of tectonic transport.

Zone and in geometric continuity with this E-W to N70E segments, a zone of faults was produced. These zones currently appear as depressed corridors, limited and crossed by faults in which vertical movements are easily discernible. Some of these corridors contain Neogene deposits clearly linked to the evolution of the corridors.

That is, the model implies the fracturing of the Internal Zone into cortical segments, a process which facilitates the westward advance. These segments, in the shape of *terranes,* moved unevenly, and generally more so as they neared the axis of the present-day Gibraltar Arc. At the same time, the Internal Zone itself underwent extension in the Alboran Sea (a continuation of that which occurred in the Argeline Basin, although in Alboran an oceanic crust did not form) (fig. 6).

The author model resembles another developed by Durand-Delga (1980) (see his fig. 5). The essential difference is that in the present one, as indicated above, the Internal Zone did not behave as a homogeneous block, but divided into various segments with different advances. This segmentation led to the formation of the corridors indicated. At the same time, in the current authors' model, the rotation of the units and the ESE to SSE vergences of the Dorsal, Malaguide and even Alpujarride, units in the area of contact with the Subbetic are seen to be the result of the resistance to the advance opposed by the Subbetic.

Chronology

The chronology of the process described above is approximately the following. In agreement with Hermes (1985) and Martín Algarra (1987), the Subbetic was disorganized since the end of the Early Burdigalian. This does not indicate that this age marks the beginning of the westward expulsion of the Betic-Rif Internal Zone, which started at the end of the Oligocene, but rather marks the time of the collision with the Subbetic. According to this, there are sedimentary formations from the end of the Aquitanian to the Early Burdigalian, unconformable over the Internal Zone and pinched in the contact with the External, as can be seen in the Colmenar or Vélez Rubio corridors.

In turn, the sediments from the (Late?) Tortonian of Chorro (to the S of the Sierra de Huma) fossilized the contact between the Internal and the External Zone in the Colmenar Corridor. According to this data, it is clear that there the contact moved between the end of the Early Burdigalian and the Late Tortonian. In addition, in the eastern sector of the Alpujarras Corridor and in its continuity through Alhamilla and Cabrera, we find strike-slip faults which affect sediments from the Late Tortonian to the Messinian and even at some points, weakly, from the Pliocene.

According to this data, the principal movements occurred during the Late Burdigalian and Middle Miocene, having almost stopped in the Late Miocene. Only in the most easterly part of the Alpujarras Corridor in its continuation towards Alhamilla do we find more modern displacement of any importance, although now generally subordinate to the vertical movements. In fact, the situation of roughly NNW-SSE compression (Ott d'Estevou and Montenat, 1985) which occurred in the Betic Cordillera from the Late Miocene, impeded the E-W faults from moving with significant displacements.

Conclusions

The aspects resolved by the model proposed in the present work are:

1. The origin and the significance of the irregularities of the contact between the Internal and External Zones are clarified, especially regarding the E-W to N70E segments, which are transcurrent faults by which part of the Betic-Rif Internal Zone advanced more towards the west, producing at the same time its division into several cortical segments.
2. The origin and significance of the corridors running approximately E-W of the interior of the Betic Zone is explained. These corridors and alignments are the easterly continuation of the previous transcurrent faults. In these faults, first transcurrent movements occurred, and later other movements took place, particularly those of vertical nature. From the beginning of their formation as narrow zones of faults, they correspond to sectors of cortical weakness and were therefore places where subsequent successive deformations were fixed. This superposition of deformations ended by the formation of the present-day corridors.
3. The importance of the strike-slip faults is emphasized, in accordance with the previous geological features. The maximum displacement of these faults is approximately 75 km in the Colmenar Corridor.
4. An explanation is provided, at least partially, for the roughly E-W extensional movements. These movements are consistent with the displacement of the Internal Zone towards the W. These displacements can be helped in the corridors by the strike-slip faults which could serve locally as transfer faults between the surfaces of the units which move towards the W. It explains the different position of some Alpujarride, and even Malaguide, units to the east of the Sierra Nevada (on the northern border of the Colmenar-Alpujarras corridors) compared with equivalent units existing in the Ardales area (on the southern border of the Colmenar Corridor).
5. The sector of Bajo Segura, of a NE-SW direction, could be one of the corridors formed from the Early Miocene, although it was later used as the NW prolongation of the Palomares-Lorca Corridor, formed from the Late Miocene.
6. The anomalous directions of some structures existing in the Subbetic are explained. They are referred to the W of Sierra Espuña and in the Sierra Gorda of Loja and its westward continuation. These structures are the consequences of the E-W compression of the Internal against the External Zone, in two sectors where the External Zone resisted especially the advance of the Internal Zone. Before the proposed model, these structures had no explanation.

Finally, it is evident that these data now assembled, and which explain each other, clearly go against the models of radial expansion of the Internal Zone from the Alboran Sea. The movements indicated need specifically a further displacement of the Internal Zone from the east.

This movement of terrains which are fragmented into cortical segments is not a new feature. For example, within the western Mediterranean, in the Apennines or in Calabria, such movements have been proposed by Boccaletti *et al.* (1983), Rehault *et al.* (1987) and Locardi (1988).

From the point of view of palaeogeographic reconstructions of the complexes of the Internal Zone, the model explains the present distances among outcrops of the same complex, produced by transcurrent movements. In this way, the original distance between Malaguide outcrops in Gaucin and the Sierra Espuña is notably reduced to some 120 km, or some 75 km between Dorsal outcrops, in Ardales and Alhama de Granada. Similarly, the clear penetration of the Campo de Gibraltar Units (Flysch units) into the Colmenar Corridor is explained.

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