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LATE CENOZOIC IDENTATION/ESCAPE TECTONICS IN THE EASTERN BETIC CORDILLERAS AND ITS CONSEQUENCES ON THE IBERIAN FORELAND

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RESUMEN

La estructuración del cuadrante SE de la Península Ibérica (Béticas orientales y antepaís Ibérico), desde el Messiniense hasta la actualidad, ha sido el resultado de una serie compleja de eventos deformativos, relacionados con la actividad de una megazona de cizalla NNE-SSO en el SE de las Cordilleras Béticas (zona de cizalla Trans-Alborán-Palomares; TAPSZ). La deformación a lo largo de esta zona de cizalla se caracteriza por dos escenarios secuenciales diferentes: 1) períodos de concentración de esfuerzos, asociados con un frenado momentáneo del movimiento a lo largo de la TAPSZ, y con procesos de identación dirigidos hacia el NO, y 2) períodos de disipación de esfuerzos, que serían el resultado del escape lateral de bloques en forma de cuña, y del movimiento transcurrente renovado a lo largo de la TAPSZ. Estos eventos han generado campos de esfuerzos en el antepaís Ibérico, con una serie de consecuencias tales como el vulcanismo alcalino de Calatrava y Cofrentes, zonas de protorift, modificaciones de directrices estructurales previas, levantamientos/abombamientos localizados, y cambios en el régimen sedimentario de algunas cuencas.

Palabras clave: *Béticas Orientales, antepaís Ibérico, tectónica de indentación, zona de cizalla.*

ABSTRACT

The structuration of the southeastern quarter of the Iberian Peninsula (eastern Betics and Iberian foreland), since Messinian time, was the result of a series of complex deformational events, as related to a major NNE-SSW sinistral shear zone disrupting the southeasternmost part of the Betic cordilleras (Trans-Alborán-Palomares shear zone; TAPSZ). Deformation along this shear zone was characterized by two differentiated and sequential scenarios: 1) periods of stress-build-up associated to momentary slip-obstruction along the TAPSZ, involving NW-directed indentation of the southeastern Iberian domain, and 2) periods of stress-release resulting from the lateral escape of wedge-shaped blocks, thus allowing full-scale strike-slip displacements along the TAPSZ. These events imposed compressional stress fields on the Iberian foreland, with a series of consequences such as alkaline volcanism in Calatrava and Cofrentes, protorift zones, changes in previous structural trends, localized uplift/doming processes, and changes in the sedimentary records of some basins.

Key words: *Eastern Betics, Iberian foreland, indentation tectonics, shear zone.*

Introduction

The Betics have been classically divided into external and internal zones regarding deformation and metamorphism (fig. 1; Fontbote, 1983). The external units (Prebetics and Subbetics) are constituted by folded and/or thrusted Mesozoic rocks (Vera, 1983). The internal units (Nevado-Filábride, Alpujarride, Maláguide, and Ultrabetic) show pre-Mesozoic and Triassic rocks with complex nappe arrangements, involving a basement and metamorphism (Fontbote and Vera, 1983). The different deformational phases have long been studied, but much controversy remains concerning ages, directions of tectonic trans-

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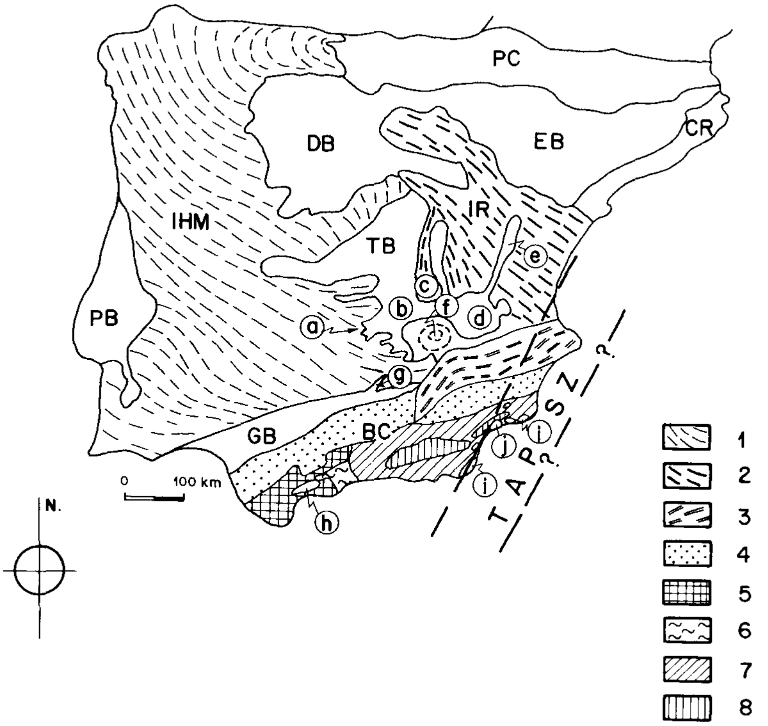

Fig. 1.—Sketch map of the Iberian Peninsula outlining the elements discussed in this paper. 1, structural trends of the Iberian Hercynian Massif; 2, structural trends of the Iberian Ranges; 3 to 8, different structural elements of the Betic Cordilleras (3 and 4, external units; 5 to 8, internal units): 3, Prebetic; 4, Subbetic; 5, Ultrabetic; 6, Malágulde; 7, Alpujarride; 8, Nevado-Filábride. Points highlighted: a, Calatrava volcanic province (CVP); b, La Mancha/Calatrava basin; c, Altomira mountains; d, Júcar/Cabriel basin; e, Teruel trough; f, Ruidera uplift; g, Bailén trough; h, Ronda peridotites; i, Cartagena/Almería calc-alkaline to lamproitic volcanism; j, Mazarrón alkaline volcanism. BC, Betic Cordilleras; CR, Catalonian Ranges; DB, Duero basin; EB, Ebro basin; GB, Guadalquivir basin; IHM, Iberian Hercynian Massif; IR, Iberian Ranges; PB, Portuguese basin; PC, Pyrenean Chain; TAPSZ, Trans-Alborán-Palomares Shear Zone; TB, Tajo basin.

port, and number of episodes (Didon *et al.*, 1973). Till recent years, the whole structuration of this orogenic edifice was regarded in terms of compressional nappe tectonics and subduction/collision scenarios (Fontbote, 1983). As such, the compressional events were supposed to range in age from late Cretaceous to middle and even late Miocene (Fontbote, 1983; Sanz de Galdeano, 1983). However, a new hypothesis has been suggested recently in the light of extensional detachment tectonics which changes the overall picture (Doblas and Oyarzun, 1989a,b; Galindo Zaldívar *et al.*, 1989; Platt and Vissers, 1989). According to Doblas and Oyarzun (1989a,b) the middle to upper Miocene evolution of the Betics was characterized by the gravitational collapse of the orogenic edifice through low-angle extensional detachments, associated to crustal upward arching, isostatic rebound, exhumation of metamorphic and mantle core complexes, and calc-alkaline to lamproitic volcanism.

However, the late Cenozoic (Messinian/Tortonian to the present) disruption of the eastern Betics still remains unexplained within a geotectonic frame fitting coherently with the previous history (basically wrench-tectonics models have been advanced) (Montenat *et al.*, 1987; Ott d'Estevou *et al.*, 1988; Sanz de Galdeano, 1990). In this sense, any hypothesis about this orogenic edifice should integrate the following:

1) Different sets of strike-slips faults in the eastern realm, with transtensional or transpressional step-overs (Sanz de Galdeano, 1983; Montenat *et al.*, 1987; Ott d'Estevou *et al.*, 1988), a scenario which is lacking in the rest of the Betics.

2) The final tectonic emplacement of the Nevado-Filábride metamorphic complex to the SW (Gar-

cía Dueñas *et al.*, 1988; Galindo Zaldívar *et al.*, 1989), an element which was previously unroofed/exhumed during the extensional event (Doblas and Oyarzun, 1989a,b).

3) The late Cenozoic welding of the Prebetic units against the Iberian foreland (with no intermediate sedimentary trough; fig. 1), triggering three different structural domains: a western sector, with a convex-to-the-NW arc geometry; a central domino-type sector; and a wedge-shaped eastern sector. Noteworthy, the Prebetic external units only exist in this part of the Betics, and hence, most deformation in them is probably related to this late Cenozoic disruption.

4) The convex-to-the-NW geometry of the arc of Aguilas, very similar to the western Prebetic arc, both being separated by strike-slip corridors (Coppier *et al.*, 1989).

5) The end, by Messinian time, of the calc-alkaline to lamproitic volcanism in the Cartagena-Almería area, and the beginning of localized alkaline volcanism in the Mazarrón sector (López Ruiz and Rodríguez Badiola, 1980; Martín Escorza and López Ruiz, 1988).

Several features of the Iberian foreland (Instituto Geológico Minero de España, 1980a,b) can be understood in terms of disturbances triggered by late events disrupting the eastern Betics (fig. 2), and must also be included in any model-to-be:

1) The presence of alkaline basaltic rocks to the NW of the frontal Prebetic arc, i.e. the Calatrava Volcanic Province (CVP).

2) The structural trends in the southeastern border of the Iberian Hercynian Massif in contact with the Tajo and La Mancha/Calatrava Tertiary basins (from Toledo to Ciudad Real and Alcaraz), are disturbed from their usual NW-SE directions, with the following effects: a) anomalous W-E to ENE-WSW trends, locally showing drag-effects in the southern sector; b) a series of structural gaps between the original Hercynian trends, thus allowing the generation of subsidiary Tertiary sedimentary troughs.

3) A subcircular dome-like zone with mostly Jurassic rocks (Ruidera uplift) is observed between Ciudad Real and Albacete in contact with the Prebetic arc.

4) The usual NW-SE structural trends of the Iberian Ranges display two anomalous NNE-SSW features pointing southward in the direction of the Prebetic arc: the southward splaying Altomira mountains; and the Tertiary Teruel trough, which disrupts the Iberian Ranges.

5) Different Tertiary sedimentary basins of central/southeastern Iberia (Tajo, Calatrava/La Mancha, Altomira, Júcar, and Cabriel) underwent, by late Tortonian/Messinian time (upper Vallesian according to a continental-facies-based terminology), a series of changes in their sedimentary records (Pérez González, 1981; Torres and Zapata, 1987; Calvo *et al.*, 1989) such as: a) intrasedimentary discontinuities; b) variations in the endorreic/exorreic character of some of the basins; c) a generalized SE-directed tilting of the Tajo trough; d) changes in paleocurrents of both fluvial and alluvial systems; e) generation of a series of new basins such as the Júcar, Cabriel, and the different troughs of the La Mancha/Calatrava region which disrupt the continuity of the Hercynian outcrops.

6) An even more distal effect is constituted by the uplifting (by means of inverse faults) of the Spanish Central System and the Toledo and Altomira mountains in central Iberia since Miocene time (Sáenz, 1976; Garzón Heydt *et al.*, 1982; Martín Escorza, 1990), constituting isolated blocks between Tertiary sedimentary basins.

7) As previously stated, the contact between the Betics and its foreland is anomalous in the eastern realm as no intermediate sedimentary basins exists between them (in the central and western Betics the Guadalquivir trough separates both domains).

The late Cenozoic structuration of the eastern Betic cordilleras

A key element in the evolution of this whole area during late Cenozoic time is constituted by a major NNE-SSW sinistral shear zone disrupting the southeasternmost tip of the Iberian Peninsula, the *Trans-Alborán-Palomares shear zone* (TAPSZ, fig. 3) or «Trans-Alborán shear zone» of Frizon de Lamotte *et al.* (1980), Hernández *et al.* (1987), and De Larouzière *et al.* (1988), whose activity since Messinian time might be related to renewed convergence between Africa and Europe (Letouzey, 1986). Coppier *et al.* (1989), have proposed a model for the Neogene evolution of this shear zone, involving rigid-plastic tectonic indentation in the Arc of Aguilas. According to them, deformation was characterized by alternating compression directions (NW-SE, N-S, and NW-SE; see also Ott d'Estevou *et al.*, 1988), giving rise to strike-slip faults, and convex-to-the-NW thrusts. However, these authors suggest a Burdigalian age for the beginning of this event which seems incompatible with the existence of a well documented extensional scheme taking place in this region during the time span Serravalian to Tortonian (accompanied by the extrusion of the Cartagena-Almería calc-alkaline to lamproitic volcanics; (López Ruiz and Rodríguez Badiola, 1980; Martín Escorza and López Ruiz, 1988; Doblas and Oyarzun, 1989a,b;

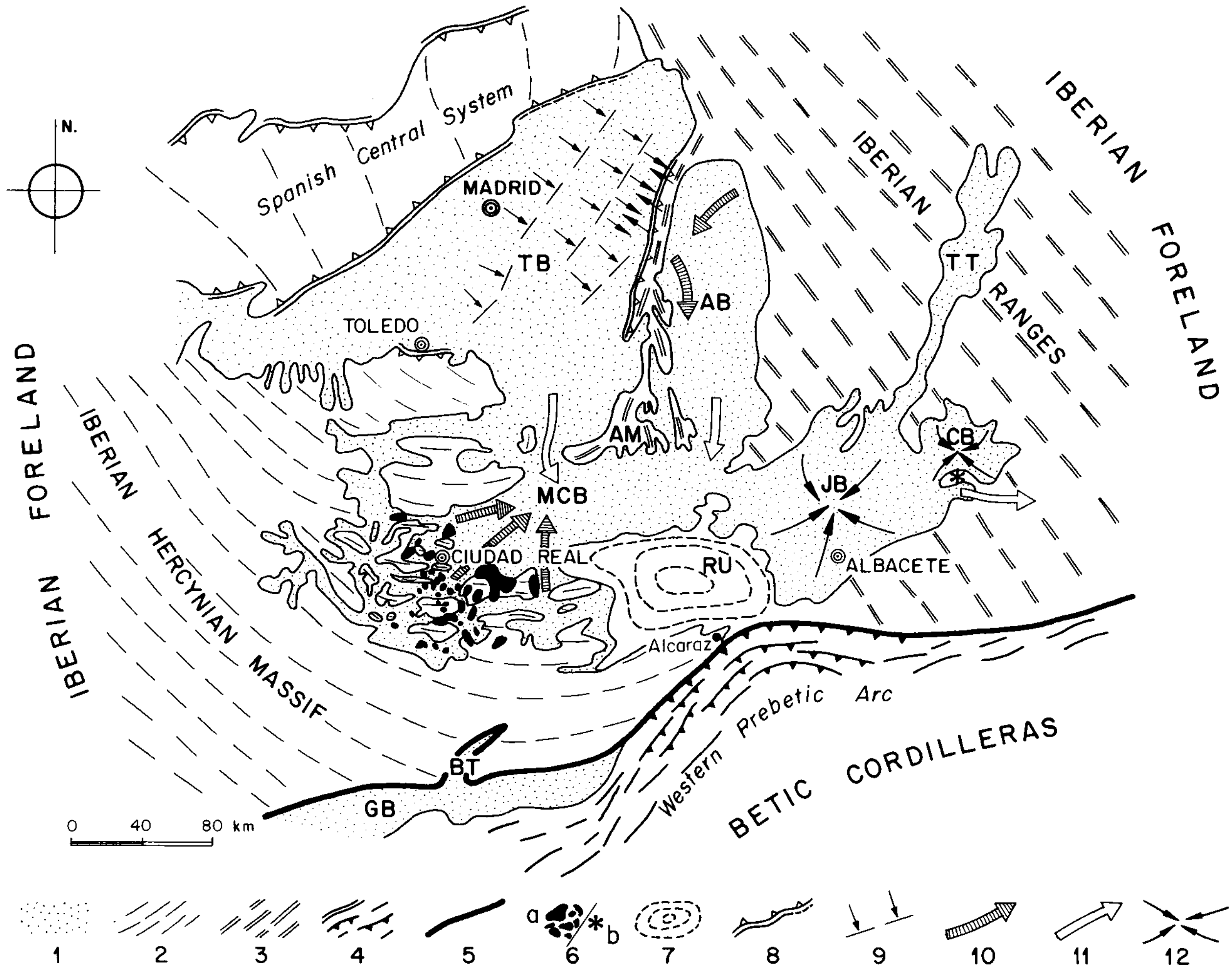

Fig. 2.—Simplified geologic map outlining the foreland deformations which can be related to the indentation process. 1, Neogene to quaternary sediments; 2, structural trends of the Iberian Hercynian Massif; 3, structural trends of the Iberian Ranges; 4, structural trends of the Betic Cordilleras; 5, contact between the Betic cordilleras and the Iberian foreland; 6a, Calatrava Volcanic Province (CVP); 6b, alkaline volcanism of Cofrentes; 7, Ruidera uplift; 8, inverse faults bounding the Spanish Central System and the Toledo and Altomira mountains; 9, tilting direction within the Tajo basin; 10, new outflow directions of the alluvial fans; 11, new outflow directions of the fluvial systems; 12, new lacustrine depocenters; AB, Altomira basin; AM, Altomira mountains; BT, Bailén trough; CB, Cabriél basin; GB, Guadalquivir basin; JB, Júcar basin; MCB, La Mancha/Calatrava basin; RU, Ruidera uplift; TB, Tajo basin; TT, Teruel trough.

Galindo Zaldívar *et al.,* 1989; Platt and Vissers, 1989). This shear zone appears to have a considerable width, its eastern boundary being presently concealed under the sea.

Four major tectonic units might be distinguished in the eastern Betics during late Cenozoic time (fig. 3): 1) the Prebetic frontal units (three different blocks); 2) the Nevado-Filábride wedge-shaped block; 3) The Murcia wedge-shaped block; and 4) a series of transtensional/transpressional WSW-ENE to SSW-NNE strike-slip corridors (López Ruiz, 1984; Montenat *et al.,* 1987). The Prebetic subdivision of the Betics constitutes the easternmost external element of this cordillera. As already stated, no similar unit in direct contact with the Iberian foreland exists in the central and western Betics. Deformation is characterized by folds, thrusts, and strike-slip faults, at most within a paraautochton scheme with no metamorphism or basement involved (Fontbote and Vera, 1983). Stratigraphic criteria allow to subdivide this unit in two domains (Vera, 1983), both bearing Triassic to lower Miocene rocks: a northern external unit, and a southern internal one with a more complete and thick stratigraphic sequence. According to Vera (1983), the discontinuities in the stratigraphic series indicate compressional events happening in the

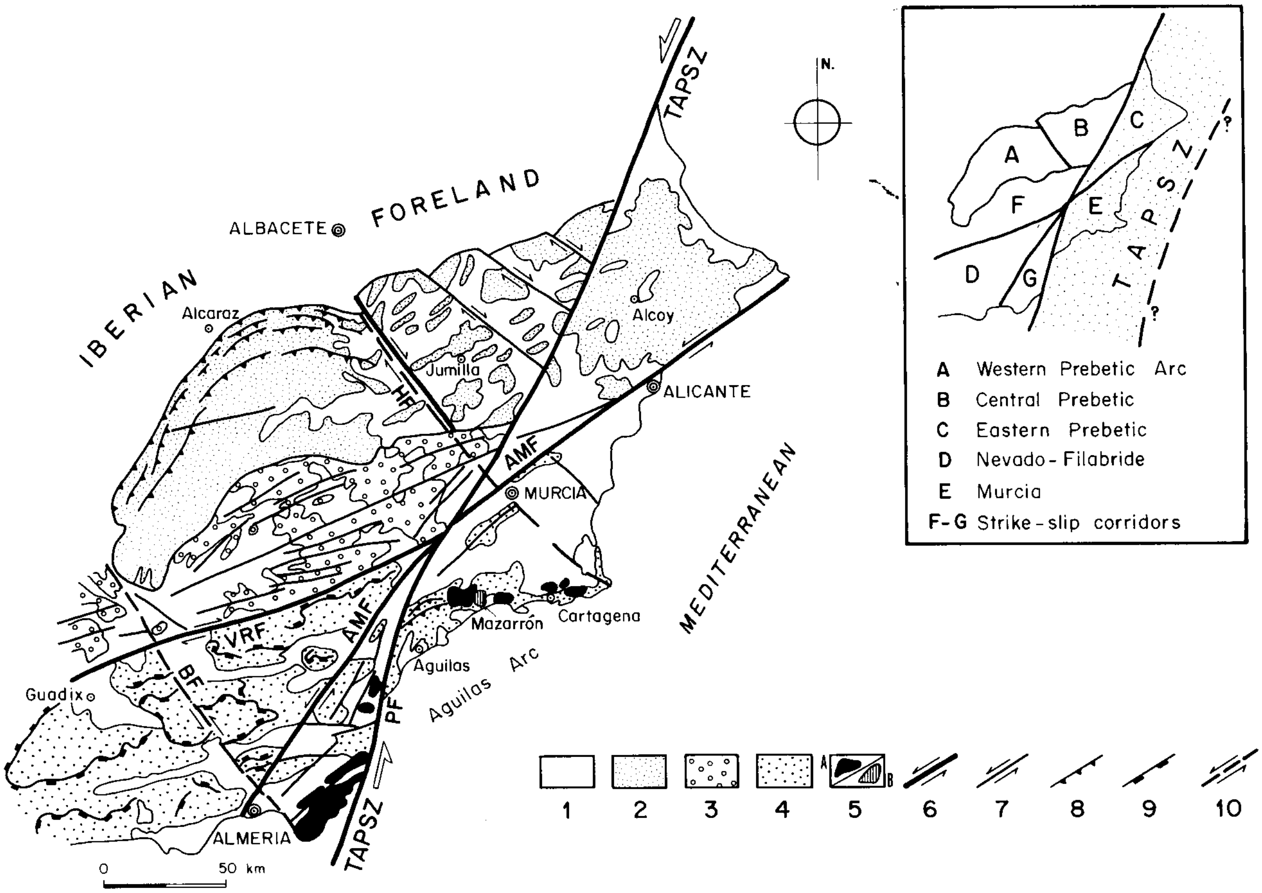

Fig. 3.—Simplified geological map of the eastern Betic showing the major structural elements. Basic geology modified after Bousquet and Philip (1976), incorporating Sanz de Galdeano (1983), and Instituto Geológico Minero de España (1980a). 1, Neogene to Quaternary sediments; 2, Prebetic units; 3, Subbetic units; 4, Internal Betic units (Nevado-Filábride, and Alpujarride); 5, Neogene volcanism (a: Cartagena/Almería calc-alkaline to lamproitic; b: Mazarrón alkaline); 6, major strike-slip faults bounding the different blocks; 7, minor strike-slip faults; 8, thrusts; 9, low-angle faults in the Nevado-Filábride metamorphic complex; 10, latest strike-slip faults. AMF, Alhama de Murcia fault; BF, Baza fault; HF, Hellín fault; PF, Palomares fault; TAPSZ, Trans-Alborán-Palomares shear zone; VRF, Vélez-Rubio fault.

time-span middle to upper Miocene. Once again, we are here confronted with the classical compressional-based views for any event occurring in the Betics. However, as previously stated, these deformational phases truly represent extensional disruptions within a generalized picture involving low-angle detachment surfaces (Doblas and Oyarzun, 1989a,b; Galindo Zaldívar *et al.*, 1989; Platt and Vissers, 1989). These listric low-angle discontinuities could have been later reactivated through inversion tectonics during the late Cenozoic compressional scenario, as ramps thrusting the Prebetic units onto the Iberian foreland. In this sense, a seismic reflection profile clearly indicates the existence of a SE-dipping listric subhorizontal reflector (Banks and Warburton, 1991) in the contact between the Prebetics and the Iberian foreland.

Three different tectonic blocks might be distinguished in the Prebetics (fig. 3):

1) A western block, which displays a convex-to-the-NW arc geometry, with folds and thrusts (Instituto Geológico Minero de España, 1980b).

2) A central block with a domino-type geometry disrupted by a series of NW-SE dextral faults, where late Cenozoic sedimentary troughs dominate.

3) An eastern block, with a NE-directed wedge-shaped geometry displaying NE-SW-oriented folds, as well as late Cenozoic sedimentary troughs. This block is bounded by the NE-SW Alhama de Murcia sinistral fault to the southeast, and by the ill-defined NNE-SSW sinistral prolongation of the TAPSZ to the northwest.

A major unit in the eastern Betics is the Nevado-Filábride complex, which outcrops as a SW-directed wedge-shaped tectonic window bounded to the north by the Vélez Rubio ENE-WSW to NE-SW dextral fault, and to the south by the Alhama de Murcia NNE-SSW to NE-SW sinistral fault (fig. 3). This complex is mostly constituted by pre-Triassic to Triassic basement rocks showing medium to high-grade metamorphic conditions (together with some sedimentary troughs; Fontbote, 1983). This unit has been interpreted as a metamorphic core complex unroofed/exhumed during a middle to upper Miocene extensional detachment tectonics scheme (Doblas and Oyarzun, 1989a,b). As shown by García Dueñas *et al.* 1988) and Galindo Zaldívar *et al.* (1989), this complex underwent a final SW-directed tectonic transport, which they interpret as related to the extensional detachment scheme. However, this hypothesis for the late tectonic emplacement of this unit is incompatible with the prevailance of compressional conditions in the region since Messinian time.

The Murcia block is a NE-opening wedge-shaped domain bounded to the southeast by the arcs of Aguilas and Alicante, and to the northwest by the NNE-SSW Palomares fault (Weijermars, 1987) and the NE-SW Alhama de Murcia faults (both sinistral; fig. 3). It is constituted mostly by late Cenozoic sedimentary troughs, together with a complex combination of allochtonous Betic fragments (Nevado-Filábride and Alpujarride), Neogene to quaternary volcanics, and a whole system of differently oriented dip- and strike-slip faults (Coppier *et al.*, 1989). According to De Larouzière *et al.* (1988), this block is formed by a thinner and denser «Cartagena-type» continental crust (as compared to the western sectors).

Two major ENE-WSW to NNE-SSW strike-slip corridors disrupt the different elements (fig. 3), generating both transtensional troughs filled with Neogene to quaternary sediments, and transpressional domains where chaotic fragments of external (Subbetics) and internal (Nevado-Filábride and Alpujarride) Betic units are found in complex associations (López Ruiz, 1984; Montenat *et al.*, 1987; Ott d'Estevou *et al.*, 1988). These strike-slip corridors separate the two arc-shaped sectors previously described in the eastern Betics, the arc of Aguilas, and the western Prebetic arc.

Finally, the latest sets to become active were two NW-SE dextral and sinistral faults (Sanz de Galdeano, 1983) which bound a block containing the arc of Aguilas and the western Prebetic arc (Hellín and Baza faults; fig. 3).

The proposal of a model

We will present a geotectonic model that accounts for the complex deformational scheme of the southeastern quarter of the Iberian Peninsula during late Cenozoic time.

As already stated, prior to the late Cenozoic disruption of the eastern Betics, the whole alpine edifice underwent extensional detachment tectonics from middle to upper Miocene (Serravalian to Tortonian or Messinian), with the following characteristics (fig. 4a; Doblas and Oyarzun, 1989a): 1) a major ENE-WSW-oriented detachment surface dipping to the SSE, with a tectonic transport in this direction, whose breakaway fault constituted the northern boundary of the primitive Guadalquivir basin (the «so called» Betic Strait who connected the Atlantic and the Mediterranean (Weijermars, 1988); 2) a series of sedimentary troughs bounded by high-angle normal faults; 3) the exhumed/unroofed Nevado-Filábride metamorphic core complex; 4) the Cartagena-Almería calc-alkaline to lamproitic volcanic province. Therefore, the extensional event which characterized this region till Tortonian time, defined an eastern Betic realm with enhanced mantle activity, leading to rapid exhumation of deep-seated metamorphic complexes, and to extrusion of volcanics. The extensional scheme during this time-span was enhanced both by a minimum rate of convergence between Africa and Europe, and by a NE-SW-oriented regional compressional field in the western Mediterranean (Biju-Duval *et al.*, 1976; Letouzey, 1986).

The Tortonian/Messinian transition (7 Ma.) appears to be a key moment which marks the beginning of the disruption of the eastern Betics (fig. 4b). This instability can be related to the onset of the disturbances generated by the TAPSZ. The change in the whole deformation picture seems due to renewed NS compression in this part of the Mediterranean, as a result of higher convergence rates between Africa and Europe (Letouzey, 1986). Moreover, the late Miocene to present deformation picture occurring along the TAPSZ will be the key element determining the evolution of this eastern Betic realm. We suggest, as a basic hypothesis for the whole evolution of this region, that the sinistral movement along the TAPSZ is characterized by sequential indentation/escape tectonics, as a result of a progressively rotating and deforming block within the TAPSZ. In this sense, we can imagine a theoretical shear zone which might account for this complex kinematic scenario (fig. 5). The initial activity along the shear zone would delimit a block within it, with a geometry depending on the width of the shear zone and the characteristics of the crust that was initially disrupted. In this sense, the easternmost Betics might have constituted a «differentiable» block of continental crust, bounded to the NE and to the S by weaker types of crust (highly attenuated continental; Valencia and

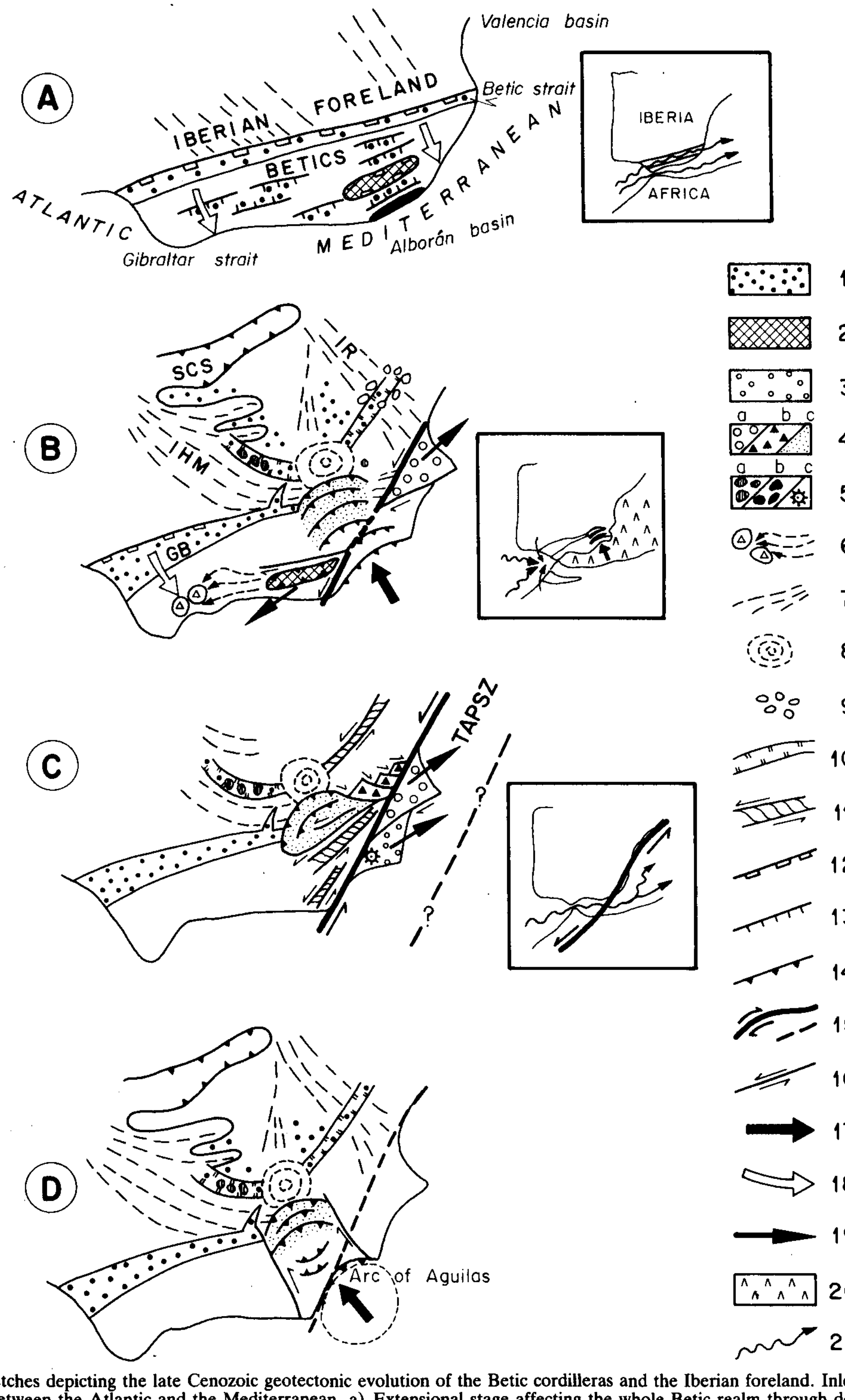

Fig. 4.—Idealized sketches depicting the late Cenozoic geotectonic evolution of the Betic cordilleras and the Iberian foreland. Inlet figures show the water circulation patterns between the Atlantic and the Mediterranean. a) Extensional stage affecting the whole Betic realm through detachment faults (Middle to Late Miocene; Doblas and Oyarzun, 1989a). b) Initial disruption of the eastern Betics realm under mostly stress-build-up conditions (late Tortonian/Messinian). c) Stage of stress-release allowing full-scale strike-slip displacements along the Trans-Alborán-Palomares shear zone, TAPSZ. d) Blockage of the TAPSZ inducing renewed stress-build-up conditions (c and d: Pliocene to the present). 1, Neogene to Quaternary sediments; 2, Nevado-Filábride metamorphic core complex; 3, Murcia block; 4, Prebetic units (a, eastern; b, central; and, c, western); 5, volcanism (a: of alkaline affinities in the Calatrava Volcanic Province and in Cofrentes, to the SE of the Teruel trough; b: Cartagena/Almería calc-alkaline to lamproitic; c: Mazarrón alkaline); 6, Ronda peridotites, and associated directional flow of mantle material; 7, structural trends of the Iberian Hercynian Massif and the Iberian Ranges; 8, Ruidera uplift; 9, doming structures in the Iberian Ranges/Teruel trough (Simón Gómez, 1989); 10, impactogen-related extensional structures; 11, strike-slip corridors; 12, breakaway fault of the major detachment; 13, high-angle normal faults; 14, thrusts; 15, Trans-Alborán-Palomares shear zone (TAPSZ); 16, strike-slip faults; 17, orientation of regional compression; 18, orientation of regional extension; 19, direction of block escape; 20, Messinian evaporitic deposits in the westernmost Mediterranean; 21, water circulation patterns between the Atlantic and the Mediterranean. GB, Guadalquivir basin; IHM, Iberian Hercynian Massif; IR, Iberian Ranges; SCS, Spanish Central System; TAPSZ, Trans-Alborán-Palomares shear zone.

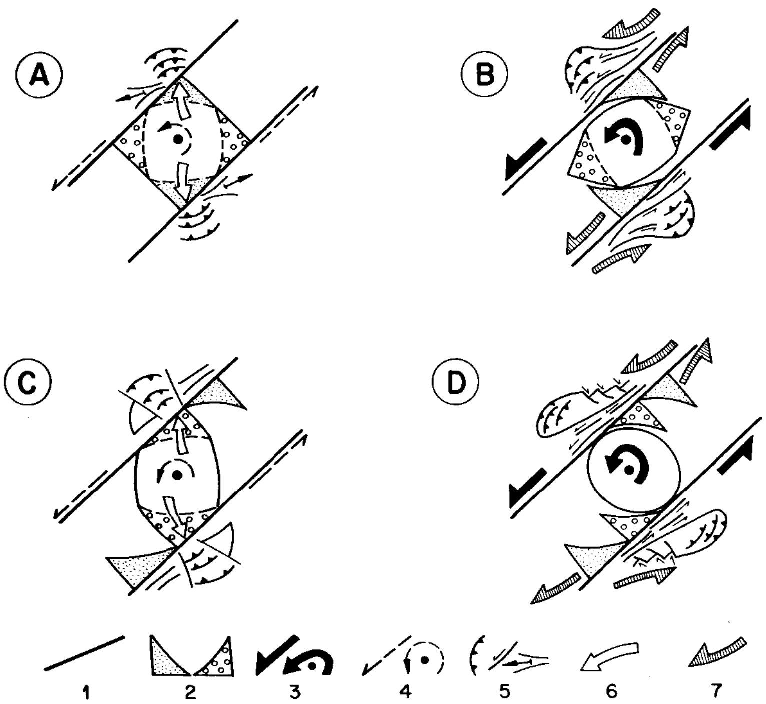

Fig. 5.—Theoretical sequential evolution of a sinistral shear zone containing a block which undergoes progressive anticlockwise rotation and deformation, involving two sequential events: periods of stress-build-up associated to slip-obstruction along the shear zone, and indentation-related effects in two corners (A and C); and periods of stress-release as a result of laterally escaping block corners allowing full-scale strike-slip displacements along the shear zone (B and D). 1, shear zone boundaries; 2, block corners; 3, periods of enhanced strike-slip displacements and block rotation; 4, periods of diminished strike-slip displacements and block rotation; 5, foreland deformations; 6, compressional stresses induced by the block corners; 7, strike-slip disruption of the block corners and the foreland.

Alboran basins). The evolution of this theoretical shear zone will be characterized by the anticlockwise rotation/deformation of this internal block, as well as by the deformation of the surrounding areas, with a continuous balance between: a) periods of stress-concentration while two of the block corners are shoved against the shear zone walls, triggering indentation-related effects in the country rocks, and momentary slip-obstruction along the shear zone (figs. 5a and 5c); and b) the tendency of the shear zone to release the stresses by means of laterally escaping block corners, whith associated strike-slip faulting in the surrounding areas, and renewed activity along the shear zone (figs. 5b and 5d). This tipe of progressive deformation of a shear zone as related to an internal rotating element will trigger a sequential evolution as the one characterizing the eastern Betics, with alternating NW-directed stress-concentration periods (involving indentation), and N-directed stress-release periods (involving escape and wrench tectonics). Theoretically (fig. 5d), the idealized evolution of such a rotating/deforming block will trigger a final subcircular block, and two wedge-shaped escaped blocks in each opposite side within the shear zone (in this way, the block would be free to rotate). Note that the easternmost Betics displays two wedge-shaped elements (the eastern Prebetic block, and the Murcia block), and that, as we will see, it is conceivable to advocate a mechanism of such a kind for the evolution of the TAPSZ, a shear zone whose eastern boundary would be presently concealed under the sea.

The initial displacements along the TAPSZ by Messinian time induced a period of stress build-up, and hence NW-directed indentation, as related to the anticlockwise rotation of a block included within the TAPSZ (fig. 4b). This situation was associated to momentary slip-obstruction along the TAPSZ, while a series of convex-to-the-NW arc-shaped structures were triggered from the Aguilas sector to the western Prebetics. Therefore the initial evolution of this area was characterized by inversion tectonics, thrusting/welding the western Prebetics on top of the Iberian foreland, probably by means of the previous low-angle listric surfaces. This process closed the seaway between the Atlantic and the Mediterranean (Betic Strait; Weijermars, 1988), which runned north of the Betics along the present Guadalquivir basin trend. This would explain why this intermediate sedimentary trough only exists in the central and western Betics: in the east it was obliterated by the welding of the Prebetic arc onto the Iberian foreland. In relation with this initial scheme of NW-directed indentation, the Iberian foreland underwent a series of disturbances (fig. 4b), which can be though of as distal effects of the stresses generated by the TAPSZ. One of such was probably the crustal upward-arching of the Ruidera uplift in the immediate contact with the welded western Prebetic arc, defining an aproximately dome-shaped subcircular area. Additionally, the usually NW-SE-oriented Hercynian structural trends were completely distorted in a direction pointing northwestward away from the western Prebetic arc, with the following consequences (fig. 4b): a) anomalous W-E to NE-SW trends, locally displaying drag-effects in the zone in contact with the Prebetic arc; b) locally, the drag-effect was so extreme that the sectors of maximum curvature were broken by tension stresses, giving rise to small sedimentary basins such as the NE-SW-trending Bailén Cenozoic sedimentary trough; and, c) a series of structural gaps between the original Hercynian trends, thus allowing the generation of subsidiary Tertiary sedimentary troughs. The beginning of the volcanic activity in the CVP occurred probably by this time, as another noticeable distal effect within the Iberian foreland. In this sense, we suggest that the CVP can be understood in terms of an impactogen scheme (Sengor, 1976), whose genesis would be directly associated to indentation-related NW-directed compressional stresses (fig. 4b). These would have favoured the tensional opening of the adequately NW-SE-oriented Hercynian structural trends, thus triggering a «passive» rifted arm where hotspot activity, crustal upward arching, and volcanism took place. Another symmetrically-oriented «rifted arm» developped to the NNE of the «frontal stacking area» (constituted by the western Prebetic arc and the Ruidera uplift), disrupting the Iberian Ranges: the NNE-SSW Cenozoic Teruel sedimentary trough (fig. 4b). Minor volcanism extruded during this event is found in one spot in the SE border of this second impactogen-related rift (Cofrentes). However, in this case the induced tensional stresses had weaker effects than in the CVP, and this is probably due to the fact that the NW-SE structural trends of the Iberian Ranges were not favourably oriented to the predominant NNE-directed stresses transmitted by the western Prebetic arc. Other elements of the Iberian Range that can be ascribed to this complex indentation/impactogen scheme are a series of crustal domes described by Simón Gómez (1989) along the trend of the NNE-SSW-oriented Teruel trough. Finally, the Spanish Central System and the Toledo and Altomira mountains underwent uplifting by inverse faults, while most Tertiary basins in southeastern Spain experimented changes in their sedimentary records (fig. 4b).

At some point during this first stage (mostly characterized by stress build-up and indentation), stresses were released by the escape of two wedge-shaped blocks, thus allowing full-scale strike-slip displacements along the TAPSZ: The Nevado-Filábride block and the eastern Prebetic block (escaping to the SW and NE, respectively). The escape of the previously exhumed Nevado-Filábride metamorphic core complex was a major event triggering stretching lineations and numerous structural features which reveal a top-to-the-SW sense of movement (García Dueñas *et al.*, 1988; Galindo Zaldívar *et al.*, 1989). The northeastward escape of the eastern Prebetic block generated NE-SW-oriented folds congruent with the sinistral displacements along the TAPSZ. Note that the western boundary of this block, i.e. the NNE prolongation of the TAPSZ, is ill-defined today, and this is probably the result of later obliteration by indentation, slip-obstruction, and thus blockage of the TAPSZ.

This indentation-related scheme was accompanied by the cessation, by Messinian time, of the calc-alkaline to lamproitic volcanic activity in the Cartagena-Almería belt. This is clearly due to the end of the extensional regime that prevailed in this area till these times, and which was replaced by the compressional regime as related to the TAPSZ.

By contrast to the eastern realm, the western Betics were characterized by continuying extensional conditions since Serravalian till Messinian time (Doblas and Oyarzun, 1989a). In this sense the wedge-shaped geometry of the Guadalquivir basin was accentuated even more toward the west, while the continued top-to-the-SSE sense of movement along the main detachment surface finally triggered the exhumation of mantle core complexes in the west (Ronda peridotites; Doblas and Oyarzun, 1989a,b). Noteworthy, the Ronda peridotites display NE-SW-oriented stretching lineations and kinematic indicators revealing a SW-directed tectonic transport (Tubía, 1985), a feature which can be explained within a scheme involving both compression in the east, and extension in the west: It is conceivable that the SW-directed escape of the Nevado-Filábride block triggered a preferred directional flow of mantle material toward a western sector where stress-releasing conditions prevailed, thus enhancing the SW-directed exhumation of the Ronda mantle core complexes (fig. 4b) (Doblas and Oyarzun, 1989b).

Finally, the Messinian salinity crisis in the Mediterranean realm (Hsü *et al.,* 1977) can be explained within this scheme of differential compressional/extensional conditions affecting the Betic realm, as it closed the two seaways connecting the Atlantic and the Mediterranean (see inlet in fig. 4b): 1) The Guadalquivir or Betic Strait in the northern boundary of the Betics, which was closed in the east by compressional-related indentation, and consequent welding of the Prebetic arc against the Iberian foreland; and 2) The Gibraltar strait, which was closed by the extensional-related collapse of the western sectors, thus resulting in the genesis of the «jaw-type» Gibraltar arc orocline.

This first stage characterized by dominant conditions of stress build-up (with an intermediate event of momentary stress release), was followed by a second Pliocene to Quaternary scenario, where the continued rotation of the block included within the TAPSZ induced mainly stress-releasing conditions, and hence, escape and wrench tectonics associated to a generalized N-S compression, the whole within a scenario involving full-scale strike-slip displacements along the TAPSZ (fig. 4c). During this event, while a wedge-shaped Murcia block escaped toward the NE, the central and western Prebetic units were differentiated as two contrasted domains subject to the predominantly sinistral conditions imposed by the displacements along the TAPSZ: 1) The central Prebetic block was affected by domino-type tectonics congruent with this sinistral sense of movement, by means of NW-SE-trending dextral antithetic faults; and 2) The western Prebetic arc was now subject to oblique indentation/wrenching. The relative movements between the Prebetic domains to the north, and the Murcia NE-escaping block within the TAPSZ, triggered an intermediate zone with a complex series of mostly sinistral ENE-WSW to NNE-SSW-oriented strike-slip corridors. These corridors developed both transtensional troughs filled with late Cenozoic sediments, and transpressional step-overs bearing allochtonous fragments of external and internal Betic units.

In the Iberian foreland, this new oblique indentation transmitted by the western Prebetic arc triggered some noticeable changes (fig. 4c). The previous impactogen-related NNE-SSW Teruel rifted arm was now the site of dominantly sinistral conditions, thus preventing the further extrusion of volcanics in an area now mostly subject to transpression. By contrast, in the western rifted arm (the CVP) the new stresses still allowed extension, rifting, and volcanism along the distorted Hercynian structural trends. However, the variation in the stress pattern had definitive consequences on the evolution of this impactogen: the previously well-defined NW-SE rift trend probably changed to a more randomly distributed cluster of volcanic centers and sedimentary troughs. These full-scale strike-slip movements along the TAPSZ triggered two additional effect: 1) alkaline volcanism in the Mazarrón area (López Ruiz and Rodríguez Badiola, 1980); and 2) this «Trans-Alborán» dislocation forced a renewed seaway connection between the Atlantic and the Mediterranean by releasing the Gibraltar arc «jaws» (this was facilitated by the southwestward escape of a northwestern African fragment, as related to the movements of the TAPSZ). Meanwhile, in the western Betics, the extensional conditions that prevailed till Serravalian time changed to minor compressional-related deformations (mostly strike-slip faulting) as compared to the eastern Betics.

Theoretically, a final stage in the evolution of the TAPSZ would be characterized by two wedge-shaped blocks in the inner part of the shear zone (eastern Prebetic, and Murcia blocks), and thus, as depicted in figure 4d, a subcircular block now free to rotate within the shear zone. However, this tendency will be refrained by the continued N-S convergence between Africa and Europe (with an anticlockwise rotational component), thus leading to the final crushing of this block against the SE tip of Iberia probably by Quaternary time, with the following consequences: 1) The blockage of the TAPSZ by the final indentation of this block against the arc of Aguilas (note that nowadays the prolongation of the TAPSZ within the eastern Prebetics is difficult to locate); 2) The disruption of the eastern Betics by two major NW-SE-oriented dextral (Hellín) and sinistral (Baza) strike-slip faults (bounding the NW-indentating subcircular block); and 3) A renewed pulse of indentation-related effects, both in the western Prebetic arc, and in the Iberian foreland (frontal doming, volcanic activity in the CVP, renewed extension in the Teruel trough, changes in the sedimentary records of most Tertiary basins, and reactivation of the inverse faults bounding the Spanish Central System and the Toledo and Altomira mountains).

Conclusions

In this paper we propose a model for the structuration of the southeastern quarter of the Iberian Peninsula since Messinian time, involving complex/sequential deformations resulting from a progressively rotating block within a NNE-SSW sinistral shear zone (the TAPSZ), with two well differentiated scenarios:

1) stress-build-up periods involving NW-directed indentation within the shear zone, a situation causing momentary slip-obstruction along the TAPSZ; 2) stress-releasing periods as a result of laterally escaping wedge-shaped blocks, thus allowing full-scale strike-slip displacements to occur within the TAPSZ, and involving localized N-S compression.

The deformations of the Iberian foreland which can be thought of in terms of distal disturbances as related to these eastern Betics events, are of five types: 1) crustal upward-arching affecting a subcircular dome-like zone (Ruidera uplift) in front of the western Prebetic area; 2) disruption and dragging of the usually NW-SE-oriented Hercynian trends; 3) generation of two symmetrically disposed impactogen-related rift arms, the CVP (characterized by alkaline volcanism), and the Teruel trough, which will have contrasted evolutions; 4) a series of effects in the sedimentary records of most Tertiary basins of central/southeastern Iberia; and 5) elevation of the Spanish Central System and the Toledo and Altomira mountains by means of inverse faults.

During late Cenozoic time, four different elements might be distinguished in the eastern Betics: 1) the three Prebetic units; 2) the Nevado-Filábride southwestward escaping block; 3) the Murcia northeastward escaping block; and 4) a series of strike-slip corridors with complex transtensional and transpressional scenarios.

The late Cenozoic evolution of the eastern Betics and the TAPSZ (as well as of its Iberian foreland), can be understood in terms of a theoretical shear zone, with the following sequential scenarios:

1) A first stress build-up period involving NW-directed indentation during the Messinian, and thus momentary slip-obstruction along the TAPSZ, with an intermediate stress releasing moment associated to the NE-directed escape of the eastern Prebetics unit and the SW-directed escape of the Nevado-Filábride complex.

2) A second period mainly characterized by stress releasing conditions, allowing full-scale strike-slip displacements along the TAPSZ, involving the NE-directed escape of the Murcia block, the sinistral disruption of the central Prebetics, the oblique indentation of the western Prebetic arc, and a series of intermediate strike-slip corridors between the different blocks.

3) A last period characterized by the final blockage of the TAPSZ, as a result of the welding/indentation of the remaining block within the TAPSZ against the arc of Aguilas, a situation which might be related to the continued anticlockwise/rotational N-S convergence between Africa and Europe.

This sequential evolution with alternating stress concentrating and releasing conditions is clearly evidenced in the CVP: 1) volcanism was discontinuous; 2) the CVP is an anomalous impactogen-related rift setting as a result of variating compressional directions imposed by the western Prebetic arc.

Some specially relevant consequences triggered by this model are as follow:

1) A unique theoretical shear zone model with sequential progressive deformations is proposed.

2) The stresses triggered by this event generated a symmetrical foreland setting with two impactogen-related rift arms and a frontal subcircular dome-like zone.

3) The escape tectonics scenario is somewhat special, in that it takes place in the central and rear parts of an indentating block, while in a typical Himalayan-type rigid-plastic indentation model (Molnar and Tapponier, 1975) the escaping wedges occur in the frontal and lateral zones. This might be explained by the fact that both the southeastern Betics and the Valencia basin were previously thinned/weakened during the extensional detachment tectonics event (Doblas and Oyarzun, 1989a and 1990). In this way, once the indentation-related compressions began, the escaping processes were favoured along these central and rear thinned/weakened corridors.

4) Two contrasted Betic domains are defined during late Cenozoic time: a western/central sector, subject to continuying extensional conditions from the Serravalian to the Messinian, and thereafter slightly affected by N-S compressions; and, an eastern sector subject to compressional stresses in the time-span Messinian to the present, within a complex scheme of indentation/escape/wrenching as related to the activity of a major shear zone.

5) The tectonics of the Betic realm during late Miocene time was a major factor determining the Mediterranean salinity crisis, by closing or opening two seaways between the Atlantic and the Mediterranean. The beginning of this crisis (dessication by closure of the seaways) was related to two contrasted events: i) the extensional-related «jaw-type» closure of the southern union (Gibraltar arc); and, ii) the indentation-related closure of the eastern part of the northern connection (Betic Strait). The end of this crisis can be related to the renewed sinistral activity along the TAPSZ (and its prolongation in north-Africa) triggering the SW-directed escape of a western wedge of north-Africa, and thus inducing the opening of the Gibraltar seaway.

6) Deep-seated processes were greatly enhanced during this late Cenozoic disrupting event. The Nevado-Filábride unroofed metamorphic core complex (which already constituted a highly attenuated crus-

tal element) was forced to escape to the SW, thus favouring the directional flow of mantle-derived material towards the western Betic realm. By this time, these western sectors were undergoing extension, thus constituting highly favourable settings for the directional emplacement of mantle-derived material such as peridotites (mantle core complexes of Ronda; (Doblas and Oyarzun, 1989b).

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