A new Geodynamic Model for the Betic Cordilleras based on P-T-t paths and Structural data from the Eastern Betic

Nuevo modelo geodinámico para las Cordilleras Béticas basado en curvas P-T-t y datos estructurales de las Béticas Orientales

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ABSTRACT

This study presents a new geodynamic model for the tectonic evolution of the Betic Cordilleras from the Cretaceous to the Miocene based on an integrated (micro) structural, petrological and geochronological study of the eastern Betic Zone.

Early Cretaceous subduction in the Betic Zone was initiated in the Jurassic transtensional Africa-Eurasia plate boundary, which was strongly weakened by extensional tectonics and strike-slip faulting, which persisted until the onset of subduction. Compression in the Africa-Eurasia plate boundary and initation of subduction in the Betic Zone resulted from ESE-ward motion of Iberia due to oceanic spreading in the Atlantic Ocean and the Bay of Biscay to the W and NW of Iberia during the 119-80 Ma period. Following subduction the high pressure metamorphic Betic nappes were partially exhumed during extension and extreme ductile thinning, which also affected the Malaguide Complex in the upper plate.

Early to Middle Eocene northward thrusting of the entire and partially structured Betic Zone over the southernmost part of the External Zone, the former rifted Betic margin, resulted in HP/LT metamorphism in the overthrust and buried part and flexural bulging in the part of the External Zone which was not overthrust and where sedimentation continued.

During the Late Oligocene and younger tectonic evolution extension and crustal shortening followed each other rapidly during continuing Africa-Eurasia convergence,

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pointing to roll-back, steepening and detachment of the subduction slab. Early Miocene inversion of the extended area and concentration of overthrusting in the most thinned area resulted from slab detachment enabling transmission of compression in the shallow remainder of the slab. Slab steepening and detachment can further explain concentration of Miocene and younger magmatism into a narrow zone and its deep source, which cannot be due to steady state subduction as Africa-Eurasia convergence falls short during this period.

1. INTRODUCTION

In most geodynamic models for the Betic Cordilleras the metamorphic part of the orogen, the Internal or Betic Zone, is considered as an allochtonous tectonic element or micro plate (Alboran Domain or Alboran Micro Plate, Andrieux *et al.*, 1971; Dercourt *et al.*, 1986; Comas *et al.*, 1990). This element is generally envisaged to have been juxtaposed to the External Zone, the former Mesozoic and Early Tertiary rifted margin of SE Iberia, along ENE-WSW trending wrench faults during the Tertiary (Hermes, 1978; De Smet, 1984). Recently, deformation in the Betic Zone has been discussed within this concept (Frizon Delamotte *et al.*, 1989; Vauchez and Nicolas, 1991). However, the occurrence of the HP/LT metamorphic Almagride Complex, consisting of Middle and Late Triassic rocks, which resemble parts of the southern External Zone (Simon, 1987), as the structurally deepest unit in the Betic Zone demonstrates that such models cannot explain the tectonic evolution of the Betic Cordilleras. The outcrop of this complex in windows 50 km south of the present day External-Internal boundary (fig. 1) implies that the External Zone is overthrust by the Betic Zone (De Jong, 1990), rather than that the two are juxtaposed by wrenching. This interpretation agrees with results of investigations in the boundary zone between the External-Internal zones pointing to presence of only minor strike-slip movements during the Langhian-Serravallian, taking place during and after major overthrusting (De Ruig *et al.*, 1987: Martín-Algarra *et al.*, 1988; Van der Straaten, 1990; Lonergan, 1991). In addition, radiometric dating implied that the early-tectono-metamorphic evolution of the Betic Zone occurred during the Cretaceous (De Jong, 1991a).

The model presented here is based on a detailed integrated (micro) structural, petrological and geochronological study of the eastern Betic Zone, which consists of four staked nappe complexes, from top to bottom: 4) the Malaguide Complex, 3) the Alpujarride Complex, 2) the Mulhacen Complex, 1) the Veleta Complex (Egeler and Simon, 1969; Puga and Díaz de Federico, 1978; De Jong, 1990, 1991a, fig. 1). The objective is to construct Pressure-Temperature-Tecto-

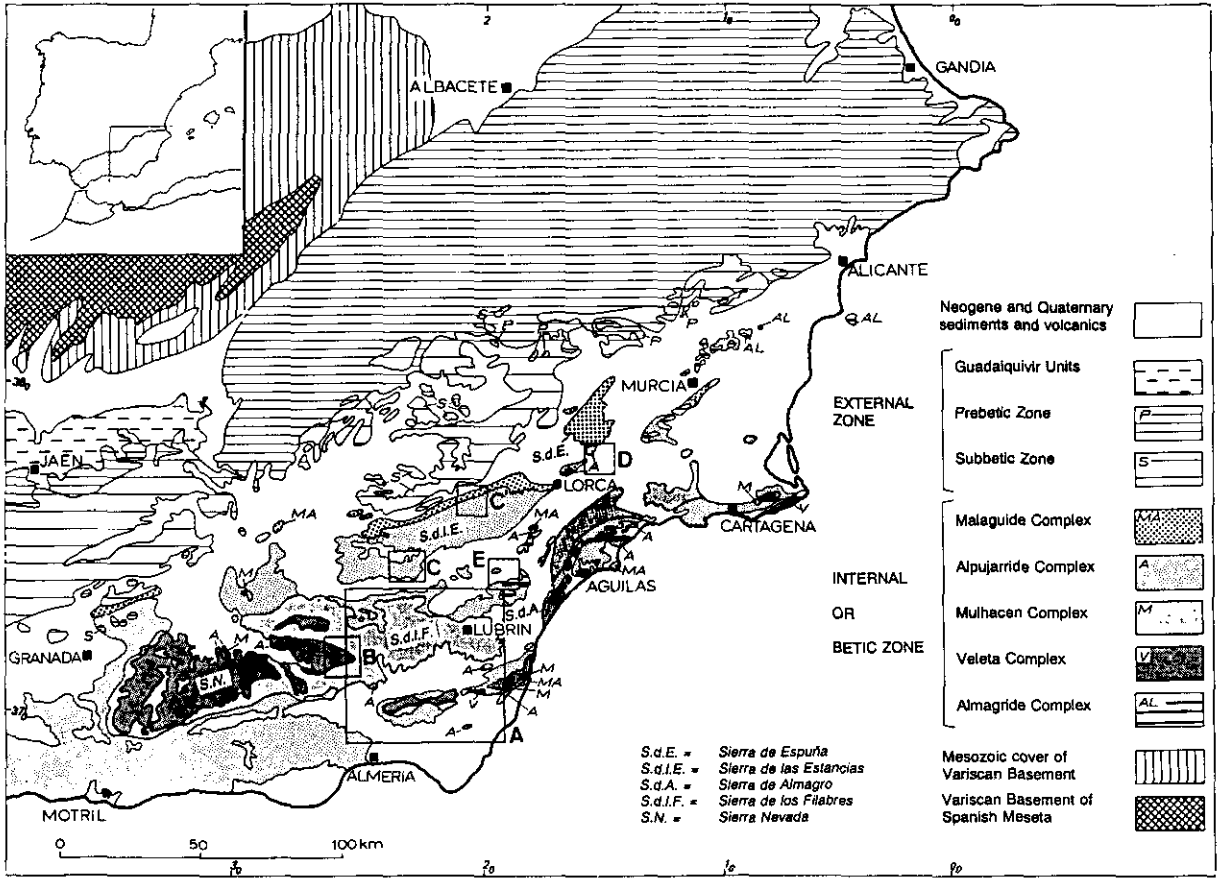


Figure 1.—Tectonic sketch map of the eastern Sierra de los Filabres, boxes A to E show the main areas of investigation.

nic-time paths for the Alpujarride and Mulhacen complexes, by tying deformation structures to mineral reactions, outlined in the first part of this article. In the second part a new geodynamic model for the Betic Cordilleras will be elaborated using this approach.

2. TECTONO-METAMORPHIC EVOLUTION OF THE ALPUJARRIDE AND MULHACEN COMPLEXES

The relation of mineral growth with respect to deformation phases showed that the tectono-metamorphic evolution of the Alpujarride and Mulhacen complexes are rather similar to each other (Bakker *et al.*, 1989; De Jong, 1991a). Both nappe complexes experienced HP conditions during early Alpine tectonics when deformation structures with similar kinematic significance were formed. HP metamorphism gave way to LP conditions concomitant with cooling, at its turn followed by important reheating during younger Alpine movements. The late Alpine structural evolution in both nappe complexes, however, shows important differences. The deformation scheme used in this article is modified with respect to the original scheme of Bakker *et al.* (1989) according to De Jong (1991a, b).

2.1. Early Alpine evolution

D_1 tectono-metamorphic phase

Early Alpine pressures in the Mulhacen Complex fall in the range of 1.0-1.2 GPa (Velilla and Fenoll Hach-Alí, 1986; Bakker *et al.*, 1989; Gómez-Pugnaire *et al.* D_1^{mulh} structures were formed at the end of the isobaric heating trajectory (fig. 2) and are mainly left untouched subsequent deformation in gneisses and glaucophane schists. D_1^{mulh} structures demonstrate important E-W to ESE-WNW stretching during top-to-the-west shear.

Early Alpine pressures in the Alpujarride Complex of the eastern Betic Zone were lower than in the Mulhacen Complex: pressures aroung 0.6-0.7 GPa at temperatures between about 300°-400° C are characteristic for a number of tectonic units (Baker *et al.*, 1989; Goffé *et al.*, 1989, De Jong, 1991a). Recently, indications for minimun pressures around 1.0 GPa have been reported in the central Betic Zone (Azañón and Goffé, 1991). Due to lack of resistant rock no D_1^{alpu} structures other than inclusions in porphyroblasts and microlithons have been left.

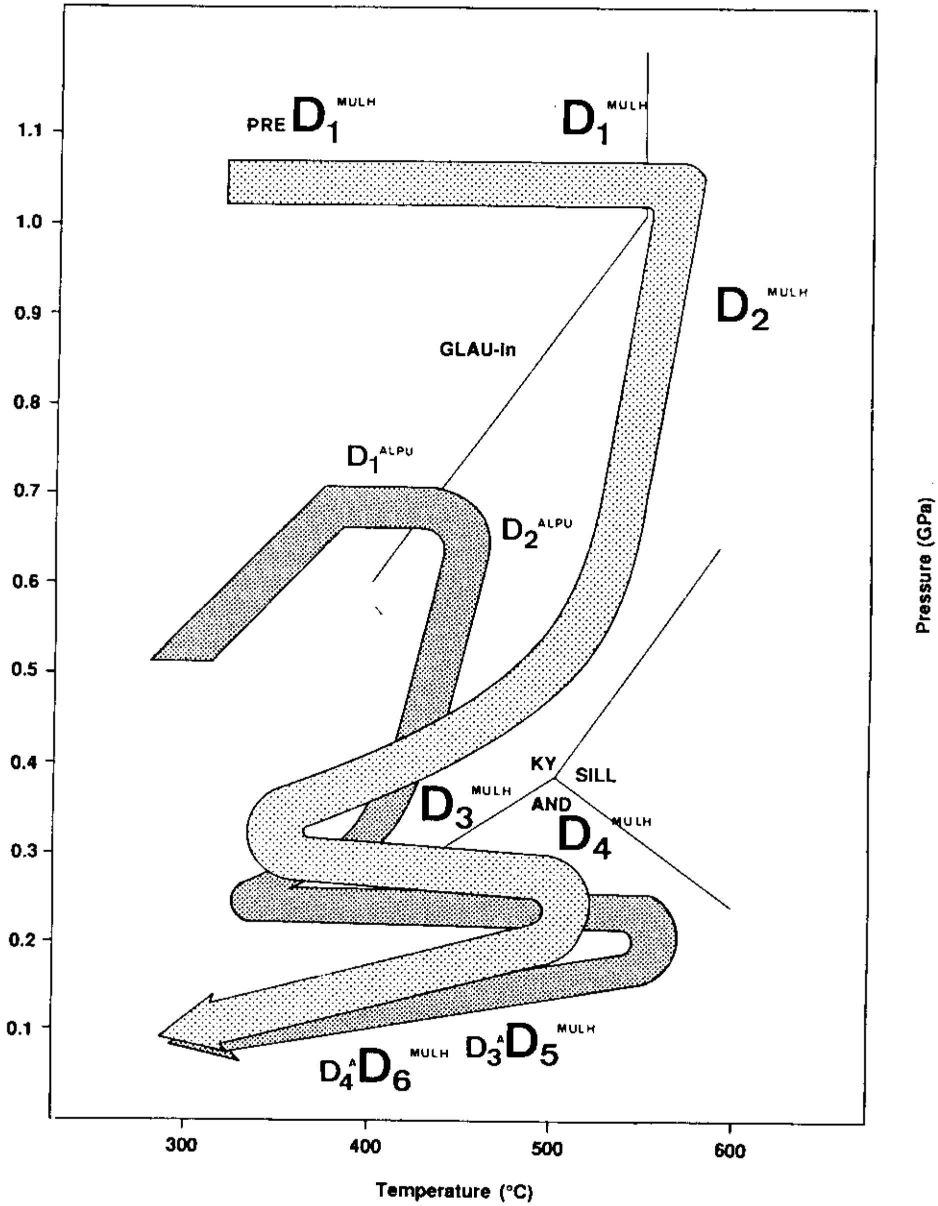


Figure 2.—P-T-t path of the Mulhacen Complex (light shading) and the Alpujarride Complex (dark shading) based on P-T-t determinations and thermo-geochronologic data from Bakker *et al.*, 1989; De Jong, 1990; De Jong *et al.*, 1992, from the Sierra de los Filabres, Sierra Alhamilla and Sierra de las Estancias. Glaucophane-in (Maresch, 1977); Al-silicate triple point (Holdaway, 1971).

D_2 tectono-metamorphic phase

The D_2 tectono-metamorphic phase in the Alpujarride and Mulhacen complexes occurred at the culmination of the heating stage and coincides with strong decompression to 0.7-0.6 GPa concomitant with cooling to about 550°-500° C in the Mulhacen Complex and to 0.5 GPa and 400°-500° C (fig. 2) in the Alpujarride Complex. In both nappe complexes D_2 resulted in the most penetrative deformation at all scales. Recumbent D_2 folds are tight to isoclinal, resulting in effective transposition of earlier fabrics parallel to the main foliation S_2, in the Mulhacen Complex resulting in a D_2 transposition stratigraphy continuous over at least 25 km along strike (De Jong and Bakker, 1991, *et al.*, encl. I). Strain determinations show an average elongation parallel to the ESE-WNW trending D_2 streching lineation of about 380 % and layer normal shortening values have an average of around 75 % in both complexes (De Jong, 1990, 1991a).

Kinematic indicators in the Mulhacen Complex, like asymmetric K-feldspar phenoclasts, fish-shapped phengite crystals, quartz filled pressure shadows and rotated garnets point to top-to-the-west shear. Symmetric lattice preferred orientations of quartz c-axes, however, demonstrate predominant coaxial deformation in isotropic quartz-rich lithologies. This points to partitioning of D_2^{mulh} strain into dominant rotational deformation in layered lithologies, like gneisses and mica schists, and a more non-rotational deformation in quartzites. Weakly developed symmetrical, quartz lattice preferred orientations in the Alpujarride Complex also point to coaxial deformation. Due to the lack of kinematic indicators, however, deformation partitioning and the dominant shear sense during D_2^{alpu} could not be established.

In the Mulhacen Complex the intensity of D_2^{mulh} increases upwards as documented by paracrystalline rotated garnets and fold structures. In the lower part of the complex rotation angles of garnets vary between 65° and 170°, whereas in the upper part rotation angles measures are between 120° and 270°. A similar trend is indicated by progressive evolution of folds: in deeper levels of the complex D_2^{mulh} folds are less tight than in higher parts and, in addition, S_2 refracts on folded bedding. D_2^{mulh} folds at this structural level are curvi-linear; fold axes commonly make a high angle to the stretching lineation, which has a constant ESE-WNW trend. In the uppermost 1-1.5 km of the complex, on the other hand, axes of isoclinal D_2^{mulh} folds are parellel to the ESE-WNW trending stretching lineation. This points to rotation of fold axes into parallelism with the shear direction during upwards increasing D_2^{mulh} strain. Because in shear zones strain is related to displacement (e.g. Ramsay, 1980), the D_2^{mulh} strain gradient demonstrates an upwards increasing displacement in the Mulhacen Complex.

Cooling during and especially after D_2 in both complexes is manifest by widespread retrogression shown by replacement of chloritoid and kyanite, and in the Mulhacen Complex also staurolite, by phengite (±paragonite) often accompanied by chlorite.

2.2. Late Alpine evolution

Mineralogical changes show that the Late Alpine tectonic evolution both complexes following the D_2 cooling occurred during reheating, again followed by cooling. In the Mulhacen Complex increase in temperature is locally well established by growth of tiny crystals of staurolite in phengite-chlorite decomposition mantles around D_2^{mulh} staurolite, chloritoid and (partly syn-D_3^{mulh}) kyanite. Growth of oxy-chlorite and locally biotite at the expense of chlorite and furthermore formation of oligoclase-andesine rims around albite probably also reflect temperature increase. In the Alpujarride Complex temperature increase is shown by growth of staurolite and sillimanite in the graphite-rich basal series and by andalusite growth locally accompained by cordierite blasteis in the Triassic series of a number of tectonic units.

Structural response of both complexes during reheating was entirely different. In the Mulhacen Complex the D_2^{mulh} shear plane was influenced by important S-vergent folding and associated thrusting during D_3^{mulh}. This event took place towards the end of the retrograde trajectory of the P-T-t path (fig. 2). Another phase, D_4^{mulh}, occurring during the second thermal peak in this complex (fig. 2), produced km-scale folds and only locally penetrative small scale structures, which are generally N-vergent. In contrast, in the Alpujarride Complex the first important deformation phase subsequent to the D_2^{alpu} main phase took place during the waning stages of the second thermal peak (fig. 2), when D_3^{alpu} folds were formed. Folds of this generation form the most important fold structures in the Alpujarride Complex. The intensity of D_3^{alpu} increases southwards and structurally downwards in the Alpujarride overthrust mass. Going downwards, tight N-vergent E-W trending folds with overturned limbs change into tight to isoclinal recumbent similar folds directly above the Mulhacen Complex, which may be strongly curvi-linear. D_3^{alpu} structures were coeval with D_5^{mulh} in the overlying Mulhacen Complex as shown by a number of observations. Firstly, the intensity of ductile D_5^{mulh} deformation increases from north to south in the contact zone, similarly as D_3^{alpu} structures. Secondly, the intensity of D_5^{mulh} increases upwards towards the overlying Alpujarride Complex. Thirdly, commonly NNE-SSW trending axes of D_3^{alpu} folds in the deeper structural level approach the orientation of D_5^{mulh} stretching lineations in the mylonite zone in the top of the Mulhacen Complex in the southern part of the contact between both nappe complexes. In this part of the nappe contact dm-spaced D_5^{mulh} extensional crenulation cleavages a few hundred metres below the thrust contact grade into mylonites directly below the Alpujarride basal thrust. Concurrent with this upwards increasing D_5^{mulh} strain E-W trending D_2^{mulh} lineations pregressively rotate to the NNW-SSE trend of D_5^{mulh} stretching lineations in the mylonites. Movement in the shear zone was top-to-the-north indicated by the asymmetry of a number of fabric elements like pressure shadows and recrystallization tails of porphyroclasts and micro faults in them, and furthermore by the asymmetry of secondary grain shape frabrics and lattice preferred orientations in quartz mylonites.

D_5^{mulh} and D_3^{alpu} occurred during falling temperatures shown by widespread chlorite growth, partly at the expense of staurolite. Post-D_3^{alpu} growth of andalusite implies that temperatures did not drop below about 400° C in the Alpujarride Complex. During D_6^{mulh} and D_4^{alpu} P-T conditions reached the field of brittle deformation, giving rise to chevron folds and associated younger extensional brittle-ductile shears and cataclasites were formed. Large scale D_6^{mulh} folds deform D_5^{mulh} mylonites and the contact with the Alpujarride Complex.

3. CONTACT OF THE MULHACEN COMPLEX WITH THE VELETA COMPLEX

In contrast to the basal thrust of the Alpujarride Complex, which cuts D_3^{mulh} and D_4^{mulh} folds, the contact with the underlying Veleta Complex is folded during D_3^{mulh} (De Jong, 1991a, c). The contact is parallel to S_2 in both complexes; the uppermost 400 m of the Veleta Complex demonstrates an increasing D_2^{vel} strain towards the Mulhacen Complex. Quartz mylonites in the top of the Veleta Complex display lattice preferred orientations indicative of top-to-the-west shear, implying a westward thrusting of the overlying Mulhacen Complex during D_2^{mulh} and D_2^{vel}. The major controversy on the sense of shear in the mylonite zone, which is interpreted as either top-to-the-east (Orozco, 1986) or top-to-the-west (García Dueñas *et al.*, 1987), is due to overturning of mylonites by D_3^{mulh} folds and overprinting of crystallographic fabrics due to renewed D_4^{mulh} shear, which have strongly modified the original characteristics of the D_2 nappe contact, as will be discussed elsewhere (De Jong, 1991c).

4. AGE CONSTRAINTS ON THE EARLY ALPINE TECTONIC EVOLUTION OF THE MULHACEN COMPLEX

Metamorphic temperatures during D_2^{mulh} were in the range of 525-575° C (fig. 2), that is in excess of the phengite closure temperatures for the K-Ar and

Rb-Sr systems (Purdy and Jäger, 1976; Jäger, 1973, respectively). Consequently, radiometric ages of the Mulhacen Complex should be considered as cooling ages, which date the passing throught the closure temperature during cooling after the peak of metamorphism during D_2^{mulh}. However, the P-T evolution clearly demonstrates the importance of late stage reheating locally elevating metamorphic temperatures close to or above the mica closure temperatures for difussion of Sr and Ar, respectively. As during reheating the temperature domain for diffusion of radiogenic isotopes was re-entered, significant resetting of metamorphic ages can be expected. The very young K-Ar and Rb-Sr mica ages of 10-15.5 Ma (Andriessen *et al.,* 1991) and $^{40}Ar/^{39}$ Ar mica ages between 14.3 and 25.9 Ma (Monié *et al.,* 1991; De Jong, 1991a, De Jong, *et al.,* 1992) can be explained accordingly.

Despite thermal resetting indications for local preservation of an older isotopic system are present. Monié *et al.* (1991) obtained a $^{40}Ar/^{39}Ar$ age of about 48.4±2.2 Ma from a baroisitic amphibole, which characteristically grows at the expense of glaucophane during D_2^{mulh} (De Jong, 1991a). $^{40}Ar/^{39}$ $^{40}Ar/^{39}Ar$ dating of tourmaline, obtained from gneisses with a D_2^{mulh} fabric and which yielded K-Ar ages between 115 and 80 Ma (Andriessen *et al.,* 1991), resulted in reference lines with ages between 89.1±0.9 and 52±1 Ma (De Jong, 1991a; De Jong *et al.,* 1991). In addition, D_2^{mulh} phengites yielded Rb-Sr ages of: 65.7±10.1 Ma and 41.1±4.6 Ma (De Jong, 1991a). These ages, being obtained from syn-D_2^{mulh} minerals, are interpreted to reflect cooling after D_2^{mulh}. The spread in $^{40}Ar/^{39}Ar$ and Rb-Sr mica ages, which may be as young as 14 Ma, probably resulted from (partial) rejuvenation due to late stage rehating, as wil be discussed below.

5. DYNAMICS OF METAMORPHISM AND TECTONICS: GEODYNAMICS OF THE BETIC CORDILLERAS

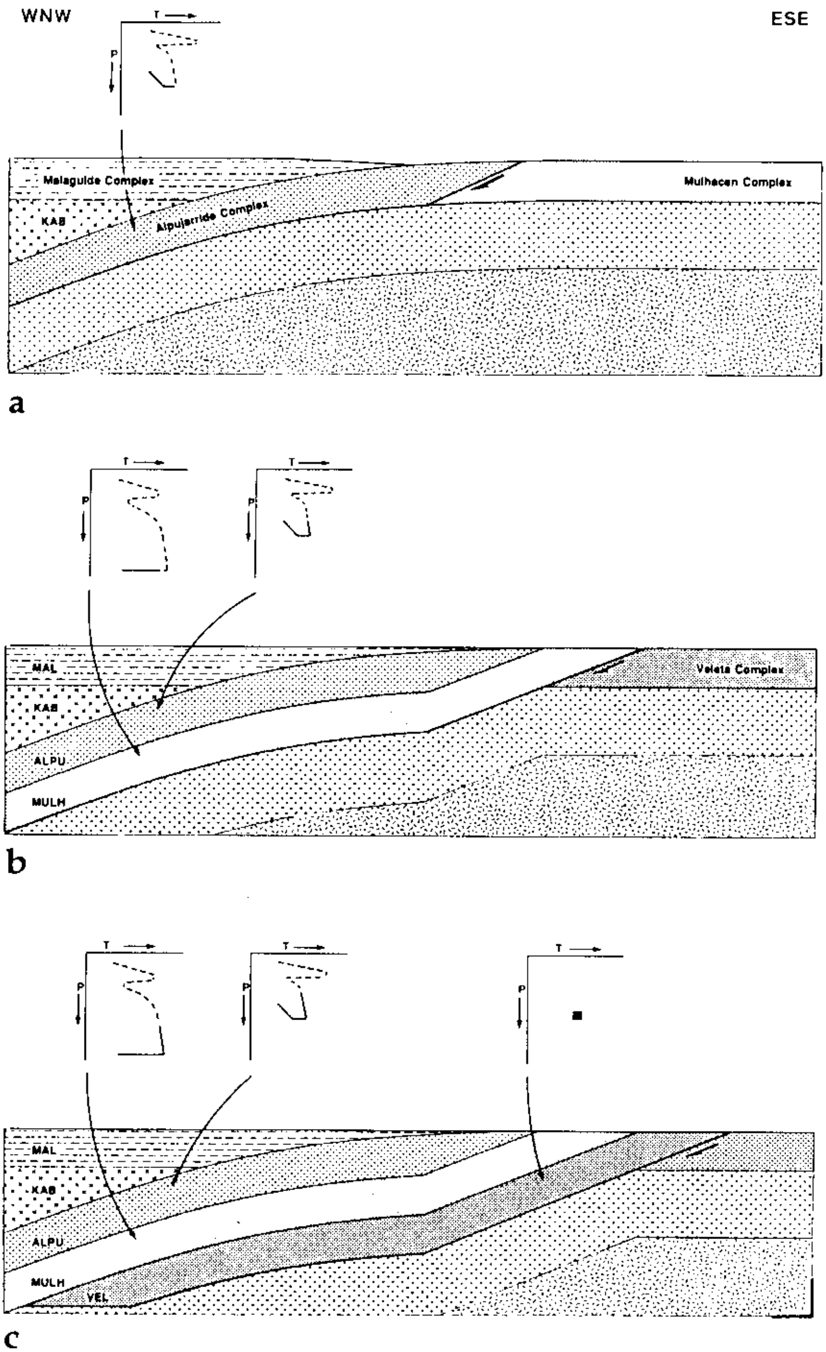
In this section the tectonic and metamorphic data will be combined to establish the P-T-t paths of the Alpujarride and Mulhacen complexes. Such P-T-t paths reflect first order tectonic movements at the scale of the crust and, hence, elucidate the stacking history in the Betic Zone and the subsequent exhumation of the high pressure metamorphic rocks. They are furthermore used to establish a geodynamic model for the tectonic evolution of the Betic Cordilleras.

5.1. Subduction

Early Alpine metamorphic pressures in the Alpujarride and Mulhacen complexes point to burial depth in the order of 27 and 37 km, respectively, implying subduction below a crustal segment with a lower crustal basement. Subduction took place below a crustal segment that contained the Malaguide Complex (fig. 3a), which has an essentially continuous sedimentary record from the Early Paleozoic to the middle Tertiary (Aquitanian), (Egeler and Simon, 1969; Geel, 1973). Although the Malaguide Complex in the Betic Zone is actually extremely thin, clastic influx of granites, gneisses and medium grade metamorphic rocks in the Late Paleozoic (Geel, 1973; Herbig and Stattegger, 1989) points to the presence of a crystalline basement at that time. Influx of fresh detrital muscovite, biotite and K-feldspar in Jurassic carbonates (Geel, 1973) points to erosion of crystalline rocks, showing that the Malaguide Complex had a normal crustal thickness before subduction was initiated. Similarities in Mesozoic stratigraphy of the Malaguide Complex, the Subbetic and the Flysch Units between the two domains (MacGuillavry, 1964; Martín-Algarra and Vera, 1982, Pineda Velasco, 1985) imply that the Malaguide Complex formed part of the same plate as the External Zone.

The nappe complexes of the Betic Zone consist of metasedimentary rocks of Triassic and/or Paleozoic age; individual nappes have thicknesses of several kilometres. The different early Alpine metamorphic pressure shows that the burial depth of the Alpujarride Complex in the eastern Betic Zone was about 10 km less than the Mulhacen Complex. This can be explained by underthrusting of the Mulhacen Complex below the crustal segment with the Alpujarride Complex (fig. 3b). Minimum shortening values in the order of 70-75 % perpendicuar to the transposed bedding show that pre-collisional thicknesses of the Paleozoic and Triassic sedimentary sequences of the Alpujarride and Mulhacen complexes were probably about 4 times the present thickness. These strain values in combination with the presence of metasedimentary rocks imply that early Alpine nappe stacking in the Betic Zone was probably the result of sequential detachment of upper segments with thicknesses in excess of 10 km. Detached segments are added to the overriding plate, while the deepper part of the lithosphere continues to subduct (figure 3).

Figure 3.—Nappe stacking in the Betic Zone by sequential detachment of upper crustal rock sequences, which are added to the hanging wall of the subduction system formed by the Malguide Complex (MAL) with a crystalline basement (KAB). The lower crust (crosses) and mantle (random striping) continue to subduct to the west. Sequential underthrusting results in dramatic cooling in the overlying earlier subducted nappe complexes shown by the insert P-T-*t* paths for the Alpujarride and Mulhacen complexes. P-T conditions of the Veleta Complex (square in the insert P-T graph of panel c) imply that it is underthrust by an upper crustal unit (coarse stipple, panel c) not exposed at the present erosion level. Scale bars: 15 km.


WNW
ESE
T
P
Malaguide Complex
Mulhacen Complex
KAB
Alpujarride Complex
a
T
P
T
P
MAL
Veleta Complex
KAB
ALPU
MULH
b
T
P
T
P
T
P
MAL
KAB
ALPU
MULH
VEL
c

Sequential stacking of cool crustal segments also has dramatic thermal consequences, which are expressed by the P-T-t path of the nappes of the Betic Zone. Thermal modelling of stacking of crustal scale segments showed that cooling or reduced heating of a plate may result from underthrusting by cooler crust (Davy and Gillet, 1986). Along these lines of evidence cooling of the Alpujarride Complex is explained by underthrusting by a relatively cool crustal segment, containing the Mulhacen Complex (fig. 3b). Isobaric heating of the Mulhacen Complex may have ceased as a result of underthrusting by another cool crustal slab with the Veleta Complex (fig. 3c). Pressures in the Alpujarride Complex imply 100 km of subhorizontal movement on a low-angle subduction slab with a dip of about 15° in the upper part (fig. 3a). Subsequent underthrusting of the Mulhacen Complex to about 37 km requires a movement of about 130 km. Cooling of the Mulhacen Complex at a depth of 37 km as a result of its underthrusting by a slab containing the Veleta Complex indicates another 130 km of plate consumption. The total amount of crustal shortening by subduction of upper crustal segments may thus have reached about 360 km.

Ocanic spreading in the Atlantic Ocean to the west of Iberia and in the Bay of Biscay was in full swing between anomalies M0 and 33 (119-80 Ma on the time scale of Kent and Gradstein, 1986), during which Iberia was displaced about 400 km ESE-wards as part of Africa (Srivastava *et al.*, 1990; Malod and Mauffret, 1990). The amount of spreading shows that the envisaged 360 km of subducted lithospheric slab in the Betic zone is feasible. Age estimates of cooling after D_2^{mulh} up to about 90 Ma, indicate that subduction has occurred earlier. Subduction in the Betic Zone is thus likely to be caused by the ESE-ward movement of Iberia due to oceanic spreading in the Atlantic Ocean (fig. 4). Subduction was initiated in the former Late Jurassic trans-tensional Africa-Eurasia plate boundary, which was continuous with the Ligurian Ocean (fig. 4). This boundary was characterized by small-oceanic basins (fig. 4) with young and weak oceanic crust, which was loaded by flysch sedimentation, hence, forming the most suited type of margin to be transferred into an active plate boundary (Cloetingh *et al.*, 1982).

5.2. **Exhumation history**

The main tectono-metamorphic phase D_2 in the Alpujarride and Mulhacen complexes occurred during decompression, showing that D_2 structures and kinematics are related to exhumation of the high pressure metamorphic rocks. Decompression in the Alpujarride Complex was less than in the Mulhacen Complex, implying differential exhumation and, hence, movements of the two

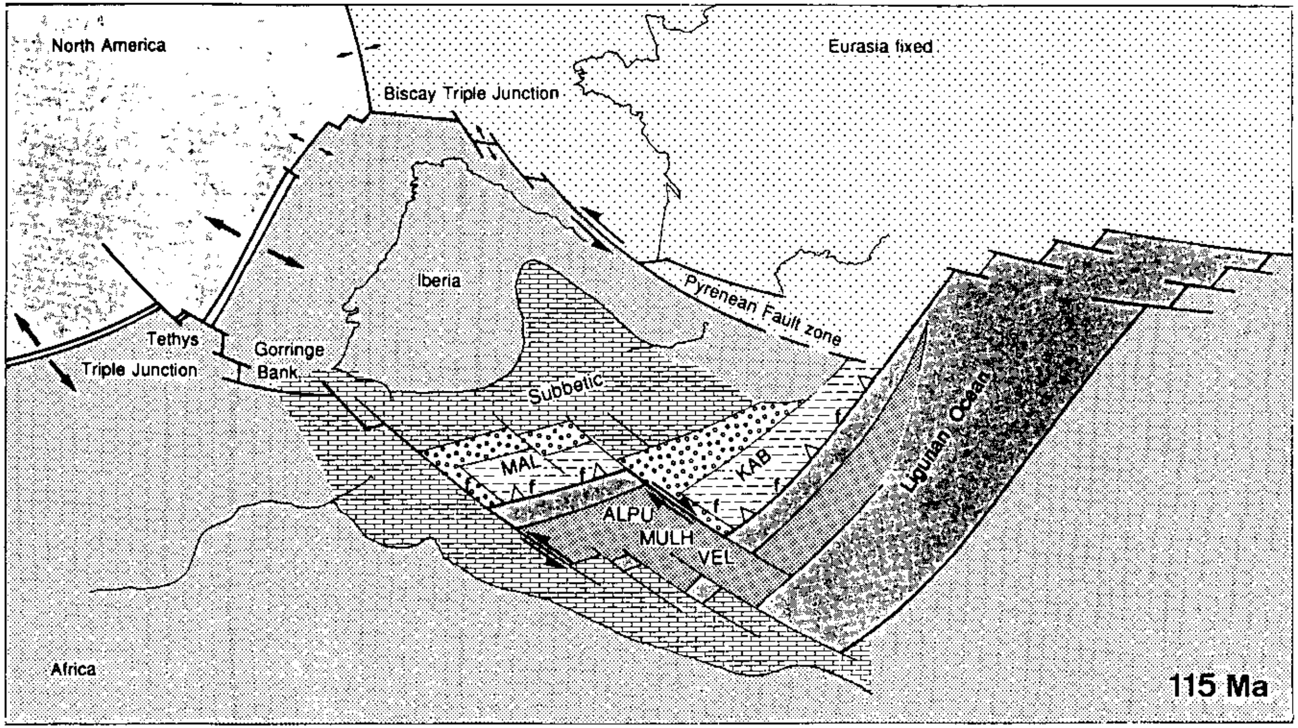


Figure 4.—Early Cretaceous plate reconstruction at the onset of W-ward subduction in the Betic Zone resulting from compression due to northward propagating North Atlantic oceanic spreading to the west of Iberia. The subduction zone (open triangles) is continuous to the Alps and probably initiated in small oceanic basins (dark shading) with flysch sedimentation (f) between the Malaguide Complex (MAL), forming the eastern margin of Iberia and the Alpujarride Complex (ALPU), forming the western margin of the subducting Betic Zone. The position of the Alpujarride (ALPU), Mulhacen (MULH) and Veleta (VEL) complexes according to the stacking model (fig. 3). Movement on spreading centres (double lines) and rift axes (single lines) indicated by arrows, on strike-slip and transform faults by harpoons. Position of Atlantic plate boundaries and continents after Malod and Mauffret (1990).

nappe complexes with respect to each other. The upwards increasing intensity of D_2^{mulh} and its augmenting rotational component are probably due to this movement. Rotation sense of syn-D_2^{mulh} garnets demonstrates that the Mulhacen Complex moved to the east with respect to the overlying Alpujarride Complex and was concurrently exhumed. Such kinematic and P-T constraints points to movements on a west-ward dipping shear zone (fig. 5). The coaxial stretching component of D_2^{mulh} and D_2^{alpu} and the translation of the Alpujarride and Mulhacen complexes point to extension of the collision belt (fig. 5). The top of the Veleta Complex also experienced deformation with a dominant rotational component, implying a westward movement of the overlying Mulhacen Complex. However, such a movement on a westward dipping plane as implied by sequential detachment model (fig. 3), would not place higher pressure metamorphic rocks on top of lower pressure rocks, but the reverse. This seems to indicate that the coaxial component of D_2^{mulh}, resulting in elongation of the Mulhacen Complex moving it eastwards updip, outweighed the westward movement in the contact shear zone with the underlying Veleta Complex. The proposed model shows that nappe emplacement was not the result of a directed force («push from behind») but was due to a body force. This force stems from the buoyancy of the subducted and detached upper crustal segments, providing a constant upward force, which is resolved into components parallel to the anisotropy provided by the detached upper crustal segments (fig. 5). Elongation and decompression of the metamorphic rocks imply extension of the upper plate where the Malaguide Complex is located

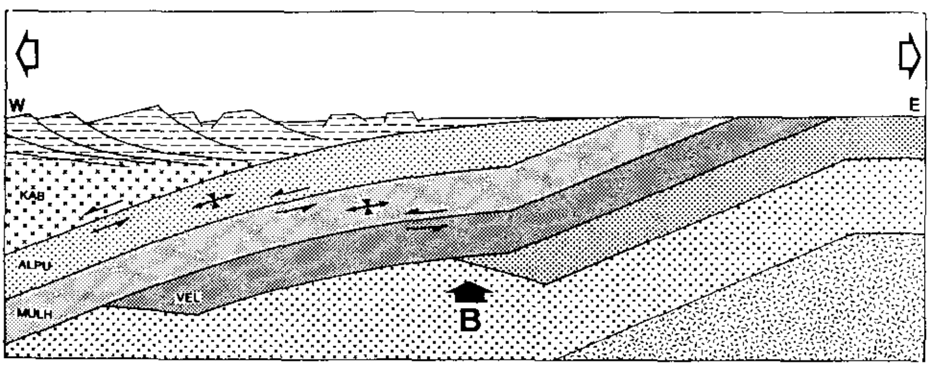


Figure 5.—Resolution of buoyancy (B) of the detached underthrust upper crustal sequences into elongation of the metamorphic nappe complexes and a shear component along the contact of the hanging wall and the Alpujarride Complex and between the stacked nappe complexes during D_2. Top-to-the-west shear on westward dipping planes implies exhumation of metamorphic rocks and extension of the metamorphic nappe pile, which is transferred to the overlying Malaguide Complex causing extensional faulting and partial excision of its crystalline basement (KAB).

ant to removal of part of its Cambrian basement. Erosion, tilting and submarine faulting and associated rapid vertical motions in the Malaguide depositional domain from the Early Cretaceous on (Roep, 1980) are explained by extension of the upper plate (fig. 5).

5.3. Advanced cooling during Eocene overthrusting of the External Zone

The P-T-t paths of the Alpujarride and Mulhacen complexes demonstrate increased cooling during advanced exhumation (fig. 2), which is explained by *thrusting of the Betic Zone over cooler crust. A number of features show that this* crust is formed by the southernmost part of the External Zone. The Almagride Complex, which is regarded as an inlier of the External Zone, contains early Alpine mineral assemblages in mafic rocks which point to metamorphic pressures of 0.35-0.55 GPa and temperatures around 350-400° C (Puga and Torres-Roldán, 1989). The Antequera-Osuna nappe in the western Betic Cordilleras has Triassic rocks which partly resemble those of the Almagride Complex (Simon, 1987); its mafic rocks record pressures of 0.3 GPa (Puga *et al.,* 1988). The nappe has overthrust the Subbetic (Cruz-Sanjulián, 1976; Pineda Velasco, 1987), of which the southern part also contains mineral assemblages pointing to pressures of about 0.3 GPa (Puga *et al.,* 1988). Burial depths of 10-20 km, implied by the metamorphic data, can only be envisaged by burial due to overthrusting of these rocks by the Betic Zone (fig. 6), resulting in cooling of the hanging wall. A thrust load of 10-20 km thickness can explain the flexure in the External Zone around 50 Ma that follows from tectonic subsidence analysis by Peper and Cloethigh (1992) of the more northern parts of the External Zone, where pelagic sedimentation persisted into the middle Miocene (Geel, 1973; Hermes, 1978; De Smet, 1984). Timing of overthrusting in the Eocene agrees with coeval vertical movements implied by results of tectonic subsidence analyses (Kenter *et al.,* 1990; De Ruig *et al.,* 1991), by non-calcareous influx into carbonates of Ypresian and Lutetian age in both the Subbetic and the Malaguide Complex (Geel, 1973) and furthermore with the presence of thrust in the Malaguide Complex which are sealed by Oligocene conglomerates (Lonergan, 1991). Taking a dip of the thrust plane of 15° the minimun amount of overthrusting is 40 km (fig. 6). Overthrusting in the southern Betic Cordilleras has a similar timing as the climax of shortening in the Pyrenees (De Jong, 1990), Both may thus be the result of initiation of oceanic spreading in the Norwegian-Greenland Sea around 55 Ma, causing an additional NW-SE component in the African-Eurasian collision (Srivastava *et al.,* 1990).

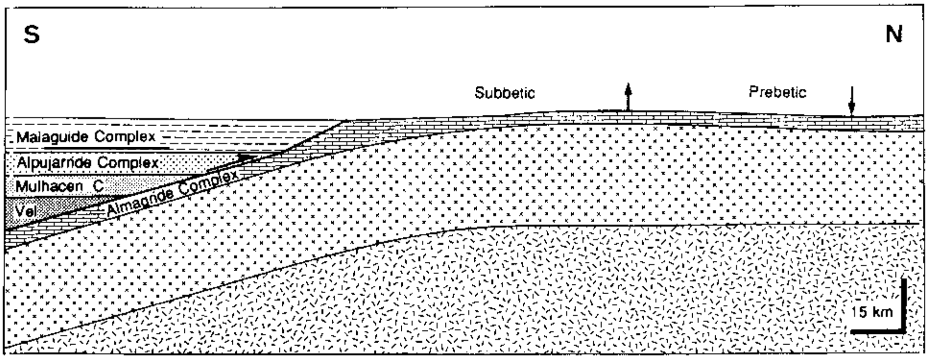


Figure 6.—Thrusting of the partially structured Betic Zone over the southernmost External Zone in the Early to Middle Eocene. Burial and loading resulted in HP/LT metamorphism in the Almagride Complex and upward and downward flexure of the Subbetic and Prebetic, respectively (arrows).

5.4. Late Oligocene to Early Miocene extension

D_3 folding in the Veleta and Mulhacen complexes has no equivalent in the Alpujarride Complex, pointing to translations of these two structural domains with respect to each other. The S-SW vergence of D_3^{mulh} and D_3^{vel} folds imply a southward movement of the overlying Alpujarride Complex (fig. 7). Progressive southward thinning leading to complete excision of the Mulhacen Complex (figs. 7, 8) indicates large scale normal faulting. Southvergent D_3^{mulh} and D_3^{vel} folding is probably due to back-rotation of the swell domain north of the normal fault (fig. 7). Folding is envisaged as resulting from accomodation of the shape of the back-rotated domain below an upward bowed extensional fault. Maximum temperatures during extension-related reheating were reached after D_3^{mulh}, showing that reheating at a particular crustal level occured after extension itself, in agreement with 2D modelling of the part of the P-T-t path pertinent to extension (Van Wees *et al.,* 1992). Stronger reheating in the southern part of the Mulhacen Complex is indicative of more advanced extension in this part of the complex.

In the Alpujarride Complex reheating-induced staurolite growth over undeformed S_2 shows that extension tectonics did not result in folding of the main schistosity as was the case in the Mulhacen and Veleta complexes. Hence S_2 in the Alpujarride Complex was located in the extensional sector of the flow field, in agreement with the position of this complex in the hanging wall of a low-angle extensional system (figs. 7, 8). Differences in maximun temperatures attained by the different Alpujarride tectonic units point to a non-uniform reheating that

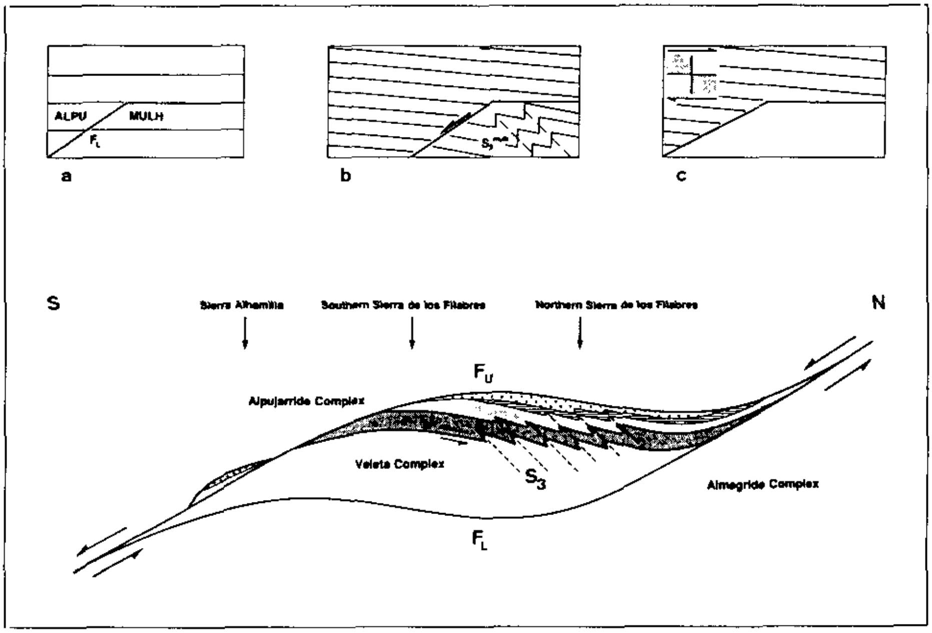


Figure 7—South vergent D_3 folding resulting from form adaption of the Mulhacen and Veleta complexes between two major curved extensional faults F_L and F_U due to extensional unloading of the hanging wall (Alpujarride Complex). Extension has resulted in progressive southward thinning of the Mulhacen Complex and excision of its lithologic units. Extreme extension produced a rider of rocks of the Mulhacen Complex (Sierra Alhamilla). Extensión gave rise to back-rotation of S_2 in the Alpujarride Complex (insert b), during subsequent inversion of the extensional structure S_2 was located in the compressional sector of the flow field (shaded areas, insert c) producing north vergent D_3^{alpu} folds.

occured, in addition, at different pressures. In the Almanzora Unit reheating produced only biotite, whereas in the Oria and Partaloa units (Sierra de las Estancias, Sierra de los Filabres) staurolite-andalusite growth occurred (Akkerman *et al.*, 1981; De Jong, 1991a). The association staurolite-sillimanite in the Adra nappe (south of the Sierra Nevada, e.g. Cuevas and Tubía, 1990) implies higher pressures at similar temperatures. The Almijara group of units experienced high grade metamorphism and local anatexis in association with emplacement of ultramafic rocks in the western Betic Zone at high pressures (Westerhof, 1977; Tubía and Ibarguchi, 1991). Different P-T conditions during extension are the result of a southward dip of the main extensional fault, cutting southwards down into the mantle (fig. 8). The less dramatic P-T evolution of the other Alpujarride tectonic units is due to their location above less thinned and thus less reheated crust, which include the Veleta and Mulhacen complexes (fig. 8).

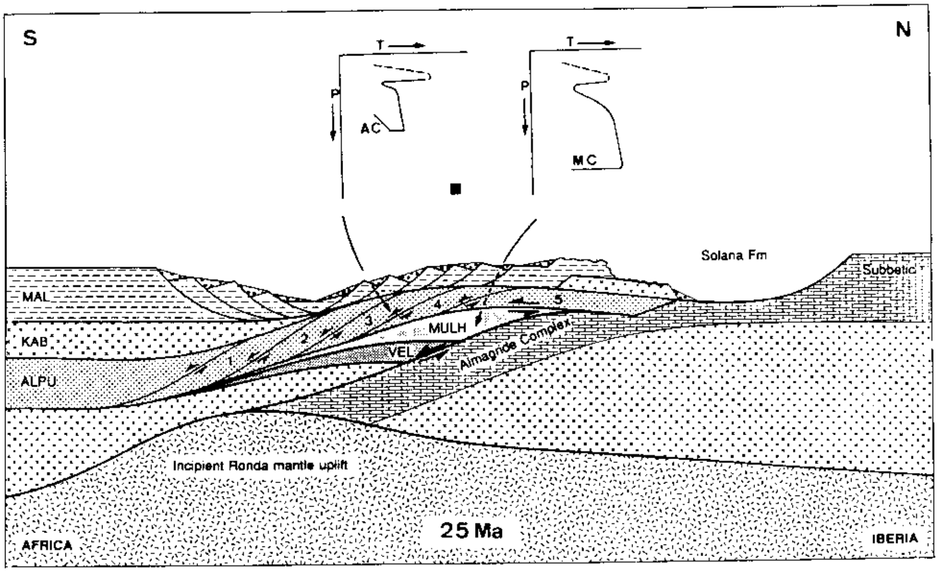


Figure 8.—Cartoon of the Late Oligocene to Early Miocene extensional structure. The Mulhacen and Veleta complexes are pinched out southwards towards an extensional mantle uplift, resulting in substantial reheating [insert P-T paths; P-T conditions at Ronda (square), after Westerhof, 1977]. The main extensional fault dips southwards resulting in reheating at progressively higher pressure in the Alpujarride units; schematically from north to south: 5) Almanzora Unit, 4) Variegato-Partaloa Unit, 3) Oria Unit, 2) Adra Unit, 1) Almijara group. The Malaguide Complex is the site of coarse clastic sedimentation, the early deposits of the Solana Formation occur in an extensional basin between the Internal and External zones.

The P-T jump at contact between the Alpujarride Complex and the non-metamorphic Malaguide Complex is also due to extension, during which the remainder of the crystalline basement of the Malaguide Complex is cut out. The extensional basin between the Internal and External zones (fig. 8) results from the outcrop of the basal detachment of the extensional system (De Jong, 1991a; Van Wees *et al.,* 1992).

Timing of extension

Reheating in the Mulhacen Complex is tentatively dated at around 25 Ma. This is based on $^{40}Ar/^{39}Ar$ laser probe dating of a D_2^{mulh} phengite single grain pointing to argon loss at around 25 Ma (De Jong, 1991a; De Jong *et al.,* 1992). In addition, modelling of a $^{40}Ar/^{39}Ar$ tourmaline age spectrum with indications for Ar-loss, resulted in a 23.5 Ma model age for this event (De Jong, 1991a; De

Jong *et al.*, 1991). Thus extension in the Betic Zone can be considered as a Late Oligocene to Early Miocene event.

5.5. Inversion of the extensional structure

Inversion of the Early Miocene extensional structure and northward overthrusting of the hanging wall of the extensional system (fig. 9) is manifest by many observations discussed in this paragraph.

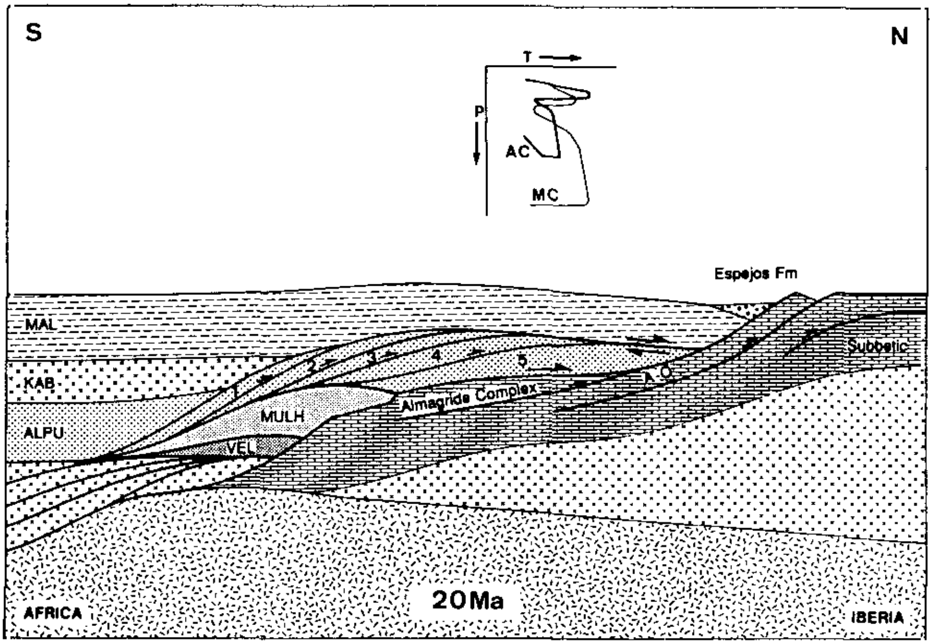


Figure 9.—Inversion of the extensional structure around 20 Ma resulting in substantial cooling of the Alpujarride and Mulhacen complexes (insert P-T paths). The regional structure of the Alpujarride Complex is characterized by superposition of higher metamorphic units on lower grade units. The Almagride Complex and the Antequera-Osuna nappe (A-O) represent thrust slices of metamorphic equivalents of the Subbetic. The extensional flysch basin between the Internal and External zones is closed; the Espejos Formation is deposited after northward thrusting.

Kinematics of small-scale structures in mylonites in the top of the Mulhacen Complex point to a NNE-to NNW-ward movement of the overlying Alpujarride Complex (Behrmann and Platt, 1982; De Jong, 1991a), thus in an opposite direction as during previous extensional tectonics. The regional structure of the stack of Alpujarride nappes is generally characterized by higher grade metamorphic units above lower grade units (Aldaya *et al.,* 1979), pointing to thrusting of stronger reheated rocks on top of less reheated units due to inversion of the extensional structure (fig. 9). Part of the extensional mantle uplift in the western Betic Zone was decapitated during inversion as indicated by the presence of up to 1.5 km thick slices of ultramafic rocks which have been thrust along a mylonite zone over high-grade metasediments of the Almijara group (Westerhof, 1977; Tubía and Cuevas, 1986). Seismic refraction data imply that the large peridotite massif of Ronda does not root in the mantle but also represents a thrust sheet (Barranco *et al.,* 1990). Thrust emplacement of ultramafic rocks resulted in an inverted gradient and in formation of anatectic leucogranites due to melting of high-grade metamorphic pelites of the Almijara group (Westerhof, 1977; Tubía and Cuevas, 1986). Overthrusting of hotter Alpujarride rocks has locally caused heating of the underlying Mulhacen and Veleta complexes in the southernmost part of the overthrust zone. This is inferred from the data of Van den Eeckhout and Konert (1983), which show an upward increase in An% of syn-overthrusting plagioclase towards the overlying Alpujarride Complex.

Two dimensional thermal modelling, using a depth dependant rheology, showed that inversion and concentration of deformation in the former extensional structure is the result of a pronounced drop in strength of the lower part of the upper crust and the lower crust as a result of extension-related reheating (Van Wess *et al.,* 1992). Deformation structures show that during inversion the Mulhacen Complex in the footwall and the stronger reheated Alpujarride Complex in the hanging wall reacted differently. Rocks of the Alpujarride Complex were strongly folded by norhtvergent D_3^{alpu} structures, indicating that S_2 was located in the compressional sector of the flow field (fig. 7). In contrast, the Mulhacen Complex was less severely affected during inversion; deformation related to overthrusting was mainly concentrated into a D_5^{mulh} mylonite zone below the Alpujarride Complex. Open D_4^{mulh} folds, forming antiforms with half wavelengths of a half to several kms, are the early expression of inversion.

Dating of inversion tectonics

D_3^{alpu} folding and D_5^{mulh} mylonitization occurred during falling temperatures indicated by widespread retrograde mineral reactions associated with it. Radiometric dating of cooling associated with this event thus constrains the timing of inversion of the extensional structure. Rb-Sr, K-Ar and $^{40}Ar/^{39}Ar$ cooling ages in the Alpujarride Complex of the entire Betic Zone cluster around 19 Ma (Priem *et al.,* 1979; Zeck *et al.,* 1989; Andriessen *et al.,* 1991; Monié *et al.,* 1991).

Deposition of undisturbed sediments with biozone N6-N7 ages after the main thrusting (fig. 9) points to a completion of inversion of the extensional structure before 17-18 Ma, using the Haq *et al.* (1989) time scale. This is shown by Espejos Formation in the eastern Betics (Geel, 1973), which contains pebbles with D_3^{alpu} folds (De Jong, 1991a) and by the Viñuelas Formation in the western Betic Zone, which seals thrust planes between high-grade metamorphic Alpujarride units and the Malaguide Complex (González Donoso *et al.*, 1983; Torres-Roldán *et al.*, 1986; Zeck *et al.*, 1989). Thus, formation of the extensional structure and its inversion were complete within a very short period of about 7-8 Ma. The concomittant extremely rapid cooling is explained by thrusting of the Alpujarride Complex over less extended and thus cooler crust (De Jong, 1991a; De Jong *et al.*, 1992; Van Wees *et al.*, 1992, fig. 9). Extension during advanced D_4^{alpu} further contributed to cooling.

5.6. Renewed Middle Miocene extension

Radiometric dating in the Mulhacen Complex has not resulted in a tight cluster of cooling ages as is the case for the Alpujarride Complex. Integrated $^{40}Ar/^{39}Ar$ ages of phengite vary between 25.9 and 14.3 Ma (De Jong, 1991a; De Jong *et al.*, 1992). Modelling of the age spectra implied that they were the result of repeated thermal resetting. Resetting has a similar timing as the main episode of volcanism in the basins bordering the metamorphic ranges. Late Miocene volcanism resulted in epigenetic ore deposits and hydrothermal alteration in the country rocks (Oen *et al.*, 1975). Hence, isotope resetting in the Mulhacen Complex might similarly be the result of fluids associated with volcanism (De Jong *et al.*, 1992).

Calc-alkaline dykes occur locally in the Alpujarride and Malaguide complexes. At least part of the dykes are intruded after cooling of the Alpujarride Complex was completed (Torres-Roldán *et al.*, 1986). The dykes are not folded indicating that intrusion took place after D_3^{alpu} overthrusting of the Alpujarride Complex, pointing to renewal of extension. This is also clearly expressed by concentration of Miocene volcanism in the most thinned crust in the western Mediterranen area (fig. 10). Interpretation of reflection profiles and borehole data from the Alboran Basin, south of the Betic ranges, also demonstrated an important Middle to Late Miocene extension (Comas *et al.*, 1990). A second phase of extension superimposed on the Late Oligocene to Early Miocene event also emerged from modelling of the gravity field of the Betic Cordilleras (Van der Beek and Cloetingh, 1992).

5.7. Slab roll-back, steepening and detachment

Rapid shifting of extension to compression and renewal of extension occurred during continuing plate convergence, implied by plate kinematic data (Srivastava *et al.*, 1990). This points to slab roll-back as likely mechanism for Late Oligocene to Early Miocene extension. Detachment of a (rolled-back) slab results in substantial decrease of the slab-pull force leading to a diminishing of the flexural bulge of the slab, giving rise to a better coupling of the shallow remainder of the slab (Spakman, 1990). Such a relatively rapid process might be the reason for the observed fast and dramatic inversion of the Early Miocene extensional structure in the Betic Zone. Reprise of extension during the Middle and Late Middle Miocene is either the result of renewed roll-back and steepening of a subduction slab or, alternatively, due to sinking of a slab (Platt and Vissers, 1989; De Jong, 1991a). Recent seismic tomographic studies point to the existence of a detached slab below the Betic Cordilleras (Wortel and Spakman, 1992), which is supported by earthquakes occurring as deep as 600 km (Grimison and Chen, 1986). Miocene and younger magmatism has been explained by partial melting of subducted lithosphere (Araña and Vegas, 1974; De Roever, 1975; Torres-Roldán, *et al.*, 1986). Concentration of magmatism into a NNE-SSW trending narrow zone (fig. 10), in which a clear chronological and chemical zonation is absent (De Larouzière *et al.*, 1988), agrees with melting of a steep, detached slab. The chemistry of Late Miocene lamproites of the eastern Betic Cordilleras points to derivation from the mantle at a maximum depth of 100 km (Venturelli *et al.*, 1988). The isotopic composition of these rocks indicates mixing of the mantle with a component which has the characteristics of continental crust or sediments derived from such a crust (Nelson *et al.*, 1986). This shows introduction of such crust into the mantle, which, however, cannot be the result of steady state subduction, as Miocene plate convergence was too slow, thus pointing to slab detachment.

Focal mechanisms of earthquakes in the most western Mediterranean area point to decoupling of tectonics at mantle and crustal level (Crimison and Chen, 1986), consistent with the presence of a detached slab. This is clearly by E-W compression of earthquakes deeper that 100 km, whereas intermediate quakes demonstrate NNW-SSE compressive stresses (Grimison and Chen, 1986). The latter direction agrees with the NW-SE to NNW-SSE compression in the Tortonian to Recent stress system in the eastern Betic Cordilleras (Montenat *et al.*, 1987; De Ruig, 1990; Buforn and Udías, 1991), which is related to the Africa-Eurasia collision (Bergerat, 1987). The approximate N-S directed crustal shortening in the Betic Cordilleras has resulted in strike-slip deformation (Montenat *et al.*, 1987; Sanz de Galdeano *et al.*, 1990), closure of extensional and strike-slip basins (Bon *et al.*, 1989; Coppier *et al.*, 1989) and overthrusting in the External Zone (De Ruig *et al.*, 1987; De Ruig, 1990).

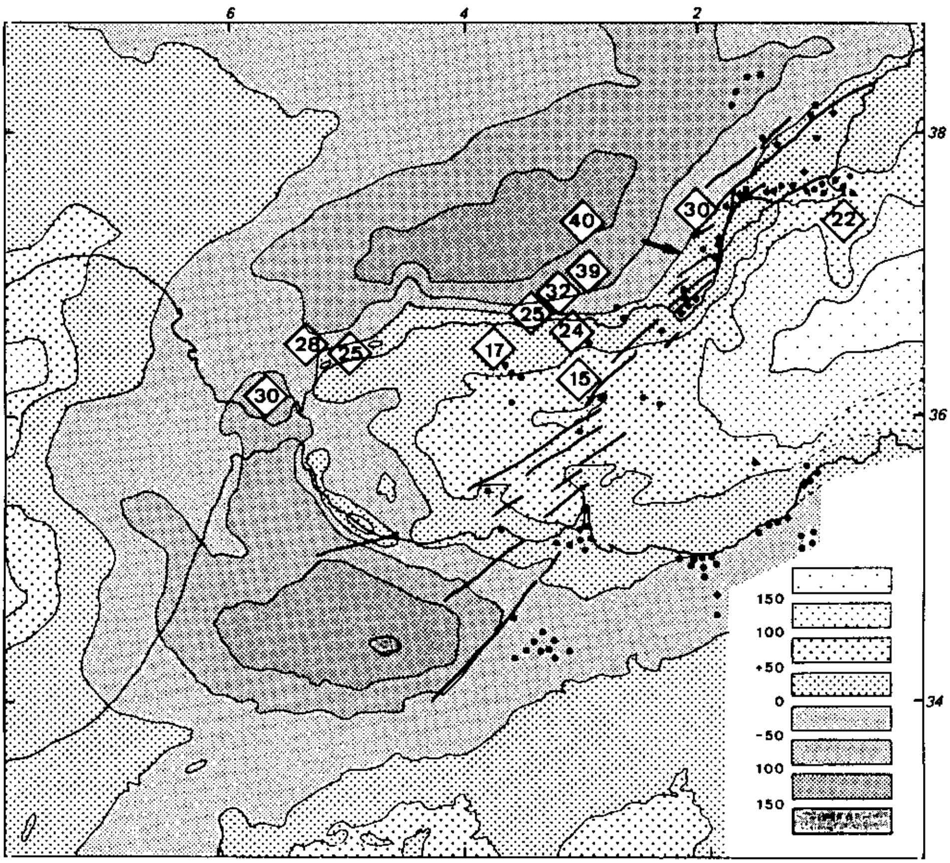


Figure 10.—Map of Bouger anomalies (in mgal) in the most western Mediterranean area (after Van den Bosch, 1974). The Betic-Rif arc is underlain by an arcuate pattern of negative anomalies; crustal thickness (diamonds, after Banda and Ansorge, 1980 and Barranco *et al.*, 1990) diminish pregressively towards the Alboran Basin. Miocene and younger strike-slip faults and volcanism (dots) (after: De Larouzière *et al.*, 1988) are concertrated in the thinnest crust.

The complex Miocene to Recent tectonic evolution of the Betic Cordilleras is thus probably due to crustal shortening resulting from Africa-Eurasia collision interfering with extension related to mantle tectonics arising from roll-back, steepening and detachment of a subducted slab below the collision zone.

CONCLUSIONS

Study of the relationship between polyphase deformation and mineral growth in the Alpujarride and Mulhacen complexes has resulted in well constrained P-T paths, which reflect the essential features of the Alpine tectonic evolution of the Betic Zone. Early Alpine HP conditions point to subduction below the lower crust of the Malaguide Complex: the Alpujarride Complex was subducted first, followed by the Mulhacen Complex, which was in turn underthrust by the Veleta Complex. Nappe stacking thus occurred by sequential underthrusting and detachment of upper crustal segments. Subsequent decompression shows exhumation of the HP metamorphic rocks, during which ductile flattening and extensional tectonics were dominant. Radiometric dating points to initiation of cooling after HP metamorphism in the Mulhacen Complex at about 89 Ma, implying an Early Cretaceous age for subduction. Thrusting of the Betic Zone over the relatively cool External Zone during the Eocene resulted in advanced cooling of the hanging wall. Important late stage reheating is tentatively dated at about 25 Ma, showing that crustal and subcrustal extension and the associated mantle upwaring in the Betic Zone are Late Oligocene to Early Miocene features. Subsequent rapid cooling is due to inversion of the extensional structure.

The tectonic evolution of the Betic Zone reflects the dynamics of compression and extension of the three main stages in the Africa-Eurasia collision in the western Mediterranean:

1. ESE-ward movement of Iberia between 119 and 80 Ma, due to spreading in the Atlantic Ocean to the west of Iberia, resulted in westward subduction of the Betic Zone below the leading edge of Iberia, where the Malaguide Complex was located.
2. Overthrusting of the most southern part of the External Zone by the partially structured Betic Zone in the Eocene (around 50 Ma) caused HP/LT metamorphism in the overthrust part of the External Zone (Almagride Complex) and flexural bulging of the part which was not overthrust and where sedimentation continued. This phase, which is coeval with collision in the Pyreness, is caused by an additional NW-SE compressional component into the Africa-Eurasia collision due to oceanic spreading in the Norwegian-Greenland Sea.
3. Late Oligocene to Early Miocene crustal and subcrustal extension and subsequent inversion of the extensional structure, which was completed at about 18 Ma, ocurred during continuing Africa-Eurasia convergence. This points to roll-back, steepening and detachment of the subduction slab. Detachment of the deeper part of the slab caused a better coupling

of the shallow remainder of the slab with the overlying plate enabling transfer of compression due to plate convergence. Resetting of isotope systems in the Mulhacen Complex, important volcanism and dyke intrusion point to renewed extension after 18 Ma. A deep source of volcanism agrees with the presence of a detached slab as plate convergence during the Miocene is not sufficient for steady subduction to such depths.

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