*Tectonophysics*, 184 (1990) 357–366
Elsevier Science Publishers B.V., Amsterdam



# A review of Alpine tectonics in Portugal: Foreland detachment in basement and cover rocks

A. Ribeiro [a], M.C. Kullberg [a], J.C. Kullberg [b], G. Manuppella [c] and S. Phipps [d]

[a] *Departamento de Geologia da Faculdade de Ciências da Universidade de Lisboa, Edificio C2, 5° piso, Campo Grande, 1700 Lisbon (Portugal)*
[b] *Sec. Autón. de Geologia da Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, Quinta da Torre, 2825 Monte da Caparica (Portugal)*
[c] *Serviços Geológicos de Portugal, Rua Academia das Ciências, 19, 2°, 1200 Lisbon (Portugal)*
[d] *Department of Geology, University of Pennsylvania, Philadelphia, PA 19104-6316 (U.S.A.)*

(Received July 17, 1989; revised version accepted March 1, 1990)

ABSTRACT

Ribeiro, A., Kullberg, M.C., Kullberg, J.C., Manuppella, G. and Phipps, S., 1990. A review of Alpine tectonics in Portugal: Foreland detachment in basement and cover rocks. In: G. Boillot and J.M. Fontboté (Editors), Alpine Evolution of Iberia and its Continental Margins. *Tectonophysics*, 184: 357–366.

The Alpine foreland in Portugal was deformed by compressional tectonism during the Miocene. In the NNE–SSW oriented Lusitanian Basin, most folds and thrusts in the Meso-Cenozoic cover are oriented ENE–WSW, parallel to the Alpine front in the Betic Cordillera, and verge towards the north-northwest and south-southeast. The thrusts are connected by lateral ramps: most of these are oriented NNE–SSW to N–S and show sinistral movement, and some are transpressional. The lateral ramps result from reactivation of older extensional faults related to crustal thinning of the continental margin. In the E–W oriented Algarve Basin a simpler basin inversion occurred, with older E–W normal faults reactivated as essentially pure thrusts. In both basins Alpine structures formed above décollements in the Hettangian evaporite–clastic complex. Variscan basement was also deformed by ENE–WSW reverse faults during Miocene time. The similarity in orientation and style of the basement structures to those in the cover suggests that they also occurred by detachment, but their larger scale indicates that the detachment is deep and involves much of the crust. Thus, we interpret the Central Cordillera, in which basement rocks are thrust over Miocene sediments on both sides, as a "pop-up" of crustal scale, elevated above downward-flattening faults that dip towards each other and merge into a single deep detachment. Alpine structures in the Iberian foreland are therefore similar in structural style to those of the Appalachian and Laramide forelands of North America and the Alpine foreland of northwest Europe.

## Introduction

In this paper we will briefly summarize our present knowledge of the Alpine structural geology of western Iberia, with the emphasis on Portugal. We will review our own recent work onshore, describing selected structures and our interpretation of each, but can here refer only in passing to offshore work that has been carried out by many authors (for reviews of various aspects, see Baldy et al., 1975, 1976; Boillot et al., 1979, 1987; Mougenot, 1983, 1989; Sibuet, 1987). We will then speculate on the larger scale structure and on the Alpine geodynamics of the region.

In the interior of the Iberian block (Hisperic massif), Alpine structures result mainly from reactivation of Variscan and late Variscan structures (Ribeiro et al., 1979) (Fig. 1). Along the continental margins of the block, however, the Variscan structures had been modified by Mesozoic extension related to the opening of the Atlantic and Tethys oceans. Near the continental margin, it was these new structures that were subsequently reactivated by the Alpine collision. We must there-

0040-1951/90/$03.50 

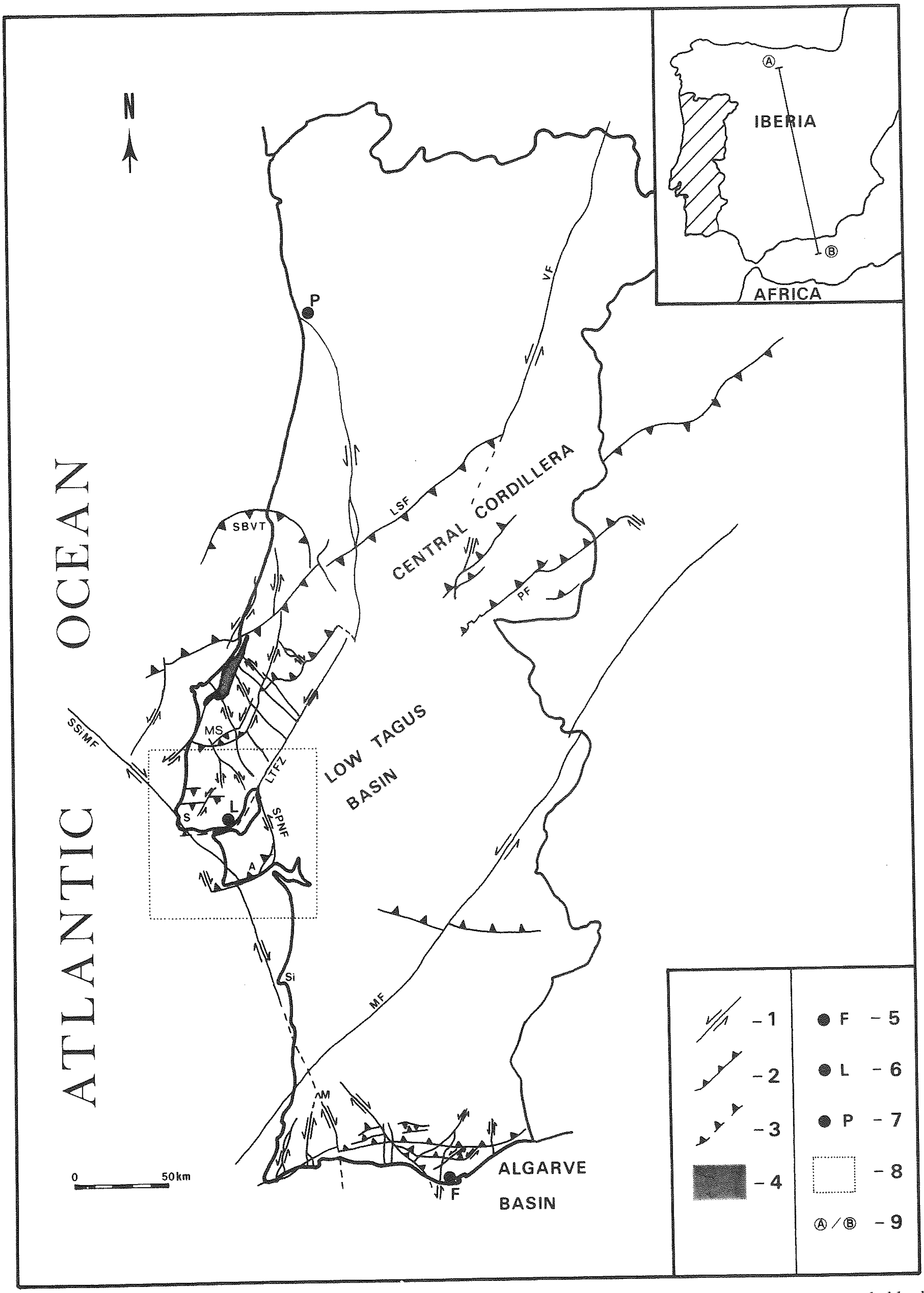


Fig. 1. Map of structures active in Portugal during the Alpine collision. *1* = Strike-slip faults; *2* = thrust faults; *3* = probable thrust faults; *4* = Caldas da Rainha salt diapir; *5* = Faro; *6* = Lisbon; *7* = Oporto; *8* = location of Fig. 2; *9* = location of schematic cross section in Fig. 4. *A* = Arrábida chain; *S* = Sintra; *Si* = Sines; *M* = Monchique; *LSF* = Lousã–Seia fault; *LTFZ* = Low Tagus fault zone; *MF* = Messejana fault; *MS* = Montejunto structure; *PF* = Ponsul fault; *SBVT* = Serra de Boa–Viagem thrust; *SPNF* = Setúbal–Pinhal Novo fault; *SSiMF* = Sintra–Sines–Monchique fault; *VF* = Vilariça fault.

fore refer briefly to the extensional structures before discussing the Alpine inversion that they control.

## The opening of the Atlantic

From Permian to Cretaceous time, the opening of the Atlantic and Tethys oceans formed passive margins in western and southern Iberia (the Lusitanian and Algarve–Guadalquivir basins respectively). The onshore evolution of these margins is well known from the geological record (Ribeiro, et al., 1979; Wilson, 1975, 1979, 1986; Wilson et al., in press), and the deep structure of the Lusitanian Basin has been studied by seismic methods (Victor et al., 1980; Wilson et al., in press), the latter have also been used extensively offshore (Mougenot, 1989).

Subsidence along the Lusitanian and Algarve margins was controlled by typical extensional tectonics. In the Algarve, the Mesozoic section thickens radically southward across flexures that trend subparallel to the coastline (Ribeiro et al., 1984; Manuppella, 1987a, b, 1988; Manuppella et al., 1988). These flexures probably overlie basement normal faults. Sedimentary facies (e.g. the abundance of conglomerates) and thickness changes suggest that these were synsedimentary growth structures (Manuppella, 1987b). The Lusitanian Basin contains normal faults oriented between N–S and NNE–SSW, some of them listric, indicating nearly E–W extension; thickness variations and local debris-flow deposits likewise suggest that these were synsedimentary structures (Crispim and Ribeiro, 1986; Guéry et al., 1986; Wilson, 1986; Montenat et al., 1988).

In Cretaceous time, the Bay of Biscay opened as a sphenochasm as a consequence of triple-junction evolution, inducing sinistral rotation of Iberia (e.g. Carey, 1955; van der Voo, 1969; Dewey et al., 1973). Subvolcanic alkaline ring complexes (Sintra, Sines, Monchique) were emplaced at that time. Rift migration may have changed the stress field and deeply fractured the previously thinned continental margins; the fractures may control the location of the alkaline complexes (Ribeiro et al., 1985; Kullberg, 1985).

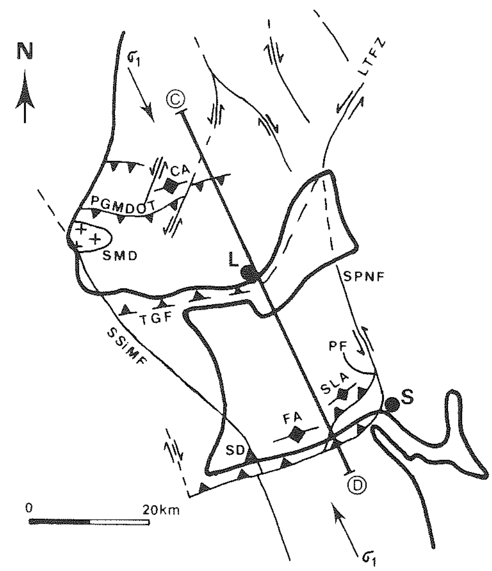


Fig. 2. Structures active in the Miocene in the Arrábida–Sintra region (modified from Ribeiro and Ramalho, 1986). $L$ = Lisbon; $S$ = Setúbal; $SD$ = Sesimbra salt diapir; $SMD$ = Sintra magmatic diapir; $CA$ = Cortegaça anticline (north of Maria Dias region); $FA$ = Formosinho anticline (Arrábida chain); $SLA$ = -São Luis anticline; $LTFZ$ = Low Tagus fault zone; $PGMDOT$ = Praia Grande–Maria Dias–Olelas thrust; $PF$ = Palmela fault; $TGF$ = Tagus Gargalo fault; $SPNF$ = Setúbal–Pinhal Novo fault; $SSiMF$ = Sintra–Sines–Monchique fault. $\sigma_1$ = Maximum compressive stress direction during the Miocene. C–D = Location of schematic cross section in Fig. 3.

The Sintra intrusion produced a dome in the overlying sedimentary rocks that is strongly elongated E–W and is cut by a N-verging thrust (Kullberg, 1984, 1986). This thrust was reactivated and lengthened during Alpine compression, forming the Praia Grande – Maria Dias – Olelas thrust (Fig. 2). The Sintra dome may be asymmetric because the diapir was sheared and rotated during its emplacement along a deep strike-slip zone.

During the Cretaceous, some late Variscan faults in the interior of Iberia (striking NNE–SSW and NE–SW) were probably reactivated with sinistral strike-slip motion (Ribeiro et al., 1979). In onshore western Iberia, Late Cretaceous–Paleogene convergence between Iberia and Eurasia is only expressed by sedimentation in foreland basins such as the Douro Basin (Carvalho et al., 1985).

**Alpine collision: geometry of structures in the cover**

The west Iberian margin and the Algarve Basin lie in the foreland of the Betic Cordillera, the Iberian segment of the Alpine chain, but are far (approximately 400 and 200 km respectively) from the northwestern margin of the thrust belt. Nevertheless, the Alpine orogeny produced structures in these distant foreland regions. Oligocene convergence between Eurasia and Africa was oriented NNE–SSW; secondary extension within the Eurasian plate produced a system of grabens oriented in that direction (Tapponnier, 1977). The Low Tagus Basin (Fig. 1) belongs to this system and is bounded to the northwest by the Low Tagus fault and to the southeast by the Messejana fault (Carvalho et al., 1985), which offsets the Moho (Hirn et al., 1983).

During Miocene time, the convergence between Eurasia and Africa rotated to a NNW–SSE direction (Tapponnier, 1977). Basin inversion was marked by basement thrusting in the Central Cordillera (Cabral, 1983; Dias and Cabral, 1988). In the Lusitanian and Algarve basins, the Meso-Cenozoic cover was deformed in a thin-skinned style with décollement in the Hettangian evaporites (e.g. Manuppella, 1987d; see also fig. 10 of Wilson et al., in press).

*Algarve Basin*

In the Algarve Basin, a complex of faults was active. Faults striking NE–SW and NW–SE acted as left- and right-lateral shears respectively. E–W-striking faults—many corresponding to Mesozoic rift-stage normal faults and flexures — acted primarily as N-verging reverse faults and overthrusts (Manuppella, 1987b, d). These are associated with anticlines with structural relief as large as 1 km (Manuppella, 1987a, b, c, d). Faults and folds are detached in the Hettangian evaporites; diapiric structures, which began to ascend during Mesozoic extension, were accentuated during the Alpine deformation (Ribeiro et al., 1984; Manuppella, 1987a, b, c, d). Along the western Algarve coast, in extreme southwestern Portugal, the strike of these structures bends to follow the coastline, becoming almost NE–SW near Lagos and Sagres (Oliveira, 1984). On the northern edge of the Algarve Basin, the contact of the Mesozoic rift sequence with the underlying Paleozoic "basement" —which here consists of weakly metamorphosed Carboniferous turbidites—is repeated along faults that parallel regional strike (Oliveira, 1984); this relationship suggests that Alpine-age thrusts involve the Paleozoic in this area. The geometry of all these structures suggests that, in the Algarve, the Alpine compression was subparallel to the previous N–S extension, and simple basin inversion occurred.

*Lusitanian Basin*

The structures in the Lusitanian Basin along the west Iberian margin are more complex than those in the Algarve Basin. The complexity owes in part to a geometrically more complicated interaction between the Alpine stress field and pre-existing fractures, and in part to the interplay of halokinesis and orogenesis as the structures were formed.

Among the more important structures are the thrust complexes of Sintra and Arrabida, the Montejunto fold/fault complex, and the Serra de Boa – Viagem thrust. The Sintra and Arrabida structures are described in the following sections. The Montejunto structure is a faulted anticline with an overall NE–SW trend, but is bent sharply in the middle, where the structural trend is almost E–W (Zbyszewski et al., 1965, 1966). To the north of this bend, the west limb of the fold is gentle, whereas the east limb is steep and is cut by a thrust that carries the Mesozoic out over the Tertiary. To the south of the bend, the east limb dips moderately while the west limb is steep. Here, overthrusting occurs in both directions, but that to the west appears to be dominant. At the bend, the highest part of the anticline is thrust both to the north and to the south; we interpret this structure as a "pop-up" structure within the Mesozoic sedimentary rocks. While salt tectonics may have contributed to the formation of the Montejunto structure (Wilson, 1986; Wilson et a., in press), abundant outcrop-scale folds and thrust and reverse faults present strong evidence for shortening, both with respect to bedding and the present horizontal. We suggest that the Montejunto structure was probably formed mostly by compressional and/or transpressional deformation. The Serra de Boa – Viagem thrust system in the Lusitanian basin 150 km north of Lisbon (Fig. 1) (Manuppella et al., 1976; Rocha et al., 1981) consists of an arcuate fault network with the frontal, E–W-striking thrust probably representing a larger proportion of dip-slip (shortening) in the total fault movement, while the more N–S-striking faults on the flanks of the arc appear to have a larger component of strike-slip.

Along the west Iberian margin, the Alpine compression appears to have been at a lower angle to the mean orientation of the rift faults, which were oriented NNE–SSW; this obliquity is probably responsible for the complex structures. Older faults that were nearly perpendicular to the compression deflected the bedding-plane thrusts upwards, forming ramps with associated folds. The rift boundary faults and subsidiary intrarift faults that were subparallel to them were oblique to the maximum compressional stress, and apparently behaved as lateral ramps and transfer zones for the Alpine thrusts (Ribeiro, 1988; Ribeiro et al., 1988a). Examples include the NNE–SSW to NE–SW boundary faults of the Montejunto structure.

*Sintra*

In the Sintra region, major thrust systems and short-wavelength folds trend between E–W and WSW–ENE (Kullberg, 1985). These structures are clearly N-verging; folds are asymmetric and their axial planes are commonly cut by faults that carry their normal limbs out over their steep limbs, partially obscuring the latter. The structures affect the Mesozoic sequence, the basaltic flows of the latest Cretaceous to Paleocene Lisbon Volcanic Complex, Paleogene continental conglomerates, and some early Miocene deposits. NE–SW-striking sinistral strike-slip faults, which were formed during the emplacement of the Sintra Eruptive Complex, were locally reactivated during the Alpine compression. These faults acted as lateral ramps for the Alpine thrust systems and delimit internally deformed but semi-independent blocks (e.g. the Cortegaça anticline and the Maria Dias region) (Kullberg, 1984, 1986; Reis, 1987). The Alpine compression also formed "pincée" structures over some early extensional structures that has formed simultaneously with the extrusion of the Lisbon Volcanic Complex (Kullberg et al., 1985). The orientation of structures in the Sintra region suggests that the maximum compression during the Miocene was oriented approximately NNW–SSE.

*Arrábida*

The most elegant example of thin-skinned Alpine tectonics in west Iberia occurs in the Arrábida chain, south of Lisbon (Ribeiro and Ramalho, 1986). The Arrábida thrust belt trends ENE–WSW, parallel to the Betic Cordillera and extends for about 30 km. At the eastern end of the thrust belt, near Setubal, seismic data shows that displacement on the Arrábida structures is transferred northward about 12 km to the vicinity of Pinhal Novo, from which the structures continue to the northeast. To the west, the Arrábida structures continue offshore on the continental platform for at least 5 km (Boillot et al., 1978).

The Arrábida chain is dominated by thrusts striking ENE–WSW and associated anticlines; the structures are S-verging (Ribeiro and Ramalho, 1986). Oblique ramps oriented N–S show sinistral strike-slip and E-vergin reverse movement. These ramps reactivate normal faults related to the rifting of the Lusitanian Basin, as shown in the pre-Late Jurassic core of the São Luis anticline. The Arrábida thrust system probably terminates offshore to the west against a right-lateral transfer zone (tear fault) conjugate to the left-lateral Setúbal–Pinhal Novo fault (Boillot et al., 1978) (Fig. 2). Both transfer zones occur above the main boundary faults of the Lusitanian Basin. The geometry of the N-verging Serra de Boa – Viagem thrust system in the Lusitanian Basin (Fig. 1) may be similar.

Two anomalous structures do not fit the general pattern of the Arrabida thrust system. The Palmela fault slice exhibits younger-on-older fault relationships, with a section removed along the fault, and contains a basal breccia, suggesting that the slice formed as Miocene cover rocks slid from

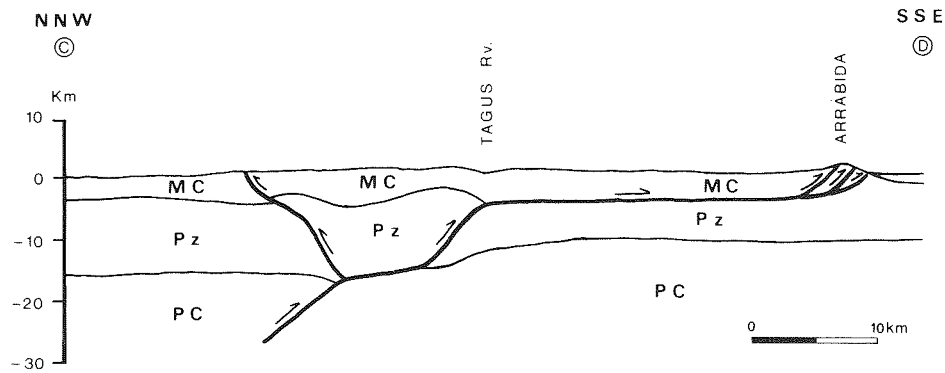


Fig. 3. Deep structure of Arrábida–Sintra region during Alpine compression (modified from Ribeiro and Ramalho, 1986); for location see Fig. 2. *MC* = Meso-Cenozoic; *Pz* = Paleozoic; *PC* = Precambrian.

the crest of the rising São Luis anticline (Fig. 2) (Ribeiro and Ramalho, 1986). The second anomalous structure, the Sesimbra diapir (Fig. 2), is cored by the Hettangian evaporite–redbed complex, and may have been formed during the Late Cretaceous along the dextral strike-slip fault connecting the Sintra, Sines and Monchique igneous complexes. The rocks presently exposed at the surface at Sesimbra were transported to the south-southeast during the main Alpine thrusting.

Thrusting in the Arrabida belt can be dated precisely. In the southern anticlines (e.g. Formosinho), the Langhian is unconformable on the Burdigalian, and the thrusts were reactivated after deposition of the Tortonian (Ribeiro and Ramalho, 1986). In the northern anticlines (e.g. São Luis), sedimentation was continuous from the Burdigalian to the Tortonian (Ribeiro and Ramalho, 1986), but the Pliocene unconformably overlies the folded and thrusted Miocene sequence. The deformation is thus Miocene in age, but there are indications that it consisted of several pulses. The S-verging deformation migrated from south to north—an example of backward progradation or an "overstep sequence".

In the Sintra–Arrábida region, erosion between the tectonic pulses apparently influenced the structural style. In the southeastern Arrábida chain, Mesozoic rocks in the short limb of the S-verging anticline associated with the Formosinho thrust were deeply eroded before the Langhian was deposited. The evaporite complex was exposed at the surface, and may have lubricated the thrust plane and permitted larger displacement to the south along a fault of low dip. In the Sintra region to the northwest, the thrust system is steeper and shows less displacement (Fig. 3).

## Alpine collision: geometry of structures in the basement

The deep Precambrian basement is itself involved in Alpine structures in west Iberia. Late Variscan basement-cutting strike-slip faults striking between ENE–WSW and NE–SW were reactivated as reverse faults and both NW- and SE-verging thrusts. The geometry of lateral ramps and duplexes shows the direction of transport of the basement rocks onto the Miocene cover. The largest structure thus formed was the Central Cordillera (Fig. 4), which was thrust over Miocene sediments both to the northwest and to the southeast (Cabral, 1983; Dias and Cabral, 1988; Madeira et al., 1988). The basement faults bounding the uplifted block of the Central Cordillera dip as gently as 30° at the surface (Cabral, 1983). We believe that the SE-verging, NW-dipping Ponsul fault, which bounds the Central Cordillera on its southeast em side, flattens at depth and converges with the NW-verging, SE-dipping Seia–Lousã fault, which bounds the Cordillera to the northwest (Fig. 4). We thus interpret this structure as a basement pop-up which is analogous to the central part of the Montejunto structure in the Lusitanian Basin but which involves basement rocks rather than the sedimentary cover. Some more northerly (NNE–SSW) striking late Variscan faults (e.g.

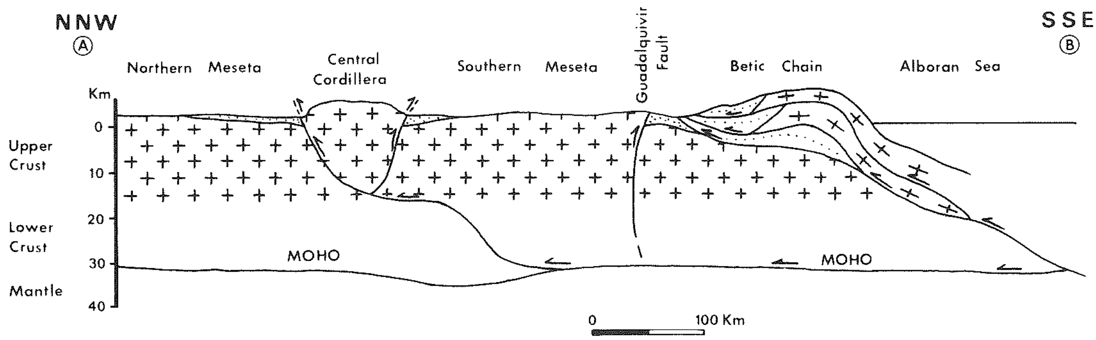


Fig. 4. Alpine reactivation of the Iberian Variscan basement: décollement along the Moho and pop-up structure in the Central Cordillera induced by Betic compression (modified from Ribeiro, 1988). For location, see inset of Fig. 1.

Vilariça) were also reactivated during Alpine deformation, principally as sinistral strike-slip faults, but with variable vertical displacements (Cabral, 1989).

As described previously, in the northern Algarve low-grade Carboniferous metaclastic rocks are involved in Alpine thrusts and associated folds in a style quite similar to that developed in the overlying Meso-Cenozoic sediments to which they constitute "basement".

## Alpine collision: kinematic interpretation of multiple décollement horizons in cover and basement

Seismic data on the deep structure of Iberia are scarce, and deep boreholes are simply non-existent. In this situation we can only speculate on the kinematics of the foreland deformation induced by the Alpine collision. This speculation focuses on two questions: (1) Is there a hierarchy of thin-skinned structures developed in the Meso-Cenozoic cover, suggesting décollement at multiple levels in the stratigraphy? (2) Do differences in the style of basement-involved Alpine structures suggest by analogy that there are multiple detachments at still deeper levels, within the crust and mantle?

The kinematics of the Alpine deformation in the Arrábida chain and the Sintra region should be understood in the context of the tectonics of the Portuguese Estremadura, the main part of the Lusitanian Basin north of Lisbon. Here, gentle folds with low amplitudes and large wavelengths ($\geqslant 10$ km) or areas of subhorizontal dip are dominant, and high-amplitude, short-wavelength folds such as those in Arrábida occur only locally. East of the Setúbal–Pinhal Novo–Low Tagus transfer zone, the rocks of the Meso-Cenozoic cover are subhorizontal.

Preliminary balanced cross sections show that in the Lusitanian Basin the low-amplitude folds can be explained by a $10 \pm 2$ km deep décollement. We suggest that this décollement corresponds to a major crustal heterogeneity, possibly the contact between low-grade metamorphosed Paleozoic rocks and the underlying Precambrian basement of the South Portuguese Zone (Ribeiro et al., 1988b).

The much shorter wavelength folds in the Arrábida imply a much shallower décollement at a depth of about 4 km. We speculate that the S-verging Arrábida thrust system flattens downward to the north into the Hettangian evaporite complex, then drops to the Paleozoic–Precambrian contact, perhaps along the Tagus Gargalo fault (Figs. 2 and 3). A N-verging thrust rises from the same (Paleozoic–Precambrian) décollement and reaches the surface to the north-northwest of Sintra, approximately along the Praia Grande–Maria Dias–Olelas line (Figs. 2 and 3). This thrust also affects the Miocene (Kullberg, 1986). The S-verging thrusts of Arrábida and the N-verging thrusts of Sintra define a pop-up structure involving the low-grade Variscan "basement" and the overlying Mesozoic–Cenozoic sedimentary rocks, which are delaminated from the underlying, high-grade Precambrian basement (Figs. 2 and 3).

Precambrian basement is also involved in Alpine structures in Portugal, most spectacularly in the Central Cordillera. We believe that the displacement on the NW-dipping Ponsul fault, which bounds this basement uplift on its southeast em side, "switches back" and joins that on the NW-verging Seia–Lousã fault: the combined displacement must then root at depth somewhere to the south. We suggest that displacement is channeled north along a deep basement detachment from the Betic Cordillera to the upper crustal structures in Sintra, Arrábida and Estremadura, as well as in the Central Cordillera (Fig. 4).

The structure of the Central Cordillera pop-up in the basement rocks (the Central Cordillera proper) differs from its structure in the Meso-Cenozoic cover of the Lusitanian Basin to the southwest (Fig. 1). In the basement structure, strike-slip faults oblique to the trend of the pop-up are not significantly deflected where they cross it. In the cover, however, the dextral strike-slip fault connecting the Sintra–Sines–Monchique ring complexes changes mean direction from N20W south of the Arrábida thrust system to N45W north of it, as the fault passes northward into the Lusitanian Basin (Fig. 1). The shortening perpendicular to this fault is much larger across its northern, more westerly striking segment. This suggests that the Alpine structures were produced by a maximum compressive stress oriented more nearly N–S than NNW–SSE. The bend in this fault may have been original, or may represent a shear response of the Lusitanian Basin to the Alpine deformation.

Alpine shortening was generally greater in the Lusitanian Basin than in the areas to the northwest or southeast, probably because its crust was more thinned by Mesozoic rifting. The main boundary faults acted as lateral ramps for the thrust systems inside the basin; e.g., at the ends of the Arrábida and Serra da Boa–Viagem thrust systems, which developed preferentially inside the Lusitanian Basin.

## Conclusions

During the Alpine deformation, represented in Iberia by the Betic Cordillera, large-amplitude, large-displacement, map-scale folds and faults were formed hundreds of kilometers into the orogenic foreland of Portugal. These structures affect both sedimentary and basement rocks. Thin-skinned structures, in which the Mesozoic cover is typically detached from the underlying Hercynian basement along a Hettangian redbed–evaporite complex, are prominent in the Algarve and in the Lusitanian Basin, especially in the Arrábida thrust belt. These structures consist of imbricate thrusts and associated asymmetrical folds, probably representing fault-bend and fault-propagation folds, and pop-up structures such as that of Montejunto. Movement of the Hettangian evaporites has extensively modified and locally disrupted these structures.

Thick-skinned (basement-involving) structures occur in the Algarve, but are most spectacular in the interior of Portugal, especially in the Central Cordillera. We interpret the uplifted block of the Central Cordillera as a basement pop-up elevated above thrusts that converge in the lower crust.

We suggest that the western Iberian crust was delaminated along the Moho from the Betic Cordillera at least to the Central Cordillera and the Lusitanian Basin (Ribeiro, 1988) in a manner similar to that suggested by Bally (1984) for northwest Europe. The north-northwestern flank of the Central Cordillera is thrust to the north along a crustal scale ramp rising from the deep detachment; a conjugate crustal backthrust carries the south-southeastern flank of the Central Cordillera to the south. Thus, the Central Cordillera is a basement pop-up separating the northern and southern Iberian Meseta. The thrust along the Paleozoic–Precambrian contact that gives rise to the structures in Arrábida and Sintra is probably a splay from the Moho-level detachment, and the pop-up structures formed above it replicated at a smaller scale those of the deep detachment and the Central Cordillera.

These structures are similar to some of those formed in the Alpine foreland of northwest Europe (Bally, 1984; Ziegler, 1987), and to those in the interior of North America in the forelands of the Alleghenian and Laramide thrust belts (Phipps, 1983, 1987). In these structures, basement and cover pop-ups and thin-skinned imbricate structures were also formed when old rifts in the continental interiors were reactivated during collisional orogeny at the continental margins.

## Acknowledgements

This is a contribution to the projects "Modelo Sismotectonofísico de Portugal", supported by the D.G.Q.A. (Portugal), and "Sismotectónica de Portugal", supported by contract G.P.S.N./ D.G.F.C.U.L. (Portugal). S.P.P.'s participation was funded by a NATO grant for International Collaboration in Research. We acknowledge discussions with geophysicists and geologists from U.L., U.N.L., S.G.P. and the O.U. (U.K.).

## References

Bally, A., 1984. Tectogenese et sismique réflexion. Bull. Soc. Géol. Fr., 7 (XXVI) (2): 279–285.

Baldy, P., Boillot, G., Moita, I. and Mougenot, D., 1975. Structure Géologique du plateau continental sud-portugais. C.R. Acad. Sci. Paris, 281 (D): 613–616.

Baldy, P., Boillot, G., Dupeuple, P.-A., Malod, J., Moita, I. and Mougenot, D., 1976. Carte géologique du plateau continental sud-portugais et sud-espagnol (baie de Cadix). Bull. Soc. Géol. Fr., 7, 19: 703–724.

Boillot, G., Malod, J.A. and Mougenot, D., 1979. Évolution géologique de la marge oueste ibérique. Ciênci. Terra (UNL), 5: 215–222.

Boillot, G., Mougenot, D., et al., 1978. Carta geológica da plataforma continental de Portugal, escala 1/1,000,000. Publ. Serv. Geol. and Inst. Hidrol. Port., Lisbon.

Boillot, G., Recq, M., Winterer, E.L., Meyer, A.W., et al., 1987. Tectonic denudation of the upper mantle along passive margins: a model based on drilling results (leg 103, western Galicia margin, Spain). Tectonophysics, 132: 335–342.

Cabral, J., 1983. Factores sismotectónicos para selecção de sîtios para centrais nucleares. Geonovas, 1: 37–45.

Cabral, J., 1989. An example of intraplate neotectonic activity, Vilariça basin, northeast Portugal. Tectonics, 8: 285–303.

Carey, S.W., 1955. The orocline concept in geotectonics. R. Soc. Tasmania Proc. Pap., 89: 255–288.

Carvalho, A.M., Ribeiro, A. and Cabral, J., 1985. Evolução paleogeografica da Basia Cenozóica do Tejo-Sado. Bol. Soc. Geol. Port., XXIV: 209–212.

Crispim, J.A. and Ribeiro, A., 1986. Tectónica extensional no bordo leste do Fosso Lusitano (area de Ancião). Maleo, 2 (13): 17.

Dewey, J.F., Pitman, W.C. III, Ryan, W.B.F. and Bonnin, J. 1973. Plate tectonics and the evolution of the Alpine system. Geol. Soc. Am. Bull., 84: 3137–3180.

Dias, R.P. and Cabral, J., 1988. A falha do Ponsul—reactivação no Cenozoico e evidências de actividade Quaternária [field guide]. 10 pp. (To be published as: Neogene and Quaternary reactivation of the Ponsul fault in Portugal. Comun. Serv. Geol. Port., 75: in press.)

Guery, F., Montenant, C. and Vachard, D., 1986. Évolution tectono-sédimentaire du bassin Portugais au Mésozoique suivant la transversale de Peniche (Estrémadure). Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine, 10: 83–94.

Hirn, A., Caetano, H., Steinmetz, L. and Victor, L.M., 1983. Moho variations across the Castilla–Alentejo–Gorringe lineament. Terra Cognita, 3 (2/3): 103 (Abstr.).

Kullberg, M.C., 1984. Controlo estrutural na instalação do maciço de Sintra. Dissert., Fac. Sci. Lisbon.

Kullberg, M.C., 1985. Controlo estrutural na instalação do maciço de Sintra. Bol. Soc. Geol. Port., XXIV: 219–223.

Kullberg, M.C., 1986. Actividade tectónica pós-Paleozóica. Maleo, 2 (13): 25.

Kullberg, M.C., 1987. Emplacement mechanism for the Sintra Diapir. Int. Conf. Plate Tectonics and Deformation (Oviedo), p. 86 (Abstr.).

Kullberg, M.C., Dias, R. and Madeira, J., 1985. Estrutura em "pincée" no flanco norte do maciço de Sintra. Bol. Soc. Geol. Port., XXIV: 224–226.

Madeira, J., Cabral, J. and Ribeiro, A., 1988. Hierarchy of active faulting: examples from Portugal: Mainland and Azores.l Semin. Earthquake Predict. (Lisbon), UN Sci. Tech. Semin 16, R.19, 5 pp.

Manuppella,, G. (Editor), 1987a. Carta geológica de Portugal, folha 53-A: Faro. Scale, 1 : 50,000 Serv. Geol. Port., Lisbon.

Manuppella, G., 1987b. Tectónica. In: G. Manuppella, M. Ramalho, A. Telles Antunes and J. Pais, Carta Geológica de Portugal. Escala 1/50,000: Notîcia Explicativa da Folha 53-A. Faro. Serv., Geol. Port., Lisbon, pp. 32–37.

Manuppella, G. (Editor) 1987c. Carta geológica de Portugal, folha 53-B: Tavira. Scale, 1 : 50,000. Serv. Geol. Port., Lisbon.

Manuppella, G., 1987d. Tectónica. In: G. Manuppella, M. Ramalho, A. Telles Antunes and J. Pais, Carta Geológica de Portugal. Escala 1/50,000: Notîcia Explicativa da Folha 53-B: Tavira. Serv., Geol. Port., Lisbon, pp. 22–23.

Manuppella, G., 1988. Litoestratigrafia e tectónica da Bacia Algarvia. Geonovas (Lisboa), 10: 67–71.

Manuppella, G., Marques, B. and Rocha, R., 1988. Évolution tectono-sédimentaire du Bassin de l'Algarve pendant le Jurassique. Int. Symp. Jur Stratigr., 2nd, pp. 1031–1046.

Manuppella, G., Rocha, R.B., Ferreira Soáres, A., de Matos, M., Rodrigues, A., Carreira de Deus, P. and Oliveira, J., 1976.Carta geologica de Portugal, folha 19-C: Figueira da Foz. Scale, 1 : 50,000. Serv., Geol. Port., Lisbon.

Montenat, C., Guery, F., Jamet, M. and Berthou, P.Y., 1988, Mesozoic evolution of the Lusitanian Basin: comparison with the adjacent margin. In: G. Boillot, E.I. Winterer et al., Proc. ODP, Sci. Results, 103: 757–775.

Mougenot, D., 1983. Les paleo-champs de contrainte au Portugal et l'interpretation structurale de l'évolution cenozoique de la marge oueste-ibérique. In: Tectonique Cassante en Distension et Coulissement. Colloq. Soc. Géol. Nord/CNRS, Orléans, pp. 38–39.

Mougenot, D., 1989. Geologia da Margem Portuguesa. Inst. Hidrol. Port., Lisbon.

Oliveira, J.T. (Editor), 1984. Carta Geológica de Portugal: Folha 7. Scale, 1:200,000. Serv. Geol. Port., Lisbon.

Phipps, S.P., 1983. Structural analysis of ancestral Rocky deformation (Pennsylvanian–Permian), mid-continent region, U.S.A. Geol. Soc. Am., Abstr. Programs, 15: 661.

Phipps, S.P., 1987. Crustal mesoplate tectonics: deformation in continental interiors during collisional orogeny. Int. Conf. Plate Tectonics and Deformation (Oviedo).

Reis, M.J., 1987. Estudo estrutural da Pedreira de Maria Dias (Algueirão–Sintra). B.Sc. Thesis, Fac. Sci. Lisbon.

Ribeiro, A., 1988. A tectónica alpina em Portugal. Geonovas, 10: 9–11.

Ribeiro, A. and Ramalho, M., 1986. Estratigrafia e tectónica da Cadeia da Arrábida. Congr. Nac. Geol., 2nd (Univ. Lisbon) (field guide for Exc. B2/B3.

Ribeiro, A., Antunes, M.T., Ferreira, M.P., Rocha, R.B., Soares, A.-F., Zbyszewski, G., Almeida, F.M., Carvalho, D. and Monteiro, J.H., 1979. Introduction a la Géologie Générale du Portugal. Serv. Geol. Port., Lisbon 114 pp.

Ribeiro, A., Manuppella, G. and Oliveira, J.T., 1984. Tectónica das orlas sedimentares. J.T. Oliveira, (Editor), Carta Geológica de Portugal. Escala 1/200,000: Notîcia Explicativa da Folha 7. Serv. Geol. Port., Lisbon, pp. 65–66.

Ribeiro, A., Possolo, A., Silva, J., Kullberg, M.C. Cabral, J. and Dias, R., 1985. Modelos tectónicos: ensaio de aplicação em Portugal. Bol. Soc. Geol. Port., XXIV: 145–151.

Ribeiro, A., Kullberg, M.C., Cabral, J., Madeira, J., Brum, A.P. and Moniz, C., 1988a. Alpine geodynamics of the West Iberia margin. In: E. Banda and L.A. Mendes-Victor (Editors), Proceedings of the 5th EGT Workshop on the Iberian Peninsula, Eur. Sci Found., Strasbourg, pp. 91–98.

Ribeiro, A., Silva, J.B., Dias, R., Araújo, A., Marques, F., Merino, H. and Fonseca, P., 1988b. Geodynamics and deep structure of the Variscan fold belt in Iberia. In: E. Banda and L.A. Mendes-Victor (Editors), Proceedings of the 5th EGT Workshop on the Iberian Peninsula. Eur. Sci. Found., Strasbourg, pp. 57–64.

Rocha, R., Manuppella, G., Mouterde, R., Ruget, C. and Zbyszewski, G., 1981. Carta geologica de Portugal, escala 1/50,000: Notîcia explicativa da folha 19-C: Figueira da Foz. Serv. Geol. Por., Lisbon, 126 pp.

Sibuet, J.C., 1987. Contribution à l'étude des mécanismes de formation des marges continentales passives. These Etat, Univ. Brest, 351 pp.

Tapponnier, P., 1977. Evolution tectonique du systeme alpin en Méditerranée poinçonnement et écrasement rigide–plastique. Bull. Soc. Géol. Fr., 1 (3): 437–460.

van der Voo, R., 1969, Paleomagnetic evidence for the rotation of the Iberian peninsula. Tectonophysics,: 5–56.

Victor, L.A.M., Hirn, A. and Veinante, J.L., 1980. A seismic section across the Tagus Valley, Portugal: possible evolution of the crust. Ann. Géophys., 36(4): 469–476.

Wilson, R.C.L., 1975. Atlantic opening and Mesozoic continental margin basins of Iberia. Earth Planet. Sci. Lett., 25: 33–43.

Wilson, R.C.L., 1979. A reconnaissance study of upper Jurassic sediments of the Lusitanian Bassin. Ciênc. Terra, Univ. Nova Lisboa, 5: 53–84.

Wilson, R.C.L., 1986. Mesozoic development of the Lusitanian Bassin. Maleo, 2(13): 45–46.

Wilson, R.C.L., Hiscott, R.N., Willis, M.G. and Gradstein, F.M., in press. The Lusitanian Basin of west central Portugal: Mesozoic and Tertiary tectonic, stratigraphic and subsidence history. In: Extensional Tectonics and Stratigraphy of the North Atlantic Margins. Am. Assoc. Pet. Geol. Mem., 46.

Zbyszewski, G., Camerata França, J., da Veiga Ferreira, O., Rodrigues, L, Rodrigues, A. and Manuppella, G., 1965. Carta geologica de Portugal, folha 30-B: Bombarral. Scale, 1:50,000. Serv. Geol. Port., Lisbon.

Zbyszewski, G., da Veiga Ferreira, O., Manuppella, G. and Torre de Assunção, C.F., 1966. Carta geologica de Portugal, escala 1/50,000. Notîcia explicativa da folha 30-B: Bombarral. Serv., Geol. Port., Lisbon, 90 pp.

Ziegler, P.A., 1987. Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine foreland—a geodynamic model. Tectonophysics, 137: 389–420.