Estudios geol., 46: 209-216 (1990)

STRUCTURE OF THE ALPUJARRIDES ON THE SOUTHERN AND EASTERN BORDER OF THE SIERRA DE LUJAR

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RESUMEN

El Complejo Alpujárride situado al Sur de Sierra Nevada y comprendido entre Motril y Adra, está formado por cinco mantos que son, en orden ascendente: Lújar, Cástaras, Alcázar, Murtas y Adra.

Estos cinco mantos presentan una estructuración que es el resultado de varios acontecimientos superpuestos. En primer lugar, reflejan un proceso de cizallamiento dúctil hacia el NE, que lleva asociado una foliación milonítica, de orientación media N40° E. A continuación se ha registrado un episodio de traslaciones hacia el Norte, en condiciones más superficiales, que desarrolla brechas y harinas de falla. Asociado a este episodio se desarrollan localmente pliegues, que no dan lugar a una blastesis mineral.

Con posterioridad se producen las deformaciones tardías, que afectan a todo el conjunto. De ellas, las más sobresalientes son las que originan pliegues de eje N-S, vergentes al Oeste y las fallas normales. Las fallas extensionales hacia el Sur quedarían englobadas en este apartado.

Palabras clave: *Complejo Alpujárride, cizallamiento al NE, traslación al Norte, milonitas, brechas de falla.*

ABSTRACT

The Alpujarride complex located to the South of the Sierra Nevada and extending between Motril and Adra is formed of five nappes, which in ascending order are: Lújar, Cástaras, Alcázar, Murtas and Adra.

These five nappes display a structure that is the result of several overlapping events. Firstly, they reflect a process of ductile shearing associated with a mylonitic foliation and a mylonitic lineation with a N40° E average orientation. Following this, an episode of translation towards the North has been recorded; this occurred under more superficial conditions and developed gouges and fault breccias. Associated with this episode are locally developed folds, which did not give rise to a mineral blastesis.

Afterwards, the late deformations occurred, affecting the whole of the ensemble. Of these, the most important are those that originated folds with a N-S axis, verging towards the West and the normal faults. The extensional faults towards the South would be encompassed in this section.

Key Words: *Alpujarride complex, NE shearing, Translation towards the North., Mylonites, Fault breccias.*

Introduction

The rocks of the Betic zone located to the South of the Sierra Nevada have been the object of study since almost the beginning of the present century. However, it was only since the work of F. Aldaya, towards the end of the sixties, that the units comprising the Alpujarride nappes have been studied individually; such studies have been based on lithological, metamorphic and tectonic criteria.

The present work, offers an overview of the data obtained since then, basing the considerations on a detailed microstructural study and on new lithological and metamorphic data. These have led us to mo-

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dify the cartography of the area encompassed between Motril and Adra to a considerable extent. The principal controversies that have arisen in recent years concerning the Alpujarrides in this sector can be summarized as follows: (1) the existence and interpretation of some of the units dealt with individually by Aldaya, (2) the tectonic (Aldaya, 1981) or sedimentary (Estévez *et al.,* 1985) nature of some of the contacts among the calcareous and pellitic formations on the southern and eastern border of the Sierra de Lújar, and (3) the existence, relative age and tectonic significance of the large recumbent folds observed in this sector and, in general, in the Alpujarride domain (Balanyá *et al.,* 1987; Campos and Simancas, 1989). From the viewpoint of the authors, in most works dealing with this area no general review has been made of the whole of the structure of the Alpujarride complex; neither has any work been done to compile a new map and neither, as far as the authors are aware, have any microtectonic studies of sufficient amplitude been carried out. As a whole, the work that has been carried out only covers small sectors, and has attempted to extrapolate from these generalized interpretations based almost exclusively on the data of Aldaya for the rest of the area.

The present work therefore attempts to deal with all the foregoing problematic aspects, at the same time offering a critical review of the work published up to the present.

Geological setting

Aldaya (1969, 1979, 1981, 1983) has differentiated the following Alpujarride nappes south of the Sierra Nevada in ascending tectonic order: Lújar, Cástaras, Alcázar, Murtas and Adra. According to the data collected by the authors in the neighbourhood of the Sierra de Lújar (Fig. 1), the Lújar nappe is restricted exclusively to the carbonate formation within the study area and forming most of the range. In the southeastern and eastern sector of this range, schists, quartzites and marbles of the Cástaras nappe rest over the carbonate formation of the Lújar nappe.

The lithological succession of the Cástaras nappe (Fig. 2) is formed of dark micaschists bearing chlorite and biotite in the lowest levels. Towards the top, the metamorphism of the sequence decreases considerably, as shown by the appearance of grey fillites intercalated with decimetric bands of white quartzites or of yellow calc-schists. Above this outcrops the carbonate formation, formed of highly crystalline banded marbles, sometimes micaceous, with centimeter-thick intercalations of pellitic levels; these marbles are specially well represented in the Sierra de la Joya, within a complex syncline structure (Estévez *et al.,* 1985).

The Alcázar nappe rests directly over the Lújar nappe on the southern border of the Sierra de Lújar and over the Cástaras nappe on the eastern border.

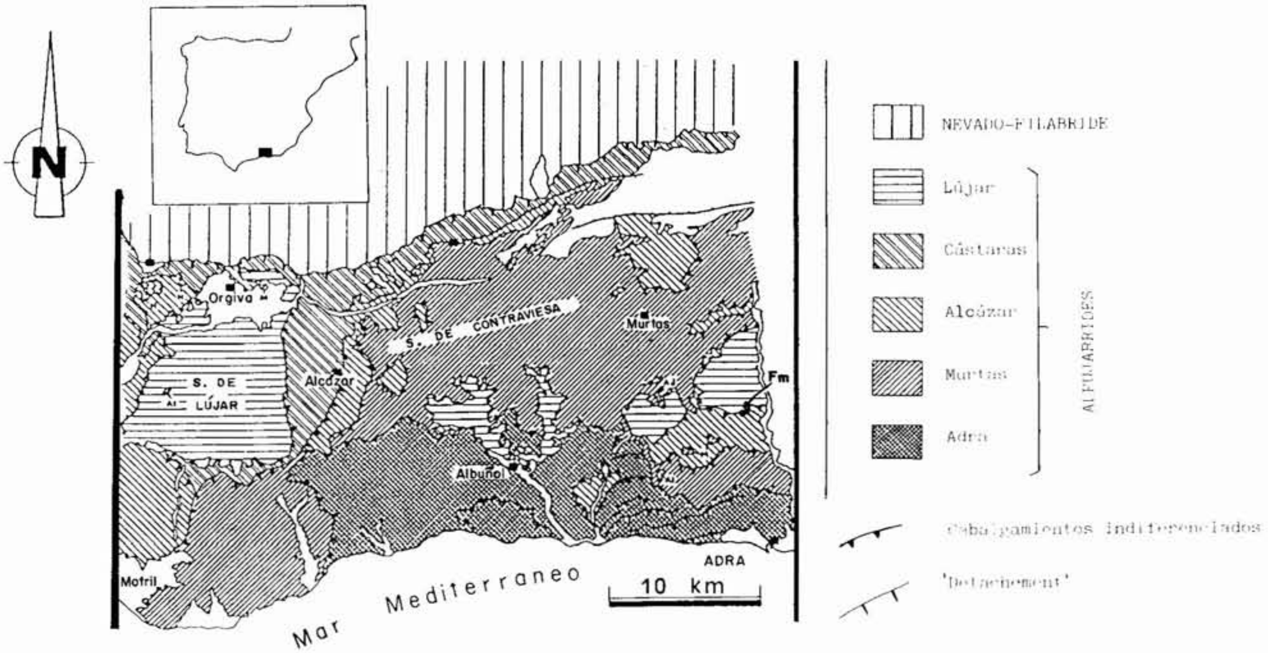

Fig. 1.—Cartographic scheme of the Alpujarride Nappes between Motril and Adra.

At its base, the Alcázar nappe (fig. 2) shows grey fillites, with porphyroblasts of chlorite that may have arisen from an alteration of chloritoid. These rocks are overlaid by green fillites and yellow calc-schists that, laterally, pass to levels of black micritic limestones and lenses of gypsum. At different levels on this lithological succession there are layers of conglomerates and of vulcanoclastic rocks. Finally, the carbonate formation is well developed in Cerro Escalate, but poorly represented in the eastern sector: there are some outcrops to the East of Bargís and on the road from Alcázar to Torvizcón.

The Murtas nappe, with brown hues, displays an important colour contrast with the foregoing nappes. The lowest rocks (fig. 2) of the Murtas nappe are brown quartz schists with garnet that are intercalated with thin layers of marbles with nodules of quartz. Above, the metamorphism decreases progressively from quartz schists with biotite, levels of fillites and finally marbles with associations of talc and tremolite on the upper part, whose best represented outcrops are seen to the Northwest of Castell de Ferro, on the road to Gualchos.

The Adra nappe is located at the highest position. To the east of the Sierra de Lújar this nappe displays (fig. 2) micaschists with sillimanite and kyanite and, in more eastern sectors, such as the Rambla de Melicena, it exhibits migmatites at their base. Like the other Alpujarride nappes, it also has a schist succession with a metamorphism that decreases upwards, reducing to mica schists with biotite/chloritoid on the upper part. In this sector there is no carbonate formation, as has been described to the East of Adra (Aldaya *et al.*, 1979a) in the form of scanty and very thin outcrops.

General structure

The structure of Alpujarride nappes of this zone is the result of different events: 1) a first stage of thrusting under ductile conditions with a top-to-the-NE motion 2) a second stage under fragile conditions, with a movement of the upper block towards the north; this is fairly well represented in this sector, and 3) several late stages of deformation that affected the foregoing structures.

The thrusting towards the NE

The Alpujarride complex as a whole exhibit structures linked to the translation under ductile conditions towards the NE and related with the metamorphic evolution of several nappes (see Tubía, 1984); this initial process of thrusting of the Alpujarride nappes led to a final result of the nappes with the highest degree of metamorphism being placed over others with a lower degree of metamorphism. This process locally affected the lithosphere as shown by the subcontinental peridotite massifs forming the base of the

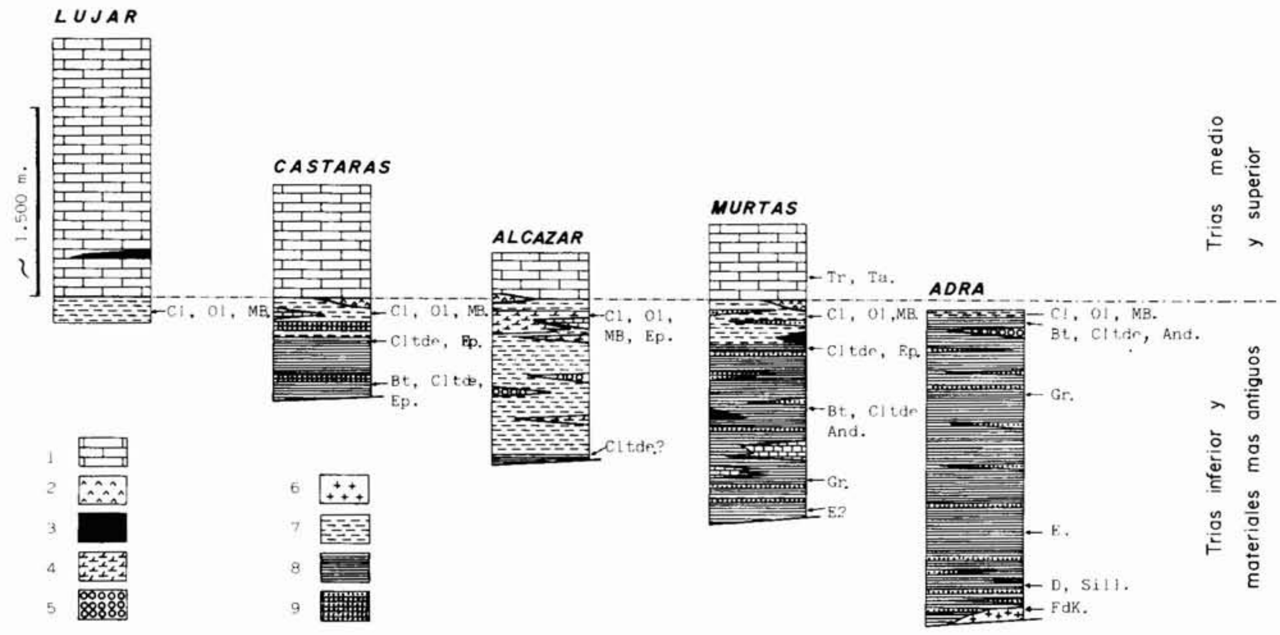

Fig. 2.—Synthetic logs of the Alpujarride nappes differentiated in Fig. 1. Note that the columns do not coincide with others lifted outside this sector for the same units.

Los Reales nappe (Navarro-Vilá and Tubía, 1983; Tubía, 1985). The age of this process is post-Triassic, since both this metamorphic event and the associated deformations are recorded in the carbonate formations dated as belonging to (or attributed to) the Middle and Upper Triassic (Delgado *et al.*, 1981). In this sector structures associated with this stage are not very abundant, although they can be recognized in:

a) the mylonitic rocks of the contact between the Cástaras nappe and the Lújar nappe on the eastern border of the Sierra de Lújar (figs. 3B and C). These were formed in the intercalated quartzitic bands and in the marbles located in the upper part of the Cástaras nappe. These mylonites show a stretching mineral lineation verging N30-N40°E;

b) the conglomeratic levels of the Alcázar nappe, with a very constant N40°E stretching lineation that coincides with the stretching mineral lineation of the more metamorphic nappes;

c) the mylonitization of the schists with kyanite and sillimanite of the Adra nappe, situated to the South of Rubite, and

d) the decimetric folds of the Sierra de la Joya, originated during the synmetamorphic structuring of the Cástaras nappe (Estévez *et al.*, 1986) which in fact are second-phase folds (Cuevas, 1988).

All these structures have been highly modified by later processes and it is therefore difficult to assign their true nature to a given contact in a given sector, although at regional or broad-sector scale the types of contact are reasonably well known (ductile with ENE vergence, ductile-fragile with N vergence, extensional with SE —or other— vergence) as is their relative chronology.

The overridings towards the North

Within the translation phase of the nappes towards the north are structures that have been described by Aldaya in the Betic zone (1969, and later works) and that have later been recognized throughout the chain. Initially, this episode was questioned (see publications of Paquet (1974) among others) although its existence is no longer debated.

The process is strongly evidenced by the structural record of the study area, particularly on the S and SE borders of the Sierra de Lújar (fig. 4). It has given rise to subhorizontal contacts deformed by later NW-SE striking folds. Near to these contacts the general schistosity displays inflections and even folds that have not developed any schistosity, although they may have a spaced set of fractures parallel to the axial plane. The fault rocks associated with such contacts are mainly dark gouges and fault breccias. At the major contacts, corresponding to those exhibiting the greatest degree of displacement, the zone of gouges and fault breccias is usually more than 10 m

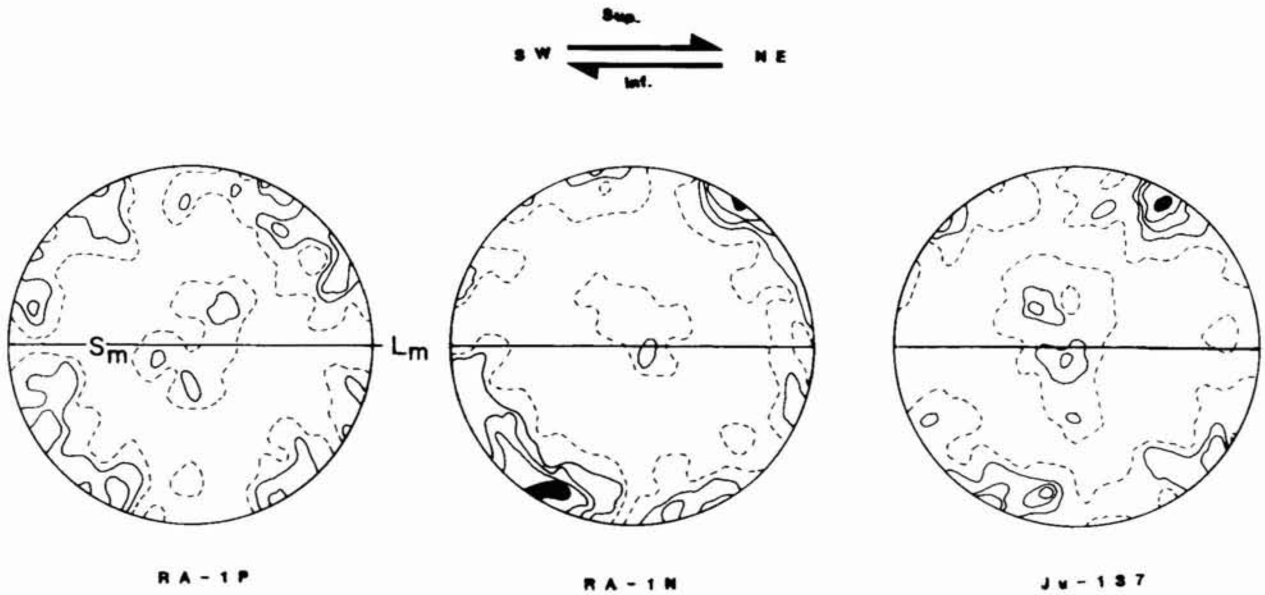

Fig. 3.—Most significant diagrams of quartz c-axes in the mylonitized quartzites of the contact between Lújar and Cástaras nappes at the eastern border of the Sierra de Lújar. Equiaerial projection, lower hemisphere. Intervals 1, 3, 5, 7 >10%. The structural framework is defined by the mylonitic foliation (S_m) and the stretching lineation (L_m). A) Inherited porphyroblasts in a mylonitized quartzite. RA-1P sample, 60 measurements. B) Quartz neoblasts. RA-1N sample, 100 measurements. C) Quartz neoblast, Ju-137 sample, 100 measurements.

thick. In the immediately neighbouring zones of the contacts to the N the original rocks are highly transformed, with an important enrichment in hydrated minerals (sericite, chlorite), oxides of iron and manganese, and have numerous veins of white quartz. These features point to an important circulation of fluids in the contact zones.

The fault rocks indicate a deformation in the fragile-ductile transition (Cuevas *et al.,* 1986): pressure was between 0.3-1 Kb and temperature lower than 150° C (Cuevas, 1988). These translations produced a strong extension towards the North of the Alpujarride nappes (Navarro-Vilá, 1976) reached in the previous stage of ductile thrusting towards the NE. On the S and SE borders of the Sierra de Lújar, there are numerous contacs of this translation towards the North. Thus, the present contacts between the Cástaras and Alcázar nappes to the north of Rubite; between the Alcázar and Murtas nappes, to the west of the Conjuro vertex and between the Murtas and Adra nappes, to the south of Rubite, belong to this episode, like the contacts between nappes towards the north and to the east of Bargís.

Related to the translation of the whole of the Alpujarride ensemble with a N10°W trend, the Alcázar nappe on the southern border of the Sierra de Lújar has a N-verging anticlinal structure (fig. 4); this is perfectly visible on the map owing to the use of the reference levels of yellow calc-schists and black micritic limestones. Thus, it is possible to observe that at the contact with the Lújar nappe, the Alcázar nappe displays an inverted limb with a thickness of some

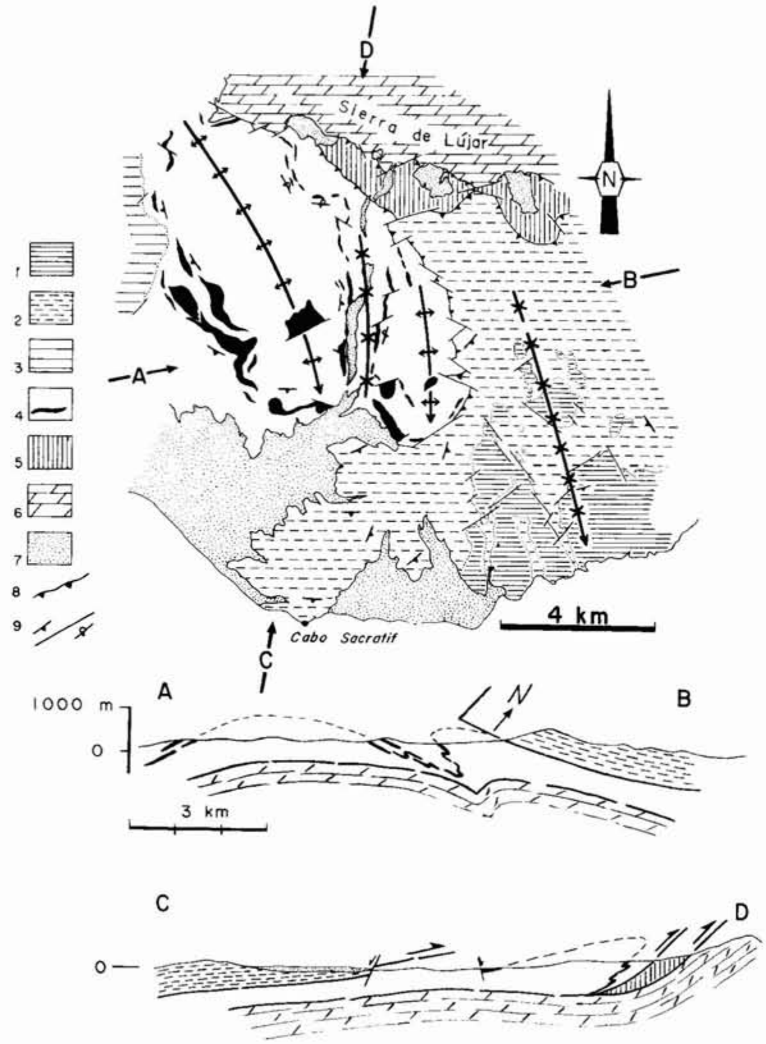

Fig. 4.—Structure of the Alcázar nappe on the southern border of the Sierra de Lújar. The levels of yellow calc-schists are represented in black.

100 m, as measured perpendiculary to S_2. This inverted limb displays a crenulation cleavage, dipping some 40° to the S, whereas the dip towards the south of S_2, on the same inverse limb, is more pronounced. The east-west axial direction of the minor folds associated with this structure, the basal shearing of the fold (fig. 4) on the southern border of the Sierra de Lújar and their clearly post-metamorphic nature are highly suggestive of the relationship between this antiform and the shearings towards the North (Cuevas, 1988). In this case, the compressional character of the antiform within a global context of extension towards the North requires further explanation. A mechanical solution for the problem would be to consider that the structure would have been due to a lateral ramp on the southern border of the Sierra de Lújar or to a normal fault older than the emplacement of the Alpujarride nappes towards the north. The earlier event would explain why the general process of extension due to the emplacement towards the north would have produced a local compression and would also account for the reduced thickness of the inverted limb of the N-verging anticlinal in the fillites of the Alcázar nappe, situated on the southern border of the Sierra de Lújar. To a certain extent, this situation is similar to what occurred to the South of the Turón tectonic window, in the zone of Las Fuentes de Marbella, 9 km to the north of Adra (see F.m in figure 1). The contact here is particulary controversial; in it the carbonate formation of the Lújar nappe outcropping in the Calares de Turón tectonic window enters into contact with the fillites and quartzites of the Alcázar nappe. This contact has been interpreted as belonging to the system of overridings towards the north (Aldaya, 1969; Cuevas, 1988) and as an inverted stratigraphic contact (Gervilla *et al.*, 1985) on the inverted limb of a N-verging syncline several kilometers in length (Balanyá *et al.*, 1987; Campos and Simancas, 1989).

Our data suggest that one is clearly dealing with tectonic contact. This is characterized by the existence, both in the limestones and dolomites of the Lújar nappe and in the fillites and quartzites of the Alcázar nappe located above, of a highly developed stretching lineation parallel to the axis of folds with frequent curved hinges. The lineations and axes of these folds range in direction between N-S and N160°E with a maximum of around N50°E. The characteristics are not consistent with those of a typical contact towards the North since they are associated with certain structures suggestive of conditions of greater ductility. The authors' opinion is that such structural characteristics point to the existence of a lateral ramp belonging to the system of ductile overridings towards the NE, that was later modified by the shearings towards the north. The ramp dips towards the SE; and would corresponds to the lineament formed by the Cerrón and Calares de Turón tectonic windows. Below the Las Fuentes de Marbella contact, the limestones and dolomites of the Lújar nappe display an inverted So, as pointed out by Gervilla *et al.*, (1985), with respect to the microfracturing generated in the contact.

Later deformations

The most striking structure, recently described, to the South of the Sierra de Lújar is undoubtedly a set of large late folds, with as NNW-SSE axis, that affected the earlier structures (fig. 4). In particular, detailed mapping has allowed these structures to be appreciated: at the core of the formation of fillites and quartzites, the levels of yellow calc-schists and their intercalations of black micritic limestones, form large anticlinal folds separated by narrow synclines, verging W, with the W limb vertical or slightly inverted (see fig. 4). These large folds are responsible for the variations in the general schistosity, S2, of the Alcázar nappe, which varies from a mean orientation of N120°E to the NE of Motril to a N-S orientation to the NW of Motril and to the SW of the Conjuro de Gualchos vertex; they have also led to marked variations in the orientations of the F_2 and F_3 folds of the Alcázar nappe, which from mean orientations of N60°E pass to orientations close to N-S, which are anomalous in the region between Motril and Adra.

The contacts between nappes have been affected by this late episode of folding, as can be seen all along the contact between the Murtas and Alcázar nappes to the West of the Conjuro vertex (fig. 1). This kind of structure has led some authors (Balanyá *et al.*, 1987) to assume the existence of two mineral lineations in this region: one with a mean orientation consistent with the general shearing phase towards the NE of the Alpujárrides nappes (N40°-N60°E), and another close to the N-S orientation. However our data clearly show that they correspond to the same mineral lineation modified by the effect of the large late folds. As minor structures related to these folds, it is only possible to recognize the existence of small vergent folds associated with the inverse limb and the local development, in the more pellitic, rocks, of a very spaced cleavage (fig. 5) with no associated neoformation of minerals (fig. 6).

As has been reported, this region contains important low-angle, normal faults that originated during an important extensional tectonic stage of Miocene age. The best known of these is the «Mecina fault» (Aldaya *et al.*, 1984) that gave rise to the current contact between the Alpujarride and the Nevado-Filábrides to the south of the Sierra Nevada. Above this

Fig. 5.—Outcrop photograph showing the spaced cleavage of the fillites of Alcázar (inverted) in contact with the Lújar limestones.

level and at the core of the Alpujarride pile other faults of the same type have been described, although they are much less important.

In this sector we have observed minor structures associated with contacts between units or between formations of the same unit (e.g. at the contact between limestones and dolomites and the fillites and quartzites of the Alcázar nappe, immediately to the North of Motril). These structures indicate a movement towards the SW of blocks situated on surfaces dipping towards the SW or W, although there seem to be no important extensional faults towards the South. Neither are there criteria, in the zones where certain units or formations are very thin, for attributing an important part of the thinning to these extensional faults. In general the structures in the rocks

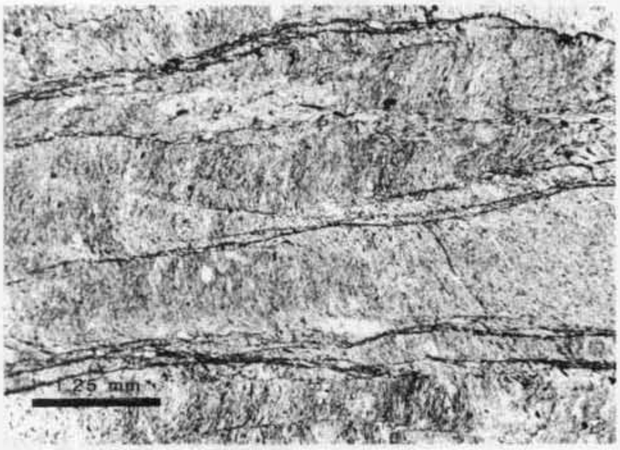

Fig. 6.—Microscopic detail of the Fig. 5 showing that the cleavage does not produce reorientation of the white micas present in the Alcázar fillites.

and the fault gouges of the thinned parts show a very uniform vergence towards the north.

Finally, it should be noted that at a local scale the role played by late fractures can be very important. Essentially, this can be seen in the network of normal faults with N120°E and N60°E orientations that have sunk the southern block and that have affected the earlier structures. There are also gentle folds with an E-W axial orientation that are responsible for the Lújar and Contraviesa ranges having an antiform structure. The general schistosity, S_2, and structures linked to emplacement towards the N dipping towards the N on the northern border and towards the south on the southern border.

Discussion and conclusions

The data offered in the present work include the novel report of microtectonic data form structures hitherto unrecognized in the sector; also offered are important changes in the cartography, as well as a description of lithological members that complete the sequences of some of the nappes. All this has led to a redefinition of some of the nappes (such as the Cástaras nappe), and to a tectonic reinterpretation of this sector. Of special relevance are the following points:

1) The large recumbent folds that would be recognized both to the East ant to the West of this sector, have been related by Balanyá *et al.,* (1987) to the emplacement of nappes towards the North. Nevertheless it should be taken into account that:

— They include within the same group syn-metamorphic folds such as those of the Tejeda and Lújar ranges (which are equivalent to the structure displayed by the Cástaras nappe in the Sierra de la Joya) and also post-metamorphic folds, such as that of the Capellanía syncline in the Herradura nappe (Avidad and García-Dueñas, 1981). Folds such as these later gave rise to limited inverse limbs, in general synform in the carbonatic rocks and antiformal in the metapellites (e.g. the fillites of the Alcázar nappe to the south of the Sierra de Lújar). Also, they fold the metamorphic isograds, and are hence later than the isoclinal folds related to the emplacement of nappes towards the NE or produced in earlier stages of deformation. In this sense, along the Arroyo de la Miel section, it is seen that the Capellanía syncline of the Herradura nappe has locally developed a spaced crenulation cleavage, without mineral blastesis, contrary to what is stated by Balanyá *et al.,* (1987), this syncline folds the S_3 whose by the metamorphic rocks.

2) Regarding the proposal of Estévez *et al.,* (1985) of omitting the Cástaras nappe and including the Alcázar nappe and the Lújar nappe within a broader set designated as the Lújar Nappe, it should be

noted that these authors were working under the assumption that the contact between the Alcázar or Cástaras nappes with the Lújar Nappe defined by Aldaya (1969) is stratigraphic. We believe that this is untenable, not only because the contacts between the nappes are marked with scattered outcrops of mylonitic rocks (fig. 3), but also because over the limestones of the Lújar Nappe are found the upper marbles, the quartzites or biotitic schists of the Cástaras Nappe; only where the Cástaras Nappe becomes layered, to the South of the Sierra de Lújar, does the Alcázar Nappe rest over that of Lújar, but in an inverted position and with the general structure clearly governed by the calc-schists layers (fig. 4) described previously.

Additionally, in the cartographic scheme offered in the work of Campos and Simancas (1989) it is seen that at the southern and southeastern borders of the Sierra de Lújar the contact between fillites and carbonate rocks is interpreted as being transitional, while in fact, and independently of the nature of the contact, there are micaschists with chloritoid and biotite and mylonitic rocks that have been described as «fillites» by these authors.

3) Finally, an important question relates to the interpretation of the inversions, because most of the units show two or three overlapping reference surfaces. This means that to speak generically of «inversion» can only lead to confusion, unless one specifies which surface is inverted and with respect to what: So with respect to S_2 or any of these surfaces with respect to the spaced cleavages developed in the large late folds.

ACKNOWLEDGEMENTS

This work was partially supported by the CYCYT project PB87-0737-CO3.

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Recibido el 27 de junio de 1990
Aceptado el 25 de septiembre de 1990