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STRUCTURE OF SIERRA BLANCA (ALPUJARRIDE COMPLEX, WEST OF THE BETIC CORDILLERA)

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ABSTRACT

Sierra Blanca, situated in the SW of Málaga, forms part of the Blanca unit, belonging to the Alpujarride Complex of the Betic Cordillera. Its lithologic sequences are made up of a group of migmatites, gneisses and schists and an upper formation of marbles (white dolomitic and the bottom and blue calcareous towards the top), linked with a transitional contact.

The structure of Sierra Blanca is comprised of folds, generally isoclinal, with reversed limbs and with important tectonic transpositions, the direction of which is approximately E-W in the eastern area and N-S and E-W in the West. In both areas the folds present opposing vergences, consistently towards the interior of the sierra. The origin of these structures is explained with a model of westerly movements of the Blanca unit, in relation to the Los Reales unit, with the formation of frontal and lateral folds. In its advancement, the western part of Sierra Blanca underwent an important anti-clockwise rotation responsible for the co-existence of folds in N-S and E-W directions. These structures occurred under ductile conditions, owing to the presence of important overthrusting peridotitic masses of the Los Reales unit. This model of westerly displacement is inserted in the process undergone by the Betic-Rif Internal Zones (with Blanca and Los Reales units included) which occurred at the end of the Oligocene-Early Miocene when the Gibraltar arch began to be formed.

Key words: *Alpujarride, Betic Cordillera, folds, ductile structures.*

RESUMEN

Sierra Blanca, situada al SW de Málaga, forma parte de la unidad de Blanca que pertenece al complejo Alpujárride de la Cordillera Bética. Su secuencia litológica está compuesta por un conjunto inferior de migmatitas, gneises y esquistos, y por una formación superior de mármoles, blancos dolomíticos en la base y mármoles calizos azules hacia la parte superior, entre los que existe un tránsito gradual.

La estructura de Sierra Blanca está formada por pliegues, generalmente isoclinales, con flancos invertidos que muestran importantes evidencias de estiramiento tectónico. Estos pliegues tienen una dirección aproximada E-W en el sector oriental y N-S y E-W en el occidental. En los bordes de ambos sectores los pliegues muestran vergencias opuestas, siempre hacia el interior de la sierra. El origen de esta estructura se explica con un modelo que considera un desplazamiento hacia el oeste de la unidad de Blanca, con respecto a la de Los Reales, formándose pliegues en posición frontal y lateral. En su avance la parte occidental de Sierra Blanca sufrió una importante rotación antihoraria, responsable de la coexistencia de los pliegues de direcciones N-S y E-W. La estructura se formó en condiciones dúctiles, a causa de la presencia de importantes masas peridotíticas de la unidad de Los Reales cabalgante. Este modelo de desplazamientos hacia el W se inserta en los desplazamientos sufridos por las Zonas Internas Bético-Rifeñas (con las unidades de Blanca y de Los Reales incluidas) durante finales del Oligoceno y el Mioceno inferior, cuando comenzó a formarse el arco de Gibraltar.

Palabras clave: *Alpujárride, Cordillera Bética, pliegues, estructuras dúctiles.*

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Introduction

Sierra Blanca, situated in the province of Málaga (Andalusia, Spain; figs. 1 and 2), forms part of the Internal Zones of the Betic Cordillera.

The Betic Cordillera is usually divided in several domains, especially in the External and Internal Zones (fig. 1). The External Zones constituted the south and southeast domain of the Mesozoic and Tertiary margin of the Iberian Massif. The Internal Zones were originally situated eastwards according to the hypotheses of Andrieux *et al.* (1971), Wildi (1983) and Sanz de Galdeano (1990), among others, corresponding approximately to the present southern Sardinian area. We must point out that there are other hypotheses explaining the present structure of the Internal Zones by a Neogene extensional collapse (Doblas and Oyarzun, 1989a and b; Platt and Vissers, 1989). These Internal Zones are divided into three tectonic complexes, which in ascending order are the Nevado-Filabride, the Alpujarride and the Malaguide complexes. The lower two are affected by alpine metamorphism, both the Palaeozoic basement and the Triassic cover. The Malaguide complex presents non-metamorphic palaeozoic deposits and a more complete cover, also non-metamorphic, of Mesozoic and Tertiary sediments.

The Nevado-Filabride Complex is restricted to the Betic Cordillera, and its most western outcrops form Sierra Nevada, near Granada. The Alpujarride and Malaguide Complexes are present in the Betic Cordillera and in the Rif (Northern Morocco) where they are called, respectively, Sebtide and Ghomaride.

All these complexes are divided into several superposed units, and within the Alpujarride complex three sets of units are generally distinguished (Junta de Andalucía, 1985; Martín Algarra, 1987): the lower units, with low-grade alpine metamorphism; the intermediate units, with a more developed

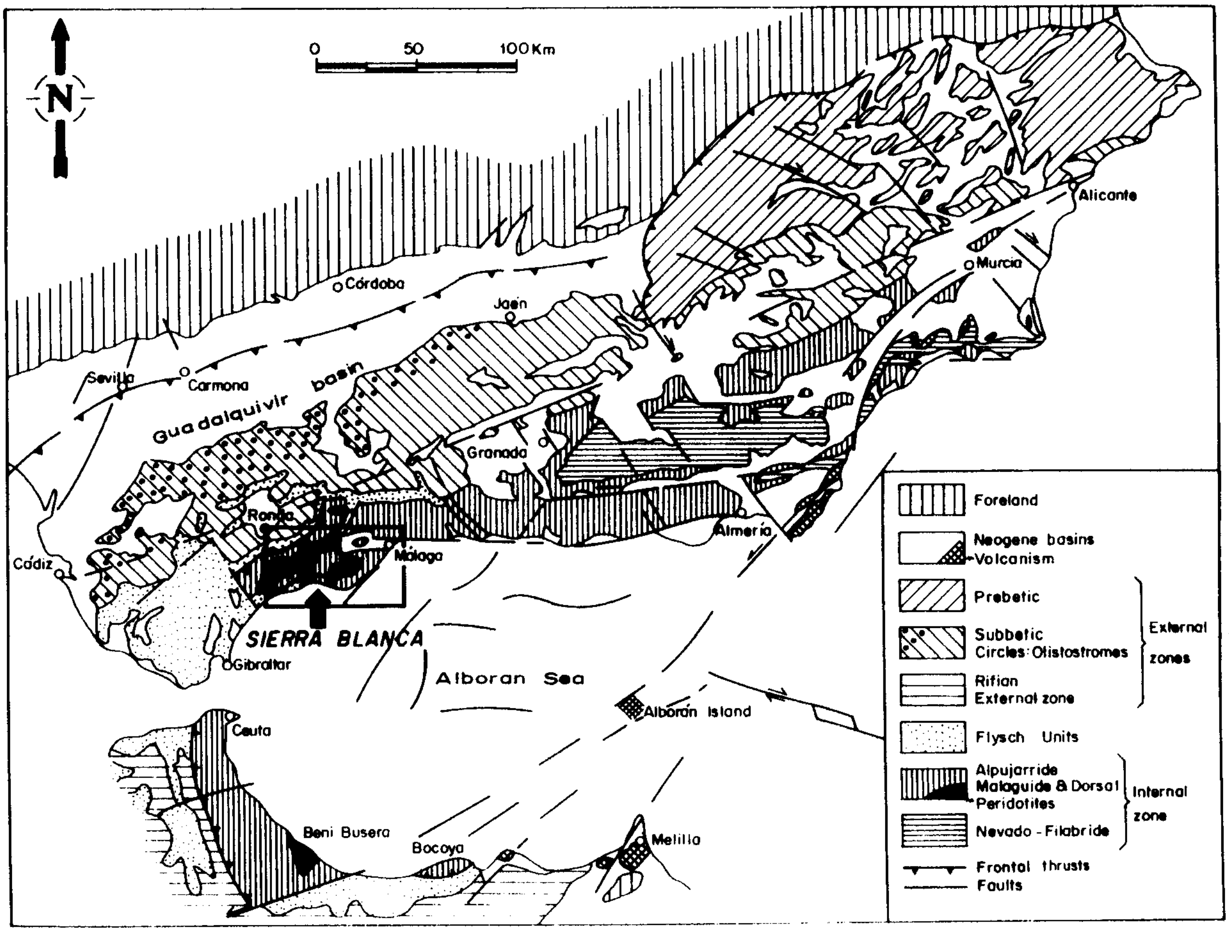


Fig. 1.—Geological situation of Sierra Blanca in the Betic Cordillera.

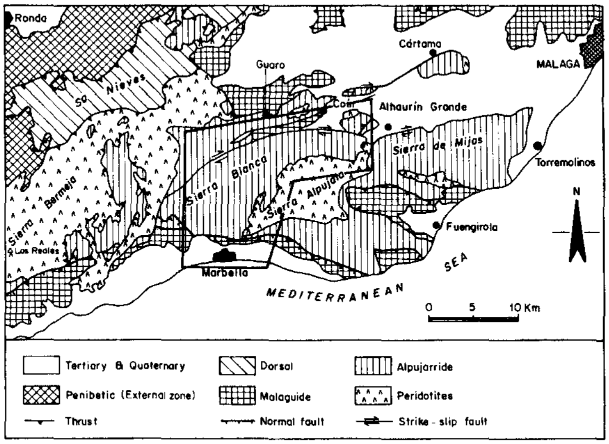


Fig. 2.—Schematic geological map of the region surrounding the Sierra Blanca.

metamorphism; and the upper units, with a metamorphism more or less similar to the intermediate units, but several of them present (in the western part of the Internal Zones) important peridotitic masses situated at the base, then increasing the metamorphic grade.

Geologically, Sierra Blanca forms part of the Alpujarride complex and belongs, by its tectonic position, to the intermediate Alpujarride units and is thrusted by the Los Reales Unit (Tubía and Cuevas, 1987), mainly composed in this area by very important peridotitic masses (fig. 2).

The first references to Sierra Blanca appeared in Orueta (1917). Lather, Blumenthal (1930, 1949) indicated some of the features of the structure and he concluded that there is stratigraphic continuity between the gneisses and schists and the marbles, so did Biot (1971) in Sierra de Mijas (situated east of Sierra Blanca). The attribution of the Alpujarride units of the western part of the Cordillera was discussed by Hoeppener *et al.* (1964). Mollat (1968) defined the Sierra Blanca Unit, also including the Sierra de Mijas. Westerhof (1975) made a petrological study in the south of Sierra Blanca. Piles *et al.* (1978a and b) published a geological map of Coín and Marbella showing Sierra Blanca, but without structural details. Tubía (1985) included Sierra Blanca in the Ojén unit and his map shows the Sierra as a marble outcrop, with no differentiation other than the metapelites in the Juanar area (in the middle of Sierra Blanca). Balanyá (1991) included Sierra Blanca in the Guaro unit, which, together with the other units situated to the north and northeast, would form the group of Blanca units (under the peridotites).

There are many other works discussing the tectonic position of the peridotitic masses in the study area. Several authors agree with the original hypothesis of Mollat (1968), that the peridotite masses lie over the Blanca Unit (Lundeen, 1978; Tubía *et al.*, 1993, among others). Nevertheless, some researchers have the opposite opinion (Loomis, 1975; Torres-Roldán, 1979). A third possibility, supported by Kornprobst (1976), involves the existence of the peridotitic masses in the bottom and at the top of the Blanca Unit. Finally, the hypothesis of Doblas and Oyarzun (1989a and b) support the idea of the exhumation of upper mantle peridotites by a very important extensional process; this process is also supported by Platt and Vissers (1989).

The main objective of the present paper on Sierra Blanca is the description of its structure, which, with a double vergence, is far more complicated than the one which was previously described. Moreover, the kinematic interpretation of this structure aids to the comprehension of the movements of the units in this area near the Gibraltar Arc, at the western end of the Betic-Rif orogeny.

The lithologic sequences

There is virtually no agreement on the lithological sequences forming the Sierra Blanca unit. Thus, Martín Algarra (1987) placed white-dolomitic marble over the gneisses and schists, and on top, blue-calcitic marbles, against the opinion of Tubía (1985), who considered the blue marble to be older than the white one (fig. 3). The structural analysis of Sierra Blanca leads us, in the present work, to maintain the sequence proposed by Martín Algarra (1987).

Migmatites, gneisses, schists (metapelites) and amphibolites

At the bottom of these rocks, migmatites appear with overlying dark gneisses. The migmatites and gneisses usually appear forming an aureole around the peridotites (fig. 3), although the present contact is tectonic. Over the gneisses there are schists and an upper member of quartzite, which serves as a guide level. In some areas these schists have also become gneisses.

The contact between the schists (or gneisses) and the marbles occurs in a sequence of up to 100 m in thickness, alternating with amphibolites and bluish, grey or white marbles, locally banded. The masses of amphibolites are extremely abundant throughout the stratigraphic series, especially within the gneisses.

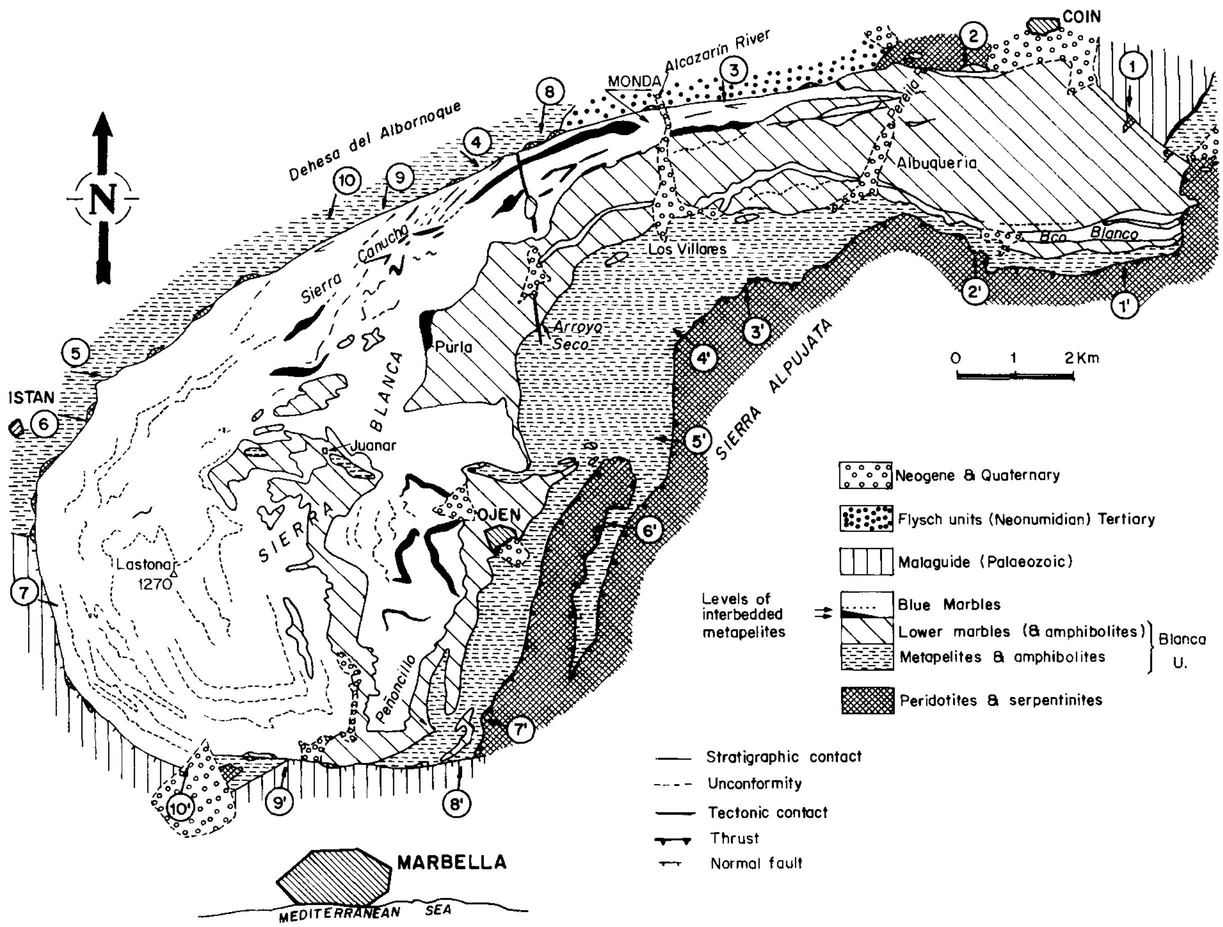


Fig. 3.—Simplified lithologic map of Sierra Blanca. Numbers indicate the position of the geological cross sections of figure 6.

The minimum estimated thickness for these rocks is 300-350 m, although a truly reliable value is hampered by the abundance of isoclinal folds and tectonically transposed structures.

In many other Alpujarride units, equivalent formations are regionally attributed to the Palaeozoic and Permo-Werfenian age (Delgado *et al.,* 1981).

Lower Marbles

These marbles are massive, fetid and generally white or at times greyish, pink and even yellowish. They are coarsed-grain, usually very recrystallized, and at numerous points have a saccharoidal appearance. These marbles are exceedingly pure, with a mineralogical composition almost exclusively of dolomite. There are local intercalations of very fine and discontinuous metapelitic levels. The upper part of this lithological sequence is comprised of a member of marbles with a characteristic blue tone.

These lower marbles appear to have a total thickness of around 300 m, according to the geological cross-sections. Equivalent rocks have been dated in other Alpujarride units as Anisian-Ladinian (Copponex, 1959; Delgado *et al.,* 1981; Estévez *et al.,* 1985).

Marbles with schists and intercalated calc-schists

This sequence is separated from the lower marbles by an intercalation of schists (which, essentially for tectonic reasons, may be absent) with a thickness reaching from 60 to 70 m. The most important outcrops of this intercalation have been found in the east and south of Sierra Canucha (northwestern area of the Sierra Blanca) (fig. 3).

The marbles are generally well stratified in beds varying in thickness from a few centimetres to one

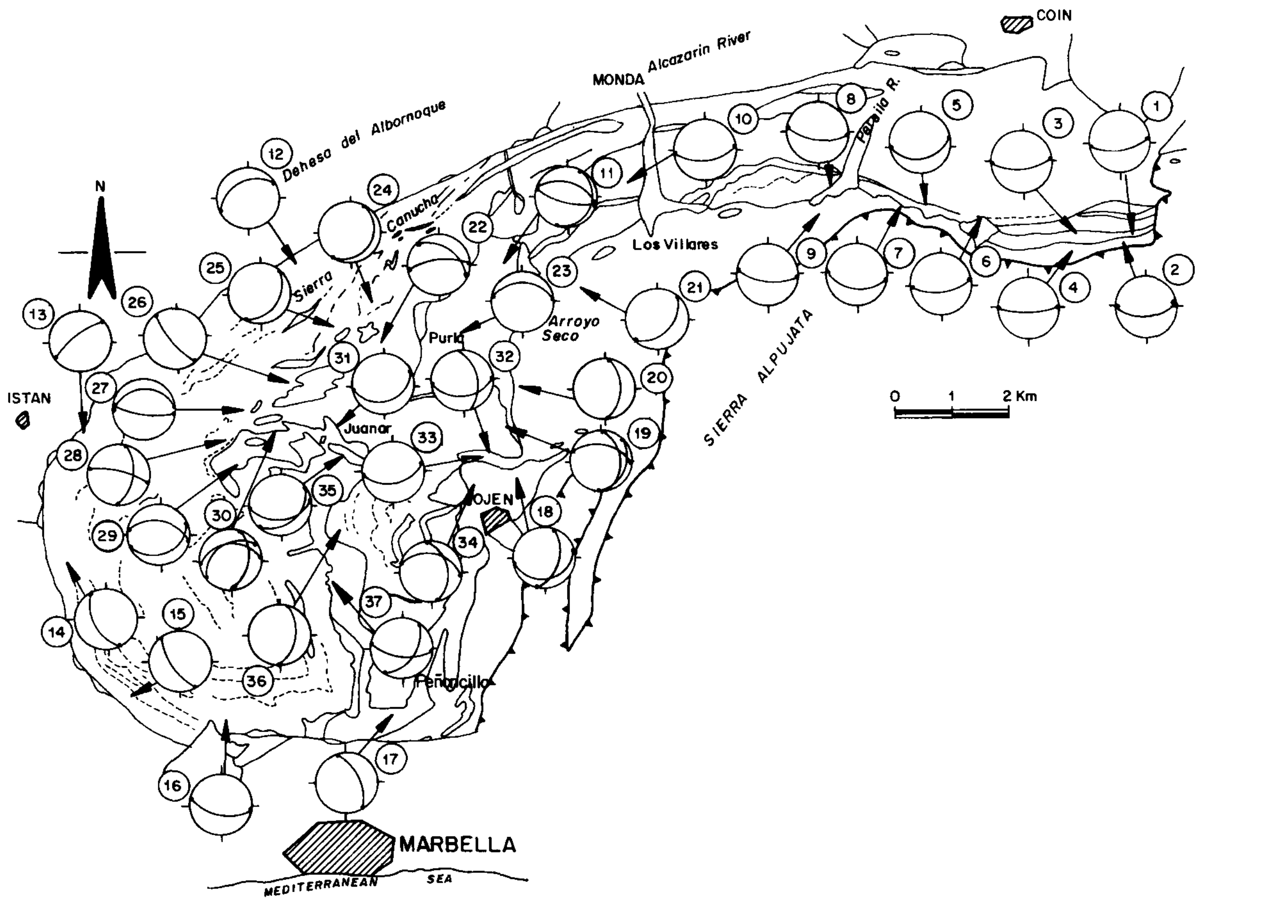


Fig. 4.—Diagrams with the axes and the axial plans of the minor folds. In the next list of diagrams the number of measurements, the direction of the mean axes and the mean axial plans, with the principal component of dip are indicated (when there are several sets of folds, the folds are indicated in descending order of measurements). **1** 35, N89, 50S. **2** 9, N89, 60S. **3** 17, N88, 65S. **4** 12, N88, 80S. **5** 23, N85, 37S. **6** 24, N88, 50S. **7** 8, N98, 45S. **8** 15, N99, 67S. **9** 6, N99, 70S. **10** 10, N85, 55S. **11** 23, N114, 74S; 8, N25, 15E; 4, N119, 35N. **12** 8, N55, 40N. **13** 7, N54, 70N. **14** 11, N154, 54W. **15** 35, N144, 65W. **16** 15, N118, 58S. **17** 7, N164, 46E. **18** 8, N84, 25S; 5, N16, 40E. **19** 21, N178, 30E (with associated stretching lineation), 10, N30, 20E (with stretching lineation associated); 7, N106, 41N. **20** 24, N3, 40E. **21** 25, N52, 35SE. **22** 13, N87, 65N; 7, N122, 35E. **23** 20, N95, 30N. **24** 7, N32, 25E. **25** 10, N39, 25E. **26** 12, N134, 80W. **27** 20, N79, 25N; 14, N93, 75S. **28** 7, N12, 40E; 7, N114, 75N. **29** 8, N94, 40N; 7, N59, 30S. **30** 10, N90, 30N; 7, N21, 30E; 5, N54, 40N. **31** 28, N82, 30S. **32** 18, N87, 33S; 12, N166, 41E. **33** 11, N87, 50S. **34** 12, N174, 38E; 10, N101, 30N. **35** 12, N84, 40S; 5, N54, 30S. **36** 10, N12, 35E. **37** 8, N41, 45E; 6, N96, 60S.

metre. The colours of these marbles are primarily blue, with grey alterations. Calcareous marble predominates, although, towards the base, it may be dolomitic, and may even present a saccharoid aspect, as in Barranco Blanco. Mineralogically, these marbles are fundamentally composed of calcite, with minor proportions of quartz, mica and talc (Salobreña, 1977; Tubía, 1985; Martín-Algarra, 1987).

In this sequence of marble, metapelitic intercalations are abundant, discontinuous (for stratigraphic and fundamentally tectonic reasons), with a thickness of between a few centimetres and a dozen metres. In reality, all types of intermediate rock between marble and pure schist are to be found.

The estimated thickness of what remains of this sequence of marbles with calc-schists is around 300 m. The age of equivalent rocks present in other Alpujarride units has been dated Late Ladinian to Carnian (Delgado *et al.,* 1981; Copponex, 1959).

Structure of the Sierra Blanca

The internal structure of Sierra Blanca mostly consists of folds, for which the orientations and vergences are obtained by the mapping and analysis of the minor structures.

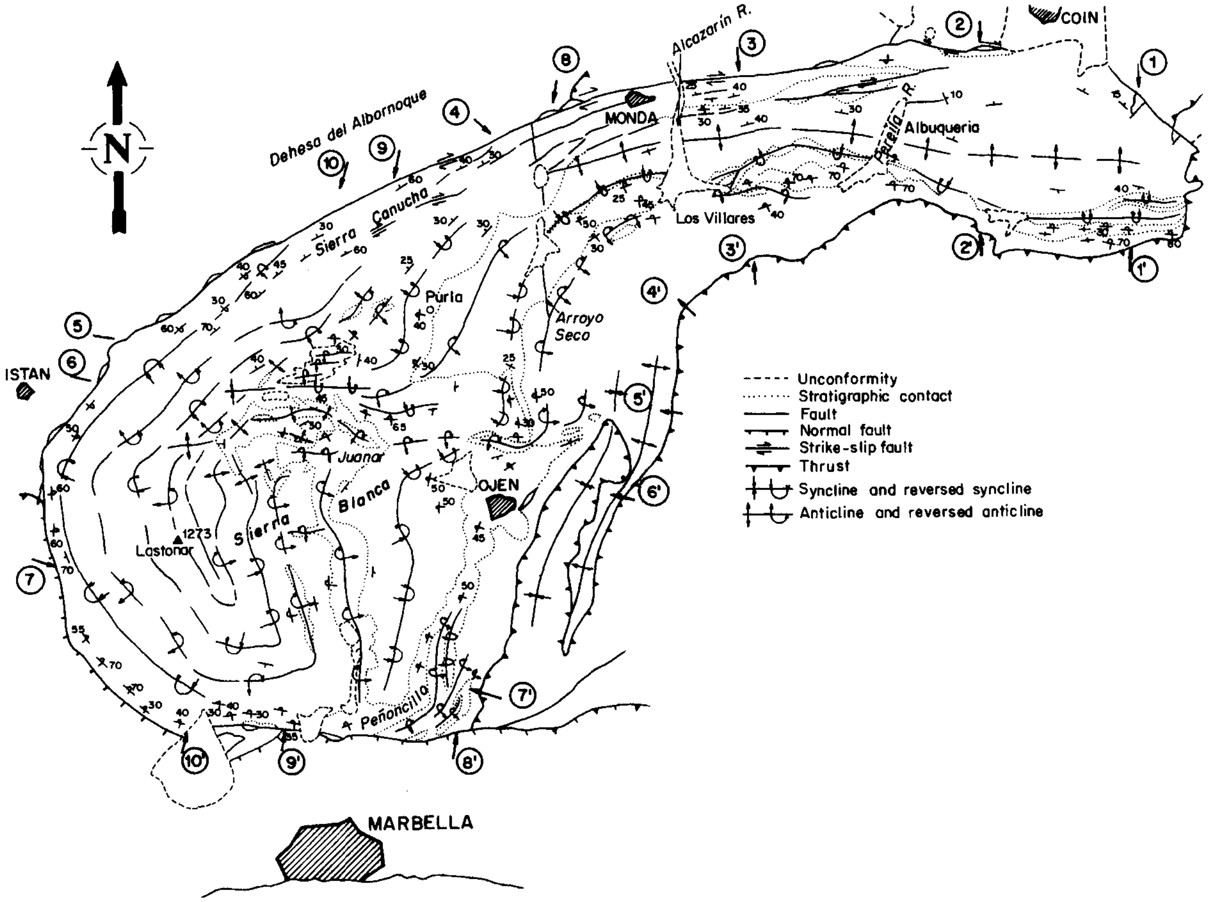


Fig. 5.—Tectonic scheme of Sierra Blanca. Numbers indicate the position of the geological cross sections of figure 6.

Minor folds

The minor folds are especially visible in the upper blue limetone marble. Here axial plane foliations are not usually found, but when these do appear, fundamentally in metapelitic intercalations, they coincide with the axial planes of the folds. In general, the fold axes are horizontal or practically so. At certain points boudinage and pinch-and-swell structures are found in the flanks of the folds, indicating a clear flattening of these folds. In only one area to the north of Ojén stretching lineation appears and has been measured, coinciding with the direction of two sets of intersecting folds.

The size of these folds varies from intrafolial types to those which can almost be considered larger structures, then measuring from 10 m to kilometres in length, although the dip of the axial planes shows a greater variability in the smallest. As a whole, the different sets of folds have similar characteristics and they are distinguishable only by the orientation of their axes and axial planes.

In the eastern part of Sierra Blanca, the direction of the fold axes, highly homogeneous, is practically E-W, and the vergence is to the N (fig. 4), somewhat greater in the metapelites than in the marbles. No indication of superposition or folding interference was noted.

Nowhere along the western edge of Sierra Blanca, between Monda and Istán, or in Marbella, was fold superposition observed and the measurements made show a clear adaptation of the fold direction to the edge of the Sierra (fig. 4), with a consistent vergence towards the interior of the Sierra. In the metapelites situated in the internal arc of Sierra Blanca, near Sierra Alpujata, a gradual change in axial orientation was also noted. Thus, the metapelites have folds which change from E-W and vergence towards the N, to another almost N-S and vergence to the W (see diagrams for this area, fig. 4).

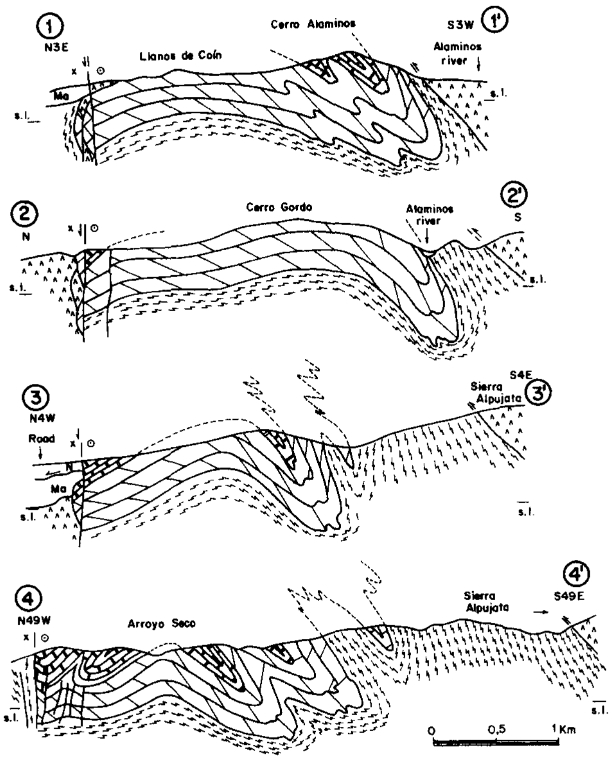


Fig. 6.—a) Geological cross-sections of the eastern sector of Sierra Blanca (their position are marked in figs. 3 and 5, and the legend in fig. 6b). b) E-W geological cross-sections of the western sector (their positions are marked in figs. 3 and 5). c) N-S geological cross-section of the western sector (their positions are marked in figs. 3 and 5, and the legend in fig. 6b).

Within this internal arc, the marbles of the Ojén area provide clear examples of folding interference. The directions of the folds are from almost N-S in the Peñoncillo area (north of Marbella) to E-W south of Monda, but in the intermediate zone both sets of folds interfere on all scales. This interference is especially clear in the interior of Sierra Blanca, in the Juanar area, where folds prersent similar directions but in many cases with opposing vergences. Some of the diagrams of this area are simple, showing folds of only one of the sets cited, but generally two or more appear (fig. 4). These features can also be directly deduced from the larger folds (fig. 5).

Larger structures

The structure of the eastern area of Sierra Blanca is relatively simple (fig. 5). The geological sections of figure 6a show a very tight and complex syncline to the south, verging to the north, oriented E-W on the extreme east and veering gradually to the NE-SW towards Arroyo Seco in the west. The northern part of this area shows a rather tabular structure and the beginnings of a change of vergence.

In the western area the structure is more complex. Throughout the borders of the area the dips are towards the exterior of the sierra, that is, the vergence of the structures is towards the interior (fig. 6b and c). The mapping (fig. 5) reveals an interference of two folds system: one, with generally the largest folds, in approximately a N-S direction, and the other oriented E-W. Both systems show different vergences, depending on location. Thus the N-S folds verge westerly in the eastern part of the area and easterly in the western part. The E-W folds verge northerly and southerly, and repeat these opposing vergences locally in two successive sets (fig. 6c, cross-sections 9-9' and 10-10').

The interference of these two directions of folding give rise, especially in the central part of this area, to a structure roughly resembling an egg cardboard carton, as explained by Ramsay and Huber (1983) for some types of superposed folding. That is, a series of basins occupied by the upper blue marble as well as domes, in the nuclei of which the lower white marbles outcrop, and in some of them even the schists, gneisses and migmatites appear (as in El Juanar). Thus, the metapelites outcropping at El Juanar and farther to the west are from the bottom of the series, as confirmed by the fact that in both cases these metapelites are lined with lower marbles (fig. 3), and at certain points the stratigraphic passage between the two types of rock can be observed.

The northern border of Sierra Blanca is affected by the Albornoque dextral strike-slip fault (Tubía, 1985). Thus, the structures from the northwest of Sierra Blanca show a spectacular stretching, with imbricated structures in various satellite faults, and there are numerous points at which the dextral movement can be deduced (figs. 3 and 5). There are many fish of variable size, from 10 m up to 1 km in length, composed of peridotites, metapelites, marble of different types, and even of Malaguide slate. The continuity between Sierra Blanca and Sierra de Mijas is cut off by the thrust of part of the peridotites of Sierra Alpujata (fig. 2). This fact caused the thinning and stretching of the metapelitic formation against the marble at the eastern end of Sierra Blanca.

The western edge of Sierra Blanca is also tectonic, as can be deduced by the fact, among others, that numerous remains of pinched serpentine appear among the metapelites and marbles of Sierra Blan-

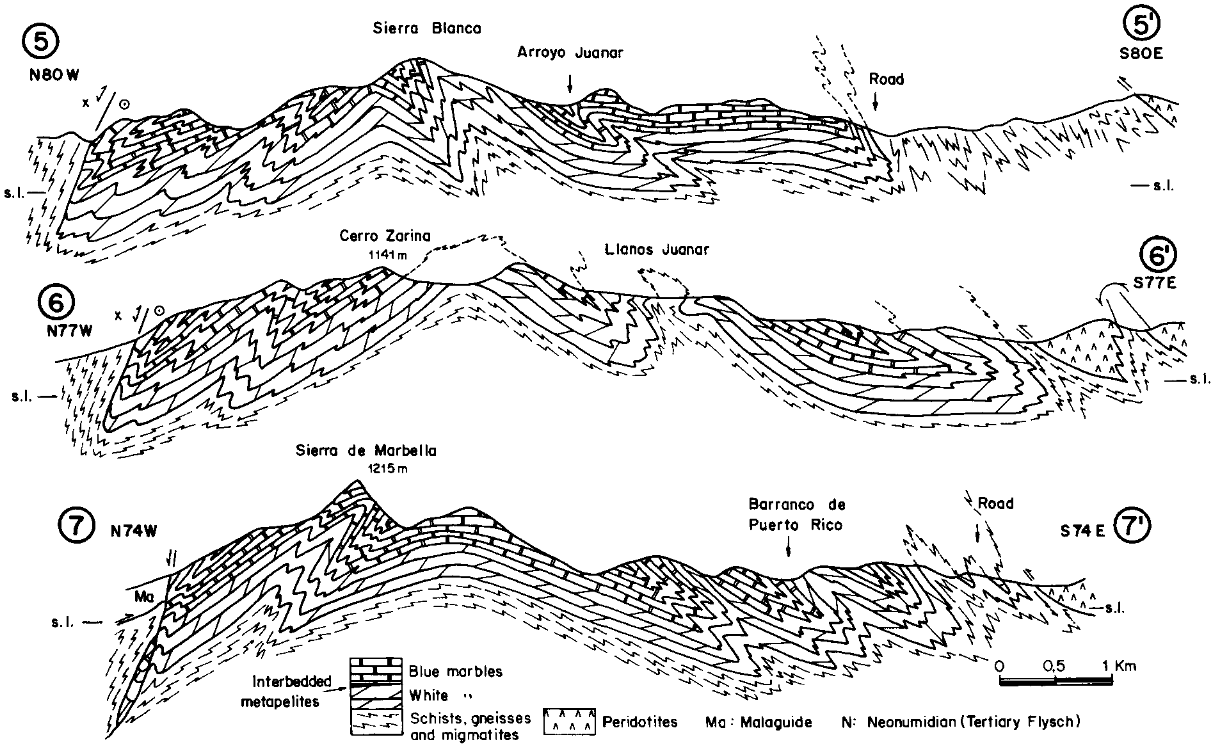
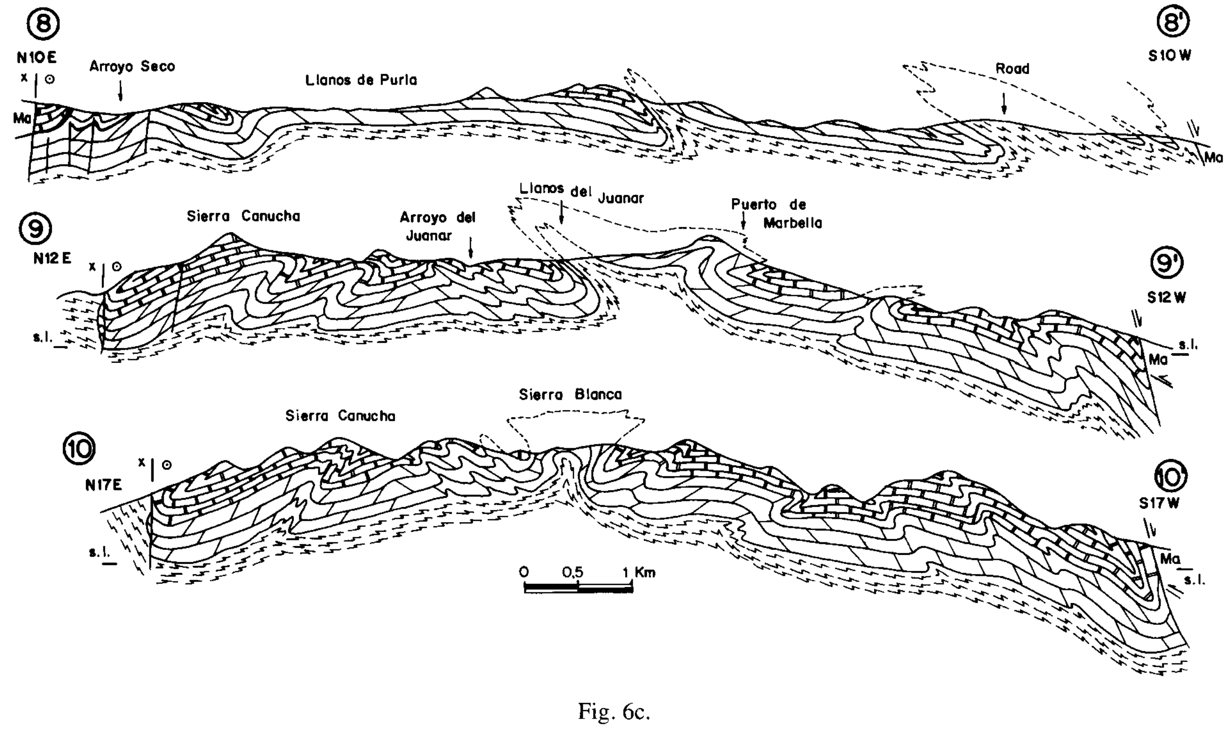

5
N80W
Sierra Blanca
Arroyo Juanar
Road
5'
S80E
s.l.
Cerro Zarina
1141 m
Llanos Juanar
6
N77W
6'
S77E
s.l.
Sierra de Marbella
1215 m
7
N74W
Barranco de Puerto Rico
Road
S74E
7'
Ma
s.l.
Interbedded metapelites
Blue marbles
White "
Schists, gneisses and migmatites
Peridotites
Ma : Malaguide
N: Neonumidian (Tertiary Flysch)
0 0,5 1 Km

Fig. 6b.


8
N10E
Arroyo Seco
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Road
8'
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Ma
9
N12E
Sierra Canucha
Arroyo del Juanar
Llanos del Juanar
Puerto de Marbella
9'
S12W
s.l.
Sierra Blanca
Sierra Canucha
10
N17E
10'
S17W
0 0,5 1 Km

Fig. 6c.

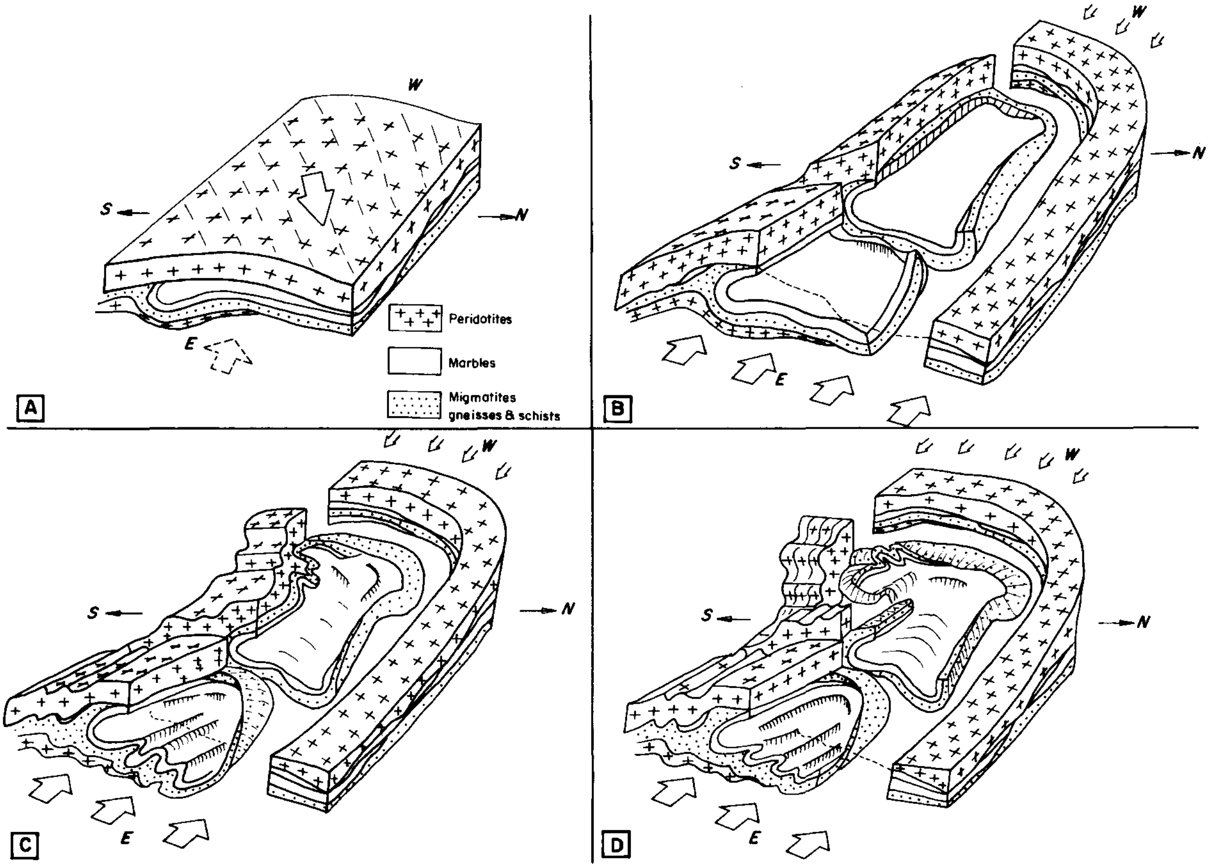

Fig. 7.—Schemes showing the model of the structural formation of Sierra Blanca. a) First displacement towards the N70E of the Los Reales unit, with peridotites at the base, over the Blanca unit as yet unstructured. b) Separation of the Sierras Blanca and Mijas as two subunits. c) Continuation of the structuring process of the Sierras Blanca and Mijas, also indicating the appearance of the antiform and synform structures in the peridotites in the area of Sierra Alpujata. d) Structure of the Sierras Blanca and Mijas before the activity of the Albornoque fault. The large arrows indicate the direction of displacement of the whole of the Internal Zones (westerly) and the small arrows the gradual increasing opposition offered against the advance.

ca, whether lower or upper. The extreme south of Sierra Blanca is affected by a fault in an E-W direction, showing a normal, fundamentally vertical movement of over a 1,000 m, with a fault-plane surface of 70-80° S. On this edge, some intercalated serpentine fish are also found.

The eastern and southeastern edges of Sierra Blanca appear to be generally in gradual stratigraphic transition, although reversed, between the gneisses and schists with the lower marble. Over the gneisses lie migmatites, and finally the overthrusting peridotites (figs. 3 and 5).

Genesis of the structure

The structure of Sierra Blanca can be explained with a model similar to that proposed by Frizon de Lamotte *et al.* (1991) for different sectors of the Betic Cordillera and that suggested by Andreo & Sanz de Galdeano (1994) to explain the structure of Sierra de Mijas. According to this model, during the movement of a unit, lateral folds are formed which could present opposing vergences and frontal deformations appear.

To apply this model to the Blanca unit, we consider a general displacement towards the W of the Internal Zones of the Betic Cordillera in relation with the External Zones. Thus, the Los Reales and the Blanca units moved jointly towards the W within this displacement, with the Los Reales unit tectonically superposed, or partially superposed, to the Blanca unit. Our reconstruction of figure 7 begins at the moment when the Los Reales unit, situated in a higher position, was partially obstructed in its westwards displacement (by the Malaguide Complex or even by the most internal units of External Zones?) and began to move eastward (in a N70E sense according Tubía and Cuevas, 1987) in relation to the Blanca unit, which continued moving westwards (fig. 7a). During this displacement, under ductile deformation conditions, the Blanca unit began to be partially stopped, as happened previously to the Los Rosales unit, and its western extreme, which currently constitutes its principal nucleus, rotated anti-clockwise owing to the impossibility of an easy westward advance. At the same time, part of the unit broke off and individualized, constituting the present-day Sierra de Mijas, whose western edge presents curved folds forming the front of a new unit or subunit within the Blanca unit (fig. 7b and c).

The rotation of the nucleus of Sierra Blanca caused the old folds of approximately E-W direction veer to a N-S direction, and the coexisting westerly movement pressed the folds even more. In the last phases of the rotation, new E-W folds formed, causing the interference described above in Section 3 (fig. 7d).

Tubía (1985) believed that the arching of the structures occurred in a clockwise direction, caused by the dextral movement of the Albornoque fault; that is, the arcuated form of Sierra Blanca would be linked to the deformations occurring after the internal structuring of the unit. It is certain that, as indicated above, the Albornoque fault arches and greatly stretches the structures in the northwestern part of Sierra Blanca, but in our opinion this effect is superimposed on the structuring process described here, because this fault does not explain the interference of folding and in many places cuts previous structures.

Owing to the displacement of the Betic-Rif Internal Zones towards the W the Gibraltar Arc was formed, well drawn by the units of the Campo de Gibraltar (fig. 1) and by the External Zones there, whereas the Internal Zones adapted less to this arc, the most important exception being Sierra Blanca.

We have refered to the hypotheses of Doblas and Oyarzun (1989a and b) and Platt and Vissers (1989) explaining the formation of the Gibraltar Arc and the Alboran Sea by an extensional collapse. Nevertheless, according to the general structure of the Sierra Blanca unit and the Los Reales unit, and many other data especially from the Internal-External contact of the Betic and Rif cordilleras, we prefer the present model of the westward displacement of the Internal Zones, admitting at the same time an extensional process that opened the Alboran sea at the back of the displacing Internal Zones, an opening process that was the continuation of the extension produced coetaneously in the Algerine basin (Sanz de Galdeano, 1990).

Chronology

The principal features of the structures described appear to have formed before the end of the Aquitanian, given that transgressive formations from this age and from the Early Burdigalian fossilized the contacts between the Malaguide and Alpujarride Complexes in this region, later thant the structuring of the units (Bourgois, 1978; Martín-Algarra, 1987; Sanz de Galdeano *et al.,* 1993). Some of these formations contain boulders of peridotites and migmatites, like the Las Millanas formation dated as Early Burdigalian (approximately 20 m.a. ago) by Bourgois *et al.* (1972). On the other hand, Monié *et al.* (1991) and Jabaloy *et al.* (1993) propose on age of 25 m.a. for the end of the HP/LT event affecting the Alpujarride nappes, that is, at the end of the Oligocene or beginning of the Aquitanian, depending on the chronostratigraphic scale used. These data suggest that the present structure of Sierra Blanca was formed at the end of the Oligocene-Aquitanian, coinciding approximately with the beginning of the cited westwards displacement of the Betic and Rif Internal Zones.

The Albornoque fault must have begun its movement at the point when ductile deformations changed to fragile, which, in the first stages caused the important stretching of the northwest of Sierra Blanca. This activity possibly began in the Middle Aquitanian and probably did not continue after the Burdigalian, or at most until the Middle Miocene. Its displacements also contribute to the westward movement of the Internal Zone.

The fault of the South of Sierra Blanca is posterior to the rest of the structures described, although its age is not possible to indicate with precision; it was probably formed during the Late Miocene.

Tectonic position of the peridotites

Tangential to the objective of this work, this section has been included because of the role played by the peridotites in the structuring of Sierra Blanca, which they overlie. On the E-SE edge of Sierra Blanca, the succession of marbles, schists, gneisses and mignatites are found inverted, with the peridotites of Sierra Alpujata on top, although separated by a tectonic contact. This seems to suggest that if the inversion were undone, the peridotites would be situated under the Blanca unit. However, the geometry of the whole peridotite outcrops, both to the E in the Sierra Alpujata and to the west in Los Reales, clearly shows that the peridotites are situated over the Blanca unit as was previously indicated by Lundeen and Obata (1977), Tubía (1985) and Tubía

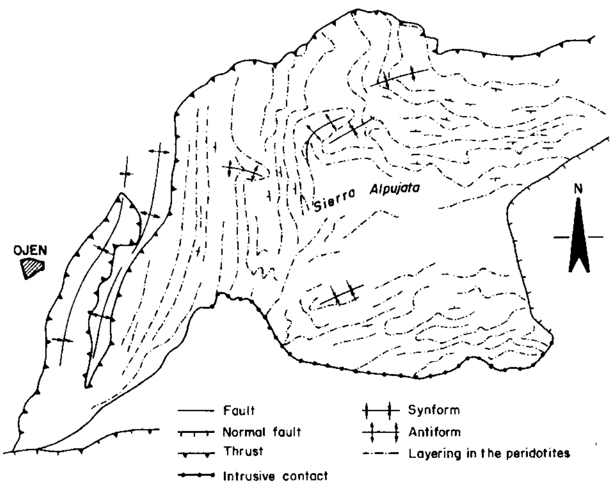

Fig. 8.—Structures deduced from the layering of the peridotites in Sierra Alpujata.

and Cuevas (1987). Furthermore, the facies mineral, Plagioclase-Lherzolite, present in this region at the bottom of the peridotites (Lundeen and Obata, 1977; Obata, 1980; Gervilla, 1990), makes contact and overthrusts the Blanca unit.

The previously discussed overthrusting is clearly visible in the field, but nevertheless the possibility cannot be discarded that there are other masses of peridotites at the base of the Blanca unit, as suggested by, among others, Orueta (1917), Blumenthal (1949), Martín-Algarra (1987) and by the general model of Doblas and Oyarzun (1989a and b). In fact, the migmatites which occur at El Juanar, in the very nucleus of Sierra Blanca, suggest that below the sierra there are peridotitic masses. Kornprobst (1976) suggested the possibility of existence of several peridotitic slices, which may be the case, and Buntfuss (1970) and Loomis (1972a and b) considered the Blanca unit partially included in the peridotites. In any case the gravity anomalies (Bonini *et al.,* 1973) and the data from seismic refraction (Barranco *et al.,* 1990) appear to indicate that the principal peridotite mass in this area is constituted by the Sierras Alpujata and Los Reales.

Folds are found which can affect the peridotites in Sierra Alpujata, a fact already indicated by Piles *et al.* (1978b). The peridotites of Sierra Alpujata show the same fold directions (figs. 5 and 8) as in the gneisses, schists and marble of Sierra Blanca. Thus, in the western part of Sierra Alpujata (Ojén area) the layering direction is almost N-S. In addition, there the peridotites form a fold involving migmatites and gneisses, the axis of which can be followed several kilometres in the N10E direction.

In the central part of Sierra Alpujata the layering shows a certain interference of fold directions, and throughout its eastern half, the predominant direction is approximately N60E to E-W, like in Sierra de Mijas or in the eastern part of Sierra Blanca. The folds indicated are only antiforms and synforms, since we do not know the polarity of the layering.

Folds in the same N-W and E-W direction in Sierra Blanca and in Sierra Alpujata, show that their deformation is at least partially simultaneous. At the same time the peridotites situated on the Sierra Blanca unit affected it thermally, facilitating the ductile deformations appearing there.

The bodies of serpentinized peridotites, present along the northern border of the Sierra Blanca are pinched fish due to the Albornoque fault. For those on the western and southern edges, the simplest explanation is that they come from the overthrusting peridotites, pinched during the structuring of the units, including here the displacement of faults.

Conclusions

Sierra Blanca, belonging to the Alpujarride Complex of the Betic Cordillera, presents a lithologic sequence formed by migmatites, gneisses and schists and an upper formation of marbles, between which is a gradual transition. Within the carbonate formation, there is a white dolomitic marble (lower marbles) of about 300 m in thickness. Over these a metapelitic intercalation usually appears, discontinuous and 60-70 m in maximum thickness, which gives way to the blue calcareous marble (upper marbles) approximately 300 m in thickness and shows numerous metapelitic intercalations.

The structure of Sierra Blanca is made up of folds in an E-W direction in the eastern area, and in the west there are N-S and E-W folds whose interference gives rise to an egg cardboard carton effect, that is, a dome-basin pattern. In both areas, opposing vergences of the structures are known which are invariably towards the interior of the Sierra, though some E-W folds show a double sequence of opposing vergences. In addition, abundant transpositions are known, especially well detected in the blue limestone marble, indicating mechanisms of ductile deformation.

The overthrusting peridotites of Sierra Alpujata, directly to the E, show the same directions of folding. That is, the Los Reales unit (including Sierra Alpujata), with important peridotite masses and its base, was already superposed over the Blanca unit during the principal structuring process of the latter. On the other hand, the outcropping of the migmatites of El Juanar raise suspicions that under Sierra Blanca there are also peridotite masses.

A model involving westward movements and forming frontal and lateral folds would explain this structure of Sierra Blanca. During its westward advance, the most westerly part of Sierra Blanca appears to have rotated anti-clockwise, practically 90° and then formed the folding interference.

These structures may have formed at the end of the Oligocene-Aquitanian inserted in the westward displacements of the Betic-Rif Internal Zones from their original position, approximately the south of Sardinia, towards the present situation within the Betic and Rif Cordilleras. It is precisely Sierra Blanca, within the units of the Internal Betic Zones, which shows a better adaptation to the form of the Gibraltar arc.

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