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# ON THE EVOLUTION OF STRUCTURE AND METAMORPHISM DURING THE ALPINE OROGENY IN THE EASTERN AND CENTRAL BETIC ZONE (BETIC CORDILLERAS, SPAIN)

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## ABSTRACT

The relationships between Alpine overthrusting, folding and regional metamorphism in the eastern and central Betic Zone are discussed, in the light of recent studies. It is substantiated that two major episodes of metamorphism had occurred, related to distinct stages of the orogenic evolution. In this there is a marked analogy with the evolutionary trend of the internal zone of the Alps. The conspicuous difference between the two belts lies in the time relationship between the final emplacement of the nappes and the 'main' episode of crystallization. In the Betic Zone it is the early episode that has determined the overall 'picture' of the metamorphism.

## INTRODUCTION

The Alpine evolution in the southeastern part of the Betic Zone was discussed in some detail in 1969 by Egeler & Simon. The concept was developed that the present nappe structures in this internal zone of the Betic Cordilleras are the result of at least two major phases of translation and that the metamorphism embraced two distinct episodes of crystallization which were in some way, related to these movements. Since 1969 considerable progress has been made, especially with respect to the understanding of the polyphase deformation suffered by the Permo-Triassic and Triassic cover sequences of the structural units and to the relationships between deformation and metamorphism. The principal new data are reviewed, in the light of the formation of the nappe structures.

## STRUCTURAL OUTLINES

According to current usage (see Egeler & Simon, 1969a), the individual structural units represented in the eastern and central section of the Betic Zone are grouped into four tectonic complexes, viz. (in ascending order): (1) the Nevado-Filabride complex, (2) the Ballabona-Cucharón complex, (3) the Alpujarride complex, and (4) the Malaguide complex. For the distribution of these major units refer to figure 1.

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Comparison of the respective Permo-Triassic and Triassic rock sequences reveals marked differences in the degree of Alpine regional metamorphism. Thus, the Nevado-Filabride sequences show a medium grade metamorphism, the Ballabona-Cucharón and Alpujarride sequences show a low grade metamorphism, and in the Malaguide sequences metamorphic crystallization is lacking or very weak. Furthermore, it should be noted that the degree of Alpine metamorphism within a given tectonic complex appears to be uniform laterally. Broadly speaking this is also true vertically, in so far that the study of the cover sequences of different units belonging to a given complex has not revealed a gradual decrease in metamorphic grade in an upward direction. Therefore, the regional pattern of the metamorphism in the Betic Zone is discontinuous, with abrupt changes in grade at contacts between elements which belong to different tectonic complexes. This is very conspicuous in the field, especially where it involves cover rocks of comparable lithology belonging to different complexes.

It follows from the foregoing that the overthrust movements, which have caused the present nappe structure of the Betic Zone, took place after the completion of the metamorphism which regionally affected this zone. This led to the conclusion that two independent phases of major overthrust movements had occurred; the phase responsible for the present structure had been preceded by an important tectonic event to which the principal metamorphism was related in some way or other (Leine & Egeler, 1962; De Roever & Nijhuis, 1963; Egeler & Bodenhausen, 1964; Egeler & Simon, 1969a, b). The character of these early movements, leading to an 'initial pile of nappes', remained hypothetical, though it was obvious that the physical conditions differed considerably from those prevailing during the later movements.

## RESULTS OF RECENT RESEARCH IN THE BETIC ZONE

### *Structural evolution*

Until recently, very little was known of the relationship between the overthrust movements and the folding on major and minor scales since studies specifically dealing with this

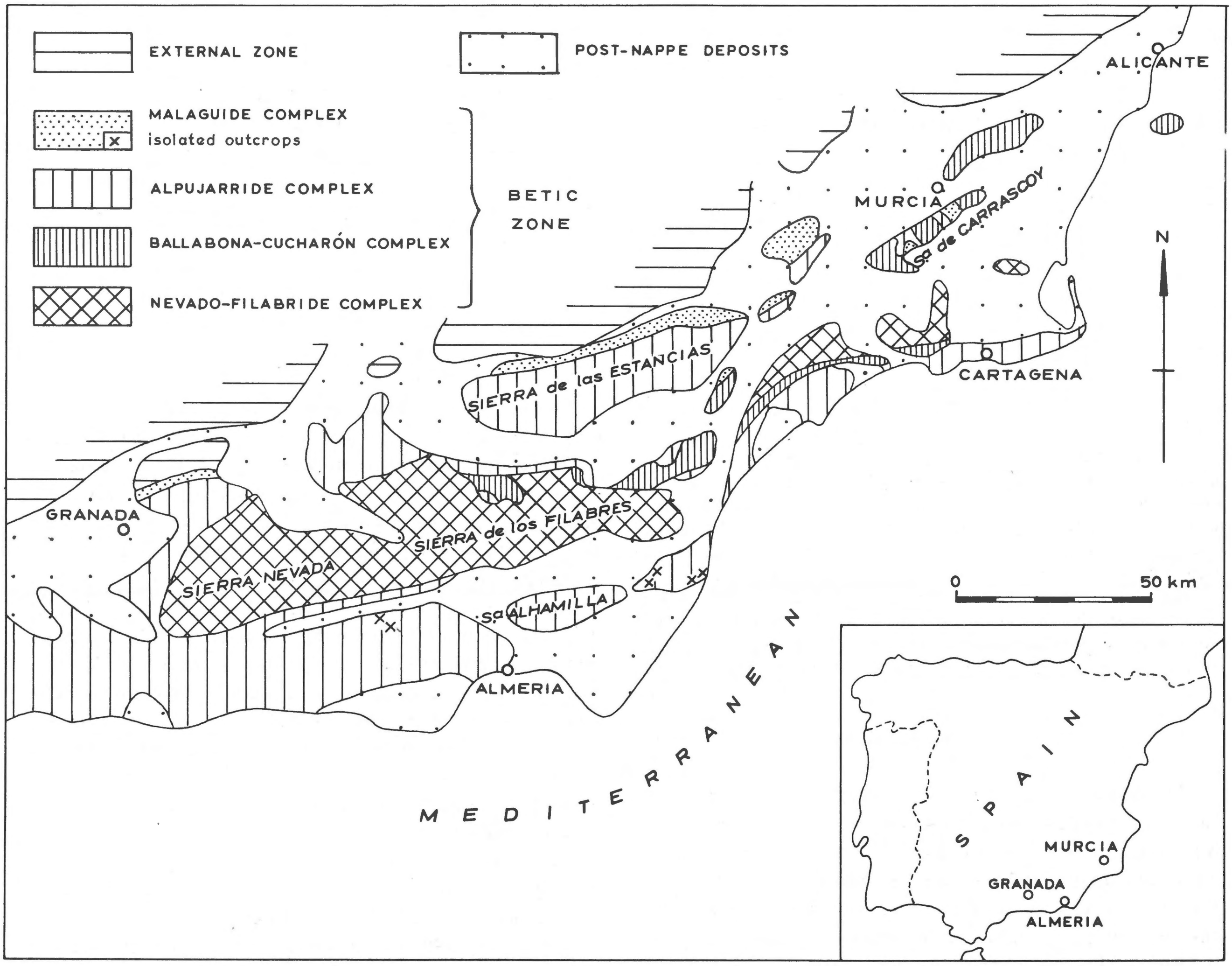


Fig. 1
Tectonic sketch-map of the eastern and central Betic Zone

Table 1
Deformation scheme of the Nevado-Filabride complex, eastern Sierra de los Filabres; slightly modified after L a n g e n b e r g (1972) and K a m p s c h u u r et al. (1973).

| deformation phases | direction of bulk shortening | structures generated | metamorphism |
|---|---|---|---|
| | | | greenschist facies |
| $D_4$ | WNW–ESE | open (to close) folds; crenulation | greenschist-amphibolite transition facies |
| $D_3$ | NE-SW | open to close folds; crenulation | |
| $D_2$ | NNE-SSW | open to tight folds; crenulation | |
| $D_1$ | (? )NNE-SSW | transposition foliation and tectonic reduction; tight to isoclinal folds; schistosity (nappe movements) | glaucophane schist facies |

subject were still in progress. The theses of L a n g e n b e r g (1972) and K a m p s c h u u r (1972) now provide valuable information on the polyphase character of the folding.

L a n g e n b e r g's investigations in the eastern Sierra de los Filabres were mainly concentrated on units of the Nevado-Filabride complex, where he distinguished a number of separate deformation phases (Table 1). The oldest phase is characterized by tight to isoclinal folding. Though he pointed out that definite proof is lacking, L a n g e n b e r g (1972, p. 73) believed that this earliest folding was largely synchronous with the intial thrust movements. This was based on the assumption that the nappe movements "did not move as rigid blocks during their individualization and overthrusting" and that the rocks have also been "subject to internal deformation, now reflected by the $D_1$-structures". Strong shearing in a late stage of $D_1$, leading to transposition and strong tectonic reduction, most probably reflected the younger phase of overthrusting envisaged by Egeler & Simon (1969a, b). It was followed by three more fold phases.

Table 2
Deformation scheme of the Balabona-Cucharón complex, Sierra de Carrascoy; slightly modified after Kampschuur (1972) and Kampschuur et al. (1973).

| deformation phases | direction of buld shortening and vergence | structures generated | metamorphism |
|---|---|---|---|
| $D_4$ | NW –>SE | gentle to close folds; crenulation cl.; upthrusts | |
| $D_3$ | NE–>SW | open to isoclinal folds; crenulation cl. | |
| $D_2$ | N –>S | overthrusts (nappe movements) | |
| $D_1$ | NE –>SW | mainly isoclinal folds; slaty cl. (nappe movements) | greenschist facies |

Kampschuur's 1972 publication on the Sierra de Carrascoy is restricted to higher units of the Betic Zone, pertaining to the Ballabona-Cucharón complex, the Alpujarride complex and the Malaguide complex (Table 2). He too related the oldest folding to the initial translations. This folding was succeeded by a phase of major displacement, leading tot the formation of the present pile of nappes. In addition two phases of post-nappe folding were distinguished.

Kampschuur et al. (1973), in a comparative study of the structural history of the Sierra de Carrascoy, the Sierra de los Filabres and the Sierra de las Estancias, have found that the deformation schemes of units belonging to different tectonic complexes show considerable uniformity. They reveal that the direction of shortening during late folding (roughly NW-SE) was transverse to that during earlier fold phases (now oriented NNE-SSW to NE-SW).

Before turning to the metamorphic evolution some remarks may be made on the supposition of Langenberg and Kampschuur that the oldest recognizable fold structures are related to the initial thrust movements. If this is correct, the implications concerning the vergence of these movements and, therefore, the paleogeography of the Betic realm are far-reaching.

Considering the Betic Zone within the framework of the Mediterranean fold belt the simplest hypothesis seems to be a northern vergence (see e.g. Egeler & Simon, 1969a, b). However, Kampschuur's findings in the Sierra de Carrascoy indicate that southwestward-directed movements took place in an early stage of the orogenic history since the first fold phase is represented *inter alia* by recumbent synclines which open towards the southwest. This led him to conclude that the nappe transport was also southwestly directed. If true, this would imply that the Malaguide units, in view of their position at the top op the pile of Betic nappes, have a northern provenance. This is an interesting point of view, though the matter still seems open to debate. For instance, the objection could be made that, until the relationship between the first act of folding and the early thrusting is proved, the possibility cannot be excluded that this folding was independent of the translations. Anyway, objection must be made to van Bemmelen's assertion (1973, p. 70), that the northward emplacement of the Betic nappes, with the Malaguide realm as southernmost element, is firmly established (see e.g. Durand Delga, 1973). Actually, it is astonishing that, despite the amount of work done, there remains so much room for speculation on such a fundamental point.

## *Metamorphic evolution*

The studies of Langenberg and Kampschuur have provided data on the relationships between metamorphism and folding. It is now known that the greenschist facies metamorphism in the Alpine rock sequences of the Ballabona-Cucharón and Alpujarride complexes (Table 2) and the glaucophane schist facies metamorphism in those of the Nevado-Filabride complex (Table 1) were both roughly synkinematic with respect to the earliest folding. It is also known that the oldest fold structures in these units reflect the same deformation phase, in view of their comparable style and orientation (Kampschuur et al., 1973). Thus the greenschist metamorphism in the higher units and the glaucophane schist metamorphism in the lower ones are roughly correlatable. Local transitions to the glaucophane schist facies, observed in metabasites of the Ballabona-Cucharón complex (Simon, 1963; Kampschuur, 1972) and of the Alpujarride complex (Rondeel, 1964), seem significant in this context. It may be noted here that H. Helmers (pers. comm.; thesis in preparation) is of the opinion that glaucophane schist facies conditions already existed prior to the first folding.

The study of the Nevado-Filabride cover sequences has revealed that in the lowermost tectonic complex the glaucophane schist phase was only the beginning of the metamorphic history, as the Alpine crystallization was "plurifacial" (de Roever & Nijhuis, 1963; Nijhuis, 1964). According to Nijhuis crystallization under kinematic conditions (glaucophane schist facies followed by quartz-albite-epidote-almandine subfacies of the greenschist facies) was succeeded by crystallization under post-kinematic conditions (greenschist facies followed by almandine-amphibolite facies). A comparable change from kinematic to post-kinematic conditions had been reported from the northern S.d.l. Filabres, in rocks of the Nevado-Filabride complex as well as in rocks of the overlying Ballabona-Cucharón and Alpujarride complexes (Bicker, 1966; Voet, 1967). Egeler & Simon (1969a, b) argued that two essentially independent episodes of crystallization were involved. They tentatively linked the two kinematic phases of Nijhuis (1964) with their "initial phase of thrusting", whereas his two post-kinematic phases were considered to represent the post-nappe event. The concept of two independent episodes of metamorphism is substantiated, in principle, by Langenberg's results. These show, however, that the distinction cannot be made on the basis of kinematic *versus* post-kinematic crystallization and that Nijhuis's second kinematic phase belongs to the second episode. In fact, Langenberg has shown that this later episode embraced at least two individual events of folding and may even have continued into a third.

The influence of the late-Alpine event of crystallization on the rocks of the Nevado-Filabride complex was strong, and often proves decisive for their present character. Higher units, on the other hand, appear to be only locally affected. The main phase of metamorphism in the Nevado-Filabride cover rocks, in the greenschist-amphibolite transition facies[1]), was succeeded by crystallization under greenschist facies conditions. Langenberg (1972) believed that this represented a separate event of static crystallization which post-dated the third phase of post-nappe folding. However, the present author would not exclude the possibility that it represents the waning stage of the second episode. It seems quite possible that towards the end of the orogeny metamorphic conditions differed from place to place. For example, the final phase of almandine-amphibolite facies crystallization reported by Nijhuis (1964), which is later than the greenschist facies crystallization afore-mentioned, clearly reflects an increase in temperature. High temperature conditions are further suggested by the static crystallization of biotite, cordierite and andalusite, which has been reported from Permo-Triassic rocks of the Alpujarride unit underlying the Sierra de las Estancias (De Vries & Zwaan, 1967; Egeler & Simon, 1969b). In this case, however, little is known on the detailed time relations with the fold phases.

## COMPARISON WITH THE INTERNAL ZONE OF THE CENTRAL AND WESTERN ALPS

The comparison of the relationships between structure and metamorphism in the Betic Cordilleras and in the so much better known Alps had led to some interesting viewpoints.

It is known that the present pattern of the Alpine metamorphism in extensive parts of the internal zone of the Central and Western Alps was determined by a major event of crystallization that was post-kinematic with respect to the final emplacement of the nappes. This holds good, for instance, for the Lepontine region (see e.g. Wenk, 1962, 1970; Niggli & Niggli, 1965; Niggli, 1970), the external part of the Sesia-Lanzo zone (Dal Piaz, Hunziker & Martinotti, 1972) and the Vanoise region (Ellenberger, 1958). It is witnessed *inter alia* by the fact that metamorphic isograds cut across nappe boundaries. Some investigators favour the hypothesis that this regional post-nappe metamorphism is related to 'thermic domes' (e.g. Wenk, 1962; Thakur, 1973); others are of the opinion that it is essentially the result of tectonic depth (e.g. Ellenberger, 1958; Niggli & Niggli, 1965; Zwart, 1967).

We have seen in the foregoing that such independence of isograds and structural boundaries does not exist in the Betic Cordilleras since here the translations responsible for the present pile of nappes post-dated the metamorphic event which has regionally affected the Betic Zone. This difference in the time relationship between the emplacement of the nappes and the "main" metamorphic event is so striking that it would appear to be of fundamental importance. Nevertheless, results of recent work in the Alps indicate that this is not so.

Like in the Betic Zone, in the internal zone of the Alps distinction is now made between two major episodes of regional metamorphism, related to separate stages of the Alpine orogeny (e.g. Dal Piaz et al., 1972; Jäger, 1973; Bearth, 1962, 1973). The early episode appears to be mainly characterized by a metamorphism under glaucophane schist facies conditions, sometimes overprinting eclogite structures. Crystallization during this event proves to have preceded the final emplacement of the nappes and its products are now more or less irregularly distributed (Dal Piaz et al., 1972). The later episode, on the other hand, appears to have been mainly developed under conditions of the amphibolite facies (Lepontine region) or the greenschist facies (*inter alia* the Sesia Lanzo zone)[2]). This event post-dated the nappe movements. It caused recrystallization on a regional scale, and in the Lepontine region, for example, it is responsible for the overall pattern of the metamorphism. Radiometric dating (Dal Piaz et al., 1972; Jäger, 1973) has shown that the two episodes in the Alps were indeed far separated in time; the early event belongs essentially within the Upper Cretaceous and the later one near to the Eocene-Oligocene boundary.

Summarizing, there appear to be several marked analogies in the evolutionary trends of the internal zones of the Betic Cordilleras and the Alps. In both cases two major phases of translation appear to have played a role during the Alpine orogeny. Further, in both cases two major episodes of regional metamorphism are distinguished, each related to a distinct stage of the evolution. Moreover, the specific facies

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[1]) The greenschist-amphibolite transition facies (Turner, 1968) corresponds with the quartz-albite-epidote-almandine subfacies of the greenschist facies (Turner & Verhoogen, 1960), mentioned by Nijhuis (1964).

[2]) It should be noted that this need not be a rule. Thus, Ellenberger (1958) concluded that the glaucophane schist metamorphism in the Vanoise region has succeeded the emplacement of the Schistes lustrés nappe. Furthermore, some results of H.J. Zwart can be mentioned, communicated at the meeting of the Société géologique de France, on the subject: "Le métamorphisme alpin dans les Alpes occidentales" (Grenoble, 1973). He reported the development of glaucophane during the later event (Lepontine phase) of the Alpine metamorphism, in a lecture entitled: "Evolution structurale et métamorphique dans les Alpes Centrales".

characterizing these episodes (glaucophane schist facies and greenschist to amphibolite facies respectively) suggest that in both belts a change from high pressure to relatively low pressure and partly higher temperature conditions has taken place in the course of the orogeny. The principal difference lies in the time relationship between the final emplacement of the nappes and the "main" event of metamorphic crystallization, In the eastern and central Betic Zone the overall "picture" of the metamorphism has been determined by the early episode of crystallization. The fact that the effects of the later episode are restricted to deeper units relates to the overburden, i.e. the limited volume of the pile of nappes. In the Sierra Alhamilla – Sierra de los Filabres – Sierra de las Estancias section of the Betic-Zone, for example, the total thickness of the nappes, measured from the highest Nevado-Filabride unit upwards, is less than 3 kilometres.

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