THE TECTONIC SUBDIVISION OF THE BETIC ZONE (BETIC CORDILLERAS, SOUTHERN SPAIN): ITS SIGNIFICANCE AND ONE POSSIBLE GEOTECTONIC SCENARIO FOR THE WESTERNMOST ALPINE BELT

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ABSTRACT. The tectonic significance of the present threefold subdivision of the Internal (or Betic) Zone of the Betic Cordilleras of Southern Spain is reviewed critically in terms of the preexisting criteria for the subdivision and of recently available data on the metamorphic and magmatic evolution of each ensemble of tectonic units. Mainly on the basis of the latter, the prior subdivision can be re-arranged into two major tectonic domains shown by clear evidence to have occupied strikingly different crustal domains during the Alpine orogenic evolution of the Alboran Region. A first domain is at present mostly exemplified by the terrains included until now in the Nevado-Filabride Ensemble of tectonic units, whose alpine metamorphic evolution started with an important high-pressure event (kyanite eclogites, jadeitic pyroxene plus quartz, glaucophane) preceded by extensive intrusion (or extrusion) of abundant ophiolite-like igneous material. The second domain is represented by most of the units of the Alpujarride (s.l.) and Malaguide Ensembles (together with their North African equivalents). In this domain, flat geothermal gradients were dominant, probably because of the emplacement of hot magma derived from the upper mantle, the most spectacular of which is constituted by such huge peridotite intrusives as those of Sierra Bermeja (Spain) and Beni-Bouchera (Morocco).

A combined analysis in space and time of the data, together with some other pertinent information, particularly from geophysical sources, enables the construction of a preliminary model of geotectonic evolution for this western end of the Alpine Belt, in which the Internal Zone of the Betic Cordilleras and the North African chains combined one and the same orogeny, prior to dislocation and block dispersal in middle Tertiary times. The model implies that, before the Late Cretaceous, a portion of “oceanoid” crust existed in the western Tethys area, which would later have been eliminated by convergence of the European and African lithospheric blocks. This convergence would also have been responsible for the differentiation of the two previously mentioned tectonic domains, whose present geometrical relationship further indicates that the diapiric uprise of anomalous mantle material above a southwardly descending crustal slab may have been the cause of the flat geothermal gradients in, and the updoming of, the Alpujarride-Malaguide crustal domain. Such an interpretation is in good agreement with the general pattern of metamorphic evolution in this domain (a shift of gradients toward lower environmental pressures), as well as with the existence here of a large feeding area for some of the peri-Mediterranean “flysch” formations. Similarly, “tectonic” demodulation, in the form of a gravity-directed migration of nappes, would have resulted from this updoming producing part of the present imbricate structure of the Betic and North African mountain belts and perhaps the arcuate structure at Gibraltar. In Early Miocene time, the arched roof of the tenuous Alpujarride-Malaguide domain would have started to collapse, giving rise to several basins and troughs including the present Alboran basin and some other intermontane depressions (those of Granada and Guadix-Baza, for instance). At this time also, calc-alkaline magma which may have originated in relation to previous tectonic stages, began extruding along new fractures or fracture zones, maybe up to a few million years ago. At present, evidence of renewed compressive tectonics in the Western Mediterranean region could be interpreted as a new onset of convergent movements, as might be expected, on the other hand, from available data on the kinematics of the intervening lithospheric blocks.
INTRODUCTION

The Betic Cordilleras of Southern Spain are usually subdivided into two distinct domains or zones, the more meridional (or internal) of which is called the Betic Zone (s. str.). In contrast to the more external zones (called Subbetic and Prebetic), the Betic Zone is characterized by extensive outcrops of rocks of pre-Mesozoic age, part of which form part of a pre-Alpine basement actively involved in the overall Alpine structure (for more details see fig. 1; and Fallot, 1948). Also, the whole domain of the Betic Zone has been more or less conspicuously affected by Alpine metamorphism, whereas particular magmatic phenomena, as for instance ultramafic intrusions, are exceptionally well represented. As a result of nearly half a century of research, this "Internal Zone" is subdivided into three subzones or tectonic ensembles which at present are known under the names of the Nevado-Filabride Ensemble, the Alpujarride Ensemble, and the Malaguide Ensemble, in ascending tectonic order. Each ensemble includes a number of overthrust (tectonic) units, grouped according to diverse criteria, mainly the different stratigraphical development of the cover series (Egeler, Rondeel, and Simon, 1971), though assumed differences in general metamorphic grade among the different ensembles have also commonly been considered an additional test.

Until now, this subdivision, with modifications such as those introduced by Egeler and Simon (1969), has proved very useful and has been widely, as well as fruitfully, quoted in the context of many discussions about the Betic Zone. Nevertheless, the growing amount of data that have become available in the last years has made it more necessary to revise the subdivision and to reconsider its general significance for future work. This problem has led Egeler, Rondeel, and Simon (1971), for instance, to reconsider the relative value of the various criteria used up to now. In this paper a somewhat different approach is followed; special emphasis is put on new views and interpretations of the now available additional data. Among these data, those concerning the differential metamorphic and igneous evolution of the various ensembles seem to deserve special attention, and therefore they are dealt with specifically in the next chapter. It is hoped that the following discussion will serve for completing previous ideas or as a stimulus for further work on the subject.

3 Detailed work in the eastern section of the Betic Zone has led diverse workers to distinguish another element, the so-called Ballabona-Cucharon Ensemble, of intermediate character between the Nevado-Filabride and Alpujarride Ensembles (Simon, 1964; Egeler and Simon, 1969, Simon, Westerhof, and Rondeel, 1976). In this paper, however, the primitive threefold subdivision will be maintained, for such an intermediate element still has not been distinguished along the Betic Zone. Anyhow, many of the lowest tectonic units of the Alpujarride Ensemble in the central and eastern segments of the Betic Zone, most of which probably belong to this Ballabona-Cucharon group, are termed here "Intermediate Units" (see below for a more detailed discussion). An excellent introduction to the geology of the Betic Zone can be found in the compilation by Egeler and Simon (1969).
Fig. 1. Tectonic sketch map of the westernmost portion of the Alpine Belt. The Alpujarride-Malaguide ensemble includes its North-African equivalents (Durand Delga, 1972). Drawn mainly after Julivert and others (1974), Durand Delga and others (1962), and Durand Delga (1969).
SOME RECENT WORK ON THE EVOLUTION OF ALPIDIC
METAMORPHISM AND MAGMATISM IN THE BETIC ENSEMBLES

To early researchers, particularly those concerned with the central and eastern segments of the Betic Zone, it seemed evident that, apart from other differences, the various Betic Ensembles had been characteristically affected by Alpine metamorphism of a particular grade. The Nevada-Filabride units, for instance, have been regarded as the more severely affected (medium grade), whereas low-grade or anchimeta-
orphic mineral assemblages have been believed commonly to be a general feature of the two higher ensembles. This view still persists in the compilation of Egele and Simon (1969), for instance, and even to the present (Kampshuur and Rondeel, 1975). Although traditionally assumed, however, all these statements are essentially baseless (as discussed below); concerning the Nevada-Filabride and Alpujarride En-
sembles in particular, it is a matter not of metamorphic grade but of metamorphic evolution. The data presented in the following para-
graphs show that the metamorphic grade is not uniform in any of the Betic Ensembles. Thus, with the possible exception of some Malaguideo units, to which traditional ideas could apply, metamorphic grade should not be used as a distinctive parameter in the Betic Zone. To make this point, one must emphasize the diversity in petrological evolution among each group of units.

THE NEVADO-FILABRIDE ENSEMBLE

Metamorphism.—Some detailed information about the type of Alpine metamorphism displayed in the Nevada-Filabride series has been available since the last decade, when De Roever and Nijhuis (1964) and Nijhuis (ms) published their work on the rocks cropping out in a little area near Lubrin, in the eastern Sierra de los Filabres. A petrographic sequential analysis led them to conclude that metamorphic conditions changed considerably during metamorphism, and the new term “pluri-
facial metamorphism” was actually proposed on this occasion to empha-
size the point. The changing sequence of mineral assemblages, described in terms of metamorphic facies, is as follows:

1. glaucophane schist facies,
2. greenschist facies, subfacies Q-Ab-Ep-Alm,
3. greenschist facies, subfacies Q-Ab-Mu-Chlorite,
4. almandine amphibolite facies (Oligoclase-B-St-Ky).

In the first event, glaucophane was observed to be accompanied by garnet, chloritoid, epidote, kyanite, sodic pyroxene, quartz, paragonite, and rutile whose significance is reviewed below.

Subsequent studies carried out over larger areas, especially in the western Sierra Nevada, seem to have largely confirmed most of the pluri-
facial scheme proposed by Nijhuis. According to Puga (ms), for instance, the corresponding sequence of Alpine paragenesis began with a mineral

*Except where expressly indicated, the North African equivalents of the internal Betic Ensembles (Durand Delga, 1972) are considered altogether.
association characteristic of the glaucophane schist facies (Chl–Bi–jadeitic pyroxene–Ky–(St–Gn–Glaucoph–Epid–Ab–Q), which was followed by other events in the greenschist and amandine–amphibolite facies. In more recent works (Puga and Díaz de Federico, 1976; Gomez-Pugnaire, Puga, and Sassi, 1976) the sequence of mineral assemblages is regrouped in two major events (termed Eoalpine and Alpine s. str., respectively), the first of which encompasses especially the first event of the previous scheme.

The precise interpretation of this first (eoalpine) event is of foremost importance for the aims of the present study. The original conclusion by Nijhuis (ms), that the entire paragenesis is the result of a typical high-pressure and moderate-temperature environment, was later restricted somewhat by Kampschuur (1975), who, in spite of the considerations presented by De Roever (1972) on the stable field of natural glaucophanes, has reinterpreted these metamorphic conditions as being in the so-called glaucophanitic greenschist facies (Winkler, 1967) (his P-T-estimate is about 500°C, 6-10kb). This estimate, however, should be discussed in detail. It is based on the kyanite-chloritoid (staurolite) assemblage, which can be considered reliable with regard to the temperature but is much less sensitive to pressure. The generalized absence of lawsonite, for instance, regarded by Kampschuur as favorable to his conclusion, could even have been expected at temperatures between 450° to 500°C where the assemblage glaucophane-lawsonite would have been replaced by equivalent assemblages such as glaucophane-zoisite or kyanite-zoisite (Winkler, 1974), which are present in those rocks (Nijhuis, ms; Puga and Díaz de Federico, 1976). On the other hand, Kampschuur seems not to have taken into account the assemblage jadeitic-pyroxene plus quartz in metagraywackes, described by Nijhuis and later by Puga and Díaz de Federico (1976), which would suggest considering pressures distinctly above 10 kb for the range of temperatures involved (400°-500°C) (Newton and Smith, 1967; Ringwood and Green, 1966), or the occurrence of metaigneous, kyanite-bearing, eclogites and, in particular, that of crosite (Puga and Díaz de Federico, 1976) which according to the experiments by Ernst (1968) would perhaps imply still higher pres-
sures (see also, De Roever, 1972). A number of other studies carried out elsewhere in the Nevado-Filabride Ensemble (Díaz de Federico, 1971; Gómez-Pugnaire, ms; Langenberg, 1972) give results in accordance with these considerations, which are summarized in figure 3.

Concerning the second (Alpine s.s.) metamorphic event, agreement among diverse workers seems rather complete. In this event various mineral assemblages developed, first in the greenschist facies, later in the amphibolite s.l. facies, both under a geothermal gradient distinctly less steep than in the first event. For a detailed discussion of this subject the reader is referred to the work of Gómez-Pugnaire, Puga, and Sassì (1976). Figure 3 (fields between heavy dashed lines) attempts to represent schematically the whole evolution of metamorphism in the Nevado-Filabride Ensemble according to the data reviewed above. Both the gradients and their evolution must be taken as an approximation whose value, however, is not expected to change significantly with the incoming of new data. To be sure, the study of the Nevado-Filabride rocks series is at present rather limited by their cropping out in tectonic windows (under the other two major ensembles) and by further complications

![Fig. 3. Generalized metamorphic P-T diagram illustrating the evolution of geothermal gradients in the various Betic ensembles.](image)

- Fig. 3. Generalized metamorphic P-T diagram illustrating the evolution of geothermal gradients in the various Betic ensembles. The stability field of several pertinent assemblages has been plotted also: (1) a possible minimum limit for natural glaucophane (De Roever, 1972), (2) jadeite pyroxene plus quartz \( \Rightarrow \) plagioclase (Newton and Smith, 1969), (3) "Staurolite in" from chlorite or chloritoid (from Hoscheck, 1969; Ganguly, 1972), (4) minimum melting of granite (Huang and Wyllie, 1974). The aluminum-silicate diagram is from Holdaway (1971). The fields between heavy dashed lines represent estimated geothermal gradients in the Eoalpine (NF-1) and Alpine s.s. (NF-2) episodes in the Nevado-Filabride tectonic domain (from data reviewed in sec. 2). The heavy continuous and dotted lines represent extreme limits for the evolution of geothermal gradients in the Alpujarride-Malaguide tectonic domain (data from the Almuñecar and S. Tejeda massifs in the central segment of the Betic Zone (Torres-Roldán, 1974; Torres-Roldán and Fontboté-Rubió, 1977).
which effectively hamper more complete observations on the areal distribution of the various assemblages.

Summarizing the above discussion leads to the conclusion that during a first event of Alpine metamorphism some of the rocks of the Nevado-Filabride Ensemble were subjected to an abnormally low geothermal gradient. A combined estimate, which takes into account data from diverse sources, leads to P-T conditions in the range between 400° to 500°C and 10 to 15 kb. The first mineral assemblages of this event have subsequently been more or less obliterated by others in a way to suggest a change of the P-T environment toward lower pressures. Nijhuis (ms) initially interpreted this change as related to the hypothetical deep emplacement of igneous masses. Puga and Díaz de Federico (1976) and the present author think the whole evolution is related to subduction.

Magmatism.—Our present knowledge about the rather complex magmatic evolution in the Nevado-Filabride Domain does not permit any simple or unequivocal interpretation. The following conclusions should, therefore, be regarded as preliminary in nature. The problem is further complicated by metamorphism, which makes difficult the task of deciding which igneous events belong to the Alpine cycle. Fortunately, some successful radiometric dating (Priem and others, 1966) indicates that the Alpine cycle was essentially characterized by mafic-ultramafic activity. Original relationships, however, have been largely obliterated, and at present these rocks have to be studied in the form of amphibolites, minor eclogites, and highly transformed ultrabasic bodies. Age of intrusion can only be approximated; emplacement seems to have affected rocks of postulated Triassic age, so that a post-Triassic (Jurassic?) intrusion or extrusion is reasonable. Detailed descriptions of these rocks can be found in Puga (ms).

At present, nothing can be said definitely with regard to the origin of this rock association, although according to the most recent studies, it would most probably constitute the remains of a previous suite with ophiolitic affinities.3 It could have been emplaced during an earlier extensive stage of the orogen for which, as is shown below, there is some additional independent evidence.

THE ALPUJARRIDE ENSEMBLE

Metamorphism.—As pointed out above, until recently the Alpujarride Domain has been thought to be scarcely touched by Alpine metamorphism, in part because available data were scarce, but mainly because of the common procedure of assigning medium- to high-grade mineral assemblages to a pre-Alpine orogenic cycle (see, for instance, Copponex, 1959; Rondeel, ms; Egeler and Simon, 1969; Aldaya, 1970; Boulin, 1970; Kornprobst, 1976). Furthermore, the rocks showing those mineral associations have consequently been assimilated to an old polymetamorphic basement complex, and the whole reasoning used as a cartographic field criterion. This procedure would give correct results

3This idea is further supported in a recent study by Puga (1977).
in some cases but has not internal consistency. Previously a few authors had concluded the opposite, as, for instance, Fernex (ms) and Orozco (ms), but definitive evidence has come from more detailed studies (Westerhof, 1975; Gallegos, ms), particularly those dealing with massifs showing progressive metamorphic parageneses (Westra, ms; Loomis, 1972a; Torres Roldán, 1974). The reasons for attributing such metamorphic series to the Alpine cycle were discussed previously by Torres-Roldán (1974) and can be summarized as follows:

1. The different mineral zones have a “progressive” character and affect rocks considered to be of Permo-Triassic age.

2. “Freshness” of the mineral assemblages in the various zones suggests that some equilibrium with the physico-chemical gradient responsible for the mineral paragenesis was attained. Evidence of retrograde replacement is almost lacking.

3. Some observations, especially a possible sharp increase in crystallinity or the alignment of one or various isograds parallel to the basement-cover stratigraphical boundary, are in agreement with the theoretically expectable consequences of a young metamorphic episode acting on a composite basement (already metamorphic)-cover (non-metamorphic) series; for example, the so-called “basement effect” (effet de socle) discussed by Fontelles and Guitard (1968, 1972). The latter statement, of course, positively supports the polymetamorphic character of the lower formation of the series, but neither direct relics of the assumed pre-Alpine metamorphic event nor definitive indications about its age have yet been acquired (compare also, Vissers, 1977).

In the Betic Zone, the few radiometric dates already available (Boulin, Ledent, and Pastels, 1969; Loomis, 1975) are in good agreement with these statements.

As mentioned above, detailed studies on the type of metamorphic evolution in the Alpujarride Domain were not available until recently, although a considerable amount of data is dispersed in the literature. Regardless of their origin, however, the compatibility among them (after some reinterpretation) leads to some generalizable statements, as in the case of the Nevada-Filabride Domain. The most interesting of these conclusions seems to be that the geothermal gradient responsible for the observed metamorphism is always an intermediate to low-pressure type. The facies series established during a first event belongs to the medium-pressure group with kyanite and sillimanite as the most significant minerals. High-pressure granulite assemblages can still be recognized in the deeper parts of some metamorphic sequences (compare Westerhoff, 1975; Torres-Roldán, in preparation.) Subsequently, the P-T gradient shifted toward lower pressures superimposing low-pressure assemblages of the type andalusite-sillimanite-cordierite. This means that in the Alpujarride tectonic domain, as in the Nevada-Filabride, Alpine metamorphism has been plurifacial. Index-mineral series characteristic of both events are summarized in figure 4 for the metapelites of the Massifs of Almuñecar and Sierra Tejeda, southwest of the Sierra
Nevada. Though for the sake of clearness the metamorphic evolution of this domain has been subdivided into two major events, it is important to note that no discontinuity seems to exist between them. On the contrary, the petrographic evidence suggests a gradational change, which for the most part might be interpreted in terms of a pressure decrease alone (Torres-Roldán, 1974; Westerhoff, 1975; Torres-Roldán and Fontboté-Rubió, 1977). The change of pressure between the two events (see fig. 3) could be calculated to be at least on the order of 2 to 3 kb and is very likely related to some almost adiabatic uplift and the denudation of a considerable portion of the overlying series, an explanation similar to that proposed by Winkler (1970) for the metamorphic evolution of the Lepontine Alps. In the case of the Alpujarride Domain, this interpretation is further supported by field evidence indicating a considerable degree of erosion prior to the last nappe movements (Blumenthal, 1935; Torres-Roldán, in preparation).

*Magmatism.*—Owing to its somewhat greater complexity, the following review is arranged in relative chronological order with regard to the main Alpine metamorphic events. The first registered igneous event in the Alpujarride s.l. Domain seems to be generalized basaltic subvolcanism which is restricted, however, to the so-called Intermediate Units of the central and eastern Segments of the Betic Zone (Simon, ms; Rondeel, ms; Dimpault-Darcy, Juteau, and Leroy, 1968; Orozco, 1969; Kamp-

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Fig. 4. Distribution of minerals in both Alpine metamorphic events along the various mineral zones distinguished in the Massif of Almuñécar (Alpujarride Ensemble, central segment of the Betic Zone). Assemblages of the first paragenesis grew essentially during an interkinematic period between two events of highly penetrative deformation (D_t and D_n, see Torres-Roldán, 1974). The second paragenesis grew mainly after D_s.
schuur, 1972). Its age can be considered post-Triassic (pre-metamorphic), for reasons similar to those for the basaltic-ultramafic event in the Nevada-Filabride Domain. In fact the genetic affinities of the two events give further support to the previously postulated (Egeler and Simon, 1969) paleogeographical relationship between the two domains. In addition, the finding of some very low grade, high-pressure indicator minerals, produced during Alpine metamorphism (Simon, ms; Rondeel, ms; Kampschuur, 1972), also suggests that these domains were close together during earlier stages of orogenic evolution.

The next step in the magmatic evolution of the Alpujarride Ensemble seems to have been the diapiric emplacement (Loomis, 1972b; Darot, 1974) of peridotite batholiths such as those of Ronda and Beni-Bouchéra, to which the onset of abnormally flat geothermal gradients in a great part of this domain seems closely related. They are not described here (the reader is referred, for more details, to the works of Orueta, 1917; Dickey, 1970; Loomis, 1927b; Darot, 1974; and Kornprobst, 1974) though it must be noted that for Kornprobst (1974, 1976) their emplacement took place in lower Paleozoic or Precambrian times. In the writer’s opinion, however, their demonstrated relationships with alpine H-T, L-P metamorphism in this domain (Loomis, 1972a, 1975; Torres-Roldán, unpub. work), as well as other considerations regarding the whole evolution of the Internal Zones (see below), makes such an ancient age quite improbable for these ultramafic intrusives.

The above-mentioned peridotite batholiths must be considered as composed mainly of almost undifferentiated upper mantle material (Dickey, 1970; Kornprobst, 1974). More differentiated magma seems not to have intruded upper crustal levels in this domain until more recent times. The first direct evidence comes from post-metamorphic dolerite dike swarms, part of which developed prior to the last nappe movements, intruding some upper Alpujarride and Malaguide units of the central and western segments of the Betic Cordilleras. Laccoliths and stocks, sometimes of even more evolved magmas (monzonite, granodiorite), have also been described in northern Africa (Thiébaut, 1952; Bofia, Hilly, and Roubault, 1952; Bellon and others, 1977), though to the author’s knowledge their ascension remains doubtful. Finally, during a last stage of distension similar materials continued to extrude, forming what could be termed the Tertiary calc-alkaline volcanic province of Alboran (maybe up to 4-7 m.y. ago, Bellon and others, 1976; Bellon and Hernandez, 1976).

THE MALAGUIDE ENSEMBLE

Metamorphism.—If from the stratigraphical point of view the Malaguide is the best known of the three Betic Ensembles (Blumenthal, 1980; Kockel, 1958, 1963; Azéma, 1951; Geel, 1973), the situation is reversed as regards metamorphic evolution. Most of the available petrographic data are from Mollat (1968), Buntfuss (1970), Boulin (1970), and still unpublished work by the author. The main difficulty is that most of the
typical Malaguide rock series are almost untouched by metamorphism. Alpine recrystallization seems always to be practically confined to the lowermost part of the series, below the first rather well dated strata (phyllic schists, quartzites, and conglomerates of probable Silurian age; Blumenthal, 1930), in what could be considered either a pre-Silurian basement of the whole Malaguide Series (see "ensemble inférieur" of Boulin, 1970, or the "basal gneiss complex" of Mollat, 1968, and Buntsfuss, 1970) or a distinct tectonic unit belonging to the Alpujarride Ensemble (compare Durand Delga, 1968). On the basis of field experience, however, most of the above-mentioned authors, as well as the writer (Torres-Roldán, unpub. work) favor the former possibility. In the eastern part of the Montes de Málaga, for instance (compare Boulin, 1970), a sharp increase of crystallinity can be observed from this limit on down, but some peculiar Alpine metamorphic minerals (for example, andalusite) can be observed to trespass it (see, also, Mon, 1971). Assuming that the boundary is mainly stratigraphic, this fact can be interpreted, as in some cases in the Alpujarride Ensemble, in terms of a "basement effect" (Fonteilles and Guitard, 1968, 1972). If so, then an important corollary is that in the Malaguide original realm (and in the Alpujarride, if the series are roughly correlated) the effects of the Hercynian orogeny have been negligible — at least from the point of view of metamorphism — and that the pre-Alpine metamorphism in the basement of the Malaguide and Alpujarride sequences is of Caledonian or older age (compare, however, Foucault and Paquet, 1971).

Currently available descriptions, as well as more recent observations by the author, permit a clear correlation between the Alpine metamorphic evolution in this group of Malaguide units and that of the Alpujarride Ensemble. Here also metamorphism has been plurifacial. The first event produced the pair biotite-garnet and/or a general increase of crystallinity, whereas the second is marked by porphyroblastesis of new biotite, chloritoid, and andalusite (staurolite, cordierite?). Above the assumed pre-Silurian basement of the series, the rocks become progressively less affected up to the Mesozoic or younger deposits, which appear completely untouched by metamorphism.

The above conclusions are particularly important, for they clearly suggest that most (or all) of the rock series that we now range in the Malaguide Ensemble were situated at the top of a stack of nappes at the time of Alpine metamorphism. In the rest of this paper the portion of the crust where the geothermal gradients were abnormally flat is referred to as the Alpujarride-Malaguide Tectonic Domain. This does not imply, of course, that the well-known differences in stratigraphic development between Alpujarride and Malaguide units are to be neglected, for they constitute the basis of the prior (mainly paleogeographical) subdivision, which should be continued in usage.

Magmatism.—No Alpine pre-metamorphic igneous rocks have been observed in the Malaguide domain. On the other hand, the syn- as well
as post-metamorphic igneous evolution is identical to that of the major part of the Alpujarride (s.str.) domain giving additional support to treating the two domains as a single one at that time. Dike rocks of basaltic to quartz dioritic composition are especially well represented in the central and western segments of the Betic Zone.

THE POSSIBLE TECTONIC IMPLICATIONS OF THE DIFFERENTIAL
PETROLOGIC EVOLUTION OF THE BETIC ENSEMBLES

It follows from the foregoing discussion that the Betic ensembles can be reclassified in a twofold way, the two groups displaying evidence of having been subjected to different physical conditions; that is, of having occupied different crustal domains. Metamorphic evolution has been quite complex in all, but a first group, which includes especially the terrains in the Nevado-Filabride Ensemble, is marked by a very important high-pressure event, whereas the second, that is the terrains ranged in the Alpujarride (s. str.) and Malaguide Ensembles, bear mainly facies series in the medium- to low-pressure range. Even at first sight, the confrontation of these metamorphic histories with the present spatial relation between the two groups of terrain (see figs. 1 and 2) leads one to approach an interpretation of the evolution of the Betic orogen in two steps. A first step should involve discussing the largely unknown original relations and dynamics of such obviously different portions of the crust, and a second should concern especially the path these originally different tectonic domains have followed to reach their present position. Taking into account the largest possible amount of already acquired data (see references), a basic evolutionary model using this two-step approach is proposed in the following sections. A more detailed discussion of the model, based mainly on available geophysical data, is given in a later section.

“Collisonal” stage.—Historically, the model implies first the collision of European and African lithospheric plates. This collision is considered responsible for individualizing both groups of terrains, according to a scheme similar to that proposed by Miyashiro (1972a, b, 1973). High-pressure assemblages, which characterize the first episode of Alpine metamorphism in the Nevado-Filabride Ensemble, would have originated by subduction of the European crustal block under the African one (compare models of Miyashiro, 1972a, b; Ernst, 1971, 1973), a hypothesis that also provides an adequate interpretation of some other peculiarities of the Nevado-Filabride terrain. The most significant of these is perhaps the kind of ultrabasic-basic rock association present here, which has been known for a long time (see, for instance, Zermatten, ms; Patijn, ms; Jansen, ms). Briefly, it consists of sheet-like interlayered bodies, most of them now strongly altered because of Alpine metamorphism. A great deal of work remains to be done on this association, but from what is known at present, they may be considered either as tectonically dismembered (and metamorphosed) relicts of an earlier ophiolite suite or as relicts of basic and ultrabasic material injected during subduction.
along zones of weakness, as suggested in general by Dewey and Bird (1970). Both explanations are in good agreement with the geological setting just proposed. The existence of a rather generalized sodium metasomatism (hydrothermal?), which resulted mainly in the growth of abundant neoformed albite (Puga and Fontboté, 1966; Gomez-Pungnaire, personal commun., 1976), could also be related to deeper petrologic processes in the descending slab, as suggested by Fyte and Mc Birney (1975).

South of the postulated subduction zone, in the overthrusting block, a strikingly different sort of environment is called for. In this realm, initial compressive stresses should have produced a first piling-up of nappes, whose existence is necessary to account for the pressure requirements of the metamorphic evolution observed in the Alpujarride-Malaguide tectonic domain (see Torres-Roldán, 1974). Such an overthrusting event could be related to the lack of post-Early Mesozoic sedimentation in most of the Alpujarride rock sequences (see Egeler and Simon, 1969; Fontboté, 1970), a question of special interest that has received diverse explanations, the most favored of which supposes it to be due to general emersion of the realm during this lapse of time. The original Malaguide domain would have occupied a slightly subsiding basin situated north (Durand Delga, 1966) or south (Fontboté, 1970) of the Alpujarride basin, according to different paleographical reconstructions. Nevertheless, an alternative hypothesis involving the concept of "tectonic transgression" had been proposed by some of the earlier students of the Betic Zone (Banting, 1933; Van Bemmelen, ms; Westerweld, ms; Patijn, ms) and further supported (although on other grounds) by Hoepfener and his collaborators (1963), particularly Dühr (1967). Effectively, it seems that the occurrence of significant tectonic activity in Jurassic time cannot be disregarded (compare Fontboté, 1970; also Bourgois and others, 1972; Bourgois, 1974), but most of it resulted from regional extensional movements (see also Dewey and others, 1973). The first compelling evidence indicating compressive tectons in this area is assigned to Late Cretaceous time (see below), and, as far as the author is concerned, the first overthrusting event in the Alpujarride-Malaguide Domain more likely occurred in a later stage (Upper Cretaceous-Paleocene?), perhaps in relation with continental collision as discussed in the next section.

As indicated schematically in figure 4, the flat geothermal gradient in the Alpujarride-Malaguide realm is interpreted as the result of diapiric uprise of hot mantle material, triggered by the descending lithospheric slab. Apart from other evidence dealt with below, there is a close relationship between huge peridotitic intrusives and nuclei of high intensity of metamorphism (Loomis, 1972a,b; Torres-Roldán, unpub. work). As discussed above, the time of emplacement of these peridotite batholiths, the best known of which are those of Serranía de Ronda in Spain and Beni-Bouchera in Northern Morocco, still seems to be a matter of debate (see Kornprobst, 1974; Fontboté, in Julivert and others, 1974), even if
most of the recent work leads one to assume a far more recent age of intrusion than previously supposed (compare Loomis, 1975). Furthermore, the presently available data on their internal composition as well as on the kinematics of intrusion (Dickey, 1970; Loomis, 1975; Darot, 1974; Obata, ms) suggest that these massifs are high-temperature intrusions of almost undifferentiated intracontinental mantle (Nicolas and Jackson, 1972). Both age of emplacement and type of intrusion can therefore be regarded as in excellent accordance with the present model.

Direct evidence of an evolved intermediate to acidic surface volcanism during this stage is very scarce if not completely lacking, perhaps merely because of the immaturity of the whole process of magma generation at that time, or perhaps because of intensive erosion of upper levels of the crust before the later nappe events. Indirect evidence favors the later possibility. Dike swarms, filled with basic to intermediate members of the calc-alkaline series, are strongly developed in some units of the Malaguide-Alpujarride Ensemble of the Betic Zone (Torres-Roldán, unpub. work), which could witness to igneous activity in this tectonic domain. On the other hand, the dike rocks probably share a parental relationship with the earlier episodes (cal-alkaline also) of the well-known volcanic province of Alboran. Two K/Ar measures on these rocks have given results of $51 \pm 3$ and $63 \pm 3$ m.y.$^4$

Recent stratigraphical examination of the post-Triassic sedimentation in the cover of some units of the Malaguide Ensemble has shown that deposition in this domain was more or less continuous at least until the Eocene (Paquet, 1969; Geel, 1973). Thus it can be assumed that the above situation continued until approximately that time. Nevertheless, the evolution of the facies series in both metamorphic realms (see fig. 3) clearly indicates the imminence of changes in the structural setting of the region. All evidence would actually suggest that, after an undetermined period of crustal consumption, convergent movements stopped, thus allowing the ascent of isotherms in the downgoing (Nevado-Filabride) slab. At this time, the tectonic development of the region seems to have become considerably more complex, because of the interaction of several (deep and surficial) processes in both tectonic domains. The overriding of the Nevada-Filabride domain by crustal slides of the Alpujarride-Malaguide domain, for instance, could be considered as the result of “tectonic” denudation, following the “normal” denudation invoked previously to explain the shifting toward lower pressures of many geothermal gradients in the Alpujarride-Malaguide tectonic domain. In both cases, the causal mechanism for denudation would have been the gravity potential induced by the doming-up of the crust in this domain, in response to diapirism of the mantle below.

Transcurrent movements.—To the north, an approximately buoyant recovery of some of the lighter crustal material (subducted in the course of the collision) must be envisaged, in order to account for the preserva-

$^4$ The author is indebted to Dr. M. Bellon (Univ. of Paris, Orsay) for determining these dates.
tion of relicts of the previously formed high-pressure, low-temperature assemblages. How this recovery occurred is still obscure, though some evidence indicates that a large amount of movement had taken place, previous to the Eocene, along the boundary between internal and external zones of the Betic Cordilleras (Paquet, 1974; Dewey and others, 1973). This boundary shows striking features, which have received different interpretations in the past. The most classical view regards it as being merely the front of the internal nappes over the external domain (Blumenthal, 1985; Fallot, 1948), although the previous existence of a furrow of double subduction has also been proposed (Durand Delga, 1966). Anyhow, more recent observations indicate that before the end of the last nappe event, this boundary acted as a large transcurrent fault (Paquet, 1974; see, also, Andrieux and Mattauer, 1973), the southern side moving westward relative to the European block. Data collected by Paquet (1966, 1968, 1970) along the eastern part of the boundary would suggest that most of this transcurrent motion took place before the Middle Eocene (see, however, Hermès and Kuhry, 1969). The occurrence of such important movements in the course of the last event of nappe translations accounts for the complexities observed in other sections, as for example the one studied by Durand Delga and Fontboté (1960) north of the Sierra Nevada, where higher Alpujarride and Malaguide units override the external zones for several kilometers (see fig. 2). Additionally, this interpretation, which implies that the internal zones were originally localized several hundred kilometers more to the east, has the advantage of offering a better “matching” of the Triassic lithological facies (see Bosellini and Hsü, 1973), supporting, moreover, the previous existence of a continuous Alpine orogenic belt, as suggested by Alvarez, Cocozza, and Wezel (1974) and Alvarez (1976).

At this step in the presumed evolution of the Betic Orogen, after the postulated juxtaposition of Internal and External Domains of the Betic Cordilleras, the way in which such an evolution could integrate with some of present features of this western end of the Alpine chains must be examined. Special attention will therefore be paid to: (1) the problem of the relation between the North African chains and the Betic Zone of the Betic Cordilleras, and (2) the origin of the Alboran and related basins.

THE RELATION BETWEEN THE NORTH AFRICAN CHAINS
AND THE BETIC CORDILLERAS

This first question involves an explanation for the so-called “Arc of Gibraltar.” The matter has been subjected to debate for such a long time (see Fallot, 1948) that it is surprising that no general agreement has been reached up to this moment, in spite of the far more advanced knowledge of the region that has resulted from research work in the last decade (see Didon, Durand Delga, and Kornprobst, 1973). Apart from those who have denied the existence of the arc itself (for example, Staub, 1934), hypotheses regarding the significance of the arc can be summarized in
two groups. The first, including Blumenthal (1933), Fallot (1948), and more recently Glangeaud, Bobier, and Bellaiche, 1967, regards the two chains on the opposite sides of the strait of Gibraltar as independent; that is, the "arc" is a secondary superimposed structure. The second interprets the "arc" as being a real virgation of the Betic Orogen, which is, therefore, thought to be continuous through it. The latter hypothesis seems to be the preferred one in more recent papers, despite different general interpretations (Andrieux, Fontboté, and Mattauer, 1971; Durand Delga, 1966, 1972). In part, the strongest basis for this way of thinking has been the geological continuity and, especially, the symmetrical placement of internal zones on both sides of the Alboran Sea (Durand Delga, 1972; Didon, Durand Delga, and Kornprobst, 1973). Unfortunately, all these statements have been based mainly on observations carried out on the western segment of the Betic Zone and have largely neglected all the data reviewed above concerning the Nevada-Filabride Ensemble. As a whole, it is important to note that this symmetry between internal zones in Northern Africa and the Betic Cordilleras does not actually exist, because terrains of the high- to medium-pressure belt (N-F) are conspicuously lacking in the former.

Thus, explanations for the Betic-Rif Orogen involving any kind of bilimalar tectonics (Andrieux, Fontboté, and Mattauer, 1971; see, also, Durand Delga, 1973) should be somewhat modified. Data dealt with elsewhere in this paper can be better interpreted by admitting that the Internal Zones of the Betic Cordilleras and those of the North-African Chain were once integrated in only one and the same orogenic belt, as schematically indicated in figure 5. In part, the arc-like bending of the front of nappes in the strait of Gibraltar could be the result of a centrifugal emplacement from the central upward of the Alboran region. This latter idea obviously resembles the perhaps more classical views on the problem (see above), though modified with regard to the unity of the westernmost alpine belt.

THE ALBORAN AND RELATED BASINS

The origin of the Western Mediterranean Basins has been a much discussed problem in the course of the last decade, and there has been a variety of propositions (Ritsema, 1970) whose bases are, fortunately, easily summarized. Van Bemmelen (1969) has proposed a composite mechanism involving subcrustal erosion as well as "in situ" substitution (basification) and subsidence, whereas a breaking of previous continental crust followed by lateral spreading of the resultant block has been claimed by others (Le Pichon, Pautot, and Weill, 1972; Auzende, Bonnin, and Olivet, 1973; Olivet, Auzende, and Bonnin, 1973). Apart from Van Bemmelen (1969, 1972a,b, 1974) the first model, or a more or less modified version, has been favored by Glangeaud, Bobier, and Bellaiche (1967) and on diverse grounds also by De Booy (1969), Ritsema (1970, 1972), Schuiling (1972), and Storevd edt (1973). The reader can easily imagine how complicated the present status of opinions and arguments is, in
view of the corresponding complexity of the starting and present situations. Nevertheless, it must be noted that, even if each of these models makes some quite correct assumptions, in general they agree only partially with geological data. The hypothetical evolution reviewed above would indicate that the origin of the Alboran Sea Basin, as well as that of the other well-known intermontane depressions in the Betic Cordilleras, should be a continuous phenomenon consequent on previous structural development. In the foregoing, for instance, evidence for vertical movements causing the undulation of the Alpujarride-Malaguide tectonic domain has been reviewed, starting with the particular evolution of the geothermal gradients in this domain and including, perhaps, an important event of gravity-directed nappe gliding, which possibly took place as a paroxysmal response to the gravity potential induced by the doming-up of the crust. In fact, at that time the local stress environment in that part of the crust may have been far from pure compressional, as is strongly suggested also by the occurrence of extensive magmatic infiltration along relatively extensional systems of fractures which, at least in part, preceded the movement of nappes (Torres-Roldán, unpub. work; see, also, Biot, 1969). When the causal mechanism of undation (in this case thought to be the process of mantle disipism) ceased, the next expectable step would have been a generalized collapse, thus initiating the development of the present basins, which are more than likely floored by foundered remnants of more or less transformed continental crust.

In summary, one could conclude that more than one mechanism would have been present in the weakening of previous continental crust in the westernmost Mediterranean. Intensive erosion at the top of an uplifted portion of the crust, “in situ” substitution of denser mantle-derived material for sialic rocks, as well as a gravity-directed migration of supracrustal slides may have played significant roles. After that, the arched roof of the undation would have collapsed, with the subsequent foundering of the central sector (Alboran s.l. basin) and the individualization of some intermontane depressions. The ages of the first sediments deposited on the floor of the new basins are fairly concordant: late Miocene (maybe earlier) in the Alboran basin (Joides Hole 121, Montenat, Bizon, and Bizon, 1974), middle Miocene for the Granada Depression (González-Donoso, 1970), and Early Miocene (Aquitanian?) for the Gaudíx-Baza Depression (Vera, 1970). A combined estimate would therefore suggest an Early Miocene age for the beginning of the event, though a more complete individualization of the basins was not achieved until late Tortonian times (Vera, 1970; Montenat, 1973; Montenat and Bizon, 1976). That some of the last movements of internal nappes seem to have taken place after the Late Oligocene (Durand Delga and Fontboté, 1960) or even after the Lower Burdigalian (allochthonous flyschs, Bourgois and others, 1972) emphasizes the continuity of the whole process.

All these data agree well with what has been called the “Mediterranean type” of oceanization (Van Bemmelen, 1969, 1974), though with
modifications with regard to the relative importance of the componental processes. They seem to be more in line, for instance, with the views of Hsü (1965) or Shuiling (1972). In any case, no clear geological evidence seems to exist that could support the hypothesis of extensive lateral spreading of blocks in the regions around the Alboran Sea.

DISCUSSION

Although the scheme of evolution proposed in the preceding chapter is based mainly on geological data, it should also be able to account for pertinent geophysical information. Thus, even if, unfortunately, the latter is not as complete as desired, available geophysical data are used here as an appropriate test for the validity of some of the inferences made in the model.

REGIONAL PLATE KINEMATICS

Initially, the most promising analysis is the one that takes into account plate kinematics in the area since Mesozoic times. Paleomagnetic data (Van der Voo, 1969; Van der Voo and Zijderveld, 1971) are, however, limited to illustrating the sinistral rotation of the Iberian Peninsula, which, on the basis of diverse reasoning (see Dewey and others, 1973), seems to have occurred between Late Jurassic and Early Cretaceous (148-111 m.y.). A much more complete approach is provided by the observed pattern of continental drift in the Atlantic and its corollaries for relative movements between the European and African major plates. The best available set of results is the one derived from the data of Pitman and Talwani (1972) by Dewey and others (1973), which will, therefore, be used for confrontation. Although not discussed previously, a first problem is that the model implies the consumption, and hence the previous existence, of a portion of oceanic crust between the European and African lithospheric blocks. From the geological point of view this implication has been the matter of long debate, mainly because it seemed in conflict with other evidence suggesting that the crust along the Tethys belt was of continental type (De Booy, 1967). Van Bemmelen (1974) has also stated that the "Tethys Zone" was not an ocean but a submerged land (called "Tethica" by him).

At present, this problem is by no means cancelled by the unanimity with which the existence of such portion of oceanoid crust is claimed in recent interpretations, where the plate tectonics approach is used to explain the evolution of the western Alpine chains (for example, for the Alps proper, see Dewey and Bird, 1970; Oxburgh, 1972; Dal Piaz, Hunziker, and Martinotti, 1972; Ernst, 1973b; Bocquet, ms). Perhaps the question would be clarified by considering also the possibility that this oceanic area was created in the lapse of time immediately preceding its own "consumption." In the case of the Western Alps, this latter possibility has received strong support from evidence of ophiolite emplacement as well as from stratigraphical analysis of Jurassic sedimentation (Trümpy, 1971, 1975; Debelmas, 1975) which, moreover,
are also found in the Betic Cordilleras (see the previous review of magmatism in the Nevado-Filabride Domain; García Hernandez and others, 1976). This interpretation would be further strengthened if relative exten-
tional movements between Europe and Africa were dominant during this interval (Dewey and others, 1973). For these reasons, even if defini-
tive data to decide the extent and the type of crust that could have resulted from this process are lacking, the writer is of the opinion that
the existence in the Late Cretaceous of more or less isolated areas with

crust of oceanic affinities cannot be absolutely rejected (compare, also,
Van Bemmelen, 1974). Anyway, the magnitude of this assumed oceanic
area, consumed in the Alboran orogen, must not have been great (per-
haps on the order of several hundred kilometers and probably diminish-
ing to the west); the main argument is, perhaps, the marked underdevel-
opment of some related phenomena, especially magma generation in the
crust and related plutonism. More accurate calculations are very difficult
to make in the absence of additional information about several para-
eters, including rate and precise time during which subduction could
have taken place.

A combined argument, which takes into consideration data coming
from geology as well as from the study of the opening of the Atlantic
Ocean, would suggest that a consuming plate margin could have been
active in the westernmost Tethys area from the Late Cretaceous to the
Paleocene (compare, for example, the existence of important nappe
movements and of generalized sedimentary hiatuses of early to Late
Cretaceous age in the Subbetic realm of the Betic Cordilleras; Garcia-
Dueñas, 1969; Fontboté, 1970; Sanz de Galdeano, 1976; Cruz-San Julian,
1976), but this same argument hardly suggests why it stopped. A change
in general plate kinematics (Atlantic 6 phase of Dewey and others, 1973)
agrees well with the possible appearance of important dextral trans-
current motions of pre-Eocene age in this area, although it does not
necessarily imply a complete end of the convergent movements between
proto-Africa and proto-Europe. One might envisage the exhaustion of
the postulated Nevado-Filabride oceanic gap and a subsequent contin-
tental collision producing the first (syn-metamorphic?) nappé event in
the Alpujarride-Malaguide tectonic domain. At this time (Eocene?) in-
icipient reversed subduction has surely taken place more to the south,
probably profiting by the existence there of a secondary zone of crustal
weakness (the North-African “flysch basins”). An important amount of
crustal shortening and other tectonic features of the present boundary
betwen external and internal zones of the North African Chains could
possibly be explained in this way (compare, also, Andrieux, Fontboté,
and Mattauer, 1971; Paquet, 1974; Fenei, ms; and others) (fig. 6). In
the Betic Zone, the preservation of high-pressure assemblages must be
related, at least in part, to this stoppage, which could have made possible
the rapid exhuming of a portion of the previously subducted crust (see
fig. 5).
Fig. 5. Interpretative crustal sections through the Betic Cordilleras and adjacent Alboran region (central segment). The drawings are intended to illustrate the main ideas in the text and, therefore, should not be taken as reflecting a detailed real picture. Cross-hatching in (A) indicates supracrustal thickening caused by an earlier stacking of nappes (previous to paroxysmal metamorphic events in the Alpujarride-Malaguide tectonic domain). In (A) and (B), the width of the crust has been almost arbitrarily chosen, though in (C), data from Payo (1965), Ansorge and others (1976), and Hatzfeld and Boloix (1976) as well as from crustal modelling based on gravimetric and magnetic information (Demnati, 1972; Bonini, Loomis, and Robertson, 1973) have been taken into account. Although not represented, the finding of some very low-grade, high-pressure index minerals in barely metamorphosed basic intrusives of the Intermediate Units (pumpellyte-croscite, Simon, 1963; croscite-glauconaphane, Rondel, ms; Kampschuur, 1974) would also suggest some dragging down of material in the margin of the upper plate. The "instantaneous" character of each frame has hampered the adequate representation of important Neogene calc-alkaline extrusive activity, part of which could be regarded in continuity with the dike intrusion pictured in (B). North of the Sierra Nevada, nappe transport may have been further enhanced by later sliding provoked by the isostatic uplift of the Sierra. Not completely to scale (see text for additional explanation).
MANTLE DIAPIRISM

The causal mechanism for the proposed undation of the Alpujarride-Malagueña tectonic domain is herein regarded as sharing a genetical relationship with the prevalence of flat geothermal gradients in that domain. There is a notable agreement among diverse workers (Hasebe, Fujii, and Uyeda, 1970; Oxburgh and Turcotte, 1971; Miyashiro, 1972a, 1973) in concluding that such flat gradients could not be established in the course of a reasonable lapse of time without the concurrence of some additional heat transport (magnatic intrusion, for instance). In the Alpujarride-Malagueña tectonic domain, corroborating a previous view of Moores and McGregor (1972), this heat transport is clearly related to hot diapiric intrusive bodies such as those of Ronda and Beni-Bouchera, the meta-

![Diagram](image)

Fig. 6. Sketch illustrating a possibly diachronous sequence of major tectonic events in the westernmost Mediterranean area from Triassic to Eocene times. Note that, prior to the Upper Paleocene, the whole system must have been situated perhaps several hundred kilometers more to the east than in present time. See text and figure 5 for explanations. Key to symbols: EF: European foreland; NF: Nevado-Filabride crustal domain; A: Alpujarride s.l. crustal domain; M: Malagueña crustal domain; AF: African foreland. The original palaeogeographical relationships among the present Betic Domains are those proposed by Egeler and Simon (1969) and Fouquet (1970).
morphic evolution of whose aureoles can be quite compellingly correlated with metamorphic evolution elsewhere in the same domain (compare, also, Westerhof, 1977). Intrusion of these batholiths in the crust should have been accompanied by the general diapiric rise of a low-density anomalous portion of the underlying upper mantle, which in turn can be considered responsible for the undation of the overlying crust, as proposed above. It must be noted that the occurrence of such phenomena in relation to consuming plate margins is supported by a large number of geological and geophysical observations, as discussed for instance by Karig (1971) and Barazangi, Pennington, and Isacks (1975). The origin of the low-density anomalous zone in the mantle can be explained, if some fusion takes place, as would be the case if some water is introduced into such a system from the descending lithospheric slab (Wyllie, 1971).

Other interpretations of the Alboran Orogen also involving mantle diapirism have been proposed by Van Bemmelen (1954, figs. 2a and 2b, 1973) and Loomis (1975). Particularly, the model of Van Bemmelen fits well with some of the data discussed here, though, in the writer's opinion, it should be filled out a good deal before it can account for many geological features of the present cordilleras. Van Bemmelen's standpoint, however, is rather different from the one proposed here, especially as concerns the causal mechanism for the process of mantle diapirism. The interpretation of Loomis (1975), on the other hand, which considers an extensional environment for the intrusion of the ultramafics, seems supported neither by recent studies on their emplacement mechanics (Darot, 1974) nor by detailed local geological studies (compare Durr, 1967; Buntfuss, 1970; Torres-Roldán, unpub. work).

Furthermore, concerning all these points, a number of similarities would suggest the treatment of the Alboran Basin (and perhaps also the Western Mediterranean Basins in general) as "marginal" (Karig, 1971), although in a wider sense than in the Western Pacific (that is, the Alboran Orogen should have been of the "Cordilleran" type). Geological setting, for instance, has just been discussed, whereas strong positive gravity anomalies are generally lacking (see fig. 7; Allan and Morelli, 1971). Data about heat flux are still scarce (Ryan and others, 1971; Hsii and others, 1976), but all the measured values are high (for example, 2.29 \(10^{-6}\) cal/cm\(^2\) sec were measured by Hsii and others, 1976, at the JOIDES drilling site 372A in the Balearic Basin); of great interest also is the apparent permanence of a low-velocity channel in the mantle, just below the crust-mantle boundary (Berry and Knopoff, 1967), even in the Alboran Region (Hatzfeld and Boloix, 1976; Ansoerge and others, 1976). Some workers (that is, Le Pichon, Pautot, and Weill, 1972; Auzende, Bonnin, and Olivet, 1973) have also regarded the Alboran and related basins as marginal and (according to ideas from Karig, 1971) have subsequently proposed lateral drifting mechanisms for their origin, which have later been claimed to be supported by patterns of magnetic anomalies (Bayer, Le Mouel, and Le Pichon, 1973). The writer, however,
Fig. 7. Map of Bouger gravity anomalies (in milligals) of the western part of the Alboran Sea and adjacent areas (from the compilation made by Bonini, Louis, and Robertson, 1973). Important geological boundaries have been added to illustrate mutual relationships. In the small sketch at the lower left, the zero isobane has been emphasized as an approximate boundary between erosion and uplift. Arrows indicate possible migration paths of material formerly on the top of the central Alboran undulation.
agrees with Storiedvedt (1973) when he remarks that the actual pattern of anomalies (see also Vogt, Higgs, and Johnson, 1971) is much more in line with a process of crustal foundering. In contrast to a model of opening by pure lateral drifting of rigid microplates, this kind of evolution, which, at least initially, involves significative vertical movements, might be suggested in general for “marginal” basins originating in this type of structural environments.

SEISMICITY AND CRUSTAL STRUCTURE STUDIES

Recent seismic activity in the Alboran and adjacent areas has been reviewed by Udías and López-Arroyo (1972), who have also investigated the focal mechanism of some of the more important earthquakes along the fracture zone from the Azores to Gibraltar. The resulting data, however, are still insufficient to provide an effective correlation with the geological framework. In particular, there still remains the problem of the western ending of the Betic Orogen, which in spite of recent proposals (Andrieux, Fontboté, and Mattauer, 1971) is not yet well understood. Focal mechanisms studied by Udías and López-Arroyo (1972) indicate that the fracture zone going from the Azores to the area of the Alboran sea changes its structural regime from transcurrent along the stretch Azores-Gibraltar to overthrust more to the east, the southern block going over the northern one. It may be suggested that the situation has been somewhat comparable in the past (compare Dewey and others, 1971), and that at present the eastern end of the fracture zone is buffered in the Alboran Region (Udías, López-Arroyo, and Mezcua, 1976). Previous deep fracturing is also suggested by gravity data (Robertson, ms; see fig. 7 of this paper), which may have contributed to the rather abrupt termination of the Nevada-Filabride outcrops west of Granada.

Up to the present, the structure of the crust in the Alboran region is rather poorly known, although some preliminary results from deep seismic sounding programs are already available (Ansoerge and others, 1976; Hatzfeld and Boloix, 1976). Apart from these, our knowledge is based mainly on gravity data, from which several models have already been derived (Demnat, 1972; Bonini, Loomis, and Robertson, 1973). In spite of possible indeterminacies caused by uncertainties in assumed density distributions, the latter are of special interest herein, because they provide the only available three-dimensional insight into the problem. In fact the most prominent feature of the map of gravity anomalies (fig. 7) is the arcuate negative zone that crosses the strait of Gibraltar. This peculiarity can be interpreted (Demnat, 1972; Bonini, Loomis, and Robertson, 1973) as reflecting the continuity of continental-type crust across the strait. In figure 7, the arrows indicate possible paths of centrifugal (normal and/or tectonic) denudation from the postulated Alboran upwarp, in relation to the model of crustal thinning proposed in the above paragraphs.
of the Betic Zone (Betic Cordilleras, Southern Spain)  

FINAL REMARKS AND CONCLUSIONS

Through the preceding sections, one of the author's main purposes was to show how important, as well as suggestive, it is to consider the available data on the petrologic evolution of the various internal ensembles as clues to the geotectonic evolution of the Alboran Orogen. It is clear that the mere discussion of these data, together with other available geological and geophysical information, could lead to a far better understanding of many geological facts in the orogen than previously achieved. The proposed model is a first attempt, even if it does not represent a unique solution to the very complex picture offered at present by the western end of the Alpine Belt. The author is well aware of his somewhat excessively schematic treatment of many problems and of corresponding gaps in the discussion of particular important questions. Part of this may be due to the writer's special familiarity with the central and western segments of the Betic Zone, whereas his knowledge of other areas (especially that of the North African chains) is heavily dependent on literature.

There have been subjects, however, which, in spite of the appropriate framework offered by the model, have not been dealt with in more detail because of the many remaining uncertainties: the kinematics of the postulated plate interactions (including the first event of overthrusting in the Alpujarride-Malagueide Tectonic Domain), for instance, and the origin of flyschoid formations. As mentioned above, the first question would demand a more refined knowledge of the internal structural development of the various internal domains (at present a number of tectonic correlation problems still remain) and particularly also of the absolute timing of the various metamorphic events. The second problem, that is, that of the origin and later evolution of the so-called "peri-Mediterranean allochthonous flysches (Durand Delga, 1972) cannot be reasonably linked to any model before their source area or areas are more certainly known. However, there is a notable convergence between the evolving history proposed here and that postulated by Caire (1971, p. 75) on grounds of regional geology. Intensive erosion of the uplifted unstable Alpujarride-Malagueide Tectonic Domain ("geanticlinal kabyle" of Caire, 1971) must have contributed to the origin of some of the flysch formations.

To summarize, the information discussed in this paper suggests that the geotectonic evolution of the Westernmost Alpine Orogenic Belt occurred in the following stages:

1. Onset of a "collisional" consuming margin between the European and African lithospheric blocks, which removed a portion of previously created oceanoid crust. Convergent movements would have started, according to various sources of evidence, in early Late Cretaceous times. This convergence is responsible for the differentiation of two crustal domains, each characterized by a particular metamorphic and igneous evolution (that is, the Nevada-Filabride and Alpujarride-Malagueide Tec-
tonic Domains), whose present geometrical relationships indicate that the subduction should have been directed southward. Diapiric rise of anomalous mantle above the descending slab caused both a flat geothermal gradient in and the doming-up of the overlying crust. Intensive denudation of the latter yields perhaps some of the material for flyschoid sedimentation in adjacent relatively subsident areas.

2. Whether because of continental collision or for other causes, the collisional process stopped, perhaps being replaced by large dextral transcurrent movements responsible for the present juxtaposition of external and internal zones in the Betic Cordilleras. Stoppage allowed for isostatic (?) recovery of part of the previously subduced materials and preservation of relics of high-pressure, low-temperature metamorphic assemblages despite ascending isotherms. More differentiated magmas, mainly of mantle origin, intruded upper levels of the crust in the Alboran center, whereas a paroxysmal, gravity-directed, tectonic denudation spread from the central part. The whole process would have been accomplished by the Early Miocene.

3. In Early Miocene time, the arched roof of the undulation began to collapse, perhaps originating the present Alboran Basin and some intermontane depressions (for example, those of Granada and Guadix-Baza). At this time calc-alkaline magma was extruded along new fractures or fracture zones unrelated to previous tectonic directions (for example, Cabo de Gata-Cartagena, others in Northern Africa).5

4. At present, there is some evidence (Auzende, Olivet, and Bonnin, 1971; Montenat, ms; Montenat and Bizon, 1976; Sanz de Galdeano, 1976) suggesting that compressive stresses, perhaps previously obliterated by the local extensive environment caused by mantle diapirism, again command the scene, as should perhaps have been expected from data of the kinematics of the major intervening blocks (Dewey and others, 1973).

Finally, some remarks must be made regarding the mostly two-dimensional nature of the evolutionary model just proposed. The writer is, of course, conscious that such a model is quite unsatisfactory, but a three-dimensional interpretation would involve such a complex reassembly of what presently seem like dislocated parts of the same orogenic belt (see Alvarez, Cocozza, and Wezel, 1974) that much more data will be needed before a truly reasonable solution can be attempted. The author, however, expects that some of the ideas in this paper could be useful for a further approach to this more desirable stage.

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5 Neglecting these points had led some workers to propose contradictory Benioff zones (compare Arana and Vegas, 1974; Delarue and Brousse, 1974) on the basis of different groups of outcrops. As a whole, however, calc-alkaline volcanism in the Alboran region should be considered as a coherent petrographic province.
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