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TERTIARY MANTLE DIAPIRISM, OROGENY, AND PLATE TECTONICS EAST OF THE STRAIT OF GIBRALTAR

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ABSTRACT. K-Ar dating of biotite, muscovite, and whole-rock samples from the metamorphic aureoles of high-temperature ultramafic intrusions in Spain (Ronda) and Morocco (Beni Bouchera) suggest an age of intrusion at the end of the Oligocene or early Miocene. In some samples the retention of inherited Ar by cordierite must be considered. The massifs have been interpreted previously as high-temperature mantle diapirs that have penetrated to continental crust on the basis of the petrogenesis of the metamorphic aureole and of basic layers within the massif, contact deformation structure, and gravity anomalies. They are part of two dense zones delineated by high positive Bouguer gravity anomalies, which radiate northeast and southeast from Gibraltar along the western margins of the Alboran Sea to about long 4° W. A central Alboran Sea high continues to the east into the Western Mediterranean.

The ultramafic massifs and associated metamorphic rocks and high gravity trends are interpreted as evidence of crustal thinning by lithospheric extension. The early Miocene age of ultramafic intrusion coincided with the onset of volcanism farther east associated with this extensional system. The geometry of extension and radiometric age dating implies counter-clockwise rotation of the Iberian Peninsula relative to Africa about a point near the Strait of Gilbraltar in the early Miocene. There is no evidence of strike-slip movement through the Strait of Gibraltar. This was also a period of upper crustal tectonic activity in the seaward zones of the Betic and Rif orogens that resulted in landward movement of allochthonous "flysch" units commonly supposed to be related to compression between Spain and Africa. From the evidence of lithospheric plate extension in the Miocene presented here, however, a model relating this upper crustal tectonic event to mantle and lower crustal extension is proposed. It is suggested that during mantle upwelling in the lithosphere the continental crust thinned plastically at depth while undergoing the observed metamorphism to maintain a continuous cover over the upwelling region. Probable extensional faulting near the surface as a result of lithospheric extension, coupled with the mobility of evaporite and "flysch" Mesozoic and Tertiary stratigraphic units, resulted in widespread allochthony driven by gravity.

The thick cover sequence above the Ronda massif in Spain during early Miocene emplacement, deduced from metamorphic petrogenesis, must have been removed rapidly to expose the massif to erosion also in early-middle Miocene time. It is suggested that the western parts of the Betic zone in Spain and the Paleozoic zone in Morocco as well as the intervening western Alboran Sea (probably similar continental crust) were the source of the abundant allochthonous "flysch" units that represent the cover sequence; the cover rocks slid off to more external (presently landward) zones to expose rapidly the Paleozoic basement and ultramafic intrusions of the Betic and Paleozoic zones in the Miocene. Tectonic loading of the external (landward) zones by the "flysch" may be responsible for the complex deformation of these zones developed also in the Miocene; because of the presence of a weak evaporite horizon this deformation apparently did not involve Paleozoic basement. Gradual cooling of the upwelled mantle may have resulted in continuing subsidence of the Alboran Sea.

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The extensional movement in the Alboran Sea can be traced eastward into the Western Mediterranean and is probably related to the opening of the Balearic Basin and Ligurian Trough suggested by others; the data presented here support an Oligocene to early Miocene age for this major extensional movement between Africa and Europe. The demonstrated plastic thinning of continental crust over plate "sutures" contrasts these areas with the rigid blocks of oceanic regions and complicates any geometrical reconstruction of the small plates of the Mediterranean.

INTRODUCTION

The occurrence of Alpine-type ultramafic rocks has received much attention in the study of tectonics, because the subcrustal source of these rocks implies that the mantle was actively involved in their emplacement. Thus, the mechanism of emplacement is a rare direct geological indicator of the tectonic activity of the mantle during orogenic movements. The usual means of determining past mantle movements is to extrapolate from upper crustal history such as sedimentary evidence of deep water, volcanicity, faulting, et cetera, but this method requires the a priori assumption of a mechanical model relating the deformation of the mantle, lower crust, and upper crust. Where mantle rocks are exposed, however, it is possible theoretically both to (1) determine plate tectonic movements of the lithosphere from the mechanism of peridotite emplacement, and to (2) compare the contemporaneous orogenic activity of the upper crust with the independent evidence of movements in the mantle (mantle lithosphere) to arrive at a mechanical model relating orogeny to its mantle origins.

The emplacement of rocks of the ophiolite association into eugeosynclinal terranes is usually explained by a subduction mechanism and *compressive strain* of tectonic plates, including both the crustal and mantle components of the lithospheric plate. There is little evidence of high-temperature emplacement of ophiolites in such terranes, except for the uncommon appearance of associated amphibolites that can, however, also be related to an earlier intrusive history. In the plate tectonic model, this mantle material must have been incorporated into the lithosphere in an earlier tectonic phase probably by high-temperature emplacement at a spreading center; but little evidence of this earlier rise of mantle material toward the crust (or to generate oceanic crust) is ordinarily preserved, because coherent, attached contact rocks are rarely present. However, in a few cases it can be demonstrated geologically that peridotite bodies came into contact with crustal rocks at high temperature—on the order of 1000°C. These bodies must represent mantle material that rose through the lithosphere from a depth of sufficient ambient temperature. The diapiric rise of hot, plastically deforming mantle material can be related to *extensional regional strain* (as at a spreading ridge) by reasoning analogous to the compressive strain interpretation of cold ophiolite obductive emplacement.

The Ronda massif in southern Spain is one peridotite body that was emplaced at high temperature, as evidenced by low-pressure, high-temperature contact metamorphism of pelitic crustal rocks (Loomis, 1972b). The similar Beni Bouchera massif crops out across the Alboran Sea in

Morocco, and both bodies are part of two zones of ultramafic outcrop, metamorphism, and high positive Bouguer gravity anomalies that extend along the margins of the Alboran Sea (Bonini, Loomis, and Robertson, 1973). The geometry and mechanism of emplacement of these bodies can be interpreted to develop a model of orogeny and plate movements as follows.

The upper mantle and lower crust (lithospheric plate) are assumed to have undergone regional extension during emplacement of the ultramafic ridges. The metamorphic and structural data supporting the model of emplacement of the Ronda massif has been treated in detail in another paper (Loomis, 1972a), and only the general geology and tectonic model are summarized here. Radiometric age data are then presented to date the emplacement of the ultramafic rocks. The orogenic deformation of the associated upper crustal rocks is reviewed to delimit contemporaneous tectonic activity, and an attempt is made to correlate upper crustal and mantle movements in an inductive orogenic model. The final step is to relate the significance of mantle upwelling to plate tectonic ideas and tender models of plate movements in the Alboran Sea.

Many authors have proposed various Tertiary tectonic movements of the lithosphere in the Alboran Sea area including compression, extension, and transform faulting; the justification of these events usually relies on the assumption that upper crustal "flysch" motion, faulting, topography, et cetera are obviously indicative of similar lithospheric activity. While this paper contains its own share of speculation, the conclusions do not rely on an extrapolation of surficial tectonics to the mantle or an attempt to classify complex orogens of continental crust into the relatively simple schemes of large-scale plate tectonics observed in oceanic crust.

ULTRAMAFIC MASSIFS

Ronda massif.—The Ronda ultramafic massif crops out over approximately 300 km^2 on the southern coast of Spain between Malaga and Gibraltar (fig. 1). The massif is predominantly harzburgite with subordinate amounts of dunite and lherzolite; significant serpentinization is generally confined to the contacts with pelitic rock and to restricted zones within the body. Layers of basic composition, commonly several centimeters thick, compose several percent of the massif and manifest a variety of mineral assemblages, some indicative of high-pressure crystallization in the mantle (Dickey, 1970). No extrusive or hypabyssal rocks are directly associated with the massif, and there is no evidence to suggest the presence of an ophiolitic assemblage.

The rocks bordering and within the outcrop area of the massif can be divided into two general bulk compositions: metapelitic rocks of Paleozoic or older age and carbonate rocks (marble) of probable Mesozoic age (in the writer's interpretation; others consider some of them to be older). Recent "stratigraphic" classifications of the contact rocks have been given by Dürr (1967), Mollat (1968), and Buntfuss (1970) who

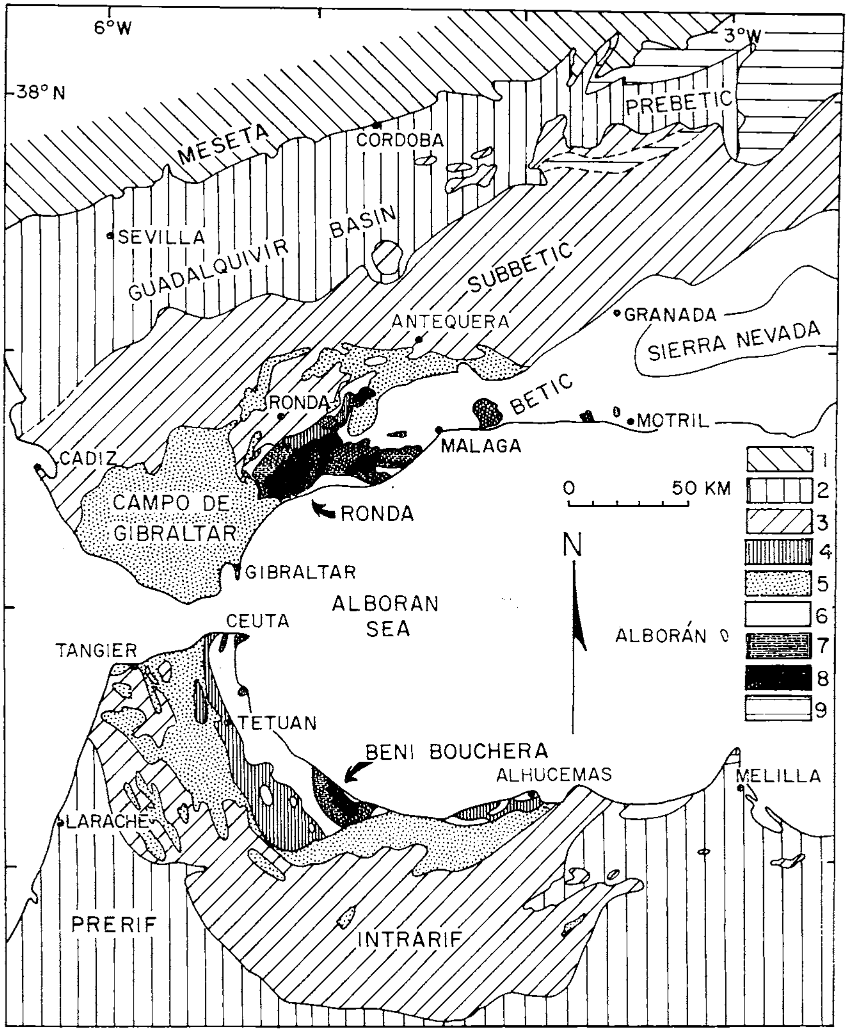

Fig. 1. Western Betic and Rif Cordilleras after Hoeppener and others (1964), Egeler and Simon (1969), Durand Delga and others (1962), and interpretation in Loomis (1972a).

Key to legend

1. Predominantly Paleozoic sedimentary, granitic, and metamorphic terrane of the Meseta.
2. Mesozoic and Tertiary zones of clastic and carbonate deposition.
3. Mesozoic Subbetic carbonate, marl, and volcanic rocks, Intrarif clastic rocks (flysch).
4. Spanish Rondaides and Moroccan Chaîne Calcaire-Triassic and Jurassic carbonate rocks considered here to be transitional with the other discontinuous cover sequences (not shown) sporadically preserved on top of the Paleozoic rocks in the western Betic and Paleozoic zones.
5. Cretaceous-Eocene marls and thin-bedded limestones; Oligocene clastic rocks (the entire sequence is called "flysch" by most writers).

consider the massif to be a thin thrust sheet that originated in the south (Alboran Sea); most of the associated metamorphic rocks are considered to be accidentally juxtaposed to the peridotite as allochthonous thrust sheets (for example, Hoeppener and others, 1964).

Alternatively, petrologic and structural study of the associated metamorphic rocks by the writer has provided data to interpret their origin as a well-developed metamorphic aureole around the peridotite massif (Loomis, 1972b). Metapelitic gneisses constitute a lateral aureole over 5 km wide preserved around the west end of the mass. Metapelitic hornfels and metacarbonate marbles and skarns form a roof assemblage preserved within the general outcrop area of the massif. Faulting has dislocated the lateral aureole from the peridotite elsewhere around most limits of the massif, but some lateral aureole rocks crop out sporadically on all margins.

High-temperature petrogenesis of metamorphic assemblages within the aureole, the differences between lateral aureole and roof assemblage histories, and petrogenesis of basic layers within the massif, together with the presence of a steeply dipping foliation in the aureole, are adduced as evidence of the high-temperature, vertical penetration of the massif (Loomis, 1972a). The peridotite body could have continued to penetrate into less dense crustal rocks as a result of its hot, buoyant root in the cooler lithosphere. The low geothermal gradient of the area indicated by the paucity of volcanism during the time of intrusion suggests the presence of a thick lithosphere; it is just such an environment in which the buoyancy of a hot diapir through the lithosphere is the greatest and maximum penetration into the crust is expected.

Petrofabric work on the peridotite body by Darot (ms, p. 109-110) confirms the concordance of deformation between the peridotite and contact gneisses and supports the model of high-temperature emplacement. No evidence of low-temperature deformation was found. A regional gravity survey has provided data consistent with the hypothesis that the Ronda mass (and other exposed peridotite intrusions around the Alboran Sea) are continuous downward to the mantle (Bonini, Loomis, and Robertson, 1973).

The flat-lying or gently dipping metamorphic foliations in the outer aureole of the intrusion (beyond approx 5 km) are exposed up to 10 km from the contact (near fault contacts and under carbonate cover masses which have moved, this metamorphic foliation is often folded by a later flexure-slip mechanism). The foliation is interpreted as having formed normal to maximum compressive strain (Loomis, 1972a); therefore, hori-

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6. Spanish Betic and Moroccan Paleozoic zones: Paleozoic geosynclinal clastic rocks and sporadically preserved Mesozoic and Tertiary discontinuous cover rocks. High-pressure metamorphic rock with kyanite is exposed in the Sierra Nevada uplift and other parts of the Betic zone east of Malaga.
7. Andalusite-sillimanite low-pressure metamorphic sequences.
8. Ultramafic rock, including an outcrop near Ceuta.
9. Late Cenozoic cover of the Prebetic zone and Meseta.

zontal crustal stretching is indicated to the side of the intrusion. The model developed from the structural and metamorphic data is that the lower crust in the entire region around the intrusion was thinning and extending laterally and simply necked where the hot intrusion pushed upward, lifted by a buoyant root in the underlying mantle. In a plate tectonic model, not only the crust but the entire lithospheric plate, including a section of the upper mantle, can be assumed to have extended laterally to allow warmer mantle from depth to well up. Thus, both the actuality of mantle upwelling from depth and the metamorphic stretching of the crust are consistent with a model of extension of the lithospheric plate during the emplacement of the Ronda massif.

Geologic evidence places only wide limits on the age of emplacement of the Ronda massif, and even these limits can be disputed. Mollat (1968) considered the age to be Upper Triassic to Upper Jurassic. A carbonate tectonic unit (Rondaides, fig. 1), dated as Triassic and Liassic by fossils (Dürr, 1967), is metamorphosed on the northern margin of the peridotite. The first possible evidence of the minimum age of the peridotite is provided by serpentine debris in Miocene molasse near Ronda (Dürr, 1967, p. 46).

Beni Bouchera massif.—The principal outcrop of peridotite in Morocco is the Beni Bouchera massif (fig. 1) described in detail by Milliard (1959b) and Kornprobst (1969). The massif is similar to the Ronda massif in composition and includes approximately 3 percent content of layers of basic composition with mineralogical assemblages indicative of crystallization at upper mantle pressures. The massif is partly enclosed by a zone of high-grade metamorphic rocks characterized by general prograde equilibration toward the massif but complex in detail (Kornprobst, 1971a and b).

Kornprobst (1969, p. 283) interprets the emplacement of the massif as follows: "The ultrabasic rocks which form the Beni Bouchera massif are schistose and folded isoclinally. They outcrop at the center of a late formed anticline under a series of granulite facies precambrian or lower Paleozoic rocks. The ultrabasic rocks appear to have been in situ during the major structural development of the series and were emplaced at the time of metamorphism. . . . One sees in the Beni Bouchera the results of anatectic melting of an aluminous peridotite which originated in the upper mantle. This partial fusion was caused by the adiabatic upward movement of the mantle material toward the lower crust where tangential tectonic movements emplaced it as a solidified mass in an orogenic root zone under granulite faces conditions." Some contact metamorphic effect is acknowledged in his model and explained on the grounds that the peridotite was hotter than the surrounding gneisses undergoing contemporaneous regional metamorphism in his model. The metamorphic rocks surrounding the massif are similar in bulk composition and mineralogical development to the rocks interpreted by the writer to be a metamorphic aureole around the Ronda massif, and it is therefore proposed to extend the hypothesis of high-temperature emplacement to the Moroccan peridotites, as originally proposed by Milliard (1959b, p. 151).

Gravity data (Bonini, Loomis, and Robertson, 1973) are consistent with the model of the peridotite as a steep-sided body, but a lateral extension or "mushroom" cap near the surface is probably necessary to include the outcrop area. Horizontal extension may be related to hot intrusion or later cold movements; cold flexural slip deformation of the foliated metapelites is widespread in the Paleozoic zone. Darot (ms, p. 109) proposes that the lack of coincidence between outcrop of the Ronda massif and positive Bouguer anomaly closure is evidence of displacement; however, the massif probably represents only one edge of the intrusive body and uncertainties in the crustal model and especially marginal serpentinization make such detailed structural interpretations hazardous. If lateral movement of the Ronda massif has also taken place flexural slip folding in the outer aureole rocks and lack of low-temperature deformation features within the massif (Darot, ms, p. 110) indicate that such movements occurred after cooling. Thus, some lateral movement of these massifs may have taken place after cooling, but features indicative of the original emplacement mechanism are not affected significantly.

Kornprobst (1969, 1971a, 1971b) considers the peridotite to be lower Paleozoic or Precambrian because Milliard (1959a) reports that conglomerate with clasts of metamorphic rock, thought to be characteristic of the contact rocks, is dated as Carboniferous by fossils. Large masses of metamorphosed dolomite included in the metapelite around Beni Bouchera may be attributed to the Triassic by analogy of facies and location (Durand Delga and others, 1962); however, Kornprobst considers these Triassic units to be separate structurally from the peridotites in Spain and Morocco (personal commun., 1972). Durand Delga and others (1962, p. 401) suggest that the post-Triassic metamorphism of carbonate rocks near Beni Bouchera may be "parallel" with that that affects lower Miocene sediments farther east near the coast (the portion of the Intrarif reaching the coast southeast of Alhucemas in fig. 1). Ultramafic rocks and high-grade metamorphic rocks crop out sporadically along the coast between the Beni Bouchera massif and Ceuta with petrographic and structural similarities to the Beni Bouchera terrane.

GENERAL METAMORPHISM IN THE BETIC-RIF

The assumed age of emplacement of the peridotite bodies is based on radiometric dating of associated metamorphic rock. The relation of these rocks to regional metamorphic sequences must be examined due to the possibility that some units could be older regional metamorphic rock in which the age has been reset by regional Alpine metamorphism.

Betic zone.—Metamorphic rocks crop out in the Betic Cordilleras only in the internal or Betic zone where predominantly Paleozoic rocks are exposed. The Ronda and associated massifs are present only in the western part of this zone, west of Malaga, in the region of low-grade (chlorite-sericite) or non metamorphic rocks. East of Malaga major tectonic units of this zone show evidence of low to moderate-grade regional metamorphism, but only highly deformed serpentine outcrops, without significant gravity expression, are found. A complete review of the geology and tectonics of the Betic zone is given by Egeler and Simon (1969).

Moderate to high-grade, kyanite-bearing metamorphic rocks are exposed in the Sierra Nevada (Sierra de los Filabres) uplift (fig. 1), and low-grade rocks in a vast, surrounding area considered to be the Alpujarride nappes. Polymetamorphic histories have been interpreted for most of these units on the assumption that the earlier phases were Hercynian or older in age (Boulin, 1962; Nijhuis, 1964; Helmers and Voet, 1967). The only direct evidence to date possible early metamorphism is the presence of gneissic rocks in the Sierra Nevada (Sierra de los Filabres) uplift, assumed to be derived from granitic intrusions, which yielded a whole-rock isochron (Rb-Sr) of 269 ± 6 m.y.; the latest equilibration deduced from a muscovite-whole rock distribution and K-Ar dating indicated an age of 12.0 ± 1 m.y. (Priem and others, 1966). The precarious correlation of these minor granitic intrusions with regional metamorphism indicates Hercynian metamorphism. A possible pre-Devonian or pre-Carboniferous metamorphic unconformity in the Alpujarride tectonic unit (Egeler and Simon, 1969, p. 63) has been taken as evidence of early metamorphism.

The primary indicators of Hercynian or older metamorphism seem to be the presence of old granitic gneiss and the identification of polymetamorphism and polydeformational events—the older events assumed to be pre-Alpine. Extensive outcrops of Paleozoic rock (correlated as the Malaguide unit) found throughout the Betic zone have undergone no significant metamorphism. The importance of metamorphism to the entire geologic understanding of the Betic Cordilleras cannot be overemphasized, because, as Egeler and Simon (1969, p. 16 and 23) note, in practice the major tectonic units of the Betic zone are often distinguished (and correlated) on the basis of general *regional* metamorphism of presumed Alpine age. Solely on this basis, metamorphic units around the Ronda massif have been variously distinguished and correlated with the Alpujarride or Sierra Nevada (Sierra de los Filabres) or Ballabona-Cucharon tectonic units (for a review, see Egeler and Simon, 1969, p. 50-53). Implicit in these correlations, of course, is the questionable (and certainly unproven) assumption of lateral continuity of metamorphic grade; Egeler, Rondeel, and Simon (1971) have emphasized the uncertainty of such correlations.

Metamorphism of Alpine age (post-Triassic) is widespread and well documented. However, the picture of Alpine metamorphism is clouded; first of all by regional correlations on the basis of metamorphic grade, and secondly by assumptions of a theoretical relationship between nappe structures and metamorphism. But Triassic rocks, identified by fossil evidence and lithologic correlation of major stratigraphic units, are part of the tectonic sequences that have undergone significant metamorphism before tectonic dislocation. Thus, the degree of Alpine-age metamorphism reached moderate grade in the rocks exposed in the Sierra Nevada (Sierra de los Filabres) and similar basement of the Alpujarride tectonic units. DeRover and Nijhuis (1963) describe plurifacial metamorphic rocks thought to be Triassic or younger that contain glaucophane and Na-rich pyroxene, but a blue schist or glaucophane schist assemblage is not present. This earliest Alpine metamorphism was succeeded by other moderate-grade events according to these authors. Serpentine is found in Triassic rocks in the same region. If subduction is to be proposed, a Triassic age much older than the late Tertiary events considered here is most probable.

The contact metamorphic effects around the Ronda massif dated in this paper are assumed not to be related directly to the common "regional" Alpine metamorphism elsewhere in the Betic zone, and any assumption of a theoretical relationship between metamorphism and either nappe movement or paleogeography—or even nappe correlation—should await independent justification by radiometric dating and stratigraphic correlation. The geologic limits placed on Alpine metamorphism in the Ronda area are essentially those of the Betic zone as a whole (post-Triassic and pre-middle Miocene). The regional tectonic model developed below may provide a speculative and theoretical explanation for regional metamorphism but not by a direct "geologic" correlation of Ronda contact and regional Alpine metamorphism. The possibility of a metamorphic "event" subsequent to contact metamorphism by the Ronda massif cannot be excluded from geological evidence.

There are, however, two restricted outcrops where metamorphic rocks appear to be related to ultramafic intrusions based on the physical conditions of metamorphism and gravity data. Regional pelitic schists that reach high grade contain kyanite, garnet, staurolite and, in general, assemblages indicative of deep crustal recrystallization. But metapelites from an outcrop east of Malaga (fig. 1), previously supposed to be old, regionally metamorphosed pelitic rocks (Boulin, 1962), contain an andalusite-sillimanite sequence implying the attainment of high temperatures at only moderate to shallow crustal depths. No volcanics are exposed. This outcrop occurs near a positive Bouguer anomally closure of approximately 70 mgal probably related to an ultramafic body at shallow depth. Rb-Sr dating of these rocks produced a muscovite-microline whole-rock isochron of 0 ± 1 m.y. according to Boulin, Ledent, and Pasteels (1970).

The second outcrop is of "almandine-bearing biotite-cordierite-labradorite dacite" (Zeck, 1968) in the Neogene volcanic province of Cabo de Gata, Spain. This unusual rock is essentially an erupted metapelite that contains abundant inclusions of almandine-biotite-sillimanite gneiss, quartz-cordierite rock, spinel-cordierite hornfels, and quartz-bearing basaltic rocks described in detail by Zeck (1968). The nearby regional schists contain garnet, staurolite, and kyanite but none of the sillimanite, andalusite, or abundant cordierite of the extrusive rock and inclusions. Zeck interprets the magma as the result of anatectic melting of pelitic rock to leave residual refractory inclusions and of mixing of the melt with basic igneous rocks, inclusions of which may also contain residual pelitic components. The cordierite-bearing eruptive rock and hornfelsic inclusions are very similar to the contact metamorphic cordierite hornfels with residual inclusions found on the roof of the Ronda intrusions, for which a similar anatectic origin was proposed (Loomis, 1972a). Furthermore, the sillimanite gneiss inclusions can be related to other contact rocks of the Ronda massif (lateral aureole gneiss series which, however, also contains kyanite), and the small amount of basic melts could be derived from the basic layers contained in the massif.

The anatexis of large amounts of pelitic rock together with the appearance of andalusite and residual sillimanite and cordierite (among other minerals) indicates the introduction of a great deal of heat at relatively shallow depths in continental crust. In view of the positive Bouguer gravity anomaly of this cape similar to that of the Ronda massif, it is reasonable to propose the emplacement of high-temperature mantle material or at least voluminous basic magma as suggested by Zeck. The lava was extruded over Miocene or Pliocene rocks and covered by Pliocene limestone (Zeck, 1968, p. 34); andesites and basaltic andesites elsewhere on the Cabo de Gata have intercalated Miocene sediments (Paez Carrion and Sanchez-Soria, 1965).

Paleozoic zone of Morocco.—The main outcrops of metamorphic rock in the Rif Orogen are in the Paleozoic zone (equivalent to the Betic zone) along the coast between (and including) the Beni Bouchera area and Ceuta; the metamorphic units have been considered to be basement underlying predominantly pelitic Paleozoic nappes (Milliard, 1959b)—a hypothesis similar to that proposed for the area near Ronda (Hoeppener and others, 1964). However, the coastal strip is also the locus of outcrops of ultramafic rock and a gravity anomaly high; the relation of the metamorphic rocks to the Beni Bouchera massif and the similarity of the association to that in the Ronda area have already been discussed. Geologic and geophysical evidence as well as the radiometric age data reported here support correlation of the Moroccan and Ronda ultramafic and metamorphic zones.

Another metamorphic sample was provided by JOIDES hole 121 in the Alboran Sea (fig. 1). The basement under Miocene sediments was originally reported as basalt but later identified as metamorphic rock. The writer finds that much of the sample consists of cordierite hornfels similar to that found atop the Ronda massif. The hole does lie at the western terminus of the central Alboran gravity high, indicative of crustal thinning and possible mantle upwelling, but the metamorphic rock may also be coarse detritus from Spain.

RADIOMETRIC DATING

Ronda massif.—Three biotite samples from the metamorphic rocks associated with the Ronda massif and one muscovite and one biotite from the Beni Bouchera massif were dated by K-Ar methods. The dating was accomplished over a period of several years both commercially and by the writer. In addition, whole rock data for three samples are available as shown in table 1 and are included for completeness. A short petrographic description of the samples is given in the appendix.

The samples from the Ronda area were selected from both major Paleozoic metapelitic units: the hornfels-series roof rock (R8 and R168) and the gneiss-series lateral aureole (R131 and R245). The hornfels samples contain muscovite and biotite (R131) and perthite and biotite (R245). The biotite separates from cordierite-bearing samples contained estimated 10 to 20 percent impurities which by virtue of its mass, shape, or magnetic properties could not be eliminated. The most probable coexistent mineral likely to have similar physical properties to biotite and to be concentrated in the separation process is Fe-rich cordierite; the unusually high percentage of contaminate in the hornfels separates may be a result of the abundance of cordierite in the sample, as discussed below. The mineral separates from other samples are reasonably clean, and there is no reason to suspect the presence of adhering material that would do other than dilute the analyses. Incipient alteration of cordierite was noted in sample R8, but other samples display little petrographic evidence of alteration.

Computed ages for whole-rock and biotite separates are given in table 1. The wide spread of metamorphic ages, even from the same hornfels units, requires an interpretation of the data. Several possible models that might explain the diverse results are considered as follows:

1. Greater deformation of the gneisses resulted in greater Ar loss.

TABLE 1

K-Ar data for samples of metamorphic rock proposed by the writer to represent contact aureoles of high-temperature mantle intrusions

Sample	Source	K wt %	Radiogenic $\text{Ar} \times 10^6$ ccSTP/gm	Age m.y.	Comments
Ronda					
*168 whole rock	hornfels	2.92	9.60(33); 9.68(35)	81.2 ± 1.4	30% cordierite
*8 whole rock	hornfels	3.05	6.76(36); 6.37(37)	53.4 ± 1.5	15% cordierite
*245 whole rock	gneiss	2.22	1.90(19); 2.03(15)	22.1 ± 0.2	
†168 biotite	hornfels	4.72	6.83(67); 6.33(57)	34.6 ± 1.4	20% impurity
‡8 biotite	hornfels	5.26	6.40(55); 6.37(58)	30.2 ± 1.0	10% impurity
†131 biotite	gneiss	6.52	6.16(63); 6.11(59)	23.4 ± 0.9	
Beni Bouchera					
‡M75.115 muscovite	vein	7.29	6.11(48); 6.17(52)	20.7 ± 0.6	
‡M7.221 biotite	gneiss	6.72	5.54(34); 5.60(38)	20.2 ± 0.6	

The number in parentheses is the percent air correction: * Isotopes, Inc., † Geochron Laboratories; ‡ Yale Univ. (author)

2. K-feldspar, present as finer-grained and coarser perthitic crystals in the gneiss (R245), allowed late Ar diffusion.
3. A later thermal event reset the biotite ages and gneiss whole rock (R245) but only partially affected the whole rock hornfels samples.
4. Radiogenic Ar from the Paleozoic (and older source) rock was retained during metamorphic recrystallization by porphyroblastic cordierite present only in the hornfels samples.

The first hypothesis is unlikely because all rocks dated are estimated to have been heated to 600° to 800°C, and the hornfels units contain foliated inclusions indicative of strong deformation followed by textural annealing (Loomis, 1972a and 1972b). Late selective Ar diffusion from K-feldspar explains neither the younger biotite than whole-rock ages of the hornfels samples nor the equality of the biotite and whole-rock age from the gneisses. Indeed, the correspondence of the whole-rock age from gneiss sample R245, in which most of the potassium is contained in fine-grained perthite, to the biotite age from R131 suggests the absence of any significant later thermal event to promote Ar loss.

There is little petrographic evidence to support the third and more plausible hypothesis. By far the freshest sample with no sign of retrograde reaction is R245 which yielded the youngest whole-rock age. The hornfels samples with incipient sercitization of feldspars and chloritization of biotite (most hornfels samples collected are partly or completely altered to sericite and chlorite) rendered older ages. It is unlikely that a thermal event capable of resetting whole-rock ages would leave no petrographic trace *only* in the sample affected most.

The preferred explanation for the discordant result is hypothesis four: cooling occurred approximately 22 m.y. ago, but recrystallized porphyroblastic cordierite trapped original radiogenic Ar present in the rock. Damon and Kulp (1958) recorded excess Ar^{40} and He^4 in five cordierites, either trapped during crystallization or absorbed by diffusion into the relatively open structure. The original Paleozoic pelitic sediments, derived from older granitic sources as shown by detrital zircon, feldspars, and tourmaline, contained several percent K (table 1) and certainly relatively abundant radiogenic Ar. Therefore, crystallization of cordierite can be expected to have taken place in the presence of abundant radiogenic Ar.

If the above hypothesis is correct, the anomaly in the date of each sample should be roughly proportional to the amount of cordierite analyzed. Cordierite-free samples (R245, R131) give concordant results, but biotite separates with a probable contamination of a few to 20 percent cordierite yield dates approximately 50 percent too old. The two whole rock samples with abundant cordierite and approximately equal K content yield anomalously old dates in proportion to their cordierite content.

It is concluded that the probable metamorphic cooling age of the contact aureole was mid-Cenozoic, and a tentative approximate age of

22 m.y. is assumed; emplacement of the peridotite intrusion probably preceded cooling of the contact rock by several m.y., and a tentative age of intrusion at the end of the Oligocene or early in the Miocene is proposed for further consideration. The correlation of the Miocene or Pliocene eruption of the pelitic anatectic melt of the Cabo de Gata, similar in part to the Ronda hornfels aureole, with ultramafic emplacement supports this hypothesis. As discussed below, the onset of volcanism associated with the Alboran Sea in the Miocene can also be related to this event.

Beni Bouchera massif.—Biotite and muscovite K-Ar dates were obtained from two samples generously provided by J. Kornprobst from the metamorphic rocks adjacent to the Beni Bouchera massif in Morocco. As shown in table 1, these dates are in excellent agreement with the proposed age of the aureole of the Ronda massif and, by the writer's model, corroborate an early Miocene intrusion age for both massifs. The young age of the emplacement of the ultramafic massifs as hot diapirs is an interpretation of obvious significance in view of the previously suggested models of Jurassic, lower Paleozoic, or Precambrian passive emplacement of these bodies; the remainder of the paper explores the geologic implications of this interpretation.

GEOLOGIC CORRELATIONS

It is proposed in the preceding sections that the Ronda ultramafic mass and analogous massifs in the region around the western Alboran Sea were emplaced in Tertiary time, probably early in the Miocene or near the end of the Oligocene. A primary objective of this paper is to correlate this event with contemporaneous regional tectonic history. However, a detailed discussion of the regional geology and tectonic hypotheses proposed for the western Betic zone and the Rif Paleozoic zone is beyond the scope of this paper, and only a brief review concentrating on the area around the Ronda massif is given; *in general, the area under discussion is that part of the Betic and Rif orogens west of long 4°W (fig. 1).* The writer must rely on published descriptions and tectonic interpretations of others for the general geology of the western Betic-Rif system.

A major regional geologic problem related to the emplacement of the Ronda massif (Loomis, 1972a and b) is the necessary thickness of the cover section. The evidence from the metamorphic aureole assemblage sequence around the intrusion suggests the presence of several kilometers of cover above the top of the peridotite; the roof of the peridotite is presently exposed and has metamorphosed probable Mesozoic rocks. Moreover, this cover section must have been removed soon after emplacement to expose the peridotite to erosion also in the Miocene. Knowledge of the probable cover thickness above the intrusion becomes a tool to deduce the paleogeographic distribution of sediments before the latest "Alpine" orogeny.

Tertiary history in the region around the Ronda massif is recorded principally by deposits in the Subbetic zone bordering the Betic zone to the west and north (fig 1). The western Betic zone itself is an outcrop area of probably Paleozoic pelitic rocks, peridotite intrusions, and some highly tectonized remnants of the Mesozoic and Cenozoic cover sequence. Extensive allochthonous "flysch" units (many units show no turbidite features) are mapped in the Subbetic zone and are often concentrated in basins near the boundary with the Betic zone; in some regions the "flysch" extends onto the Betic zone. By far the most extensive region of outcrop is the Campo de Gibraltar (Didon, 1960, and 1962; Dürr, 1967), although significant series occur near Antequera (Peyre, 1962), and vast areas of analogous deposits are mapped in the tectonically corresponding site in the Rif (Durand Delga and others, 1962).

In the areas of allochthonous "flysch" accumulation studied in any detail several tectonic units that show stratigraphic differences have been identified, but several generalities are apparent. The section rarely reaches back to late Jurassic in a carbonate facies with radiolarites followed by an early Cretaceous flysch, in part with a terrigenous source. The late Cretaceous to middle or late Eocene section included in many units is a fairly uniform, thin-bedded marl and marly limestone sequence. Conglomerate horizons are found in the middle Eocene, and the facies then changes radically to a thick accumulation of terrigenous and carbonate clastics and marls.

The age of movement was presumably after the late Oligocene, because Oligocene units have been superposed and the Betic zone and Chaine Calcaire slightly overthrust the "flysch" units in places. However, the Betic zone and Chaine Calcaire commonly have steeply-dipping fault contacts with the "flysch", and both zones can be overlapped by "flysch"; the Chaine Calcaire may be overthrust in places by the Paleozoic zone (Dürr and others, 1962, p. 224; Durand Delga and others, 1962, p. 406-409). Didon (1962, p. 226) reports a flysch unit (Estepona) that is proposed to be transgressive over the Betic zone pelites (and therefore autochthonous) southwest of the Ronda massif; it contains locally blocks of Paleozoic sediments and is dated paleontologically nearby as Late Oligocene. There is the possibility that the blocks were tectonically included during "flysch" movement or were derived elsewhere. Other "flysch" units thought to be autochthonous to the Subbetic are discussed below.

A general transgressive phase in the Miocene is recognized widely throughout the Betic. Predominantly carbonate conglomerate molasse near Ronda (fig. 1) is reported to contain serpentine debris (Dürr and others, 1962, p. 221); the Paleozoic Betic zone and peridotite must have been exposed by this time. The popular model for the Betic and Rif orogens, therefore, assumes a major (or the major) tectonic "event" at the end of the Oligocene or Early Miocene resulting in the emplacement of these "flysch" units. The principal conclusion of this paper is that this orogenic event in the Betic-Rif system must have been related temporally to the emplacement of the mantle rocks, proposed to have been a result of high-temperature diapirism in the mantle.

Before proceeding with a general discussion of Betic-Rif tectonics, some evidence of the possible extent and source of the "flysch" must be considered. The stratigraphic composition and distribution of allochthonous "flysch" units around the Betic zone are not universally agreed upon; the distribution shown in figure 1 (after Egeler and Simon, 1969) is subject to debate by various workers. Detailed geologic maps of the areas near the Ronda massif are given by Didon (1960; 1962) and Dürr (1967) in more detail than can be reproduced here.

In the region of the Campo de Gibraltar southwest of the Ronda massif, lower rocks are exposed in places through the allochthonous "flysch". The exposed section includes Paleozoic pelites and characteristic red sands and conglomerates (as in the Betic zone), Jurassic limestones, and Cretaceous to Paleocene marls and limestones of the Subbetic (Didon, 1960, p. 353). Proceeding north and east around the Betic zone, there is more outcrop of the Triassic-Jurassic section, but the Cretaceous-Eocene marls and limestones and Oligocene turbidites can be traced also into this area south of Ronda, studied in detail by Dürr (1967). Here he considers the entire section to be continuous and *autochthonous* to the Subbetic zone, although significantly tectonized. The Cretaceous overlies the Jurassic concordantly and is followed by Late Eocene and Oligocene flysch of the same facies as the units to the southwest. The transition from the underlying marls and limestones implies nearby (proximal) derivation (Dürr and others, 1962, p. 218) of the Oligocene clastics. Didon (1962, p. 267) also notes the similarity of Oligocene facies in the Subbetic (external Penibetic) and some of his allochthonous "flysch" units. Thus in several areas the "flysch" seems to be an integral part of the Subbetic section; hence, the uncertainty of the distribution of allochthonous units as interpreted by various writers. It is possible that units of the entire Triassic through Oligocene section in parts of the southern Subbetic are allochthonous.

The general hypothesis that the Mesozoic and Tertiary southern Subbetic (or Penibetic) is allochthonous has been expressed earlier, for example, Blumenthal (see Egeler and Simon, 1969) and Egeler and DeBooy (1962). Several lines of evidence that support this hypothesis for the western Betic Cordilleras can be cited: (1) evaporite-clastic horizons are present in the Permo-Triassic and Triassic section, especially in the Subbetic, and are known to be important zones of movement which have played a major tectonic role (for example: Dürr and others, 1962, p. 225); the same is true in the Rif; (2) Paleozoic basement is found nowhere in the complexly tectonized terrane of the Subbetic and only rarely is exposed in the Intrarif; (3) very low Bouguer gravity anomalies are associated with the Subbetic and Intrarif zones, and a high gravity gradient is found between these zones and the Betic-Paleozoic zones (Bonini, Loomis, and Robertson, 1973); (4) the Subbetic zone has been shown to contain many thrust units and to have overthrust the Prebetic-Quadalquivir Basin as late as the late Miocene (for example: MacGillavry, 1964; Fontboté and Garcia-Dueñas, 1968; Garcia-Dueñas, 1969); (5) the cover sequence above the Ronda massif in the Betic zone must have been removed rapidly, a process facilitated by tectonic denudation, and could represent a source area for the allochthonous rocks as discussed below.

The source of the "flysch" or parts of the southern Subbetic is a matter of long conjecture. Most of the "flysch" units around the western Betic zone and in Morocco are usually presumed to have an "ultra" origin; that is to be allochthonous units transported *over* the exposed Betic or Paleozoic zones and Chain Calcaire from an area now in the Alboran Sea, assumed to be oceanic or intermediate crust (for example: Durand Delga and others, 1962, p. 407 and 409; Didon, 1960, p. 360). Andrieux, Fontboté, and Mattauer (1971, p. 193) propose that the Mediterranean oceanic basin rose after the main Alpine compressional tectonic phase to shed these ultra units. The justification for this hypothesis is that the "flysch" was a late allochthonous arrival and possible source areas are difficult to propose in more external zones.

The exposed Betic and Paleozoic zones have not been generally considered as possible source areas, but this possibility is proposed here for the area west of Malaga. In the area south of Ronda, the Cretaceous and Oligocene section in the Subbetic zone is similar to that preserved in tectonized Mesozoic and Tertiary sections remaining on the Betic zone nearby (internal Penibetic), and, in places, the "flysch" is transgressive on the remaining carbonate cover of the Betic zone. Dürr and others (1962, p. 224) note the similarity of Triassic facies between Subbetic rocks and a partly metamorphosed carbonate unit (Nieves) considered by the writer to correlate with metacarbonate roof rock of the Ronda massif; this Mesozoic carbonate mass overthrusts Subbetic rocks several kilometers in a northward direction and may still be sliding off the Betic zone.

The general comparison of Triassic and Jurassic limestones associated with the Betic and Paleozoic zones is frustrated by rapid facies changes and their tectonized state. For instance, Dürr and others (1962, p. 214) note the strong facies changes characteristic of even neighboring units along the western end of the Betic zone; correlation with metamorphosed units near the Ronda massif, with the reduced and tectonized section studied by Azema (1961) near Malaga, or with the Paleozoic-Chaine Calcaire zones is probably unreliable. The lithologic variation of these scattered remains generally results in their differentiation into many units and assignment to diverse paleogeographic origins. The presence of evaporites, massive dolomite, algal structures, and oolites is suggestive of a shallow-water origin and carbonate banks which might explain rapid facies changes. Egeler, Rondeel, and Simon (1971) have also emphasized that it is not yet possible to correlate the many tectonic units containing Permo-Triassic and Triassic rocks in the entire Betic zone including that part east of Malaga. MacGillavry (1964) has emphasized the similarities of stratigraphic successions between the Subbetic zone and parts of the Betic zone (Malaguide as discussed later). It is concluded that the Betic and Paleozoic zones are possible source areas for the "flysch" or Subbetic rocks as well as the Alboran Sea. The allochthonous sequence may represent the entire post-Paleozoic cover sequence of these zones and parts of the western Alboran Sea.

The thickness of the probable Mesozoic-Tertiary cover section of the Betic zone can be estimated from that of the remaining units and the Subbetic section detailed by Dürr (1967). The Mesozoic section in the Subbetic is approximately 900 m thick; the Triassic-Liassic section in the remaining Betic zone cover units may reach approximately 1300 m north of the peridotite (Nieves) according to Dürr (1967). The abundant transgressive Oligocene clastics could be concentrated in variable thicknesses. Moreover, significant allochthonous movement could have augmented the thickness of post-Paleozoic rock in basins during and at the end of the Oligocene.

The necessary cover sequence above the Ronda massif during emplacement is explained, if the Oligocene clastics or already-allochthonous units were present in addition to the probable Mesozoic section. Tectonic denudation, facilitated by evaporite horizons, would rationalize the rapid exposure of the Betic zone as a result of subsidence of the Subbetic basins relative to the Betic zone. In summary, this hypothesis is supported by: (1) the similarity of remaining Betic zone cover units and nearby Subbetic units; (2) the accumulation of allochthonous Mesozoic-Tertiary units in the Subbetic zone, especially near the Ronda massif; (3) the identification of tectonic slices of cover rock bridging the Betic-Subbetic boundary and overthrusting the Subbetic; and (4) the continued Neogene subsidence of basin areas of the nearby Subbetic relative to the Betic zone and accumulation of Neogene deposits.

GENERAL TECTONIC SYNTHESIS

Some of the more general problems proposed in the Betic-Rif system include: (1) the arc shape of the system, (2) the composition of the Alboran Sea zone, (3) the origin of the allochthonous "flysch", and (4) the driving force of outward thrusting in the external zones. These problems are considered in the following tectonic model which is based principally on work on the emplacement of the ultramafic massifs, radiometric dating, and gravity; the model is an attempt to present a coherent explanation for the upper crustal Tertiary tectonic development of the system on the basis of mantle activity. The tectonic development of this region has been explained primarily as the result of compression between Spain and Africa, as shown in figure 2 (for example: Glangeaud, Bobier, and Szep, 1970; Andrieux, Fontboté, and Mattauer, 1971), but the inverse model of lithospheric extension is considered here.

Gravity data compiled by Bonini, Loomis, and Robertson (1973) indicate that the western part of the Alboran Sea is probably close to continental in character and has been thinned (necked) markedly over the ridges of mantle intrusions in Spain and Morocco. In view of the compositional similarity of the Betic zone of Spain and the Paleozoic zone of Morocco, the western Alboran Sea can be considered to be a subsided region similar to these zones—here called the "Betic-Paleozoic" province. The autochthonous nature of the western Betic and Paleozoic (Rif) zones is not generally assumed, because both zones show evidence of some overthrusting of more external zones and internal nappe development in the east. However, the gravity evidence of approximate vertical emplacement of mantle material and the age proposed here fixes the location of these zones west of Malaga in *mid Tertiary*; the Moroccan Paleozoic zone may have been thrust slightly southwestward.

The reader should be aware that the proposed autochthony of the "Betic zone" is a radical idea in terms of some popular tectonic hypotheses for the Betic Cordilleras as a whole, and some digression and clarification is necessary for those familiar with these hypotheses. A full description of the Betic zone is given by Egeler and Simon (1969).

East of Malaga (only an approximate division point) the Betic zone has been divided into 3 or 4 major tectonic units which can be shown to be superposed. The units, in order downward, are Malaguide (or Betic of Malaga), Alpujarride, and Sierra Nevada; they show a general but discontinuous increase of metamorphic grade downward and consist predominantly of Paleozoic pelitic rocks and sporadically preserved Triassic rocks (especially carbonate units). The upper Malaguide unit contains tectonized remains of its Mesozoic and Cenozoic cover sequence. Stacking of the units is Alpine in age, post-Triassic, and pre-middle or late Miocene. The identification and correlation of these units is commonly based on metamorphic grade, as discussed above.

There is general agreement as to the order of stacking, but the units, moving upward in the present section, could have been derived from source areas progressively farther north or south; there are proponents of both paleogeographic reconstructions. The hypothesis of a southern origin is most popular, but MacGillavry (1964) has summarized the

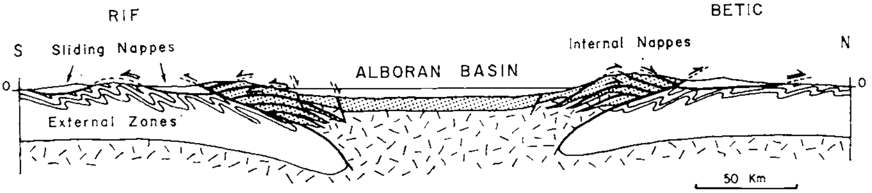

Fig. 2. Schematic cross section of the Betic-Rif system by Andrieux, Fontboté, and Mattauer, 1971 (relabelled). The vertical scale is slightly exaggerated in the zones of folding and nappes. (Reproduced by permission of the authors and Earth and Planetary Sci. Letters.)

stratigraphic similarities between the Malaguide unit (uppermost) and the southern Subbetic zone; he suggested that the Malaguide unit was deposited on the southern flank of the Subbetic zone, where much of it is presently located.

West of Malaga, primarily low-grade metamorphic rocks are found. These are correlated with the Malaguide unit, whereas the higher-grade metamorphic rocks, related here to high-temperature ultramafic intrusion, have been variously correlated by metamorphic grade with the other nappes. Yet all these rocks, the "Betic zone" of this article, can be interpreted as the western part of the Malaguide tectonic unit and contact-metamorphosed equivalents, as convincing evidence for the presence of any of the other units is lacking. The similarity or transition of stratigraphic sequences of the cover units in the Betic zone, the "flysch" units, and the southern Subbetic zone units, reviewed in a previous section, is very similar to the evidence provided by MacGillavry east of Malaga and was considered by him.

It would be pure speculation for the writer to attempt a detailed evaluation of the tectonic evolution of the area east of Malaga, because he sees no evidence of an Alpujarride or Sierra Nevada tectonic unit in the West and does not have the years of first-hand experience in the east necessary to evaluate the several tectonic hypotheses proposed for that area. Thus, he can only conclude that the evidence from rocks in the Ronda area is consistent with the derivation of the Malaguide tectonic unit (identified as a "tectonic unit" only in the east) from just south of the Subbetic zone; the source of the Alpujarride, Sierra Nevada, or other tectonic units must be determined in the area where those rocks are exposed.

A main argument of this paper is that there is a temporal and geometric relation between the upper crustal activity and the emplacement of high-temperature peridotite. I will not try to predict theoretically the surface manifestations of diapirism in the mantle but rather attempt to outline an "observational" model consistent with the (admittedly controversial) geologic constraints of the Tertiary. The model is suggested for the Betic-Rif system west of long 4°W.

The Betic and Moroccan Paleozoic zones represent the exposed edges of a "Betic-Paleozoic" province of continental crust in the western Alboran Sea. The province comprised basins of deposition of limestones (with evaporites) in the Triassic, limestones in the Jurassic changing to marls, and limestones in the Cretaceous through Eocene. Some of the basins were shallow at times, and scattered uplifts shed some terrigenous debris and even clastics; facies changes and certainly thicknesses of accumulation may have varied rapidly in part of the Mesozoic but were rather uniform in the Cretaceous to Eocene. The rapid change from marl and marly limestone deposition to deposition of often transgressive terrigenous and calcareous clastic rocks implies differential uplift (erosion and proximal deposition) in the late Eocene and Oligocene. This activity may be related to the onset of *lithospheric* plate extension (by a change of boundary conditions on the plates at a distance) as shown in figure 3. There is no direct evidence of the extension of the lower crust or mantle *in the Oligocene,* only probable continuity of the mechanism of differential uplift and subsidence which can be related to lithospheric extension at the end of the Oligocene when clastic rocks were still being deposited.

An example of this same mechanism has been intensively studied in the Basin and Range province of North America where lithospheric extension and mantle upwelling are indicated by seismology, heat flow, and crustal tectonics. An example of extensional models proposed for this region is reproduced as figure 4 from Scholtz, Barazangi, and Sbar (1971). The observed upper crustal response is block faulting. Some differential uplift in the Alboran Sea is suggested by analogy, although differences in the area of extension (note the scale difference of figs. 3 and 4) and volcanism are apparent. Differential uplift is a possible mechanism to expose the carbonate and Paleozoic pelitic section to rapid erosion and form depositional basins nearby. The Basin and Range analogy can be cited to indicate the *type* of upper crustal response to lithospheric extension, but surficial processes, such as sedimentary deposition and gravity sliding, will depend also on rate of uplift, relative sea level, climate, strength of source rocks, et cetera as well as the general tectonic regime. Thus the analogy with the Basin and Range cannot be extended to the sedimentary environment. However, Armstrong (1972) has recently reviewed evidence for gravity-driven denudation faulting restricted to the Basin and Range province and corresponding to late Tertiary extension.

By the end of the Oligocene, upwelling mantle penetrated to the thinning continental crust in two zones along the northwestern and southwestern margins of the present Alboran Sea as shown in figure 3.

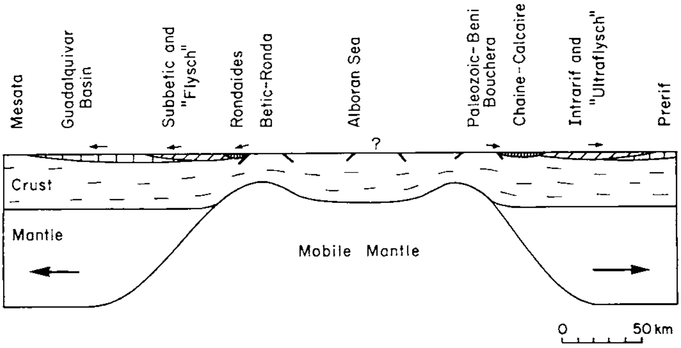

Fig. 3. Schematic cross section of the Betic-Rif orogenic system near long 5°W (present) at the end of the Oligocene. Fine arrows at the surface indicate the direction of sliding and rapid sediment transport, and dashed lines represent flattening (foliation).

The problem of the depth of cover needed above the Ronda massif, which penetrated up to Triassic rocks (marbles) can be explained by the thickness of the normal Triassic through Oligocene sedimentary section and by possible accumulation of sediments in an overlying basin. In fact, there may have been a tectonic basin in the western Betic zone that acted as the source of the abundant allochthonous "flysch" units concentrated in the nearby Campo de Gibraltar and Subbetic.

During or after intrusion of the ultramafic masses into the crust, the Betic, Paleozoic, and perhaps other areas remained uplifted *relative* to marginal subsiding areas and resulted in allochthonous movement of the cover sequence off these zones. A direct mechanical relationship between zones of mantle intrusion into the crust and denuded zones is not clear; in general, the massifs lie along the seaward margins of the presently exposed zones. The massifs exposed in the crust are only 10 to 20 km across and may have limited isostatic effect. The rapid exposure of the Ronda massif is explained by the process of tectonic denudation by gravity sliding of rocks primarily into the Subbetic basin. The actual sequence of unloading probably proceeded in units from top to bottom producing the inversion (Mesozoic limestone over "flysch") seen today on some contacts.

Loading of the Subbetic and Intrarif basins near the Betic-Paleozoic province with allochthonous debris may have produced the "lithostatic head" responsible for the movement of the Mesozoic-Tertiary cover sequences of these zones outward in the Miocene, lubricated by the Triassic evaporite horizons. Apparently the uplifted parts of the Betic-Rif province remained high relative to the subsiding marginal basins as shown by high-angle faulting. As newly emplaced mantle lithosphere cools, continued subsidence of the general area is expected. Andrieux,

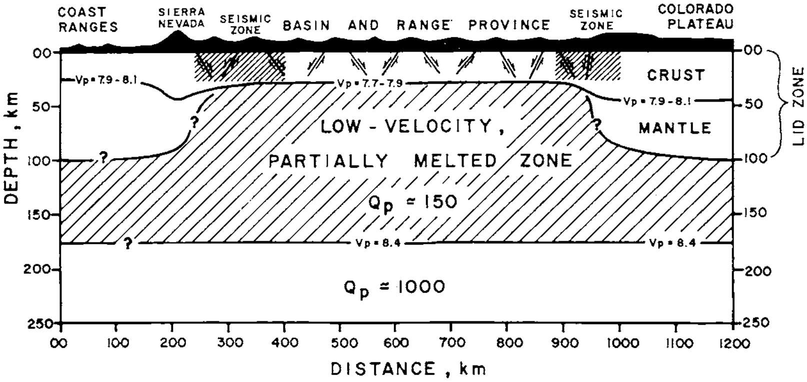

Fig. 4. Schematic cross section of the Basin and Range province of North America after Scholtz, Barazangi, and Sbar (1971). Continental crust has extended to retain a cover above upwelling mantle; however, faulting probably does not extend to the depths suggested in the figure. (Reproduced by permission of the authors and Geol. Soc. America.)

Fontboté, and Mattauer (1971) have suggested that some of the "flysch" units slid from high zones in the Alboran Sea during a tectonic phase after compression and have emphasized later extensional structures. Maxwell (1970) has also proposed a model of extension and mantle upwelling in the Alboran Sea.

PLATE TECTONICS

Zones of mantle upwelling.—The tectonic activity described in the foregoing can be properly related to plate tectonic models. The penetration of mobile mantle material through the lithosphere actually defines an extensional plate margin. The zones of mantle intrusion, delineated by peridotite outcrop and gravity anomalies, are indicators of the geometry of lithospheric plate extension. As a first approximation, the geometry of movement is here deduced from the pattern of mantle diapirs into the crust, and this extension geometry related to possible rotation of the Iberian Peninsula. Finally, the more general problem of plate extension in a continental environment is considered.

The outcrop pattern of ultramafic and associated metamorphic rock and the gravity anomaly distribution can be interpreted as indicative of two zones of mantle intrusions which radiate northeastward and southeastward from the Strait of Gibraltar to long 4°W. The gravity data (Bonini, Loomis, and Robertson, 1973) indicate that this entire region is probably continental crust into which the tops of the diapirs have penetrated in the radiating pattern. The radiating pattern appears from the gravity survey to end at long 4½° to 4°W, at which point an axial high appears in the Alboran Sea and continues eastward into the Mediterranean. Presumably these areas of thinned or absent continental crust mark spreading areas as shown in figure 5. Implicit in the model are transform faults between the central Alboran center and the western marginal ones, but these movements may be absorbed by plastic response of the crust as discussed below; there is a notable change in the Betic zone along this line from unmetamorphosed Paleozoic rock west of 4°W to regionally metamorphosed rock east of this longitude as discussed above.

The eastward continuation of spreading probably resulted in crustal thinning over a large area, but some idea of the geometry can be deduced from gravity evidence of localized thinning. The Alboran Sea gravity high probably represents such a zone; it extends eastward into the western Mediterranean high. Volcanic outcrops which can be related to the high (fig. 5) are late Miocene to Quaternary near Melilla (Durand Delga and others, 1962, p. 411), probably Miocene andesites and andesitic basalts on Alboran Island (Hernandez-Pacheco and Ibarrola, 1970), and early Miocene and later dacites and andesites on the Cabo de Gata (Paez Carrión and Sanchez-Soria, 1965; Leon, 1967). The composition of the volcanic rocks is probably strongly influenced by crustal contamination. The early Miocene age of the onset of volcanism correlates well with the age of extension proposed here from radiometric dating of mantle intrusion. Apparently upwelling was more rapid in the eastern Alboran Sea than in the western, and, hence, the general geothermal gradient was raised higher to produce volcanism, greater extension (see fig. 5), and perhaps the more extensive regional metamorphism.

Rotation of the Iberian Peninsula.—The extension model proposes the rotation of the Iberian Peninsula counterclockwise relative to Africa about a point in the Strait of Gibraltar in the Oligocene and Miocene. The movements suggested in the Alboran Sea are small relative to major plate motions, and the relationship to spreading models for the Atlantic also depends critically on poorly known details of possible decoupling in boundary areas such as the Atlas and Pyrenean system.

The hypothesis can be compared with rotation models deduced from paleomagnetism and the geology of the Bay of Biscay, although similar motions are not necessary if Africa has rotated relative to Europe. The rotation of the Iberian Peninsula to open the Bay of Biscay was proposed on geologic grounds by du Toit (1937) and Carey (1958) and as a result of the geometrical fit of the continents (Bullard, Everett, and Smith, 1965). Paleomagnetic evidence has been collected and reviewed by Irving (1964), Girdler (1965), Van Dongen (1957), Van der Voo (1969), Watkins and Richardson (1968), and Van der Voo and Zijderveld (1971). The consensus of opinion from this work is that the rotation of the Peninsula between the Triassic and present is on the order of 35° counterclockwise relative to stable Europe. The presence of a radiating magnetic

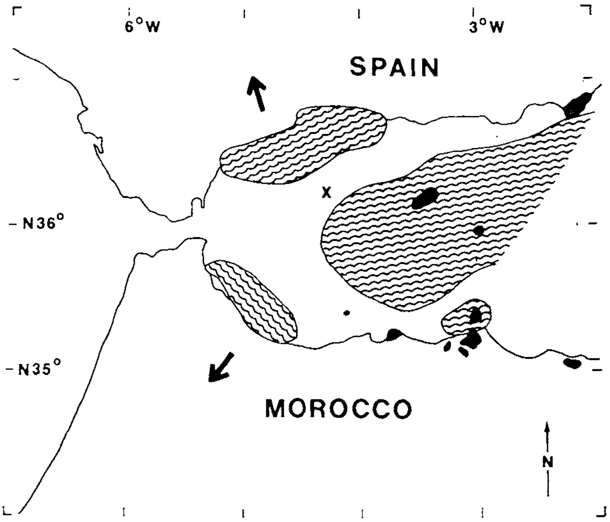

Fig. 5. Pattern: zones of crustal thinning suggested by outcrop of mantle diapirs and high gravity anomaly closures. Black: Miocene volcanic rocks (distribution after LePichon, Pautot, and Weill, 1972). Cabo de Gata, where both Miocene basic-dacitic volcanics and partial pelitic melts were erupted, is the most southerly part of Spain shown in the figure. X: JOIDES hole 121. The arrows show the implied rotation of Spain relative to Morocco about a point near the Strait of Gibraltar.

anomaly pattern in the Bay (Matthews and Williams, 1968) and sediments on the abyssal plain (Jones and Ewing, 1969) support this contention.

However, the age of rotation is still debated. Watkins and Richardson (1968), studying late Eocene volcanic rocks, suggested the possibility that as much as 22° rotation occurred later; more recently (1970) they have concurred with a lower value of approximately 12° post-Cretaceous rotation suggested by Jones and Ewing (1969) from the distribution of sediments in the Bay of Biscay. An early Miocene undisturbed layer implies that motion had stopped by then. Van der Voo and Zijderveld (1971) have concluded from a study of Eocene rocks that any later rotation was small. However, Storetvedt (1973) has restudied these Eocene volcanics and concluded that the rotation of Iberia followed deposition. Atlantic sea-floor magnetic anomaly patterns indicate that most of the rotation occurred before approximately 80 m.y. B.P., and Larson and Pitman (1972) interpret the radiating anomaly sequence in the Bay to imply spreading between 110 and 85 m.y. B.P.

A point of consideration on this subject is that only net rotations are measured by discrete paleomagnetic data points; the Peninsula may have undergone episodes of clockwise rotation as well. Pitman and Talwani (1972) compared Cretaceous paleomagnetic poles from North America with those of Iberia, based on a fit of the continents, and suggested the possibility of a clockwise rotation. The sense of shear stress between Africa and Europe would reverse from left lateral to right lateral in late Cretaceous as also noted by Smith (1971). Le Pichon and Sibuet (1971) have tried to relate clockwise rotation to Eocene orogeny in the Pyrenees and supposed trench development north of Spain. Pitman and Talwani (1972) emphasized that major rotations of the Peninsula did not include major blocks of the Atlantic sea floor.

The rather vague history of the rotation of the Iberian block, then, includes a large counterclockwise rotation relative to Europe either in the Mesozoic or Tertiary and possible rotations of a few degrees clockwise probably in the Eocene. The age and magnitude of post-Eocene counterclockwise rotation is in doubt from paleomagnetic evidence. I would add the possibility of an Oligocene and early Miocene counterclockwise rotation of the Peninsula relative to Africa based on evidence from ultramafic outcrops, volcanism, and gravity of increasing crustal extension eastward from the Strait of Gibraltar; the Strait is proposed to be a pivot point through which little shear movement has taken place. If the Peninsula were acting as a roller block between Europe and Africa at this time, the opening of the Alboran Sea may be related to opening of the Bay of Biscay. However, another possibility is that Africa has rotated relative to both Iberia and Europe as follows.

Tertiary opening of the western Mediterranean.—The plate tectonic movements in the Alboran Sea discussed here are critical to models of plate motion in the western Mediterranean. Extension in the Alboran

Sea probably increased eastward from the pivot point near the Strait as indicated by the appearance of volcanics and the increased area of thinned crust delineated by gravity anomalies toward the east. The central Alboran gravity high (Bonini, Loomis, and Robertson, 1973) continues eastward into the Balearic Basin. Evidence from salt diapirism and deposition, from seismic refraction identification of thinned crust, and from sedimentary transport studies was summarized and interpreted by Ryan and others (1970, p. 453) as indicative of a probable opening between the Corsica-Sardinia block and Europe beginning in the late Eocene-Oligocene and continuing into Miocene time (fig. 6). Le Pichon and others (1971) also argue for extension in these areas in the middle Oligocene based on the contemporaneous formation of grabens on the continent; however, Le Pichon, Pautot, and Weill (1972, see fig. 3, p. 85) propose later opening of part of the Alboran Sea in the middle Miocene as a result of strike-slip movement on several postulated faults.

The extension in the Alboran Sea proposed here is probably related to the opening of the western Mediterranean and supports an Oligocene to lower Miocene age for these movements, as shown in figure 6. However, strike-slip movement through the Alboran Sea area is not in evidence, and the opening was about a pivot point near Gibraltar. Thus, eastward movement of Africa relative to Europe during opening must have been accompanied by Oligocene-lower Miocene opening of the Bay of Biscay or strike-slip movement in other areas. Any mechanical coupling between Atlantic sea-floor spreading and the Iberian Peninsula-

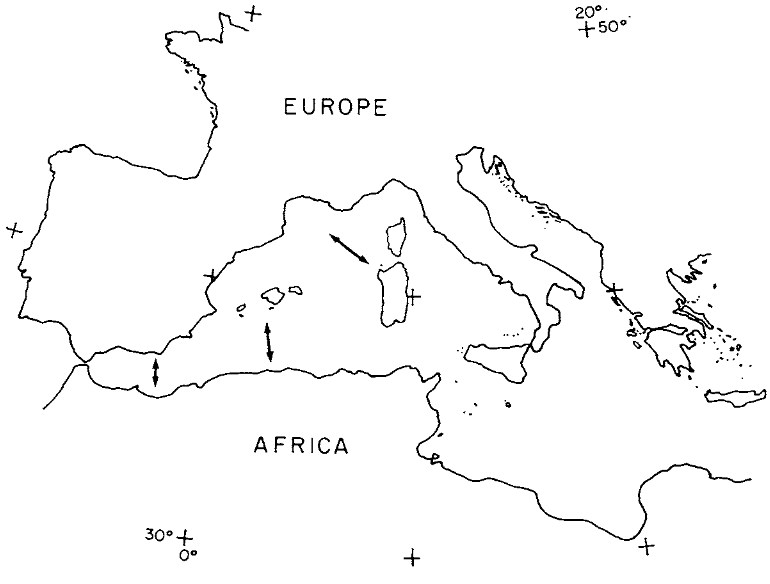

Fig. 6. Western Mediterranean. Arrows indicate probable zones of lithospheric extension and extensional crustal thinning in the Oligocene-early Miocene.

Betic-Rif system is strongly dependent on strike-slip movements in the Pyrenean or Atlas systems.

Intraplate tectonics.—The previous model of plate motion has been deduced utilizing the simplifying assumptions of rigid lithospheric plate tectonics. While the rigid plate assumption allows formulation of a model of gross movements of large blocks, the tectonic model proposed for the western part of the Betic-Rif system and western Alboran Sea can more properly be called "Intraplate" or "Plastic Plate" tectonics: the activity took place beneath or inside a continuous cover of continental crust, and a sea-floor spreading ridge was not exposed.

The model of rigid plate tectonics must be modified when plate activity occurs in continental crust. Several modifications applicable to a continental intraplate tectonic model, deduced from this work and related studies, are summarized below:

1. A thick layer of insulating continental crust can deform plastically at depth during plate extension to maintain a cover over the spreading zone. Plastic deformation is probably augmented by heating above the spreading zone. Indeed, the upwelling of mantle material can efficiently heat the crust in a localized area and, coupled with plastic deformation of the heated crust, may result in regional metamorphism. The best example of crustal continuity and high heat flow over an intracontinental spreading zone is probably the Basin and Range province of North America.
2. The rate of spreading should greatly influence the surface tectonic manifestations. Slow extension may result in simple crustal thinning and surface subsidence. As the rate of extension increases, introduction of hot buoyant athenosphere into the mantle lithosphere man lift the crust during extension, and rapid extension will raise the geothermal gradient sufficiently to promote volcanism. The Alboran Sea example presented here apparently represents an intermediate rate of extension, and the Basin and Range a relatively rapid one.
3. Plastic extension of the crust at depth will result in a more brittle response near the surface. Such an extensional tectonic environment at depth may foster gravity sliding and allochthony in the upper crust.
4. The demonstrated plastic thinning of continental crust over plate boundaries contrasts these areas with the rigid blocks of oceanic regions and complicates any geometrical reconstruction of small, continental plates.

Many of the Mediterranean orogenic systems show tectonic features similar to the Betic-Rif (derivation of tectonic units from an "oceanic" area); as suggested by several authors, as well as the work reported here, this tectonic development can be a result of intraplate extension rather than compression.

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APPENDIX

Analyzed sample descriptions

R168: Cordierite hornfels. Approximately 7 km north-northwest of Estepona near peridotite contact on logging road, Spain. Quartz 40 percent, coarse grained porphyroblastic microperthite 25 percent, euhedral normally zoned plagioclase 10 percent, subhedral porphyroblastic cordierite 15 percent, biotite 5 percent, minor fibrolite, hercynite, opaques, zircon, and apatite. Incipient alteration of cordierite and plagioclase.

R8: Cordierite hornfels. Approximately 6½ km east of Igualeja in pendant, Spain. Quartz 50 percent, porphyroblastic microperthite 10 percent, euhedral, normally zoned plagioclase 10 to 20 percent, biotite 3 percent, porphyroblastic cordierite 10 percent, minor fibrolite, garnet, opaques, hercynite, zircon, and apatite. Some alteration of cordierite and plagioclase.

R131: Medium-grained schist. Approximately 4 km north-northeast of Casares on logging road, Spain. Quartz 50 percent, plagioclase 30 percent, biotite 15 percent, staurolite 1 percent, fibrolite 3 percent, minor apatite, tourmaline, zircon, and opaques.

R245: Gneiss. Approximately 6 km north-northeast of Casares near peridotite contact, Spain. Quartz 40 percent, microperthite 15 percent, plagioclase 10 percent, garnet 20 percent, biotite 2 percent, sillimanite 10 percent, minor kyanite, zircon, and opaques.

75.115: Andalusite pegmatite crossing micaschists in Oued M'Ter, Morocco. Coarse-grained muscovite supplied by M. J. Kornprobst.

M7.221: Medium-grained schist, Morocco. Quartz 40 percent, plagioclase 20 percent, biotite 15 percent, fibrolite 5 percent, K-feldspar 15 percent, minor apatite, opaques, and kyanite. This rock is very similar to that found 2 km from the peridotite contact in Spain. Sample supplied by M. J. Kornprobst.

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