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Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almería, Sorbas and Tabernas Basins of the Betic Cordilleras, SE Spain)

R. Weijermars[1], Th.B. Roep[2], B. Van den Eeckhout[3], G. Postma[4] & K. Kleverlaan[2]
[1]The Hans Ramberg Tectonic Laboratory, Institute of Geology, Uppsala University, Box 555, S-75122 Uppsala, Sweden; [2]Geological Institute, University of Amsterdam, 130 Nieuwe Prinsengracht, NL-1018 VZ Amsterdam, The Netherlands; [3]Institute for Earth Sciences, University of Utrecht, Budapestlaan 4, NL-3508 TA Utrecht, The Netherlands; [4]Geological Institute, University of East Anglia, Norwich NR4 7TJ, United Kingdom

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Abstract

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Structural, stratigraphical and sedimentological studies of the Alhamilla region show that the Sierra Alhamilla was elevated relative to the surrounding basins by open folding towards the end of the Tortonian period (about 7 Ma ago) and before the onset of Messinian sedimentation. The main arguments are: (1) the dominant current direction in the Neogene cover changes from southward to southeast- and southwestward during the Late Tortonian, (2) Late Tortonian seismites suggest contemporaneous major tectonic activity which is contrasted by low tectonic activity during the Messinian, (3) Messinian reefs colonise Nevado-Filabride basement exposed (near Polopos) in the eroded hinge of the Alhamilla Anticlinorium, (4) the Northern Boundary Fault which is interpreted to be cogenetic with the formation of the Alhamilla Anticlinorium transects Tortonian sediments but is covered (near Cantona) by unfaulted Messinian reefs, and (5) the base of an almost non-tectonised Messinian succession (in the Sorbas Basin) unconformably overlies an erosion surface of folded Tortonian sediments,

Neogene uplift of the Alhamilla region is interpreted here to be due to isostatic recovery after the emplacement of the Alboran Diapir between 20 and 25 Ma ago. Estimates of the average uplift rates vary between 0.7 to 0.5 mm a^{-1} for the Miocene and 0.15 to 0.1 mm a^{-1} for the Pliocene and Quaternary. Pliocene and Quaternary uplift rates are almost identical to the sedimentation rates of 0.23 to 0.2 mm a^{-1} estimated previously for the Alboran Basin.

Introduction

The Sierra Alhamilla is an Alpine basement inlier within Neogene sediments in southeastern Spain. (Fig. 1). The morphology of the range is largely determined by a Neogene anticlinorium which exposes several nappes (Platt et al. 1983). The Aguilón fold nappe, the principal tectonic element, lies on a carpet of mylonitic schists, carbonates and quartzites (Platt 1982). Geothermometry of a marble specimen from the mylonitic carpet indicates that ambient temperatures during flow were in

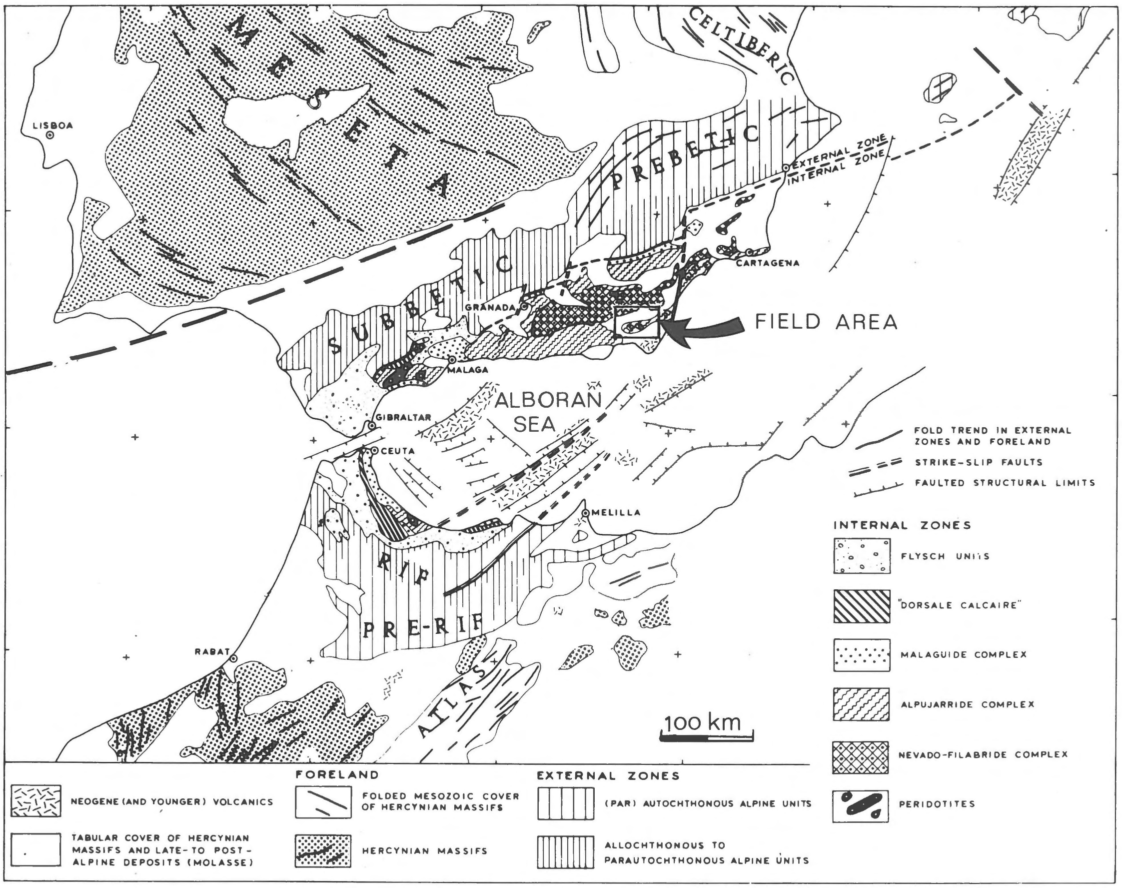


Fig. 1. Birds-eye view of the Betic-Rif orocline (after Kampschuur & Rondeel 1975). The location of Figure 2 is outlined.

the order of 300°C (Behrmann 1983). Greenschists-facies metamorphism, syngenetically developed with minor structures in the Aguilón fold-nappe, indepently suggests that nappe emplacement occurred at a depth of 10-15 km by gravity spreading (Platt et al. 1983). The internal geometry of the nappe and oriented quartz c-axes in the footwall rocks both indicate that the spreading which emplaced the Aguilón nappe involved northward transport (Behrmann & Platt 1982, Platt et al. 1983).

Mylonites, cataclasites and extensional crenulation cleavages similar to those developed beneath the Alpujarride Aguilón fold nappe (Platt & Vissers 1980, Konert & Van den Eeckhout 1983, Behrmann 1984a, b, 1985) also occur beneath Alpujarride nappes exposed in other parts of the Betic Zone (see Geological Setting and Fig. 1). The base of all the Alpujarride nappes has therefore been interpreted as a single major intracrustal shear zone within the Betic Zone and has been termed the Betic Movement Zone (BMZ) (Platt & Behrmann 1985, cf. Platt et al. 1984). The nappes and BMZ were both formed between 25 and 15 Ma BP according to a tectonic scenario recently developed to explain the evolution of the Betic-Rif orocline (Weijermars 1985a, b).

An explanation is still required for when and how the 25 to 15 Ma old Aguilón nappe and the underlying BMZ were brought to exposure after their formation at 10 to 15 km depth. An attempt to analyse the uplift history of the nappe and the superposed folding is presented here based on extensive geological studies in the Neogene basins adjacent to the Alhamilla mountain range.

Geological setting

The basement of the Iberian peninsula consists of rocks affected by the Hercynian orogeny. Structural trends end abruptly to the south in the Quaternary-Neogene basin of the Guadalquivir river (fig. 1). The Betic Cordilleras emerge southeast of the Guadalquivir depression. This Alpine belt is subdivided into an External Zone in the north and an Internal Zone in the south (Egeler & Simon 1969). The External Zone, divided into Prebeticum and Subbeticum (Fig. 1), comprises non-metamorphic Mesozoic and Tertiary sediments. The Subbeticum was thrust northward onto the Prebetic rocks in Tortonian times (Hoedemaeker 1973, Jerez-Mir 1973, Azéma 1977).

The Internal or Betic Zone comprises predominantly E-W trending mountain ranges and intramontane depressions. The Betic ranges expose faulted and refolded Alpine nappes which formed the basement to Neogene sedimentation. The nappes are classically grouped into three complexes which regionally overlie each other in the basement. These are in ascending order the (1) Nevado-Filabride, (2) Alpujarride, and (3) Malaguide complexes (Egeler & Simon 1969, Torres-Roldán 1979). The first two nappe complexes show polyphase deformation and comprise mainly metamorphic rocks. The Malaguide complex is mainly non-metamorphic.

The cover has been subdivided into the Older (Burdigalian and Serravallian) and Younger Neogene (Serravallian-Pliocene) according to Völk & Rondeel (1964). Arguments for this subdivision were based on the sudden change from Alpujarride to Nevado-Filabride detritus in Younger Neogene sediments and on an alleged angular unconformity between Older and Younger Neogene sediments. The majority of the sediments in the Alhamilla Region are of Younger Neogene age.

Detritus in the Neogene sediments of the eastern Betic Zone can be classified as Nevado-Filabride, Alpujarride or Malaguide, according to its derivation. The following lithological characteristics are therefore appropriate to establish which basement complex supplied the detritus.

The *Nevado-Filabride* nappes have a lowermost part consisting of dark coloured low-grade metamorphic mica schists and quartzites and its upper part is lithologically heterogeous, comprising medium-grade metamorphic schists, quartzites, marbles, amphibolites and gneisses (Egeler 1963). The *Alpujarride* nappes comprise low-grade metamorphic Triassic carbonate rocks (Kozur et al. 1974), phyllites and quartzites (Egeler & Simon 1969), and locally they contain black, medium-grade metamorphic schists (Vissers 1981, Akkerman et al. 1980, Platt et al. 1983). The *Malaguide* nappes in the eastern part of the Betic Zone consist of non-metamorphic to very low-grade metamorphic carbonate rocks, sandstones, shales and conglomerates, ranging from Silurian to Oligocene in age (Roep 1972, Soediono 1971, Geel 1973, Mäkel & Rondeel 1979). Oligocene sediments have been found in the Malaguide klippes of the Vélez Rubio region, near Huercal Overa and in the Sierra Cabrera (cf. Egeler & Simon 1969).

Neogene stratigraphy and sedimentology

The Sierra Alhamilla is surrounded by the basins of Tabernas and Sorbas to the north and of Almería to the south (Figs. 2 and 5). The stratigraphy of the Tabernas-Almería and Sorbas Basins (Fig. 3) is characterised by three major transgressive cycles of the following ages: (1) Serravallian-Tortonian, (2) Messinian, and (3) Pliocene; their importance is decreasing in this order. Relief existed during all deposition episodes as can be inferred from the spatial distribution of the exposed Neogene sediments (Fig. 2). These three major sedimentary episodes are discussed below.

Relicts of a poorly dated Older Neogene transgression are exposed at the western termination of the Sierra Alhamilla (too small to be indicated in Fig. 2). This oldest formation is deposited upon Alpujarride basement as a 35 m thick sequence of marine sediments. It comprises heterogeneous rocks in which the following tripartite division can be distinguished: (1) basal conglomerates and sandstones, laterally and vertically grading into marls, (2) conglomeratic dolomites, and (3) limestone conglomerate composed of Malaguide de-

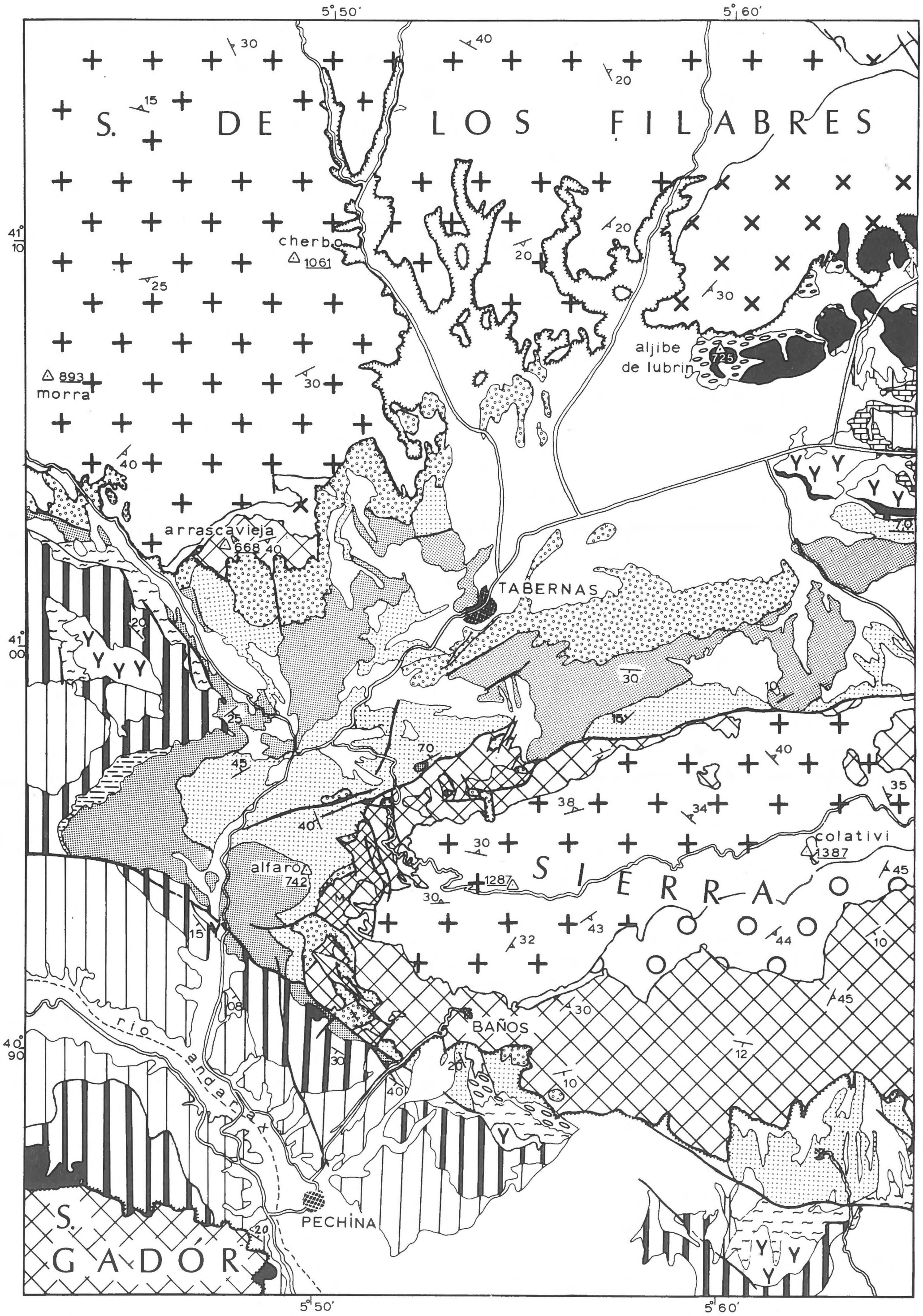
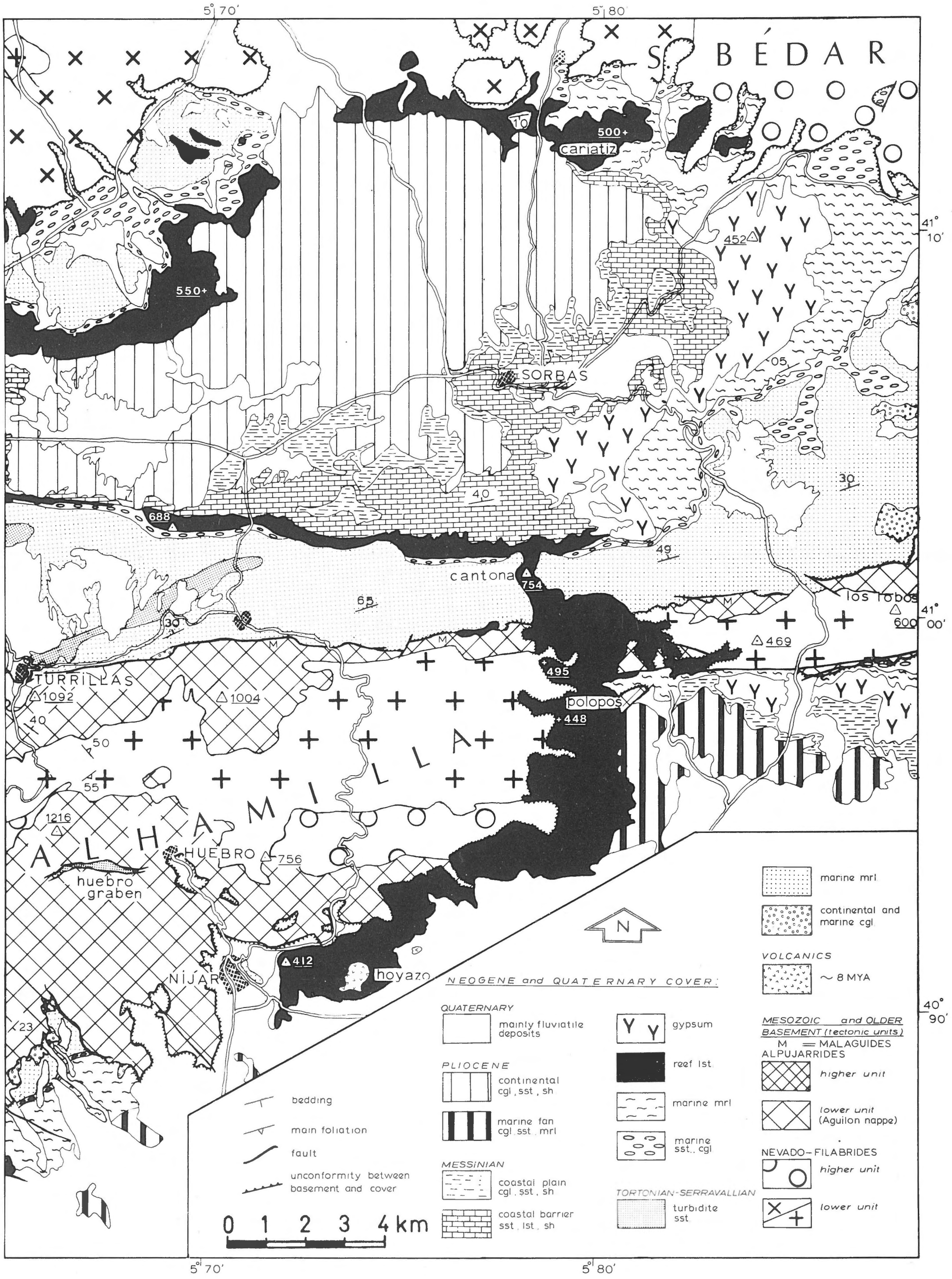


Fig. 2. Detailed geological map of the Sierra Alhamilla basement and the adjacent Neogene basins. Topographic height of Messinian reef limestones and triangulation points are indicated in metres. Compiled on the basis of published (Jacquin 1970, Iaccarrino et al. 1975, Roep et al. 1979, Vissers 1981, Dabrio et al. 1981, Platt et al. 1983, Postma 1984) and unpublished maps (Janzen 1981, Kleverlaan 1980, Van den Eeckhout 1980, Weijermars 1980).


5°70'
5°80'
BÉDAR
10
500+
cariatiz
550+
452
SORBAS
05
41° 10'
30
40
688
49
cantona
754
65
30
los lobos
600
41° 00'
M
469
495
polopos
+448
TURRILLAS
1092
1004
40
50
55
1216
ALHAMILLA
HUEBRO
756
huebro graben
412
NIJAR
hoyazo
23
40° 90'
N
NEOGENE and QUATERNARY COVER:
QUATERNARY
mainly fluviatile deposits
PLIOCENE
continental cgl, sst, sh
marine fan cgl, sst, mrl
MESSINIAN
coastal plain cgl, sst, sh
coastal barrier sst, lst, sh
gypsum
reef lst
marine mrl
marine sst., cgl
TORTONIAN-SERRAVALLIAN
turbidite sst
marine mrl
continental and marine cgl
VOLCANICS
~ 8 MYA
MESOZOIC and OLDER BASEMENT (tectonic units)
M = MALAGUIDES
ALPUJARRIDES
higher unit
lower unit (Aguilon nappe)
NEVADO-FILABRIDES
higher unit
lower unit
bedding
main foliation
fault
unconformity between basement and cover
0 1 2 3 4 km
5°70'
5°80'

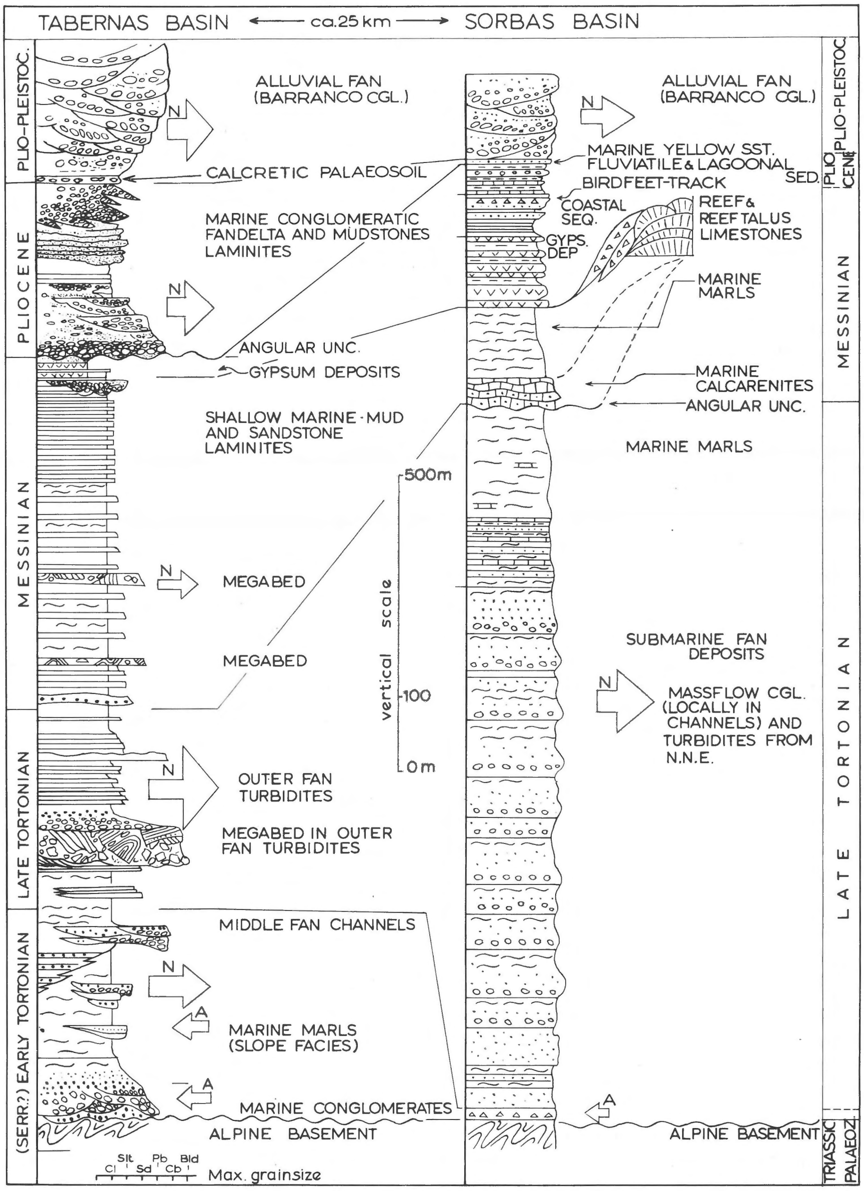


Fig. 3. Composite stratigraphic columns of: a) Almería and Tabernas Basins and b) Sorbas Basin. Major influxes of early Alpujarride (A) without Nevado-Filabride detritus are shown by left-facing arrows. Right-facing arrows denote introduction of predominantly Nevado-Filabride detritus (N). The megabeds in the Tabernas Basin have been interpreted as seismites.

tritus. The formation is discordantly overlain by Serravallian-Tortonian sediments.

(1) Serravallian-Tortonian

The majority of the sediments exposed and resting on the basement of the area outlined in Figure 2 was deposited during Serravallian-Tortonian times. During this period the sea transgressed from south to north. This is inferred from the observation that areas south of the Sierra Alhamilla were already transgressed during the Serravallian (Van de Poel & Manuputty pers. comm., Ott d'Estevou 1980), whereas areas to the north of the Sierra Alhamilla were transgressed during Early Tortonian and higher parts towards the north and east during the Late Tortonian (Ott d'Estevou 1980, Kleverlaan 1980).

This marine transgression was preceeded by the deposition of red continental conglomerates bearing Malaguide and Alpujarride detritus. This oldest Younger Neogene conglomerate overlies Alpujarride basement of the Sierra Alhamilla and remnants of Older Neogene sediments at its western termination. Red continental conglomerates, probably of similar age, are also exposed in the core of an anticline in the Tabernas Basin and along the southern slope of the Sierra de los Filabres. The detritus is mainly derived from their substratum. Imbricated pebbles and the orientation of channel axes indicate a predominantly southward transport along a local depression near Tabernas and the future Rioja Corridor (Fig. 5).

Marine basal conglomerates commonly fill local depressions of mesoscopic and megascopic scales on a shallow regional basement high at the site of the future Sierra Alhamilla. The most common conglomerate occurs in up to 20 m thick, massive sheets. Components are directly derived from the underlying basement rocks, and consist of Alpujarride and to a lesser extent Malaguide detritus. Coarse basal breccias up to several metres thick locally underlie the clast-supported dolomite-quartzite pebble conglomerate which has a carbonaceous sand matrix. The latter, in turn, grades upwards into medium-grained marine sand, which forms the transition to an overlying marl sequence (Fig. 3). The total sequence represents a transition from coastal to deeper water facies.

The existence of a shallow Alhamilla basement high can be inferred since it supplied reef debris and Alpujarride detritus to conglomeratic intercalations in the lowermost marine marls of the Tabernas Basin (Fig. 3). Similar reefs intercalated in conglomerates have been reported from the northern slope of the Sierra de Los Filabres where they mark the onset of a Tortonian transgression (Dabrio 1974). Minor reef complexes are exposed above an abrasion surface on the southern flank of the Sierra de Los Filabres (too small to be indicated on Fig. 2). Progressive transgression drowned the shallow Alhamilla basement and consequently inhibited the supply of conglomerates from the south.

The marl sequence is intercalated with turbidite sandstones and conglomerates supplied by a submarine fan-system which extended from the Sierra de Los Filabres (N of Tabernas, Fig. 2) towards the south and southwest. This fan-system is called the Tabernas Fan (Kleverlaan 1980, 1984) and feeder channel, inner and outer fan lobe sediments have been recognized. Detailed mapping of the Tabernas Fan and the recognition of seismite intercalations (very coarse-grained up too 100 m thick megabeds, see Figure 3) indicate major tectonic activity in the Tortonian. Southerly current directions within the sandstone layers and imbrications in the conglomerates together with a general southward decrease in grain size confirm that the palaeobathymetry was that of a roughly southward dipping submarine fan. Current directions changed towards the southwest near Tabernas and to the east near Turrillas in the Late Tortonian. The composite thickness of the marl sequence with the turbiditic intercalations is about 1000 m in the Tabernas Basin (Fig. 3). Synsedimentary slumps are abundant (Fig. 4).

Summary: The Tortonian period was tectonically unstable as indicated by (1) the abundance of detritus which is deposited in a southward building submarine fan-system, (2) a shift in the major current direction from S to SW and SE during the Upper Tortonian, and (3) the presence of seismites and synsedimentary slumps.

(2) Messinian

The lower part of the Messinian is a transgressive sequence of onlapping coastal and shallow marine sandstones and conglomerates which attain a maximum tickness of 50 to 100 m. The contact between the Messinian basal sequence of the Sorbas basin and the Tortonian marl turbidite sequence of the Tabernas basin is an angular unconformity with angles up to 60° between the respective bedding planes (Fig. 2, locations near Cantona, and unconformity on Fig. 5). The coarse clastic basal rocks grade upwards and basinwards into marine marls which are at the most 120 m thick (Fig. 3). Benthonic foraminifera indicate a maximum sea depth of about 200 to 300 m (Troelstra et al. 1980).

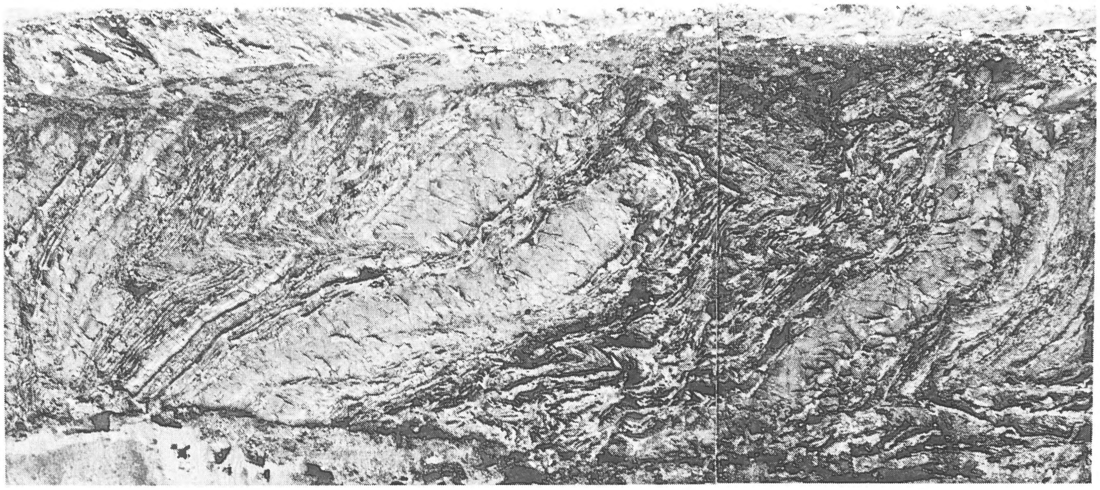


Fig. 4. Syn-sedimentary slumps in Tortonian marls in a road cut south of Tabernas. Strata are slumped towards the south, photograph is taken facing east (Photograph: R. Weijermars).

The margins of the Messinian Sea, after reaching its largest extent, are marked by large barrier reefs indicated in black on Figure 2 (*cf.* Pagnier 1976, Dabrio et al. 1981).

After a minor regression, sedimentation continued in the deeper part of the basin, but changed from a normal marine environment to a hypersaline facies. The deeper parts of the Messinian Sea

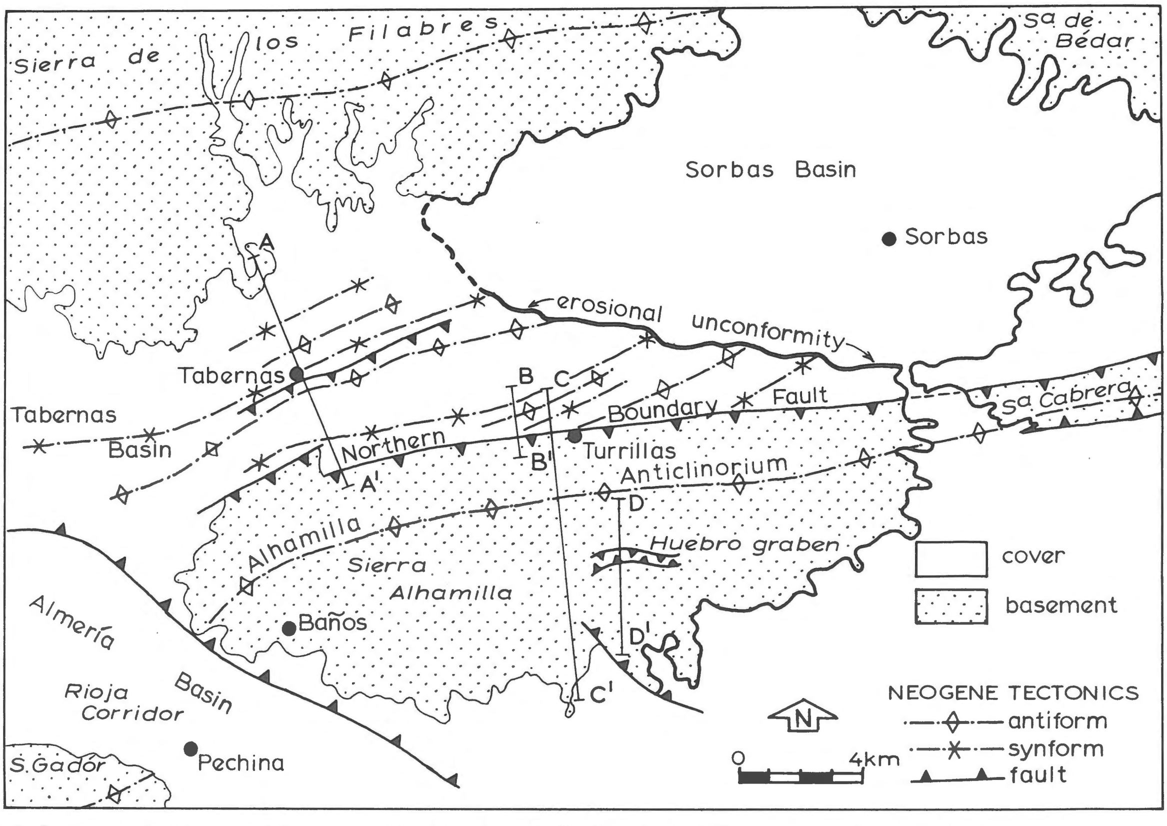


Fig. 5. Structural sketch map of the area outlined in Figure 2. Section lines of Figure 6 are indicated.

are outlined by up to 130 m thick gypsum deposits. Initial and final water depths of gypsum deposition are estimated to vary between 10 and 100 m (Dronkert 1976, Pagnier 1976, Beets & Roep 1978). Laminites of mud, marl and limestone intercalated between the gypsum and the absence of wave ripples or dessication cracks indicate deposition below wave base. Laminites on top of the gypsum gradually pass upwards from a wave-built coarsening upwards sequence into beach deposits (Roep et al. 1979).

Gypsum precipitated during the 'Messinian Salinity Crisis' (Hsü et al. 1977) is generally correlated with two South Atlantic glacial events occurring between 5.7 to 5.1 Ma ago (McKenzie et al. 1984, c.f., Van Couvering et al. 1976). The Late Messinian gypsum also demarcates the end of uniform regional facies in the Neogene basins of southeastern Spain. Four typical stratigraphic elements of the Messinian period have been found in nearly all these basins, *i.e.*: transgressive sands, marls, reefs and gypsum.

Different facies occur in the Almería and Sorbas Basins after the cessation of the Messinian transgression. Coastal sand, continental flood-plain and coastal plain deposits with lagoonal limestone containing Caspi-brackish Cyprideis (Lago Mare facies) and other ostracods occur in the Sorbas Basin (Roep & Van Harten 1979). The upper part of this continental facies with a final marine intercalation is considered to be of Pliocene age (Roep & Beets 1977, Ott d'Estavou 1980). Alluvial fan-type deposits overly marine Pliocene deposits in the Almería and Tabernas Basins.

Summary: The Messinian succession is separated from Tortonian sediments by an erosional uncomformity in the Sorbas Basin, whereas a concordant relationship exists along the western margin of the Tabernas Basin. The Messinian was a tectonically quiet period within an Upper Miocene minor regression which was followed by non-uniform evolution of the basins surrounding the Sierra Alhamilla. Major erosion began at the end of the Messinian.

(3) Plio-Pleistocene

The majority of Plio-Pleistocene deposits in the Sorbas Basin consists of southward sloping alluvial fans indicating uplift of the Sierra de Los Filabres. The Almería and Tabernas Basins underwent a Pliocene transgression and subsequent regression. The Rioja Corridor, a graben connecting the Tabernas and Almería Basins, subsided further and remained a shallow submarine canyon during the Early Pliocene funnelling large amounts of conglomeratic detritus towards the Mediterranean. Angular unconformities between Messinian and Pliocene sediments are locally exposed to the west of Tabernas and in the Rioja Corridor. The final Pliocene regression resulted in the infilling of the remaining shallow marine bay, first with sandstones, then by marls covered by a marine conglomeratic fan-delta, and finally by continental barrancotype river deposits and debris-flows (Postma 1984a, b).

Summary: Great amounts of detritus were transported southwards through the Rioja Corridor, which was finally filled by Pliocene conglomerates.

Structure

The polyphase deformation history of the nappes exposed in the Sierra Alhamilla basement has been discussed in detail elsewhere (Platt et al. 1983, Konert & Van den Eeckhout 1983, Van den Eeckhout & Konert 1983, Weijermars 1985c). The main foliation indicated in the basement of Figure 2 is a gently dipping schistosity. The east-west strike of the Sierra Alhamilla coincides with the axis of the folded contact between the Nevado-Filabrides and the Alpujarride Aguilón fold-nappe and is also expressed by the change in strike and dip of the main foliation in both units (Fig. 2.) The basement fold is here termed the Alhamilla Anticlinorium. It is strongly asymmetric with a steep to overturned northern limb as illustrated in the cross-section of Figure 6c.

The axis of the Alhamilla Anticlinorium continues eastward into the Sierra Cabrera but is truncated in the west by the normal fault which enhanced subsidence of the Rioja Corridor relative to the Sierra Alhamilla (Fig. 5). The direction of Middle Pliocene mass flows and angular unconformity between Messinian and Pliocene sediments in the Rioja Corridor suggests that this depression was principally formed during the Lower Pliocene. The formation of the Rioja Corridor may have involved an approximate 4 km sinistral strike-slip displacement of the Sierra Alhamilla relative to the Sierra de Gádor. This would explain the displacement of the anticlinorium axis of the Sierra Alhamilla relative to that of the Sierra de Gádor (Fig. 5). This strike-slip displacement may be related to the formation of the Palomares Shear Zone exposed further eastwards (Bousquet et al. 1975).

The Alhamilla Anticlinorium is bounded to the north by the E-W trending Northern Boundary Fault (NBF) which imbricates Alpujarride carbonates, quartzites and phyllites in a 100-200 m wide thrust zone separating the Neogene cover of the Tabernas Basin from the Nevado-Filabride Alhamilla basement (Fig. 6b). The dip of the NBF changes along strike. It is exposed as a 35° south-dipping overtrust near Turrillas (Fig. 2) and gradually steepens towards the west and east. The vertical upthrow of the southern block is of the order of 200-500 m. There is no evidence for a strike-slip component.

NE-SW trending fold axes in the Tortonian cover of the Tabernas Basin are cut-off by the NBF in the SW and truncated in the NE by an erosional unconformity at the base of the Messinian succession in the Sorbas Basin (Figs. 2 and 5). The structural style of the open to tight folds in the Tortonian sediments of the Tabernas Basin is illustrated in Figure 6a. This folding was accompanied by upthrusting of southern blocks (Fig. 6d).

Serravallian (–Tortonian?) conglomerates and marls are also preserved in the E-W trending Huebro Graben in the central part of the Sierra Alhamilla (Fig. 5). The Huebro Graben has a maximum width of 400 m and is 2 km long. Remnants (10-20 m thick) of a Serravallian-(Tortonian) basal conglomerate are also exposed directly north of the Huebro Graben, unconformably overlying carbonate rocks of the Aguilón fold-nappe in a topographic low. These tectonically undisturbed exposures suggest that a palaeorelief of at least 200 m existed before their deposition.

Discussions

(A) Age of the Alhamilla Anticlinorium

The structural and stratigraphical data discussed above yield the following critical observations which led us to conclude that the folding of the Alhamilla Anticlinorium and its cover in the Tabernas Basin occurred principally during the late Tortonian close to the Messinian time boundary about 7 Ma ago (the Tortonian-Messinian time boundary is dated at 6.5 Ma ago by Steininger & Rögl 1983):

1 - Pebble imbrication and orientation of channel-axes in Serravallian-Early Tortonian continental conglomerates suggest a southward transport direction at that time.

2 - Early Tortonian current directions in the Tabernas Fan are still predominantly southward but change towards the SW and SE in the Later Tortonian.

3 - Late Tortonian seismites suggest contemporaneous major tectonic activity.

4 - Tortonian sediments in the Tabernas Basin are folded and separated by an erosional unconformity from the relatively undeformed Messinian succession exposed in the Sorbas Basin. However, a concordant relationship exists between Tortonian and Messinian strata in the western part of the Tabernas Basin (fig. 3 and 5).

5 - The Northern Boundary Fault transects Tortonian sediments but is covered by undisturbed subhorizontal Messinian reefs near Cantona (Fig. 2).

6 - The Alpujarride Aguilón nappe in the hinge of the Alhamilla Anticlinorium had to be eroded away before Late Messinian reefs could grow onto exposed Nevado-Filabride basement near Polopos (Fig. 2).

7 - The Huebro Graben contains Serravallian-(Tortonian) sediments which subsided after depo-

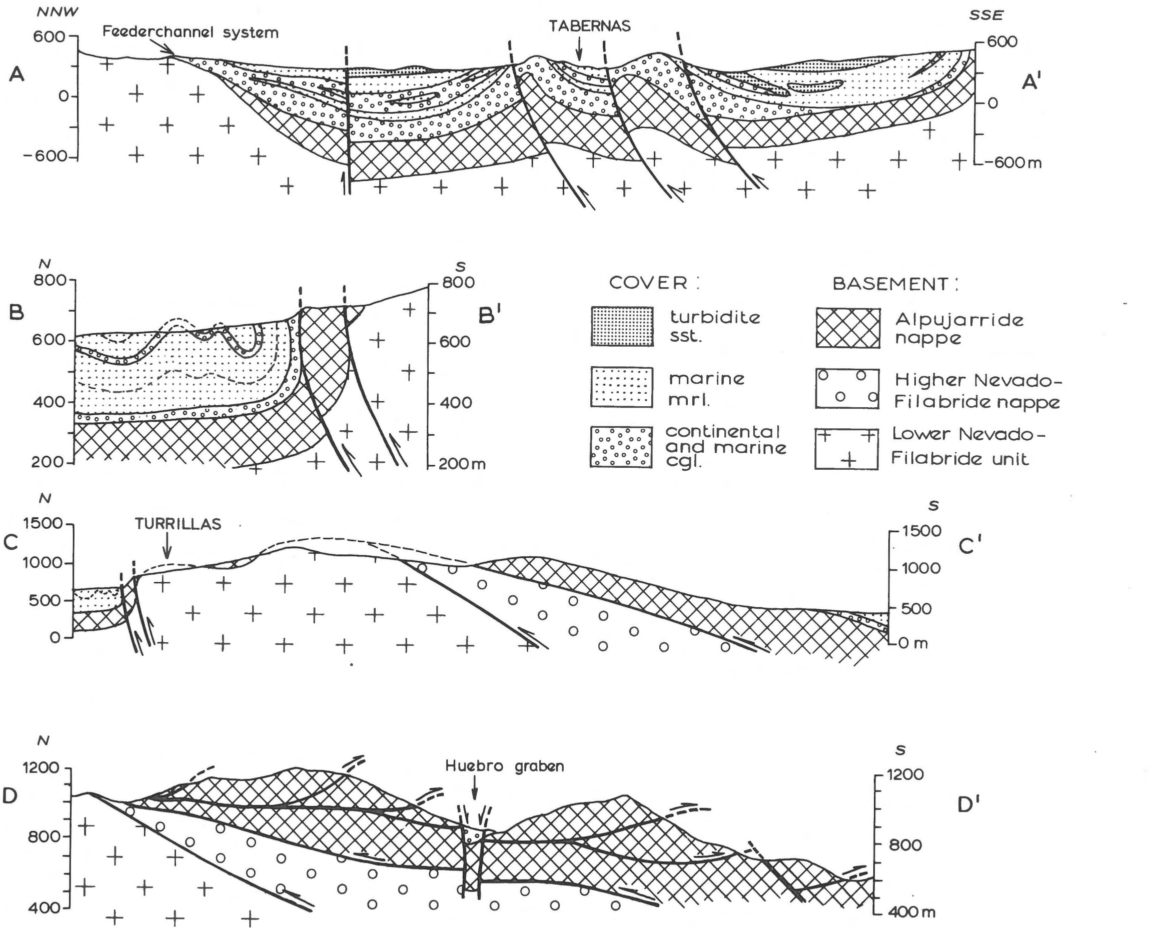


Fig. 6. a) A-A': Serravallian-Tortonian sediments in the Tabernas Basin are folded and faulted (after Kleverlaan 1980).
b) B-B': imbricated Alpujarride rocks separate the Nevado-Filabride basement of the Sierra Alhamilla from the folded Neogene sediment in the Tabernas Basin (after Weijermars 1980).
c) C-C': Alhamilla Anticlinorium has a gently dipping southern limb and a steeply faulted northern limb (after Weijermars 1980).
d) D-D': the Huebro Graben preserved Serravallian-Tortonian conglomerate and marls from erosion in the central part of the Alhamilla within Alpujarride basement (after Weijermars 1980).
Vertical and horizontal scales are equal. Locations of the cross-sections are indicated in Figure 5.

sition as the graben faults transect the basal unconformity.

8 - Messinian sedimentation occurred in a tectonically quiet period.

9 - The barrier reefs indicated in black on Figure 2 outline the greatest extent of the Messinian Sea and demarcate which part of the Sierra Alhamilla was elevated above sea level during the Late Messinian.

(B) Regional implications

Emplacement of the Aguilón fold-nappe at 10-15 km depth can be inferred from the syngenetic greenschist-facies metamorphism (Platt et al. 1983) and a temperature of 300°C from marbles in its mylonitic foot-wall (Behrmann 1983). Ostracods in carbonates of the Alpujarride Aguilón fold-nappe have yielded Middle Triassic (Ladinian) dates (Kozur et al. 1974). The regionally overlying Malaguide nappe contains Oligocene sediments

(MacGillavry et al. 1963). This fact has been used to argue that the emplacement of all the Betic nappe complexes presumably took place after the Oligocene (Weijermars 1985a, b). If the (hot) emplacement of the Betic nappes took place between 20 and 25 Ma ago, then how was the Aguilón fold-nappe brought to the surface?

The Betic nappes are likely to result from nappe shedding from a former topographic high at the site of the Alboran Sea (Van Bemmelen 1952, Torres-Roldán 1979). The topographic high may have been caused by the emplacement of a mantle diapir, because the continental crust beneath the Alboran Sea is still thinned (Banda et al. 1983, Marillier & Mueller 1985) and crustal cooling could explain the onset of subsidence of the Alboran Basin between 20 and 15 Ma ago (Weijermars 1985b). Seismic reflection profiles and data from bore hole 121 cored during Deep Sea Drilling Project Leg 13 revealed that 15 Ma old Serravallian sediments occur above the crystalline basement of the Alboran Basin (Nesteroff & Ryan 1973, Olivet et al. 1973, Mulder & Parry 1977). Circumstancial evidence for the emplacement of the Alboran Diapir 20-25 Ma ago is provided by 22 Ma Rb-Sr and Sm-Nd ages for the Ronda Ultra Mafic Complex near Malaga (Priem et al. 1979, Zindler et al. 1983) which has been interpreted as an apophysis of the Alboran Diapir (Loomis 1975).

A mechanism of isostatic recovery of the downwarps of the lithospheric base peripheral to the Alboran Diapir (*cf.* Neugebauer 1983, fig. 3) has previously been proposed to explain the uplift of nappes in the Betic-Rif orogen (Weijermars 1985a, b). The data from the Alhamilla Region discussed here suggest that the Aguilón nappe finally rose above sea level during the Messinian 7-5 Ma ago. This would imply that the uplift of the Aguilón fold-nappe from 10-15 km depth to the surface took, at the most, about 20 Ma. This corresponds to a time-averaged minimum isostatic uplift rate of 0.5 to 0.7 mm a^{-1}, before the Pliocene, which seems reasonable if compared to glacial uplift rates of up to 2 mm a^{-1} (Cathles 1975). Late Messinian Reefs are now exposed in the Alhamilla Region at heights between 400 and 750 m above present-day sea level (Fig. 2, Cantona). The uplift of 400 and 750 m in 5 Ma gives average uplift rates of 0.1 and 0.15 mm a^{-1}, respectively, for the Pliocene-Quaternary period. The maximum variation in sea level during the Neogene has been less than 200 m (Hallam 1984) and this could either increase or reduce our estimates of the isostatic uplift by 0.05 mm a^{-1} at the most.

The 4 to 6 km thick Neogene fill of the Alboran Basin (Mulder 1973) might be the erosive remnant of the missing relief in the Betic-Rif orocline. The surface areas of the Alboran Basin and internal part of the Betic-Rif orocline are approximately the same (Fig. 1). Sedimentation rates in the Alboran Basin would then have to have been of the same order of magnitude as the average uplift rates in the order of 0.1 to 0.7 mm a^{-1} estimated for the Aguilón fold-nappe in the Sierra Alhamilla (tentatively assuming that this range is representative for the entire Betic-Rif orocline). The various sedimentation rates, estimated for the Alboran Basin are 0.35 mm a^{-1} during the Holocene (Stanley et al. 1970), 0.2 mm a^{-1} during the Quaternary and 0.23 mm a^{-1} during the Pliocene (Nesteroff & Ryan 1973, Olivet et al. 1973). These figures support our assumption that the range of uplift rates estimated above may be representative for the entire Betic-Rif orocline.

(C) The terminal Tortonian folding event

The Late Tortonian folds in the basement of the Alhamilla Region have an amplitude of 1 km and wavelength of about 16 km (Figs. 6a and 6c). The isostatic uplift estimates and the nature of the folds induced in the Serravallian-Tortonian cover both suggest that the Aguilón fold-nappe was near the surface (say less than 1 km deep) when it was refolded. The refolding may have been caused by differential isostatic uplift rates due to lateral variations in crustal structure. However, the fact that the refolding has occurred during a restricted time span seems to suggest that lateral crustal shortening was superposed upon the isostatic uplift during the Late Tortonian. The mechanism which could have caused this lateral crustal shortening is most likely due to plate reorganisation forces.

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