Paleomagnetic Study of Tectonic Rotations in the Eastern Betic Cordillera, Southern Spain

Estudio paleomagnético de rotaciones tectónicas en las Cordilleras Béticas orientales

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ABSTRACT

To investigate the timing of tectonic rotation of the Betic Cordillera, a palaeomagnetic study undertaken in a Permo-Triassic to upper Miocene sedimentary succession in the Sierra Espuña, part of the Malaguide unit of the Internal Zones of Betic Cordillera, has been completed. Sites from Upper Miocene, Upper Oligocene, Oligocene, Upper Jurassic and Permo-Triassic sediments have yieded useful palaeomagnetic results. These results suggest that the Sierra Espuña rotated 200° clockwise as a coherent block between early-middle Miocene and late Miocene times.

In a study of the distribution of rotational deformation in the External Zones, 21 sites from the Subbetic and 1 from the Prebetic have been sampled in the Upper Jurassic *ammonitico rosso* facies limestones. In the majority of these, a high temperature component can be identified which passes fold tests (middle Miocene age) and a conglomerate test (Eocene-early Oligocene age).

Palaeomagnetic declinations from individual tectonic blocks in the Subbetic are consistent, but indicate differential rotations between blocks. The largest rotations occur on relatively small isolated blocks of Jurassic carbonates in a highly deformed Triassic evaporite sequence. The single site in the Prebetic has not rotated significantly relative to stable Iberia.

The dominant structural style in the eastern Subbetic is one of southeast —to east-directed or northwest— to west-directed thrusting, locally associated with dextral strike-slip faulting, oblique to the margin of Iberia. This oblique dextral convergence during the early-middle Miocene can account for the pattern of rotation in the Subbetic.

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INTRODUCTION

The Betic Cordillera of Southern Spain is the western most part of the Alpine chain. It is divided into an Internal Zone of mostly metamorphic rocks (eg. Egeler and Simon, 1969; Torres-Roldán, 1979) and the External Zones consisting of fold and thrust belts of unmetamorphosed Mesozic to Tertiary sediments (eg. Hermes, 1978).

In the Internal Zone, pre-Triassic rocks are fully involved in the deformation, whereas in the External Zones no rocks older than Triassic are exposed at the surface, and they do not appear to be involved in the deformation. Compressional tectonics in the External Zones started in early Miocene (Burdigalian) times and continued on into the Late Miocene in the most external parts of the thrust belt (García-Hernández *et al.,* 1980). In contrast, deformation in the Internal Zone started at least in Palaeogene and possibly as early as Late Cretaceous times (Monié *et al.,* 1981). The External Zone itself is subdivided into an external, Prebetic zone composed mostly of shelf sedimennts and a Subbetic Zone of basinal sediments.

The nature of deformation is the subject of debate. Many workers have considered the External Zones to be a classic foreland fold and thrust belt to the Internal zone, with thrust transport dominantly directed to the north or northwest (eg. Egeler and Simon, 1969; Paquet, 1969, García-Hernández *et al.,* 1980; Banks and Warburton, 1981). Others have recognised the importance of south-directed back-thrusting, particularly along the southern margin of the Subbetic (McGillavray, 1964). Yet others have noted the importance of dextral strike-slip, particularly in Late Miocene to Recent times (Hermes, 1978; Paquet, 1972; De Smet, 1984, and LeBlanc and Olivier, 1984).

Recent palaeomagnetic studies in the External zone have demonstrated the existence of significant rotations about vertical axes. Osete *et al.* (1989) suggested that these may either be related thrusting in middle Miocene times or to subsequent strike-slip in late Miocene-Recent times. Some preliminary work in the eastern Betics (Ogg *et al.,* 1988; Osete *et al.,* 1989) has suggested that rotational deformation does not follow the relatively simple pattern observed in the western Betics.

In this contribution we report a summary of the results of two linked palaeomagnetic and structural studies within the eastern Betics (figure 1): an investigation of the timing of rotational deformation in an unmetamorphosed sequence of Mesozoic and Tertiary sediments from the structurally highest unit of the Internal Zone in the Sierra Espuña (Allerton and Lonergan, submitted); and a study of the variation in rotation within Upper Jurassic *ammonitico rosso* facies limestones

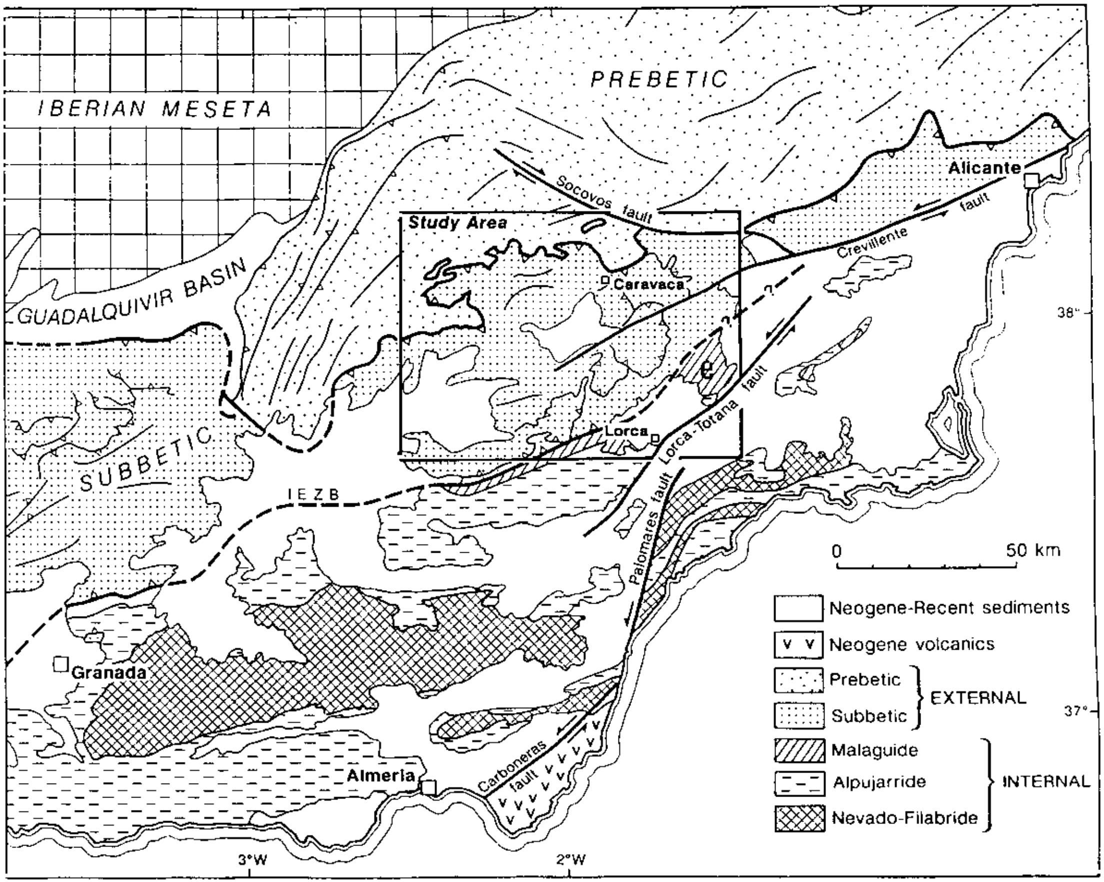

Figure 1.—Geological map of southeast Spain, showing location of study area. The Sierra Espuña is marked by and «e».

across the eastern Subbetic (Allerton *et al.*, submitted). These studies form part of a major, ongoing, research project into the tectonic evolution of the Gibraltar arc.

PALAEOMAGNETIC STUDY

Techniques

Typically, between 8 and 14 standard 2.5 cm diameter cores were taken from each site. Rock magnetisations were measured in Oxford using the CCL cryogenic magnetometer. Standard treatment involved stepwise thermal demagnetisation, althought a few samples were demagnetised using alternating field techniques. Directions were analysed using principal component analysis techniques. To investigate the magnetic mineralogy, IRM acquisition and thermal demagnetisation of two component IRM experiments (Lowrie, 1990) were completed.

Timing of Rotation: Sierra Espuña Stratigraphic Section

To determine the timing of rotational deformation in the Eastern Betics, we have sampled a sequence of unmetamorphosed Mesozoic and Tertiary sediments of the Malaguide unit of the Internal Zones in the Sierra Espuña. Although this unit has enjoyed a different structural history to the Subbetic Zone to the north, it does preserve a near complete Tertiary sequence (usually absent from the Subbetic stratigraphy) including some sediments suitable for palaeomagnetic study. The Sierra Espuña has been the subject of a detailed tectonic analysis by one of us (Lonergan, 1991), providing invaluable structural control for the interpretation of the palaeomagnetic data.

The Permo-Triassic to lower Eocene rocks of the Sierra Espuña were thrust into an imbricate stack in late Eocene times. Deformation propagated into the foreland basin in the late Oligocene with renewed thrusting. Subsequently, the whole stack has been folded into a norhtwest-vergent regional recumbent fold, the Espuña fold, during the early to (?) middle Miocene. Early in middle Miocene time Subbetic rocks were thrust south-east over the Internal Zone along the Internal/External Zone Boundary (IEZB). Subsequently in the middle to late Miocene, the thrust stack was dissected by normal faults. Minor strike-slip faulting has also occurred related to neotectonic events in the Betic realm.

Palaeomagnetic Results

Upper Miocene

Upper Miocene, Tortonian marine marls from a conglomerate/calcarenite-marl sequence in the Neogene extensional basin on the eastern edge of the Sierra Espuña were sampled at two localities about two kilometres from the basin margin. NRM intensities are relatively high, up to 9mA/m. The magnetic mineralogy is dominated by a high coercivity, high blocking temperature (650° C) phase; presumably specular haematite (Collinson, 1974).

Thermal demagnetisation reveals clear, stable, north-down directed components. As these rocks are not folded, no fold test can be applied, so it is difficult to assess the age of the magnetisation. The mean direction (declination = 351°, inclination = 43°, a_{95} = 11°, table 1) is within error of the Miocene reference direction, so if this component is primary there has been no rotation since the upper Miocene.

Upper Oligocene-Lower Miocene

Red, yellow, and grey marls interbedded with coarse sandstone and polymict conglomerates make up the Upper Oligocene to Aquitanian Amalaya Formation. Red marls of the Amalaya formation were sampled from 6 sites at 3 separate localities. the magnetisation is dominantly carried by a high coercivity phase (probably haematite) which typically unblocks by about 650° C. NRM values are in the range 0.25 mA/m-2.5mA/m. A high-temperature component exists in most samples, although it is often difficult to define, being partially or completely overprinted by a lower-temperature present-field component. To define our high-temperature component, we have relied on only those samples which yield a clear, discrete, well defined, high-temperature component. The fold test is positive, and significant at the 95 % confidence level, indicating that the magnetisation predates the formation of the fold. The mean direction (declination = 142°, inclination = 42°, a_{95} = 11°, table 1) of the stable component indicates a rotation of about 140°±11° clockwise.

Oligocene

Oligocene carbonate conglomerates pass both distally and upwards into pale grey calcareous marls with thin interbedded calcarenite and rare bioclastic beds (described as Facies C of the Bosque Formation in Lonergan, 1991). The marls, sampled in two sites, one on each limb of a minor (2-3m wavelenght) anticline, gave stable components. The initial intensities were relatively weak, varying from 0.1 to 0.3mA/m.

The magnetic carriers could be separated into high coercivity/low temperature phase, probably carried by goethite, and a higher temperature, lower coercivity phase which carries the charateristic remanence. As thermal treatment started to produce additional phases above about 200° C (as indicated by an increase in the bulk susceptibility), a compromise treatment procedure was devised: a low-temperature step of 150° C removed the low-temperature component. A. F. treatment then isolated a consistent signal, even with very magnetised samples.

The fold test is significantly negative (at 95 % confidence), suggesting that the magnetisation was acquired after folding. The *in situ* direction (declination = 207°, inclination = 42°, a_{95} = 26°, table 1) gives an inclination consistent with its predicted, Neogene palaeolatitude, and a clockwise of 201°±7°.

Upper Jurassic

The Upper Jurassic, represented by yellowish/pinkish, faintly nodular, fine-grained limestone was sampled at site B31. The samples from this site have NRM values between 0.75 and 0.2mA/m. All samples show similar demagnetisation behaviour. A present field component (presumably carried by goethite) is removed by about 12° C, and then a stable, high temperature component, probably carried by magnetite, is progressively removed, completely unblocking at about 520° C.

The age of the stable component from site B31 has not been assessed by appropriate field tests: none have been identified. Other Jurassic limestones in the Subbetic, of approximately the same age but different lithologies, host magnetisations that predate a Miocene folding event.

Tectonic correction does not significantly change the direction of the high temperature component; both are directed south and down (declination = 178°, inclination = 50°, a_{95} = 11°, table 1). This does not fit with reference directions from the Jurassic or younger so this site must have been subjected to approximately 200° clockwise rotation. The inclinations from this site are steep, but within error of those predicted for Iberian sites in the late Jurassic (calculated from Wesphal *et al.*, 1986 and Dewey *et al.*, 1989).

Permo-Triassic

We present results from three sites sampled in the upper imbricate slices of the thrust stack in medium grained, quartz-rich, red sandstones. These red-bed facies have a magnetic mineralogy dominated by a high-temperature, high-coercivity component (probably specular haematite), with initial intensities between 2.0 mA/m and 0.3 mA/m. Thermal demagnetisation revealed a low-temperature, approximately present-field component, stable to about 250° C, and high-temperature component, which is removed by about 650° C.

Two of the sites (B102 and B103) spanned a minor anticline providing a fold test which proved positive for the high temperature component. This magnetisation thus predates folding which probably formed during Eocene thrusting. The shallow inclinations are consistent with the equatorial palaeolatitude of Iberia predicted for the Permian (Wesphal *et al.,* 1986 and Dewey *et al.,* 1989). This perhaps gives greater confidence in the age of the magnetisation, although it is recognised that a positive fold-test does not necessarily indicate that the inclinations are correct, as the magnetisation could have been acquired when the beds were planar, but tilted.

The amount of rotation recorded in these Permo-Triassic rocks (declination = 184°, inclination = 06°, a_{95} = 21°, table 1) is ambiguous, because where inclinations are sub-horizontal it is difficult to distinguish between a normal-polarity, unrotated direction, and a reversed-polarity, rotated direction. If the mean directions are reversed (as is most probable for Permian times), then the north, and slightly up (or south and down, if the results are projected to a normal polarity) direction requires a large rotation to have affected these sites, consistent with the results from the Oligocene and Jurassic sites. If, however, the mean directions are assumed to be normal, the inclination error still overlaps that of the Permian reference direction, so it is possible that the true mean is unrotated.

TABLE 1

Mean directions from each unit

Unit	*D(°)*	*I(°)*	*N*	a_{95}	*K*	*D*
Tortonian	351	43	15	11,0	11,0	–11
U. Oligocene-Aquitanian/Amalaya	142	42	33	11,4	5,8	140
Oligocene/Bosque	207	42	26	6,8	18,9	201
Jurassic	178	50	11	11,0	16,0	196
Permo Trias	184	06	21	6,5	25,1	192

N = total number of samples in statistics. a_{95} = radius of 95 % circle of confidence about mean direction. K = dispersion parameter. D = Declination anomaly relative to the Iberian reference declination (from Westphal *et al.,* 1986, Dewey *et al.,* 1989).

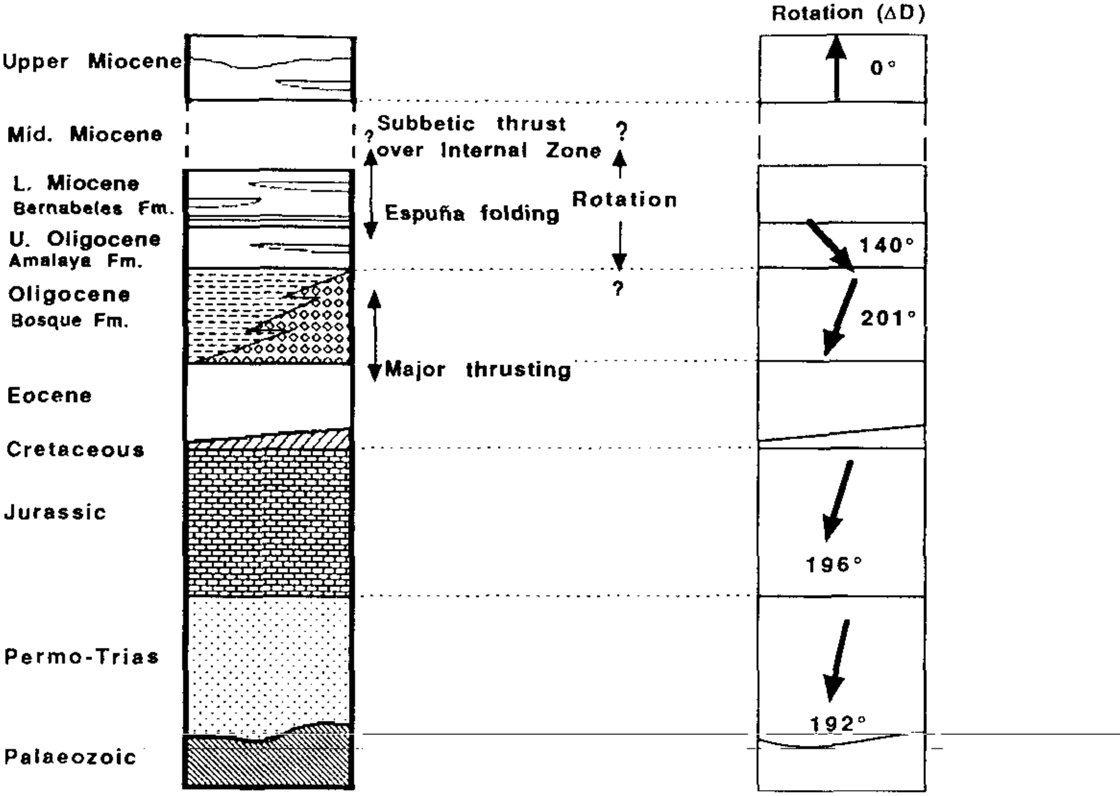

Figure 2.—Summarised palaeomagnetic results for the Sierra Espuña. The first column summarises the stratigraphy and structural history. The second column shows the mean absolute rotation ΔD [i. e. Reference declination (D_0) – measured declination (D)] for different stratigraphic horizons (data from table 1). Note that the position of the rotated vector at a particular horizon does not imply that the rotation is of that age, but only refers to the age of the rock sampled.

Discussion of Results

The Upper Miocene unit shows no significant deviation from the reference declination. If this lithology carries a magnetisation acquired during or soon after deposition, then there has been no rotation since Tortonian times.

The Upper Oligocene to Aquitanian (Amalaya Formation) red marls have a stable, high temperature component which passes a fold test, and indicates a rotation of about 140° ± 11° clockwise. The rotation must have occurred between the deposition of the Amalaya formation and the Tortonian.

The stable component from the Oligocene (Bosque Formation) grey marls fails a fold test, yet indicates a clockwise rotation of 201° ± 7°. This implies some 61° of clockwise rotation after folding but before the acquisition of the magnetisation of the Amalaya Formation. That this unit fails a fold test requires the local folding that produced the minor outcrop scale fold to be relatively earlier that the deformational event that produced the fold in the Amalaya formation. It was probably produced during late Oligocene thrusting.

The Permo-Triassic red-beds contain a stable magnetisation that predates an Eocene folding event. The Upper Jurassic and Permo-Triassic units yield rotations relative to the reference declination of 196° ± 11°, respectively, comparable to the value of 201° ± 7° obtained from the Oligocene Bosque formation. This result suggests that there was no rotation associated with the late Eocene/early Oligocene thrusting and imbrication, and that subsequently, the Sierra Espuña rotated as a coherent block. The rotational deformation that affected the Sierra Espuña must have been active before the middle Miocene deformation that produced the main Espuña fold structure, and may have continued on until the Tortonian.

Deformation in the Internal Zone occurred earlier than in the External Zones, and it may be false to the draw direct conclusions about the timing of rotation in the Subbetic from data the Internal Zone. Nevertheless, the fact that movement on the backthrust of the Subbetic over the Internal Zone (IEZB) coincides with the time-window available for rotation suggests that rotation may have occurred synchronously in the Internal Zone and the Subbettic.

Rotation in the Sierra Espuña was complete by Tortonian (late Miocene) times, when the IEZB was sealed and inactive, and we suggest that it is unlikely that major tectonic rotations affected the Subbetic after this time.

Mapping of rotation; Upper Jurassic Limestones

To investigate the spatial variation in rotational deformation, 21 sites from the Subbetic and 1 site from the Prebetic were sampled from Upper Jurassic limestones. The age of these *ammonitico rosso* facies red/pink nodular limestones ranges from the Oxfordian through to the Tithonian (Seyfried, 1978).

Studies of the magnetic mineralogy identified a low coercivity (< 0.15T) phase, with unblocking temperatures below 585° C, and a high coercivity (> 0.15T) phase, with unblocking temperatures below 650° C; probably (titano) magnetite and hematite, respectively. The rocks are moderatly strongly magnetised, with natural remanent magnetisation (NRM) intensity values ranging from 0.04mA/m to 400mA/m.

Thermal demagnetisation typically isolates either 2 or 3 components. The majority of samples from the Subbetic *ammonitico rosso* facies carry a low temperature component, unblocking below 260° C, and a high temperature component, typically completely unblocked below 600° C. Both normal and reversed directions are commonly observed within the high temperature components from a single site.

A few sites from the central part of the Subbetic, display three-component behaviour; a low-temperature component, an intermediate-temperature component (260° C < T < 480° C), and high-temperature component (480° C < T < 600° C). In a few cases the intermediate component is dominant, and the high temperature component very poorly defined. The intermediate component has a constant polarity in any single site, and generally has a direction distinctly different to that of the high temperature component.

In a few sites we believe that the intermediate component completely obscures the high temperature component. We identify these where a neighbouring site exhibits three components, and the intermediate component can be equated with the high temperature component in the «overprinted» site. The recognition of this overprinting component clearly throws some doubt on the nature of the high temperature components in the sites that carry only two components. We use the observation that the intermediate component has a single polarity at any individual site as a criterion for identifying which two-component sites may been overprinted. Most of these can be directly linked to an adjacent site which has mixed-polarity high temperature components (which can thus be considered reliable). A more complete description of the identification of overprints is given in Allerton *et al.*, submitted.

The low temperature component consistently fails fold tests and a conglomerate test. It is close to the axial dipole field, and represents a recent overprint.

The intermediate temperature component gives variable results to field tests, and is not rotated. This component is probably the result of a Mid-Miocene intra-deformational remagnetisation.

The high temperature component consistently passes fold test (eg. figure 3), indicating a magnetisation predating Mid-Miocene deformation. This component also passes a conglomerate test, indicating a pre-Eocene-early Oligocene age for the magnetisation. The mean inclination derived from the corrected high temperature component is consistent with the position of the southern margin of Iberia during the Late Jurassic, calculated from Dewey *et al.*, 1989 and Westphal *et al.*, 1986. This component may thus represent a magnetisation formed very early in the history of the sediment. These high temperature components are a useful indicator of Neogene rotational deformation in the Subbetic.

Mean site declination data for the high temperature component are displayed

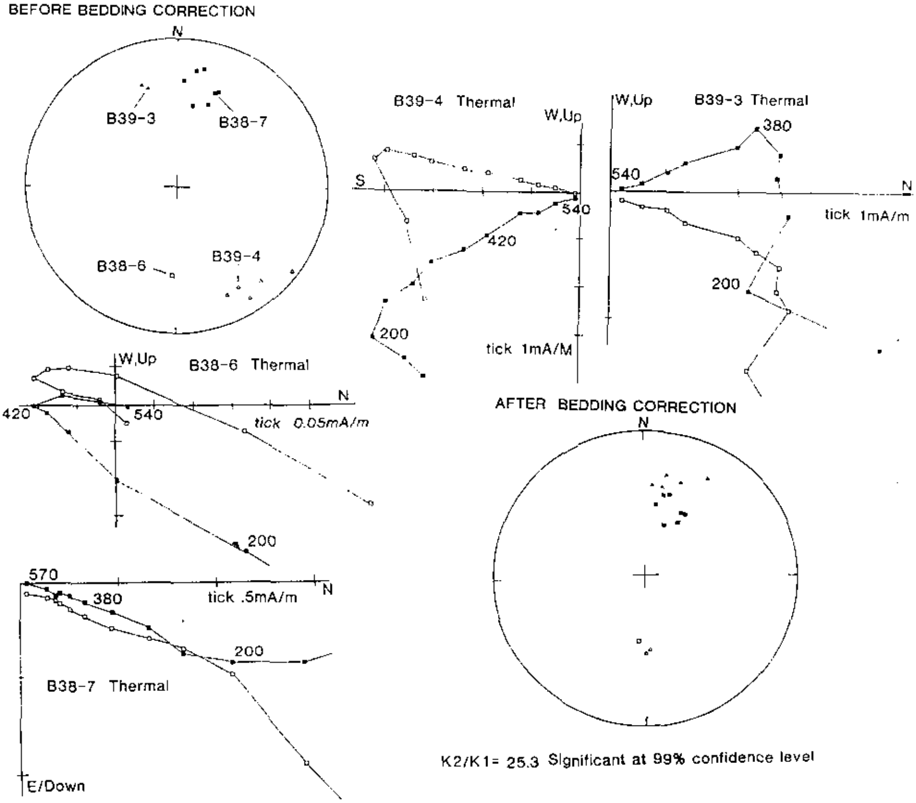

Figure 3.—Fold test: Sierra de Mojantes (see Figure 4 for location): Directions of high blocking temperature components, before and after bedding correction, displayed on equal area stereographic *projections (open symbols represent points in the upper hemisphere; closed symbols in the lower).* Demagnetisation behaviour is illustrated on orthogonal vector diagrams (in situ; open symbols represent points in vertical plane, closed symbols, points in horizontal plane (from selected samples, both normal and reversed, for each site. The positive result indicates that the magnetisation predates Miocene folding.

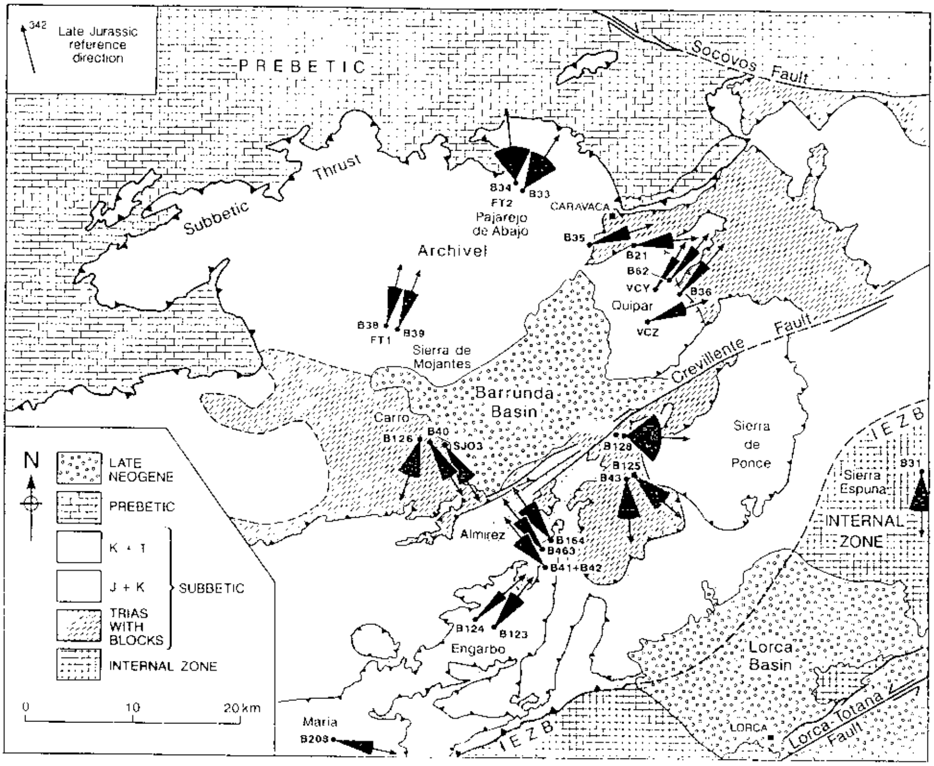

Figure 4.—Tectonic map of the eastern Subbetic showing mean site declinations with declination errors (Demarest, 1983). Also shown are results from an Upper Jurassic site in the Sierra Espuña and from two Lower Cretaceous sites in the Quipar block (Ogg *et al.*, 1988). The main thrust sheets are distinguinshed, for convenience, by the stratigraphic characteristics that control their mechanical behaviour. Trais with blocks: thick sheets of highly deformed Triassic marl, dolomite and evaporite, with scattered blocks of mainly Jurassic limestone, which formed decollement carpets between the more rigid thrust sheets (see cross-section). J + K: Thick sequences of massive Jurassic limestones with some mainly lower Cretaceous marls and limestones. K + T: Strongly folded and imbricated Cretaceous and Tertiary marls and marly limestones, including the Late Oligocene to Early Miocene clastic sequences along the Internal/External Zone Boundary (IEZB).

TABLE 2

Upper Jurassic *(Ammonitico rosso)* limestones, high temperature components

Site	*Before Correction*						*After Correction*				*Bedding*		*Block*
	D(°)	*I(°)*	*K*	*N*	*n*	a_{95}	*D(°)*	*I(°)*	*K*	a_{95}	*Dip*	*Direction*	
B21	101	34	34.0	5	5	13.0	82	29	34.0	13.0	30	010	Quipar
B33	45	81	44.6	7	7	9.1	34	51	24.4	12.5	30	030	Archivel
B34	175	1	11.5	8	6	20.6	354	29	11.5	20.6	30	180	Archivel
B35	43	32	66.7	8	7	7.4	71	44	66.7	7.4	35	165	Archivel
B36	62	46	50.8	9	9	7.3	46	50	50.8	7.3	15	310	Quipar
B38	12	22	61.7	8	8	7.1	19	38	61.7	7.1	20	160	Archivel
B39	148	–11	37.5	8	7	10.0	12	26	37.5	10.0	16	169	Archivel
B40	334	7	27.8	8	8	10.7	148	33	27.8	10.7	47	004	Carro
B41&B42*	306	31	16.9	12	10	13.9	319	51	17.1	13.8	28	010	Almirez
B43	177	9	12.2	9	8	16.5	174	23	12.2	16.5	17	27	Gonzalo
B49	348	49	90.2	9	7	6.4	327	48	90.2	6.4	18	250	Prebetic
B62	38	32	30.1	9	9	9.5	38	28	30.1	9.5	5	20	Quipar
B123	97	68	18.7	13	13	9.8	35	35	18.7	9.8	52	8	Engarbo
B124	61	36	174.5	6	5	5.8	46	21	174.5	5.8	30	352	Engarbo
B125	308	40	21.0	12	9	11.5	132	25	12.7	15.0	60	320	Gonzalo
B126	219	12	8.3	13	12	16.0	201	31	10.1	14.3	50	90	Carro
B128	108	35	7.7	6	5	29.5	90	33	7.7	29.5	25	14	Tornajo
B163	268	56	38.9	11	11	7.4	323	44	38.9	7.4	43	11	Almirez
B164	291	61	19.3	8	8	12.9	323	30	19.3	12.9	41	353	Almirez
B208	38	15	34.0	9	9	9.0	103	31	34.0	9.0	74	346	Maria
SJ03	149	20	17.7	12	12	10.6	150	47	30.8	8.0	25	300	Carro

N = total number of samples. n = number of samples in statistics a_{95} = radius of 95 % circle of confidence about mean directionn. K = dispersion parameter.

* B41 and B42 are two adjacent sites, which have been combined.

on figure 4 and in table 2. On this figure we have also included data from two sites in a magnetostratigraphic study of a Lower Cretaceous sequence in the Quipar block (Ogg *et al.*, 1988), and the site in Upper Jurassic limestones from the Sierra Espuña. These show an interesting distribution: within any individual, coherent structural unit the results are consistent; yet between these units the declinations are highly variable. This suggests that the Jurassic units deformed as relatively coherent blocks, with rotations accommodated by large displacements at their boundaries. The scale of blocks is often difficult to estimate, as we are limited to the present surface expression, which will yield a minimum size. Some have a present outcrop limited to only a few square kms (eg. Carro, Tornajo). Others are relatively large; for instance Quipar occupies about 100 km^2.

These declinations should be compared with a palaeomagnetic reference declination calculated from the apparent polar wander curve for Iberia. The actual data available from Iberia are limited, so we calculate our reference declination (342°) from the Eurasian polar wander path (Wesphal *et al.*, 1986 and Dewey *et al.*, 1989), with a correction applied to account for the rotation associated with the Early Cretaceous opening of the Bay of Biscay (Platzman and Lowrie, 1992).

A wide variety of declinations are observed, from 311° through a majority between 030° and 060°, to 200°. This distribution is consistent with a general clockwise rotation from the reference direction of 342°. This general result is consistent with that obtained by Osete *et al.*, 1989, and Platzman, 1992.

The distribution of rotational deformation is not sysmmetrical across the Subbetic. The Archivel Block, north and west of Caravaca, is a relatively thin, gently dipping thrust sheet (Banks and Warburton, 1991, IGME sheets 889 and 910), which appears to have rotated about 20° as a single unit. The adjacent Quipar block has rotated considerably more; about 60°. These blocks together approximately define the region of Subbetic forethrusting. To the south of this area, the maximum amount of rotation is greater, and the amounts are very variable.

Further south, the Engardo and Maria blocks exhibits rotations of up to about 110°. The Almirez block has not been rotated; a result which complicates the otherwise consistent pattern of clockwise block rotations.

Only one succesful site, B49, has been obtained from the Prebetic Zone. The declination from this site is close to the Iberian reference direction, suggesting that there has been little rotation of this part of the Prebetic Zone. The structure is far more coherent than in the Subbetic Zone, and the lack of rotation at site B49 suggests that the overall rotation in the Prebetic could be significantly less than in the Subbetic. However, some differential rotations about vertical axes may be expected to be associated with this highly arcuate fold-belt.

TECTONIC SIGNIFICANCE OF THE OBSERVED ROTATIONS

Two aspects of the declination anomalies need to be considered in a discussion of their tectonic significance. The first is the amount and sense of the rotations. The fact that in common with the rest of the Subbetic the rocks of the eastern Subbetic have undergone large clockwise rotations of the order of many tens of degrees clearly points to a major component of dextral shear between the Alboran domain and the Iberian massif at some time in their history. As discussed above, this is most likely to have occurred during early to middle Miocene time.

The second aspect is the variability in the rotations. In the eastern Subbetic the amount of rotation appears to vary on a scale of a few tens to kilometers from zero to more than 180°. This variability is, on the face of it, substantially greater than presently published data suggest for the central Subbetic (Osete *et al.,* 1989) or western Subbetic (Platzman, 1992). The largest rotations (>120°) within the Subbetic come from sites within the Carro, Tornajo and Don Gonzalo blocks. These are in relatively isolated blocks only a few km across of Jurassic carbonate shelf facies limestones lying within an extensive sheet of highly brecciated Triassic marl and dolomite, with a large component of remobilised gypsum in the matrix. De Smet (1984) has described this facies as part of the Crevillente strike-slip fault belt. The widespread distribution of this Triassic breccia, and its relationship to other units, however, suggest to us that it forms decollement carpets between the major thrust sheets (figures 4 and 5). Fragmentantion of the relatively rigid Jurassic limestones into small blocks and their dispersal within this evaporitic breccia may have facilitated the extreme differential rotations we observe.

Even if we discount these small blocks, however, there is still considerable variability in rotation among the major fault-bounded blocks within the region, and this requires that there have been differential motions, and hence deformation, between adjacent blocks. It is the variability in rotation that gives information about the nature and extent of the tectonism that accompanied the rotation. The question as to how and why the differential rotations occured therefore depends on indentifying the nature of the block boundaries and the kinematics of motion along them.

The eastern Subbetic shows evidence for a wide variety of styles and types of faulting and folding. Some dominant features are clear, however. The northern boundary of the Subbetic over a considerable distance consists of a major subhorizontal overthrust, with a minimum displacement of about 40 km (Banks and Warburton, 1991) determined from outcrop and seismic data (figure 5). The direction of motion on this thrust is towards the north west (Platt and Allerton,

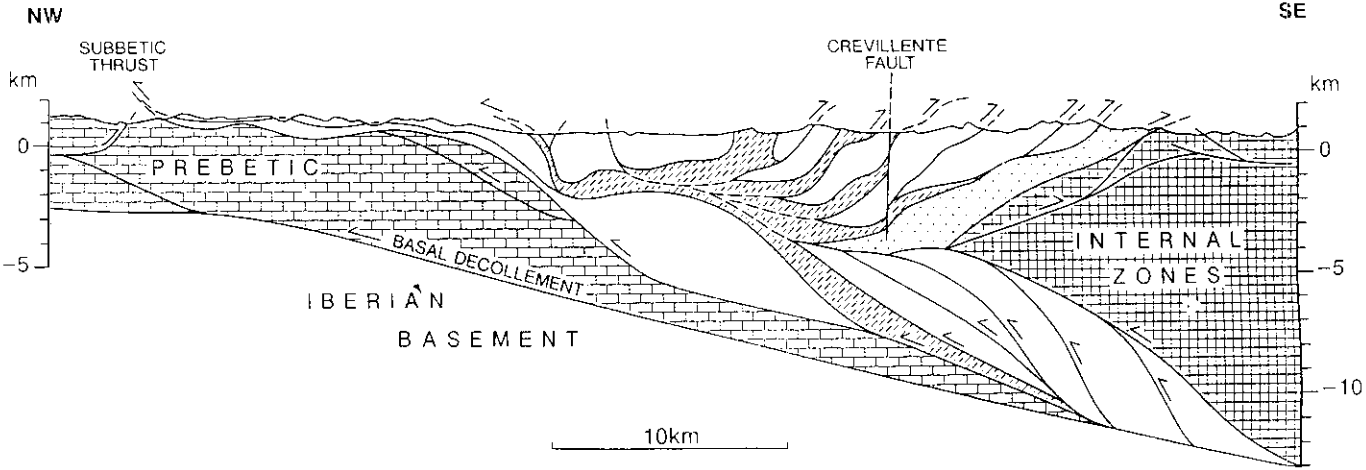

Figure 5.—Schematic section from the Prebetic through the eastern Subbetic near Caravaca to the Sierra Espuña in the Internal Zones, in part after Banks and Warburton (1991). Ornament as on figure 10. Northwestern half of section is constrained by seismic and drill-hole data (see Banks and Warburton, 1991), southeastern half is drawn to illustrate how the double vergence of the Subbetic is caused by insertion of a wedge of Internal rocks into the Subbetic.

in prep.), and in view of the low rotations of both the northern Subbetic Archivel block and the Prebetic, these thrust directions are likely to be unrotated. Towards the east, this thrust is cut and modified by the Socovos fault, which effectively replaces the thrust as the northern boundary of the Subbetic. This fault is a near vertical dextral strike-slip fault, which swings from a westerly to a northwesterly trend as it passes into the Prebetic. It terminates westwards within the Prebetic, transferring its displacement onto west-northwest-directed thrusts within the Prebetic (Mandeville, in prep.). This fault is therefore a thin-skinned transfer fault: there is no geological or geophysical evidence to suggest that it cuts the underlying Variscan basement.

The southern margin of the Subbetic is a major backthrust with a gentle northerly dip. Kinematic data from this contact indicate thrusting relatively to the southeast or south over the Internal Zones (Lonergan *et al.*, in prep.). Both southern Subbetic and Internal Zone rocks have experienced very large rotations, so the kinematic data may have been rotated also. Their consistency over a considerable distance, compared with the variable rotations experienced by the rocks on either side of the boundary, suggests that they have not been strongly rotated, however. There is no evidence for dextral strike-slip faulting along this boundary, as suggested by Paquet (1972) and Leblanc and Olivier (1984).

The Crevillente fault forms an important lineament running parallel to the regional trend along the middle of the eastern Subbetic (figure 4), and has been interpreted by De Smet (1984) as a fundamental dextral strike-slip fault that has controlled the entire tectonic history of the Subbetic Zone. There is structural evidence for both dextral and subsequent sinistral motion on this fault (Allerton *et al.*, in prep.), but several observations suggest that although it is important, it does not have the fundamental character that has been attributed to it.

1. The zone of intense strike slip faulting is a few kilometres wide, but immediately outside this zone, the rocks show a dominance of mainly southeast-directed thrust-faulting (Allerton *et al.*, in prep.), characteristic of much of the surrounding Subbetic. No set of significant dextral strike-slip faults parallel to the Crevillente fault can be identified.
2. The fault dies out within the eastern Subbetic, swinging to a more easterly trend and apparently transferring its displacement onto thrusts.
3. There are no outcrops of basement rocks anywhere along the fault, or any geophysical evidence to suggest that it cuts basement.
4. There is no clear association between the dextral rotations and the Crevillente fault. Large rotations occur well away from the fault; some rocks very close to the fault show no rotation al all (figure 4).

For these reasons we concur with Banks and Warburton (1991), that the

Crevillence fault is a thin-skinned structure related to, but not controlling, the dominant thrust tectonics of the region.

Within the eastern Subbetic, away from the Crevillente fault, the dominant deformational style involves thrusting and overturned folding (figure 5). These structures are directed towards the east in the southern half of the zone, and towards the northwest or west in the northern half (Banks and Warburton, 1991). The two sets of thrusts probably link at depth, and are a response to the northwest emplacement during early to middle Miocene time of a wedge of Internal Zone rocks into the Mesozoic and Tertiary sedimentary prism on the southern margin of Iberia. Kinematic data from individual thrust surfaces within the Subbetic are variable, and may have been affected by rotation about vertical axes.

Several sets of minor strike-slip faults can be identified within the Subbetic, and some of these form boundaries to individual blocks. The variations in orientation and sense suggest that these have either formed at different times in response to different directions of bulk shortening, or that some have been strongly rotated. The most widely identifiable sets are west —the northwest— trending dextral faults (probably transfer faults during early to middle Miocene thrusting), and north —to northeast— trending sinistral faults that may be related to the late Miocene and younger sinistral faults, such as the Lorca-Totana and Palomares faults, that occur in the Internal Zones (De Larouzière *et al.*, 1987). Locally, however, conjugate sets of dextral and sinistral faults occur that accommodate shortening parallel to local directions of thrust transport, varying from est-west to north-south.

To summarize, the dominant structural style in the eastern Subbetic is one of southeast —to east— directed or northwest —to west— directed thrusting, locally associated with dextral strike slip faulting. The dominant sense of tectonic transport is oblique to the west —southwest— trending former southern margin of Iberia, and this dextrally oblique motion provides an explanation for the dominant clockwise sense of rotation during convergence. The rotations are not directly attributable to strike-slip faulting, or to dextral shear imposed subsequent to the thrusting.

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