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ON THE PARALLELISM OF BEDDING AND CLEAVAGE IN DEFORMED ROCKS FROM THE INTERNAL ZONE OF THE BETIC CORDILLERAS–S.E. SPAIN[1]

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ABSTRACT

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Bedding-parallel foliations may cause serious problems for structural geologists who try to unravel the sequence of deformational events in polyphase deformed rocks. In many cases it may be difficult to prove whether an early bedding-parallel foliation represents an inherited sedimentary fabric or has formed during an early phase of deformation. In the past there have been such problems in several tectonic units in the Internal Zone of the Betic Cordilleras of S.E. Spain.

This paper describes the microstructure of early foliations in low grade slates and metasandstones from the Almagro and Almanzora Units in the Sierra de Almagro and upper greenschist facies micaschists from the Variegato Unit in the N.E. Sierra de los Filabres (province of Almeria). It is shown that the dominant planar structure in the Almagro and Almanzora Units represents the first tectonic cleavage (S_1) that has been formed in these rocks. The foliation is axial planar to first phase folds and shows different stages of cleavage development from initial sedimentary microstructures to the fully developed slaty cleavage fabric.

In upper greenschist facies micaschists of the Variegato Unit there is a preferred orientation of phyllosilicates parallel to bedding. In contrast to previous interpretations it is argued that this fabric does not represent an inherited sedimentary fabric. Pressure solution processes were involved in cleavage formation indicating non-hydrostatic stress conditions during tectonic deformation. Metamorphic conditions–culminating in upper greenschist facies grade after formation of the early foliations–can not be explained by contact metamorphism during burial underneath a thick pile of undisturbed sediments. They indicate that the rocks have been transported deep into the crust during a tectonic event prior to the peak of metamorphism.

INTRODUCTION

Preferred orientation of phyllosilicates parallel to bedding in the absence of early isoclinal folds may confuse structural geologists, who work in polyphase deformed metamorphic rocks. In general there are two alternative explanations for such fabrics: (1) the fabric has formed by parallel replacement of initially bedding-parallel phyllosilicates by metamorphic micas, (2) the fabric represents an early tectonic cleavage, that initially formed at an angle to the bedding, but that has rotated into approximate parallelism under the influence of finite strain, while early fold hinges were obscured during the transposition process.

Sedimentary foliations in shales and very low grade slates result from (1) bedding–parallel gravity settling of detrital micas and clay minerals during sedimentation, (2) mechanical reorientation of platy mineral grains during the early stages of compaction, and (3) preferential growth of phyllosilicates parallel to the bedding during diagenesis and very low grade metamorphism.

The first of these processes most probably is not very effective in general. Clay particles tend to form flocculae by mutual attraction and the fresh sediment is then characterised by card-house type microstructures (MEADE, 1964). Parallel sedimentation depends on geochemical factors present in the environment at the time of deposition (INGRAM, 1953; MEADE, 1964). Low salinity in the sedimentary basin will improve mineral sedimentation in the dispersed state (WHITE, 1961) and also the presence of absorbed colloidal organic molecules enhances dispersion and parallel settling (VAN OLPHEN, 1963).

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The preferred orientation of the sediment may be improved by low rates of sedimentation (O'BRIEN ET AL., 1980) or low concentration of clay particles in suspension (ROSENQVIST, 1966). On the other hand the fabric will be less pronounced if there are high concentrations of quartz and other non-platy mineral grains (CURTIS ET AL., 1980) or if the fabric is modified at an early stage by bioturbation (O'BRIEN ET AL., 1980) or synsedimentary deformation.

The mechanical reorientation process is particularly effective in the uppermost part of the sediment pile, where clay particles may adjust themselves into a position of greatest mechanical stability under the influence of a vertically directed overburden stress (RIEKE & CHALINGARIAN, 1974). With increasing depth of burial the clay mineral fabric will be locked in by cement and is no longer controlled by mechanical rearrangement (HELING, 1970).

The process of replacement of initially bedding-parallel phyllosilicates by metamorphic micas parallel to bedding may take place under the influence of a dominant component of stress that acts perpendicular to bedding. However rocks at great depth do not behave like linear elastic materials and there will be a decrease in the dominance of the vertically directed overburden stress (PRICE, 1966; JAEGER & COOK, 1976). In the absence of deformation the stress system at great depth tends towards a lithostatic state and loading under conditions of deep burial can not explain why metamorphic micas should grow parallel to bedding.

It has been suggested recently that burial in the absence of a tectonic stress may enhance mimetic recrystallisation (MALTMAN, 1981). Under such conditions the dominant control on the orientation of the new phyllosilicates would be the pre-existing lattice (DEVORE, 1958; RAST, 1965; DIVIS & MCKENZIE, 1975) so that the fabric becomes metamorphic in appearence, while retaining its bedding-parallel orientation. However the opposite observation has been reported as well. MAXWELL & HOWER (1967) have described a 13 km thick section in which a strong foliation at the top – that probably had formed in the early compaction stage – changed to one showing an increasing disorientation downwards in the section. These authors concluded that recrystallisation at depth, under conditions approximating hydrostatic pressure, could account for the lesser preferred orientation downwards.

Many of the problems concerning the interpretation of bedding-parallel foliations may be solved if the microstructures of the early foliations are carefully examined. The microstructure may indicate whether the foliation has formed during tectonic deformation or merely as the result of metamorphic processes in the absence of deformation. Any interpretation however has tectonic implications and these should be considered as well. If sedimentary phyllosilicate fabrics have been replaced mimetically by metamorphic micas in the absence of deformation one has to assume that metamorphism took place during deep burial. One can only maintain such an interpretation if the metamorphic grade of the rocks can be explained in the absence of tectonic processes during which the rocks were emplaced at great crustal depth.

In several tectonic units in the Internal Zone of the Betic Cordilleras of southern Spain there have been problems in the interpretation of early foliations. This paper describes the microstructure of low grade slates, phyllites and metasandstones that have been selected from the Sierra de Almagro and from the north-eastern Sierra de los Filabres in the province of Almeria and discusses the nature of the early phyllosilicate fabrics.

REGIONAL GEOLOGICAL OUTLINE

The Betic Cordilleras of southern Spain consist of an Internal (or Betic) Zone of metamorphosed Triassic and older rocks and a northern thin-skinned fold and thrust belt of non-metamorphosed Triassic to Middle Miocene rocks, generally subdivided into a Prebetic and a Subbetic Zone (Fig. 1).

The large scale structure of the Betic Zone originated from the superposition of nappes. They have been assigned to three nappe complexes. In ascending order these are (1) the Nevado-Filabride Complex, (2) the Alpujarride Complex, and (3) the Malaguide Complex. Recent investigations have shown marked differences in tectono-metamorphic evolution between the different nappe complexes (VISSERS, 1981; AKKERMAN ET AL., 1980; MÄKEL, 1981).

In the Sierra de Almagro the 'higher' (Alpujarride and Malaguide) Betic nappes are situated directly upon low grade metamorphic rocks of the Almagro Unit (SIMON, 1963, 1964). The Almagro Unit represents another major tectonic element that is also present in the Sierra de Enmedio, the Sierra de Carascoy and the Sierra de Orihuela (Fig. 1) (SIMON, 1964; BODENHAUSEN & SIMON, 1965; KAMPSCHUUR, 1972). The lithostratigraphy of these 'Almagride' elements closely resembles part of the Triassic sequence of the Subbetic Zone in the province of Murcia, implying deposition in a simple paleogeographic realm (BESEMS & SIMON, 1982). The Almagro Unit may thus represent the southern continuation of the Subbetic Zone in a position underneath at least the 'higher' Betic nappes. The relationship with the Nevado-Filabride Complex is not known since the contact is not exposed. In the Sierra de Almagro the Almagro Unit is tectonically overlain by the Almanzora Unit, the lowermost Alpujarride element (BLOEMENDAAL, 1982). The Almanzora Unit consists of Permo-Triassic rocks of low metamorphic grade. It can be traced from the Sierra de Almagro westwards along the northern border of the Sierra de los Filabres where it rests upon mesozonal rocks of the Nevado-Filabride Complex. In these areas the Almanzora Unit is generally present in an incomplete and highly brecciated form (BICKER, 1966; VOET, 1967; LEINE, 1968).

In both the Sierra de Almagro and the north-eastern Sierra de los Filabres the Almanzora Unit is tectonically overlain by the Variegato Unit of the Alpujarride Complex. The northern

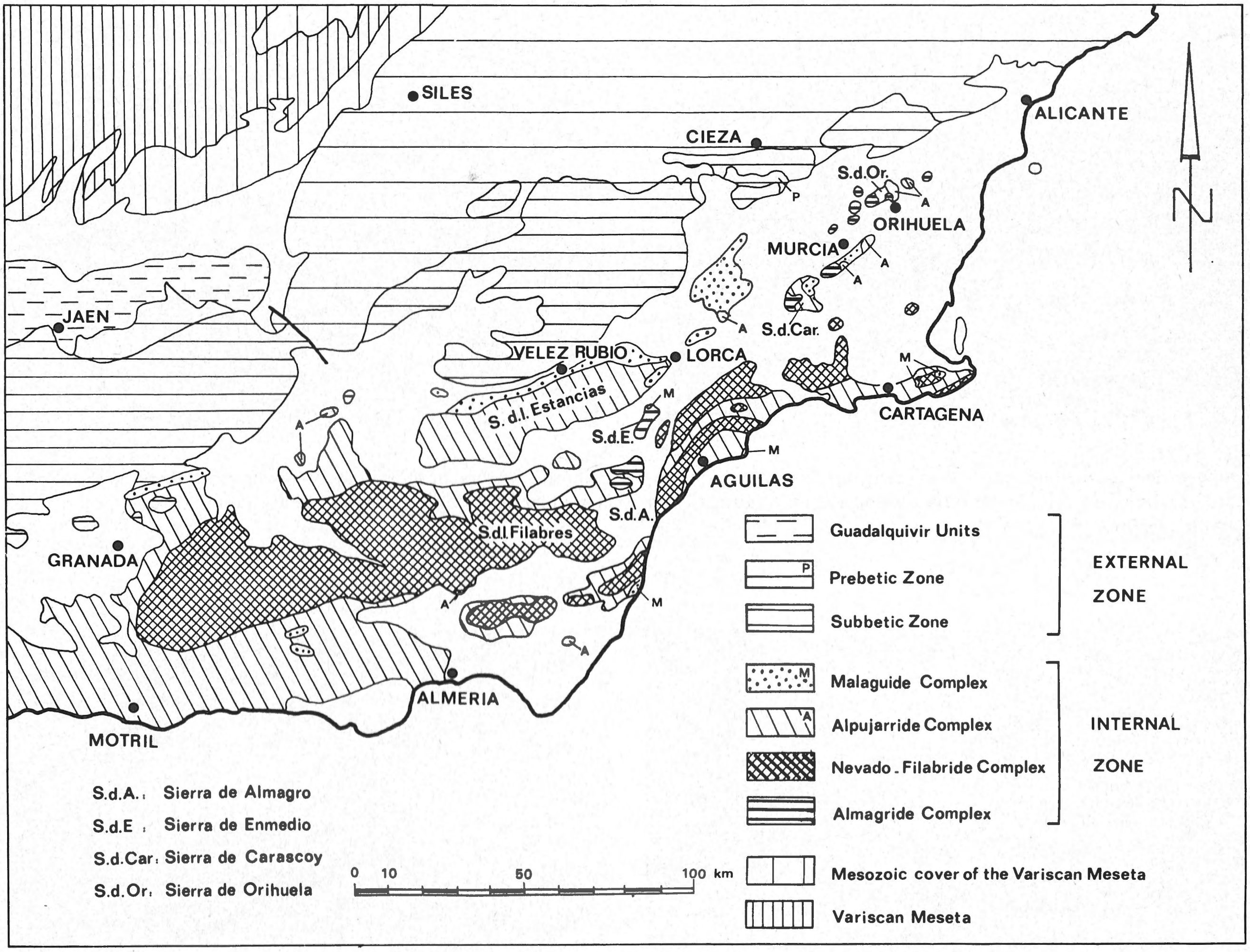

Fig. 1
Tectonic sketchmap of the Betic Cordilleras of S.E. Spain showing the distribution of the major tectonic complexes.

continuation of the Variegato Unit is found in the Sierra de las Estancias (Fig. 1), where it is named Partaloa Unit. The lithostratigraphy, polyphase deformation and plurifacial metamorphism of the Partaloa Unit have recently been described (AKKERMAN ET AL., 1980).

DESCRIPTION OF THE FOLIATIONS

The Almagro Unit (Sierra de Almagro)

The lithostratigraphy of the Almagro Unit consists of a clastic sequence of metapelites and metapsammites of Langobardian (and older?) age, and an overlying carbonate-rich sequence with intercalations of metapelites, metapsammites and gypsum of Langobardian to Carnian age (BESEMS & SIMON, 1982).

The rocks have been deformed in macroscopic south-overturned folds with an associated axial plane cleavage (S_1). The cleavage is at an angle to the bedding as can be well observed in a series of marly limestones (Fig. 2). Within the marly layers the cleavage is at a low angle to the bedding and it refracts through the more competent carbonate interlayers. Intense solution of carbonate material has taken place along the cleavage planes resulting in discontinuous carbonate beds in lenticular domains parallel to the cleavage. In the clastic sequences the cleavage is generally subparallel to the bedding in the metapelites and at a higher angle in the more quartzitic litholcgies.

Primary sedimentary features have been found on a microscopic scale within the least deformed quartzites. These rocks contain well rounded detrital quartz grains (Fig. 3a), rock fragments and detrital micas. Grain size differences between small phyllosilicate particles and much larger detrital quartz grains have prevented the development of preferred orientation of phyllosilicates parallel to the bedding (Fig. 3b). Cleavage is generally poorly developed and only localised pressure solution seams to indicate the incipient stages of cleavage formation (Fig. 3b, d). In the metapelitic rocks the cleavage is well developed. The microstructure is characterised by an anastomosing pattern of phyllosilicate-rich cleavage planes curving around lenticular domains of quartz,

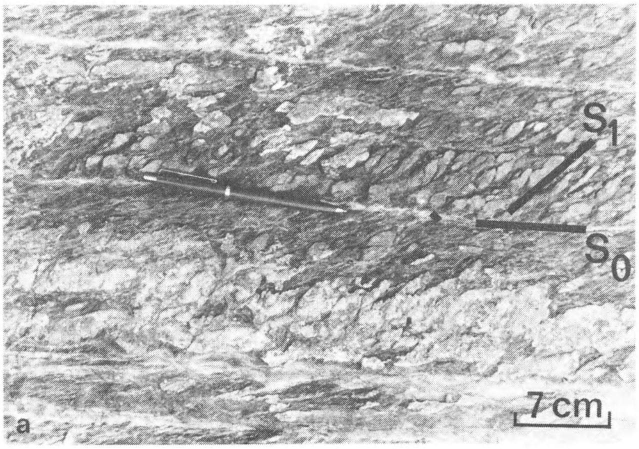

Fig. 2a
Oblique cleavage-bedding relation in marly limestones of the Almagro Unit. Extensive solution of carbonate beds leads to formation of carbonate lenses parallel to S_1

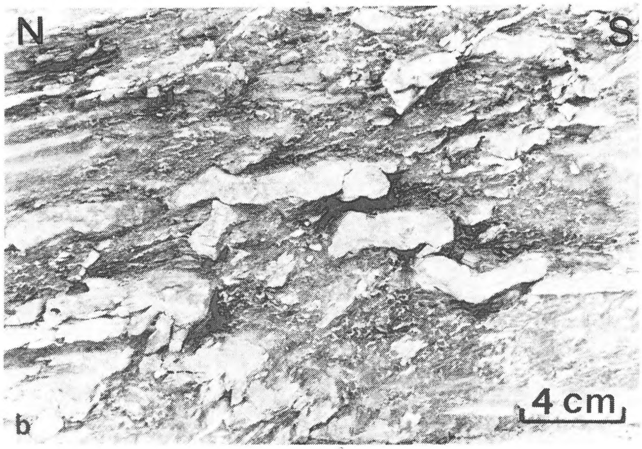

Fig. 2b
Extensive solution of short limbs of S-overturned mesoscopic folds in marly limestones of the Almagro Unit (Sierra de Almagro).

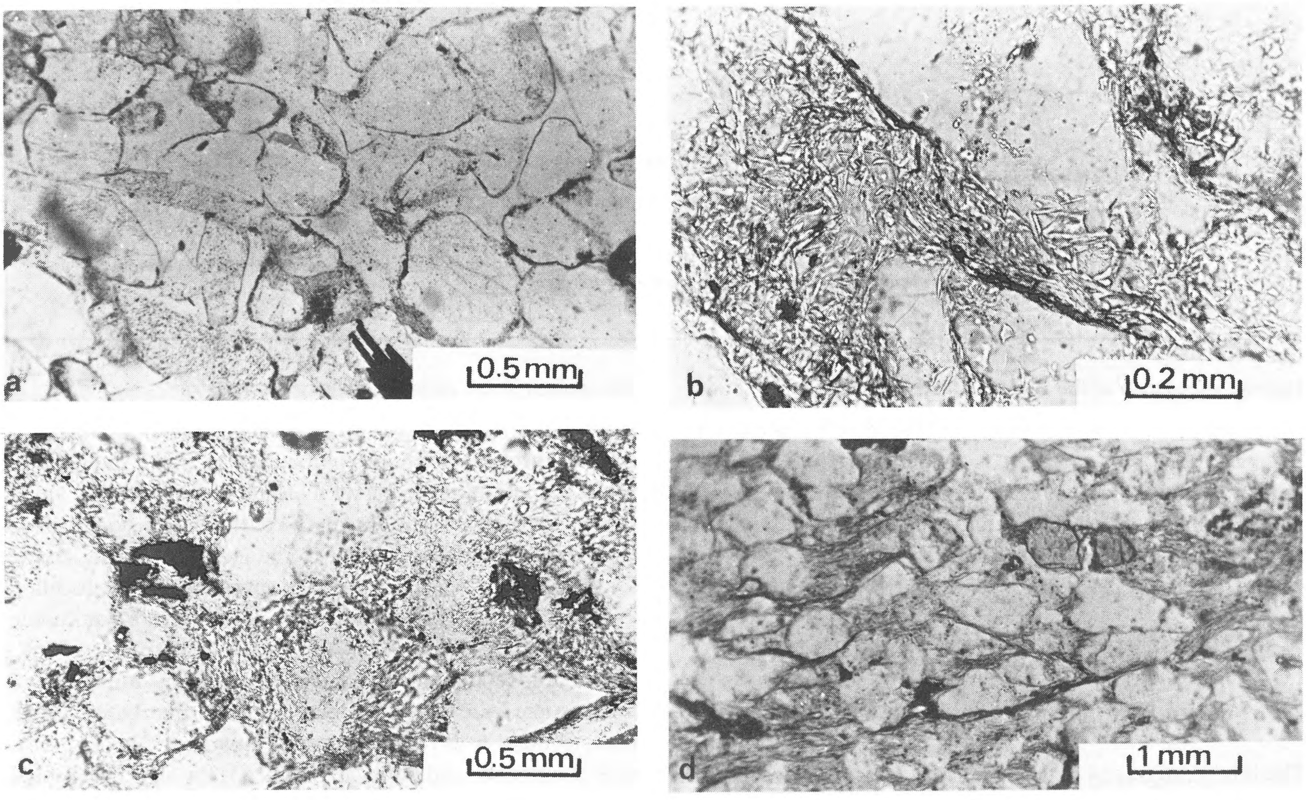

Fig. 3a
Detrital quartz grains outlined by dust rings. Quartzites of the Almagro Unit (Sierra de Almagro). Plane polarized light.
Fig. 3b
Very small phyllosilicates in the matrix of a metaquartzite of the Almagro Unit (Sierra de Almagro). Incipient pressure solution seams along the margins of detrital quartz grains. Plane polarized light.
Fig.3c
Very fine grained phyllosilicates result from reaction between detrital quartz grains and the matrix. The outlines of the quartz grains are not well defined. Quartzites of the Almagro Unit, Sierra de Almagro. Plane polarized light.
Fig. 3d
Pressure solution seams and incipient cleavage formation in quartzites of the Almagro Unit, Sierra de Almagro. Plane polarized light.

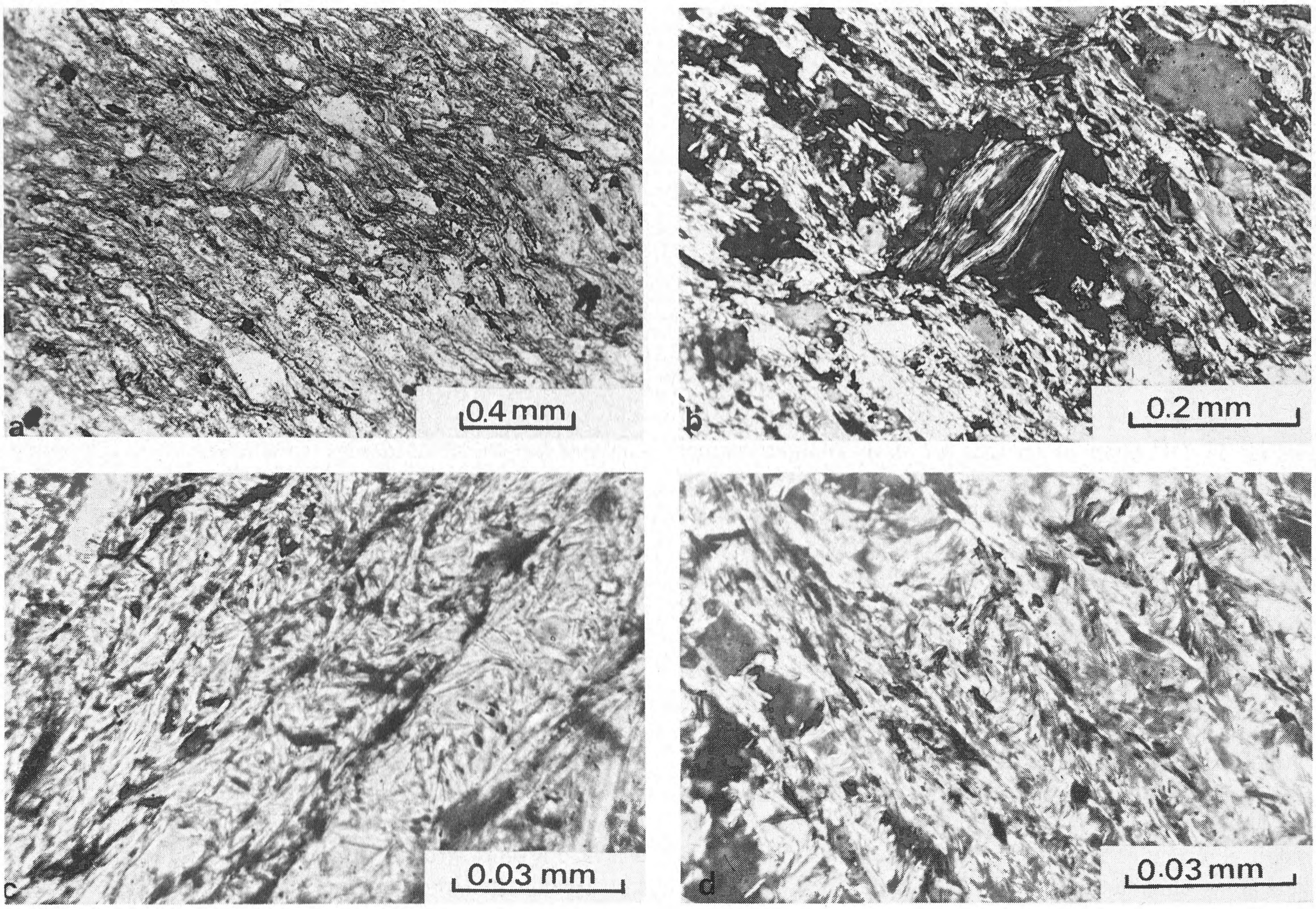

Fig. 4a
Domainal slaty cleavage fabric in low greenschist facies slate of the Almagro Unit, Sierra de Almagro. Plane polarized light.
Fig. 4b
Deformed chlorite porphyroblast. Detail of Fig. 4a. Crossed polarized light.
Fig. 4c
Crenulated sedimentary fabric in low grade slate of the Almagro Unit, Sierra de Almagro. Plane polarized light.
Fig. 4d
Crenulated sedimentary fabric in slate of the Almagro Unit, Sierra de Almagro Plane polarized light.

carbonate or mica-aggregates (Fig. 4a). Locally the lens-shaped domains contain an early fabric of very small phyllosilicates (Fig. 4c, d). This early fabric is often discontinuous and crenulated. It is generally oriented at a high angle to the cleavage planes and may represent a sedimentary preferred orientation of phyllosilicates.

Within the cleavage planes there is a parallel alignment of very small (10-30 µm wide and 300-500 µm long) phyllosilicates and larger (0.1 mm wide and 0.5 mm long) phyllosilicate porphyroblasts. Porphyroblasts of chlorite outside the cleavage planes show basal (001) lattice planes at a high angle to the cleavage (Fig. 4b). These chlorite stacks may have been deformed by kinking during cleavage development. The microstructures indicate cleavage formation under maximum metamorphic conditions of lower greenschist facies grade.

The Almanzora Unit (Sierra de Almagro)

The Almanzora Unit in the Sierra de Almagro consists of a clastic sequence of metapelites with intercalations of metapsammites and locally gypsum and an overlying carbonate-rich sequence with intercalated metapsammites and gypsum. On the basis of correlation with rock sequences elsewhere in the Betic Zone a Permo-Triassic age is tentatively attributed to the rocks of the Almanzora Unit (BLOEMENDAAL, 1982).

Within the clastic sequence SIMON (1963) has described north-overturned macroscopic tight to isoclinal folds on a 100 m scale. Parallel to the axial plane of these folds there is a prominent cleavage. The cleavage/bedding angle may be small but it is clearly demonstrated by refraction through the more competent metasandstone layers.

The cleavage microstructure is identical with that described for the Almagro Unit. In mica-rich slates most phyllosilicates have been aligned parallel to the cleavage planes. In quartz-rich slates the cleavage microstructure is domainal, showing mica-rich cleavage planes curving around lenticular quartz-rich domains. The main porphyroblasts are chlorite, chloritoid and white mica. Chloritoid and white mica porphyroblasts are aligned parallel to the cleavage planes. Chlorite porphyroblasts are oriented at high angles to the cleavage planes. The S_1 planes curve around these porphyroblasts. The microstructures indicate that cleavage formation took place under maximum conditions of lower greenschist facies metamorphism.

The Variegato Unit (Sierra de los Filabres)

The lowermost part of the Variegato Unit in the north-eastern Sierra de los Filabres consists of dark-coloured garnet micaschists and intercalated metasandstone layers. A Paleozoic (and older?) age is generally attributed to these rocks. They have been metamorphosed under upper greenschist facies conditions. The sequence is overlain by a series of Permo-Triassic clastic sediments, metamorphosed under greenschist facies conditions. The Permo-Triassic sediments are covered by a series of low grade carbonate rocks of Middle to Late Triassic age.

In the lowermost part of the Variegato Unit bedding is preserved as centimetre to decimetre thick metasandstone layers within the micaschists. Bedding is discontinuous and can not be followed over more than a few decimetres. The oldest deformational structures that can be observed in the field are isoclinal to tight folds. The hinges of these folds are

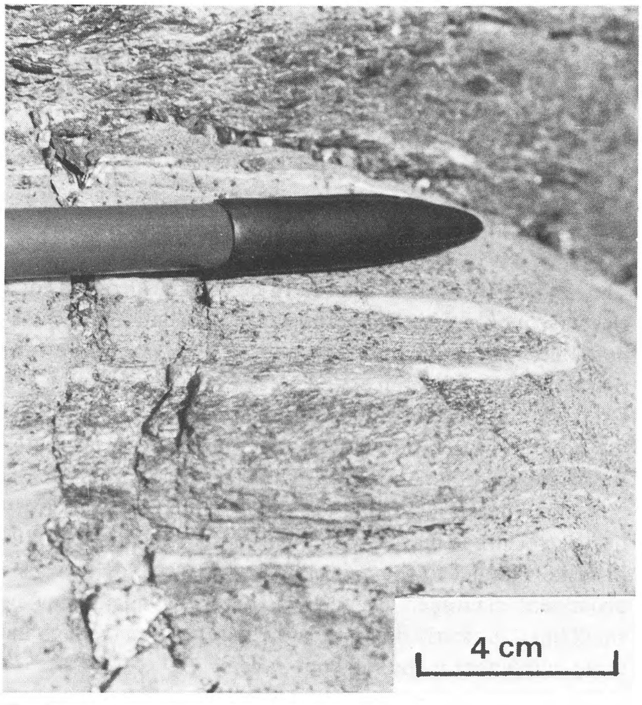

Fig. 5
Isoclinal folds of quartz veins in garnet micaschists of the Variegato Unit. N.E. Sierra de los Filabres.

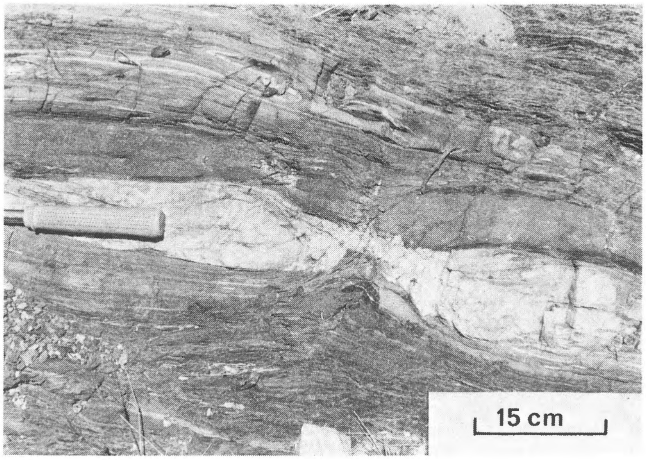

Fig. 6
Boudinaged quartz veins in garnet micaschists of the Variegato Unit. The main foliation plane represents a crenulation cleavage or schistosity. Note the isoclinally folded quartz vein in the upper part of the photograph. N.E. Sierra de los Filabres.

often isolated. The rocks contain abundant quartz lenses and veins that have been isoclinally folded and boudinaged (Figs. 5 and 6). Parallel to the axial plane of the folds of the bedding and the quartz veins there is a prominent foliation. On a microscopic scale this foliation represents a crenulation cleavage or schistosity, folding an earlier preferred orientation of phyllosilicates parallel to bedding. The crenulation cleavage is often strongly differentiated and the microstructure is dominated by alternating quartz-rich microlithons and mica-rich cleavage planes with a strong preferred orientation of phyllosilicates (Fig. 7a, b).

The crenulated bedding-parallel foliation is a differentiated 'spaced' cleavage as well (Figs. 7 and 8). The foliation is defined by parallel arrangement of phyllosilicates separating quartz-rich domains in which the individual quartz grains possess a shape-preferred orientation parallel to the foliation. Small porphyroblasts of biotite are aligned within the crenulated bedding-parallel foliation (Fig. 8). The biotites have been deformed in the microfold hinges of the crenulations. Almandine porphyroblasts have grown over the bedding-parallel foliations and contain either straight or rotational inclusion trails of graphite and non-equidimensional quartz grains. (Fig. 7b).

DISCUSSION AND INTERPRETATION

From the angular cleavage/bedding relations it is evident that the prominent foliations in both the Almagro and Almanzora Units represent a tectonic cleavage. It can be demonstrated that the foliations are the first tectonic fabrics in the rocks. Recent studies have provided detailed descriptions of the microstructure of slaty cleavage and clarified many of the problems concerned with its formation (WEBER, 1976, 1981; KNIPE, 1979, 1981; KNIPE & WHITE, 1977; WHITE & KNIPE, 1978;

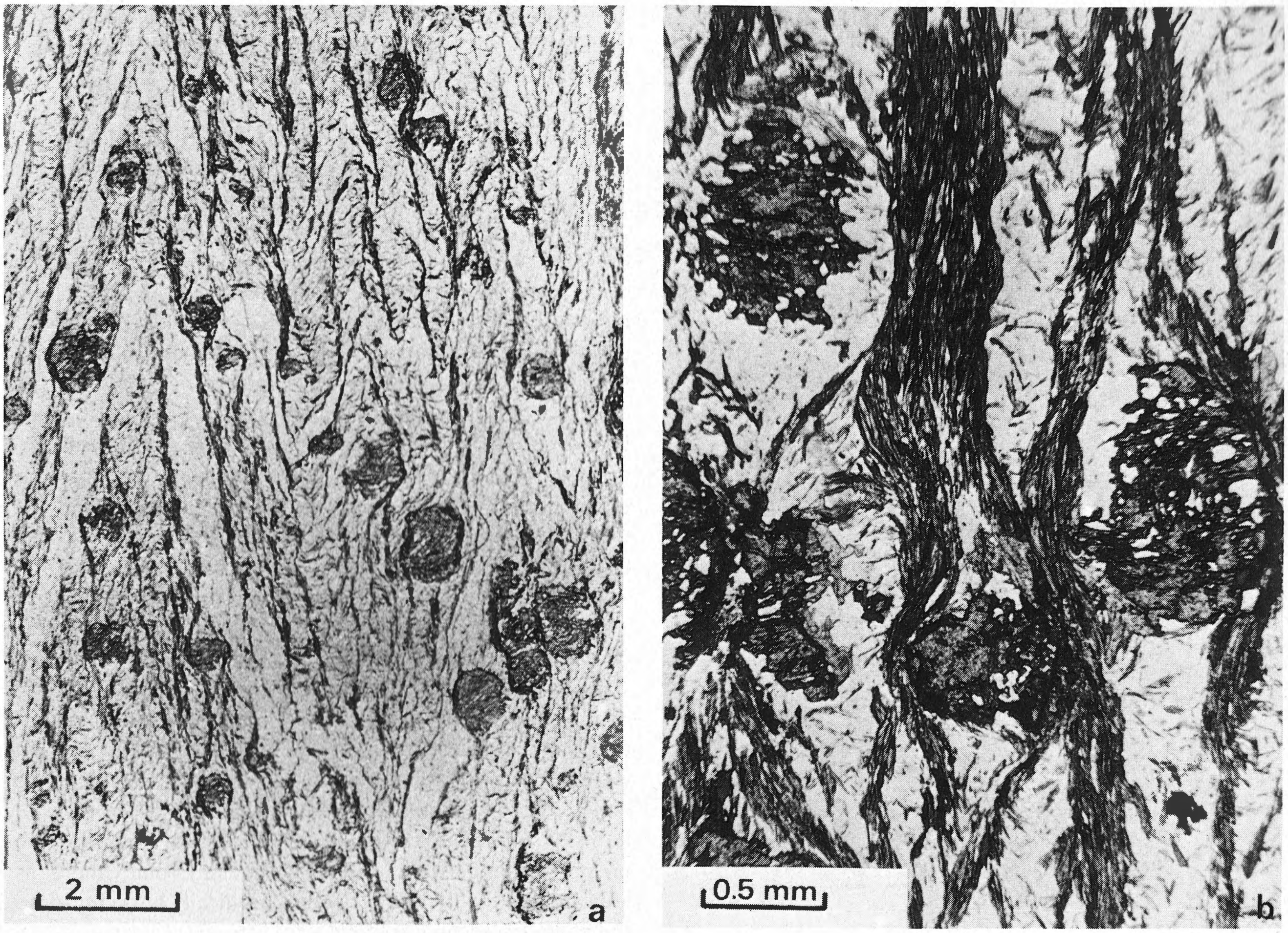

Fig. 7a
Main foliation plane (N-S) in garnet micaschists of the Variegato Unit represents a differentiated crenulation cleavage. The crenulated fabric represents the bedding-parallel foliation. Plane polarized light.
Fig. 7b
Detail of the differentiated main crenulation cleavage in garnet micaschist of the Variegato Unit (N.E. Sierra de los Filabres). Almandine porphyroblasts have grown over the early bedding-parallel foliation and contain planar and rotational inclusion patterns. Plane polarized light.

WHITE & JOHNSTON, 1981; BEACH, 1979). It has been shown that shape transformations of mineral grains, such as quartz and carbonate, are controlled by pressure solution deformation mechanisms (ELLIOTT, 1973; DE BOER, 1977). These processes may operate together with mechanical reorientation, deformation and chemical recrystallisation of phyllosilicates (BEACH, 1979; KNIPE, 1981).

The microstructures of the rocks from the Almagro and Almanzora Units show different stages of cleavage development from the sedimentary microstructures to the fully developed slaty cleavage fabric. Pressure solution of quartz is evidenced by detrital quartz grains that are truncated against incipient pressure solution seams and by the shape-preferred orientation of quartz-rich domains between the cleavage planes. Neoformation of fine grained phyllosilicates (Fig. 3c), reorientation into parallelism with S_1 and parallel growth of porphyroblasts of white mica reinforce the cleavage fabric. Progressive cleavage development leads to the ultimate destruction of the initial sedimentary microstructure and only locally relics of the sedimentary preferred orientation of phyllosilicates have survived within the lenticular domains.

In the rocks of the Variegato/Partaloa Unit there is no evidence that the early bedding-parallel foliation is axial planar to isoclinal folds of the sedimentary layering. AKKERMAN ET AL., (1980) have therefore interpreted this foliation to represent an initial bedding fabric that has been overgrown mimetically by metamorphic micas, while retaining its bedding-parallel orientation.

The interpretation of Akkerman et al., (1980) disregards the important role of pressure solution processes prior to the phase of isoclinal folding and crenulation cleavage development. Pressure solution processes have operated on a large scale as is shown by (1) the abundant occurrence of quartz lenses and veins, that have subsequently been deformed during the phase of isoclinal folding, (2) the differentiated character of the 'spaced' bedding-parallel foliation, and (3)

Fig. 8
Crenulated bedding-parallel foliation in garnet micaschist of the Variegato Unit (N.E. Sierra de los Filabres). Small biotite flakes parallel to the early foliation have been deformed during microfolding. Plane polarized light.

the flattened shape of individual quartz grains and quartz domains in the bedding-parallel foliation and of quartz inclusions in almandine porphyroblasts. Pressure solution processes on this scale operate under non-hydrostatic stress conditions during tectonic deformation. They can not be compared with minor pressure solution processes during compaction that may be responsible for bulk volume reduction, cementation, and pore space reduction, but which do not produce foliations as local stress concentrations reduce quickly when pore space decreases.

The interpretation that the rocks of the Variegato/Partaloa Unit have been deformed during a tectonic event prior to the phase of isoclinal folding is supported by the crustal environment of the rocks during metamorphism. Metamorphic evidence indicates that the porphyroblastesis of biotite and almandine started prior to the phase of isoclinal folding and crenulation cleavage development. Interpretation of these structures as first phase deformation structures implies that the rocks have been metamorphosed at temperatures of 450-500°C before deformation started. The only possible way to explain those temperatures then is to assume deep burial under a pile of undisturbed sediments of many kilometres thickness with or without an additional heat flow from the mantle.

The earliest phases of metamorphism in the Alpujarride nappes are generally related to the emplacement of hot mantle peridotite domes in the crust (LOOMIS, 1972a, b; WESTERHOF, 1977; TORRES ROLDAN, 1981). Recent investigations on the metamorphic parageneses in the crustal envelope of the Sierra Bermejo peridotite (TORRES ROLDAN, 1981) have indicated an average geothermal gradient of 27°C/km for the earliest phase of metamorphism. This value closely corresponds with the estimate that the peridotite equilibrated at a crustal depth of 28 km at temperatures of 675-880°C and 10 kbar (SCHUBERT, 1979). Using the 27°C/km geothermal gradient as the maximum gradient for the earliest phase of metamorphism in the Variegato Unit, it can be calculated that the rocks have been metamorphosed at the considerable depth of at least 16 km at pressures of 4-5 kbar.

There is no evidence whatsoever that there has been a pile of 16 km of sediments on top of the first biotite and almandine bearing rocks of the Variegato Unit before deformation started. The only rocks available are Permo-Triassic sediments. Post-Triassic sediments do not occur in the Alpujarride nappes and neither are they present in the erosion material within the intramontane basins. It is therefore impossible to explain the metamorphic grade of the rocks in terms of simple burial with an additional heat flow from the underlying hot peridotite dome. The metamorphic conditions indicate that the rocks have been tectonically buried prior to the phase of isoclinal folding.

Tectonic deformation prior to the phase of isoclinal folding explains the non-hydrostatic stress conditions during which large-scale pressure solution deformation processes operated in the rocks.

On the basis of the evidence presented the bedding-parallel foliations in the Variegato Unit have been interpreted as tectonic foliations formed during an early phase of deformation. Metamorphism that started during the formation of the early foliations culminated in upper greenschist facies conditions after completion of the fabric. These metamorphic conditions continued during the second phase of deformation during which the rocks have been isoclinally folded under continuing conditions of pressure solution deformation. These processes finally resulted in the highly transposed sequences we can observe today and that are characterised by isoclinal folding, parallelism of bedding and axial plane cleavages, discontinuity of bedding and obliteration of early F_1-fold hinges.

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