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The development of a single cleavage in an area of repeated folding

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Abstract—Structural investigations in the Variscan fold interference pattern of SW Sardinia (Italy) document an intriguing example of the relationship between cleavage, folding and finite strain. Although Palaeozoic sediments were affected by two major folding events, both under identical low-grade metamorphic conditions, only a single penetrative cleavage formed, which is not unambiguously correlated with either of these events. Cleavage orientation changes smoothly along sigmoidally curving trajectories throughout the interference pattern. Thus, the same cleavage can be axial planar to either the first or the second phase folds, or transect both when curving from one set into the other. The singularity of the cleavage is supported by microscopic studies, which show no evidence of a pre-existing or overprinting tectonic cleavage. Finite strain determinations and numerous field observations demonstrate that cleavage always parallels the principal plane of finite strain, even though local strain varies according to the relative position in the fold interference pattern. Similar strain patterns were achieved by forward modelling of superposed buckle folds. Based on our findings we propose (i) that the finite strain pattern is due to the superposition of the heterogeneous strain fields associated with the individual folding events and (ii) that cleavage reflects the cumulative deformations that effected the rock. This has consequences for the regional interpretation of cleavage in our study area and elsewhere, and for the distinction between deformation phases in general. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Structural patterns in most orogenic belts reflect complex deformation histories that result from the superposition of two or more heterogeneous deformation fields. In attempting to understand the evolution of these belts, structural geologists are faced with problematic and often controversial issues concerning the relationships between folds, cleavages and strain and their overprinting patterns, in order to determine a history of deformation.

This deformation history is commonly divided into successive phases which are defined by individual fold systems and sets of cleavages, distinguished by their style and orientation, as well as by the metamorphic conditions at the time of their formation. It is widely assumed that each folding phase is associated with a fabric, forming an axial planar cleavage or schistosity (e.g. Passchier and Trouw, 1996, p. 3). However, in many areas the concept of deformation phase subdivision based on "each folding phase has its particular cleavage" is not applicable. Controversial regions have, for instance, been described where two cleavages formed during a single phase of folding (Boulter, 1979; Powell and Rickard, 1985; Williams, 1985) or shear zone formation (Platt, 1984), or where folds are transected by the cleavage (Stringer and Treagus, 1980; Ridley and Casey, 1989; Treagus and Treagus, 1992). In regions of progressive deformation or deformation partitioning the concept of deformation phases may prove insufficient for describing the structural complexity (Campbell *et al.*, 1985; Williams, 1985; Tobisch and Paterson, 1988; Mawer and Williams, 1991).

These problematic areas indicate that the geometrical and genetic relationships of folds, cleavages and finite strain are not as simple as often assumed. The critical questions we have to address concern the parameters which control the development of cleavage and folding as well as their timing, the relationship between cleavage and finite strain, and the active or passive behaviour of fabrics during a non-coaxial deformation history (e.g. Ramsay, 1967; Ramsay and Graham, 1970; Treagus, 1973, 1985; Williams, 1977; Hobbs *et al.*, 1982; James and Watkinson, 1994).

In an attempt to explore the above issues we have studied the relationships between cleavage, strain and two generations of folds in a 200 km^2 area of the Iglesiente region in Southwest Sardinia. This region is famous for its well exposed and beautifully developed regional fold interference pattern in which many layers contain excellent strain markers (e.g. Teichmüller, 1931; Arthaud, 1963; Poll and Zwart, 1964; Dunnet 1969a,b). Thus, it is an ideal region for analysing cleavage/fold geometries and their relationship to the state of finite strain within a complexly folded region. However, instead of two or more cleavages we were surprised to find only a single cleavage in this region that has a complex relationship to the fold geometry. It is the relationship of this single cleavage to the two major folding events that prompted our more detailed work presented in this paper.

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Based on our mapping (1:10 to 1:10,000), microstructural investigations (>300 thin-sections), finite strain determinations (>100 samples) and fabric analyses (110 samples), as well as numerical modelling, we suggest that in Southwest Sardinia the cleavage reflects the finite strain accumulated during various folding events. This conclusion has significant consequences for the interpretation of multiply deformed regions because it shows that structures can reflect different time segments of a deformation history.

GEOLOGICAL SETTING

Sardinia, an Italian island in the western Mediterranean Sea, is characterised by a Palaeozoic basement preserving a transect through the European Variscan orogenic belt (Ziegler, 1988; Carmignani *et al.*, 1994). In the north-eastern part of the island axial zone, amphibolite-facies rocks are exposed which decrease in metamorphic grade towards the southwest (Carmignani *et al.*, 1982, 1990, 1992) (Fig. 1).

The Iglesiente/Sulcis region of Southwest Sardinia belongs to the external zone of the Variscan belt and consists of low-grade metamorphic Lower Palaeozoic sediments which have been deformed in two principal fold forming events (Fig. 2). Excellent exposures allow the description of fold interference patterns and of a complete, well preserved Palaeozoic sediment cycle (Rasetti, 1972; Cocozza and Jacobacci, 1975; Cocozza, 1979; Bechstädt *et al.*, 1994). The cycle begins with Lower Cambrian clastic sediments (Nebida Formation) followed by a carbonate platform series (Gonnesa Formation), condensed nodular limestones (Campo Pisano Formation) and finely laminated siliciclastic sediments (Cabitza Formation) continuing into the Lower Ordovician (Cocozza, 1979; Fanni *et al.*, 1981; Carannante *et al.*, 1984; Bechstädt *et al.*, 1988, 1994; Bechstädt and Boni, 1989). This succession is truncated by the so-called Sardic unconformity and overlain by heterogeneous clastic sediments of Ordovician age. The Post-Sardic sediments (Monte Argentu Formation, after Laske *et al.*, 1994) consist of local mega-breccias at the base and conglomerates with upward as well as lateral transitions into sandstones and siltstones, as is to be expected in fan deposits (Martini *et al.*, 1991; Laske *et al.*, 1994; Lebit, 1995). The series is covered by fossil-rich clastic sediments of Caradocian to Ashgillian age.

The entire Palaeozoic succession has been deformed under low-grade metamorphic conditions (Franceschelli *et al.*, 1992; Lüneburg, 1995) resulting in

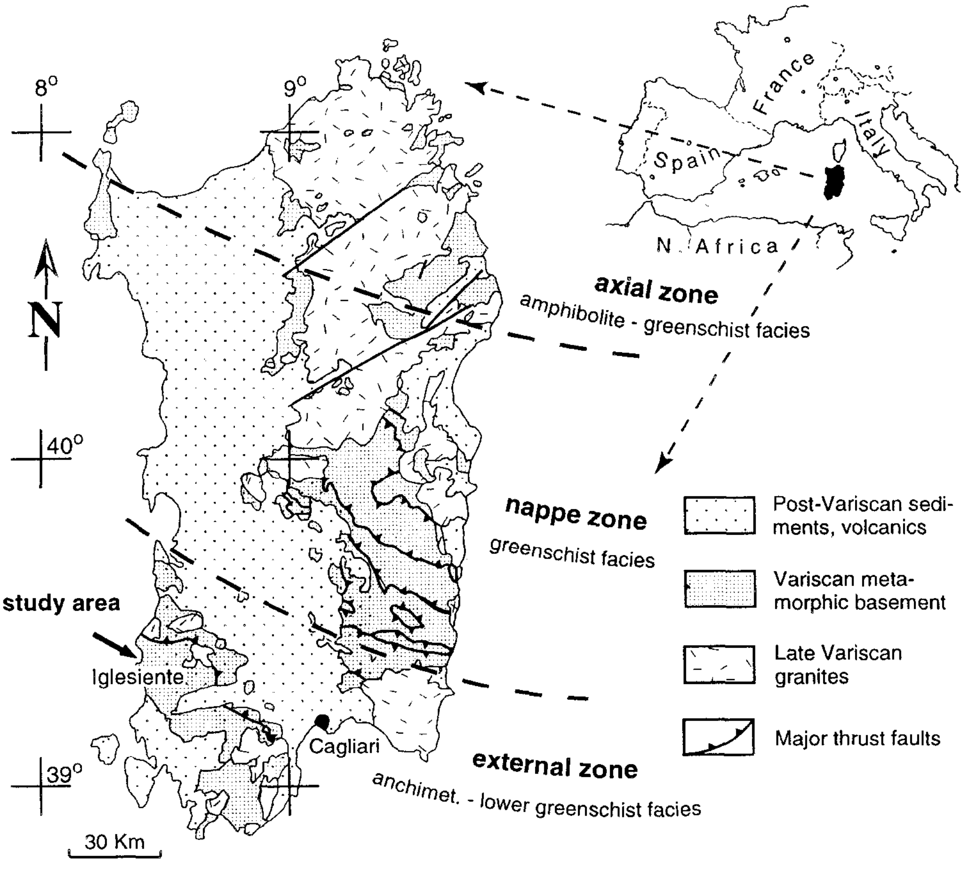

Fig. 1. Simplified geologic map of Sardinia with location of the study area and the Variscan tectono-metamorphic zonation in the basement (after Carmignani *et al.*, 1992). The actual geotectonic position in the Western Mediterranean Sea is due to a Tertiary anticlockwise rotation of the terrain away from the Franco-Iberian mainland.

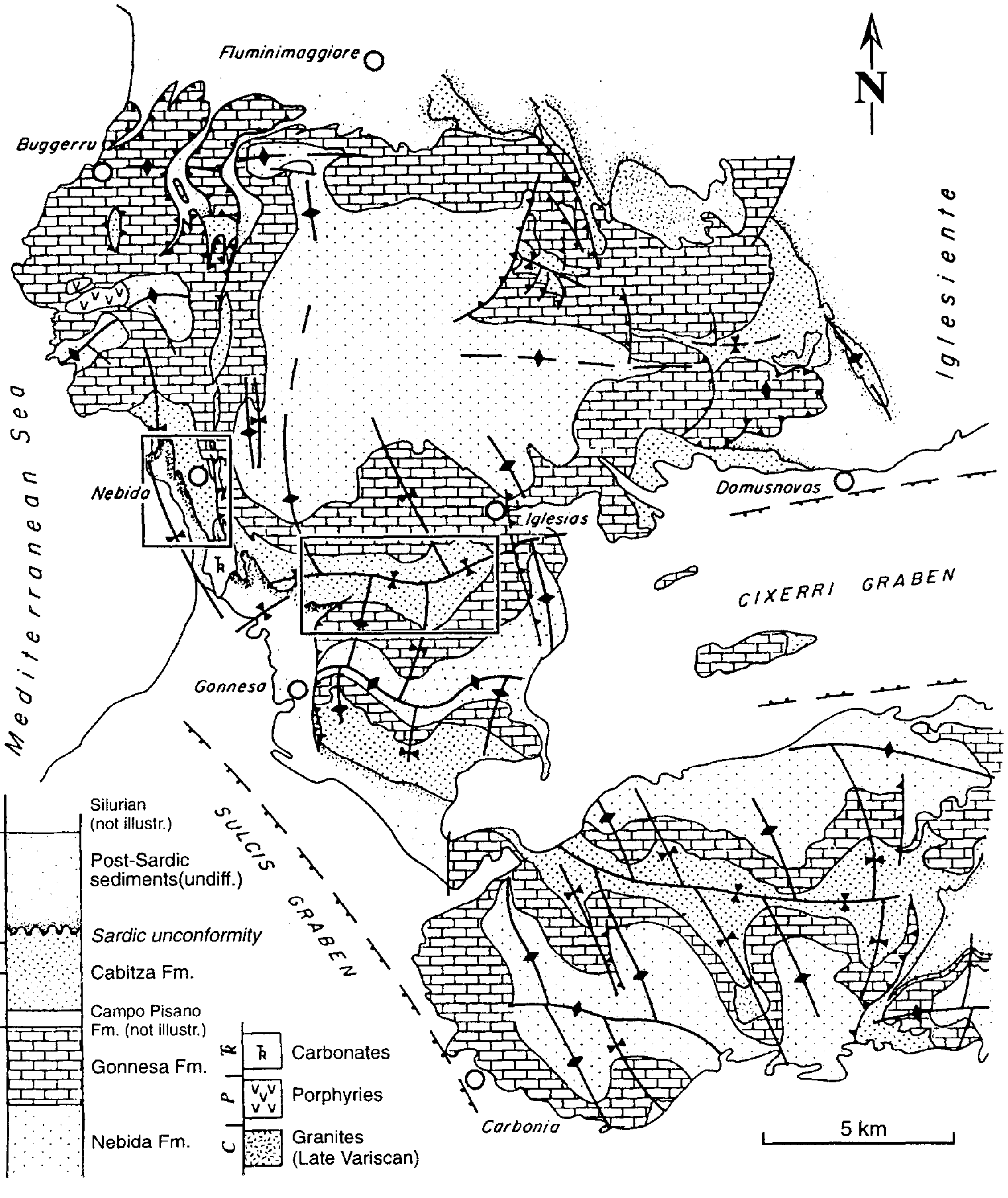

Fig. 2. Fold interference pattern of the Iglesiente/Sulcis, documented by the distribution of the major lithologic units of early Palaeozoic sediments (modified after Carmignani *et al.*, 1982). Older, approximately E–W-trending folds overprinted by N- or S-plunging folds. Axial traces of earlier folds are refolded, and those of the later folds are offset where they pass from one pre-existing fold limb to another.

a complex fold interference pattern of Variscan age (Fig. 2). An approximately E–W-striking fold set is refolded by N–S-trending folds forming dome–basin and crescent–mushroom patterns. Although these two folding events sufficiently describe the main features of the fold interference pattern shown in Fig. 2, two additional deformation phases have been proposed by some authors (Arthaud, 1963; Poll and Zwart, 1964; Poll, 1966; Dunnet, 1969a; Carmignani *et al.*, 1982). These authors believe that an earlier (Caledonian) deformation phase folded the Pre-Sardic sediments (Carmignani *et al.*, 1978; Barca *et al.*, 1985), an opinion which they base on the original interpretation of Stille (1939) that the Sardic angular unconformity was evidence for a significant tectonic event (Teichmüller, 1931; most publications cite Stille's oral communication from 1939). They suggest that the Sardic phase developed small-amplitude folds which are not recognisable in the fold interference pattern because they are 'in phase' with the first Variscan fold set forming E–W-directed folds. In contrast, the second Variscan N–S-trending folds clearly refold the ear-

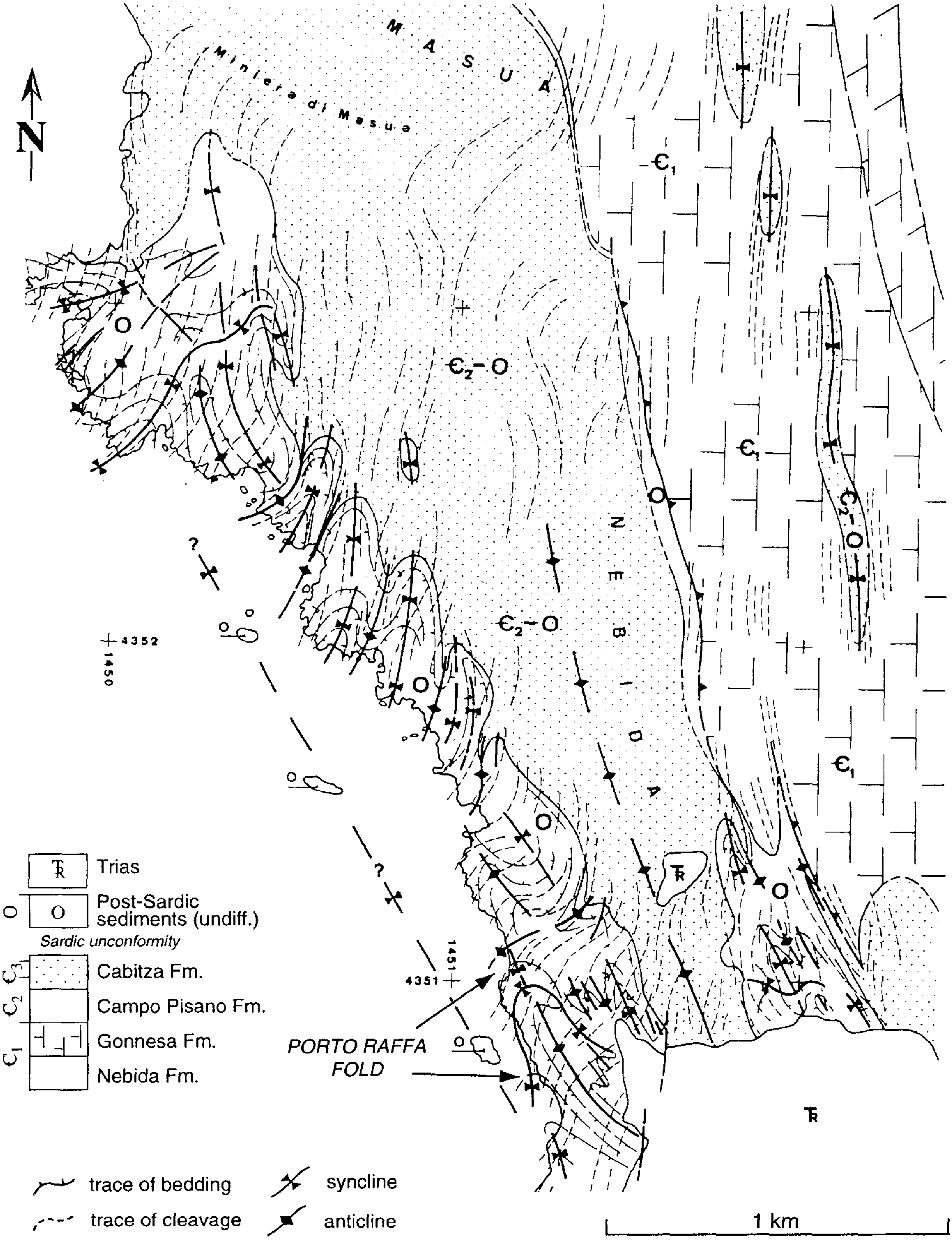

Fig. 3. *Coastal area*: detailed fold interference pattern. Axial-plane traces of the two fold sets and cleavage trajectories continue smoothly from Cambro-Ordovician to Post-Sardic sediments. In this area the earlier fold axial planes strike mainly ENE–NE and are refolded by the later folds with axial planes striking NNW.

lier folds, forming a classical regional dome-and-basin interference pattern. This folding event is regarded as the dominant deformation phase associated with regional metamorphism, developing the cleavage and major fault systems (Arthaud, 1963; Dunnet, 1969a; Moore, 1969). Local kink folds with variably striking axes formed in a third Variscan phase which is given only secondary importance.

It is important to emphasise that of the four suggested deformation phases only two produced widespread regional folding and only one phase is commonly recognised as causing penetrative internal rock deformation in the form of a slaty or penetrative cleavage.

ANALYSIS OF FOLD INTERFERENCE PATTERN

Any analysis of the geometry and chronology of superimposed folds requires determination of the axial orientations of the component folds and their spatial variation along the fold axial traces (Ramsay, 1957, 1967 p. 358; Turner and Weiss, 1963 p. 169; Ramsay and Huber, 1987 p. 480). To determine fold axes orientations in the field, the cleavage/bedding intersections are commonly used, with the assumption that they are coaxial with the fold hinge. In complexly deformed areas, such as Southwest Sardinia, the intersection lineation is not necessarily parallel to the fold axis because the cleavage shows no simple geometrical relationship to either of the fold systems. Therefore, the orientations of fold axes were derived mainly from projection methods of bedding attitudes, such as π- or β-diagrams. However, these techniques can produce complex π-pole distributions or spurious concentrations of β-points in the complex non-cylindrical shapes arising from fold superposition. We have tried to avoid this problem by only analysing bedding attitudes found along sections perpendicular to the strike of the local axial plane. The successive application of this method along a hinge line leads to the best evaluation of the change in orientation of the local fold axis.

Within the fold interference pattern, domains are distinguishable in which later folds with the same geometry and orientation dominate. These domains are separated by the hinge line of refolded earlier folds. For instance, in the Post-Sardic sediments of the *coastal area* (Fig. 3), one common domain is characterised by NNW-plunging second-phase fold axes with subvertical to downward-facing fold orientations. Adjacent domains to the south and to the north are dominated by upward facing folds plunging gently or moderately towards NNW, indicating that these folds have been superposed on an asymmetric fold system trending ENE. Such arrangements are interpreted as a type 2 fold interference pattern (Ramsay, 1967, p. 525) which is supported by the change of individual synformal anticlines into synclines and of antiformal synclines into anticlines (Fig. 3).

When all axes of the later folds are combined into a synoptic equal-area projection they show a broad great-circle distribution (Fig. 4). The great-circle fit of these axes coincides with the axial planes of the later folds. This axial plane divides the projection into two sectors corresponding to the limb regions of the superposed folds. Within these two sectors the earlier fold axes spread along complex loci reflecting their reorientation.

Although the change in fold axis orientation is potentially due to different kinds of imposed deformation, certain fold mechanisms form characteristic patterns in projection. The observed axis orientations (Fig. 4) form loci comparable to those formed when linear elements are reoriented in flattened flexural folds (Ramsay, 1960, 1967, p. 461). Our numerical experiments on superposition of mechanical buckle folds, which will be described in the section on strain, also yield similar patterns of reoriented fold axes. When we imposed the fold-related heterogeneous deformation on linear structures, those located near the new hinges have their initial angles with the new fold axis reduced, and those in the limbs have them increased. The close coincidence of the theoretical with the natural distribution of refolded fold axes suggest that the superposed folds were probably due to buckling or flexural flow folding.

Although we were able to assess the geometrical arrangement of the component folds, the initial orientation of the first fold set cannot be fully determined for a fundamental reason: none of the pre-existing folds remain in its original orientation after the superposition. However, the average trend of the earlier fold

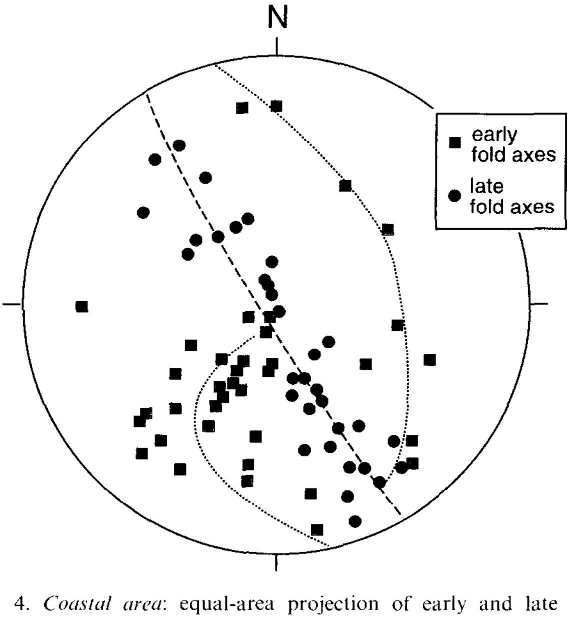

Fig. 4. *Coastal area*: equal-area projection of early and late fold axial orientations (see Fig. 3). Early axes are spread along a curved locus by being differentially reoriented by the late folding. The later fold axes fit a great-circle along the new axial plane.

hinges can be estimated by joining geometrically analogous points in the interference pattern (Ramsay and Huber, 1987, p. 496). In our field areas, the estimated average trend of the earlier fold axes is approximately east–west.

In summary, the regional fold superposition in the Palaeozoic sediments of the Iglesiente/Sulcis is characterised by dome–basin as well as by crescent–mushroom structures as shown by the distribution of the major lithostratigraphic units in Figs 2 and 3. This fold pattern can be defined as type 1–2 (after Ramsay, 1967 p. 520; Ramsay and Huber, 1987 p. 494) with suborthogonal fold axes and variable angles between poles to first-fold axial planes and second-fold displacement direction. The regional consistent refolding of the E–W-trending fold axial planes suggests that these folds formed earlier than the N–S-trending ones. Both fold systems show similarity in fold style and interfere with approximately the same average wavelength.

CLEAVAGE ANALYSIS

Although the folded bedding clearly indicates the presence of two fold phases, there is only one cleavage developed. In the siliciclastic sediments of the Cabitza Formation and the Post-Sardic series it forms a penetrative feature (Figs 5 & 7) mainly developed as a slaty cleavage.

The Cabitza Formation consists of irregularly alternating layers of sandstone, siltstone and mudstone of thicknesses varying from millimetres to centimetres. Macroscopically, a well developed slaty cleavage is present as a continuous and regular fabric when sandstone layers are absent (Fig. 5a). In and around small-scale folds of the sandstone layers, cleavage is more disjunctive and varies in intensity due to the differences in deformation between the lithologies (Fig. 5b). The Post-Sardic sediments consist of fining-upward sequences of conglomerates at the base, followed by decimetre-thick, relatively homogeneous sandstones

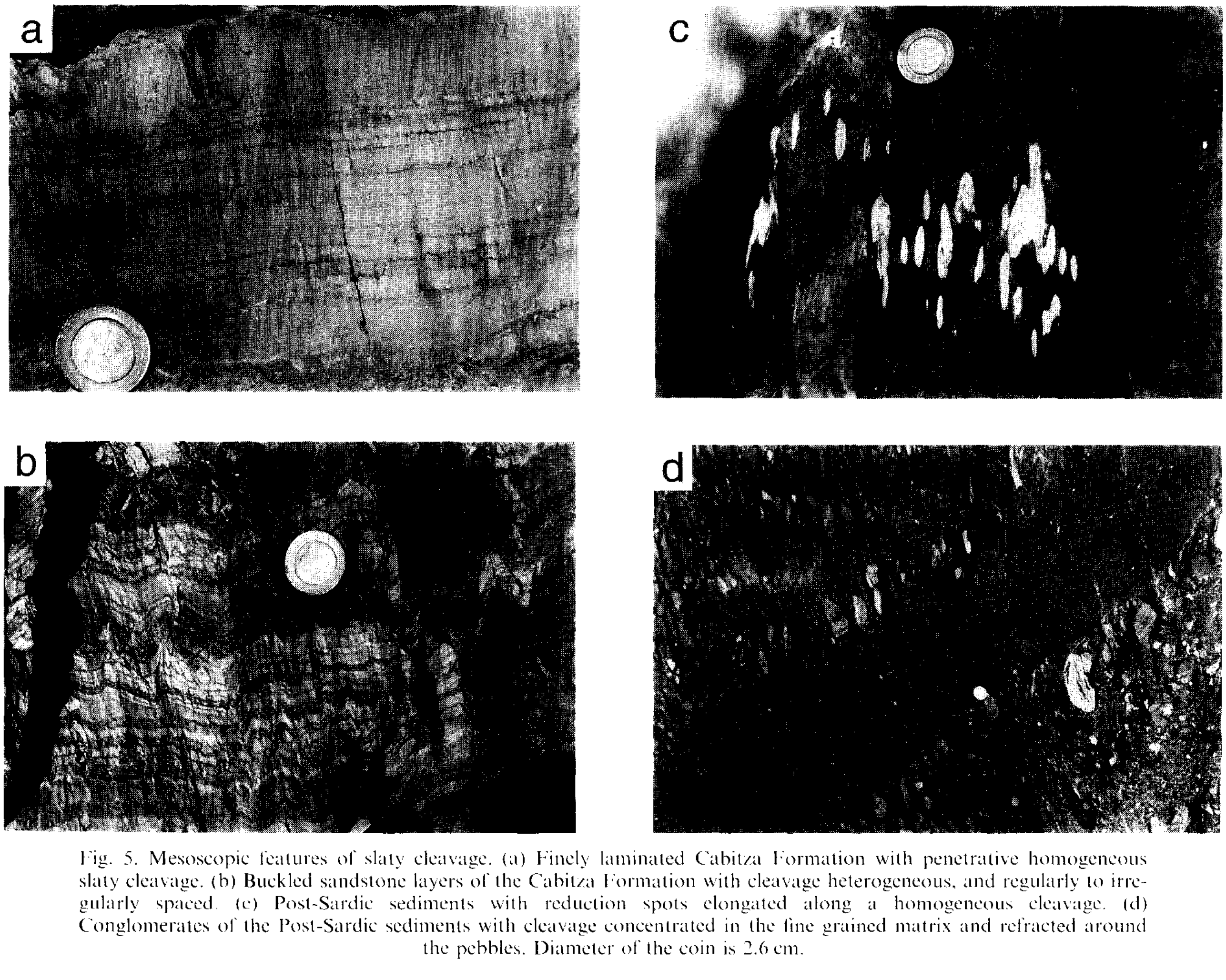

Fig. 5. Mesoscopic features of slaty cleavage. (a) Finely laminated Cabitza Formation with penetrative homogeneous slaty cleavage. (b) Buckled sandstone layers of the Cabitza Formation with cleavage heterogeneous, and regularly to irregularly spaced. (c) Post-Sardic sediments with reduction spots elongated along a homogeneous cleavage. (d) Conglomerates of the Post-Sardic sediments with cleavage concentrated in the fine grained matrix and refracted around the pebbles. Diameter of the coin is 2.6 cm.

and siltstones with little internal bedding lamination. Folds have greater wavelengths than in the Cabitza Formation, and at the outcrop scale the slaty cleavage is more uniform in intensity and orientation (Fig. 5c). In the conglomerates, cleavage is developed predominantly in the fine-grained matrix and refracts around pebbles elongated in the cleavage plane (Fig. 5d).

Cleavage changes continuously in orientation and in intensity depending on its location within the fold interference pattern. This phenomenon has been observed at all scales in the fold systems. Regionally, the cleavage strikes approximately north–south, subparallel to the axial planes of the later folds, but locally it curves toward the axial plane of the earlier E–W-trending folds. The cleavage traces form a smoothly curving trajectory pattern which can be followed through the different lithologies of the Post-Sardic sediments, the Cabitza Formation and adjacent units (Figs 3 & 6). The continuous trajectory pattern is one of the most illustrative arguments for the singularity of the cleavage within the fold interference pattern.

In the Post-Sardic sediments of the *coastal area* (Fig. 3) certain areas are dominated by the early folds. Here the cleavage is approximately parallel to the axial surfaces of these folds. In other areas, the fold interference pattern is dominated by the superposed deformation (southeast part), and here the cleavage is oriented closer to the axial planes of the late folds. In still other areas (northwest part) the cleavage is not axial planar to either of the fold sets. However, all the cleavage-trace trajectories in the Post-Sardic sediments form a smoothly curving pattern.

In the Cabitza Formation of the *Iglesias syncline* comparable patterns have been recognised, although they are regionally less consistent because the wavelengths of folds in each system are smaller. In order to determine the intraformational fold interference patterns the formation has been subdivided by the relative proportion of the sandstone layers and the mineral content of the pelitic sediments (Lüneburg, 1995). In Fig. 6 we illustrate sectors within the Iglesias syncline as examples of cleavage trajectory patterns at specific

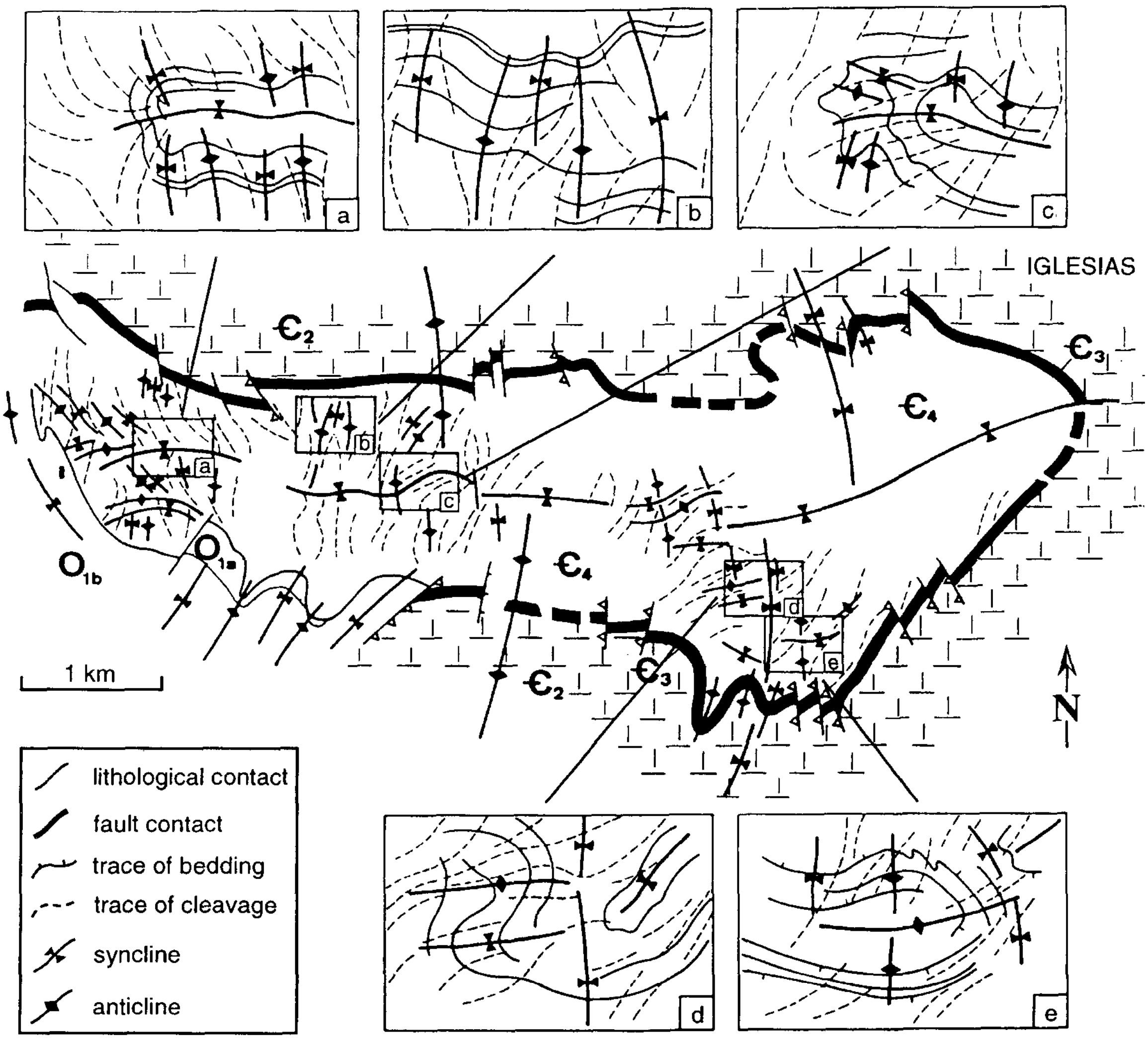

Fig. 6. *Iglesias syncline* interfering folds and cleavage. Selected details of fold interference pattern illustrate complexity of cleavage/fold geometries (a)–(e).

positions in the fold interference pattern. In the centre of the major E–W-trending syncline the earlier minor folds are dominant, and the cleavage curves toward parallelism with their axial planes (Fig. 6c & d). Near the northern and southern limbs of the syncline the cleavage becomes increasingly north–south oriented and thus approaches the attitudes of the axial planes of later and minor folds that locally are dominant (Fig. 6a & b). In transitional zones cleavage generally transects both fold systems (Fig. 6e).

These transections of the fold axial planes are characteristic features of the Cabitza Formation as well as of the Post-Sardic sediments. Cleavage sub-orthogonally transects one fold system when it approaches an axial planar orientation to the other fold system. In transitional zones the angle between cleavage and axial planes varies gradually for both fold systems, making the sense of transection of the fold axes either clockwise or anticlockwise.

FABRIC ANALYSIS

The microscopic cleavage development in the Cabitza Formation and the Post-Sardic sediments is very similar to the macroscopic one. In the absence of competent sandstone layers, cleavage is uniformly developed with regularly and narrowly spaced domains (Fig. 7a). Where sandstone layers alternate with less competent material, deformation is heterogeneous and cleavage domains are irregularly spaced and refracted (Fig. 7b). In the Post-Sardic sediments cleavage is rather uniform and the domains are regular but widely spaced since the material is coarser grained and has a higher quartz content than in the Cabitza Formation (Fig. 7c). In conglomeratic layers the cleavage intensity tends to be irregular because the pebbles resist deformation (Fig. 7d).

Microscopic studies of cleavage in the Cabitza Formation and the Post-Sardic sediments support the field observations of a single cleavage. The cleavage seems to be developed from an initial compactional and diagenetic fabric which was more strongly developed in the argillaeceous Cabitza Formation than in the coarser grained Post-Sardic sediments. The nature of the cleavage is independent of its orientation and geometrical relationship to both fold systems, although its intensity varies. The microscopic features also indicate that different mechanisms are involved in cleavage

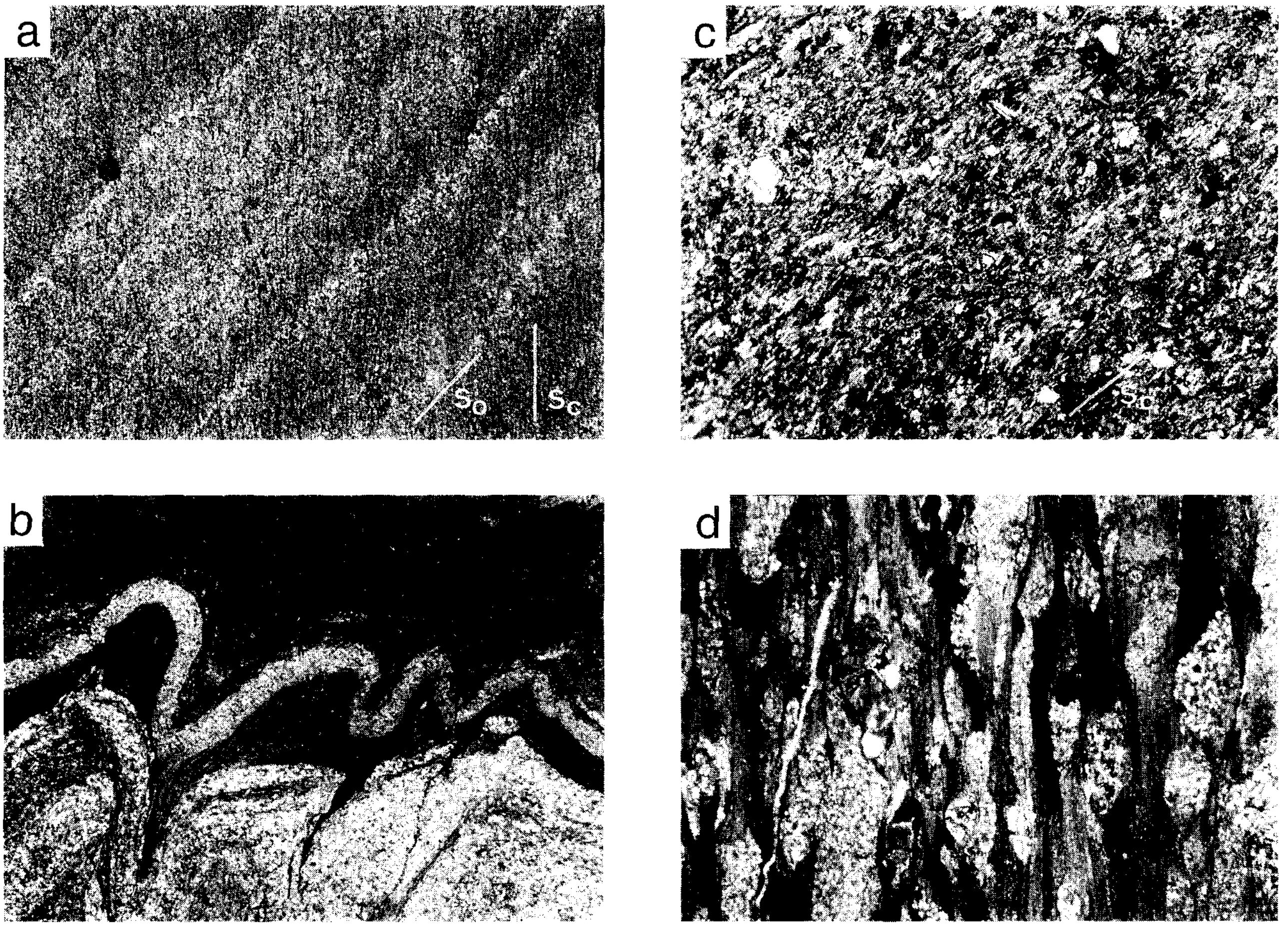

Fig. 7. Micrographs of (a,b) Cabitza Formation and (c,d) Post-Sardic sediments. Cleavage seams are either (a,c) regularly spaced and smooth, or (b,d) irregularly spaced and refracted either around sandstone buckle folds or around micro-pebbles. (s_0 = bedding, s_c = cleavage.) Long directions of photographs are (a) 30, (b) 20, (c) 30 and (d) 25 mm across.

formation including mechanical reorientation of grains, solution and recrystallisation processes.

Observations on the grain scale with Scanning Electron Microscopy (SEM) indicate that detrital phyllosilicate grains are mechanically reoriented by local micro-folding of grain clusters and by rigid-body rotation, kinking or bending of individual grains (Fig. 8a). The macroscopic cleavage plane coincides with the axial planes of the kinked crystals. The deformed phyllosilicates often show fine fissures in areas of stress concentration such as fold hinge zones which could indicate incipient solution processes. In these areas, oriented new phyllosilicate grains often grow along the axial planes of the kinks leading to the concentration of cleavage lamellae in domains. Detrital and newly grown grains could be distinguished not only by their geometrical arrangements in the fabric but also by their chemical characteristics such as iron-content and Fe/Mg ratio (as determined by micro-probe analyses).

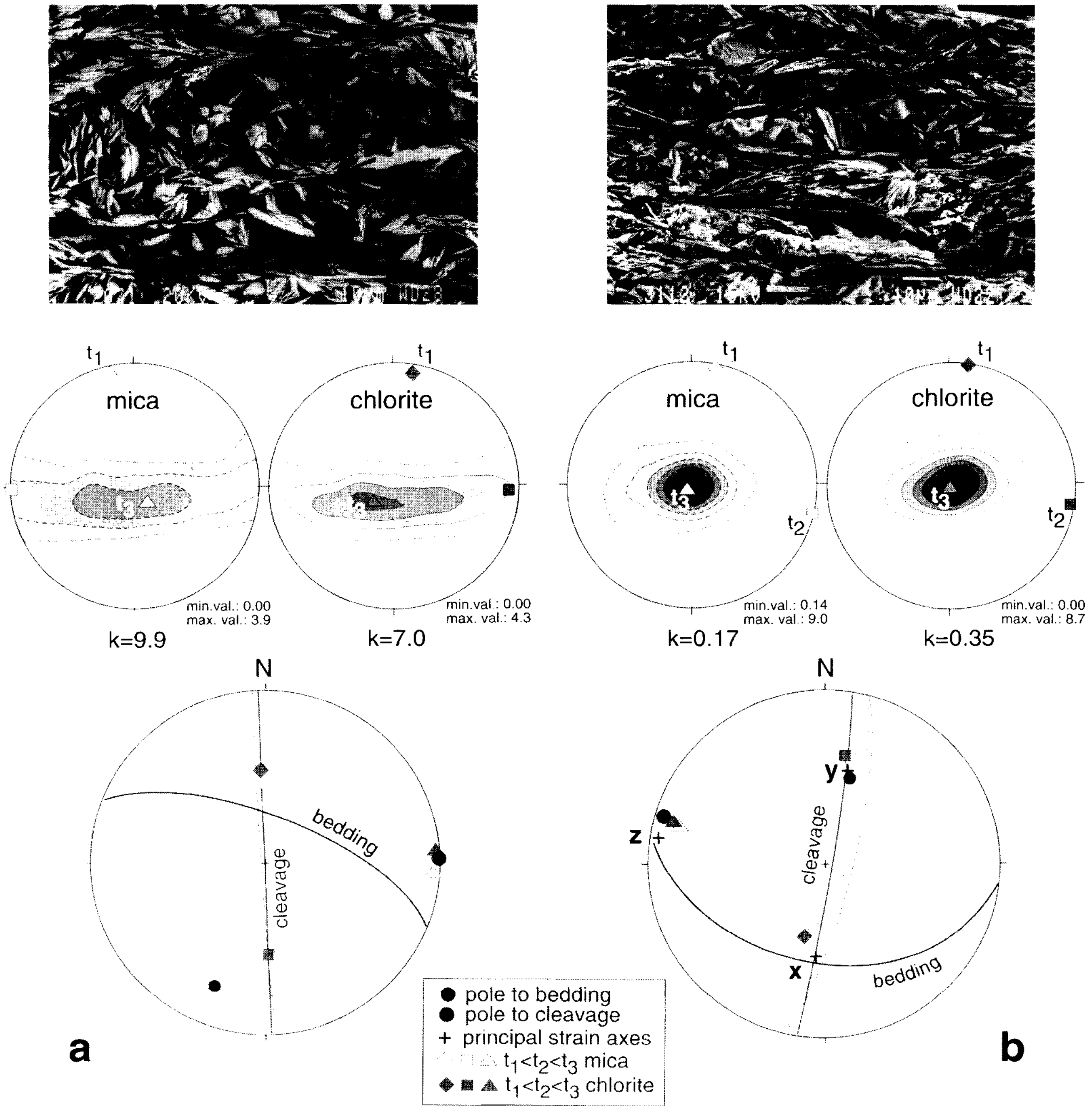

Fig. 8. SEM micrographs, phyllosilicate basal-pole distributions, and field data from two localities. (a) Kinking and micro-folding produce phyllosilicate pole girdles. (b) Grain growth produces a cluster with a strong point maximum. Fabric data have been rotated into geographic co-ordinates to compare with field data. ($t_1 > t_2 > t_3$ = eigenvectors, $x > y > z$ = strain axes, k = ellipsoidal shape factor.)

We suggest that the observed deformation mechanisms dominate during different stages in the progressive development of a cleavage. Mechanical processes are known to be active mainly in the early stages of cleavage development, in areas of less deformation and low metamorphic grade (Knipe and White, 1977; Knipe, 1981; Weber, 1981). We propose from our microstructural observations that chemical processes become more important than physical at higher strains, because micro-folding and kinking accommodate shortening up to a certain degree, and thereafter, progressive 'lock up' is reached (Ramsay, 1967, p. 444). The preferential new growth of phyllosilicates leads to new development and successive widening of the cleavage lamellae. In late stages of cleavage development the fabric is dominated by a strong preferred orientation of newly grown grains and locally preserved detrital grains (Fig. 8b).

The samples analysed by SEM show a wide range of microscopic features. Some samples are dominated by kinking and a weak preferred orientation whereas others are dominated by recrystallised grains and a strong preferred orientation. This also is reflected macroscopically in the regional variation of the cleavage intensity observed in the field. In order to quantify this we have measured the preferred orientation of the phyllosilicate grains by X-ray texture goniometry.

Slaty cleavage is mainly caused by the preferred orientation of platy phyllosilicate minerals. This preferred orientation can be statistically defined by measuring the orientation of phyllosilicate crystallographic planes with a X-ray texture goniometer (Siddans, 1976; Casey, 1981; Oertel, 1983; Lüneburg, 1995). The method is based on the diffraction of X-rays by crystallographic lattices which, in the case of phyllosilicates, are the strongly developed (00 l) basal planes which also dominate the shape of the grains. Therefore, the measurements provide not only a crystallographic but also a grain-shape preferred orientation. The data are represented as pole figures, which are developed by measuring the diffraction intensity in different orientations and contoured according to the density distribution of basal-plane poles (Fig. 8). By finding the eigenvalues and eigenvectors through numerical distribution analyses (Bingham distribution analysis) the three principal axes ($t_1 < t_2 < t_3$) are calculated which define the fabric ellipsoid.

Samples from the Cabitza Formation and the Post-Sardic sediments yield a wide variety of pole-figure patterns. In Fig. 8, two pole figures with contrasting distributions are shown as examples together with SEM micrographs of the same samples. Cluster distributions (Fig. 8b) or oblate fabric ellipsoids are characteristic of rocks that show a strongly developed macroscopic cleavage in the field. The point maximum or maximum principal distribution axis (t_3) of phyllosilicate basal plane poles always coincides with the pole to cleavage of the specimen. In contrast, the maximum principal axis (t_3) of girdle distributions (Fig. 8a) is poorly defined whereas the minimum principal axis (t_1) is well defined and coincides with the cleavage/bedding intersection measured in the field. The girdle distributions are characteristic of a weakly developed cleavage in the field.

We suggest that the pole-figure distribution patterns are indicative of the different stages of cleavage development described above. In girdle structures, the highest pole densities lie on the girdle and represent the limbs of micro-folds and kinks developed in early stages. The minimum principal axis (t_1) represents the rotation axis of the phyllosilicate grains (cleavage/bedding intersection). Increasing new growth of phyllosilicates leads to the development of a pole maximum (t_3) on the girdle until, with intense tectonic deformation, a sharp maximum (cleavage pole) may be reached (Fig. 8b).

The regional distribution of the pole figure patterns correlates with the cleavage intensity variation we observe in the field. In single folds, for example, the strongest preferred orientations occur in the fold limbs, whereas hinge regions show low intensities. In refolded folds the distribution of the pole figure patterns is more complex. In the refolded steep limbs of asymmetric folds, for example, the pole figures show mainly girdle structures with steep rotational axes. In moderately dipping refolded limbs the superposed folds dominate and the pole figures show cluster distributions with the maxima correlating with the cleavage observed in the field.

In addition to the fabric analyses, X-ray diffraction techniques have been used to determine the metamorphic grade by illite crystallinities. Mineralogical observations as well as the illite crystallinity data (Lüneburg, 1995) indicate that the conditions for cleavage formation were low grade (anchimetamorphic to lower greenschist facies) throughout the Variscan folding history. Illite crystallinities were measured on the $< 2\,\mu m$ fraction of mica. This fraction contains the newly grown grains (Kübler, 1968), as seen in the SEM analyses of the same samples. Samples with new grown grains, either parallel to the earlier or later folds, do not significantly differ in illite crystallinity.

STRAIN ANALYSIS

To determine the geometrical relationship between cleavage and strain, and to investigate the strain field associated with the fold interference pattern, finite strain measurements were made in rocks where appropriate strain markers were present.

We use the term finite strain, according to Ramsay (1967, p. 55), to describe the final state of strain observable in the rocks, as the end product of all deformation processes (Ramberg, 1959; Flinn, 1962). Other authors have introduced the term total strain to compare strain, accumulated during the entire deformation history, with strain (finite), that has accumulated at any moment of a progressive deformation (Schwerdtner, 1976; Wood and Oertel, 1980). This distinction is, however, often difficult to make since we can hardly reconstruct the complete deformation history of an area.

The most conspicuous strain markers are deformed pebbles in conglomerates of the Post-Sardic sequence, which can be directly observed in field outcrops (Fig. 5d) and locally reach metre size. Elongated reduction spots occur in siltstone horizons of the same sequence (Fig. 5c). They are ideal strain markers because they consist of material with the same mechanical properties as the surrounding matrix (Sorby 1853; Wood, 1974; Wood and Oertel, 1980), and the shape of the deformed spots directly represents the strain ellipsoid (Ramsay, 1967, p. 187; Lisle, 1994). Most strain data were obtained from samples of fine-grained conglomerates with average grain sizes from 1 to 4 mm (e.g. Fig. 7d). Strain analysis with this material has the advantage that image analysis can be applied to thin sections containing many markers in a small homogeneous field. The strain analyses are based on the R_f/ϕ-method, a technique which allows two-dimensional strain to be determined from initially non-spherical markers such as conglomerate pebbles (Ramsay, 1967, p. 202; Dunnet, 1969b; Dunnet and Siddans, 1971; Lisle, 1994). We, therefore, employed a graphical computer program, designed by Martin Casey (ETH, Zurich), which allows an interactive fit of the scanned strain data to a set of curves of certain initial shape (onion curves). Each curve represents the finite strain as a hyperbolic function of the orientation of elliptical markers when a particular tectonic strain is applied. In order to gain a representative result from these analyses we usually sampled 50–200 objects of the same material in each section.

Strains calculated from two-dimensional analyses of three suborthogonal sections were combined to define the shape and orientation of the three-dimensional finite strain ellipsoid (Ramsay, 1967, p. 121; Siddans, 1980; Ramsay and Huber, 1983, p. 167). Although the three sections were usually made parallel and perpendicular to the cleavage plane we tried to avoid any initial assumption for the orientation of principal axes or principal planes in our calculation. For this purpose we used the program TRISEC (Milton, 1980), which computes the finite strain ellipsoid from three arbitrarily oriented two-dimensional strains without initial assumptions for the orientation of the principal sections.

The orientation of the two greater principal strain axes is found from these calculations to lie always in the plane of the local cleavage. It does so throughout the entire fold interference pattern, even where the cleavage changes orientation. We therefore have used the cleavage, according to the results of our unrestricted strain analyses, to trace the strain trajectories in rocks without strain markers. The analysis also shows that the strain varies continuously and systematically through the two interfering fold systems from constriction to flattening (Fig. 9). This is also reflected by the cleavage which, although preserving a planar fabric, is less well defined in the constrictional than in the flattening strain field. Constrictional strain occurs mostly in domains of subvertical to downward-facing later folds, flattening strain mostly in domains of upward facing later folds (Fig. 10). These different domains coincide in turn, with the overturned and normal limbs of the early folds, respectively.

We suggest that the strain pattern is complex because it depends on the interaction of two strain fields, both highly variable. This implies not only a variable strain but also variable rotations (e.g. Ramsay, 1967, p. 121; Hobbs *et al.*, 1976, p. 31, or any textbook on continuum mechanics). When two strains follow each other, the strain tensors are matrix-multiplied. The resulting displacement gradient tensor is no longer symmetric and thus implies not only strain but also rigid body rotation.

In order to test whether the regional finite strain pattern could be caused by the superposition of two strain fields associated with the two folding events, numerical simulations were performed. For the modelling we cumulated the deformations of two separate foldings, obtained by buckling experiments in multilayered finite element models (Lebit and Casey, 1995). Each folding represents a mechanical amplification of transversely isotropic materials (Biot, 1961; Cobbold, 1976) and is comparable to flexural flow folding, which coincides well with our field observations. The numerical

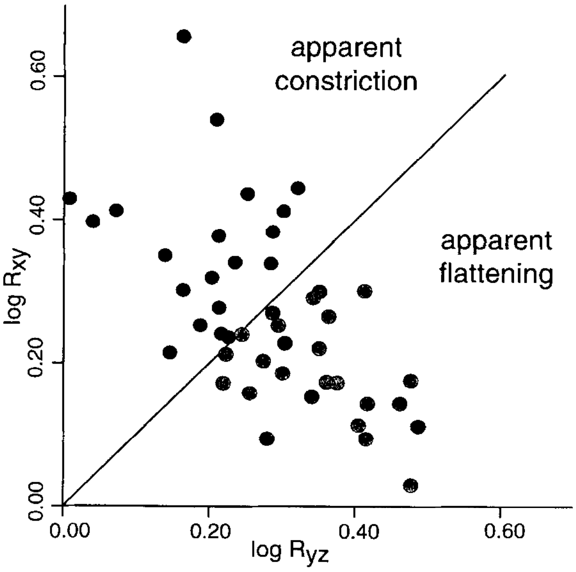

Fig. 9. Logarithmic Flinn diagram of finite strain measured at different locations in the fold interference pattern. Strain ellipsoids range from prolate (constriction) to oblate (flattening), given by the ellipsoid shape factor $k = \log R_{xy}/\log R_{yz}$ (Ramsay and Huber, 1983, p. 178).

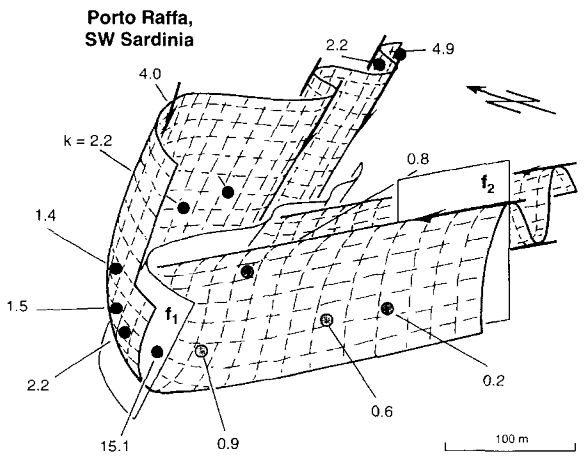

Fig. 10. Porto Raffa fold. Sketch of a refolded fold in Post-Sardic sediments of the *coastal area* (see Fig. 3 for location). Shape and orientation of the strain ellipsoids vary from the steeply to the gently dipping limb. The cleavage plane follows the XY-plane of the strain ellipsoid. (k = ellipsoidal shape factor.)

fold interference pattern is the result of superposing two sets of perfectly cylindrical folds and does not, therefore, consider the mechanical influence of the pre-existing layer curvature. The final three-dimensional state of finite strain is calculated by diagonalisation of the positively defined symmetric decomposition of cumulated nodal velocity gradient tensors (e.g. Cobbold and Percevault, 1983). The final topography of the refolded layers is obtained by summation of the corresponding displacement vectors.

When the folds are arranged as in the mapped interference pattern (suborthogonal type II fold superposition) the computed strain pattern resembles cleavage/strain orientations and strain magnitudes obtained by our measurements. Figure 11 illustrates the excellent coincidence in calculated XY-plane of finite strain (a) and cleavage (b), by their contoured pole figures. The spatial variation of the finite strain orientation also resembles well the sigmoidally curving cleavage trajectories in the field (Figs 3 & 6). The fluctuation of calculated ellipsoidal strain shapes correlates with their measured counterparts as it is shown in Fig. 11(c) and (d) by logarithmic Flinn-diagrams. Comparisons of finite strain shapes between locations in the numerical model and the observed fold interference pattern yield further similarities. Both form equivalent distribution patterns, characterised by flattening in the gently dipping limb of the earlier fold system and constriction in the overturned limb as it is demonstrated by the natural example of Fig. 10.

SUMMARY AND DISCUSSION

The results of our field and analytical investigations have significant implications for the interpretation of tectonic regions and their deformation histories. They also provide new insights into ongoing debates on cleavage development in complex deformation histories and its relationship to finite strain, and raise new questions regarding the behaviour of fabric during non-coaxial deformation.

The most important result from our studies in Southwest Sardinia is that a single penetrative cleavage is developed during the generation of two fold sets, and is related to both of them. The well exposed interference pattern in the low-grade metamorphic Cambro-Ordovician rocks consists of early E–W-trending folds refolded by N–S-trending folds. Cleavage orientation changes locally from north–south to east–west directions, resulting in sigmoidally curving cleavage trajectories. Thus, cleavage is locally parallel to the axial planes of both fold systems or transects them, so that it cannot be unambiguously related to either of the fold sets. Instead, we suggest that the cleavage is related to the state of finite strain, that is always perpendicular to the direction of principal finite shortening.

The singularity of the cleavage is supported by microscopic studies, which show no evidence of a pre-existing tectonic cleavage or any later overprinting, such as newly formed crenulation cleavage. Electron microscopy shows that phyllosilicate preferred orientation is achieved by rotation, kinking, or micro-folding of detrital grains and by preferential growth of new grains parallel to the cleavage plane. As slaty cleavage develops, it is suggested that mechanical accommodation mechanisms give way to chemical processes with increasing shortening. These deformation mechanisms are reflected in the pole-figure patterns obtained from X-ray texture goniometry, in which the statistical distribution of the phyllosilicates is measured. The patterns indicate the local stage of cleavage development which varies in the interference pattern.

Finite strain analyses of deformed pebbles and reduction spots vary statistically from flattening to constriction. This variation is systematic throughout the fold interference pattern, showing strong correlations of constrictional and flattening strain domains with certain geometrical arrangements of fold superposition. Similar to the cleavage orientation, strain in the interference pattern depends on the local strength of both folding phases. This suggests that the cleavage orientation is a function of the relative degree of deformation caused by the two folding events. Where strain caused by one fold set is dominant, cleavage orientation approximates its axial plane; where neither is dominant the cleavage orientation is intermediate between the two axial planes (Fig. 12a). On a regional scale, the heterogeneous strain shows the same interference pattern we obtain by superposing folds and their associated deformation fields numerically (Fig. 11). The trace of the XY-plane in the numerical models simulates well the sigmoidally curving and transecting cleavage in the field.

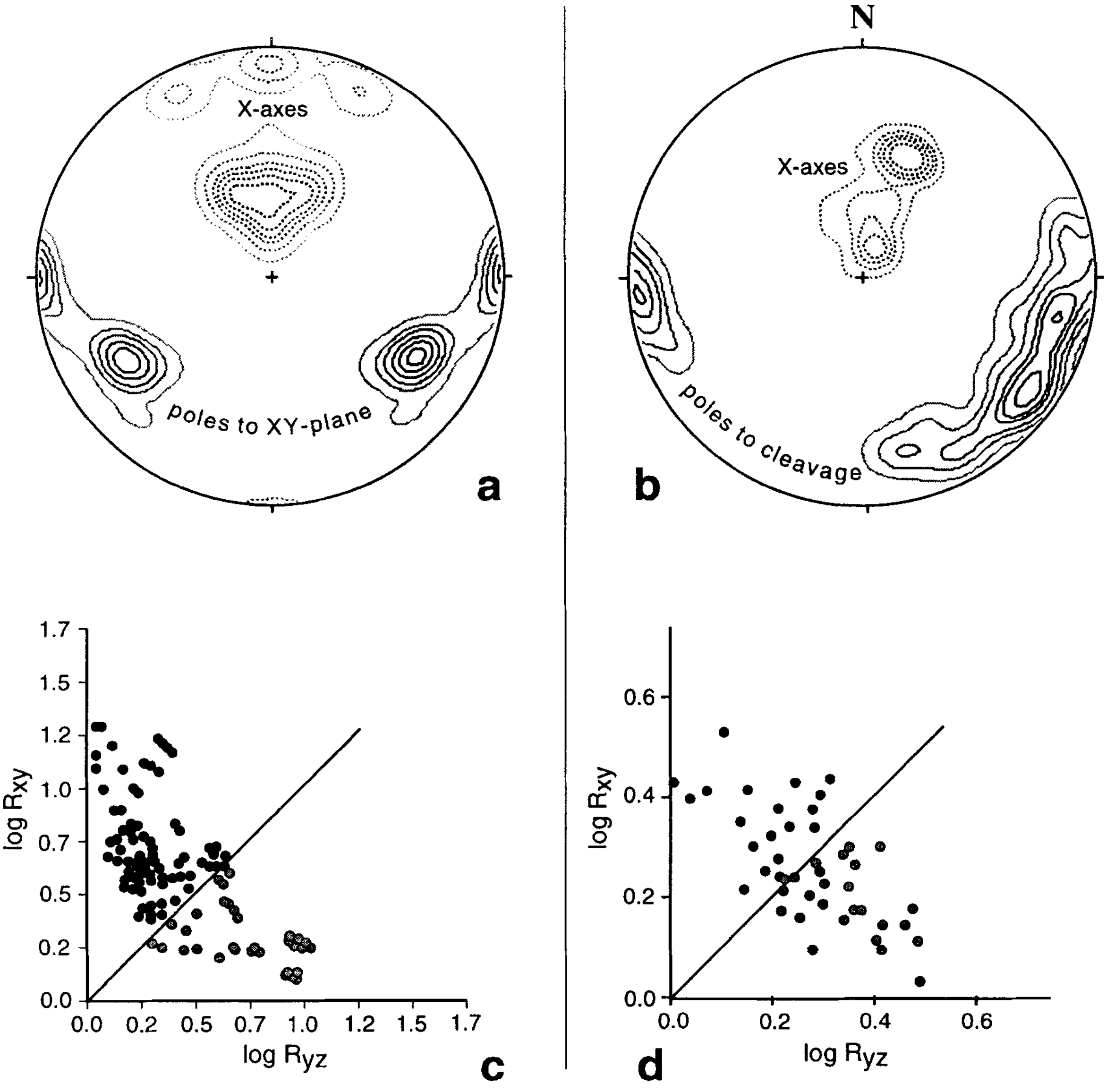

Fig. 11. Comparative equal-area projections and logarithmic Flinn diagrams of populations of finite strains. (a,c) From a numerical model of superposed folds and the cumulative strain field. (b,d) From an observed fold (Porto Raffa fold, Fig. 10). Note the similarities in principal strain orientations and the distributions of strain ellipsoid shapes.

Different hypotheses to explain the appearance of a single cleavage in multiply deformed rocks are discussed below.

Many workers in Southwest Sardinia have assumed that only one of the folding phases developed a penetrative cleavage. They assign this cleavage to the second Variscan deformation phase, concluding that the first Variscan phase, as well as the Sardic phase, did not develop a penetrative fabric (Dunnet, 1969a). This is a common explanation, used also in other regions where the number of cleavages does not reflect the number of folding events. However, it seems very unlikely that only one of the folding episodes developed a cleavage, since both fold systems show similar deformation intensities, metamorphic grades, and folding mechanisms. Especially in pelitic material, a shortening of 30% is considered sufficient to produce a macroscopic fabric (e.g. Cloos, 1947). By fold length measurements we estimated the shortening components for each of the two fold systems in the Cabitza Formation to be approximately 40–60%, or higher.

Our mapping shows that the single cleavage in the region is locally axial planar with respect to either fold generation. This has indicated to some workers that both fold systems developed their own cleavage (Arthaud, 1963; Poll, 1966). In this case, we would expect cross-cutting relationships of two cleavages, at least in critical locations within the fold interference pattern. We never encountered such a relationship although we mapped at scales ranging from 1:10 to 1:10,000 and completed detailed micro-fabric investigations. What we did find, at all scales, is the same slaty cleavage smoothly curving from the axial plane

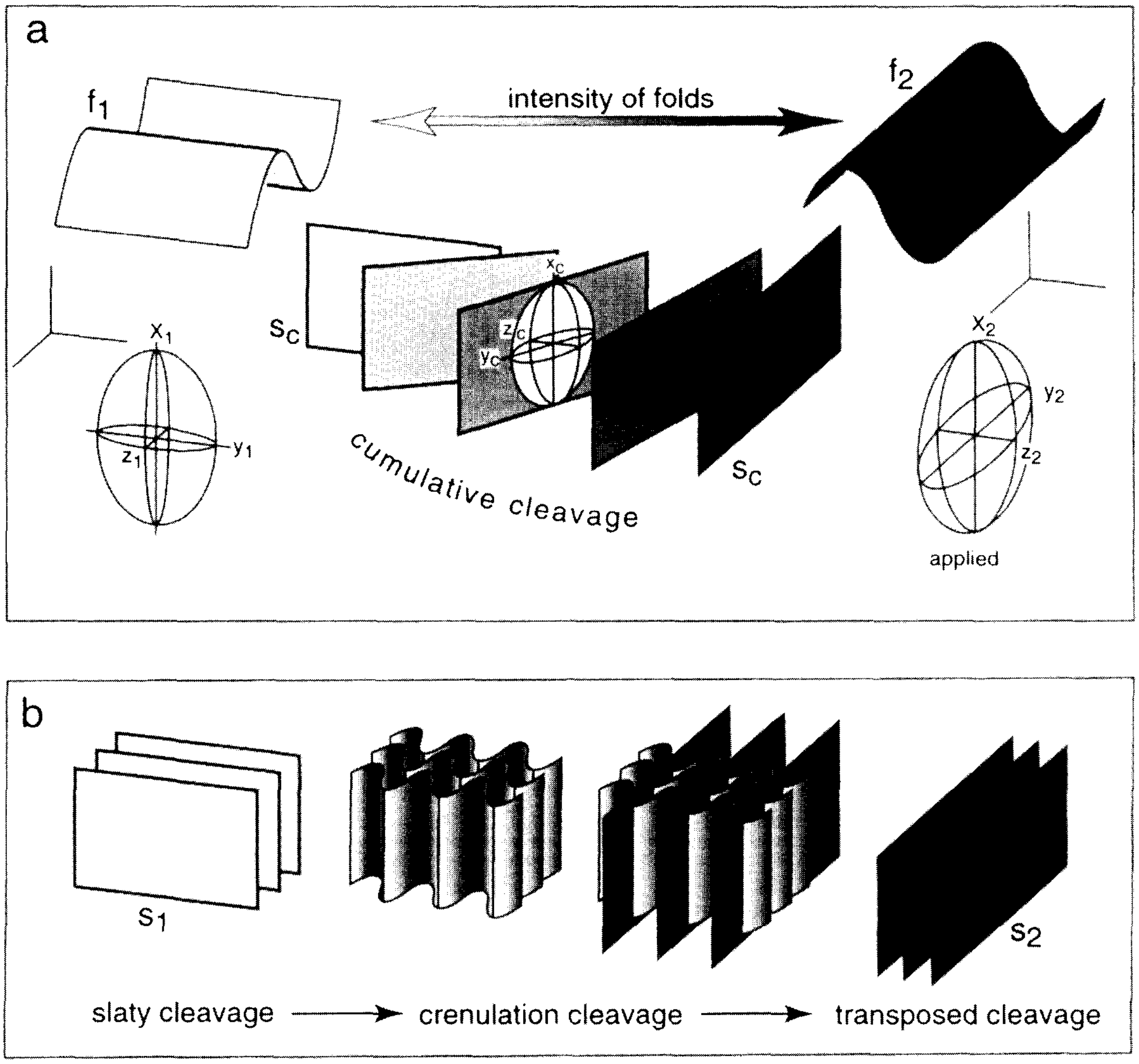

Fig. 12. Schematic illustration of different concepts of cleavage behaviour in polyphase deformation. (a) Cumulative cleavage (s_c) reflects the heterogeneous strain field resulting from the superposition of the different foldings (f_1, f_2). Local cleavage orientation is a function of the relative intensity of both foldings. (b) Transposed cleavage (s_2) forms by progressively deforming (crenulating) an already existing cleavage (s_1).

of the early fold system to that of the later one (Figs 3 & 6).

Another possibility is that the first phase cleavage might not be observable in the field, either because it was completely transposed into a new, second cleavage (Fig. 12b), or because it developed (sub-)parallel to the bedding plane. The latter hypothesis can be ruled out, because subparallelism of cleavage and bedding requires strong layer-parallel shearing on the fold limbs, such as would occur in isoclinal folds or by a flexural slip mechanism. However, folds of the first set are not isoclinal (Fig. 10) and the layer composition does not contrast strongly enough to concentrate flexural slip shearing in the limbs (Figs 5 & 7). In addition, an early cleavage should be evident in the first-phase fold hinges, where the cleavage is expected to be perpendicular to the bedding. Although we found this to be the case in earlier hinges, the cleavage does not become subparallel to bedding in the limbs. Nowhere did we observe transposition of this cleavage by a later deformation. Transposition of the first cleavage can be ruled out by the micro-structural analyses, which demonstrate that cleavage always developed from a bedding plane defined by detrital grains. For instance, in pelitic sediments, a compactional fabric parallel to bedding is manifest by some alignment of detrital grains. This has led to speculation that a first-phase cleavage might have been preserved in early fold hinges, which resisted later deformation, and was not overprinted by the second cleavage. In such a case cleavage should be seen to be overprinted in the limb regions instead of changing orientation to become subparallel to the axial planes of the later folds.

As yet another possibility, we considered whether refolding could passively reorient a first-phase cleavage. This certainly would cause complex geometries, but not transections of the axial plane by the cleavage, as frequently observed. Initially parallel lines such as cleavage/bedding intersections and fold axes can become non-parallel due to heterogeneous deformation, but they cannot cross each other. It also seems unrealistic to assume that a first cleavage was refolded without being transposed into a second one. As outlined before, there is no reason why one of the folding events should be associated with a cleavage and the other not, considering that both fold generations produce similar degrees of regional shortening under similar metamorphic conditions.

All these considerations lead us to conclude that the single cleavage results from the combination of both folding events and that its orientation depends on the relative intensity of the participating fold deformations (Fig. 12a). In areas of intensive first-phase fold deformation and minor second-phase folding, cleavage orientation approximates the axial planes of the early folds. In areas dominated by the superimposed fold deformation, cleavage becomes nearly parallel to the axial planes of the late folds. Between these two end-members, cleavage orientation is intermediate, transecting the axial planes of both fold sets (Fig. 12a). Thus, cleavage is a cumulative fabric reflecting the total deformation arising from the superposition of the two fold-related heterogeneous finite strain patterns. This interpretation is supported by the strain determinations in the Post-Sardic sediments, where cleavage is indistinguishable from the XY-plane of the strain ellipsoid. The shape of the strain ellipsoid fluctuates between flattening and constriction, forming a pattern which we simulated by numerical superpositions of fold-related strains.

This conclusion has significant implications for the interpretation of deformation histories in multiply deformed regions, particularly the use of cleavage/fold relationships to distinguish deformation phases. It shows that cleavage and folding are not unambiguously related to individual phases of deformation and can reflect different time segments of the deformation history. The proposed concept also offers new views on structural development in progressive deformation, cleavage transected folds and complex deformation histories in general.

One possible scenario explaining our results would be that both fold systems formed synchronously in an overall compressional environment. The resulting constrictional bulk strain would, however, not favour the formation of any planar fabrics or any preferred fold axial orientations such as N–S- and E–W-trending folds. Analogue experiments under similar conditions were performed by Ghosh and Ramberg (1968) and have shown the mutual refolding of folds resulting in a complex crumpling of the layers. Our analysis of the fold interference pattern (Figs 3 & 4) indicates that in Southwest Sardinia a north–south-trending fold system always refolds initially east–west-oriented folds. Although it is not possible to determine the difference in time between the folding events we assume successive fold formation in a progressive deformation regime. This assumption is primarily based on the fact that the metamorphic conditions remained the same throughout fold superposition. Under such deformation conditions we suggest that cleavage might form continuously, in contrast to folding which becomes evident only where bedding attitudes are favourably oriented to the shortening direction. If cleavage began forming during the first folding it must have been continuously modified during the superposition by the second folding, reflecting the changing cumulative strain field (Fig. 12a). Modification of the fabric was, however, not homogeneous due to the heterogeneity of fold deformation. In places where second fold deformation was minor the fabric remained in an axial planar geometry to the first folding. In places where the later fold deformation was dominant the fabric was modified towards an axial planar geometry of these folds. In between, all transitions are possible leading to fabrics transecting both fold sets. This includes also the total lack of a planar fabric in places where the component fold deformations possess equivalent shortening components in an orthogonal arrangement.

The proposed model of cumulative fabric and strain will provoke new discussions on the controversy of fabric development in a non-coaxial deformation history. It also raises a fundamental question of how cleavage can remain co-planar to the XY-plane of finite strain in rocks that underwent a complex deformation history. The discussion often focuses on the question of whether cleavage behaves passively or actively during progressive deformation. One group of investigators claims co-planarity of cleavage and the principal plane normal to finite shortening strain (e.g. Sorby, 1856; Harker, 1886; Cloos, 1947; Ramsay, 1967; Ramsay and Graham, 1970; Siddans, 1972; Treagus, 1983, 1985). This is based on numerous structural analyses where finite strain markers parallel the cleavage, as well as on theoretical considerations on cleavage refraction. It also requires that cleavage behaves as an active non-material plane during deformation.

Another group of investigators denies such behaviour and states that cleavage develops immediately as a material plane during an ongoing deformation process (e.g. Williams, 1977; Hobbs *et al.*, 1982; Wright and Henderson, 1992). Hence, subsequent reorientation of the cleavage is treated as a passive marker which deviates from the principal finite strain orientation (Bayly, 1974). It is argued that this deviation is no more than a few degrees, which is commonly below the angular resolution of structural analysis (Williams, 1976; Ghosh, 1982). Such small differences between passively reoriented markers and finite strain are observed when homogeneous simple shear is considered. Where the deformation is more complex, the angular deviation is expected to be significantly larger (e.g. Hobbs *et al.*, 1982). However, in the superposed fold system of Southwest-Sardinia we never detected such angular differences. Where cleavage and strain markers are present, cleavage orientation always corresponds with the flattening plane of the finite strain ellipsoid.

Therefore, the critical question, pointed out for example by Hobbs *et al.* (1982), concerns the reorientation mechanisms which are able to adjust cleavage constantly to the state of finite strain. Although cleavage appears in the field as a material plane, it was not necessarily one when the rocks were subjected to deformation. Fissility planes and weathering of the rocks may preferentially propagate in the direction of the fabric anisotropy but these are secondary effects and post-date the actual deformation (Durney and Kisch, 1994). As our fabric analyses have shown (Fig. 8), cleavage represents mainly a fabric anisotropy determined by the final preferred orientation of certain minerals, rather than a material plane (Siddans, 1976; Oertel, 1983). Under these circumstances, the cleavage plane appears as a statistical property, reflecting an average of the entire fabric. In order to keep this statistical average parallel to the XY-plane of finite strain the fabric modification processes as identified in our micro-structural analyses must be efficient enough. However, this controversial subject needs further consideration, which we will present in a forthcoming paper on our studies of cleavage and fabric development.

CONCLUSIONS

Throughout a group of refolded low-grade metamorphic Palaeozoic sediments in Southwest Sardinia, a single cleavage reflects their cumulative strain. We suggest that this single cleavage results from the temporal superposition of the heterogeneous deformation fields associated with two Variscan folding episodes. Everywhere in the fold interference pattern the slaty cleavage tracks the XY-plane of the finite strain cumulated during this superposition. Therefore, cleavage is not simply related to either fold system and changes in orientation from close to the local axial plane to transecting it.

We conclude that cleavage can reflect the finite strain even in multiply deformed rocks which have undergone a progressive deformation history with changing overall shortening direction and repeated folding, but more or less constant metamorphic conditions. This finding can be generalised in the interpretation of other tectonic areas and reconstructions of deformation histories. Therefore, strain sensitive structures, such as cleavage or fold geometry, cannot always be used to separate hypothetical deformation phases. Cleavage can express the cumulative strain even where the kinematics change through time.

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