Formation of spaced cleavage and folds in brittle limestone by dissolution

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ABSTRACT

Mesozoic pelagic limestones in Umbria (northern Italy) were deformed by Miocene-Pliocene flexural slip folding under 1 to 2 km of cover; there are no signs of metamorphism. Under these conditions the deformation was brittle, as indicated by extension veins and by foraminifera that show no measurable distortional strain. Nevertheless, the limestone is often tightly folded; the folding mechanism combined dissolution of limestone along stylolites subparallel to fold axes with deposition of sparry calcite in extension veins normal to the stylolites. Thus, at the scale of a hand specimen, deformation occurred through rigid-body displacements, but e-twinning in the vein calcite shows a minor component of distributed strain. Spaced cleavage on the limbs of major folds also formed by dissolution. This is shown by (1) the presence of insoluble residues on the cleavage surfaces, (2) imbrication of insoluble chert nodules that indicates tens of percent shortening parallel to bedding, (3) deflection of cleavage away from strain shadows protected by chert nodules and toward places where the nodules have been telescoped, and (4) offsets of bedding at bedding-cleavage intersection that resulted from removal of limestone by dissolution along the cleavage surfaces.

INTRODUCTION

The literature of structural geology is rich in studies of limestones that have been folded while in a ductile condition. In recent years, however, a few papers have appeared that describe folding of limestone under brittle conditions. These include the studies by Dunnington (1967), Choukroune (1969), Carannante and Guzzetta (1972), and Groshong (1975a, 1975b). Brittle folding proceeds through solution and removal of calcium carbonate along stylolites; this permits a large body of rock to change its shape, although there is no shape change within the small volumes of rock bounded by discrete stylolite surfaces. The term "pressure solution" is often used for this process, but because it is not clear whether compressive stress across the stylolite actually facilitates removal of $CaCO_3$ in solution or merely keeps the suture closed, the more neutral term "dissolution" is to be preferred.

In this paper we document another occurrence of brittle folding in limestone. In this case, as in that described by Carannante and Guzzetta (1972), some or all of the $CaCO_3$ removed from the stylolite surfaces has been redeposited in extension veins. In addition, we show that spaced cleavage in limestone can also be produced by dissolution. It may be that this is the mechanism by which many examples of "fracture cleavage" have formed. The observations reported here support the suggestion of Burger (1974) that "pressure solution" is probably much more important in rock deformation than has generally been realized.

The formation studied is the Scaglia rossa, a pink, pelagic, foram-coccolith limestone that represents the Upper Cretaceous to middle Eocene part of the miogeosynclinal sequence of the Umbrian Apennines of northern peninsular Italy. The Scaglia rossa has been the subject of a number of recent paleomagnetic studies (references in Alvarez and others, in prep.). Although there have been no major sedimentological studies of this formation, some information can be found in Bortolotti and others (1970; also M. A. Arthur and A. G. Fischer, in prep.).

Minor folds are abundant in the Scaglia rossa of the Umbrian Apennines; some examples have recently been described by Fazzini (1973). These folds appear to have formed by a variety of mechanisms. Some are clearly due to soft-sediment slumping; others formed when portions of the section came loose from their substratum along décollement horizons in the more shaly layers and slid down the flanks of the rising anticlines. Still other folds have distributions, profiles, and orientations that indicate that they are parasitic folds (De Sitter. 1958) on the flanks of major anticlines. It is in these parasitic folds that we have found evidence for brittle folding. On the flanks of other major anticlines we have found examples of spaced cleavage also produced by dissolution.

BRITTLE FOLDING

Figure 1 shows a small syncline in the Scaglia rossa. It is part of a train of parasitic folds on the southwest flank of a major anticline that is overturned toward the northeast (locality: Gola delle Fucicchie, km 218.46 on the Via Flaminia, between Scheggia and Cantiano). In gross outline the bedding passes smoothly around the hinge of the fold, but in detail the smoothness is interrupted by breaks and offsets of the bedding, so that the general effect is rather blocky and irregular.

The Scaglia rossa is rich in foraminifera that should make excellent strain markers. However, foraminifera in thin sections cut from a sample in the core of the fold are untwinned and show no measurable distortional strain (Fig. 2, a), which indicates that, although the rock is folded, the limestone did not suffer any measurable penetrative ductile deformation. This agrees well with what we can infer about the conditions at the time of deformation. There is no sign of metamorphism in the limestone, and stratigraphic thicknesses given in the literature indicate that deformation occurred under 1 to 2 km of overburden. Experimental deformation of another fine-grained carbonate unit, the Solenhofen limestone (Rutter, 1972, Fig. 1), indicates that rocks like the Scaglia rossa limestone should fail by brittle fracture at effective confining pressures equivalent to depths of 1 to 2 km under a normal geothermal gradient and at strain rates down to at least 6×10^{-7} sec^{-1}. This agrees with the absence of distortion in the foraminifera.

The brittle folding of the Scaglia rossa limestone seems to have occurred through a mechanism that involved removal of $CaCO_3$ through dissolution on stylolite surfaces subparallel to the axial surface (Fig. 2, b and c), combined with redeposi-

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tion of at least part of the dissolved material in extension veins whose plane is oriented roughly normal to the stylolites and contains the axial direction (Fig. 2, d, e, and f). Through this mechanism a body of rock some metres on a side may undergo the changes in shape required by folding, but all the deformation occurs by loss and addition of material on the discrete stylolite and vein surfaces, respectively, while the millimetre- to centimetre-scale bodies of rock bounded by these surfaces remain completely undeformed.

From features observed in the folded limestone we can obtain partial information on the deformation processes that occurred during folding. It is important, however, to recognize clearly which aspect of the deformation is being studied in each case. The rocks involved in the folding have undergone an inhomogeneous strain on the scale of a single parasitic fold. On a smaller scale, it is misleading to speak of strain in hand specimens or thin sections; at this scale the deformation occurred by translations and rotations of rigid bodies of limestone bounded by discrete surfaces where $CaCO_3$ was removed or deposited. Observations on stylolites and veins thus offer information on rigid-body displacements. In addition, we can learn something of local strain orientations by study of e-twins in calcite crystals filling the extension veins.

There is strong evidence that stylolites are sutures formed by removal of soluble rock material (Stockdale, 1943), and the alignment of columns and pits on the irregular stylolite surfaces has been used as an indication of the orientation of the maximum compressive stress during the formation of the stylolite (Arthaud and Mattauer, 1969, 1972; Plessmann, 1972; Schäfer, 1974). Although this is probably correct in many cases, it would be more accurate to say that the axes of the roughly conical pits and columns give the direction of the last increment of rigid-body convergence, while the amplitudes of the pits and columns give a minimum value for the amount of convergence. The orientation of the highly irregular surface itself is less significant. The stylolites in the Scaglia rossa folds are seen in thin section as serrated sutures marked by clay selvages that are clearly accumulations of insoluble residues. The overall trend of the stylolite surfaces is roughly parallel to the axial plane of the fold, but more importantly, the axes of the pits and columns—seen as serrations in cross section (Fig. 2, c)—are aligned perpendicular to the axial plane. It is common to find forams that have been partially consumed by solution on a stylolite (Fig. 2, g). The smaller stylolites often die out in one direction or show en echelon offsets. Stylolites along which greater amounts of limestone have been removed, as shown by greater accumulations of insoluble residues, seem to have less markedly serrated contours (Fig. 2, b). We suspect that local solubility differences in the limestone on opposite sides of the stylolite cause the serration and that these differences become less important as the much less soluble clay selvages build up, so that the surfaces become smoother. Incipient stylolites do not noticeably weaken the rock, but stylolites with thick

Figure 1. Parasitic fold examined in this study. Location of sample illustrated in Figure 2 is circled.

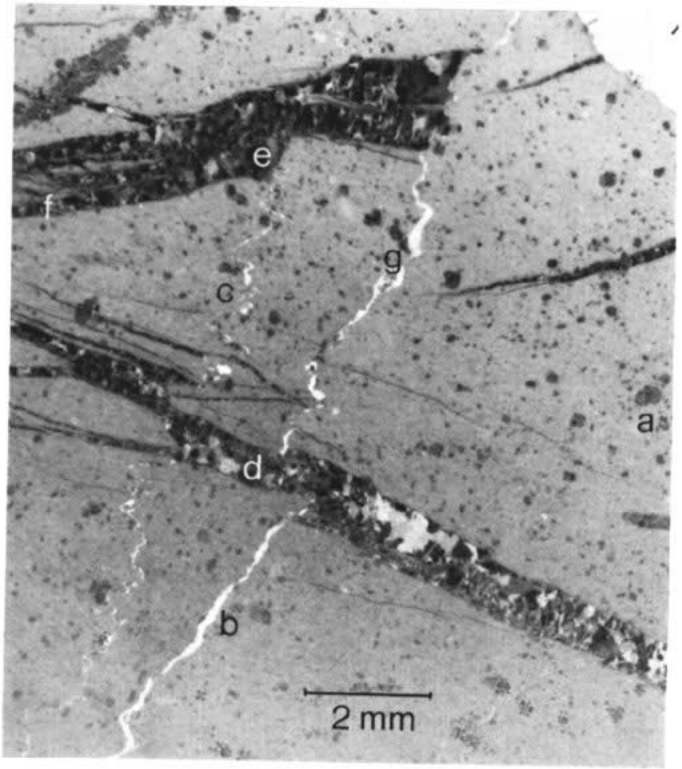

Figure 2. Thin section from core of fold in Figure 1. This is a negative photograph under crossed nicols; therefore, clay selvages along stylolites, which are roughly parallel to the axial plane of the fold, appear white. Letters refer to text.

clay selvages divide the beds into independent blocks that are responsible for the blocky appearance of the fold in Figure 1.

The extension veins are filled with sparry calcite, occasionally in fibers growing normal to the vein walls, but more commonly in blocky crystals. Both fibrous and blocky crystals tend to have their optic axes oriented normal to the vein walls; this agrees with the observations of Durney and Ramsay (1973) on calcite-filled extension veins elsewhere. The crystals of vein calcite contain many e-twin lamellae that clearly formed in response to differential stress during folding. Preliminary dynamic analysis of the calcite twinning indicates that the direction of maximum finite shortening was oriented roughly normal to the axial plane, but the strong preferred orientation of the calcite crystals reduces the utility of this method.

The temporal relationships between stylolites and veins are often complex, with several generations of crosscutting structures. This suggests that as the fold grew, the deformation was accommodated by a succession of stylolites and veins. Durney and Ramsay (1973) have shown how, during progressive deformation, an extension vein may become so rotated that it is no longer favorably oriented to accommodate the strain, and then a new vein will form; this process occurred with both stylolites and veins during brittle folding of the Scaglia rossa. A further complication is introduced by bedding planes, which in the Scaglia rossa have been exaggerated due to dissolution during compaction prior to the folding (M. A. Arthur and A. G. Fischer, in prep.). The bedding planes are marked by clay selvages, and in the hinge regions of the folds these planes of weakness are favorably oriented to become extension veins. It is thus common to find calcite-filled veins containing broken-up portions of the clay selvages that originally marked the bedding. Flexural slip along bedding planes was often accompanied by the growth of fibrous calcite with the fibers oriented at a small angle to the bedding planes.

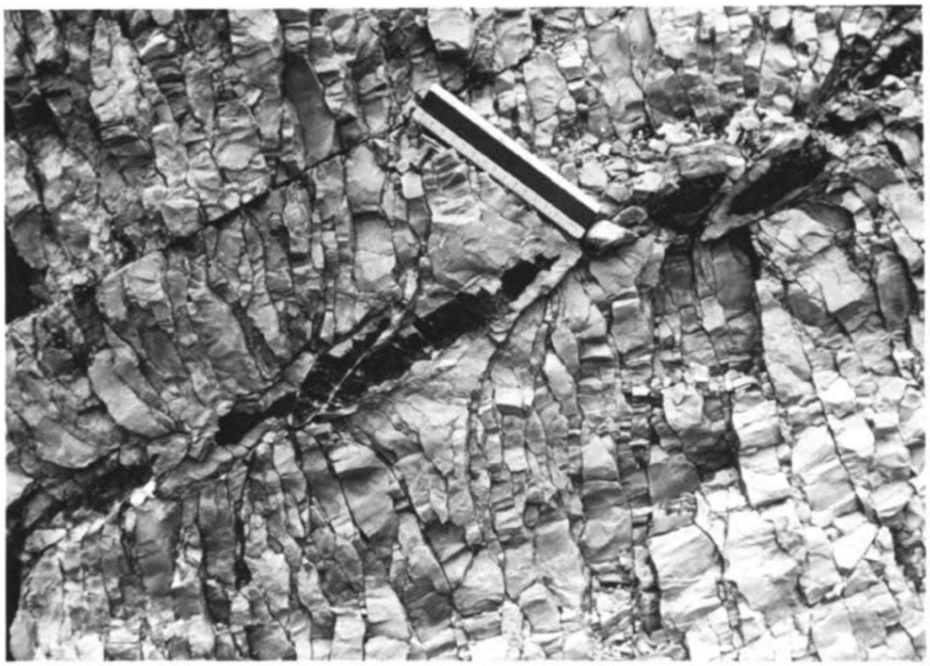

Figure 3. Spaced cleavage in Scaglia rossa dips steeply to the right in this photograph. Bedding dips gently to the left and is marked by a horizon of chert nodules with dark cores and lighter rims. Ruler is 15 cm long. Origin of the cleavage through dissolution is shown by imbrication of chert nodules and by convergence of cleavage surfaces toward points where nodules have been telescoped.

SPACED CLEAVAGE

In addition to the evidence that dissolution plays a role in brittle folding of limestone, the Scaglia rossa provides evidence that dissolution can produce a well-developed and widespread spaced cleavage. A similar conclusion was reached by Nickelsen (1972) and Geiser (1974) for examples of spaced cleavage observed in limestones, mudstones, and siltstones in the folded Appalachians of Pennsylvania and Maryland.

Of the various kinds of cleavage observed in folded rock sequences, spaced cleavage is perhaps the least understood. There is a voluminous literature on slaty cleavage, recently summarized by Siddans (1972) and Wood (1974). This type of cleavage is manifested by the parallel alignment of phyllosilicates, and is generally thought to form perpendicular to the axis of maximum finite shortening strain.

Spaced cleavage (Dennis, 1967) is more difficult to explain, for it consists of numerous discontinuity surfaces bounding undeformed slabs of rock and is oriented subparallel to the axial planes of associated folds, often with a fanning arrangement. In trains of buckle folds the axial planes should be oriented roughly perpendicular to the direction of maximum overall shortening; this is not the orientation one would expect for closely spaced fractures, which normally indicate extension rather than shortening. The commonly used term "fracture cleavage" thus entails a genetic interpretation that is probably incorrect and should be replaced by the descriptive term "spaced cleavage."

In the Umbrian Apennines, spaced cleavage is commonly found in the Scaglia rossa limestone on the moderately dipping flanks of the major anticlines (Fig. 3). Four lines of evidence lead us to the conclusion that this spaced cleavage is the result of dissolution related to shortening in a direction roughly normal to the axial planes of the folds.

1. The cleavage surfaces are invariably coated with a film of reddish clay. In the case of the more marked cleavage surfaces, the clay could have been washed into an open fracture, but we have broken open many of the cleavage surfaces, and no matter how incipient and tightly sealed the cleavage surface, a film of clay is always present. We conclude that these clay selvages are accumulations of insoluble residues and that the cleavage was formed by dissolution; spaced cleavage thus appears to be of stylolitic origin.

2. Beds of chert and horizons of chert nodules are common in certain intervals in the Scaglia rossa. In undeformed outcrops chert nodules are strictly confined to precise stratigraphic horizons; they are never randomly scattered, overlapping, or imbricated. These relatively insoluble portions of the unit provide an excellent marker by which the shortening of the limestone parallel to bedding may be evaluated. At all localities where we have observed spaced cleavage in portions of the Scaglia rossa that contain chert nodules, these nodules have been thrust one over another into an imbricate pattern (Fig. 3). This clearly shows shortening parallel to bedding, which was accommodated by dissolution of $CaCO_3$ on spaced cleavage surfaces in the limestone and by imbricate thrusting in the layers of chert nodules. Only minimum values of shortening can be calculated, because the original separation between adjacent nodules is not known, but as an example, the minimum shortening

Figure 4. View of a bedding plane in the Scaglia rossa showing offset produced by dissolution along spaced cleavage surfaces. This mechanism for producing offset bedding is shown schematically by Groshong (1975a, Fig. 4B) and in Figure 5.

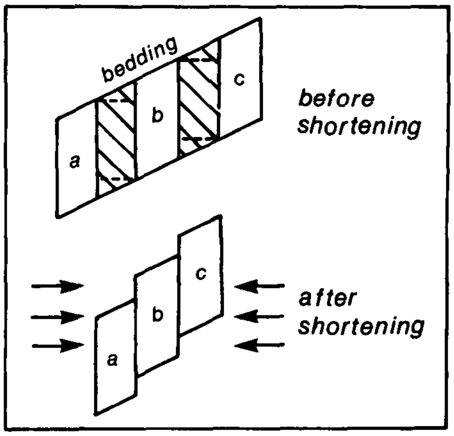

Figure 5. Mechanism for producing offset bedding by dissolution.

shown by the telescoped chert nodules in Figure 3 is about 30 percent.

3. Where chert is absent, the spaced cleavage surfaces are quite consistently oriented in a given outcrop. Figure 3 shows a case where the presence of chert nodules has distorted this pattern. The nodules protect the adjacent limestone from being removed by dissolution, thus producing strain shadows. As a result the spaced cleavage surfaces, which are rather evenly spaced in beds that lack chert nodules, tend to converge toward places where the nodules have been telescoped.

4. In some outcrops the bedding shows a consistent offset where it is intersected by cleavage surfaces (Fig. 4), but there is no slickensiding that would indicate movement parallel to the surfaces. An alternate explanation is that the offset of the bedding planes could have been produced by solution of limestone as the section was shortened perpendicular to the cleavage (Fig. 5); the sense of offset is correct for this interpretation.

Thus there is rather compelling evidence that spaced cleavage in the Scaglia rossa limestone was formed by dissolution. This mechanism may account for "fracture cleavage" in other rock types as well. For example, I.W.D. Dalziel (1976, personal commun.) noted that cleavage surfaces in the Baraboo quartzite in Wisconsin are typically coated with a film of phyllosilicates; this may indicate an origin through dissolution, although in the absence of a marker lithology less soluble than quartzite, demonstration of an origin through dissolution would be difficult.

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