Classification of solution cleavage in pelagic limestones

Walter Alvarez
Department of Geology and Geophysics, University of California, Berkeley, Berkeley, California 94720
Terry Engelder
Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964
Peter A. Geiser
Department of Geology and Geophysics, University of Connecticut, Storrs, Connecticut 06268

ABSTRACT

Spaced cleavage formed by rock dissolution can represent major amounts of shortening parallel to bedding; much so-called fracture cleavage is of this origin. We classify the solution cleavage developed in Mesozoic pelagic limestones of the Umbrian Apennines into four intensity types (*weak, moderate, strong, very strong*) on the basis of qualitative attributes and mean spacing of cleavage surfaces. Shortening can be determined from imbricated chert beds and reaches 50% in rocks with *very strong* cleavage. In the Umbrian Apennines, solution cleavage is commonly associated with detachment thrusts. We describe an example in which the dissolution mechanism "damaged" the rock beneath a thrust by creating closely spaced discontinuities; fragments bounded by these discontinuities were torn up and incorporated in a nearly chaotic shear zone as the thrust sheet moved forward.

INTRODUCTION

Unmetamorphosed pelagic limestones and marls of Mesozoic and Tertiary age, which are abundantly exposed in the Umbrian Apennines foldbelt of northern peninsular Italy (Bortolotti and others, 1970; Arthur and Fischer, 1977; Alvarez and others, 1977), commonly display a spaced cleavage which, until recently, would have been identified as "fracture cleavage." A recent paper (Alvarez and others, 1976) presented evidence that this structure is a stylolitic solution cleavage that can represent tens of percent shortening parallel to bedding. This type of cleavage has been interpreted in the same way by workers in other areas (Platt, 1976; Bayly and others, 1977; and references in Alvarez and others, 1976).

INTENSITY

Solution cleavage varies in intensity from outcrop to outcrop, but because of the toothed or irregular surfaces of the stylolitic cleavages and their anastomosing and discontinuous form, it is difficult to develop an entirely quantitative classification. (For a quantitative study of bedding-parallel compaction stylolites, see Bodou, 1976.) We have thus found it useful to distinguish four categories of cleavage intensity: *weak, moderate, strong,* and *very strong*. Each cleavage type is characterized by qualitative attributes. We have also specified a particular range of spacings between adjacent cleavage surfaces that were chosen to correspond as closely as possible to changes in the qualitative attributes. Our experience is that the characteristics are so recognizable that there is almost never disagreement between field geologists over the cleavage type present in a given outcrop.

Table 1 lists the characteristics of the four cleavage types, and Figure 1 shows, at a constant scale, typical examples of each type, looking both parallel and perpendicular to the bedding surface. The following comments amplify the information in the table:

1. Solution surfaces develop more intensely in marls than in limestones; this is true both for solution cleavage and for the bedding-parallel stylolites discussed by Arthur and Fischer (1977). When clay content varies across a single bed, cleavage intensity increases and the cleavage-bedding angle often diminishes in the more marly part. To standardize our observations, we have restricted our measurements to nearly pure limestone beds and to the least marly part of impure beds.

2. The progression from *weak* to *strong* cleavage and the increasing thickness of the selvages of insoluble clay residues on individual cleavage surfaces both seem to represent evolutionary trends. *Weak* cleavage surfaces show the toothed form typical of stylolites. With increased solution shortening, the wave length of the toothed structure increases faster than the amplitude of the teeth, so that the toothed structure is gradually damped out. Figure 2 shows three stages in this process in surfaces from a single bedding plane. In the more intense, more closely spaced cleavage types, toothed structure is rarely seen.

3. *Very strong* cleavage may or may not be a further step in this evolutionary sequence of increasing intensity. Its association with the other cleavage types and the observed values of shortening for *very strong* cleavage suggest that this may be the

TABLE 1. CHARACTERISTICS OF SOLUTION CLEAVAGE INTENSITY TYPES

Intensity type	Characteristics	Average distance between cleavage planes	Shortening accommodated by cleavage (from Table 2)
Weak	- Surfaces generally of toothed, "stylolite" type; - No clear preferred orientation.	>5 cm	0-4%
Moderate	- Both parallel cleavage and 120° sets common; - Surfaces discrete.	1-5 cm	4-25%
Strong	- Cleavage surfaces may be wispy and anastomosing, in places concentrating into major surfaces; - Toothed surfaces and 120° sets rare.	0.5-1 cm	24-35%
Very strong	- Cleavage sigmoidal; - Bedding transposed, often beyond recognition; - Abundant calcite veins perpendicular to cleavage.	<0.5 cm	>35%

case. It is also quite similar, however, on a smaller scale, to the pattern of sigmoidal imbricate thrusts described by Fermor and Price (1976). In this case it may form parallel to surfaces of high resolved shear stress.

4. In *moderate* cleavage it is common to find two sets of solution surfaces whose traces on the bedding show an angle of roughly 120° (Fig. 1). The orientation of stylolitic teeth and of the 120° cleavage relative to nearby single cleavage sets shows that in this pattern it is the 120° angle that is bisected by the shortening direction, not the acute angle, as would be the case if these were conjugate shear sets.

5. Cleavage surfaces show a wide range of angles relative to bedding, apparently in response to several controls, including clay content and position relative to thrust levels and fold axes. We have experimented with measuring cleavage spacing both parallel to bedding and perpendicular to the cleavage. In high-angle cleavage (that is, roughly perpendicular to bedding) the two values are essentially equivalent; in low-angle cleavage we find that measurements perpendicular to the cleavage are better correlated with intensity types distinguished on the basis of the qualitative characteristics (Table 1). Spacing characteristics of the different cleavage intensities given in this paper are therefore based on measurements taken perpendicular to the cleavage surfaces.

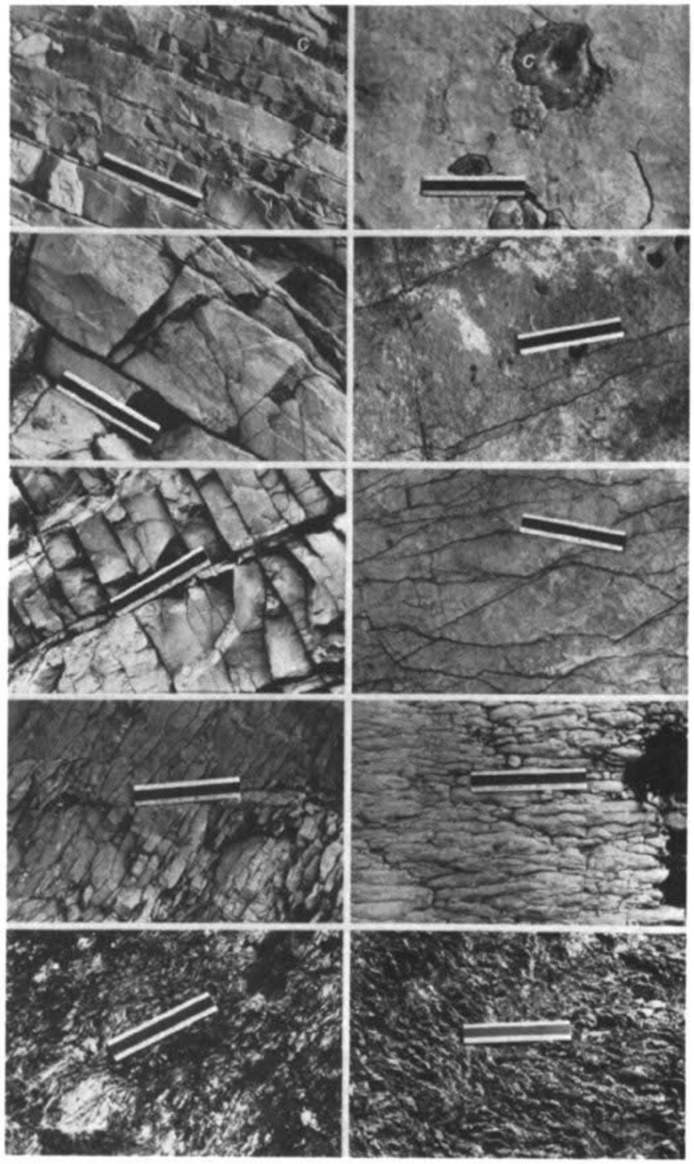

Figure 1. Photographs, at a constant scale, of undeformed limestone and of the four cleavage types, from top to bottom: no cleavage; *weak, moderate, strong,* and *very strong* cleavage, as viewed looking along bedding plane (left, with ruler parallel to bedding) and perpendicular to bedding (right). Overall length of the ruler is 17 cm. All photographs are of Scaglia Rossa limestone (c = chert) except right-hand picture of moderate cleavage, which is from Majolica limestone and shows "120° cleavage sets."

SHORTENING ACCOMMODATED BY CLEAVAGE

Telescoping of the much less soluble chert beds (Alvarez and others, 1976) provides a means of determining the shortening represented by the different cleavage types. In this technique, the total length of individual chert segments gives the length before shortening, which can be compared with the present length of the telescoped bed. Figure 3 shows typical examples of telescoped chert beds from outcrops showing the four cleavage types. Table 2 lists shortening values obtained by this technique.

Comparison of these shortening values with the spacings observed in the different intensity types indicates that individual cleavage surfaces represent, on the average, the removal of 1 to 5 mm of limestone; this agrees with observed tooth amplitudes, which give minimum values for shortening on individual surfaces (Stockdale, 1926). It is also apparent that increasing cleavage intensity involves the formation of new cleavage surfaces, not simply the reduction of spacing between originally more widely separated surfaces as more limestone is removed.

APPLICATION OF THE CLEAVAGE CLASSIFICATION: AN EXAMPLE

We have measured the various attributes of solution cleavage at intervals of roughly one metre in several limestone-marl sections in the Umbrian Apennines. The cleavage commonly shows an unmistakable, if complicated, relation to detachment surfaces.

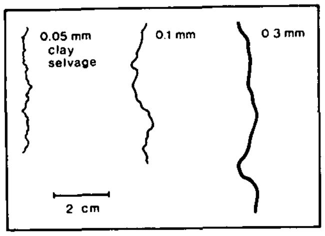

Figure 2. Tracings of cleavage surfaces, from single bedding plane, with thickness of clay selvage indicated (but not drawn to scale).

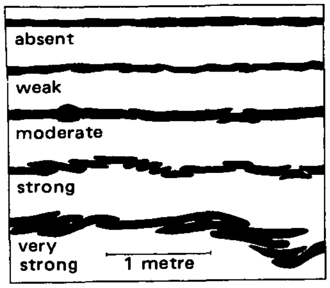

Figure 3. Telescoping of originally continuous chert beds in outcrops showing four types of cleavage intensity. (Drawings are based on field sketches and photographs.)

TABLE 2. SHORTENING VALUES FROM TELESCOPED CHERT BEDS

Cleavage type	Shortening*
Weak	2% (250 cm); 2% (300 cm); 2% (600 cm); 4% (500 cm).
Moderate	4% (200 cm); 6% (150 cm); 8% (400 cm); 8% (600 cm); 9% (410 cm); 16% (300 cm); 20% (312 cm)**.
Strong	27% (237 cm); 27% (240 cm); 28% (215 cm); 28% (260 cm).
Very strong	38% (290 cm); 41% (430 cm); 45% (440 cm); 46% (350 cm); 50% (400 cm).

* Each pair of values represents one determination. The first value is the shortening $e = (l_1 - l_0) / l_0$; the second value is the present length of the telescoped chert bed (l_1). The original length l_0 (not given) is the sum of the lengths of the telescoped segments.

** Value measured in the upper part of the Majolica limestone (Neocomian); all other values measured in the upper cherty member of the Scaglia Rossa limestone (Eocene).

An example is shown in Figures 4 and 5. Cleavage in interval A, more than 30 m below a prominent detachment, is *weak* to *moderate* and shows high positive angles to bedding. Interval B, immediately beneath the detachment, has more intense cleavage (*moderate* to *strong*) at a variety of angles to bedding—frequently in the range +20° to +50°—but also perpendicular to bedding and even in the negative direction. Interval C, above the strongly sheared zone associated with the detachment, shows a more consistent cleavage, mostly of the *strong* type, with bedding angles in the range +25° to +60°.

The pattern of interval A is typical of zones well removed from detachment levels. If we assume, as is commonly done, that stylolitic surfaces form roughly normal to the maximum compressive stress, the cleavage of interval A would have formed

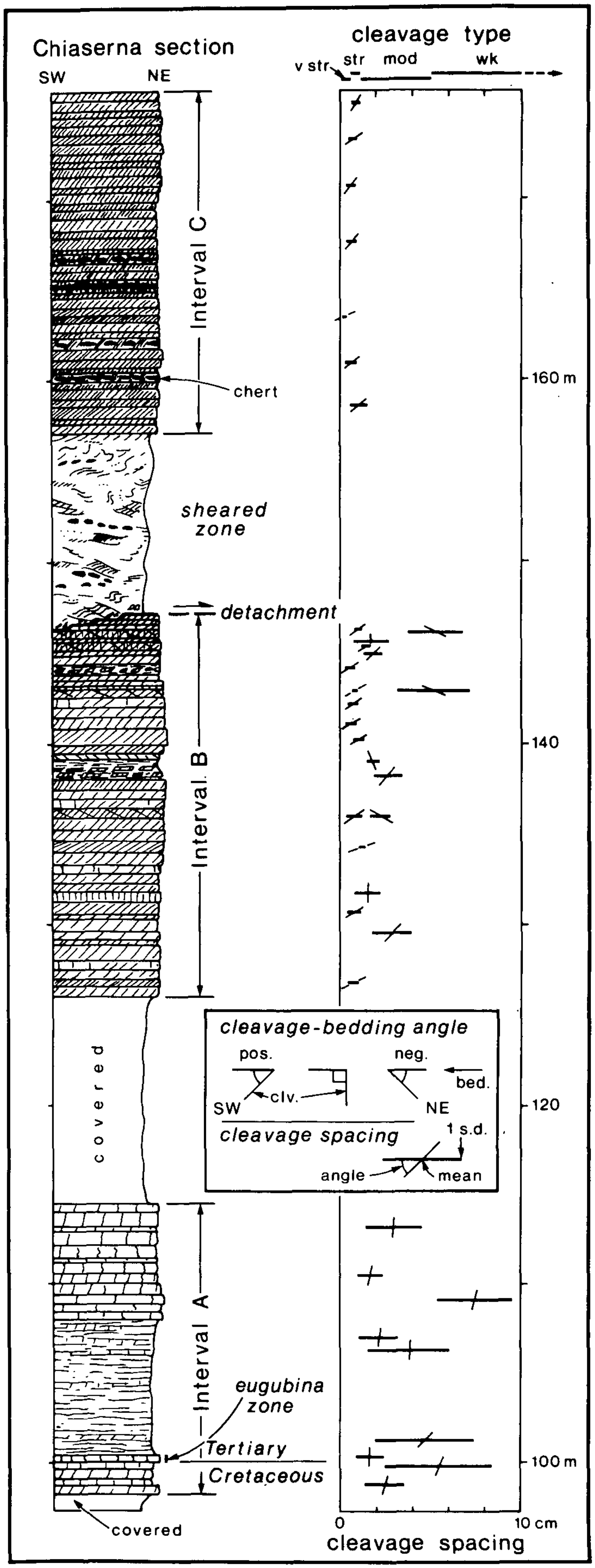

Figure 4. Stratigraphic-structural column of part of Scaglia Rossa limestone near Chiaserna, on the road to Monte Catria (43°27.3′N, 0°12.9′E of Rome, 12°40.1′E of Greenwich). The column at right shows cleavage spacing (mean and standard deviation) and cleavage-bedding angle for sampled beds; inset shows sign convention for cleavage-bedding angle. Note that ornamentation on stratigraphic column is not standard limestone-dolomite symbol; it shows schematically orientation and spacing of solution cleavage.

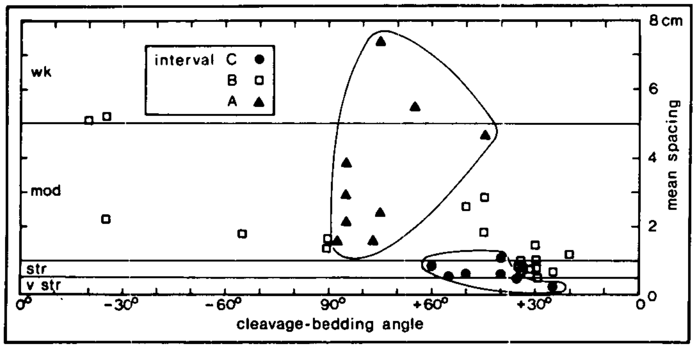

Figure 5. Plot of cleavage spacing versus cleavage-bedding angle for measured beds in Chiaserna section (Fig. 4). For sign convention, see inset in Figure 4.

through bedding-parallel shortening in a part of the section where σ_1 was roughly parallel to bedding. In interval B, as we approach the detachment, the cleavage rotates to a positive angle; this is probably due to a combination of rotation of σ_1 near a zone of simple shear and rotation of early solution surfaces formed at high angles to bedding. The sense of rotation is consistent with motion of the detachment sheet toward the northeast, in conformity with the well-known northeastward vergence of the Apennine fold belt (Bortolotti and others, 1970). The increasing intensity of cleavage in interval B shows the way in which the dissolution mechanism "damages" the rock beneath a detachment by creating closely spaced discontinuities. The detachment itself climbs the section toward the northeast, up the 45° to 60° dip, in three steps within a 5-m-high outcrop. It appears that each step has moved progressively forward (toward the northeast) by detaching successive cleavage microlithons and shearing them upward and forward along positive-angle cleavage surfaces. Within the shear zone above the detachment there is a nearly chaotic mixture of fragments that were probably detached from the lower plate in this fashion. Thus the damage produced by solution cleavage formation facilitated the development of the detachment. The plate above the sheared zone—interval C—shows a similar, though more homogeneous, damage but does not seem to have been invaded by the shear zone.

It is our impression that detailed mapping of the varying intensities and orientations of solution cleavage, based on measurement of numerous sections of this type, will prove to be a useful tool in unraveling the intricate structure and stratigraphy of this and other foreland fold-and-thrust belts.

REFERENCES CITED

Alvarez, W., Engelder, T., and Lowrie, W., 1976, Formation of spaced cleavage and folds in brittle limestone by dissolution: Geology, v. 4, p. 698-701.

Alvarez, W., Arthur, M. A., Fischer, A. G., Lowrie, W., Napoleone, G., Premoli Silva, I., and Roggenthen, W. M., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy—V. Type section for the Late Cretaceous-Paleocene geomagnetic reversal time scale: Geol. Soc. America Bull., v. 88, p. 383-389.

Arthur, M. A., and Fischer, A. G., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italy—I. Lithostratigraphy and sedimentology: Geol. Soc. America Bull., v. 88, p. 367-371.

Bayly, B. M., Borradaile, G. J., and Powell, C. McA., eds., 1977, Atlas of rock cleavage—Provisional edition: Hobart, Univ. Tasmania.

Bodou, P., 1976, L'importance des joints stylolithiques dans la compaction des carbonates: Centre Recherche Pau Bull., v. 10, p. 627-644.

Bortolotti, V., Passerini, P., Sagri, M., and Sestini, G., 1970, Development of the Northern Apennines geosyncline—The miogeosynclinal sequences: Sed. Geology, v. 4, p. 341-444.

Fermor, P. R., and Price, R. A., 1976, Imbricate structures in the Lewis thrust sheet around the Cate Creek and Haig Brook windows, southeastern British Columbia: Canada Geol. Survey Paper 76-1B, p. 7-10.

Platt, L., 1976, A Penrose Conference on cleavage in rocks: Geotimes, v. 21, p. 19-20.

Stockdale, P. B., 1926, The stratigraphic significance of solution in rocks: Jour. Geology, v. 34, p. 399-414.

ACKNOWLEDGMENTS

Reviewed by R. H. Groshong. Supported by National Science Foundation Grants EAR-77-13000 and EAR-77-14431. Lamont-Doherty Geological Observatory Contribution no. 2646. The 1976 Penrose Conference on cleavage, organized by Lucian Platt, was a key factor in focusing attention on the widespread importance of solution cleavage. We thank Ettore Sannipoli for field assistance and Giampaolo Pialli and Bruno D'Argenio for valuable discussions of these ideas in the field. We appreciate the useful comments of I.W.D. Dalziel and R. A. Schweickert.

MANUSCRIPT RECEIVED DECEMBER 19, 1977

MANUSCRIPT ACCEPTED FEBRUARY 27, 1978