Journal of Structural Geology, Vol. 11, No. 4, pp. 457 to 461, 1989
Printed in Great Britain

0191-8141/89 $03.00 + 0.00

Primary crenulation pencil cleavage

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(*Received* 29 *June* 1988; *accepted in revised form* 29 *November* 1988)

Abstract—Previous pencil cleavage models rely on either pressure solution or independent grain rotation as the principal shortening mechanism. In contrast, samples from the Rose Hill Formation and the Marcellus Shale from the Central Appalachians show a primary tectonic crenulation fabric dominated by domainal grain rotation in microfold limbs. The crenulations are identified in crossed-polarized light where they appear as alternating light and dark bands of optically aligned phyllosilicates in the microfold limbs. Relatively rare pressure solution developed concentrations of insoluble residue and thinned bedding laminae within microfold limbs. A systematic relationship of pressure solution to microfold limbs in more deformed samples indicates that microfolding preceded pressure solution. Shortening, in six samples without pressure solution, ranges from 9.2 to 20.4% and exhibits no direct relationship to the length/width ratios for the pencils. A new model for pencil cleavage begins with compacted shale having a strong bedding-parallel alignment of inequant grains. Compression causes microfolding, developing a primary crenulation pencil cleavage fabric. Pressure solution is then initiated within the microfold limbs and continues as a major shortening mechanism which overprints bedding to form planar cleavage.

INTRODUCTION

PENCIL cleavage is common in shale, siltstone, and argillaceous limestone in tectonically deformed areas, and is characterized by subplanar fractures that intersect with bedding fissility, during weathering, to develop elongate pencil-like rock fragments (Crook 1964, Graham 1978, Engelder & Geiser 1979). Pencil cleavage differs from planar cleavage at the mesoscopic level by the presence of bedding fissility along which the pencils tend to break. Bedding fissility is produced by compaction, developing a bedding-parallel alignment of inequant grains and an oblate *compactional* strain ellipsoid with the short axis normal to layering. Compaction is followed by tectonic compression which causes the *composite* strain ellipsoid to evolve to a prolate shape (Graham 1978, Ramsay 1981). However, the *tectonic* strain ellipsoid is oblate with the short axis parallel to the tectonic shortening direction (Reks & Gray 1982). The major difference between the pencil cleavage in the present study and previous models for pencil cleavage development is the mechanism of tectonic shortening. Previous models involve either pressure solution with mineral growth (Reks & Gray 1982), or independent grain rotation and possible mineral growth (Ramsay 1981, Ramsay & Huber 1983). In this study, thin sections of pencil cleavage in shale of the Rose Hill Formation and Marcellus Shale from the Appalachian Valley and Ridge Province of Maryland and West Virginia show a primary tectonic crenulation fabric characterized by domainal grain rotation in microfold limbs.

PRIMARY CRENULATION PENCIL CLEAVAGE

Pencil cleavage in shale of the Silurian Rose Hill Formation and the Devonian Marcellus Shale was mesoscopically analyzed at 18 stations in the central Appalachian Valley and Ridge Province (Fig. 1). Field measurements of pencil cleavage length/width ratios (averaged for 50 pencils) ranged from 4.5 to 15.2 with a mean value of 9.54 ± 3.11 (Ferrill 1987). Thin sections were made for samples from six of the 18 field stations (Figs. 2 and 3). Four of the thin sectioned samples are from the Rose Hill Formation exposed within the Wills Mountain anticlinorium at Pinto, Maryland. Another sample of the Rose Hill Formation, and one from the Marcellus Shale, were collected within the Cacapon Mountain anticlinorium between McCauley and Wardensville, West Virginia (Fig. 1). All of the thin sections show crenulations, with fractures along bedding laminae and parallel to the axial surfaces of the crenulations. The crenulations are difficult to recognize in plane-polarized light, but are easily discernable as alternating

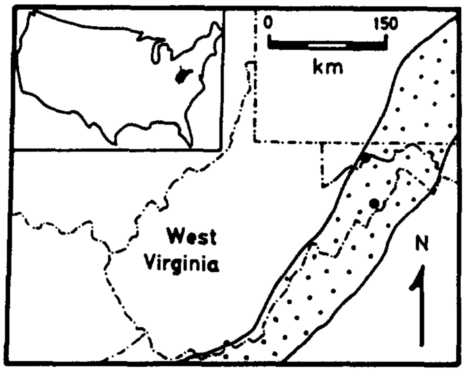

Fig. 1. Map showing the location of the two sampling areas (large dots) within the Appalachian Valley and Ridge Province (stipple pattern). The northern dot represents four samples of the Rose Hill Formation from a railroad cut at Pinto, Maryland, within the Wills Mountain anticlinorium. The southern dot represents one sample of the Rose Hill Formation and one of the Marcellus Shale from outcrops within the Cacapon Mountain anticlinorium between Wardensville and McCauley, West Virginia.

light and dark bands parallel to the crenulation axial surface traces in cross-polarized light, because of the optical alignment of the phyllosilicates in the microfold limbs (Fig. 2). The microfolds generally have straight limbs and narrow hinges, as illustrated by simultaneous extinction of phyllosilicates in crenulation limbs, as opposed to sweeping extinction for broad rounded hinges. Shortening by microfolding in the six samples was calculated from tracings of crenulated bedding laminae in the plane normal to the microfold axes using the following equation:

$$[(L_i - L_d)/L_i] \times 100 = \% \text{ shortening}, \qquad (1)$$

where L_i = original bed length and L_d = deformed-bed length. Values for the six samples range from 9.2 to 20.4% with a mean of 16.0 ± 3.6% (dots in Fig. 4).

Zones of pressure solution are visible in approximately one-third of the pencil fragments in the four thin-sectioned samples from the Wills Mountain anticlinorium in Pinto, Maryland. The evidence for pressure solution consists of concentrations of insoluble residue and thinned bedding laminae within some microfold limbs (Fig. 3b). The two samples from the Cacapon Mountain anticlinorium do not show this pressure-solution deformation. None of the six shortening measurements came from pencil fragments with this evidence for pressure solution.

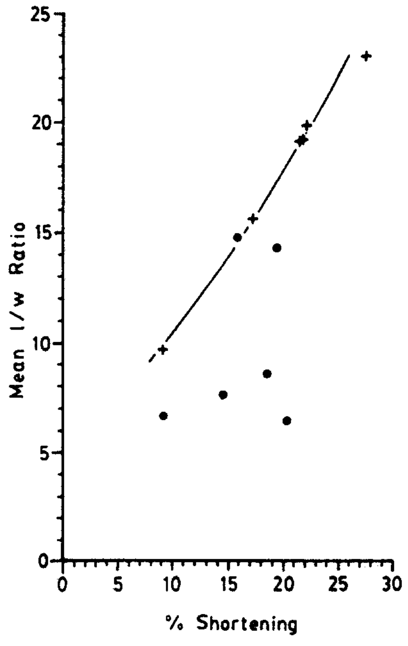

Fig. 4. Percent shortening is plotted vs length/width ratios for primary crenulation pencil cleavage (dots) in detrital shales from the Silurian Rose Hill Formation and the Devonian Marcellus Shale, from the Appalachian Valley and Ridge Province of Maryland and West Virginia. Plus signs represent pyrite framboid overgrowth data from samples of pressure-solution type pencil cleavage in the Ordovician Knobs Formation, Virginia, from Reks & Gray (1982). The data from the present study neither fit an equation nor conform to the data of Reks & Gray (1982).

DISCUSSION

Primary crenulation pencil and planar cleavage model

A four-stage model for the development of pencil cleavage and planar cleavage in shale (Fig. 5) was constructed based on measurements taken from thin section samples (Figs. 5b & c). The other stages were then constructed, assuming no change in compression direction, by reducing or increasing microfolding and pressure-solution deformation. Compacted shale (Fig. 5a) is microfolded, developing crenulations with narrow hinges and planar limbs (Fig. 5b). Pressure solution is initiated along bedding laminae, within microfold limbs, in zones parallel to the microfold axial surfaces (Fig. 5c). The onset of this pressure solution is probably a function of limb dip relative to the maximum principal compressive stress direction (Cosgrove 1976, Gray 1979). Progressive pressure solution causes passive rotation and shortening of the bedding laminae by removing soluble minerals along the laminae within the zone. Eventually, a narrow zone of insoluble residue results, which appears to truncate bedding laminae and acts as a

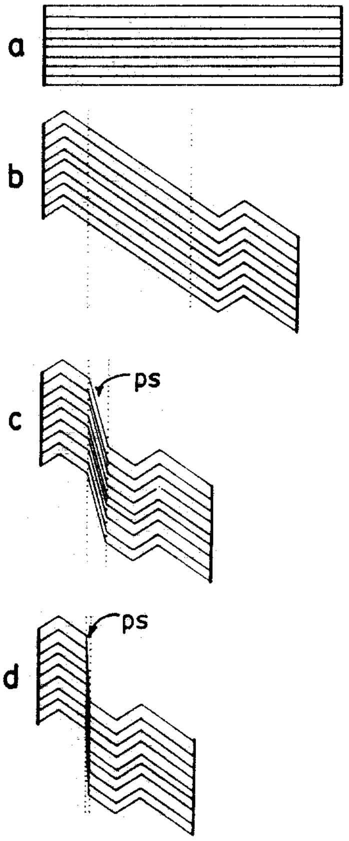

Fig. 5. Kinematic model for the development of primary crenulation pencil cleavage and planar cleavage, starting with undeformed bedding laminae (a) which are then microfolded (b), followed by dissolution along bedding laminae in a zone within microfold limb (c), and causing passive rotation of bedding laminae with insoluble residue into near-parallelism with pressure-solution zone (ps) boundaries (d). Stages (b) and (c) represent features observed in pencil cleavage samples. Stage (d) represents planar cleavage similar to that shown in Nickelsen (1986). Shortening in this diagram may not directly correlate with bulk shortening in the rock because the bulk shortening also depends on the abundance of the pressure-solution zones within the rock.

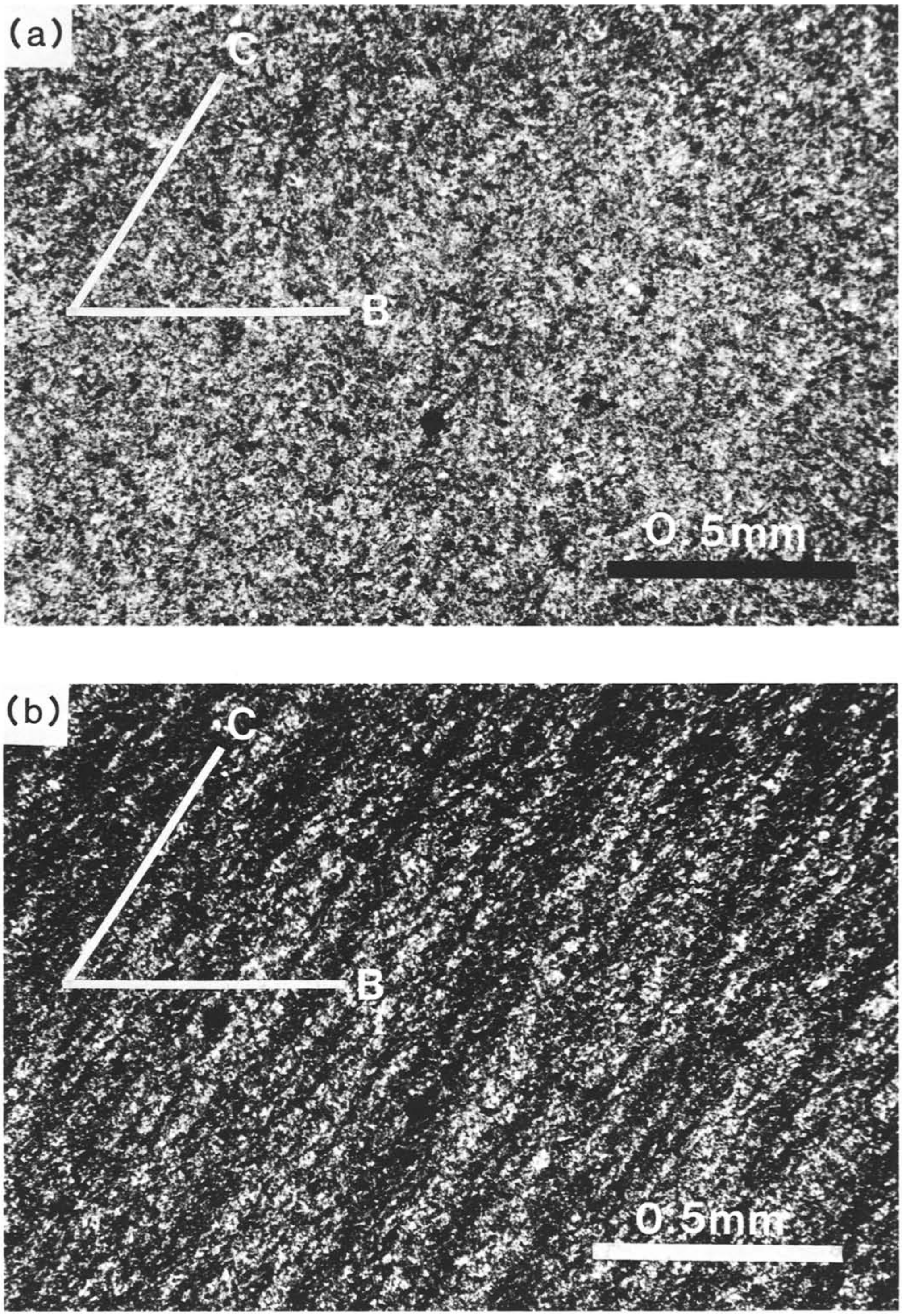

Fig. 2. Matched photomicrographs of primary crenulation within pencils from the Rose Hill Formation in plane-polarized and crossed-polarized light. Bedding (B) is horizontal in each photograph and the crenulation axial surface orientation (C) is at a high angle to bedding. (a) Plane-polarized light. (b) Same field of view as (a) in crossed-polarized light. Light and dark bands, parallel to the crenulation axial surfaces, are the result of the optical alignment of phyllosilicates in the microfold limbs and simultaneous extinction.

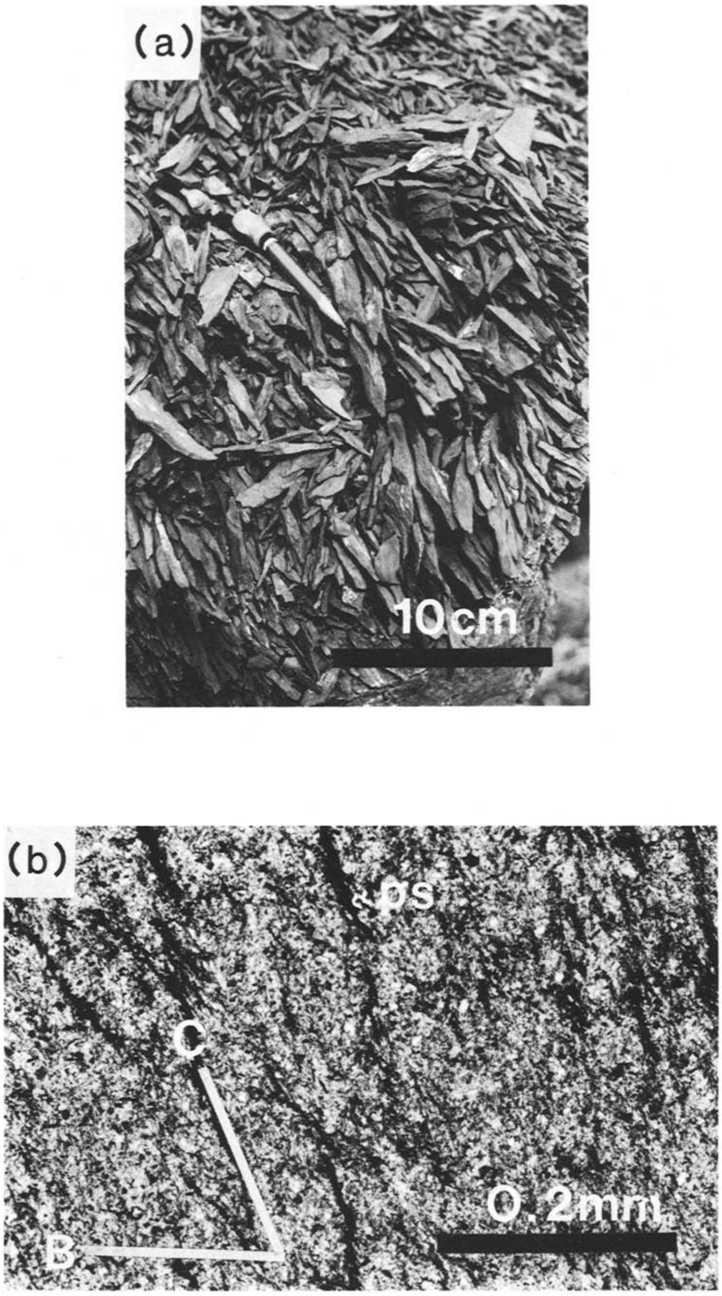

Fig. 3. (a) Field photograph of pencil cleavage in detrital shale of the Rose Hill Formation. (b) Photomicrograph of pencil cleavage in shale of the Rose Hill Formation with bedding (B) and crenulation (C). This photomicrograph shows well-developed (for these pencil samples) pressure-solution zones (ps) with concentrations of insoluble residue, and thinned bedding laminae that have apparently been passively rotated. Pressure-solution zones occur in approximately one-third of the pencil fragments, only in the four Rose Hill samples from the northern sampling area.

mechanical weakness, overprinting bedding, and leading to planar cleavage (Fig. 5d) (see fig. 7 in Nickelsen 1986). This model can account for the microstructural geometries observed in the thin sections, does not require a change in stress orientation, and can explain the evolution to the planar cleavage microstructures (crenulations and pressure-solution zones).

Weathering of deformed shale at the stage shown in Fig. 5(b) apparently produced the bulk of the pencils in this study, although the secondary pressure-solution zones partially controlled fracturing in about one-third of the pencils seen in thin section from the northern sampling area (Fig. 1). Photomicrographs of planar cleavage from the Devonian Marcellus Shale in central Pennsylvania (Nickelsen 1986) show crenulations like those observed in the present study. Pressure-solution deformation, however, is more abundant in Nickelsen's (1986) samples, as indicated by a greater abundance of cleavage laminae with insoluble residue and truncated grains. Also, the crenulations in Nickelsen's (1986) samples with planar cleavage are tighter, recording greater minimum shortening values, up to 40%. The initial lithologic similarity and presence of the strong crenulation fabric suggests that this planar cleavage represents a further stage, beyond pencil cleavage, in the fabric evolution from shale bedding fissility to slaty cleavage.

Length/width ratios

Length/width ratios for pencils in the Ordovician Knobs Formation in Virginia were shown to be directly related to strain magnitudes from six samples with pyrite framboid overgrowths by Reks & Gray (1982). Reks & Gray (1982) derived an equation to fit the six data points (Fig. 4; plus signs) and suggested that this equation could be used with mean length/width ratios, calculated by averaging field measurements, as a strain quantification technique. In contrast, the data from the present study (Fig. 4; dots) do not plot along a linear trend and do not conform to the data or equation of Reks & Gray (1982). The comparison of the results of this study with those of Reks & Gray (1982) suggests that quantitative strain analysis using pencil cleavage field data should only be used with caution and supported with microstructural or other independent strain data.

CONCLUSIONS

(1) Pencil cleavage in shale samples from the Rose Hill Formation and the Marcellus Shale of the central Appalachians formed by the intersection of bedding fissility and subplanar fractures controlled by a primary crenulation fabric. Pressure-solution deformation is secondary and was evidently initiated after the development of the crenulation fabric.

(2) Shortening of 9.2–20.4% was measured from crenulated bedding laminae, for pencil fragments lacking pressure-solution features, in thin sections from six samples. These shortening values show no direct relationship to corresponding mean length/width ratios.

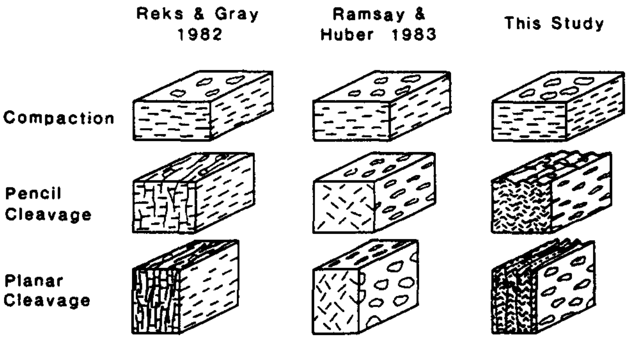

Fig. 6. Schematic sequences of deformation from compacted shale, to pencil cleavage, and planar cleavage by; (left) pressure solution and mineral growth (after Reks & Gray 1982), (center) independent grain rotation with possible mineral growth (after Ramsay & Huber 1983) and (right) primary crenulation followed by pressure solution (this study). Pencils in Reks & Gray's (1982) model are formed by the intersection of weak pressure-solution cleavage and bedding fissility. In the models of Ramsay & Huber (1983) and this study, pencils are formed by the intersection of bedding fissility and irregular fractures at a high angle to bedding which are generally controlled by grain-alignment rather than pressure-solution seams.

(3) Primary crenulation can occur relatively early in the deformation history of shale and may be an important mechanism in the development of grain alignment fabrics in some planar and slaty cleavage.

Acknowledgements—I would like to thank Betsy J. Dransfield, Benjamin A. Ferrill and Richard H. Groshong, Jr, and two anonymous reviewers for helpful reviews of the manuscript.

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