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Cathodoluminescence petrography of microstructural fabrics in deformed limestones

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Abstract—Cathodoluminescence petrography is a valuable tool for the analysis of strain microfabrics in deformed limestones. Finely banded growth zones in calcite cements, visible only in the cathodoluminescent mode, act as very sensitive displacement markers. They reveal the varied and heterogeneous nature of microstructures within the deformed calcite.

INTRODUCTION

CATHODOLUMINESCENCE petrography has been shown to be a valuable tool for analysis of strain microfabrics in deformed rocks (e.g. Sprunt & Nur 1979, Dietrich & Grant 1985, Blenkinsop & Rutter 1986, Kanaori 1986). In this paper, we show application of cathodoluminescence petrography for elucidating the details of the microstructures observed in deformed carbonate rocks.

ORIGIN OF CATHODOLUMINESCENCE AND METHODS USED

Cathodoluminescence is one type of electromagnetic radiation (mostly within the visible range) emitted from a material when it is bombarded by electrons. Variables which might affect the intensity and wavelength of cathodoluminescence include (Nickel 1978):

(1) mechanically induced strain defects within crystals or at intercrystalline boundaries;

(2) omission defects, formed when atoms or molecules are omitted from lattice sites;

(3) lattice defects caused by abnormally sized or ionized atoms; and

(4) trace element substitution for major ions.

Cathodoluminescence in calcite and dolomite is generally attributed to substitution of trace amounts of Mn^{2+} (the dominant 'activating' ion) and Fe^{2+} (dominant 'quenching' ion) in the crystal lattice (Pierson 1981, Frank *et al.* 1982, Fairchild 1983). Cathodoluminescent zoning in carbonate cements has been attributed to varying pore fluid chemistry during growth of the cement crystals (Meyers 1978, Grover & Read 1983, Dorobek 1987).

Polished thin-section samples used in this study were examined with a Technosyn^{TM} Cold Cathode Luminescence Model 8200 Mk II attached to a Nikon Optiphot Pol microscope. Operating conditions for cathodoluminescence petrography and photography were ~0.01 Torr vacuum, 20 kV gun potential and 300 μA beam current.

ANALYSIS OF DEFORMED CARBONATE ROCKS

The samples illustrated in this paper are from exposures of the folded and thrusted Siluro-Devonian Helderberg Group, Valley and Ridge Province, Central Appalachians (Virginia–West Virginia–Maryland). The Helderberg Group reveals evidence for only one generation of deformation, during late Pennsylvanian–early Permian time (the Alleghenian Orogeny).

Calcite twin lamellae and cathodoluminescent zones

Calcite crystals have been shown to deform by intracrystalline gliding in response to induced stress (Turner 1953, Turner *et al.* 1954, Friedman & Heard 1974, Jamison & Sprang 1976). It is commonly inferred that microscopically visible deformation lamellae in deformed calcite crystals are produced by twin gliding along preferred crystallographic planes (cf. Jamison & Spang 1976).

The advantage of viewing deformed calcite grains under cathodoluminescence is that fine-scale luminescent growth zones which may be present in the grains act as very sensitive displacement markers. The displacements associated with the microstructures within the deformed calcite can be observed, and the shear-sense of the displacements can be clearly determined. We use structural, rather than crystallographic, terms to describe the fault and fold displacements of the growth zones. Therefore, our terminology describes microstruc-

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tural fabrics which are observable with cathodoluminescence units attached to regular petrographic microscopes. Our observations are, in no way, intended to supplant careful crystallographic analysis of deformed calcite crystals. Instead, we hope to show that cathodoluminescence petrography, using routinely available cathodoluminescence units, provides direct evidence of displacements along deformation microstructures in deformed carbonate rocks. Additionally, cathodoluminescence petrography is useful for observing the variable mechanisms and senses of shear associated with development of deformation microstructures.

Coarse-grained skeletal limestones in the Helderberg Group contain calcite cements which are zoned under cathodoluminescence. These cathodoluminescent zones record the varying geochemistry of diagenetic pore fluids during growth of individual cement crystals (Dorobek 1987). During Alleghenian thrusting and folding, the growth zones were deformed. The deformed growth zones reveal a variety of modes of deformation from kink-like bands to discrete slip planes, with combinations of both. Figure 1(a) shows a highly twinned crinoid fragment and syntaxial overgrowth of calcite cement. Under cathodoluminescence (Fig. 1b), luminescent growth zones in the syntaxial cements contain abundant, closely spaced, chevron-shaped microstructures which are coincident with twinned regions shown in Fig. 1(a). Closer examination of the deformation microstructures suggest that there has been rotation in the zones between twinned regions (Fig. 1c), i.e. what Johnson (1977, fig. 21, p. 174) refers to as back rotation between kinks.

In other examples, however, the dominant mode of displacement of the luminescent growth zones is by slip along discrete planes. In Fig. 2, the prominent twin planes in the plane light photomicrograph (Fig. 2a) coincide exactly with small offsets in the brightly luminescent and non-luminescent cement zones in the cathodoluminescence photomicrograph of the same area (Fig. 2b). The greatest amount of offset apparently occurs along discrete dislocation surfaces and the direction of offset shown suggests right lateral shear (Fig. 2c).

However, detailed examination of one of the deformed zones suggests that the bands may have initially 'kinked' by twinning, then slipped in discrete slivers in a right lateral sense (Fig. 2c). The sense of deflection of the growth bands adjacent to the shear zone appears to be incompatible with right lateral shear. A reversal in shear sense does not appear to be a likely cause. An alternative suggestion is that the initial kink had rotational zones with a 'reverse' sense of displacement adjacent to the kink boundary. Hamblin (1965), J. J. Walsh and J. Watterson (personal communication 1987), refer to this sense of displacement as reverse 'drag'. The kinked zone then failed by discrete slip in one or more planes (Fig. 2c). Figure 2(d) illustrates a possible sequence of formation for these microstructures.

COMMENTS ON STRUCTURAL ANALYSIS

These types of samples, with well-defined diagenetic growth zones as defined by cathodoluminescence, are clearly ideal for detailed stress analysis (e.g. Turner 1953) or strain analysis (e.g. Groshong 1972). The sample from which Figs. 1 and 2 were selected, overall shows dominant directions of microstructural bands over the whole sample. A detailed strain analysis is in progress to check that directions and senses of shear displacements in the calcite grains are compatible with other strain microfabrics in the thin section, such as pressure-shadow fibres on detrital quartz grains and pressure-solution seams between grains.

SUITABLE CARBONATE ROCK SEQUENCES FOR ANALYSIS

This technique should work well in many different deformed carbonate rock sequences where zoned carbonate crystals occur. However, deformed, coarse-grained skeletal limestones with abundant echinoderm fragments which have been subjected to some phase of meteoric diagenesis during their burial history are probably most likely to contain the features described here. Echinoderms secrete their skeletal parts as single crystals of calcite (Bathurst 1975) and syntaxial calcite cement overgrowths form rapidly on the unit crystal substrates provided by echinoderm fragments (Evamy & Shearman 1965, 1969). Zoning in the calcite overgrowths is more likely to occur if some of the cements were precipitated in near surface diagenetic environments that were affected by meteoric groundwaters (cf. Meyers 1978, Grover & Read 1983, Dorobek 1987).

Some cathodoluminescent zoned calcite cements may contain very irregular growth zones which are due to dissolution events between periods of cement precipitation or to syntaxial growth on irregular cement crystal faces. Therefore, small-scale irregularities in primary cement crystal growth fabric must be carefully considered to be certain that they are not mistaken for deformation microfabrics. Clearly, if irregularities in the luminescent cement zones are *not* coincident with deformation microstructures observed in transmitted light, then they are probably primary growth irregularities.

CONCLUSIONS

This short note further illustrates the usefulness of cathodoluminescence petrography for studies of microstructural fabrics in deformed limestones. More importantly, cathodoluminescence petrography may show the varied and heterogeneous nature of mechanisms involved in the formation of deformation microstructures in calcite crystals.

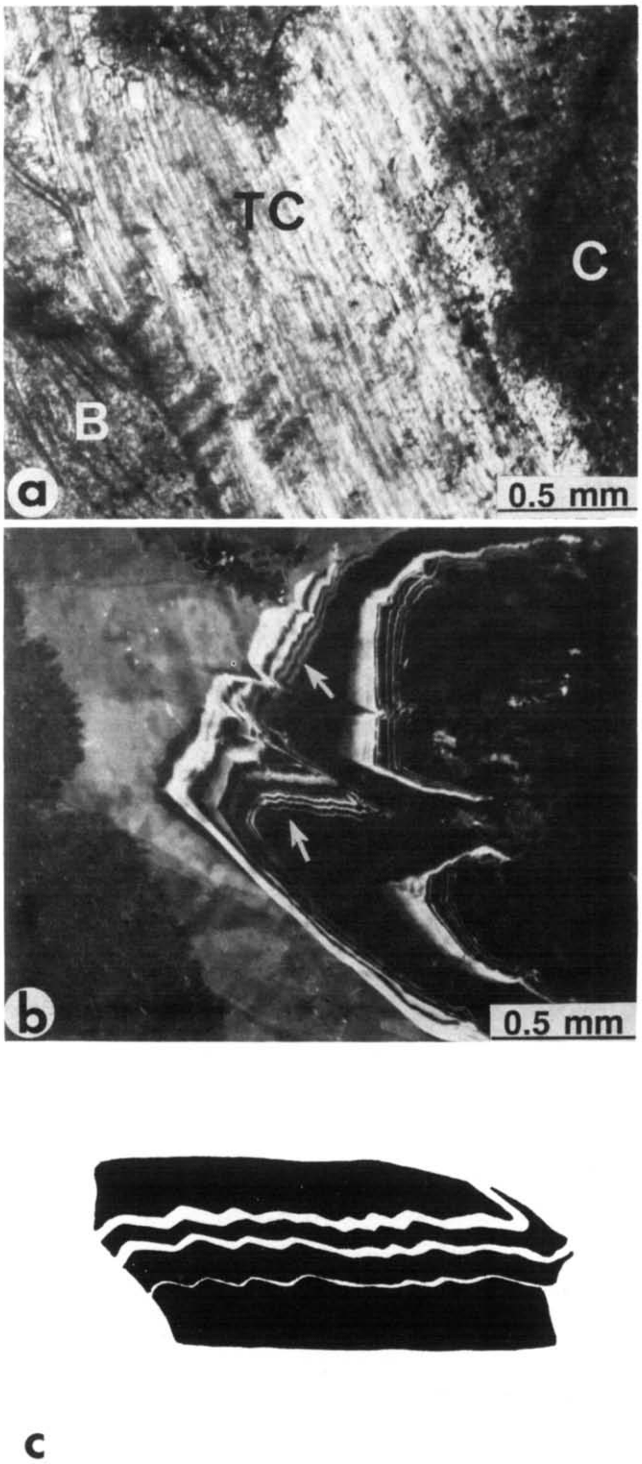

Fig. 1. (a) Plane light photomicrograph of crinoid fragment (C) and highly twinned syntaxial calcite cement (TC). Brachiopod fragment (B) to the left. (b). Same region as (a), under cathodoluminescence. Note abundant, closely spaced, asymmetric chevron-like structures in brightly luminescent growth zones (arrows). These structures are coincident with the twinned regions shown in (a). (c). Line drawing of region indicated by lower arrow in (b). Drawing shows predominant left lateral kinks with intermediate zones of rotation which are similar to back rotation zones in kink folds as shown by Johnson (1977).

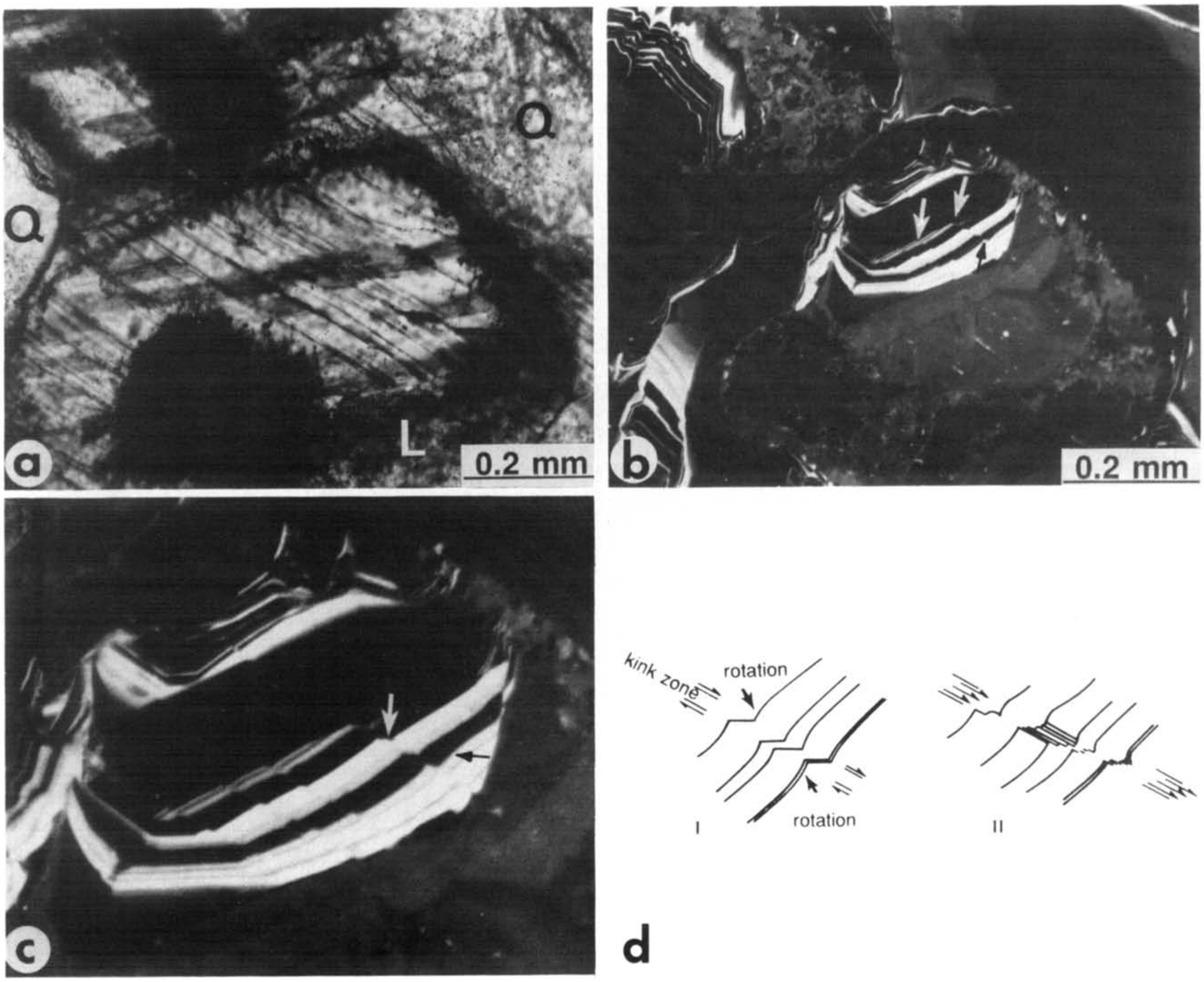

Fig. 2. (a) Plane light photomicrograph of leached crinoid fragment (L), now filled with calcite cement and quartz grains (Q). Opaque regions are authigenic iron oxides. (b). Same region as (a), under cathodoluminescence. Note discrete offsets in non-luminescent and bright zones (arrows) which are coincident with the twinned regions shown in (a). (c). Higher magnification image of offset regions. Note discrete stepped offset of luminescent zones (white arrow) and rotation adjacent to twinned zones (black arrow). (d). Interpretation of mode of formation for region shown in (c). Initial kinking with adjacent zones of rotation (I). Final configuration with discrete slip within the kink zone (II).

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