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Letter Section

Segregation bands in plagioclase: non-dilational quartz veins formed by strain enhanced diffusion

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ABSTRACT

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Quartz-filled intra- and transgranular veins in plagioclase are frequently identified as brittle, dilational "tension gashes or cracks". Similar veins also form in plagioclase by initial ductile kinking and microfracturing modified by strain enhanced impurity segregation by diffusion. Some of the veins are demonstrably non-dilational. These veins are termed "segregation bands".

INTRODUCTION

Optical descriptions of naturally deformed plagioclase commonly attribute much of the deformation to brittle fracture, cataclasis, kinking and twinning under epizonal to catazonal metamorphic conditions (e.g., Sturt, 1969; Eisbacher, 1970; Wakefield, 1977; Sylvester et al., 1978; Debat et al., 1978; Berthé et al., 1979). The commonest feature attributed to brittle fracture and dilation are quartz-filled intragranular veins making a high angle with the maximum instantaneous extension direction, generally known as tension gashes.

The questions considered here are: (a) do intragranular quartz-filled veins constitute *a priori* evidence for brittle behaviour in plagioclase?; (b) if not, by what mechanisms do such veins form? In the examples given here, the veins are attributed to ductile, non-dilational strain and strain induced impurity segregation by diffusion. They are therefore called segregation bands, in contrast to "tension gashes".

Oriented specimens were collected from granites deformed in a major ductile shear zone in northeast Newfoundland (Hanmer, 1981). Conditions of deformation were 500—600°C at 5 kb (Hammer, in prep.). The granites contain large microcline (≅ 5 cm) and plagioclase (An ≅ 28; ⩽ 3 cm) megacrysts in a quartz-biotite matrix. All stages from undeformed granite to ultramylonite are present (see Blackwood, 1977; Jayasinghe, 1978; Hanmer, 1981). Oversize (10 × 15 cm) thin sections were examined on a flat-stage microscope. All compositional determinations are from microprobe analysis.

OPTICAL MICROSTRUCTURE

The plagioclase exhibits several types of planar deformation structures which are best seen in sections containing the maximum and minimum strain directions, cut in poorly foliated rocks (i.e. low bulk strain): deformation bands (Hobbs et al., 1976, p. 98), fractures, kink bands and twins. Development of the deformation bands has been studied in a number of specimens from different outcrops. A morphological sequence of increasing maturity is apparent with increasing strain and even within a single specimen.

(a) Incipient deformation bands

These are elongate, narrow (25—100 μm) bands of sodic plagioclase (An 9—23) compared to the host grain (An 28) and generally oriented at a high angle to the host (010) plane. Where the host is dusted with fine inclusions and sericitized, the deformation band is "clear" (Fig. 1A). The bands may appear intra- or transgranular, straight, irregular or with right-angle steps.

Morphologically there are three types of incipient deformation bands:

(1) Twin lamellae of the host grain end abruptly at the deformation band boundaries.

(2) Host twin lamellae pass in continuity across the band, but are moderately (10°–30°: non-dihedral hence minimum) deflected within it (Fig. 1A). They initiate by kinking apparently in response to slip along (010) (Fig. 1B). The kinks have rounded hinges and correspond in orientation and off-set to other, non-albitic kinks in the same grain.

(3) Host twin lamellae pass into the deformation band without deflection. They are off-set across a discrete discontinuity which lies parallel to the band boundaries and symmetrically divides the bands in two (Fig. 1A). Note that a deformation band of one type may change along its length into another (Fig. 1A).

(b) Mature deformation bands

Deformation bands of all three types undergo further mineralogical modification. Spherical beads of quartz (10 μm) form within the albitic band (Fig. 1C), irregularly distributed in single file along the centre of the band. At bead diameters greater than 40 μm small bulges or buds decorate the bead surfaces. Where the bead diameter attains 80—90% of the band width, beads are elongate along the trace of the band. The band boundaries may bulge adjacent to larger beads, suggesting that quartz bead formation locally modifies the boundary morphology, apparently at the expense of the host grain. The band core is therefore occupied by elongate sections of quartz, separated by bridges of albite. In type (2) bands, deflec-

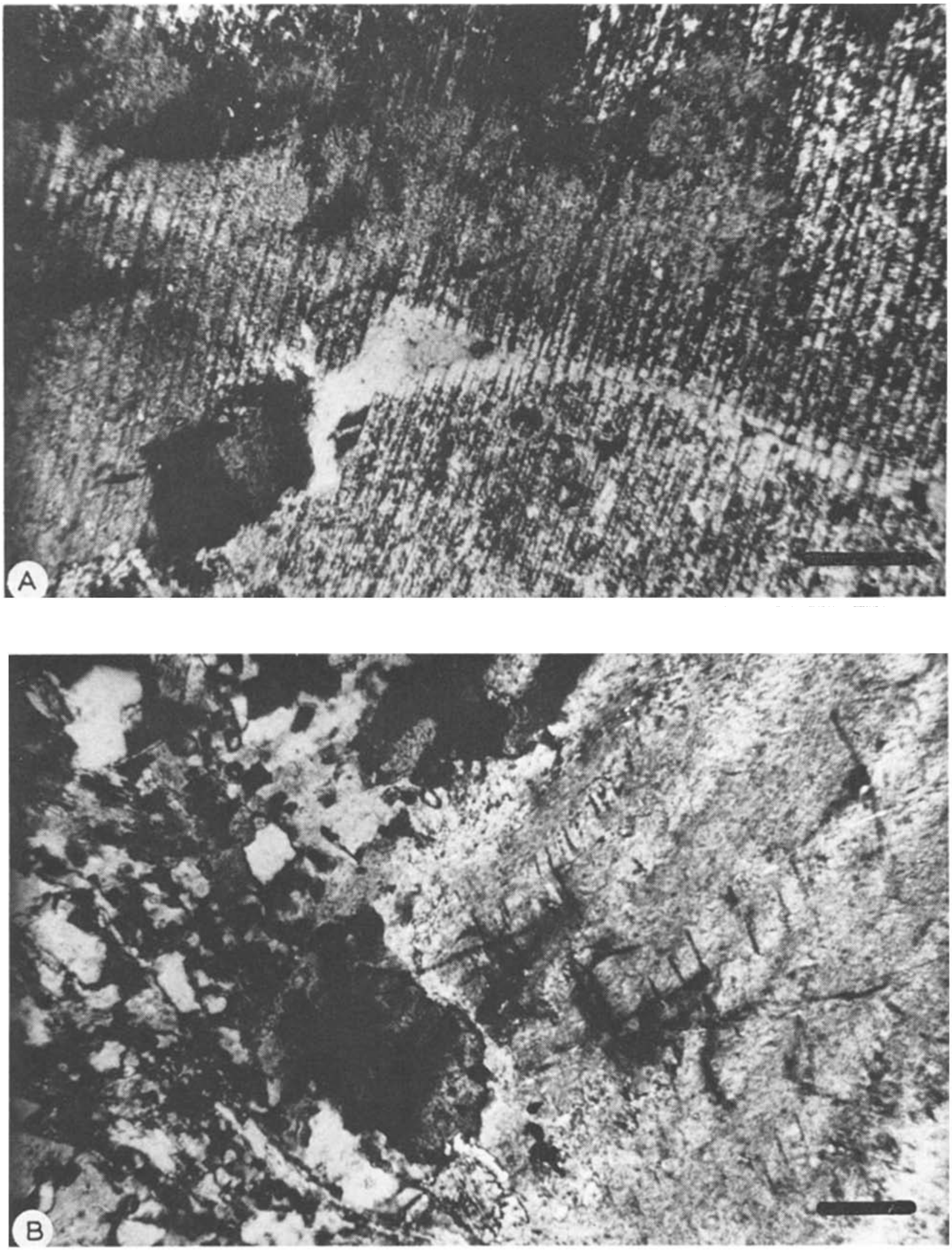
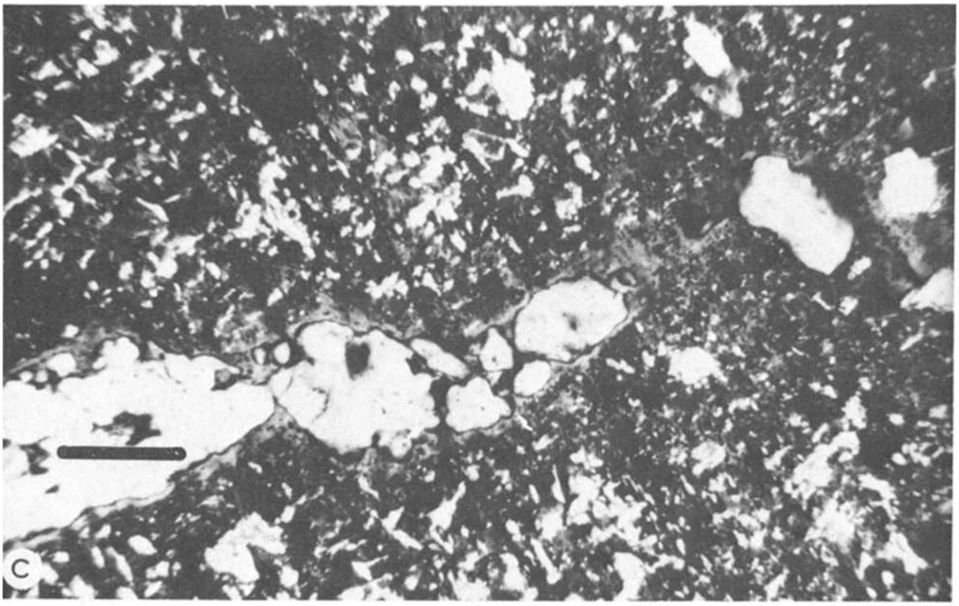


Fig. 1A,B. For legend see p. T57.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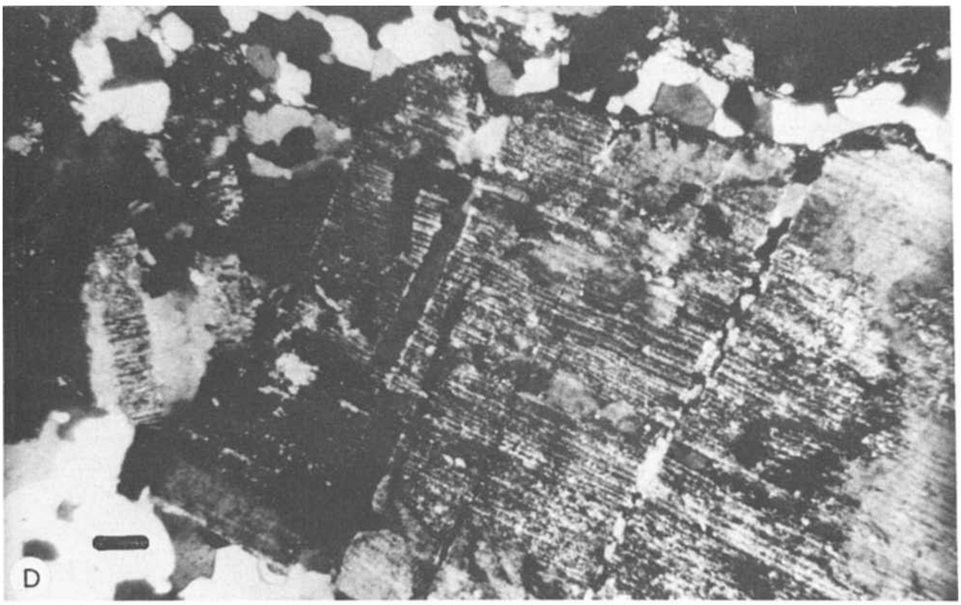
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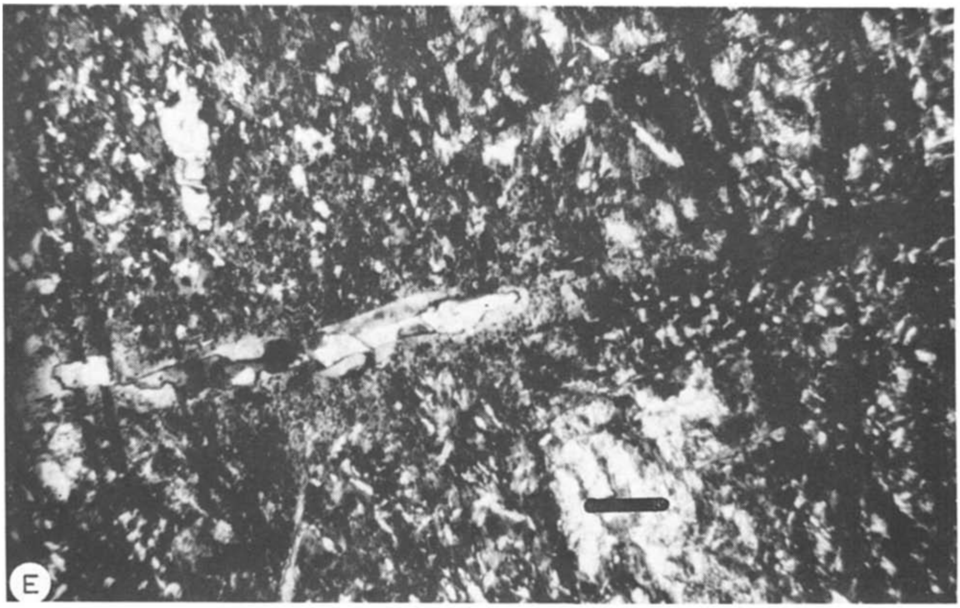

Fig. 1. Photomicrographs of segregation bands. A. Incipient stage. Note kink band (type 2) mode (upper left) passing into off-set (type 3) of host twins across discontinuity (lower right). Segregation band distinguished from host by sodic plagioclase composition and absence of impurities and sericite. B. En-echelon veinlets in zones aligned along plagioclase twins. Interpreted as sub-perpendicular to grain-scale maximum extension and indicating (010) slip, here sinistral. C. Quartz beads forming within sodic plagioclase, inclusion-free segregation band. Note buds on coalescing bead surfaces and persistance of sodic plagioclase selvedge. D. Mature segregation bands either intragranular (centre) or transgranular (centre right). Quartz core, either monocrystalline or polycrystalline, is bounded by thin sodic plagioclase selvedge. Note thin, discontinuous segregation band and numerous mild kinks between the two mature examples. E. Clinozoisite grain in inclusion and sericite-free sodic plagioclase segregation band. Scale bars 100 μm except 50 μm in C. See text.

tion of the twin lamellae and rounded kink hinges are visible within the bridges. Finally, the quartz may occupy all of the band core and be bounded symmetrically by continuous 5—10 μm wide albite selvedges (Fig. 1D). Chlorite, calcite, muscovite, epidote or clinozoisite may be associated with the quartz in the core (Fig. 1E).

ORIENTATION

The deformation bands make a variable angle (30°—90°) with the plane of maximum shear at the mesoscopic scale, but they generally lie at between 30°—45° (non-dihedral angle hence minimum) (Fig. 2). From the sense of shear (Hanmer, 1981), the deformation bands make a high angle with the instantaneous maximum extension direction (Ramsay and Graham,

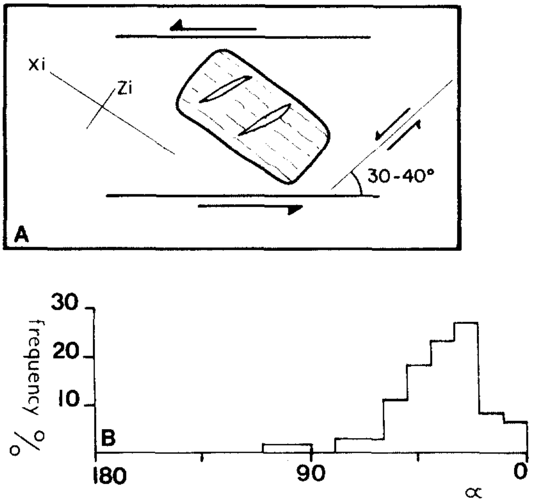

Fig. 2. A. Schematic angular relationships between plane of maximum bulk shear, instantaneous principal strains (left), shear band foliation (right), segregation bands and plagioclase (010) twin planes. Discussed in text. B. Frequency histogram of angle α between trace of segregation bands and maximum shear plane in a single thin section. Angles measured counter clockwise. 78 measurements, mean 36.9°; standard deviation 18.6°.

1970). Deformation bands, therefore, only form in suitably oriented grains. They also correspond in orientation and synthetic sense of shear (in types (2) and (3)) to a mesoscopic shear band foliation (White et al., 1980) in the same specimen (Fig. 2A).

GEOCHEMISTRY

Mineralogical modification of the host grains adjacent to the deformation bands was investigated using a microprobe, the details of which study will be presented elsewhere (Hanmer, in prep.). Briefly, the microprobe data (a) confirm the more sodic composition of the deformation bands and (b) establish the presence of concentration gradients for Ca and Na away from and towards the band boundaries respectively. These gradients are qualitatively compatible with the mineralogical modifications observed within the deformation bands and constitute the evidence for the role of diffusion in their formation.

DISCUSSION

Tension gashes are dilational structures associated with brittle failure (e.g., Beach, 1975; Knipe and White, 1979). The deformation bands of this study are not brittle fractures since: (a) The observed mineralogical modifications occur irrespective of band type and therefore cannot be specifically related to the discontinuities in type (3) bands. (b) The persistance of rounded kink hinges within the bridges of mature type (2) bands is not associated with brittle failure. (c) The discrete discontinuities of type (3) bands, although suggestive of fracturing, are microcracks which do not produce macroscopic fractures and therefore they are not unequivocal brittle structures (Paterson, 1978, p. 2). While a minor component of dilation within the size range of the incipient and mature bands (25—100 μm) cannot be excluded in the type (1) deformation bands, the existence of bridges and the persistance of rounded kink hinges and of discrete discontinuities within the bridges precludes dilation in bands of types (2) and (3).

The concentration gradients for Na and Ca indicate the role of diffusion in deformation band formation. At the initiation stage, the bands resemble those described by Vernon (1975) and White (1975). By analogy they are zones of high dislocation concentration. Dislocation concentrations are known to greatly facilitate diffusion (White, 1975). The mineralogical and geochemical modifications noted here suggest diffusion of alkalis and impurities across the band boundaries by strain enhanced diffusion (White, 1975; Barnett and Kerrich, 1980). An impurity segregation mechanism whereby vacancy-interstitial ion pairs diffuse towards dislocations (Byerly and Vogel, 1973; Petrovic, 1974; Knipe, 1980) would extend the radius of diffusion into the host grain, away from the deformation band. The presence of extra-granular water, indicated by the hydrous phases within the bands, will tend to enhance diffusion (White and Knipe, 1978).

Because of the inferred role of impurity segregation in the formation of these structures, it is proposed that they be called "segregation bands".

Finally, attention is drawn to the resemblance of quartz bead distribution, as described here, to the periodic microtubes associated with slip dislocations and microcracks (Forty and Forwood, 1963; Shirey et al., 1980).

CONCLUSIONS

Segregation bands in plagioclase initiate as microcracks or rounded kink bands in response to slip along the (010) plane. While type (2) and type (3) segregation bands are non-dilational, a minor component of dilation cannot be excluded for type (1) bands. Mechanical strain enhances ion impurity diffusion and the entry of water into the bands and leads to the observed mineralogical modifications within the bands. Studies of brittle-ductile behaviour in naturally deformed rocks should not always assume that intra- or transgranular quartz veins in feldspars represent brittle, dilational "tension gashes or cracks".

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