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Large-scale foliation boudinage in gneisses

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Abstract—Large-scale extensional structures in gneisses (symmetric and asymmetric foliation boudinage, *C′* type shears) are common in crustal-scale shear zones and may constitute shear criteria, as well as being indicators of high strain.

INTRODUCTION

THE DUCTILE deformation of layered rocks is mainly characterized by folding or boudinage of the competent layers. Boudinage, well documented in the literature (e.g. Cloos 1947, Hobbs *et al.* 1976), is related to the contrasting rheological behavior of layers of different viscosity (Wegman 1932, Ramberg 1955). By contrast, localized 'extensional' structures, resembling boudinage, occur in deformed homogeneous granitoid rocks; and these cannot be directly related to the stretching of initially more competent layers alternating with more ductile ones.

This paper draws attention to large-scale boudinage in gneisses, including foliation boudinage of the type described by Platt & Vissers (1980) at centimetre-scale and by Hambrey & Milnes (1975) at a larger scale in ice, and extensional shear zones: *C′* type shears (Berthé *et al.* 1979) or extensional crenulation cleavage (Platt & Vissers 1980). I emphasize that these large-scale structures are common in gneisses, particularly in crustal-scale shear zones, and may be reliable shear criteria.

GEOLOGICAL AND TECTONIC SETTING

The boudinage structures described here occur in part of the strongly deformed Cézarenque gneisses (Cévennes) lying south of, and structurally below, the Hercynian crustal-scale thrusts of the Massif-Central in France (Burg & Matte 1978). They have been considered as a slice of the basement of the Cévennes series (micaschists), either situated in the core of a recumbent fold (e.g. Burg & Matte 1978) or thrusted onto micaschists (Mattauer & Etchecopar 1976).

Strong ductile deformation has produced a pervasive foliation (Burg & Matte 1978) that is horizontal or dips gently (0–20°) N or E. A well-defined stretching lineation (*L*) trends 010° on average (Mattauer & Etchecopar 1976, Burg & Matte 1978, Lacassin & Van Den Driessche 1983).

Coherent shear criteria demonstrate the non-coaxial character of the deformation. These include strongly recrystallized feldspar porphyroclast systems (Lagarde 1978, Simpson & Schmid 1983, Passchier & Simpson 1986, Van Den Driessche 1986a) either with a sigmoidal shape synthetic to the bulk shear sense, or with an internal shape asymmetry in which the tails form incipient rolling structures (Passchier & Simpson 1986, Van Den Driessche 1986a). Other shear criteria, such as rare *C′* planes or sheared quartz veins, are consistent with the porphyroclast asymmetry. Shear senses are commonly southwards despite the local occurrence of antithetic shear senses. Every outcrop described here was affected by southward shearing.

FOLIATION BOUDINAGE AND EXTENSIONAL STRUCTURES

Foliation boudinage at decametre-scale, together with smaller structures, can be observed on continuous cross-sections parallel or perpendicular to N–S lineations. In all sections parallel to *L* the various geometries described below are shown. Larger extensional structures (100 m at least) are suggested by undulations of the foliation, forming fish-like pods separated by shear zones.

Symmetric foliation boudinage

Symmetric foliation boudinage is characterized by fractures, almost perpendicular to the foliation, filled by quartz. Structures are comparable on both sides of the fracture zone (Fig. 5), which constitutes a symmetry plane (orthorhombic). Foliation pinches in towards the quartz-filled void sometimes to the point that the boudin resembles a fold. Several geometries can be observed from incipient to mature boudinage.

The first stage is characterized by quartz-filled gashes (Fig. 1a), almost perpendicular to the foliation. These gashes separate boudins 1–10 m long, with only slight pinching of the foliation. During progressive boudinage, the gashes widen and fill with large quartz masses of square or irregular shape, sometimes with tails, parallel to the foliation, which penetrate into the boudin core (Fig. 1b). Late gashes may grow away from the earlier quartz fills; they are often oblique to the foliation, generally inclined S, and may form 'star-like' structures with three or four branches (Fig. 4b). Gashes, fractures zones and boudin noses are perpendicular to the lineation, so the extension accommodated by boudinage is parallel to the lineations.

Asymmetric extensional structures

Asymmetric foliation boudinage passing into ductile shear zones (Figs. 2 and 4a), also on a decametre-scale, are characterized by oblique shear or fracture planes dipping 20–50°, and an asymmetric pinching of the foliation which gives the system a monoclinic symmetry (Fig. 5). Quartz-filled voids are smaller than in symmetric boudinage. Intermediate boudinage structures (between symmetric and asymmetric patterns) are often observed as well as an asymmetric evolution of initial symmetric boudins (Fig. 3).

Most of these asymmetric extensional structures have fracture planes inclined to the south (Figs. 2, 4a and 5), so that the down-dip movements are synthetic to the bulk sense of shear. Nevertheless, there are some N-dipping structures in restricted areas, or in association with S-dipping ones, thus forming symmetric extensional systems at a larger scale. In all cases, the extension resulting from these structures is parallel to the lineation.

Shear criteria

These boudinage patterns are related to the kinematics of deformation and may be used as shear criteria (Fig. 5) like other boudinage structures (Hanmer 1986).

(1) Late tension gashes inclined towards the south, and probably parallel to σ_1, suggest southward shearing. Note, however, that ambiguity may arise with earlier gashes rotated in the same sense as the shear flow.

(2) Most asymmetric structures (foliation boudinage, Fig. 2, which can be interpreted as incipient shear zones, and ductile shear zones between sigmoidal pods of gneiss, Fig. 4a) are synthetic to the bulk shear sense (e.g. Platt & Vissers 1980, Platt 1984, Gaudemer & Tapponnier 1987).

(3) Strings of boudins commonly have geometries indicative of the shear sense (Fig. 4b): boudin noses and quartz fills are connected by extensional shears synthetic to the bulk shear sense.

CONCLUSION

The part of the Cévennes gneisses described here is affected by an intense S-directed shear subparallel to a N–S to NNE–SSW stretching lineation. Various extensional structures (Fig. 5) formed progressively during this deformation and affect the gneisses on the scale of 1–10 m or more. Such structures are symmetric and asymmetric foliation boudinage, 'extensional' shear zones and tension gashes. They result from extension subparallel to the ductile stretching lineation. The general occurrence of many S-dipping ductile shear zones with down-dip displacements, demonstrates that the boudinage occurred (probably late) during the progressive shearing.

Such large-scale 'extensional' structures are observed in many crustal-scale shear zones, generally with a mixture of symmetric and asymmetric structures (e.g. Quinquis 1980, Van den Driessche 1986b, Gaudemer & Tapponnier 1987) and are generally synthetic to the bulk sense of shear, rarely antithetic. They do not constitute criteria of regional flattening. I emphasize that some of the structures described here may be used as shear criteria (Fig. 5). I think also that such structures probably affect highly deformed rocks only; indeed they require particular mechanisms to form, such as the occurrence of a strong foliation anisotropy (Platt & Vissers, 1980) or strain softening–hardening processes in an initially homogeneous rock.

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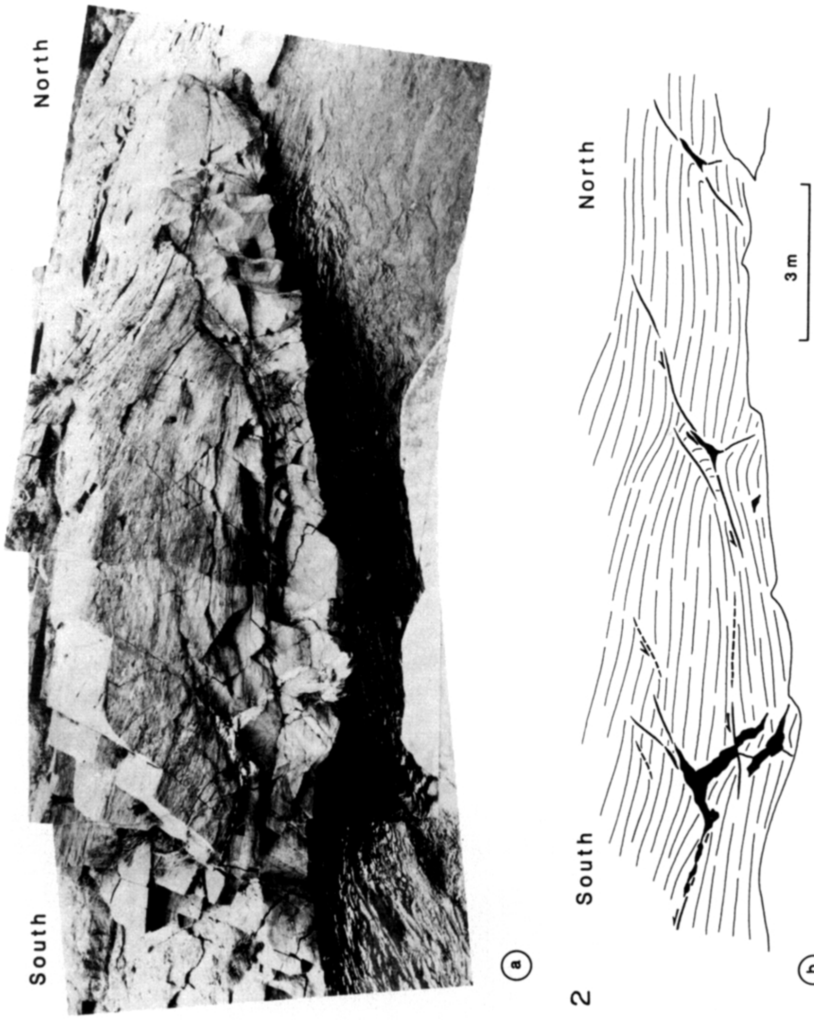

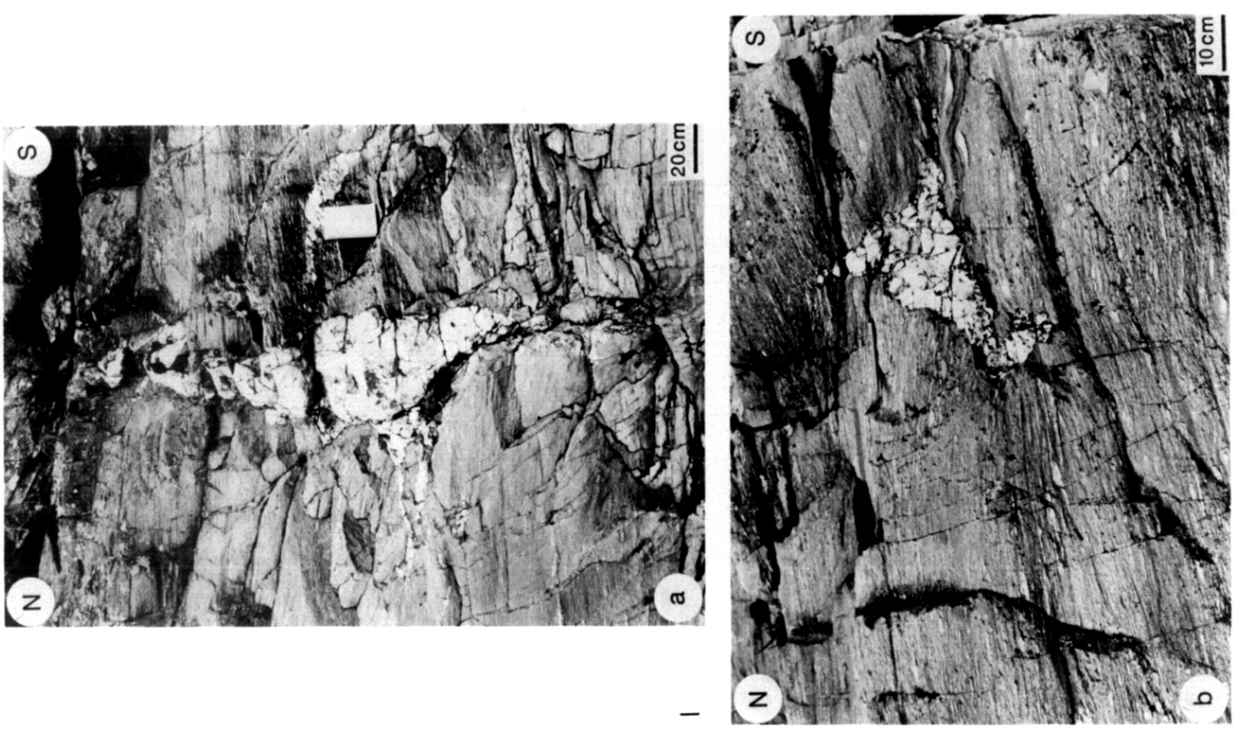

Fig. 1. (Left) Symmetric foliation boudinage in gneisses: (a) incipient; (b) mature boudinage with pinched-in foliation.

Fig. 2. (Above) Asymmetric foliation boudinage at decametre-scale. Sketch drawing (b) restores optical distortions due to perspective in (a).

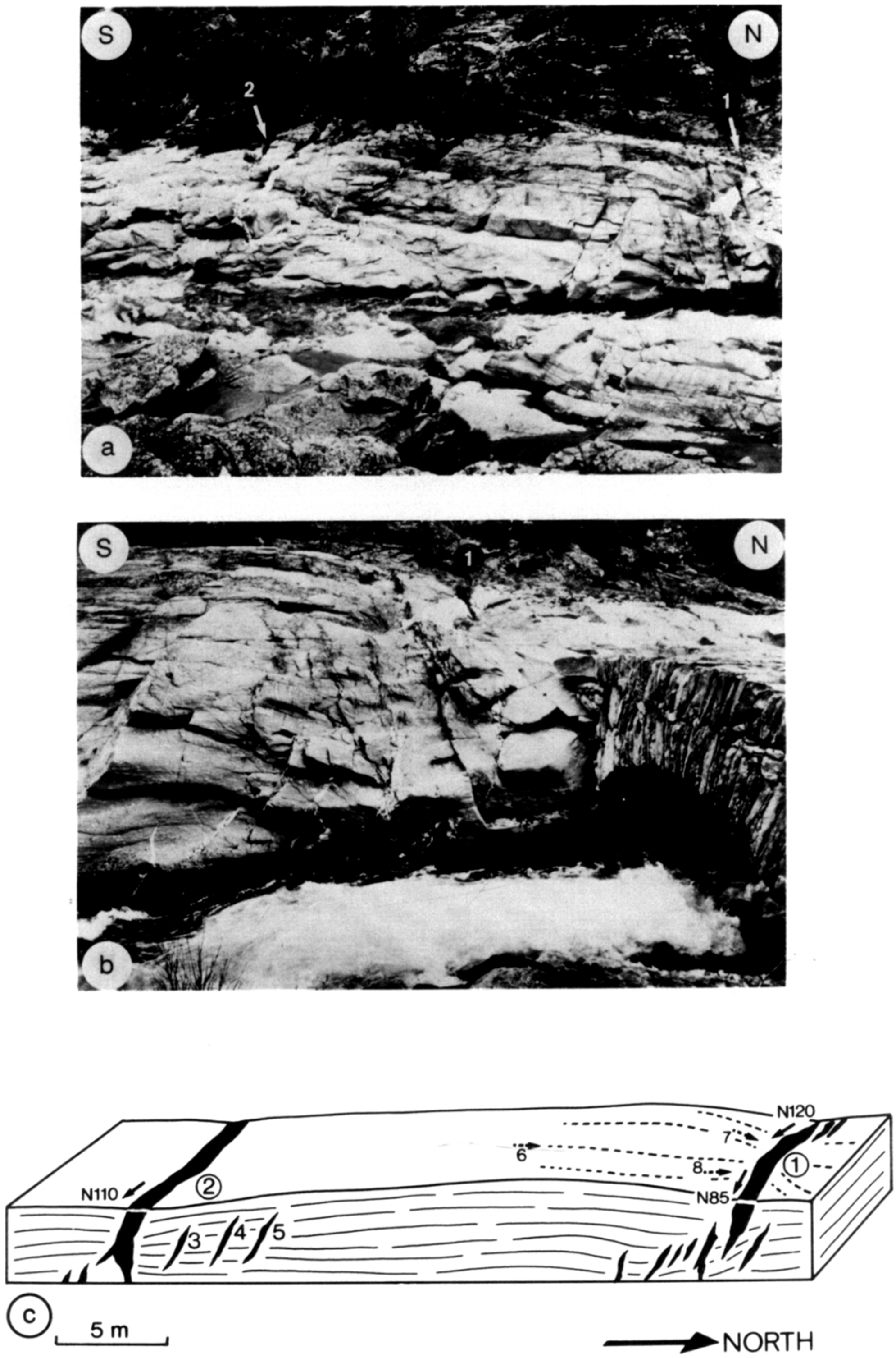

Fig. 3. Incipient boudinage at decametre-scale, of type intermediate between symmetric and asymmetric structures. (a) General view; large quartz-filled gashes (1 and 2), slightly inclined to the foliation, separate large boudins of almost symmetrical shape. (b) Detail of metre-scale gashes. (c) Schematic 3-D view: 1 and 2, large gashes; 3, 4 and 5, small gashes oblique to foliation, respectively, N 98°, N 105° and N 100° in direction, suggest S-directed shear; 6, 7 and 8, lineation directions, respectively, 005°, 035° and 175°; lineation trend is schematized by dashed lines showing 005° directions perturbed toward boudin noses.

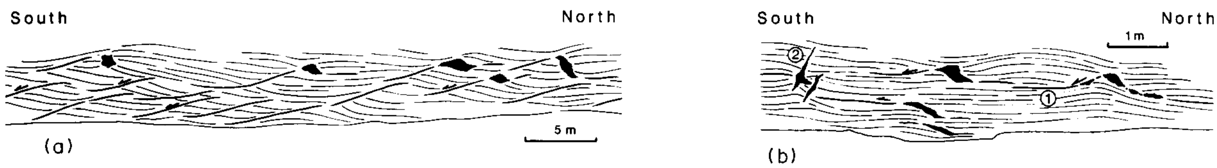

Fig. 4. Asymmetric 'extensional' structures observed on 10 m-scale cross-sections. (a) Asymmetric foliation boudinage passing to C' type shears. (b) Geometry of strings of boudins; quartz rhombs and boudin noses are connected by asymmetric fracture zones (1). Note (2) 'star-like' structure and oblique gashes.

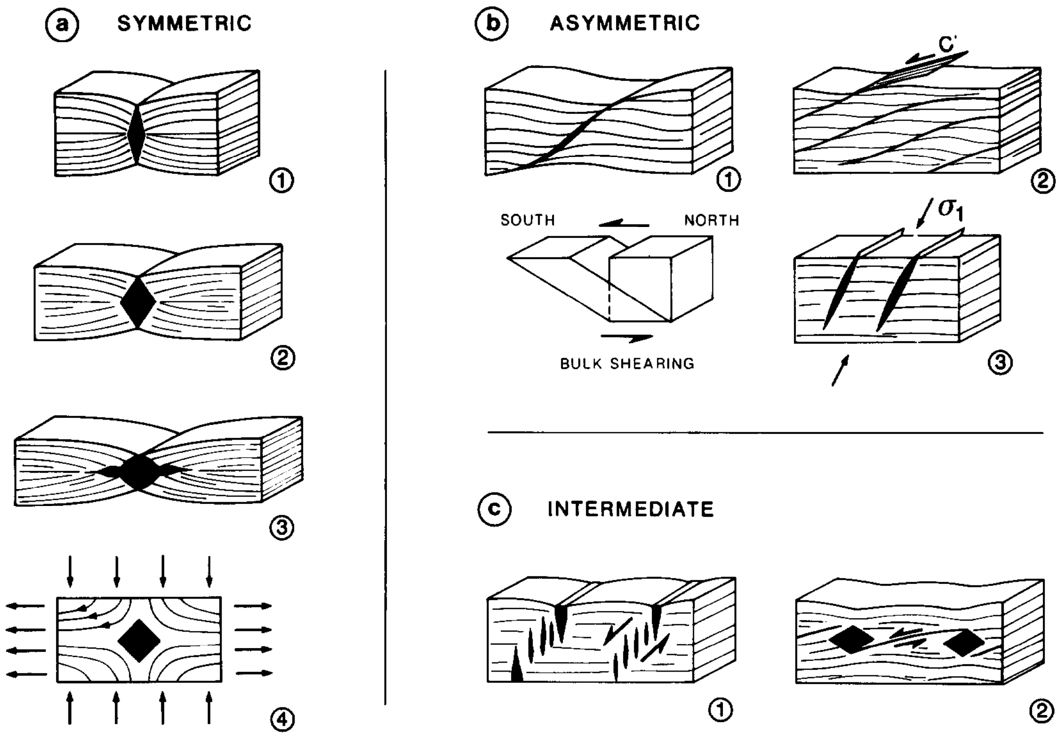

Fig. 5. Kinematic significance of different boudinage patterns observed in Cézarenque gneisses. (a) Progressive development (1–3) of symmetric foliation boudinage, compared to ductile flow during pure shear (4); symmetric boudinage thus suggests foliation-parallel extension. (b) Asymmetric 'extensional' structures, generally synthetic to the bulk sense of shear, may be accounted for by simple shear. 1, asymmetric foliation boudinage; 2, C' type shear zones; 3, late oblique gashes. (c) Intermediate structures suggest asymmetric evolution of early symmetric structures. Asymmetry is synthetic to the shear sense. 1, en échelon gashes in boudin noses (Fig. 3); 2, asymmetric strings of boudins (Fig. 4b).