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'Bone-shaped' boudins in progressive shearing

J. MALAVIEILLE

Laboratoire de Géologie Structurale, Université des Sciences et Techniques du Languedoc, Place E. Bataillon, 34060 Montpellier-Cédex, France

and

R. LACASSIN

Laboratoire de Tectonique, Mécanique de la Lithosphère, Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cédex 05, France

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Abstract—Some peculiar 'bone-shaped' boudins are observed in two areas of progressive shearing. They are characterized by large quartz-filled gashes that separate thinner boudins. These gashes often have a consistent obliquity, suggesting a rotation synthetic to the shear sense. These may be formed by rigid material that crystallizes in tension gashes between the boudins; during further ongoing deformation these behaved as rigid inclusions in a more ductile matrix and show systematic rotations. The sense of rotation of the gashes constitutes a shear criterion.

INTRODUCTION

THE term 'boudinage' is often used for any structures produced by heterogeneous extension of various markers in deformed rocks: stretched competent layers, fractured objects (pebbles, minerals, fossils) or 'extensional' structures in strongly foliated mylonite. In a more restrictive sense, 'boudinage' describes the deformation of extended layers that are less ductile than the surrounding matrix. The competent layers are fractured and the fragments progressively separated (Lohest 1909, Cloos 1947, Ramberg 1955).

Various geometries may form according to the relative importance of brittle vs ductile behaviour of the layers (e.g. Ramberg 1955, Talbot 1970, Smith 1975, 1977, Fullagar 1980, Lloyd & Ferguson 1981, Lloyd *et al.* 1982).

(a) If the competent layer is mainly brittle, it fractures under tensile stress to form rectangular-shaped boudins (Ramberg 1955); the further separation of fragments is accommodated by ductile flow of the matrix and/or crystallization of material in the gaps between the boudins.

(b) On the other hand, if the stretched layer is mainly ductile (but less so than the matrix) it forms pinch-and-swell structures (Smith 1975, 1977, Van der Molen 1985). Generally, extension fracture boudinage (brittle) is associated with ductile necking prior to or after fracturing. These combined mechanisms give the generally observed basic characters of boudinage, which are thick bi-convex boudins separated by thinner interboudin zones (Fig. 1a).

This paper focuses on the remarkable 'bone-shape' of some boudins which are characterized by thin concave boudin elements and thick interboudin zones (Fig. 1b). We discuss different possible mechanisms to explain the observed structures and present a progressive deformation model which involves: (1) extension-fracture boudinage with the formation of crystalline fill in the interboudin zone; (2) rotation of these gashes during the ongoing shearing; and (3) thinning of the previously-formed boudin elements. We suggest that this type of boudinage can help to determine the non-coaxial character of the deformation.

GEOLOGICAL SETTING

The examples of boudinage presented here are taken from two metamorphic core complexes of the eastern Basin and Range province, situated close to the Utah–Nevada border (U.S.A.) (Fig. 2a). The first example comes from the southern Deep Creek Range (Fig. 2b), where the flyschoid Precambrian series displays alternating centimeter- to decimeter-scale silt and phyllitic

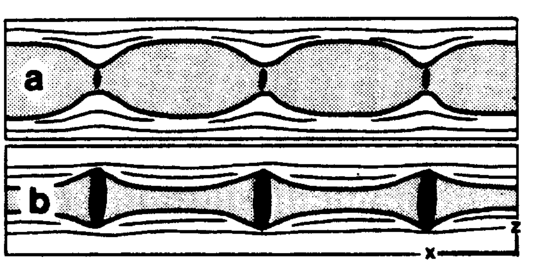

Fig. 1. Two contrasting shapes of boudins. (a) 'Classical' bi-convex shape, extension fractures are associated with pinch-and-swell. (b) 'Bone-shaped' concave boudins described here.

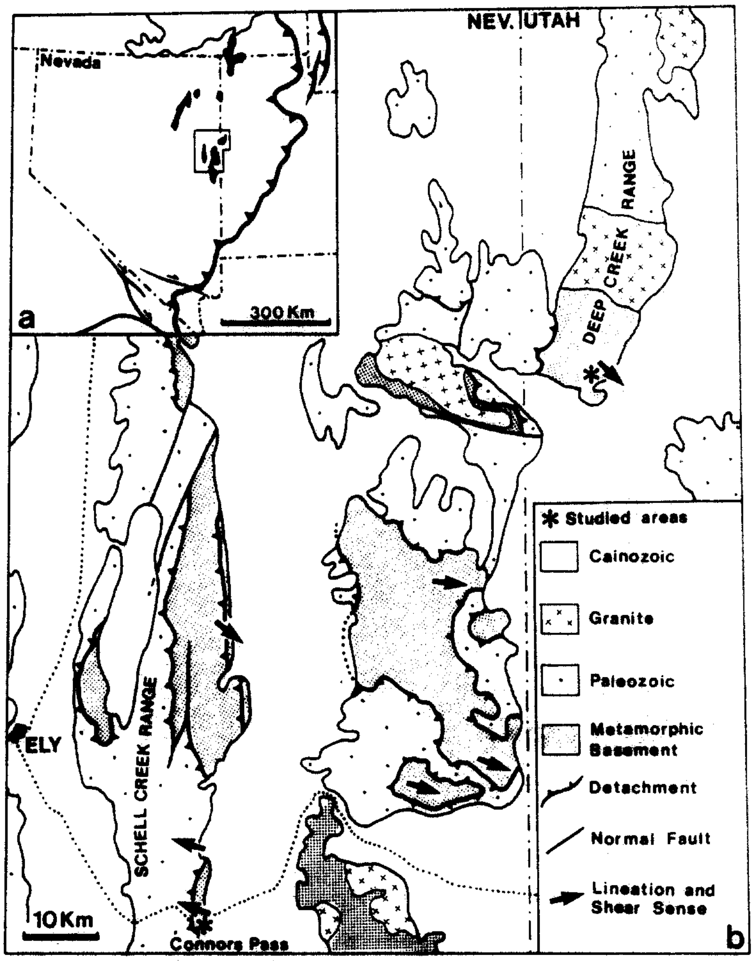

Fig. 2. Schematic structural map. Studied areas are located by asterisks; arrows show shear senses. Insert (a) shows location of structural map (b) in Basin and Range province.

layers deformed under upper greenschist conditions (Misch 1960, Misch & Hazzard 1962, Nelson 1969). The second area is situated in the Schell Creek Range (Fig. 2b) (Nevada) along the Connors Pass road. The Cambrian black shales with thin layers of dark grey limestones have been deformed under epizonal conditions (Drewes 1967).

Both areas are characterized by well developed cleavage or foliation at a low angle to the sedimentary bedding. In the Deep Creek Range, the foliation and stratification dip 50° NE in the northern limb of a kilometer-scale upright antiform (Nelson 1969). Strong lineations are defined by elongated pressure shadows of quartz and/or micas on garnets, stretched porphyroclasts such as andalusite, and elongated metamorphic minerals; they trend N135°E on average.

In the Schell Creek Range, the whole lithological series dips gently W. Along Connors Pass road, the cleavage and stratification dips 15° SSW on average. N110°E lineations are marked by elongate pressure-shadows of quartz or calcite on pyrite porphyroclasts and by elongate detrital clasts.

Consistent shear criteria demonstrate the non-coaxial character of the deformation (Malavieille 1987). In the Deep Creek Range (Fig. 3a), an eastward sense of shear (prior to the large-scale antiformal folding) is demonstrated by C and C' planes (Fig. 4a) (Berthé *et al.* 1979), asymmetric pressure-shadow crystallizations (Fig. 4b) (Malavieille *et al.* 1982, Etchecopar & Malavieille 1987), rotated porphyroclasts (Fig. 4c) (Passchier & Simpson 1986) and a uniform sense of overturned small-scale isoclinal folds. In the Schell Creek Range (Fig. 3b), a vertical section across the Cambrian carbonate series shows gradients of deformation accounted for by westward shearing. Slightly deformed areas are characterized by incipient cleavage oblique ($\approx$30°) to the bedding (Fig. 4d), and more deformed domains by well developed cleavage at a low angle ($<$10°) to the bedding. Small-scale shear criteria (mainly pressure shadows around pyrite crystals) also indicate W-directed shear.

BOUDINAGE GEOMETRY

In the two studied areas, the competent layers are stretched in the XZ plane (Fig. 7) and show separated boudin elements with a crystalline fill of quartz in the interboudin-gaps (Figs. 5 and 6). No boudinage is observed in the YZ sections, suggesting no elongation along the Y axis. Two main geometries of boudinage are observed: 'bone-shaped' boudins with large oblique

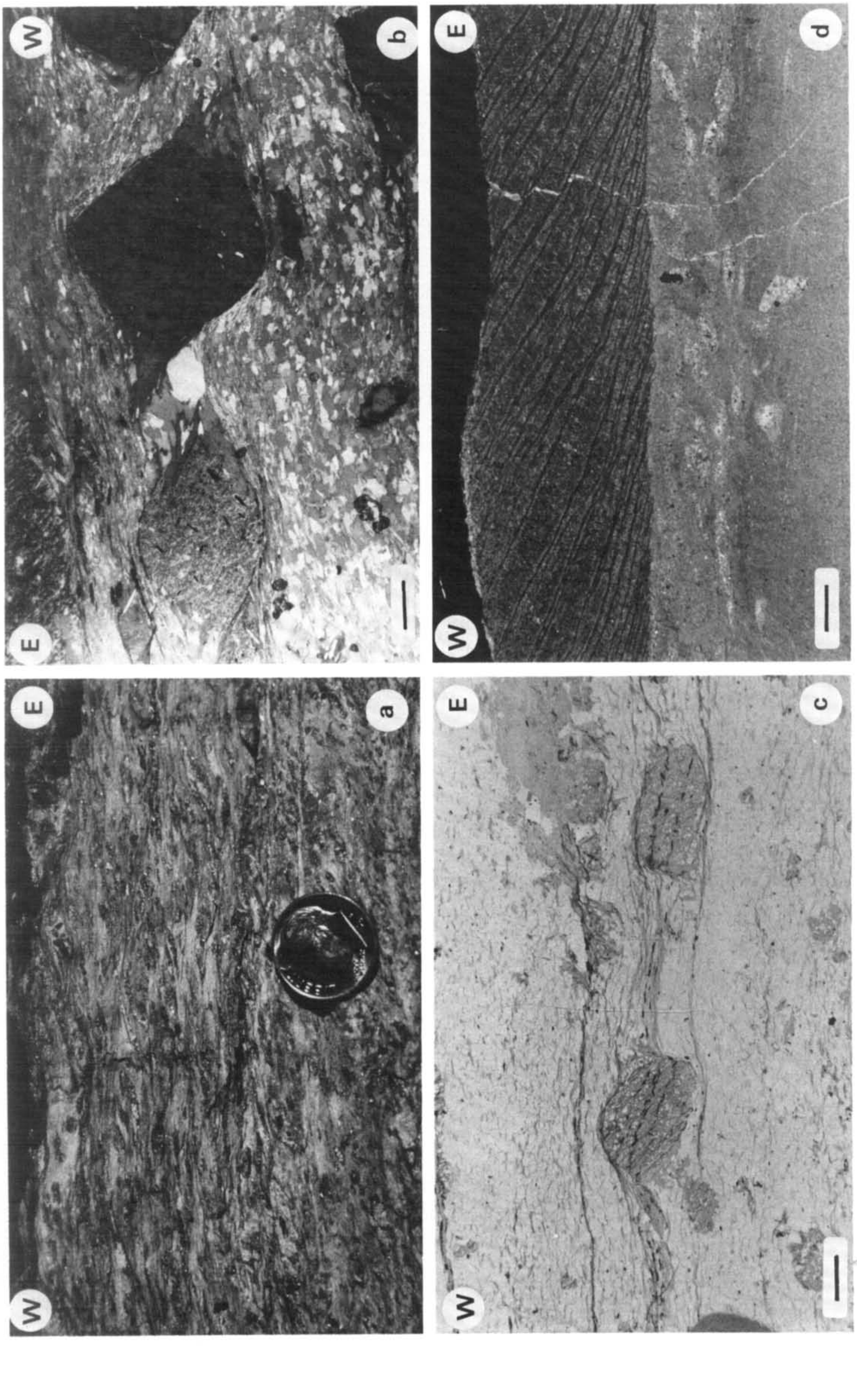

Fig. 4. Microstructural shear criteria. (a) C planes in paragneisses of Deep Creek Range; (b) asymmetric pressure shadows around garnets (Deep Creek Range); (c) rotated garnets (Deep Creek Range); (d) incipient cleavage in phyllitic layer (upper part of photograph), in weakly deformed area of the Schell Creek Range.

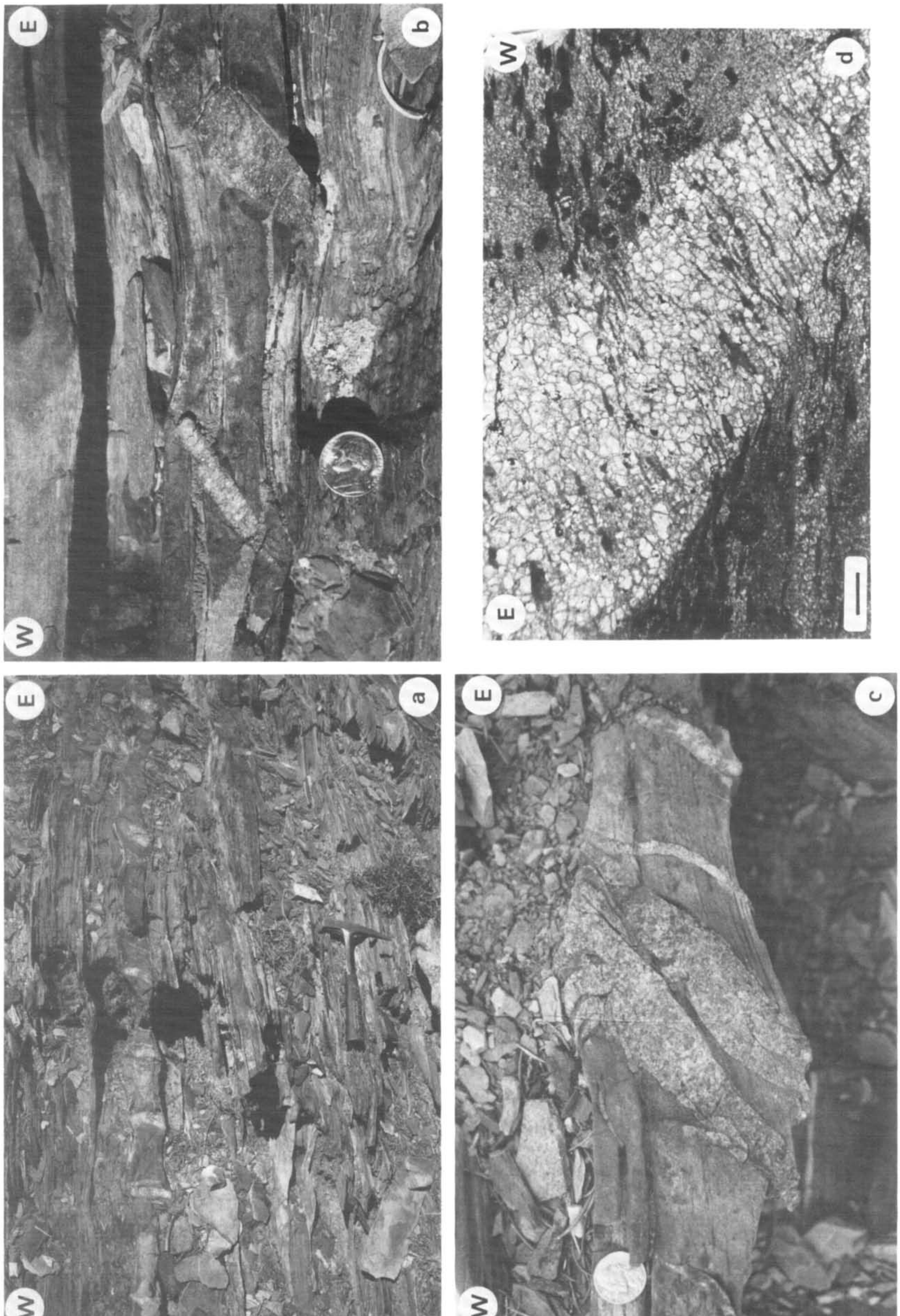

Fig. 5. Boudinage in the Deep Creek Range. (a) Example of trails of 'bone-shaped' boudins, note sigmoidal (on left-hand side) or inclined (on right-hand side) quartz fills; (b) and (c) inclined quartz fills between 'bone-shaped' boudins; (d) microstructure of quartz-filled gash, note rotated internal cleavage planes in the coarse-grained fill (scale bar = 5 mm).

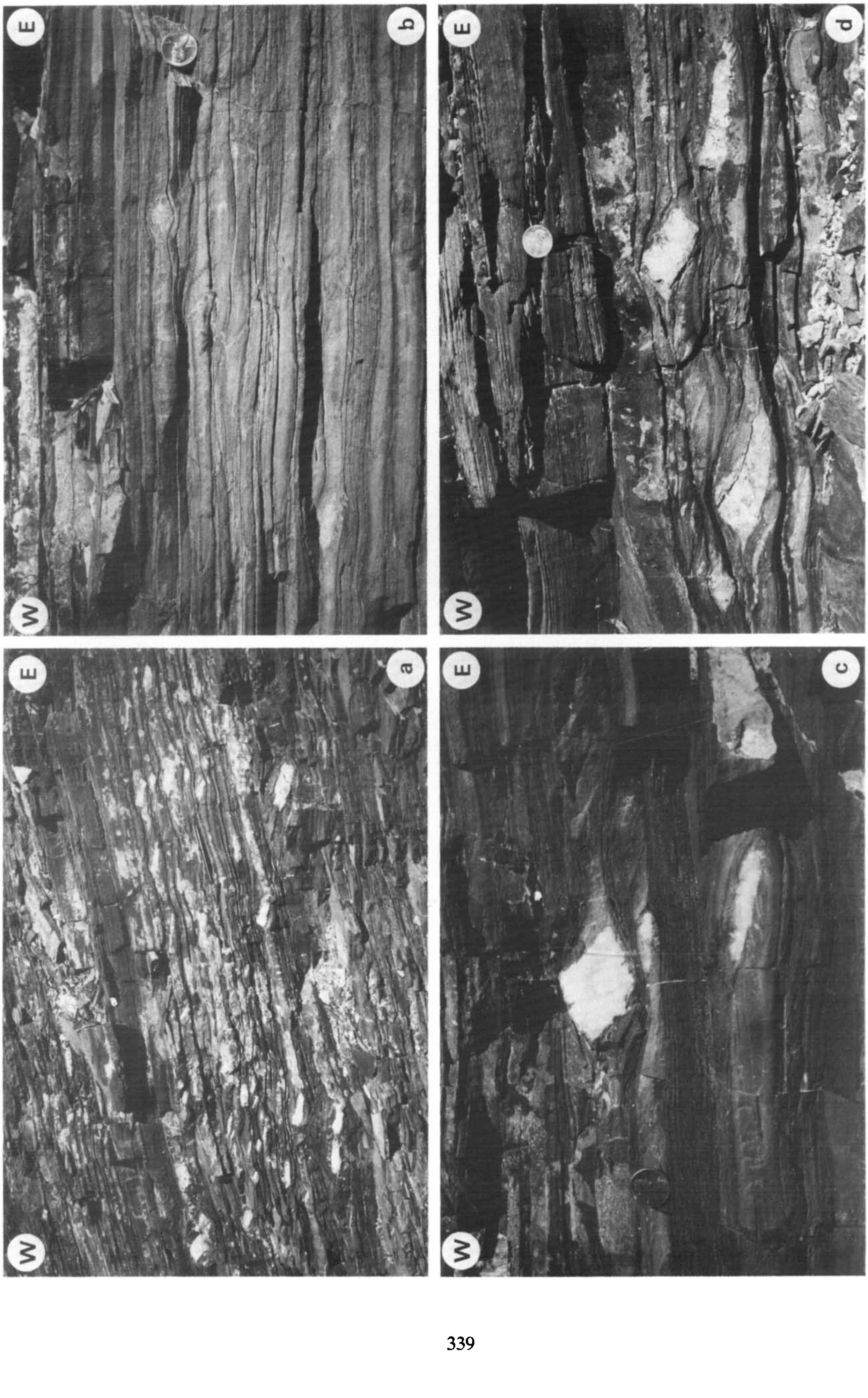

Fig. 6. Boudinage in the Schell Creek Range. (a) Meter-scale view showing consistent obliquity of quartz fills; (b)–(d). boudinage geometry; note large inclined quartz fills of rhomboidal shape.

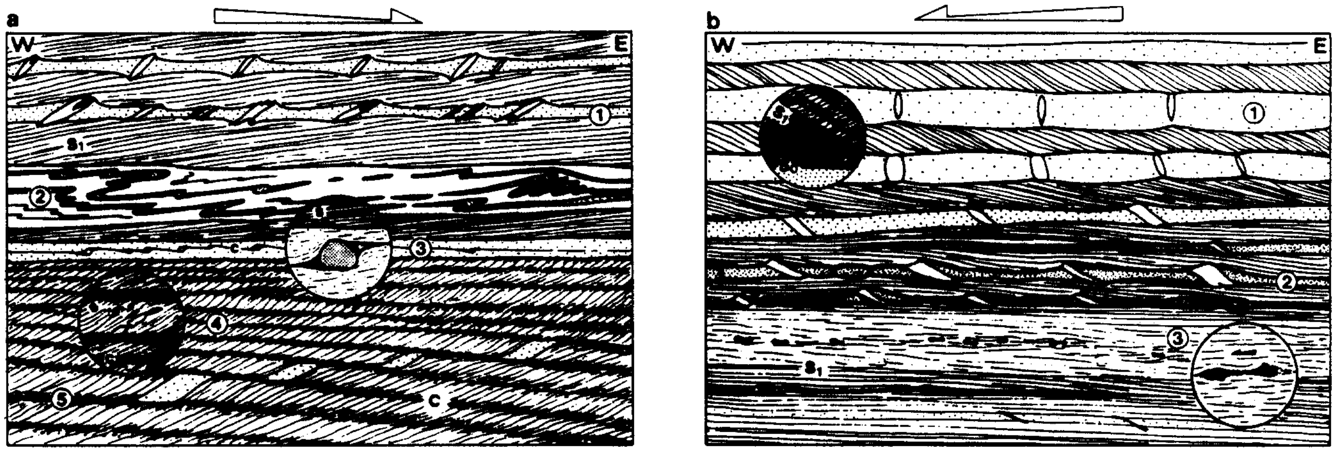

Fig. 3. Deformation geometry in the studied shear zones (synthesis of several outcrops, not to scale). (a) East-directed shear in the Deep Creek Range accounts for the following features: (1) S_1 oblique to extended layers which form 'bone-shaped' boudins; (2) overturned folds (see Figs. 5a and 8a); (3) asymmetric pressure shadows around garnets (see Fig. 4b), (4) *C-S* microstructures in paragneisses (see Fig. 4a); and (5) sheared quartz veins. (b) West-directed shear in the Schell Creek Range is indicated by: (1) S_1 oblique to bedding in less deformed areas (see Fig. 4d); (2) obliquity of S_1 is strongly reduced in more deformed areas where 'bone-shaped' boudinage is observed; and (3) asymmetric pressure-shadows around pyrites. In both areas, note the consistent obliquity of quartz-filled gashes in 'bone-shaped' boudins.

quartz gashes; and smaller boudins, with gashes perpendicular to bedding, associated with necking.

The first and most obvious type is characterized by the protuberances formed by the quartz gashes between thinner boudin elements of concave shape, resembling strings of bones. The interboudin fill is on average twice as thick as the center of the boudin elements. The length to thickness ratio of the observed 'bone-shaped' boudin elements is generally between 3 and 6 at Deep Creek, and between 5 and 10 at Schell Creek. In the cleavage plane, the intersection of the quartz gashes is often oblique to the stretching lineations, with an angle close to 70° (Fig. 7). If this angle is primary it would suggest that interboudin fractures might be the site of initial 'Lüders bands' (Burg & Harris 1982).

The quartz crystalline fills in the interboudin gaps present various geometries.

In the Deep Creek Range, the gashes are few cms thick and are always restricted to the quartzitic layers. The most common patterns are straight overturned gashes with consistent obliquities (Figs. 5b, 5c and 8). They are always more inclined to the west than the bedding: the inclination angle varies from 90° up to 30°. Some other gashes present an 'S-shaped' sigmoidal fabric, or are gently folded (Figs. 5a and 8a). The quartz crystals filling the gashes are very coarse (0.5–2 mm) in comparison to the fine-grained quartzitic beds, and are slightly deformed, mainly by cataclasis. Subtle internal cleavage planes, marked in the gashes by micas, are oblique to the adjacent planes in the quartzite (Fig. 5d). They are inherited from that of the wall rock and have thus been rotated with rotation of the gash.

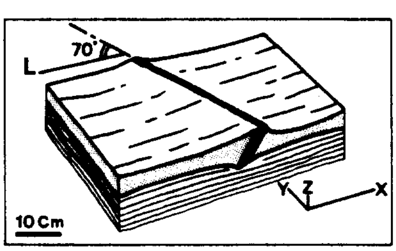

Fig. 7. Three-dimensional drawing showing obliquity of gashes relative to the stretching lineation on the *XY* plane.

In the Schell Creek Range, the boudinage is characterized by large rhomboidal quartz fills inclined towards the east (their inclination relative to the bedding varies from 60° to 20°), and scarce thinner overturned gashes (Figs. 6 and 9). The common asymmetric shape of the quartz fills (Figs. 6 and 9) suggests deformation and rotation of the gashes towards the west.

The second geometry of boudinage, observed in the same layers, affects the previously formed 'bone-shaped' boudins and probably corresponds to the initial stages of boudinage. The new boudin elements present the classical bi-convex shape with slight necking of interboudin zones (Figs. 6d and 9b). The thin quartz gashes are straight or slightly sigmoidal, irregularly spaced and subperpendicular to the bedding. Locally, some late gashes cross-cut earlier deformed ones.

DISCUSSION

In the two areas studied here, the deformation is characterized by a significant stretching marked by lineations and boudinage. The observed lack of extension along the *Y* axis suggests plane strain. The regional consistency of the shear criteria in both areas indicates a non-coaxial deformation regime: shear senses are towards the west in the Schell Creek Range, and towards the southeast in the Deep Creek Range. At the regional to outcrop scale, variations in strain intensity occurred normal to the bedding with consistent relations between cleavage and bedding plane. Small-scale shear zones and *C*-planes are generally parallel to the bedding (Fig. 3).

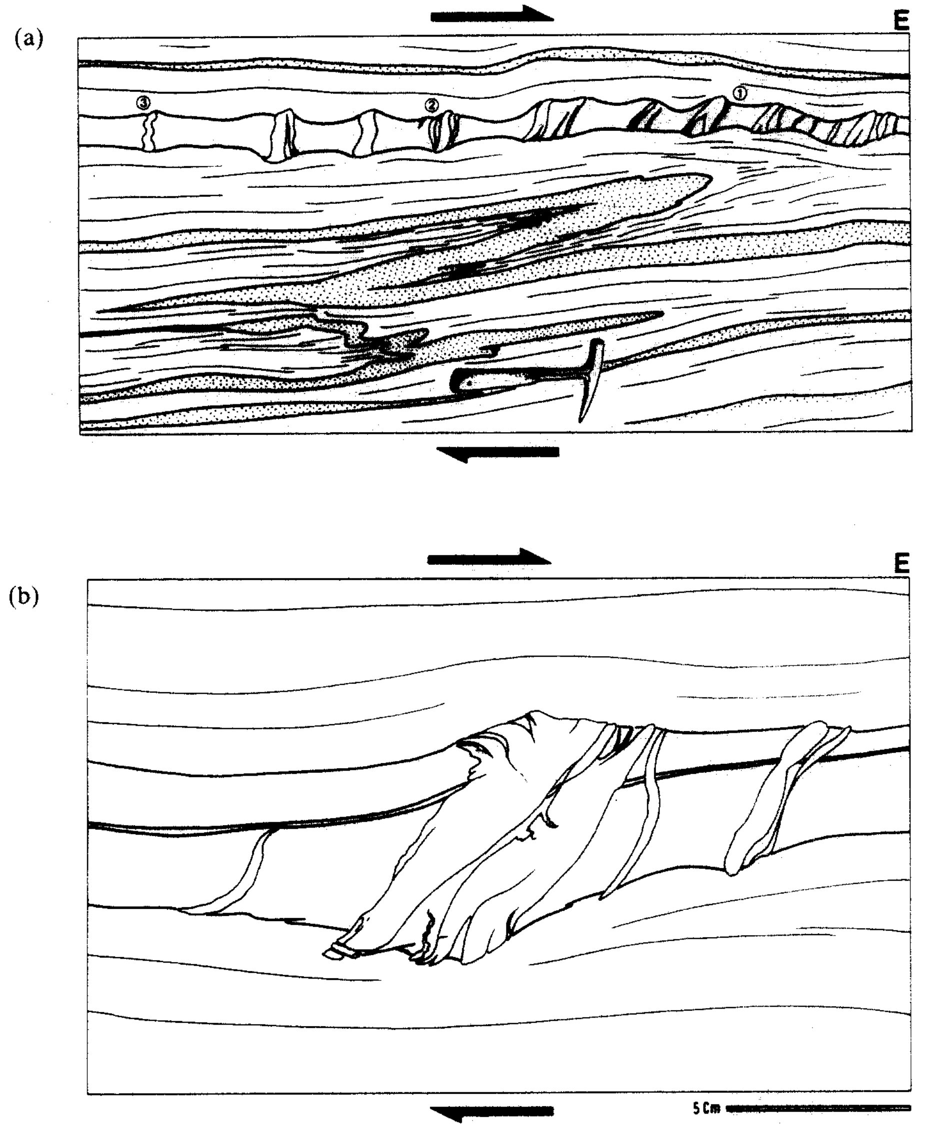

Fig. 8. Sketches of Figs. 5(a) & (c). (a) Quartz-filled gashes, generally overturned (1), may also be sigmoidal (2) or folded (3); note overturned folds. (b) Typical 'bone-shaped' boudins with overturned gashes.

Figure 10 summarizes the different possible deformation regimes. Note that simple shearing of inclined layers (Fig. 10b) does not account for the parallelism of shear plane and bedding deduced from microstructural observations. On the other hand, layers parallel to the shear plane should not extend during simple shearing (Fig. 10a). The superposition of coeval or alternating simple shear and pure shear is thus required to explain respectively the non-coaxial regime, and the extension of layers parallel to shear plane (Fig. 10c).

The mature boudins described here are mainly characterized by their 'bone-shape' and by overturned or sigmoidal gashes. In both areas, the poles to these oblique gashes are systematically situated in the instantaneous shortening field for simple shearing. This could be explained in several ways.

(1) The gashes formed oblique to the bedding as tension gashes parallel to σ_1. In this case, they must have been strongly rotated to fit the observed geometry.

(2) The gashes may have formed with the presently observed obliquity, parallel to cleavage planes refracted in competent layers. These refracted planes could then have been pulled apart during dominant layer-normal pure shear. This is unlikely to have formed the oblique cleavage and the observed shear criteria, however. Furthermore, the gashes obviously cross-cut the cleavage planes.

(3) Another approach would be to compare the 'bone-shaped' boudinage to asymmetric foliation boudinage (Platt & Vissers 1980). In this case shear fractures form synthetic to the bulk shearing (Platt & Vissers 1980, Gaudemer & Tapponnier 1987). This is in strong disagreement with several characters observed here: (a) the gashes would have been formed in shear fractures antithetic to the bulk shear sense; (b) the obliquity between the gashes and the bedding varies from 90° up to 20°, whereas shear fractures are likely to occur with a maximum inclination of 45° relative to the bedding (Murrell 1977); (c) the significant opening of the interboudin zones observed here is not observed in asymmet-

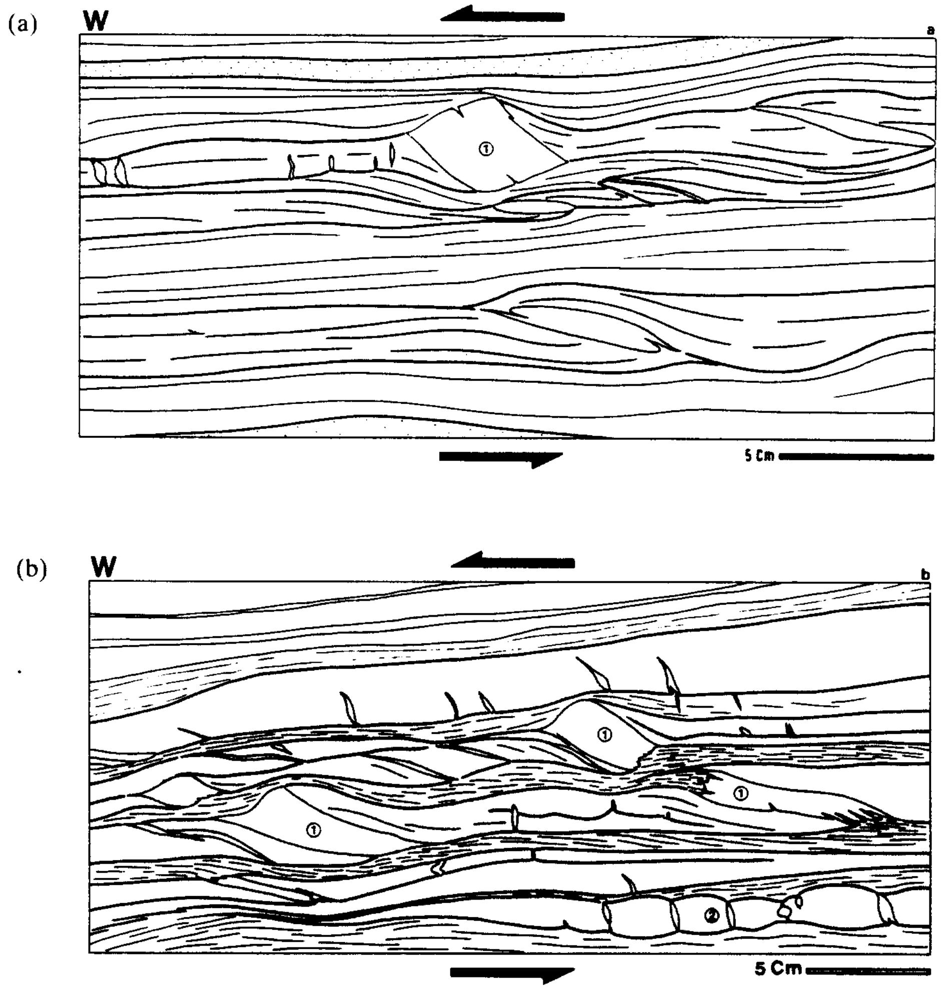

Fig. 9. Sketches of Figs. 6(c) & (d). (a) Quartz infill with rhomboidal shape (1); (b) late gashes (2) between 'classical' bi-convex boudins.

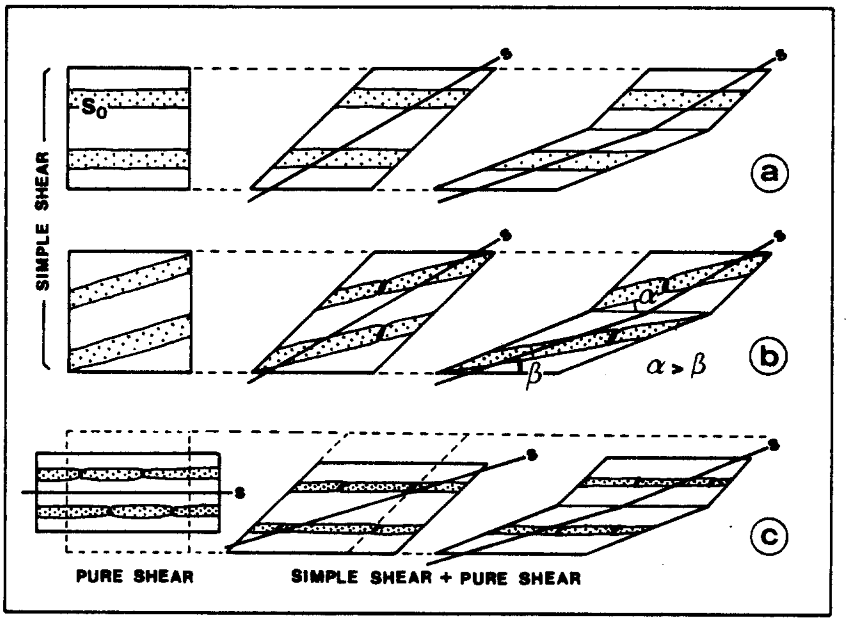

Fig. 10. Possible deformation regimes. (a) Simple shear parallel to bedding, (b) simple shear oblique to bedding, (c) associated simple shear and pure shear. The right-hand side of figure presents cases of heterogeneous shearing. the model (c) best explains observed structures such as extension of competent layers (not accounted for by a), and parallelism of heterogeneous deformation zones and *C* planes with bedding, oblique in (b).

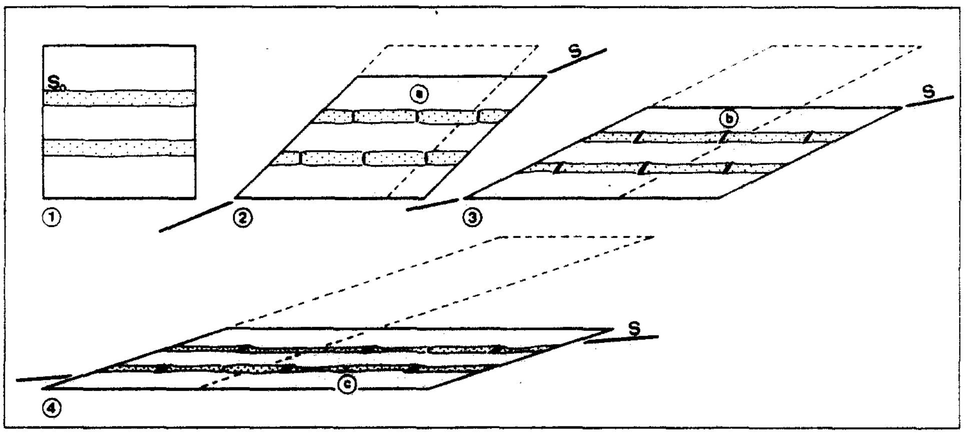

Fig. 11. Schematic model for the evolution of 'bone-shaped' boudins. Deformation regime involves coeval simple-shear and pure-shear components. S_0 and S are bedding and cleavage, respectively. (1) Undeformed state; (2), (3), (4) successive stages of deformation. (a) Formation of boudins with 'classical' bi-convex shape and quartz crystallizations in inter-boudin zones; (b) progressive rotation of quartz-filled gashes and thinning of previously formed boudin elements; (c) formation of late tension gashes.

ric boudinage (Platt & Vissers 1980, Lacassin in preparation); and (d) there is no displacement of the layers along the fracture zones.

The alternative model we present (Fig. 11), involves the progressive stretching of layers parallel to the shear plane and the formation of quartz-filled gashes almost perpendicular to the bedding. The quartz crystalline fills act as rigid bodies in a more ductile medium, and then progressively rotate toward the observed obliquity (Ghosh & Ramberg 1976). Their rotation, systematically consistent with the shear sense, accounts for the observed microstructures such as the internal cleavage tilted in the gashes (Fig. 5d), and their constant obliquity. The sigmoidal shape of some gashes was probably caused by increased shear strain toward the wall of the stretched layers. The late gashes, which may cross-cut earlier rotated ones, and form perpendicular to the bedding, probably represent the initial geometry of incipient boudinage. We think that this systematic reorientation of the crystalline fills between 'bone-shaped' boudins could represent a useful shear-sense criterion.

The most important factor that controls the 'bone-shape' and the reorientation of the gashes is the relative rheological behaviour of the ductile matrix, the competent layers and the more rigid interboudin fills. 'Bone-shaped' boudins result from a two-stage progressive deformation. Incipient boudinage seems to form by tensile fracture associated to minor ductile necking (Ramberg 1955). After their formation, the quartz-fills, which are very coarse-grained, become the less deformable objects between which the boudin elements are extended mainly by ductile thinning (Fig. 11). The rotation of the quartz fill is accommodated by this deformation and thinning of the boudin elements. It suggests that the ductility of the stretched layers increased, perhaps in response to strain softening or temperature rise. Nevertheless, tensile fracturing, with the formation of gashes perpendicular to the bedding (Fig. 11), seems to occur throughout the progressive deformation. It is therefore probable that the development of 'bone-shaped' boudinage involves coeval ductile and brittle behaviour of the stretched layers. The development of the fractures might be related to perturbations of flow during the deformation of viscous layers (Smith 1975, 1977) which initiates pinch-and-swell structures. The hard quartz crystalline fills that form in fractured pinches probably affect the initial flow pattern with subsequent thinning of the previous swells.

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