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Interaction of bed-parallel stylolites and extension veins in boudinage

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Abstract—A form of discontinuous boudinage (styloboudinage) involves extension along and shortening across layers due to the contemporaneous development of extension veins and localized bed-parallel stylolites. Styloboudins develop under anchimetamorphic conditions and occur in the thinnest parts of hummocky-bedded limestone layers enclosed by calcareous mudrock within the Martinsburg Formation of southwest Virginia, U.S.A. They show complex subfabrics defined by sets of orthogonal veins and stylolites. The boudins are late-stage deformation structures associated with reactivation of early bed-parallel stylolites and development of bed-normal calcite veins. Pressure-solution shortening across these stylolites is 10–15% whereas finite elongations recorded by veins ranges from 40–70% in thin parts to 10–25% in the widest parts of layers. Latest pull-apart and veining in some cases utilized existing stylolites at high angles to bedding.

INTRODUCTION

BOUDINAGE is a process involving extension of a stiff layer enclosed by a ductile medium (Ramberg 1955, Sanderson 1974, Mitra 1979). Layer extension is due either to tensile failure producing fractures (discontinuous boudinage) or to differential thinning producing pinch-and-swell structures (continuous boudinage). At low metamorphic grade, boudins are discontinuous types and tend to have rectangular form defined by mineral-filled, bed-perpendicular fractures. Ductile thinning is non-existent or relatively minor (cf. Beach & Jack 1982, fig. 5). Important considerations in boudin development include hardness differences between layer and matrix, fracture toughness, timing of fracturing and the relative role of brittle vs ductile processes (Lloyd & Ferguson 1981).

This paper examines a variant of discontinuous boudinage, referred to here as *styloboudinage*, in limestone layers of a thin-bedded, alternating limestone and calcareous mudrock sequence. Morphology and subfabrics of the styloboudins are defined in an attempt to determine the mechanics of boudin development. The nature and timing of boudin-defining fractures are also considered. Acetate peels from serial sections of five styloboudins, combined with thin sections of selected parts, form the basis of the paper.

GEOLOGIC SETTING

The boudins occur within the Ordovician Martinsburg Formation on the southeast limb of the Clover Hollow anticline in the Narrows thrust-sheet (see Simon & Gray 1982, fig. 1). The rocks are part of the Appalachian Valley and Ridge Province and have been subjected to temperatures between 250 and 300°C determined by illite crystallinity measurements on clays in the mudrock (Mullenax 1981). Associated structures include minor folds, cleavage and stylolites, and contraction faults. Folds are asymmetric, subhorizontal to gently plunging, upright to steeply inclined with rounded hinges and straight limbs (Fig. 1). Interlimb angles range from 30 to 90°. Contraction faults truncate the folds and in some places produce fold trains where anticlines are ramped over anticlines (Fig. 1b). Boudinage though not a dominant structure is locally well developed in SE-dipping limestone beds (Figs. 1a & b) where mudrock-cleavage makes an angle less than 20° with bedding (Fig. 2).

The Martinsburg Formation is a storm influenced, open-marine platform sequence (Kreisa 1981), where limestone layers (10-30 cm thick on average) are enclosed by calcareous mudrock to form a natural multilayer with an approximate thickness ratio (t_1/t_2) of 3:1. The multilayer package consists of repeated storm cycles defined by a skeletal (whole fossil) packstone, followed by a laminated unit capped by shale (calcareous mudrock) (Kreisa 1981, fig. 3). Most of the boudinage is associated with the skeletal packstone and laminated carbonates, where lamination types include plane lamination, hummocky cross-stratification and climbing wave-ripple lamination (Kreisa 1981).

LIMESTONE BOUDINS

Boudins have either apparent pinch-and-swell form (Fig. 2) due to the hummocky bedded nature of the limestone layers, or rectangular shapes (see Ramsay 1967, fig. 3–44A, layer 1) where the bedding surfaces are relatively planar. Boudins are all discontinuous and separated by calcite veins. They are best developed in beds from 2 to 5 cm thick. Styloboudins are only associated with the hummocky-bedded layers, and are the only boudin type examined.

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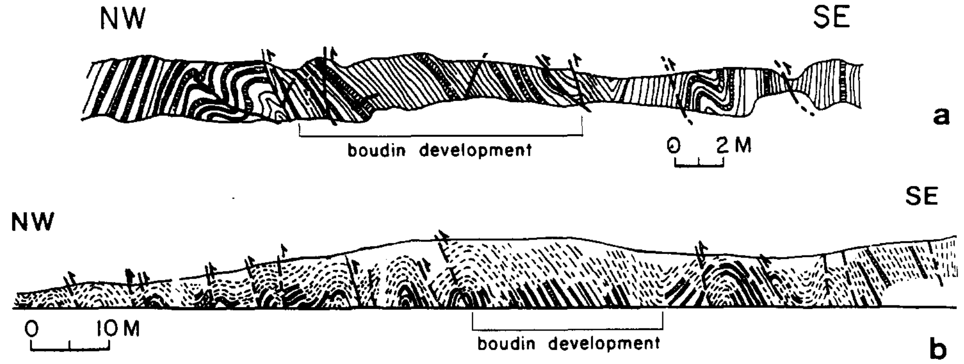

Fig. 1. Minor fold and fault relations in outcrops containing styloboudins. (a) Road outcrop near covered bridge on Virginia Route 601, 1 km northwest of Newport, VA. (b) Road outcrop on U.S. Route 460, 0.5 km west of Newport, VA.

Boudin subfabrics

Boudins are characterized by either two or three systematic sets of veins and stylolites. These form a complex, intersecting network in both 'neck' and 'centre' portions (Figs. 3 and 4). Each set of stylolites has an associated set of veins oriented approximately perpendicular to the stylolites.

Veins. There are three distinct morphological types of veins. Large veins (up to 4 cm wide) composed of fibrous calcite occur in the 'necks' of boudins (Fig. 2) and either have approximately uniform thickness or tapered form across the limestone layer. Thinner veins (up to 1 cm wide) with wedge-like form (Fig. 3) taper toward the centre of the limestone layers. These occur adjacent to the 'neck' regions of the limestones. Thin veins (up to 1 mm wide) which occur in closely spaced, parallel sets (Figs. 4a & b), although developed throughout 'neck' and 'centres' of boudins show greatest intensity in the 'neck' portions.

Veins occur in sets categorized by orientation with respect to bedding. Set 1 veins (V_1, Figs. 3a & b) are perpendicular, set 2 veins (V_2, Fig. 3a) are subparallel, whereas set 3 veins (V_3, Fig. 4c) are oblique, up to 45° to bedding.

Stylolites. Stylolites are discontinuous and have undulating forms. They also occur in sets; set 1 is oriented parallel (S_1, Figs. 3 and 4a), set 2 nearly perpendicular (S_2, Figs. 4a & c), and set 3 oblique at approximately 30–50° (S_3, Fig. 4c) to bedding. The bedding-parallel stylolites are more numerous and thicker, especially in the 'neck' regions of the boudins, than the stylolites oriented obliquely to bedding. The thinnest parts of the hummocky bedded limestone layers contain thick, bedding-parallel stylolites which die out towards the 'centres' of the boudins (Figs. 4a and 5a).

Clay microfabrics. The mudrock layers adjacent to boudin 'neck' regions have an unusually strong preferred orientation of constituent grains. The fabric parallels the concave shape of the limestone bed and is defined by alignment of platy clay minerals and elongate calcite grains (Fig. 5). Veins within mudrock and limestone show truncation at limestone–mudrock boundaries (Fig. 4a). Also, stylolites located near boundaries of limestone layers (Fig. 3a) can be traced into the mudrock where they become part of the bedding-parallel fabric (Figs. 4a & c).

BOUDIN STRAINS

Strain in the boudinage structures was determined at both mesoscopic and microscopic scales. All measurements were done in two dimensions within a plane perpendicular to local fold axes.

Mesoscale strain

Mesoscale strain is recorded by calcite extension veins which define the discontinuous boudins (Figs. 2a & b). Values of layer elongation (e) were calculated by summation of vein widths (Δl) and segments of unfractured rock (l) along 2–3-m segments of limestone layers using:

$$e = \frac{\Sigma\, \Delta l}{\Delta l} \quad \text{(cf. Ramsay 1967, p. 248).} \qquad (1)$$

Stretch ($1 + e$) ranges from 1.03 to 1.25 with average layer elongations of 10–15%.

Microscale strain

Indicators of microscale strain include calcite extension veins, stylolites, and twin lamellae in calcite of the limestone host. Lack of measurable shell fossil distortion within skeletal lime packstone indicates that intragranular strains are low, and probably in the order of 1–5% (cf. Groshong 1975, Engelder 1979). These were not determined.

Microscale elongations were calculated by measuring extension of fossil fragments, phosphatic intraclasts, and pyrite grains in thin section (Fig. 4b). Stretch (S) values were derived from individual markers by

$$S = 1 + e = 1 + [(l_1 - l_0)/l_0], \qquad (2)$$

where l_0 is the original length of the marker and l_1 is the length after extension. Values from thin parts of hummocky bedded limestone layers were between 1.4 and 1.7, while those in wider portions were between 1.12 and 1.22.

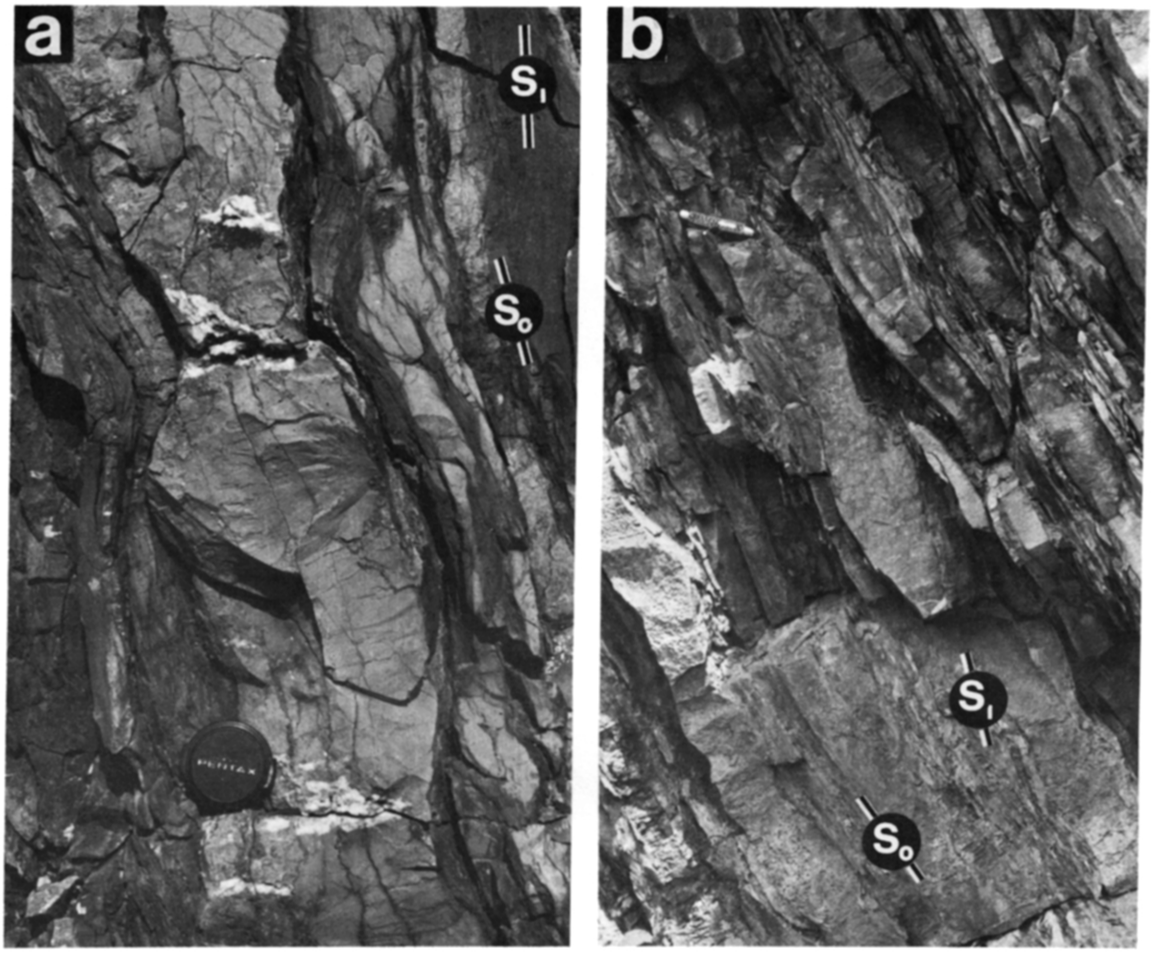

Fig. 2. Styloboudins in outcrop. (a) Limestone (skeletal packstone) layer surrounded by calcareous mudrock with nodules and lenses of carbonate sediment (lime mudstone to pellet packstone). Location: outcrop shown in Fig. 1(b). (b) Hummocky cross-stratified skeletal packstone layers. Location: outcrop shown in Fig. 1(a). S_0 = bedding, S_1 = cleavage.

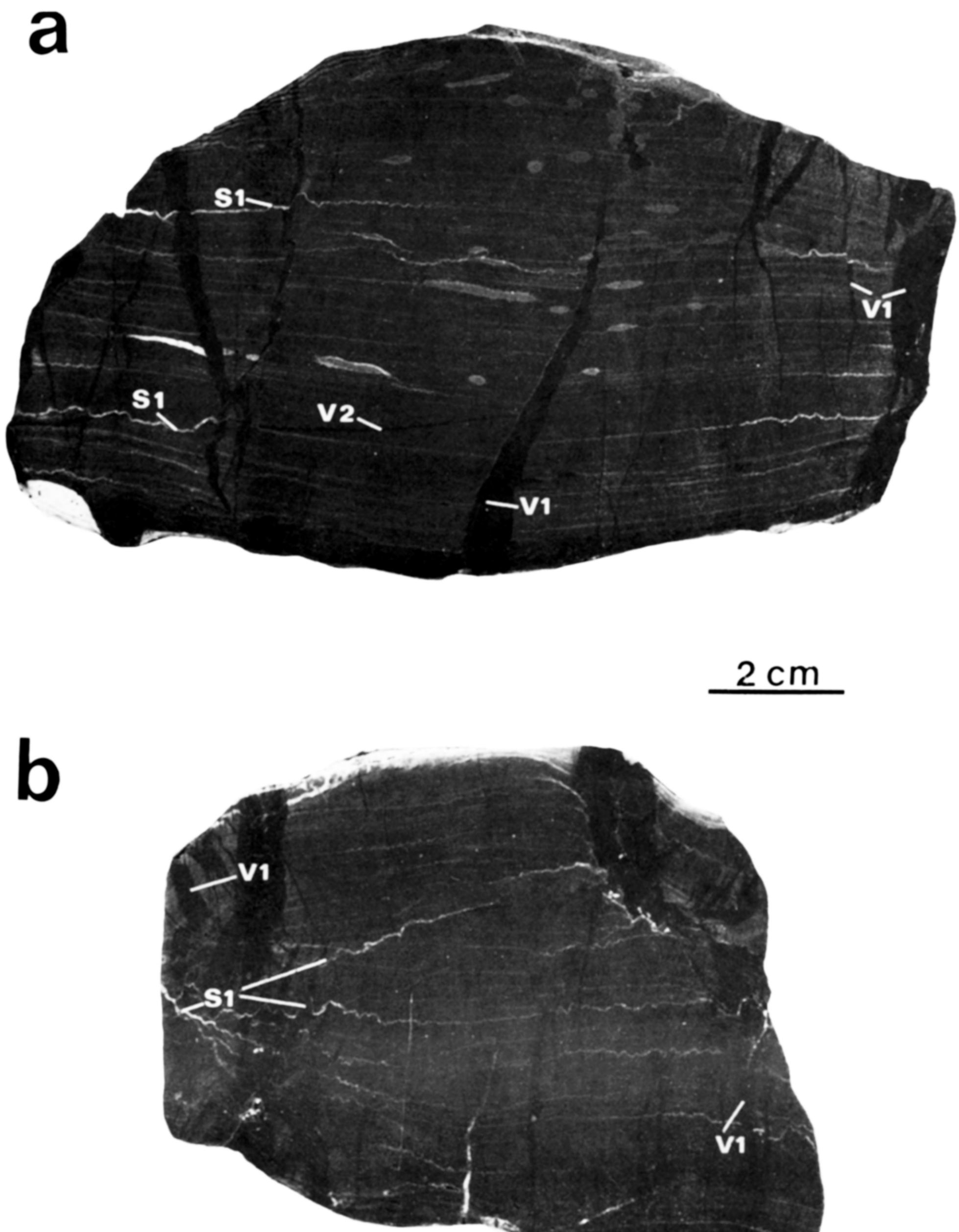

Fig. 3. (a) and (b) Styloboudins showing relations between boudin, veins and stylolites (negative prints of acetate peels). S_1: set 1 stylolite (bed-parallel), V_1 = set 1 veins (bed-perpendicular) and V_2 = set 2 veins (bed-parallel). Location: outcrop shown in Fig. 1(b).

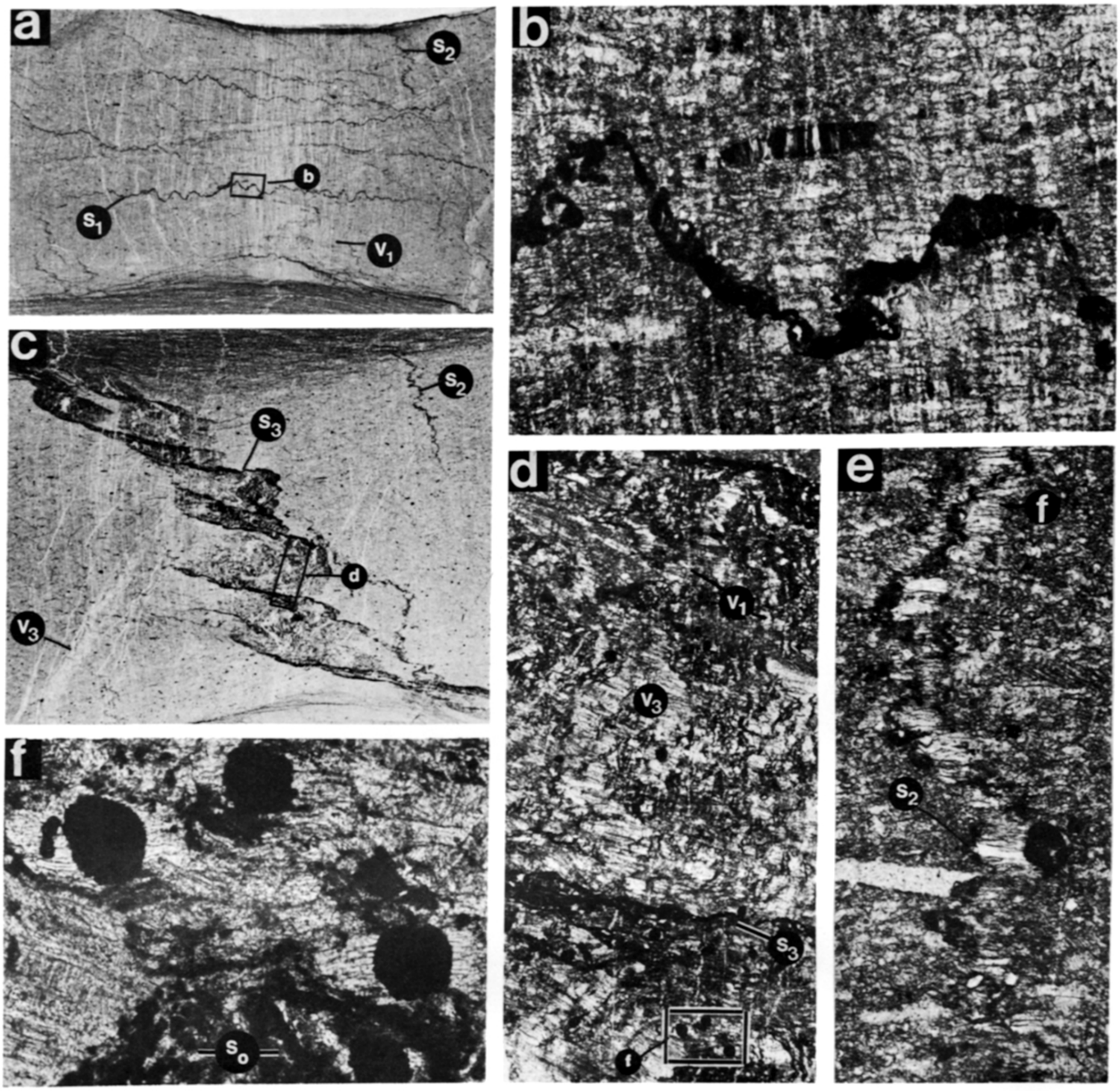

Fig. 4. Photomicrographs of styloboudin subfabrics. (a) Boudin 'neck' region showing intense development of calcite extension veins and bed-parallel stylolites. (b) Bed-parallel (S_1) stylolite showing veins and segmented phosphatic intraclast. Location shown in (a). (c) Oblique stylolite (S_3) seam cut by both bed-perpendicular (V_1) and oblique (V_3) veins. (d) Enlarged portion of stylolite seam showing marked V_3 veining with minor V_1 veins. Location shown in (c). (e) S_2 stylolite showing late pull-apart with fibrous calcite vein-fill. f = calcite fibres. (f) Pressure-fringes on framboidal pyrite within S_3 stylolite. Note fibres are elongate parallel to bedding.

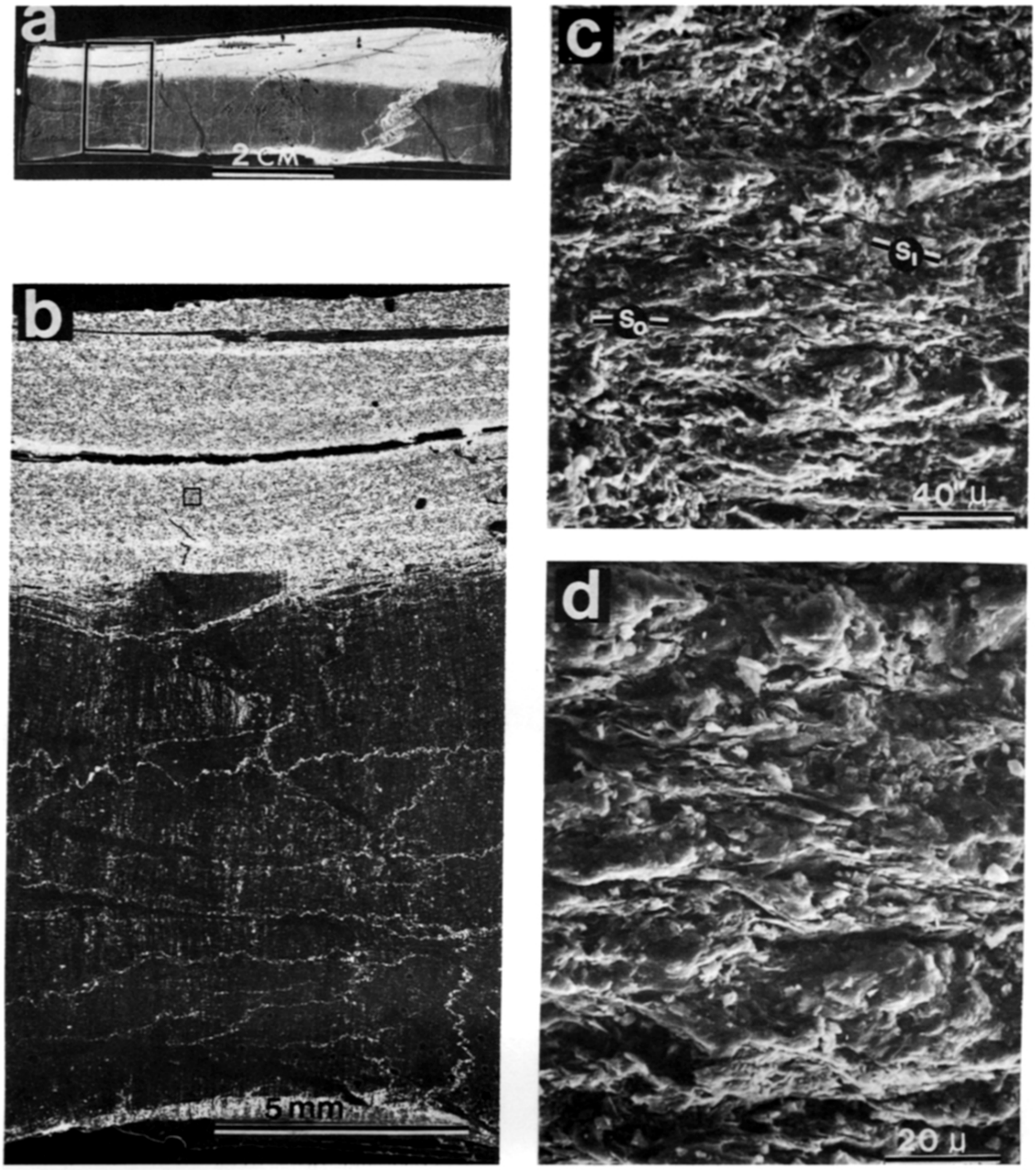

Fig. 5. Clay microfabrics in mudrock adjacent to boudin 'neck'. (a) Negative print of acetate peel showing location of (b). (b) Enlarged area of inset in (a) showing location of SEM sample in (c) and (d), and general microfabric elements. (c) SEM micrograph of mudrock fabric. Note the strong alignment of clays and elongate calcite grains. (d) Enlargement of central portion of (c). Note apparent intersecting fabric elements S_0 = bedding, S_1 = seams of well oriented clay flakes slightly oblique to bedding fabric.

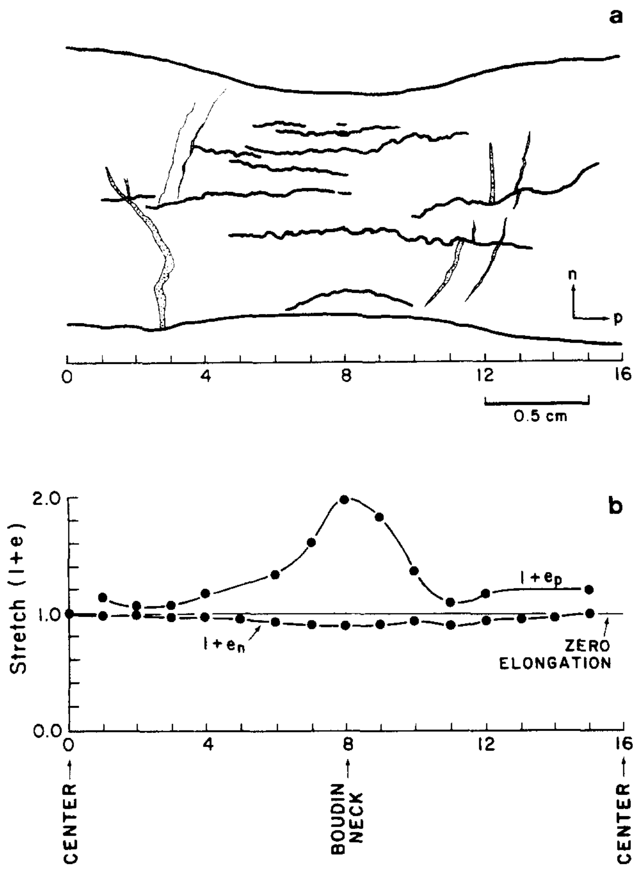

Fig. 6. Strain distribution across styloboudin 'neck' depicted in Fig. 4(a). (a) Sketch of subfabric elements across the 'neck' showing grid for strain determination locations. n, direction normal to layer; p, direction parallel to layer. (b) Stretch ($1 + e$) profile for directions both normal and parallel to layer across boudin 'neck' in (a).

Pressure-solution strain was determined by measuring offsets in veins cut by stylolites (see Alvarez *et al.* 1976, fig. 5, Hancock & Atiya 1975, fig. 1) and relief on stylolite teeth/undulations (see Figs. 4a & b). Values of the latter are at best minimum estimates of solution shortening, but were used when no other markers were available. Shortenings range between −0.10 and −0.13 with highest values at the centre of the thin parts of hummocky bedded layers.

A strain profile (Fig. 6) across the styloboudin depicted in Fig. 4(a) shows relative variations in elongations along ($1 + e_p$), and across the layer ($1 + e_n$) from boudin 'centre' to boudin 'centre'. Elongations (e_p) are mean values determined from segmented markers encountered along the traverse lines (positions 0–16, Fig. 6), whereas shortenings (e_n) are summations of vein offsets at all stylolites along the traverse lines. The boudin 'neck' (position 8) has the highest stretch value ($1 + e_p = 2$) indicating 100% local elongation due to calcite-filled veins (see Fig. 4b). 'Centres' of boudins (positions 1 and 15) show minor extension veins and give a mean local stretch value of 1.18 (S.D. = 0.047). Dissolution along bed-parallel stylolites is also maximum in the boudin neck ($1 + e_n = -0.80$) and decreases to zero at boudin centres.

IMPLICATIONS OF SUBFABRICS FOR BOUDIN DEVELOPMENT

Mutual cross-cutting relations of associated veins and stylolites in each of the three vein and stylolite sets suggests fracturing and stylolite formation were contemporaneous. Similar relations between orthogonal networks of veins and stylolites have also been described (Choukroune 1969, Laubscher 1975, Mitra 1979, Ramsay 1980). Their cross-cutting relations define a chronology of development depicted schematically in Fig. 7. Important considerations include the following observations.

(a) Set 2 veins intersect set 1 stylolites (i.e. set 1 is older than set 2) (Fig. 3a).
(b) Set 3 veins intersect set 2 stylolites (i.e. set 2 is older than set 3) (Fig. 4c).
(c) Many set 1 stylolites and veins show penecontemporaneous development (i.e. some veins intersect stylolites while some stylolites cut veins) (Fig. 3).
(d) Most of the thin set 1 veins cut all other veins and stylolites (see Figs. 4a & c).
(e) Some bedding-parallel stylolites (set 1) cut set 2 veins (Fig. 3a).
(f) Set 1 veins also intersect set 2 and set 3 stylolites and veins (i.e. set 2 and set 3 are older than set 1) (Fig. 4c).

Contradictory cross-cutting relationships (see a, b, e and f above) suggest that set 1 subfabric elements were reactivated late in the deformation sequence.

These require sequential development during a protracted non-coaxial deformation. Each orthogonal set of contemporaneous veins and stylolites represents an episode in the deformation sequence (see Fig. 7). Set 1 stylolites are considered to have been initiated by compaction due to burial, since they are found at all positions around limestone layer folds and are observed in the undeformed Martinsburg Formation of other thrust-sheets. Set 1 veins and vein/stylolite sets 2 and 3 are relatable to tectonic deformation. Set 2 structures were probably initiated during early layer-parallel shortening prior to buckling of the multilayer package (see also Groshong 1975). During subsequent folding, layer rotation and local stress refraction caused set 3 structures to develop oblique to bedding, but these are not present in all styloboudins. With continued rotation of SE-dipping limbs and/or accompanying rotation of the stress field, the beds entered the extension field of the bulk strain ellipse and underwent discontinuous boudinage (see Ramsay 1967, pp. 119–120). This is supported by the low bedding-cleavage angle ($\widehat{S_0S_1} \approx 20°$) in layers containing styloboudins. Reactivation of bed-parallel stylolites coupled with extensive veining normal to them led to formation of the styloboudins.

Pre-existing tectonic structures are also modified during styloboudin development. S_3 stylolites have undergone shape change as indicated by pressure-fringes development on framboidal pyrites within their selvages (Figs. 4d & f). Calcite fibres in fringe parallel bedding and define bed-parallel elongation. Measured elonga-

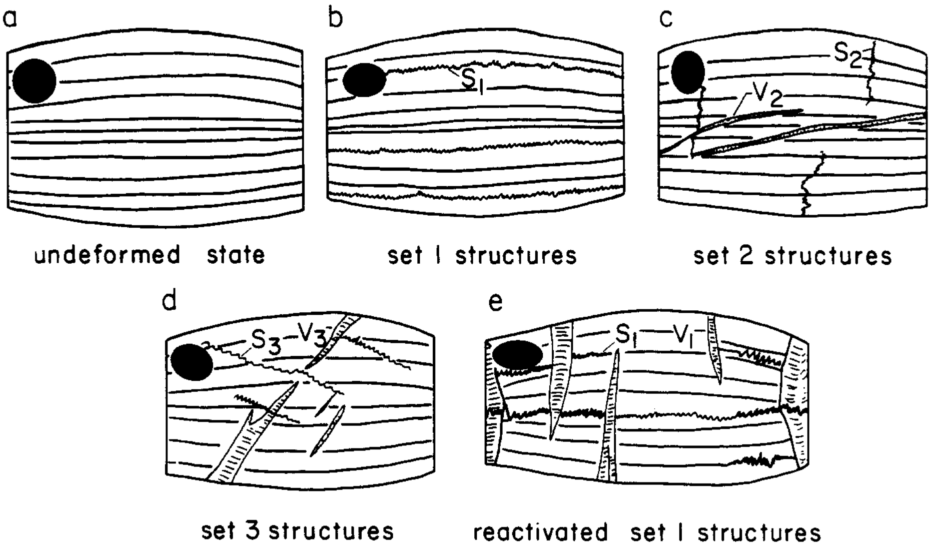

Fig. 7. Sketches illustrating the evolution of styloboudins in the Martinsburg Formation of southwest Virginia. (a) Original bed-shape due to hummocky cross stratification. (b) Structures resulting from compaction due to burial. (c) Set 2 structures related to layer-parallel shortening. (d) Set 3 structures resulting as bed (or stress field) rotated. (e) Set 1 structures reactivated with further rotation of bed. Ellipses give state (orientation and shape) of incremental strain for each deformation stage.

tions range from 1.4 to 2.3. Set 2 stylolites have commonly been pulled apart (Fig. 4e) with vein-fill-calcite fibres also indicating layer elongation.

Truncation of veins at limestone–mudrock interfaces (Fig. 4a) and enhanced bed-parallel clay/calcite fabrics within mudrock immediately adjacent to styloboudins (Fig. 5) indicate dissolution was also responsible for a component of shortening across mudrock layers. This suggests pressure-solution shape modification of limestone layers particularly where they are hummocky bedded. Furthermore, mudrock provides another source of calcium carbonate for the vein-fill material. Although no detailed analysis has been undertaken to compare proportions of calcite within veins to carbonate removed along stylolites, inspection of styloboudins (Figs. 3 and 4a) suggests stylolitization does not account for all the calcite in the veins. It is suggested that calcite, dissolved from the adjacent mudrock, was introduced into the larger through-going veins, which either separate, or partially separate, limestone layers. The development of the styloboudins is therefore also dependent on deformation processes within the mudrock (i.e. matrix) adjacent to the limestone (i.e. stiff layer) undergoing separation.

CONCLUSIONS

Hummocky-bedded limestone layers of storm-deposit sequences which have undergone protracted non-coaxial deformation at anchimetamorphic conditions may contain *styloboudins*. These are discontinuous boudins characterized by an orthogonal set of contemporaneous extension veins and bed-parallel stylolites. Boudinaged layers have undergone concomitant bed-parallel extension (by fracturing and vein formation) and bed-normal shortening (by localized stylolite growth). Boudin development involves volume redistribution since carbonate dissolved within the layer and adjacent mudrock is redeposited in veins. This mode of deformation is however, probably restricted to deformed, weakly to non-metamorphosed, platform to shelf transition sedimentary rocks typical of foreland fold and thrust belts, such as the Valley and Ridge Province of the Appalachian Orogen.

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