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Development of asymmetric shale pull-aparts in evaporite shear zones

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Abstract—Antithetically rotated lozenge-shaped shale pull-aparts are quite common in the shallow domains of the evaporite shear zones of the Jura in northern Switzerland. The pull-aparts are formed by synthetic shear fractures related to a transpressive strain field that also induces the antithetic rotation of the pull-aparts immediately after their formation. A simple analytical model shows that the acute angle of fracture, α, and the antithetic rotation, δ, are determined by structural and rheological parameters and the direction of maximum compressive stress. The pull-aparts are commonly separated by sulphate veins, as the elongation resulting from antithetic rotation does not compensate for the bulk elongation. Despite this, some pull-aparts are bordered by synthetic drag zones.

Antithetically rotated pull-aparts are indicative either of compression normal to shear zone boundaries in décollement-type shear zones or, in shear zones deformed by simple shear, of an initial obliquity of the dismembered layers relative to the shear zone boundary. Resemblance of the shale pull-aparts to type 1 asymmetric pull-aparts and book-shelf structures, both of which rotate synthetically, demonstrates that rotated and asymmetric pull-aparts may be ambiguous kinematic indicators.

INTRODUCTION

CHARACTERISTIC lozenge-shaped pull-aparts (Fig. 1a) have been frequently encountered in the course of recent structural investigations of the evaporite shear zones of the Swiss Jura (Jordan 1988, Jordan & Nüesch 1989a,b, Jordan *et al.* 1990). They give the opportunity to study the nucleation and development of antithetically rotated asymmetric pull-aparts. The scope of this paper is to describe the natural appearance of the pull-aparts, to discuss a model for their genesis, and to compare this model with the models for type III boudinage (Goldstein 1988), type IIb pull-aparts (Hanmer 1986) and asymmetric extension boudinage (Gaudemer & Tapponnier 1987) (Figs. 1b–d).

Lozenge-shaped (rhomboid) pull-aparts are not uncommon in nature and have been recorded, for example, by Cloos (1947), Ramberg (1955), Gaudemer & Tapponnier (1987), Malavieille (1987), Goldstein (1988) and Stock (1989). Strömgård (1973) analysed the factors leading to their genesis. Antithetically rotated pull-aparts have been reported by Hanmer (1986), Gaudemer & Tapponnier (1987) and Stock (1989). The geometric aspects of rigid antithetically rotating lozenges have been discussed by Freund (1974) and Garfunkel & Ron (1985), while the requirements for antithetic rotation of isolated rectangular pull-aparts have been outlined by Ghosh & Ramberg (1976).

FIELD EVIDENCE

Occurrence of pull-aparts

Pull-aparts are found at all sampled locations (0–1400 m depth) of the two evaporite decoupling horizons of the Alpine Jura overthrust (Fig. 2). At the Schafisheim well,

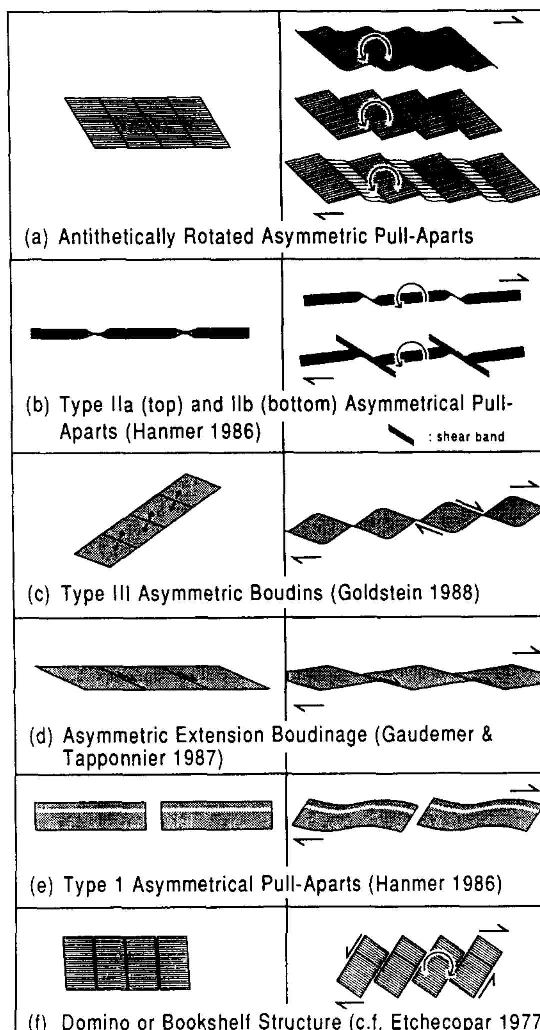

Fig. 1. Synopsis of various forms of asymmetric pull-aparts with initial stage at left and final stage at right (see text). In (a, right) three forms of antithetically rotated asymmetric pull-aparts are shown. They are (from top): with drag zone, angular and distinctly separated by veins.

where the gently inclined evaporite sole thrust is actually located 1.4 km below the surface, exclusively rectangular pull-aparts have formed (Jordan & Nüesch 1989a). Asymmetric pull-aparts predominate at the three other locations, which expose the two evaporite decoupling horizons in a ramp position and at shallower depth (Wisen well, Jordan *et al.* 1990, Kienberg quarry, and Belchen tunnel, Laubscher 1976, 1984, Jordan 1988, cf. Fig. 2). Asymmetric pull-aparts are found in more or less planar shear zones as well as in limbs of flexural flow folds.

The mineralogy of the dismembered layers varies from pure clay to dolomitic marl (Matter *et al.* 1988, Jordan & Nüesch 1989a, Jordan *et al.* 1990). These layers are embedded in low strength ductile anhydrite (at Schafisheim well, parts of Wisen well and the Belchen tunnel) or gypsum. At Kienberg and at some places in the Belchen tunnel where the relative competence of (relic) anhydrite and the surrounding gypsum-rich shales (*shale–gypsum tectonites*, Jordan & Nüesch 1989b) is reversed, anhydrite asymmetric pull-aparts have formed (Fig. 3a).

Geometry of the asymmetric pull-aparts

The lozenge-shaped pull-aparts are formed by shear fractures, s_c (Fig. 4), cutting the competent layer at an acute angle α, and s_l-surfaces that are either the initial top or bottom of the competent layer or layer-parallel surfaces inside the competent layer. The pull-aparts are commonly separated by sulphate films or, rarely, by slickensides. The contact between two pull-aparts may be formed as a drag-zone (i in Fig. 4a) or as a sharp surface (ii). Some of the lozenges are distinctly pulled apart and separated by sulphate veins (iii) or dismembered into 'sub-lozenges' by additional internal s_l-surfaces (iv).

For statistical and analytical purposes, the height, h, and length, l_o, of a lozenge are measured normal and parallel, respectively, to internal layering. The thickness of a lozenge, t_o, is defined as the space between two fractures normal to the fracture surface:

$$t_o = l_o \sin(\alpha).$$

The long diagonal of the lozenge, a, forms an angle Φ with the layering (Fig. 4b), where

$$a = h/\sin(\Phi) \quad \text{and} \tag{1}$$

$$\Phi = \arctan\left(\frac{1}{\cot(\alpha) + l_o/h}\right). \tag{2}$$

The internal antithetic rotation, δ_{int}, is the apparent antithetic rotation relative to a co-ordinate system with x-axis parallel to initial layering (forward-modelling) or parallel to a line connecting the centres of a sequence of lozenges that is assumed to be a passive material line (field observations, Fig. 4c). The quantity δ_{ext} is the absolute antithetic rotation of the lozenge relative to the shear zone boundaries. Consequently, δ_{ext} differs from δ_{int} in a shear zone that is oblique to internal layering, while the two are equal in a décollement type shear zone. The internal backward rotation ('tilting') of a set of lozenges, δ_{int}, results in an extension parallel to the x-axis with (cf. Garfunkel & Ron 1985)

$$(1 + e_x)_{loz} = \left(\frac{\sin\alpha}{\sin(\alpha - \delta_{int})}\right). \tag{3}$$

As most of the lozenges are separated by sulphate films or veins, the total extension, $(1 + e_x)_{tot}$, is generally

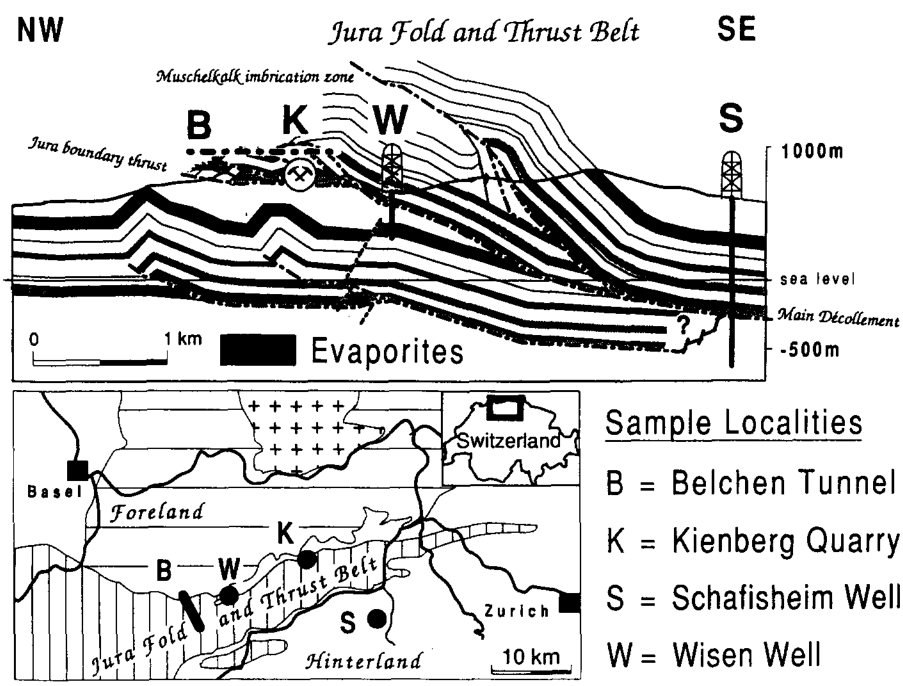

Fig. 2. Location of sample sites. On top, projection of sites to a cross-section close to Wisen by Thomas Noack (in Jordan *et al.* 1990). On bottom, simplified tectonic map of north central Switzerland (inset: map of Switzerland showing the study area).

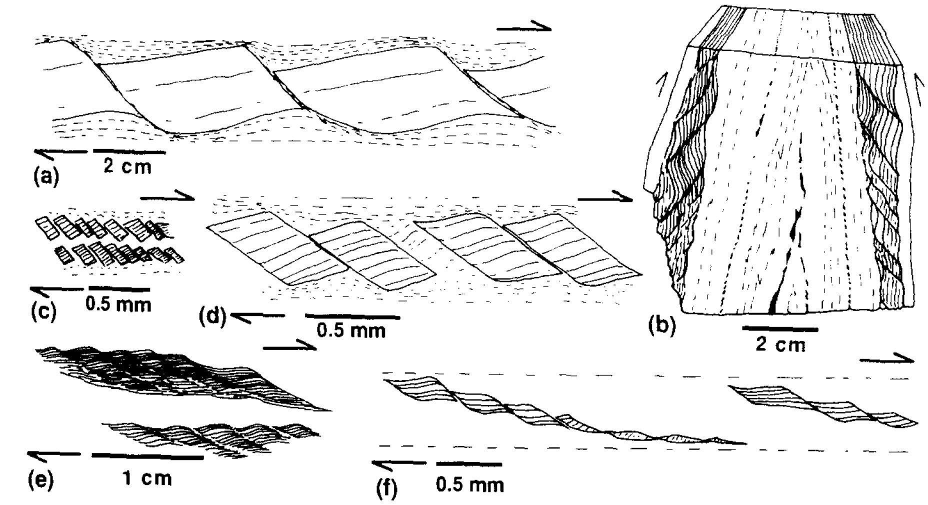

Fig. 3. Antithetically rotated asymmetric pull-aparts from evaporite shear zones in the Jura. (a) Anhydrite pull-aparts in shale–gypsum tectonites (Kienberg quarry); (b) axial plane-symmetric shale pull-aparts in a tight flexural flow fold in anhydrite (Belchen tunnel); (c) sub-rectangular shale pull-aparts in anhydrite (Wisen well); (d) unevenly separated sequence of angular shale pull-aparts in anhydrite (Wisen well); (e) laminated shale–anhydrite multilayer sequence resembling extensional crenulation-features (Wisen well); (f) sequences of elongated shale pull-aparts in gypsum starting with large slightly rotated lozenges and ending with small strongly rotated and stretched lozenges (Wisen well).

larger than the extension $(1 + e_x)_{loz}$ originating from tilting only (Fig. 4).

Natural appearance of asymmetric pull-aparts

The size of the asymmetric pull-aparts varies from tenths of a millimetre to tens of centimetres with many

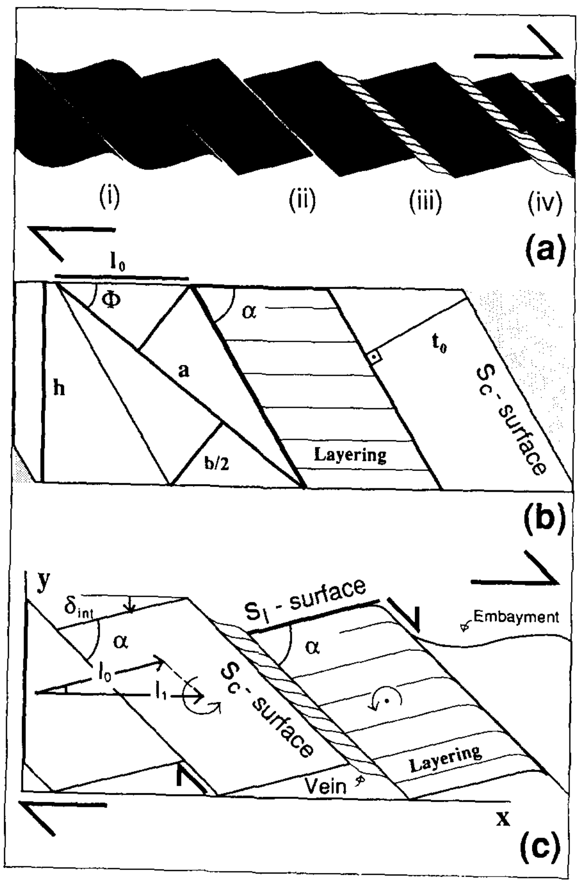

Fig. 4. Schematic elements of geometry and terminology of asymmetric pull-aparts in evaporite shear zones (right lateral shear) from the Jura. (a) Various manifestations; (i) with drag contact; (ii) with sharp contact; (iii) separated by sulphate veins; (iv) with sub-pull-aparts. (b) & (c) Terminology to describe the initial and final states.

pull-aparts being subdivided into similar sub-lozenges (Fig. 3b). The inclination, α, of s_c-surfaces of 100 measured asymmetric pull-aparts varies between 25° and 65°. The mean is 44° (Fig. 5a). A few pull-aparts (not included in the group of 100 used for statistics) are 'sub-rectangular' (α = *ca* 78°, Fig. 3c). The logarithm of the ratio, (l_0/h), between spacing of s_c-shear surfaces and height varies from −0.44 to 0.70, with a mean of 0.04 (Fig. 5c). There is a relationship between minimum α and minimum log (l_0/h), such that no pull-apart is thinner than $t_0/h = 0.25$. (Fig. 5c). The relative thickness, t_0/h, of most pull-aparts varies between 0.25 and 2.0 (Fig. 5d). The inclination, Φ, of the longest diagonal of the lozenge varies between 10° and 40° (Fig. 5b).

The antithetic rotation, δ_{int}, mostly varies between 0° and *ca* 25° (Fig. 5). Occasionally, very large (e.g. in Fig. 3c, where mean $\delta_{int} = 33°$) or negative ($\delta_{int} < 0°$, synthetic rotation) values are found. The mean internal rotation of 100 measured lozenges is 11°, and $(1 + e_x)_{loz}$ (equation 1) varies between 0.76 and 2.83, with a mean value of 1.31. At localities where the lozenges are still in direct contact, even when distinctly rotated, the interfaces are strongly polished, mirror-like slickensides (cf. Jordan & Nüesch 1989b), and the contact formed as a drag zone causing characteristic embayments of these pull-aparts (Fig. 3b). However, many of these drag-zone bounded lozenges are also separated by sulphate veins (Fig. 6a), as are most of the lozenges with undragged borders (Fig. 6b). At some places, these veins of secondary sulphate, anhydrite or gypsum may become quite thick (Fig. 6d) showing that the growth direction became sub-normal to the s_c-surfaces after an initial phase with shear sub-parallel to these surfaces (Fig. 6c). Also, some pull-aparts are so isolated from their neighbours that they may be denoted as asymmetric porphyroclasts (Figs. 6e & f). Often, the additional extension accommodated by sulphate veins is unevenly distributed along a single layer, and groups of two or three lozenges are still in contact (Fig. 3d).

Table 1. List of parameters

s_c	shear surfaces cutting layer and forming pull-aparts
s_l	surface parallel to initial layering
α	inclination of s_c-surfaces relative to layering
h	height of pull-apart normal to initial layering
l_o	length of pull-apart parallel to initial layering
t_o	thickness of pull-apart normal to s_c-surfaces
δ_{int}	rotation of pull-aparts relative to a line interconnecting the centers of the pull-aparts
δ_{ext}	rotation of pull-aparts relative to shear zone boundary
a	long diagonal of pull-apart = long axis of ellipse replacing pull-apart
Φ	inclination of long diagonal relative to layering
b	short axis of ellipse
R	$= a/b$, aspect ratio of ellipse replacing pull-apart
$(1 + e_x)_{tot}$	total extension parallel to x-axis
$(1 + e_x)_{loz}$	extension of pull-aparts parallel to x-axis due to rotation ('tilting')
$\eta_{comp}/\eta_{incomp}$	competence contrast between layer and matrix
σ_1	maximum compressive stress
ϕ	inclination of maximum compressive stress direction relative to x-axis
σ_3	minimum compressive stress
h_{comp}/h_{incomp}	height relation between competent layers and incompetent matrix
s_r	$= \dot{\varepsilon}_x/\dot{\gamma}_{yx}$, Ghosh & Ramberg's (1976) factor of transpression
$s_{r_{crit}}$	minimum value of s_r that results in antithetic rotation of a specified pull-apart
$\dot{\varepsilon}_x$	$= (1 + e_x)_{tot}/\partial t$, logarithmic extension rate parallel to x-axis

There is not a striking correlation between antithetic rotation, δ_{int}, and the angle α, the angle Φ or the relative thickness t_o/h (Figs. 5a, b & d). However, lozenges with α close to 45° can obviously rotate more than pull-aparts with α significantly smaller or bigger than 45°. The average observed antithetic rotation increases with Φ, and there are no unrotated lozenges with $\Phi > 27°$ (or $t_o/h > 1.2$). *Synthetic* rotation is restricted to lozenges with $\alpha < 40°$, or $\Phi < 17°$.

With decreasing thickness of individual layers in shale–sulphate multilayers, there is a transition from distinct pull-aparts to structures (Fig. 3e) that resemble extensional crenulation cleavage (ecc 1, Platt 1984) or normal-slip crenulation (NSC, Dennis & Secor 1987).

Evidence for simultaneity of pull-apart formation and antithetic rotation

Axial plane-symmetric arrangements of lozenge-shaped pull-aparts in both limbs of flexural flow folds (Fig. 3b) document simultaneity of dismembering ('boudinage') of the competent layers and folding. The fact that nearly all observed lozenges are either unrotated or antithetically rotated suggests that the lozenges were forced to rotate against the bulk sense of rotation immediately after they formed. Synthetic rotation of the lozenges would be expected if simple shear flexural flow is assumed (Ghosh & Ramberg 1976, see discussion).

Further evidence is given by asymmetric arrange-

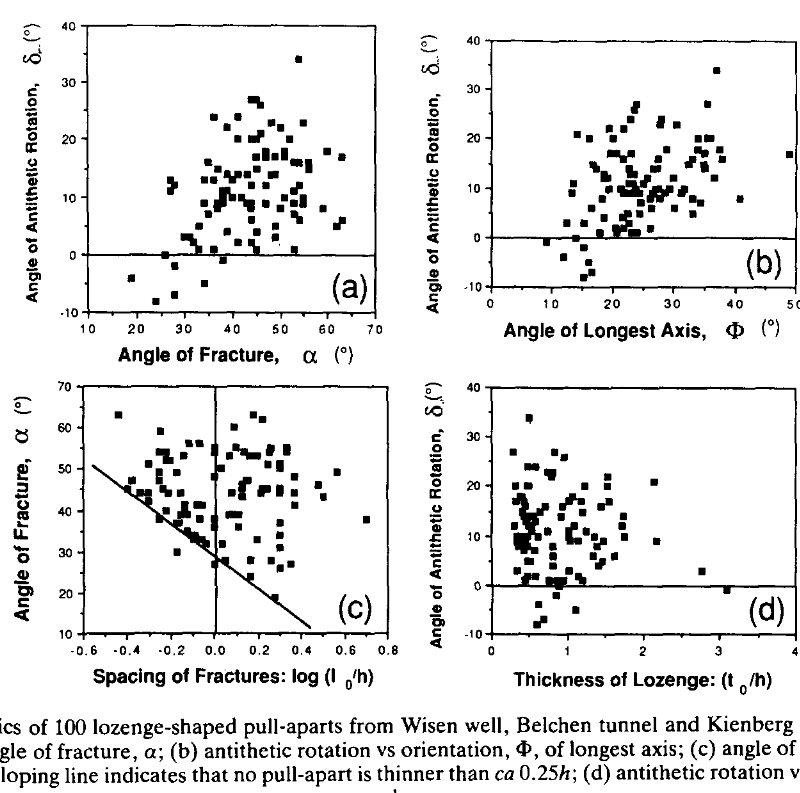

Fig. 5. Statistics of 100 lozenge-shaped pull-aparts from Wisen well, Belchen tunnel and Kienberg quarry: (a) antithetic rotation vs angle of fracture, α; (b) antithetic rotation vs orientation, Φ, of longest axis; (c) angle of fracture vs spacing of fracture; the sloping line indicates that no pull-apart is thinner than *ca* $0.25h$; (d) antithetic rotation vs relative thickness of lozenges.

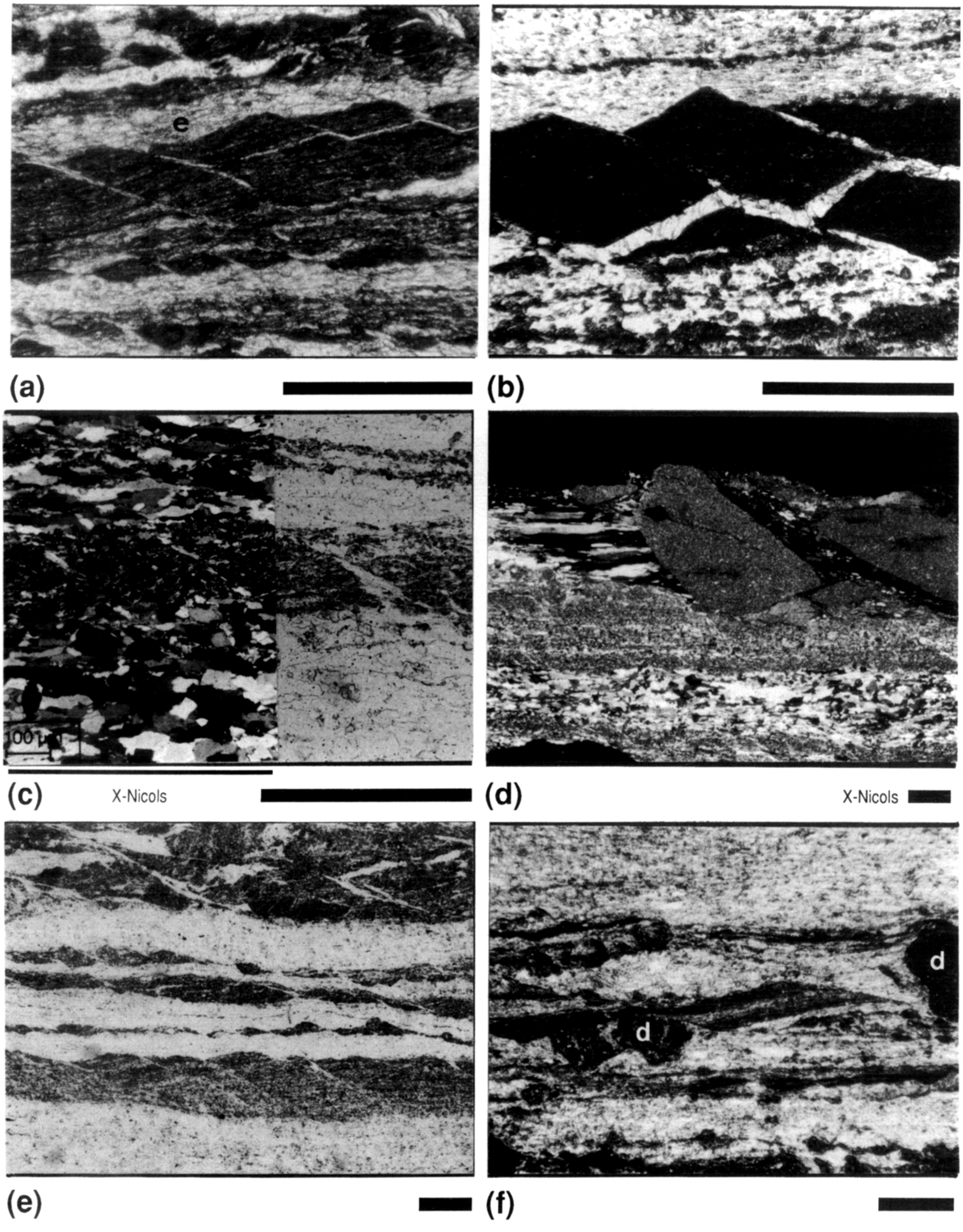

Fig. 6. Antithetically rotated asymmetric shale pull-aparts in right-lateral shear zones (from Wisen well, scale bar is 0.5 mm): (a) pull-aparts with drag zones and embayment (**e**), subdivided into sub-lozenges; (b) angular pull-aparts subdivided into sub-lozenges; (c) pull-aparts separated by anhydrite veins that grow subparallel to the s_c-surfaces; (d) pull-aparts separated by anhydrite veins that grow subnormal to the s_c-surfaces (the right vein is partly gypsified); (e) sequences of strongly rotated pull-aparts: note various types (angular to *ecc*-type) and various amounts of rotation; (f) isolated pull-apart (**d**: dolomite).

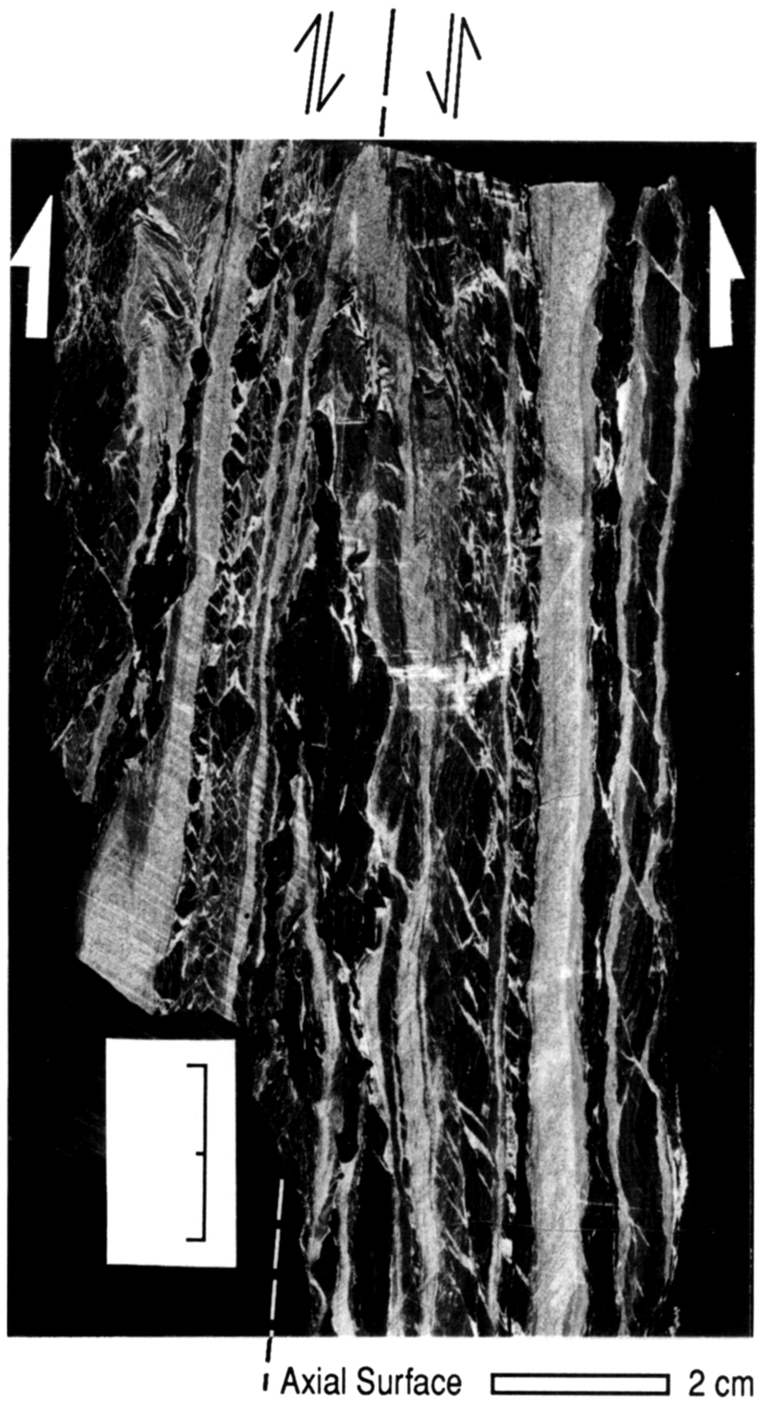

Fig. 7. Isoclinally folded shale–anhydrite multilayer with well developed asymmetric pull-aparts in the right fold limb, and chaotic structures in the left one (although some of the pull-aparts are symmetric rhombs) resulting from left-lateral and right-lateral overprinting, respectively, during folding of an initially planar left-lateral shear zone.

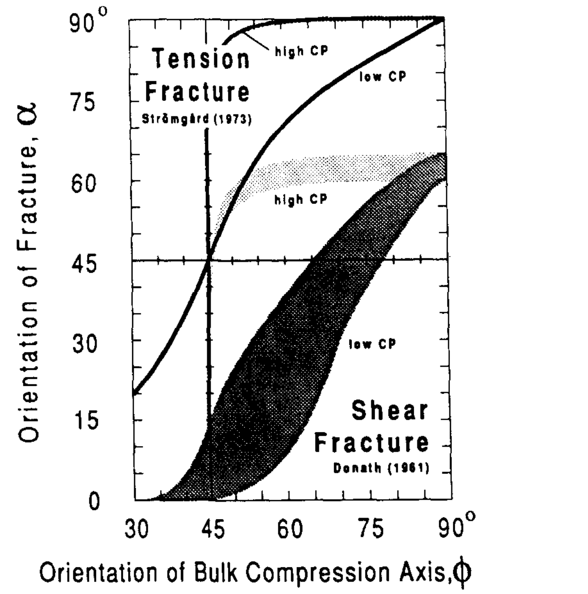

Fig. 8. Orientation, α, of tensile and shear fractures relative to layering resulting from a specific orientation, ϕ, of maximum principal compressive stress relative to the layer (based on Strömgård 1973 and Donath 1961, respectively).

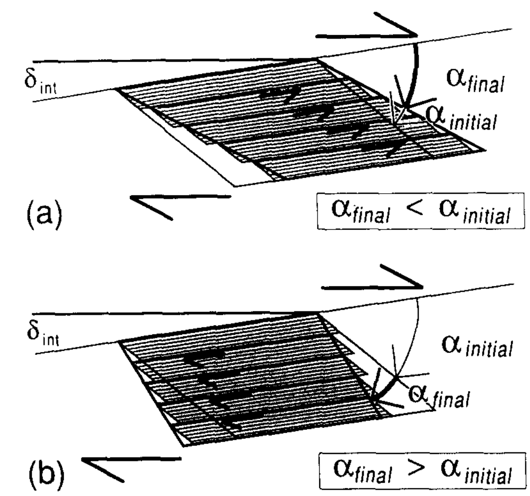

Fig. 9. Change of angle α due to internal antithetic (a, 'stretching') or synthetic (b, 'squeezing') shear parallel to lamination.

ments of pull-aparts relative to the axial plane of a fold (Fig. 7). Lozenge-shaped asymmetric pull-aparts in one limb and chaotic structures in the other document nucleation and antithetic rotation of lozenge-shaped pull-aparts in an early left-lateral layer-parallel shear zone that is amplified by left-lateral transpressive flexural flow in one limb, while it is overprinted by right-lateral shear in the other.

Strong but not conclusive indications of simultaneity of pull-apart formation and antithetic rotation are also suggested by Gaudemer & Tapponnier (1987, p. 170) and Stock (1989), and are further given by the various stages of pull-apart formation and rotation found in one section (e.g. Fig. 6e). A consequence of simultaneity is that both processes have to result from the same strain field.

DISCUSSION

Origin of lozenge shape

According to Strömgård (1973), the stress field within a competent layer is controlled by: (1) the competence contrast, $\eta_{comp}/\eta_{incomp}$, of the layer to the matrix; (2) the angle ϕ between the maximum compressive stress direction (σ_1) and the layering, s_l; (3) the ratio of layer thicknesses, h_{comp}/h_{incomp}; and (4) the ratio σ_3/σ_1. While tensile fractures generally form normal to the local σ_3-direction, the angle that shear fractures make with the local σ_1-direction is quite variable (*ca* 0–60°) as it depends on the angle between the lamination and the σ_1-direction (Donath 1961). This variability is most prominent at low confining pressures (Fig. 8). At high confining pressures (or very low h_{comp}/h_{incomp} ratios), the local σ_1-direction becomes normal ($\phi > 45°$) or parallel ($\phi < 45°$) to layering (Strömgård 1973) and synthetic shear fractures form at α = *ca* 60° and α = *ca* 15°, respectively (Donath 1961), while extensional pull-aparts have to be rectangular (Strömgård 1973), as is confirmed by evidence from Schafisheim (Jordan & Nüesch 1989a).

Assuming a high competence contrast ($\eta_{comp}/\eta_{incomp} \gg 10$), a thickness ratio near unity ($3 \geq h_{comp}/h_{incomp} \geq 0.3$) and a low confining presure ($\leq$25 MPa $\cong$ 1 km depth) relative to compressive stress (σ_1 assumed for Jura overthrusting is *ca* 50 MPa, and consequently $\sigma_3/\sigma_1 \geq 0.35$), then the orientations of the observed shear fractures indicate an angle ϕ = 50–90° or, for very low confining pressures, ϕ = 70–90°. Assuming, however, the s_c-surfaces to be tensile fractures, an assumption that is reasonable for the sub-rectangular group of Fig. 3(c), ϕ would be *ca* 70° for the latter group and *ca* 30–60° for the group of 100 used for statistics (Figs. 7 and 8).

Unfortunately, the observed values of α cannot be directly related to an initial ϕ-value, as the angle α of some of the boudins has obviously been changed by stretching, and, possibly, also by squeezing. In the first case (Figs. 3f and 9a) (Stock 1989), the lozenges are stretched by antithetic shear parallel to sedimentary lamination, and, as a consequence, α and t_o decrease with increasing δ_{int}, while l_o increases and $(1 + e_x)_{tot} > (1 + e_x)_{loz}$. In the second case (Fig. 9b), synthetic shear along shale laminations results in an increase of α and t_o and a decrease of l_o with increasing δ_{int}, and, consequently, $(1 + e_x)_{tot} < (1 + e_x)_{loz}$ (cf. Ramsay & Huber 1987, p. 453; and type I asymmetric pull-aparts, Fig. 1e).

Nevertheless, according to Figs. 5, 8 and 9, the observed s_c-shear-surfaces can be traced back to an initial σ_1-direction given by ϕ = *ca* 70°. This is consistent with the sub-rectangular blocks of Fig. 3(c) if they are regarded as tensile pull-aparts. Thus, lozenge-shaped asymmetric pull-aparts form at places where deformation is distinctly transpressive. The scatter in values of α from *ca* 35–55° (Fig. 5a) can be related either to variations in mineralogical composition and confining pressure, or, as is necessary to explain the values of α outside this range, to variations of stress field in time relative to layering or to later stretching or squeezing (Fig. 9).

A different interpretation of the s_c-surfaces as tension cracks would yield a σ_1-direction, ϕ, of between *ca* 35 and 55° and thus indicate a simple shear regime with slight variations into transtension or transpression. This conflicts with the simultaneity of pull-apart formation and antithetic rotation (see below).

Reasons for antithetic rotation

As field evidence shows, the total elongation parallel to the x-axis may be equal to [lozenges in contact; $(1 + e_x)_{tot} = (1 + e_x)_{loz}$] or, as in most cases, greater than [sulphate veins between the lozenges; $(1 + e_x)_{tot} > (1 + e_x)_{loz}$] the elongation calculated from pull-apart rotation only (equation 3).

In the first case, the block rotation model of Freund (1974) would apply if it is assumed that the lozenge rotation and the resulting layer-parallel extension reflected only the shortening normal to the shear zone. In such a case, the lozenges are supposed to be unaffected by shear parallel to the x-axis, which implies that the layer in question has to be oriented parallel to a principal direction of strain (i.e. parallel to the line of maximum elongation) during all increments of deformation. Such a layer, however, exists neither in a transpressive nor in a simple shear regime, as the line of finite maximum elongation migrates through the material in both these cases. Consequently, the antithetic rotation of the lozenges that keep in mutual contact has to be consistent with both the rotational and the extensional components of bulk deformation, and the lozenges that keep in contact must be a special case of the model that will be outlined in the next paragraph.

In the second case, where $(1 + e_x)_{tot} > (1 + e_x)_{loz}$, the lozenges are distinctly pulled apart. Being surrounded by incompetent matrix or secondary sulphate, they may be denoted as isolated objects. Ghosh & Ramberg (1976) showed that whether an isolated rigid object rotates synthetically or antithetically depends on its aspect ratio, R, the angle Φ, and the ratio of transpression, $s_r = \dot{\varepsilon}_x/\dot{\gamma}_{yx}$ with $\dot{\varepsilon}_x = (1 + e_x)_{tot}/\partial t$ (Fig. 10a). In order to predict the rotational behaviour of a lozenge-shaped pull-apart, the lozenge is replaced by an ellipsoid defined by Φ and $R = a/b$ (Fig. 10b), where a is defined in equation (1) and

$$b = 2 \cdot l_o \cdot \sin(\Phi). \qquad (4)$$

Following Ghosh & Ramberg (1976), the rigid body will rotate to a stable position if $s_r > R/(R^2 - 1)$, and this rotation is antithetic if the initial orientation of the body $0° < \Phi < 90°$ and

$$s_r \geq \frac{R^2 + \cot^2(\Phi)}{2 \cdot \cot(\Phi) \cdot (R^2 - 1)}.$$

As R and Φ are derived from h, l_o and α (equations 1, 2 and 4), the minimum rate of transpression, $s_{r_{crit}}$, causing antithetic rotation is a function of inclination and

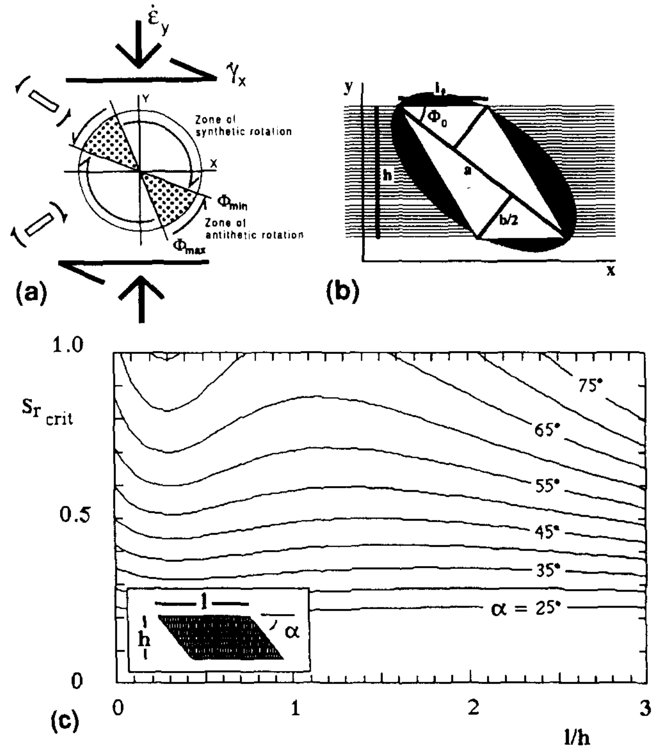

Fig. 10. Adaptation of the Ghosh & Ramberg (1976) model to lozenge-shaped pull-aparts. (a) Zones of synthetic and antithetic rotation (modified after Ghosh & Ramberg 1976) for which the angles Φ_{min} and Φ_{max} depend on the value of s_r and R. (b) Substitution of the lozenge defined by a, h and l_o by an elliptic body defined by $R = a/b$ and Φ_0. (c) Plot of critical minimal values, $s_{r_{crit}}$, for a lozenge of dimensions α, h and l_o.

spacing of the s_c-fractures (Fig. 10c). The amount of relative rotation of a certain pull-apart can be assigned a distinct value of γ_{yx} if an arbitrary value for s_r is predetermined, or vice versa. If the body is not rigid but deformable, the lozenge will be stretched parallel to the direction of the longest axis, Φ (cf. Fig. 3f and Fig. 9a), and the necessary value of s_r for a given rotation of initial internal foliation, δ_{int}, decreases with decreasing competence contrast (Stock 1989).

Because the lozenge-shaped pull-aparts would rotate synthetically in the case of simple shear, while in the case of pure shear they would be separated without any rotation, it can be concluded, that the antithetic rotation of the pull-aparts is definitely related to transpressive regimes, independent of whether the pull-aparts are separated or not. The characteristic shape of lozenge pull-aparts, with their inclined long diagonal, is quite favourable for antithetic rotation (cf. Ghosh & Ramberg 1976, Stock 1989) and relatively low values of s_r are required. Evidence for the applicability of the Ghosh & Ramberg model to the configuration in question is also given by the data (Fig. 5b), which show that all pull-aparts with $\Phi > 27°$ are rotated antithetically, and that synthetic rotation is restricted to pull-aparts with $\Phi < 17°$.

Unfortunately, the value of s_r that leads to a specific observed configuration is determined by too many factors to be unambiguously estimated from field data. These factors are the anisotropy factor (Cobbold 1976), the competence contrast, the layer thickness ratio and the σ_3/σ_1 factor (Strömgård 1973), as well as the temperature, the grain size, the mineral composition and the confining pressure that determine the angle of fracture and the competence contrast. As these factors also determine the internal deformational behaviour of an isolated lozenge (Stock 1989), variations in time and space of these factors are responsible for whether the rotation of the pull-aparts is in concordance with bulk elongation or not; that is whether the pull-aparts stay in mutual contact or are increasingly separated by sulphate veins.

In detail, the transpressive regime that is indispensable for the genesis of the antithetically rotating asymmetric pull-aparts may be (1) in concordance with a bulk transpressive shear regime ('compressive shear zone', Fig. 11a), for example, in ramp thrusts (Malavieille & Ritz 1989, Jordan *et al.* 1990) or in flexural shear folds with shortening normal to axial plane. Alternatively, it may be (2) local in a bulk simple or pure shear regime. In Fig. 11(b), a layer initially oblique to the shear zone boundary is dismembered by shear fractures induced by a stress field with $\phi = 45°$. Following Ghosh & Ramberg (1976), the lozenges start to rotate synthetically (δ_{ext}) in a simple shear regime. With respect to a passive material line, however, the rotation is antithetical (δ_{int}). Because the compositional foliation formed by all layers (dismembered or not) behaves like a passive material line that tends to become subparallel to the shear zone boundary, it becomes increasingly hard to tell an external rotation from an internal one as shear strain increases. The same holds true for a situation in which the shear zone boundaries are not known. In this light, type III-boudinage can also be interpreted as lozenge-shaped shear pull-aparts forming in a bulk simple shear regime. However, the separation of the pull-aparts would be much greater than indicated in figs. 6(b) & (c) of Goldstein (1988).

Comparison with other asymmetric or rotated pull-aparts

The proposed genetic model for the asymmetric shale pull-aparts of the Jura evaporite shear zones has similarities to the model of Gaudemer & Tapponnier (1987, in the origin of the s_c-surfaces), and the model for type IIb pull-aparts (Hanmer 1986, in the rotational behaviour). Significant differences from Hanmer's type IIb-model are, however: (1) that the competent layer is segmented ('boudinaged') by brittle shear fractures (rather than by shear bands developing from 'pinches'); (2) that segmentation and subsequent antithetic rotation are linked to one and the same stress and deformation field (rather than the deformation affecting a preformed pinch-and-swell structure); and (3) the l_o/h-ratio is relatively large in Hanmer's model (*ca* 4:1) while the ratio observed in the Jura evaporite shear zones and used for the present model is relatively small (5:2 to 2:5, Fig. 5c). However, in broad terms, the shale pull-aparts developing within brittle–ductile multilayers may be regarded as equivalent to type IIb pull-aparts, and

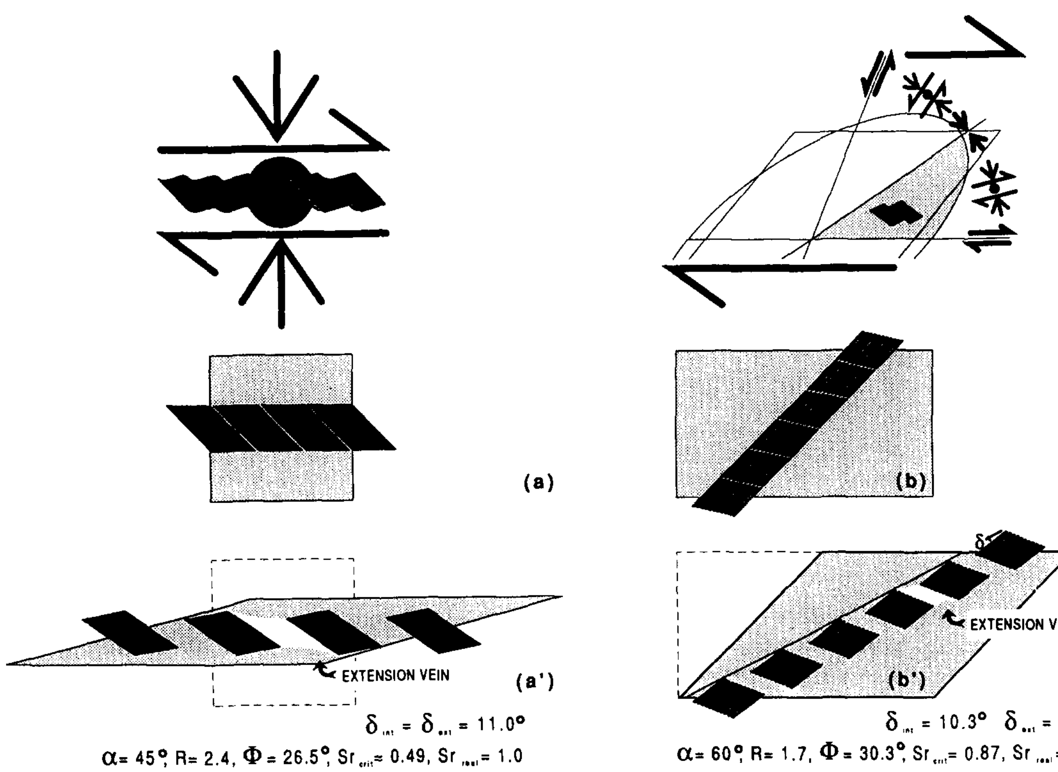

Fig. 11. Occurrence of antithetically rotating asymmetric pull-aparts: (a) in compressive 'décollement-type' shear zones and (b) in shear zones oblique to initial layering. (a') & (b') give the deformed states with $\gamma = 1$ and $s_r = 1$ and 0, respectively. The angle of shear fracture, α, the values R and Φ of the ellipse replacing the lozenge, as well as the minimum value for antithetic rotation, $s_{r_{crit}}$, the real value of s_r relative to a passive material line initially parallel to layering, and the internal and external antithetic (+ve) rotation of the pull-aparts, δ_{int} and δ_{ext}, are indicated. The grey area in the schematic diagram on the top right shows the domain of the stress ellipsoid where layers are dismembered into antithetically rotating asymmetric pull-aparts.

possibly to *ecc*-features (Platt 1984) developing in the fully ductile domain.

As outlined earlier, the type III boudinage as observed by Goldstein (1988) in natural shear zones can also be interpreted as shear pull-aparts in the terms of Fig. 11(b). However, Goldstein's model differs from the present model in (1) the competent layer is segmented by shear fractures (rather than tension fractures), and (2) the rheological behaviour of the resulting lozenges. The obliquity of the competent layer relative to the shear zone boundary as postulated by Goldstein is a possible but not necessary requirement for the formation of lozenge shaped pull-aparts.

The antithetically rotated lozenge-shaped pull-aparts recorded by Malavieille (1987), Gaudemer & Tapponnier (1987), Malavieille & Ritz (1989) and Stock (1989) from other evaporite and non-evaporite shear zones are suggested to have a genesis similar to that of the Jura shale pull-aparts. This points to a certain universality of the mechanism.

In natural shear zones, the lozenge-shaped pull-aparts in question can be easily confused with bookshelf structures (domino, or stack of card structures, Etchecopar 1977) (Fig. 1e), or type I asymmetric pull-aparts (Hanmer 1986) (Fig. 1f) with badly developed curved ends, both of which indicate a sense of rotation opposite to that of the shale pull-aparts. This points to the fact already outlined by Hanmer (1986) and Goldstein (1988) that lozenge-shaped or rotated pull-aparts are quite ambiguous kinematic indicators, if their kinematics are not known.

CONCLUSIONS

The asymmetric shear pull-aparts of the Jura evaporite shear zones are characterized by the combination of lozenge shape and antithetic rotation. The oblique shear fractures outlining the lozenges result from a σ_1 direction steeply inclined relative to layering ($45° \ll \phi < 90°$) inducing transpressive strain which, in turn, causes the subsequent antithetic rotation of the pull-aparts. Antithetically rotating lozenge-shaped pull-aparts develop either in compressive décollement-type shear zones or in shear zones that are oblique to initial layering. The rotational behaviour of the pull-aparts can be described independently, whether the lozenges are isolated or not, in the terms of Ghosh & Ramberg (1976) (cf. Stock 1989). During on-going deformation, the lozenges may keep their shape, or they may be stretched and possibly also squeezed. If the rotation and stretching of the pull-aparts compensates for the over-all stretching $[(1 + e_x)_{tot}]$, the lozenges keep in contact. Commonly it does not, and the lozenges are separated by sulphate veins.

Generally, the formation of lozenge-shaped pull-aparts is restricted to the shallower domains of the evaporite shear zones and to layers equivalent in thickness to the nearby incompetent layers (cf. Strömgård 1973). As a consequence, clearly recognized antithetically rotated lozenge-shaped pull-aparts are good indicators for (local or over-all) transpressive regimes in shallow or fast deforming shear zones.

On the other hand, the shale pull-aparts show some similarities in shape with bookshelf structures and type I pull-aparts. As both of these indicate an opposite sense of rotation to the shale pull-aparts, rotated blocky- to lozenge-shaped pull-aparts have to be denoted as quite ambiguous kinematic indicators.

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