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Sidewall ripouts in strike-slip faults

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Abstract—Distinctive splay fault configurations in wallrocks associated with pseudotachylyte-bearing strike-slip fault structures at three different localities are recognized as 'sidewall ripouts'. Sidewall ripout structures occur as asymmetric, doubly-tapered, fault-bounded lenses or slabs adjacent to a dominant planar fault surface. Scallop-shaped lens ripouts develop in isotropic or weakly anisotropic host rocks and elongate slab ripouts develop in strongly anisotropic host rocks. The tapered ends of these structures consist of leading contractional *P*-type ramp structures at a low-angle to the dominant planar fault surface and trailing extensional *R*- or *X'*-type ramp structures at higher angles to the dominant fault surface. The formation of ripout structures is attributed to transient variations in the coefficient of friction that cause adhesion between fault surfaces leading to rupture of the sidewalls. Ripouts are interpreted as large outcrop-scale examples of adhesive wear during rupture of the sidewalls developed along planar fault surfaces during slip. The asymmetry of the ripout structures in these exposures allows their use as a kinematic indicator where the narrow-tapered leading end points in the direction of movement of the ripout lens or slab during adhesion to the opposing fault block wall.

INTRODUCTION

Distinctive fault structures associated with the production and preservation of pseudotachylyte have been recognized in brittle strike-slip faults within the mylonitic rocks of the Rye Formation and the phyllitic quartzites of the Cape Elizabeth Formation (Fig. 1) of southern coastal Maine in the northeast U.S. (Swanson 1985, 1987, 1988). Identical fault structures were subsequently recognized associated with the pseudotachylyte-bearing brittle zones in the Ikertôq shear belt of western Greenland originally described by Grocott (1977, 1981). This report represents the results of detailed mapping of fault zones in these three localities and serves to introduce a distinctive structural configuration termed the 'sidewall ripout'.

Fault interaction with an effective layer-anisotropy results in the development of elongate fault-bounded slab ripout structures that are similar to the slab–duplex complexes of Swanson (1988) and the pseudotachylyte generation zones of Grocott (1981) described in earlier reports. Ripout formation in conjunction with an effective layer-anisotropy is yet another method of producing paired layer-parallel fault structures. The lens and elongate slab ripouts (Fig. 2) as described in this report are, in effect, duplexes of fault-bounded, internally deformed, host rock slices commonly observed in thrust belts but recently recognized in the strike-slip environment (Woodcock & Fischer 1986, Swanson 1988). The sidewall ripouts in the strike-slip faults discussed here are defined by coupled extensional and contractional end ramps (coupled ramp duplexes) in contrast to the strictly contractional or extensional duplexes (Swanson 1988) typically developed at en échelon overlaps (en échelon linkage duplexes).

The pseudotachylyte associated with these and other similar exposures has been interpreted as a friction melt (Sibson 1975, Grocott 1981, Maddock 1982, Maddock *et al.* 1987) developed along the fault surfaces during displacement. Frictional melting during displacement requires fairly rapid slip rates (Sibson 1975) that are characteristic of fault ruptures developed during seismic events. The study of exhumed pseudotachylyte-bearing fault structures, then, is important in understanding the catastrophic rupture processes associated with earthquake generation at depth and in formulating valid earthquake source zone models. The ripout structures described in this report for pseudotachylyte-bearing strike-slip fault structures are attributed to adhesive wear processes associated with fault displacement at seismic slip velocities. The formation of ripout structures may be characteristic of the style of rupture developed at seismogenic depths within the crust.

GEOLOGIC SETTINGS

The structures from two fault localities in southern coastal Maine and one in western Greenland described in this report are developed in a variety of metamorphic host rocks. All of the NE-trending fault structures are dextral strike-slip and pseudotachylyte-bearing, associated with rocks from both the mylonitic and cataclastic fault regimes within and above the brittle–ductile transition. The correlation of fault configurations in these three localities will allow a comparison between faults developed at shallow and moderate crustal levels and between faults developed in isotropic (or weakly anisotropoic) and strongly anisotropic host rocks.

Two Lights fault structures, coastal Maine

The Two Lights fault structures (Swanson 1987) are developed in the Cape Elizabeth Formation of the Casco

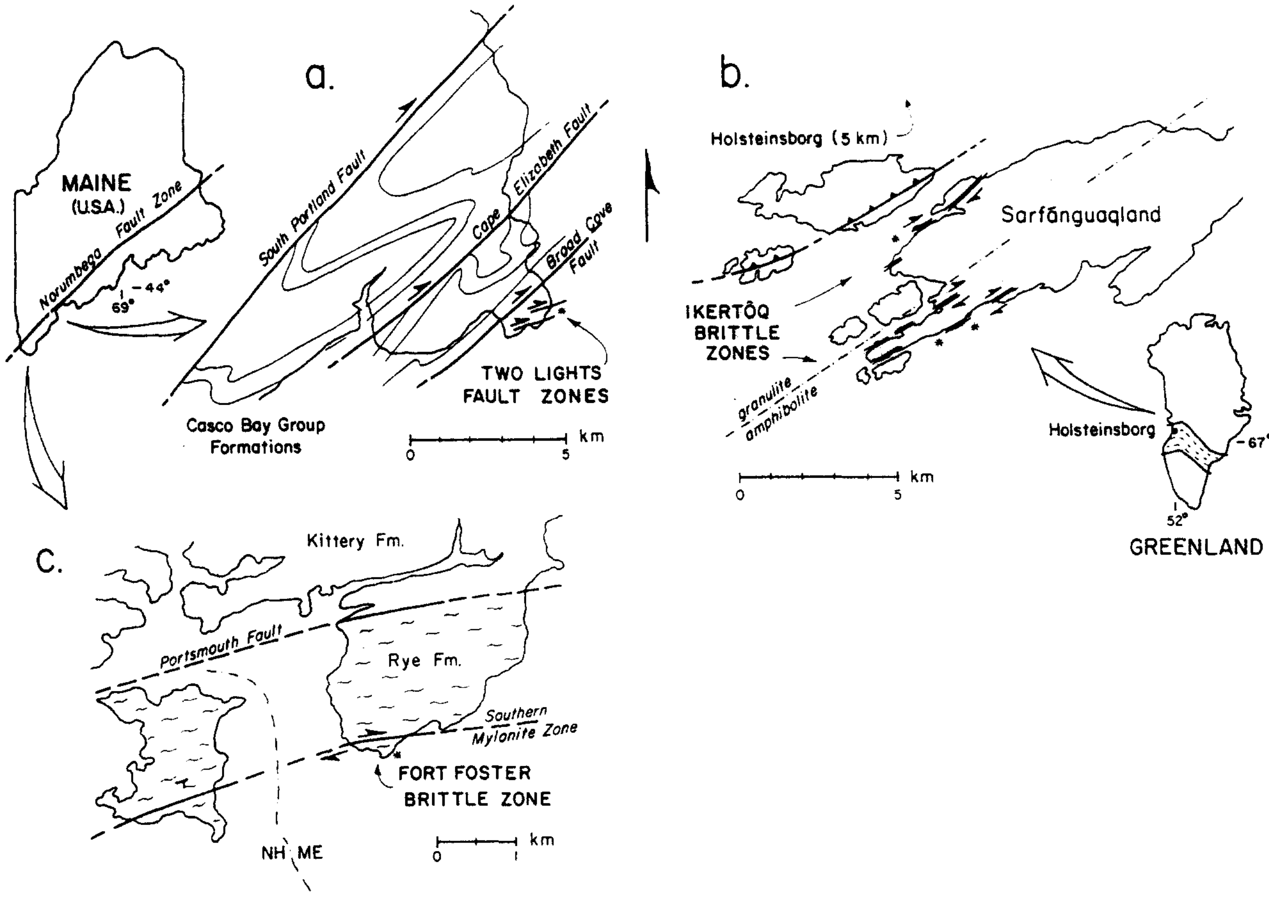


Fig. 1. Location, orientation and distribution of strike-slip faults described in this report. (a) The Two Lights fault structures of the Cape Elizabeth Formation, Casco Bay, Maine. (b) The Ikertôq brittle zones in western Greenland. (c) The Fort Foster brittle zone of southernmost coastal Maine. Asterisks indicate approximate outcrop localities for mapped fault structures presented in the following figures.

Bay area of coastal Maine (Fig. 1a). The host rocks consist of highly deformed, chlorite to biotite grade phyllitic to schistose quartzites and metasiltstones that have been subjected to a multiple deformational history (Hussey 1971, 1985) prior to strike-slip faulting. The dominant F_1 fold phase is responsible for an early large-scale recumbent folding and nappe emplacement that leaves the original bedding and any weak cleavage anisotropy in a near-horizontal orientation. Upright F_2 folds are not significantly developed in this area. The F_3 fold phase (not previously recognized) consists of small-scale asymmetric folds and shear surfaces oblique to the foliation that develop a sporadically pervasive asymmetric foliation boudinage similar to an outcrop-scale asymmetric crenulation cleavage. The dextral shear strain associated with this F_3 fold phase is also responsible for the development of the discrete dextral strike-slip fault structures of late Paleozoic age. Several of these faults have been mapped in detail, parts of which are described in this report. The dextral high-angle faults in these exposures show little interaction with the low-angle bedding-anisotropy. The fault structures represent multiple slip events with approximately 5–10 m of cumulative displacement. The faults are generally cataclastic and are associated with only minor amounts of pseudotachylyte. The host rock layer-anisotropy is subhorizontal and does not control the orientation or geometry of the brittle strike-slip fault structures.

Ikertôq brittle zones, western Greenland

The dextral strike-slip fault structures of the Ikertôq brittle zones of western Greenland (Grocott 1977, 1981) are developed in highly deformed, high-grade (granulite to amphibolite) gneisses as part of the overthrust Ikertôq shear belt (Fig. 1b). The late brittle strike-slip structures are interpreted as a minor zone of structural reactivation at fairly shallow crustal levels developed during the late Proterozoic (Bak *et al.* 1975, Piper 1981). Fault structures are dominantly single-slip events with typical metre-plus displacements and are associated with relatively large volumes of pseudotachylyte. Concordant fault veins parallel to the gneissic foliation, discordant injection veins and tabular breccias with pseudotachylyte matrix are commonly developed. The layer-anisotropy in the host gneisses is at a high-angle orientation and does control, to some degree, the orientation of the later brittle strike-slip fault structures.

Fort Foster brittle zone, coastal Maine

The pseudotachylyte-bearing faults of the Fort Foster brittle zone in southernmost coastal Maine (Swanson

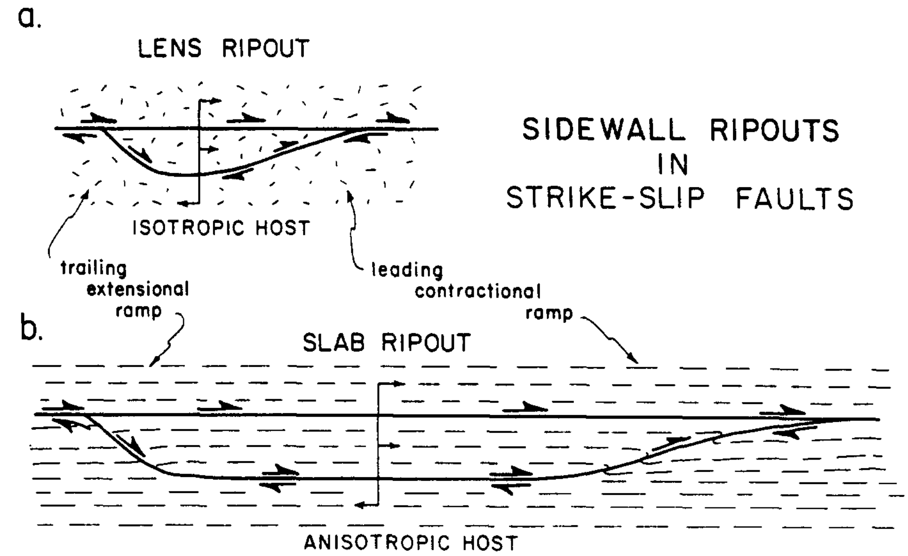


Fig. 2. Generalized geometry of sidewall ripouts in strike-slip faults. (a) Lens ripout with leading contractional ramp and trailing extensional ramp in typical scallop-shaped geometry characteristic of isotropic or weakly anisotropic host rocks. (b) Slab ripout characteristic of more strongly anisotropic rocks. (Arrow arrays indicate relative motion during ripout formation.)

1985, 1988) are developed within a mylonitic zone of extremely high ductile dextral shear strain (Fig. 1c). The host rocks of the Rye Formation are highly strained and mylonitized but show an earlier history of isoclinal folding, sillimanite-grade metamorphism, migmatization and andalusite-grade metamorphism of probable Precambrian age (Hussey 1980, Carrigan 1984a,b). The fault structures represent single to multiple slip events with generally small, cm- to m-scale, displacements. Brittle faulting is interpreted to have occurred at a moderate crustal depth within the brittle–ductile transition as evidenced by the ductile reworking of earlier formed pseudotachylyte. The mylonitic layer-anisotropy is strongly developed at a high-angle orientation that controls, to a large degree, the orientation and geometry of the brittle strike-slip fault structures.

GEOMETRY

The distinctive ripout structures described here are defined by arcuate or listric splay faults that cut out scallop-shaped lenses (Fig. 2a) or elongate slabs (Fig. 2b) of host rock from the sidewalls adjacent to straight planar strike-slip fault surfaces. Such fault-bounded lenses and slabs, typically with a single flat side, are here termed *sidewall ripouts*. These ripouts are marked at their ends with splay faults that define ramp structures relative to the dominant planar fault surface, giving them a double-tapered asymmetric geometry. The splay faults converge with the dominant planar slip surface that marks the flat side of the structure. The sense of shear on the bounding faults that define the ripout structures suggests that they have been displaced parallel to the slip vector for the dominant planar faults and in the direction of motion of the opposite sidewall block. The geometry of these structures can then be described in terms of leading and trailing end ramps relative to their interpreted direction of displacement. The end ramps are developed in front of and directly behind the ripout lenses or slabs relative to this displacement. The shear fracture terminology (*P*, *P'*, *X*, *X'* *R* and *Y*) used to describe the orientations and senses of shear in these end ramp structures and the internal deformation follows that of Logan *et al.* (1979) and Swanson (1988). Typical shear fracture assemblages and their respective classification terminology are illustrated in Fig. 3.

The characteristic ripout geometries found in these exposures are illustrated in the dextral strike-slip fault maps of Figs. 4–6. All of these strike-slip fault structures are NE-trending and depicted with the NW direction to the top of the page. The ripout structures are developed as distinctly asymmetric, doubly-tapered lenses and slabs distributed on either side of the dominant planar fault surfaces (see Figs. 4c and 5a). The geometry of these ripout structures (Fig. 2) consists of one flat side that is coincident with the dominant planar fault surface and a second arcuate to flat side that defines the lens or slab configuration. The tapered leading and trailing end ramps are distinctly different in geometry and are discussed in more detail below.

Length: width ratios from several of these ripout structures were found to be quite variable, ranging from approximately 3 : 1 for the scallop-shaped lens ripouts in

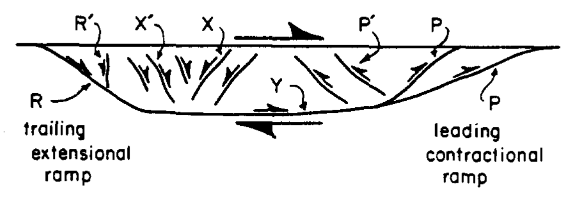


Fig. 3. Shear fracture terminology used in this report after Logan *et al.* (1979) and Swanson (1988).

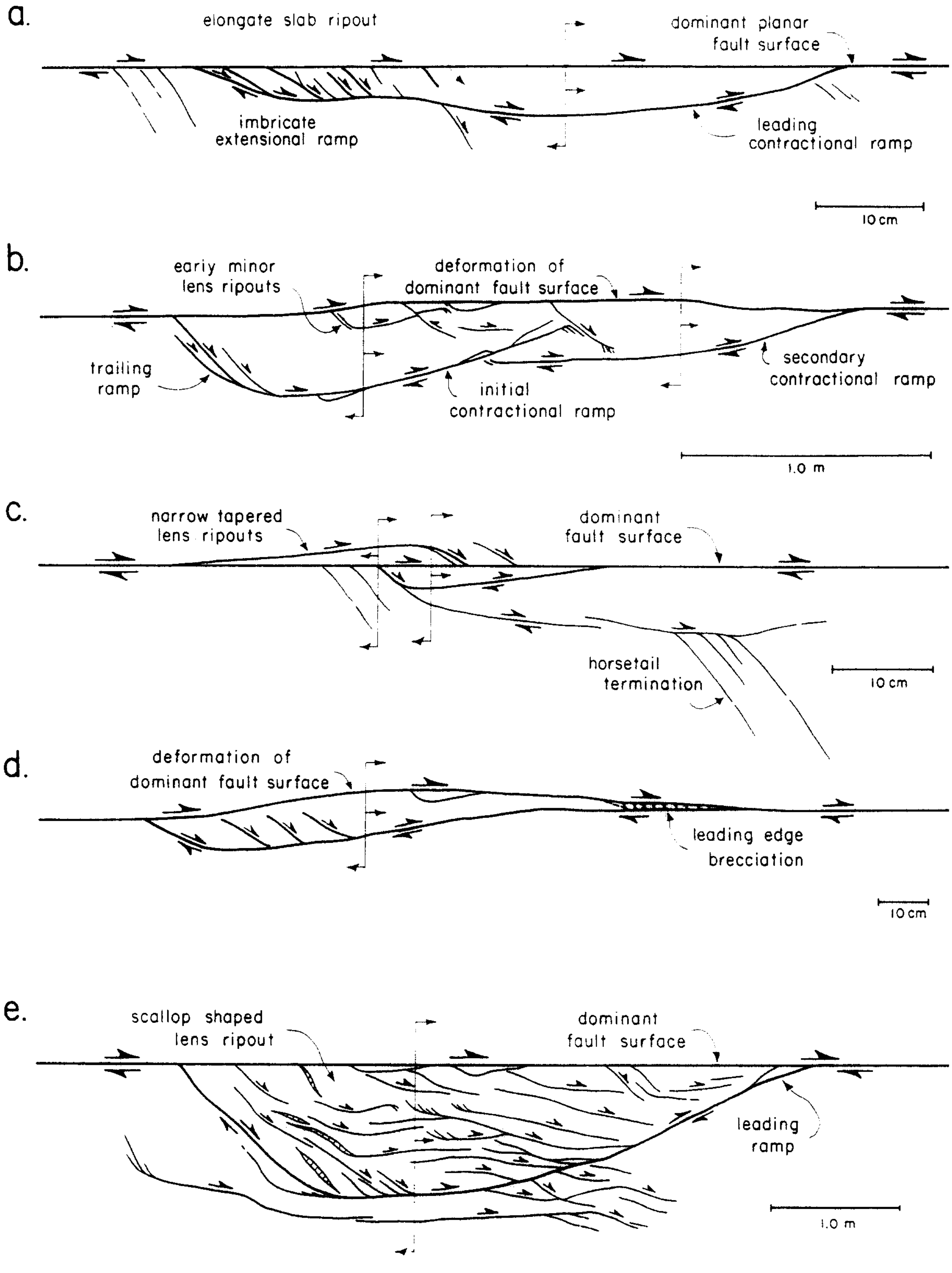
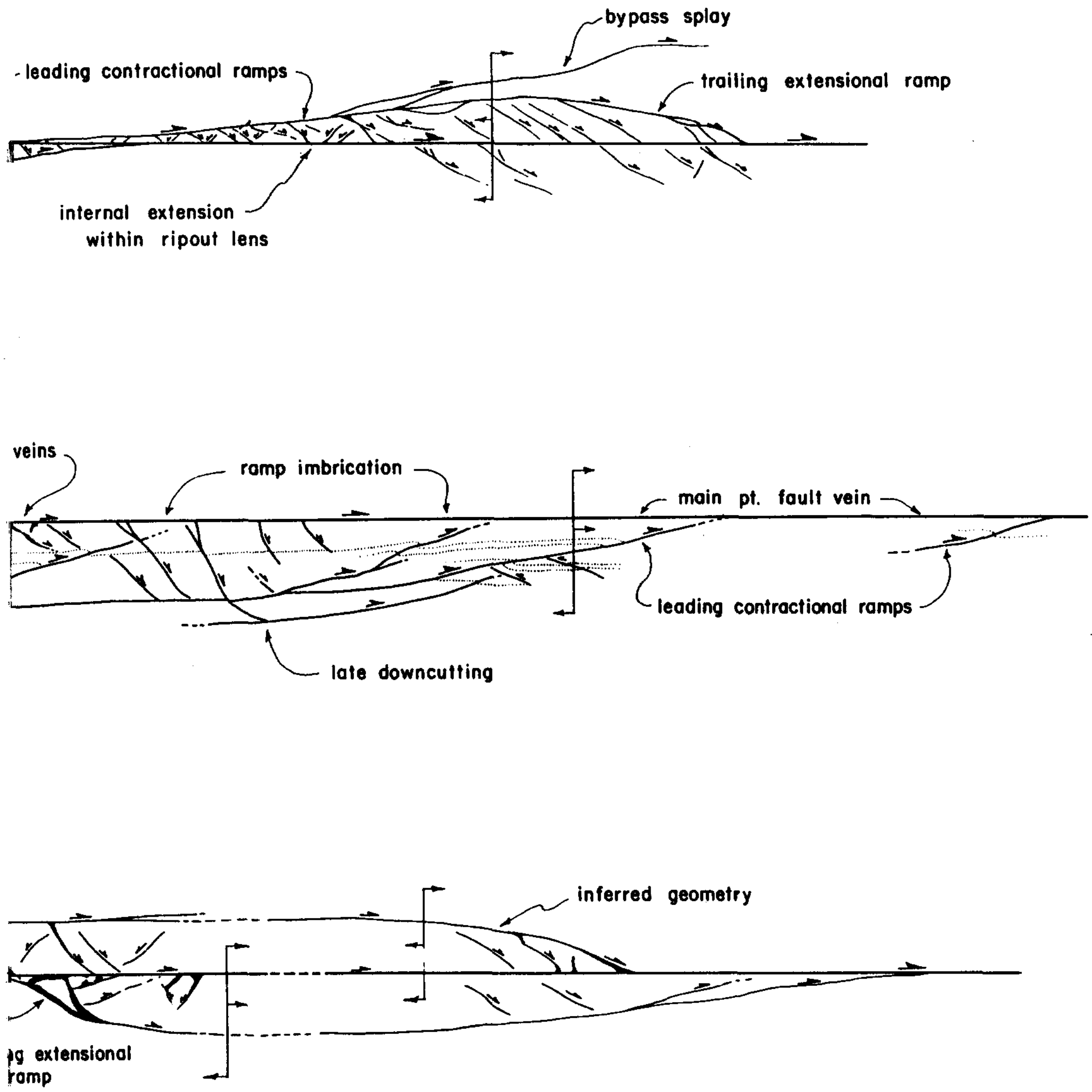


Fig. 4. Ripout structures in the Two Lights fault structures of Casco Bay, Maine. (a) Elongate slab ripout structure with imbricate extensional ramp adjacent to dominant planar fault surface. (b) Composite lens ripout structure with imbricate extensional ramp and initial leading ramp with horsetail termination, secondary contractional ramp and evidence for deformation of the dominant planar fault surface. (c) Narrow-tapered lens ripouts developed on both sides of the dominant fault surface with minor extensional splay faulting with horsetail termination. (d) Narrow-tapered lens ripout showing deformation of the dominant fault surface that creates a releasing bend with minor breccia associated with the contractional ramp. (e) Scallop-shaped lens ripout structure with complex internal structure dominated by minor splays parallel to dominant planar fault surface with extensional kink band terminations (ladder-like symbols). (Arrow arrays indicate relative motion during ripout formation.)



kertôq brittle zones of western Greenland. (a) Multiple ripout structures on a single fault ometry in relation to the interpreted sense of slip. (b) Single ripout structure with complex velopment of leading and trailing ramp structures. (c) Multiple ripout structures showing res of leading and trailing ramp structures. (Arrow arrays indicate relative motion during ripout formation.)

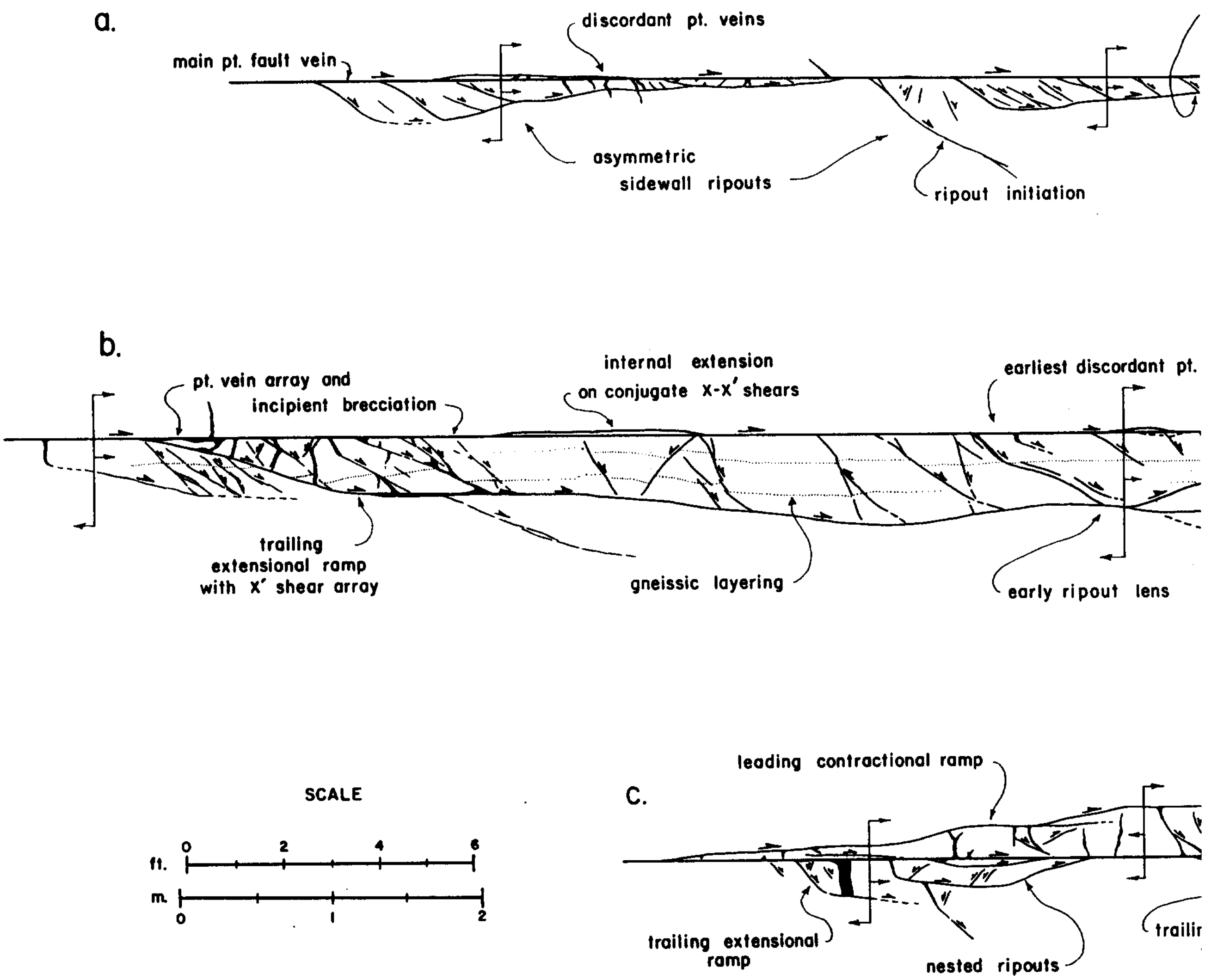


Fig. 5. Ripout structures in the I
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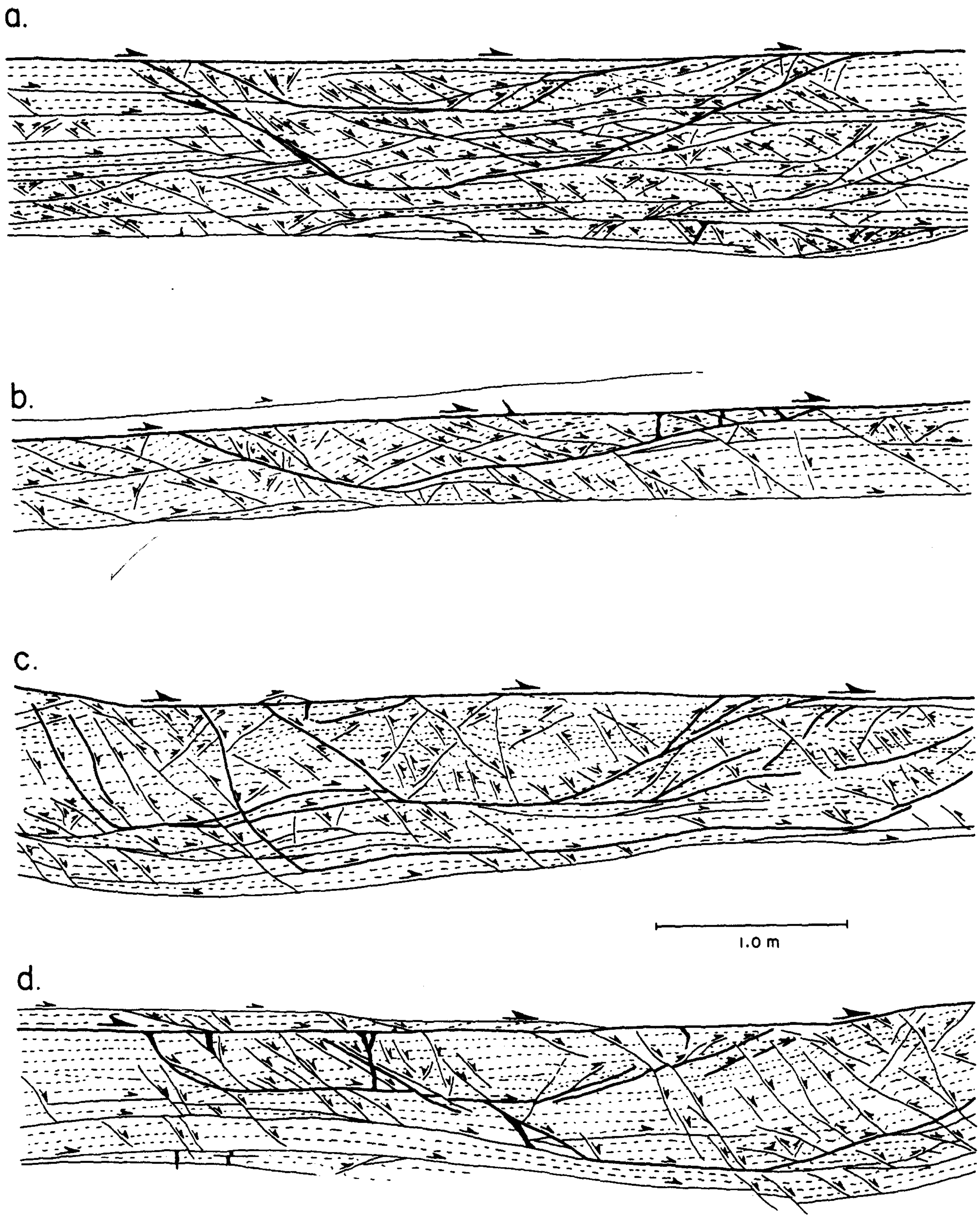

Fig. 6. Ripout structures in the Fort Foster brittle zone of southern coastal Maine. (a) Scallop-shaped ripout cutting earlier layer-parallel fault systems. (b) Asymmetric ripout growth by the expansion of the trailing extensional ramp system. (c) Symmetric growth from early scallop- to later, deeper slab-shaped ripout structures. (d) Pseudotachylyte vein systems associated with slab ripout structures. (Dashed lines represent mylonitic foliation.)

some of the Two Lights exposures (e.g. Fig. 4e) to 20:1 or greater for the elongate slab ripouts as in the Ikertôq exposures (e.g. Fig. 5b). An idealized ripout lens consisting of linking X'- and P-shear ramps at 60 and 30° to the dominant slip surface, respectively, would define a ripout structure geometry with a length:width ratio of 2.3:1. Fully-exposed ripouts were found to range from 5 cm to over 15 m in length and were generally restricted to less than 1 m in width. Larger structures may have been developed in some of these exposures but their recognition is limited by the extent of outcrop. The development of larger elongate slab ripouts may be a contributing factor in the dominance of paired parallel fault zone patterns in some of these exposures.

The nature of the anisotropy in the layered metamorphic host rocks is important in determining the ripout geometry. In general, an effective layer-anisotropy will promote the development of long flat-sided slabs with high length:width ratios as illustrated in Figs. 2(b), 5(b) & (c) and 6(c) & (d). Long flat-sided slab ripouts typical of some of the Fort Foster structures (see parts of Fig. 10) are due to the strong mylonitic layer anisotropy in the host rocks. The lack of a controlling anisotropy will lead to the development of more scallop-shaped lenses with low length:width ratios as illustrated in Figs. 2(a), 4(b) & (e) and 6(a). Typical ripouts in most of these exposures appear in a distinctive configuration with strongly scalloped, trailing ramps and long gently-tapered leading ramps (see Figs. 4c and 5a, for examples).

Leading contractional ramps

The leading ramps for these ripout structures are typically P-type contractional splays that develop at a low-angle to the dominant planar fault surfaces. Measured orientations from 16 leading ramps range from 4 to 26° and average 14°, relative to the dominant planar fault surface. The leading contractional ramps occur where the ripout lens or slab has been forced laterally against the adjoining wallrocks during displacement. Several examples (Figs. 5b and 6a,c & d) show drag folding in the gneissic and mylonitic layering in the host rocks along these contractional ramps. Many of the leading ramp assemblages also show the development of antithetic sinistral P' shears at high-angles to the dominant planar surface (Figs. 4b and 6a & c). These form a conjugate P–P' shear set that contributes to the shortening of the leading ripout edge during displacement.

Several ripouts illustrated in Figs. 4(b), 5(b) and 6(a)–(c) also show evidence of imbrication of the leading ramp structures. The contractional ramps may build out a typical imbricate fan array that coalesces with a single detachment along the flanks of the ripout structures. There is also a general tendency for the younger ramps to cut progressively deeper into the sidewall during development, detaching along new flanking surfaces. This effectively increases the size of the ripout structures, thereby accommodating increased displacements. A result of this style of imbrication where younger ramps cut deeper into the sidewall is the development of nested ripouts with larger ripouts formed about the earlier smaller ripouts as in Figs. 4(b) & (e), 5(c) and 6(c).

Trailing extensional ramps

The trailing ramp structures are more listric-shaped, generally R- or X'-type splay faults that develop at higher angles to the dominant planar slip surfaces. Measured orientations from 18 extensional ramps range from 20 to 67° and average 42°, relative to the dominant planar fault surface. The extensional ramps mark the tail or trailing end of the ripout structures where the lens or slab has pulled away from the adjacent wallrocks during displacement. The extensional ramp structure in the Fig. 5(b) ripout from the Ikertôq exposures and perhaps the Fig. 4(a) ripout from the Two Lights exposures consists of a dominant low-angle R-shear ramp that serves as a detachment for numerous higher-angle X' shears that accommodate a significant portion of the trailing ramp extension. Many of the extensional ramps may also have initiated as oblique tension fractures as suggested by their 45° orientation although many of them have suffered rotation to lower angles during displacement. The extensional ramp assemblages in the Two Lights exposures (Figs. 4b & d) may be the best examples of initiation by tension fracturing with strong similarities to the horsetail termination arrays (Fig. 4c) that are so abundantly developed in these fault structures.

Imbrication is also evident in the trailing extensional ramp structures as in the leading contractional ramp structures. Ramp imbrication appears as the dominant mechanism for the growth of the trailing end of the ripouts by the progressive collapse of the endwalls into the trailing dilatant zone. Figures 4(a)(b) & (e), 5(a) and 6(b) illustrate the typical pattern of extensional ramp imbrication. The development of a lone extensional dextral shear splay in the central part of Fig. 5(a), suggests that ripout formation may proceed from an initial shear fracture at the trailing dilatant end of the structure.

The trailing end of the ripout structures develops as a zone of dilatation leading to the formation of pseudotachylyte veins and breccias. It is the trailing end that preferentially collects the pseudotachylyte produced elsewhere along the main fault surface. In several of the smaller-scale structures from the Fort Foster and Ikertôq exposures, the trailing ends have developed from a single pseudotachylyte injection vein, as tension fractures orthogonal (Figs. 5b & c) or oblique (Figs. 5c and 6d) to the dominant planar fault surface rather than as the R- or X'-shear fractures. This suggests a possible genetic link between the development of the pseudotachylyte injection veins and the formation of the ripout structures.

The ripout structure in Fig. 5(b) has a trailing end that is marked by a mesh of conjugate shear fractures and linking pseudotachylyte-filled dilatant zones. These interconnected shear and dilation zones are similar to the extensional stepover zones in en échelon fault segments envisioned by Hill (1977) and Sibson (1986), except that these are filled with pseudotachylyte. The trailing end in Fig. 5(b) also suggests a sequence of development in the formation of localized tabular breccias and pseudoconglomerates (Sibson 1975), common in the Greenland exposures and less so in the Maine exposures, where they have the typical tapered trailing end geometries. These breccias could have developed from the initial mesh configuration of Fig. 5(b) with increased disruption during continued displacement.

KINEMATICS

The overall kinematic development of these ripouts is deduced from the sense of slip on the bounding fault splays that comprise the end ramps and are the outer flanks of the structures. Clear and measurable offsets of distinctive compositional layers can be found at most of the ramp and flank structures, often preserved in the most intricate detail. From these observed offsets, the ripout lenses and slabs have clearly been displaced along with the opposite wallrocks during slip along the dominant fault surface. The rupture and displacement of these ripouts as depicted in Fig. 7, result in the formation of the contractional and extensional structures in the leading and trailing ends of the ripouts relative to their direction of displacement. The origin of these ripout structures is attributed to a localized increase in frictional resistance developed during sliding of a fault surface (Figs. 7a & b). This rise in frictional drag represents a form of adhesion that locks or slows a particular area along the fault plane (Fig. 7b) during displacement. This creates localized compressional and tensional zones adjacent to the fault due to transient velocity contrasts (Fig. 7b) in the sidewalls. As rocks are weaker in tension than in compression, failure in the wallrocks would be expected to have initiated in the tensional field (Fig. 7c) where the wallrock was pulling away from the locked zone during slip. Continuing displacement must bypass this locked or slowed zone and rips out a section of wallrock across from and immediately adjacent to the locked zone (Figs. 7c,d & e), hence the name 'sidewall ripout'. In simple terms, the ripout structures represent skid marks or seize marks of one fault block against another developed during slip. A more general term would be 'wallrock ripouts' to take into account the footwall and hangingwall configurations of dip-slip faults as well.

Strain accommodation

The internal deformation of the more elongate ripout slabs (Figs. 4a and 5a & b for example) other than that associated with the end ramps is, overall, one of distributed layer-parallel or fault-parallel extension. This extension is accommodated by sets of conjugate X–X'-shear fractures at moderate angles to the dominant planar fault surface. This internal extension implies that the ripout slabs are also being 'smeared out' during their limited displacement. A few of the smaller ripouts show a dominance of internal layer- or fault-parallel shortening. Many of the ripouts, however, show a more complex pattern of distributed strain, with cross-cutting extensional as well as contractional structures, most likely related to overlapping growth of separate structures at their leading and trailing end ramps (Figs. 4b & e, 5b and 6c & d).

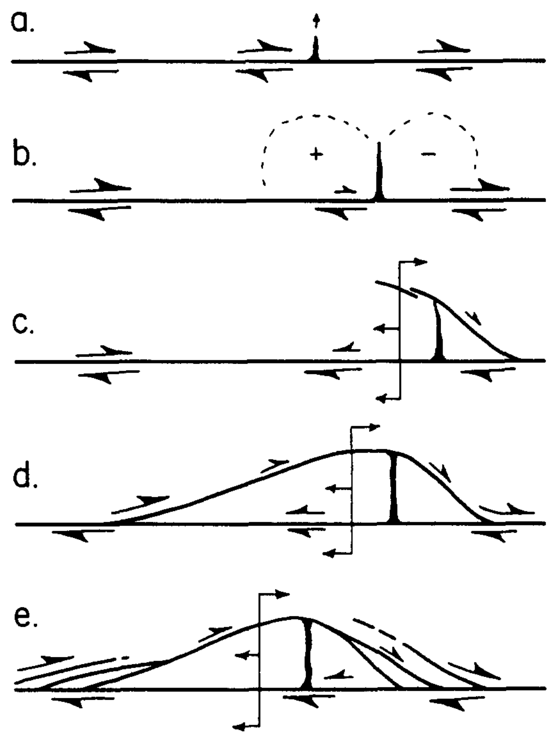

Fig. 7. Dynamic model for the development of sidewall ripouts in strike-slip faults. (a) Rupture initiation and displacement at a uniform slip velocity with rapid slip leading to pseudotachylyte generation, melt lubrication and excessive fluid pressures that hydrofracture into the wallrocks. (b) Melt injection into sidewall fractures drains the fault surface with collapse of excessive fluid pressures, an increase in the effective normal stress and frictional resistance leading to velocity variations in the wallrocks. (c) Ripout initiation at extensional field as wallrocks pull away from the slowed or stuck section. (d) Detachment of ripout lens or slab with development of and linkage with the leading contractional ramp. (e) Continued displacement during adhesion accommodated by symmetric growth of ripout by imbrication in leading contractional ramp and dilational collapse at the trailing extensional ramp. (Arrow arrays indicate relative motion during ripout formation.)

The end result of the adhesion and rupture during ripout formation is the lateral rigid-body translation of the ripout rocks relative to the adjoining wallrocks. The total extension developed in the trailing ramp structures should, in theory, match the contractional strain developed in the leading ramp structures and indicate the amount of displacement involved in ripout formation. The total displacement accommodated by the formation of the ripouts appears to be directly proportional to the overall length of the ripout structures. From the examination of several leading and trailing structural assemblages, there appears to be a limiting amount of layer-parallel or fault-parallel strain that can be accommodated within the ramp structures. That limiting strain value is approximately 10% fault-parallel shortening or extension at the leading and trailing ramps when distributed over the full length of the corresponding ripout structure. As a first-order approximation, then, the amount of main fault displacement accommodated by ripout formation would be less than or equal to about 10% of the length of the observed ripout block. Once this strain limit is reached further displacement along the main fault can only be accommodated by growth or expansion of the ripout structure or rupturing the adhesive bond across the fault between the ripout and the opposite fault wall. The strains involved in ripout formation also only represent displacements associated with the development of that particular structure. Considerable slip may have occurred prior to, or immediately after, ripout formation with rupturing of the adhesive bond during the same slip event.

For the ripout example in Fig. 5(b), approximately 60 cm of shortening in the leading *P*-shear ramp can comfortably account for the 52 cm of measurable extension developed in the tail by *R*- and *X'*-shear fracturing as well as several centimeters distributed as internal extension on conjugate *X*–*X'* shears. Using a 10 m overall slab length, the extension or shortening accommodated by the end ramp structures represents about 6% of the ripout slab length. Similar results can be obtained from the Fort Foster structures using a quartzo-feldspathic marker layer and earlier layer-parallel fault veins within the mylonitic host rock. Three of the Fort Foster ripouts (Figs. 6a,c & d) with lengths of 2.8–3.5 m have leading ramp displacements of 20–22 cm. This leads to typical displacement : length ratios comparable to those for the Ikertôq structures of 6–7%. The Two Lights structures were found to range from 15 cm to 4.5 m in length with displacements from 1 to 35 cm and an average displacement : length ratio of 9.3%.

These results are illustrated in a plot of length vs displacement (Fig. 8), where the displacement : length ratios (the inverse slope in this plot) represent the slip-parallel strain (Muraoka & Kamata 1983) or the average linear strain (Watterson 1986) associated with faulting. The limiting value of 10% slip parallel strain for these ripout structures compares favorably with larger-scale faults described by Watterson (1986) and is an order of magnitude greater than values reported by Muraoka & Kamata (1983) for smaller-scale minor fault structures.

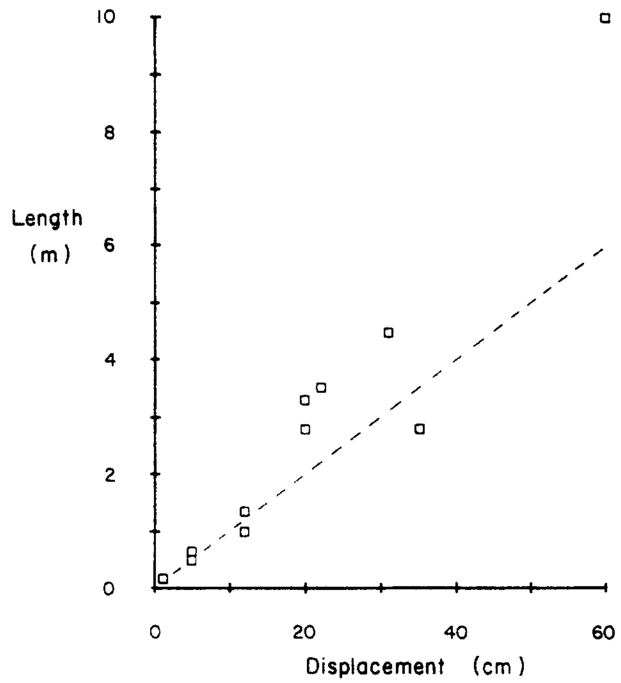

Fig. 8. Graph of measured length and displacements for ripout structures from all three localities. Inverse slope of dashed line represents displacement : length ratios of 10%.

Ripout evolution

A progressive growth of some of the ripouts by ramp imbrication is apparent in several of the mapped structures in both symmetric (Figs. 5b and 6c) and asymmetric (Figs. 4a, 5a and 6b) patterns. At both the front and rear of the Fig. 5(b) ripout, the youngest structures appear to be caught in an incipient stage of development. This ripout was apparently in the process of picking up another 'leading' ramp when displacement ceased. Imbrication in the leading contractional ramps is evident in other ripout structures illustrated in Figs. 6(c) & (d). In Figs. 5(b) and 6(c) the youngest leading ramps also cut deeper into the fault block wall. These new leading ramp structures are coupled to trailing ramp structures where new sections of sidewall are plucked or ripped out during displacement.

Minor cross-cutting relations within the structures, particularly in Fig. 5(b), also suggest a sequential development with successive additions of coupled leading and trailing ramp structures. The oldest part, or nucleus, of the structures in Figs. 5(b), 6(a) or (c) would be the center of the ripout. In each case the initial stout, scallop-shaped lens ripout appears to have acted as an indented asperity during translation. Growth of the structure occurred while locked to the opposing wallrocks across the main fault surface during displacement where this geometric asperity was forced to plow its way through the adjoining wallrock. The plowing of this asperity during displacement builds out imbricate contractional ramps in front and leaves extensional structures, veins and breccias flooded by pseudotachylyte in its wake. Several exposures in the Fort Foster structures show complex cross-cutting relations in overlapping ripouts (Figs. 4b & e, 5c and 6a & c) where repeated adhesion ruptured and reruptured the sidewall rocks during displacement.

Shortening in the leading contractional ramps

One problem for this kinematic model, is the nature of the accommodation of shortening recorded in the leading contractional ramps. Confinement of the leading ripout edge by the dominant planar fault surface and the adjoining wallrock creates a space problem in accommodating the displacements on the leading ramp. Material could have been removed by frictional melting at the area of contact with the dominant planar fault surface. This area of contact along the fault would be expected to have relatively higher normal stresses and a higher potential for the generation of frictional heat. This could be a possible source for the pseudotachylyte preserved in the extensional trailing ramp systems. There is abundant field evidence to suggest localized areas of 'melt attrition' such as at the corners of rotated fault blocks where the internal layering is truncated against the planar fault surfaces.

The space problem arising due to displacements on the leading ramp may be largely solved by slip on the gneissic banding accompanied by displacement on high-angle extensional faults in the ripout structure. Such a mechanism is necessary because the volume of material required to be lost by attrition on the principal fault often seems far greater than the volumes of pseudotachylyte in the Greenland exposures. The role of layer-parallel slip has been considered in detail by van Nes (1989).

A more likely possibility for accommodating the leading ripout edge material may be the development of distributed strain in the adjoining wallrocks. Drag folds are prominently developed at the leading ramp surfaces and are often significant sources of shortening in the end ramp wallrocks. Figures 5(b) and 6(a), in particular, show the development of drag folds and imbrication at the leading ripout edge. This pattern of strain reflects the plowing of the ripout slab through the adjoining wallrocks during adhesion, rupture and displacement.

Several exposures also show evidence of the deformation of the dominant planar fault surface and adjoining wallrocks on the opposite side of the fault. Figures 4(b) & (d), in particular, show the deformation of the dominant fault surface where adjacent to the leading ripout edge. Translation of the ripout lens or slab along the leading contractional ramp during adhesion has impinged on the dominant planar fault surface. A result of this fault surface deformation, in some cases, is the creation of a subtle releasing bend in the dominant fault at the leading ripout edge. As depicted in Fig. 9, the reactivation of the dominant fault surface results in the development of localized dilation breccia associated with this releasing bend at the leading ripout edge. This is evidence for the rupturing of the adhesive bond responsible for ripout formation and the back transfer of the ripout lens to its original position relative to the active fault surface. Both the loss due to melting and the distributed strain processes are probably at work to some extent during ripout formation.

Ripout sequences

The composite diagram in Fig. 10 shows the size and distribution of a number of ripout lenses and slabs developed in the sidewalls of the layer-parallel strike-slip faults within the northwestern boundary of the Fort Foster brittle zone. The abundance and distribution of ripouts within the layer-parallel dextral strike-slip faults in these exposures suggests that ripout formation is a common mechanism of strain accommodation within these faults and that ripouts develop repeatedly along the same fault surface. The diagram also seems to suggest a pattern of preferential rupture from the southeast sidewall, the lower block in each of the diagrams. Some ripouts do form in the northwest wall as well but they are not as common.

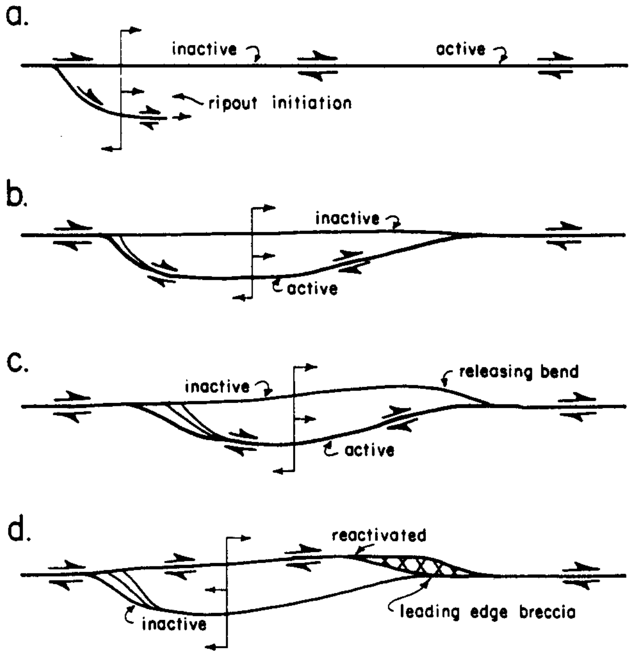

Fig. 9. Kinematic model for the development of leading edge breccias. (a) Initiation of ripout at extensional trailing ramp. (b) Translation of ripout along contractional leading ramp. (c) Deformation of the dominant planar fault surface to accommodate translation of the ripout, creating a releasing bend in the inactive section of the fault. (d) Reactivation of this fault section and the releasing bend with the development of localized dilation breccia. (Arrow arrays indicate relative motion during ripout formation.)

Considering the abrupt termination of an actively propagating rupture at a barrier as illustrated in Fig. 11, the continued displacement along the fault approaching the termination causes severe, but transient, velocity contrasts within the wallrocks. This will generate a compressive and a tensional stress field about the termination on either side of the fault surface (Sibson 1986). The wallrocks pulling away from the termination develop a tensional field and wallrocks slipping toward the termination develop a compressional field. Platt & Leggett (1986) presented a similar analysis using stress equilibrium equations for thrust faulting. Since rocks are weaker in tension, initial failure would be expected in the tensional field and would trigger the development of wallrock ripouts in the sidewall under tension. This would result in the development of ripout accommodation structures exclusively on the tensional or dilatant side of the fault surface with ripout 'dislocations' piling up at the strike-slip termination. This provides a simple mechanism for the apparent preferential development of the ripouts along the southeast sidewall in the Fort Foster structures in Fig. 10. It is the central fault in this

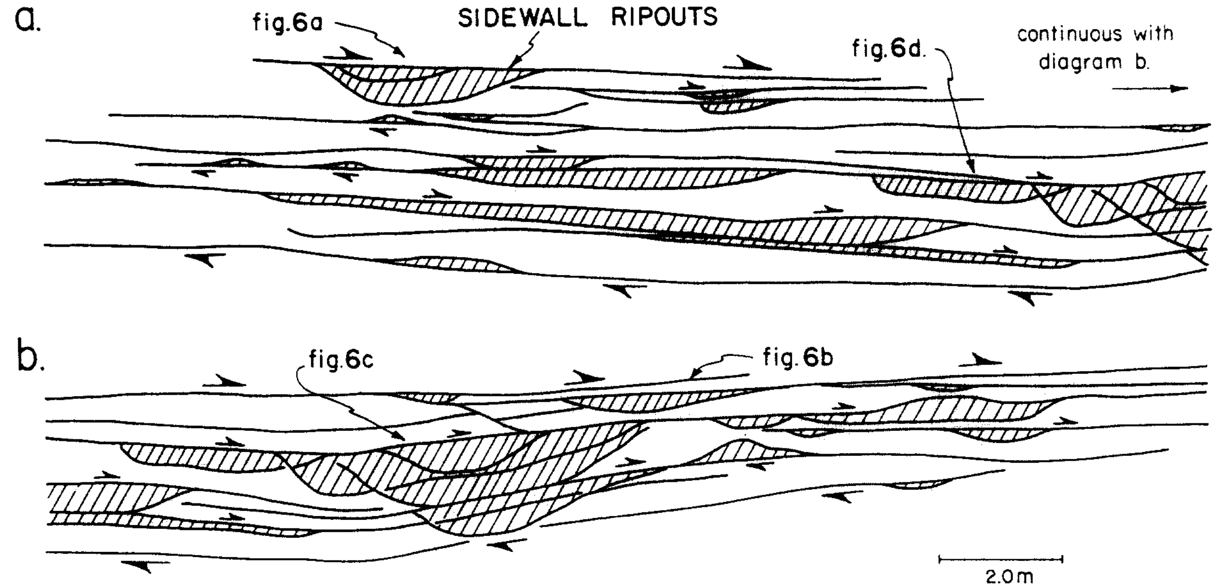

Fig. 10. Composite array of ripout lenses and slabs in the northwestern boundary of the Fort Foster brittle zone showing the size and distribution of these structures. Diagrams (a) & (b) combine to form a single continuous strip map.

figure that is modeled in the termination sequence of Fig. 11. The preferential rupture of the southeast sidewalls in the Two Lights structures as depicted in Fig. 4 can also be explained using this model in that all of the illustrated examples come from near the northeastern terminations of various NE-trending strike-slip faults in these exposures.

Pseudotachylyte and ripout development

Several of the dextral strike-slip fault surfaces in Fig. 10 have developed multiple ripouts along their length. It would be unlikely that each ripout structure was formed in a separate slip event, due to the overall simplicity, in many cases, of the dominant planar pseudotachylyte fault-vein. Multiple ripouts are even evident in the 'single jerk' displacement structures in the Ikertôq exposures. This suggests that the adhesion and ripout process had occurred repeatedly during a single slip event. One fault within the center of Fig. 10, for example, has developed approximately 10 ripout panels with a cumulative length of about 23 m. This would imply that approximately 2.3 m of displacement along the dominant planar fault surface was accommodated by multiple ripout formation, entirely appropriate for these fault exposures.

The cross-cutting pseudotachylyte veins and vein systems associated with the ripout structures suggest a genetic relation between fracturing and injection of pseudotachylyte and the process of adhesion and ripout formation. Several ripout structures (Figs. 5a–c and 6b–d) have early orthogonal veins within the ripout lens or slab, many exhibiting flow banding developed during injection from the dominant planar surface. This suggests that fracturing and injection of the sidewall rocks during displacement would drain the fault surface of any lubricating melt, thereby inducing abrupt and transient increases in the coefficient of sliding friction.

A few of the orthogonal veins connect both flanking slip surfaces that define the ripouts as linking dilation zones. Preliminary observations suggest a single flood of frictional melt. The structures in Fig. 6(d), for example, contain a discordant orthogonal vein nearly 35 cm long that connects the flanking slip surfaces that define the

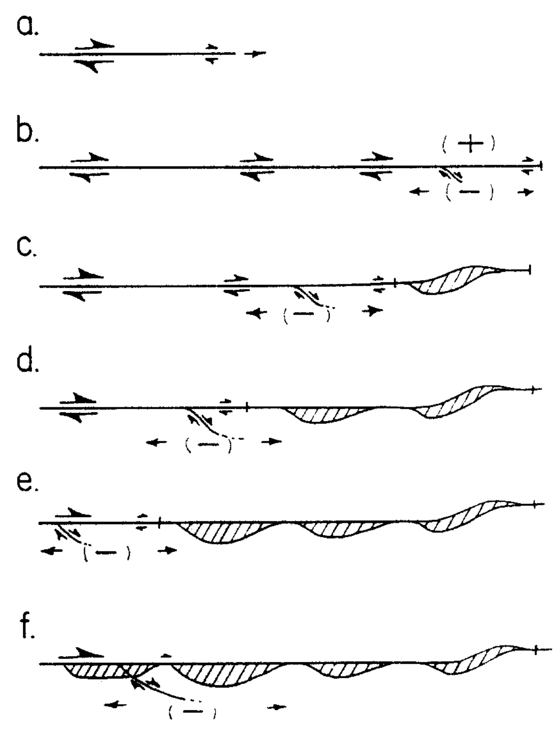

Fig. 11. Proposed kinematic model for the asymmetric development of ripouts associated with the termination of rupture and slip deterioration. (a) Maximum slip velocities developed behind the advance of a propagating shear fracture. (b) Termination of the propagating rupture at some barrier imposes severe velocity variations in the adjoining sidewalls leading to the development of compressional and tensional stress fields on opposite sides of the fault surface. (c) Rupture of the tensional sidewall as wallrocks are pulled away from the termination. (d)–(f) Initial ripout displacement deforms the fault surface and adjoining wallrock advancing the termination along with the retreating slip front and initiating sequential ripout development.

early slab ripout. This same vein also cross-cuts the trailing ramp structures of a younger ripout that cuts this older slab structure. This would suggest that the occurrence of melt during displacement is relatively long-lived, surviving the formation of several sidewall ripout structures developed during a single slip event.

Kinematic indicators

The end result of the development of these ripouts along specific leading and trailing ramp structures is a distinctly asymmetric geometry that can be used as a kinematic indicator for the sense of shear along the dominant planar fault surfaces. In the examples illustrated here, the contractional *P*-type leading ramp is marked by the narrow tapered end of the structure and points in the movement or translation direction for the ripout. The movement of the ripout lens or slab follows the direction of displacement of the wallrocks on the opposite side of the main fault surface and thus will give the overall sense of shear. These ripout structures with their distinctive asymmetric geometry would be particularly useful for faults in isotropic rocks that lack any offset markers to determine the sense of shear.

DISCUSSION

Similar structures

Sidewall ripout structures in strike-slip faults as described here have not been previously reported in the geologic literature. However, a few similar structures have been observed at drastically different scales in a variety of settings. Platt & Leggett (1986) have described "footwall plucks" on the 100 m-scale as examples of localized stratal extension in the footwalls of thrust complexes. Spray (1987) has also described "transferred metadolerite slivers" on the mm-scale in friction welding experiments that closely approximate the ripout structures described here. Both of these examples have been attributed to some form of adhesion during displacement due to variations in frictional resistance from loss of fluids (Platt & Leggett 1986) or to increased viscosity and solidification of frictional melts (Spray 1987).

Butler (1982) has described "exotic" horses in thrust faults and Woodcock & Fischer (1986) have also described "exotic" lenses in strike-slip faults that are similar to the distinctly asymmetric structures presented here. On a smaller scale, Magloughlin (1989) has also described "planoconvex" configurations for some pseudotachylyte fault-parallel veins that resemble the fault-bounded host rock lens configurations of these ripouts. Any geometric similarities between any of these structures are due to similar fracture mechanisms developed during adhesion and rupture of the ripouts. In general, this will involve *P*- and *R*- or *X'*-shear fractures in the leading and trailing ramp structures, respectively.

The *Y*-slab gouges described by Rutter *et al.* (1986) may also be comparable structures to the elongate slab ripouts. The flanking shear surfaces in these *Y*-slabs in fault gouge must also link to other segments in the fault zone along probable tapered end ramps. Displacements are apparently being transferred laterally to new adjacent slip surfaces during deformation. Deformation of the principal fault plane also seems to be an inevitable consequence of displacement variations due to lateral transfer at en échelon overlaps and along individual fault traces. This problem has been explored by van Nes (1986, 1989) and a slightly different, but complementary solution to that presented here was reached. Similarly, ripout formation and localized lateral displacement transfer may play an important role in producing the braided lens structure or the paired parallel fault structure of strike-slip fault systems.

Role of adhesion

As indicated above, the origin of these ripout structures is attributed to the development of some form of adhesion between the two fault block walls. Adhesion across the fault may occur through a variety of static as well as dynamic mechanisms. Static adhesion between the two fault surfaces would readily develop by a welding of the stationary fault blocks due to the cooling and final solidification of the fault-generated pseudotachylyte after the cessation of slip. The duration of any frictional melts relative to the slip event is extremely important in this process. Observations suggest that most fault-generated melts survive through the duration of the entire slip event and are preserved as a single flood of pseudotachylyte. Welding of the fault surfaces by solidification of the frictional melts after displacement, appears to be an extremely effective process as few pseudotachylyte fault veins show any signs of rupture or strain during a second phase or a continued phase of displacement. In this case, ripout formation would develop with initial rupture during a subsequent slip event.

Adhesion could also occur in a dynamic mode related to fluctuations in frictional resistance during displacement on the fault. The increase in viscosity of pseudotachylyte during cooling, after generation during slip, would increase the frictional drag along the fault surfaces. Increases in frictional resistance, or the coefficient of sliding friction, could also result from sudden drops in supporting fluid pressure, in this case frictional melt, that tends to lubricate the slip surface. Melt lubrication of sliding surfaces (Bowen & Tabor 1973) would result in a drop in surface temperatures and a corresponding increase in the coefficient of sliding friction due to an increase in the viscosity of the lubricating melt.

Due to the projected volume increases upon the generation of pseudotachylyte (Maddock *et al.* 1987), melt lubrication of the fault surfaces would also be associated with relatively high transient fluid pressures. Such high fluid pressures are reflected in the fracturing and injection of pseudotachylyte into the adjoining wallrocks (Figs. 7a & b) as is commonly observed in these exposures. The fracturing and injection of pseudotachylyte into the wallrocks during slip would drain the fault surface, eliminating the supporting fluid pressures and the lubricating effects of the melt. This would lead directly to an increase in the effective normal stress on the fault surface and an increase in the coefficient of sliding friction.

Any increase in frictional resistance during slip along the fault would then cause localized transient variations in slip velocities within the wallrocks (Fig. 7b). Severe localized reductions in slip velocities will lead to the development of slowed or stuck patches along the fault. Continued displacement must bypass these slowed or sticking sections (Fig. 7c) leading to the formation (Fig. 7d) and growth (Fig. 7e) of the observed ripout structures as the specific bypass mechanism. The ripout slab can only be carried along for a limited distance through the adjoining wallrock before it must be sheared off to continue motion on the dominant planar surface.

Engineering studies

The ripout structures described in these exposures are interpreted to represent outcrop-scale examples of adhesive wear (Rabinowicz 1965) common in engineering materials subjected to sliding friction. In adhesive wear, patches of one material surface adhere to the opposing surface during frictional sliding, forming junctions at the asperity contacts. It is, essentially, the rupturing of these adhesive junctions at asperity contacts that controls the coefficient of friction during sliding. The rupturing of the larger junctions by failure within the adjoining surfaces results in the transfer of material as adhesive wear fragments from one surface to another across the sliding interface. It is, then, the transferred adhesive wear fragments in engineering material developed during frictional sliding that are the small-scale equivalents of the outcrop-scale fault-generated ripout structures described here.

The geometry of transferred adhesive wear fragments in engineering materials has been studied in detail using microscopic and autoradiographic techniques (Rabinowicz 1965) for copper riders on steel surfaces. The typical adhesive wear fragments were found to be ellipsoidal in plan view with a length : breadth ratio of 1.7 : 1, elongate in the direction of sliding. In cross-section, the typical length : height ratio (equivalent to the length : width ratios for ripouts as described here) for the adhesive wear fragments was 3.4 : 1. More specifically, a particular type of adhesive wear fragment with length : thickness (or height) ratios of 10 : 1 was found as wedge-shaped wear particles and corresponding pits in the wear surface (Samuels *et al.* 1981). These adhesive wear pits were described as "distinctly asymmetric with a shallow end and an edge with a deep step". The shallow ends of the pits were found to point in the direction of sliding. These wear fragments and surface pits bear a remarkable similarity to the asymmetric ripouts described here.

Factors found to promote adhesive wear in metals and non-metals during frictional sliding (Vingsbo & Hogmark 1981) include contact pressure, sliding velocity, displacement, ductility, corrosion resistance, heat resistivity, chemical inactivity and temperature. These factors would be directly related to increases in confining pressures, slip velocity, displacement and temperature in dry rocks expected for earthquake faults at increasing depths within the crust and as a result would promote adhesion as a dominant wear mechanism at seismogenic depths. There is also some suggestion that the size of the adhesive wear fragments is proportional to load pressure and velocity of sliding (Rabinowicz 1965). This would provide a way of scaling the load stress and slip velocities from the microscopic scale in engineering materials to the outcrop-scale ripout structures for the fault exposures described here.

Relation to fault grooves and striations

One aspect of the formation of the ripout structures is that of asperity plowing (Fig. 7e), after Scholz & Engelder (1976), as a form of abrasive wear. In this case, however, the asperity responsible for the abrasion is not formed by indentation but by adhesive bonding across the fault and rupture of the ripout. This creates a distinct geometric asperity that is 'indented' into the adjoining fault wall. Due to the restraining aspects of the ripout geometries on slip, continued displacement will cause the ripout lens to either be sheared off or to plow its way through the adjoining wallrocks. The displacement and growth of the ripout slabs during translation through the adjoining wallrocks represent this sidewall deformation as examples of abrasive wear.

The development and displacement of ripouts through an adhesion–rupture and asperity–plowing mechanism and its relationship to natural and experimentally-produced wear grooves (Engelder 1974, Scholz & Engelder 1976) leads to some speculation as to the third dimension (depth within the outcrop) for these structures. If this dimension is small, the ripout structures described here could represent the longitudinal profile through outcrop-scale fault grooves. In this case the grooves would be 'dug' by splay faulting during ripout formation and plowing of that geometric asperity through the wallrocks. The sense of asymmetry of typical wear groove structures formed by asperity indentation and plowing, relative to the displacement direction as described by Scholz & Engelder (1976) however, is at odds with that described here. Their tapered ends point in different directions relative to the displacement but different models are invoked. In the formation of typical wear grooves, the displacement of the asperity proceeds from the tapered end of the groove to the blunt end as indentation forces the asperity deeper into the opposing surface (Engelder 1974).

If the third dimension for these structures is not relatively small as suggested by studies of engineering materials, the ripouts may represent ruptured panels or patches of wallrock elongate in the direction of displacement rather than grooves. The geometry of transferred adhesive wear fragments in engineering materials (Rabinowincz 1965) suggests a length: width ratio of 1.7:1, giving them an overall ellipsoidal shape in plan view, elongate in the direction of displacement. Whatever three-dimensional geometry is envisioned it will be largely influenced by the nature of the adhesion process, the size and shape of the locked or slowed zones and the amount of displacement developed along the fault surface.

Ripout formation and coseismic slip

An important aspect of ripout development is the timing of formation of these structures relative to the duration of the displacement event. Ripout formation may be part of the pre-failure or early-failure rupture sequence associated with a particular fault structure. Ripout formation is an effective mechanism to temporarily bypass static locked zones along fault surfaces. The main displacement event may itself be subject to localized transient variations in frictional resistance and related slip velocities, thus leading to ripout formation. The development of ripouts could also be a consequence of the later stages of the displacement event as well, where slip deterioration eventually leads to lock-up of the fault planes. The collapse of an actively slipping rupture surface along a fault would certainly be non-uniform and would lead to inherent transient variations in slip velocities along the fault as illustrated in Fig. 11. Variations in slip velocities within the wallrocks would be overcome by the formation of the ripout structures where more rapidly slipping wall sections would pull away from or ride over the slower slipping sections. The ripout structures, in turn, may serve as an energy absorbing braking mechanism for the deteriorating slip event leading to rupture termination.

The apparent restriction of these distinctive ripout structures to pseudotachylyte-bearing fault structures suggests that their formation may be inherently related to the rapid slip rates associated with frictional melting and thus are of seismogenic importance. Due to the self-similar nature of fault geometries at a variety of scales (Sibson 1986), the outcrop-scale structures described here may have larger km-scale equivalents along major fault systems. Such larger-scale structures may play a significant role in the rupture processes associated with earthquake generation and would be a likely source for multiple events or subevents within 'single' earthquakes. A bypass rupture sequence along a larger locked fault structure may also have a recognizable and possibly predictable pattern of seismicity that would correspond to the model proposed here for ripout formation.

CONCLUSIONS

A distinctive structural configuration, the fault-bounded 'sidewall ripout', is found associated with pseudotachylyte-bearing fault structures. Ripout structures are developed where motion of the host rock blocks along planar fault surfaces plucks or rips out a section of the opposing wall during displacement. Their origin is attributed to the development of adhesion across the fault due to variations in the coefficient of friction and its effect on slip velocities within the fault walls. The ripout structures are interpreted as examples of adhesive wear developed during frictional sliding between the fault blocks. The asymmetric geometry of these ripouts makes them useful kinematic indicators. The narrow tapered ends marked by contractional ramps at a low angle to the main fault surface point in the direction of displacement of the ripout slab and the opposing wallrocks during adhesion and rupture to give the sense of slip. Finally, the development of these structures can be attributed to fairly rapid slip rates due to their association with fault-generated pseudotachylyte and may be a characteristic style of rupture within the strike-slip seismogenic zone.

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