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Pseudotachylyte-bearing strike-slip duplex structures in the Fort Foster Brittle Zone, S. Maine

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Abstract—Detailed (1:60 scale) mapping of the Fort Foster Brittle Zone in the mylonitic Rye Formation of southernmost Maine has revealed the intricate internal duplex structure of a system of probable Paleozoic-age dextral strike-slip faults that have produced abundant pseudotachylyte and minor breccia. The internal configuration of this brittle zone consists of a mosaic of individual pseudotachylyte generation zones as slab-duplex structures. Individual duplex zones are up to 100 m in length and 1 m or less in width and are defined by pairs of layer-parallel slip surfaces along which frictional melts were produced. These slab-duplex structures are interpreted as zones of displacement transfer between long, overlapping, layer-parallel en échelon strike-slip fault surfaces. Contractional duplexes develop layer-parallel compressional structures that tend to shorten and thicken the fault-bounded slabs by the formation of lateral ramps and conjugate faults, kinks and asymmetric folds. Extensional duplexes develop layer-parallel stretching and thinning by the formation of oblique dextral shears, high-angle conjugate pairs and localized fault breccias. The production of pseudotachylyte by friction melting along layer-parallel fault surfaces in these exposures is attributed to rapid slip during paleoseismic events. The rupture structures developed during these events may be characteristic of fault structure and mechanics at near-focal depths in a strike-slip seismogenic zone.

INTRODUCTION

PSEUDOTACHYLYTE is regarded as a friction melt (Park 1961, Philpotts 1964, McKenzie & Brune 1972, Cardwell *et al.* 1978, Allen 1979, Maddock 1983, Spray 1987) or as a product of extreme cataclasis (Wenk 1978) developed during brittle faulting at depths within the crust that approximate the seismogenic zone. Older mylonitic fault zones containing pseudotachylyte structures that are now exhumed by erosion represent the closest sampling of the earthquake generation process at near-focal depths. Direct observation of pseudotachylyte-bearing fault zones, therefore, can provide insight into the geometry, structure and kinematics of the earthquake rupture process.

Distinctive and possibly characteristic fault geometries associated with the production of pseudotachylyte were first recognized by Grocott (1977, 1981) in the Amitsuarssuk Brittle Zone in western Greenland. These distinctive parallel fault configurations, termed pseudotachylyte generation zones, were defined by pairs of overlapping layer-parallel slip surfaces that served as the dominant displacement structures. The fault-bounded slabs between these overlapping displacement surfaces often exhibit a complex strain history with the development of distinctive internal shear fracture assemblages associated with the production and injection of pseudotachylyte.

Similar pseudotachylyte-bearing fault configurations have also been recognized at the Fort Foster Brittle Zone (Fig. 1) located on the southeast Gerrish Island shoreline in southernmost Maine (Swanson 1982, 1985, 1986a,b, 1987). These deformed fault-bounded slabs between overlapping layer-parallel slip surfaces are interpreted as examples of duplexing in the strike-slip environment, following Woodcock & Fischer (1986) in extrapolating the terminology from the thrust fault environment.

The pseudotachylyte-bearing slab-duplex structures within the Fort Foster Brittle Zone are interpreted to be significant and repeatable geometric fault configurations that may be characteristic of depths within the crust that approximate the seisomogenic zone. These exposures, and others like them, provide the opportunity for direct observation of an actual earthquake rupture structure from near-focal depths. The style of structural duplexing preserved in these exposures represents a distinctive kinematic pattern for strain accommodation during en échelon strike-slip faulting in strongly anisotropic mylonitic rocks. These exposures of pseudotachylyte-bearing fault structures therefore offer a unique opportunity for detailed structural verification and refinement of the proposed seismological models through detailed study of the geometry and kinematics of these focal-depth rupture structures.

GEOLOGIC SETTING

The late Precambrian (?) Rye Formation (Fig. 1) in southern Maine and New Hampshire (Billings 1956) is exposed along the NW limb of the Rye Anticline (Hussey 1962, Novotny 1969), a SW-plunging antiformal structure overturned to the SE. Recent studies by Hussey (1980) at Gerrish Island indicate that the Rye Formation is a highly sheared and migmatized metasedimentary sequence. The rock types within the Rye Formation consist of variably-sheared metasedimentary quartzites, pelitic schists, amphibolites, calc-silicate-bearing amphibolite, graphitic-sulfidic schists and

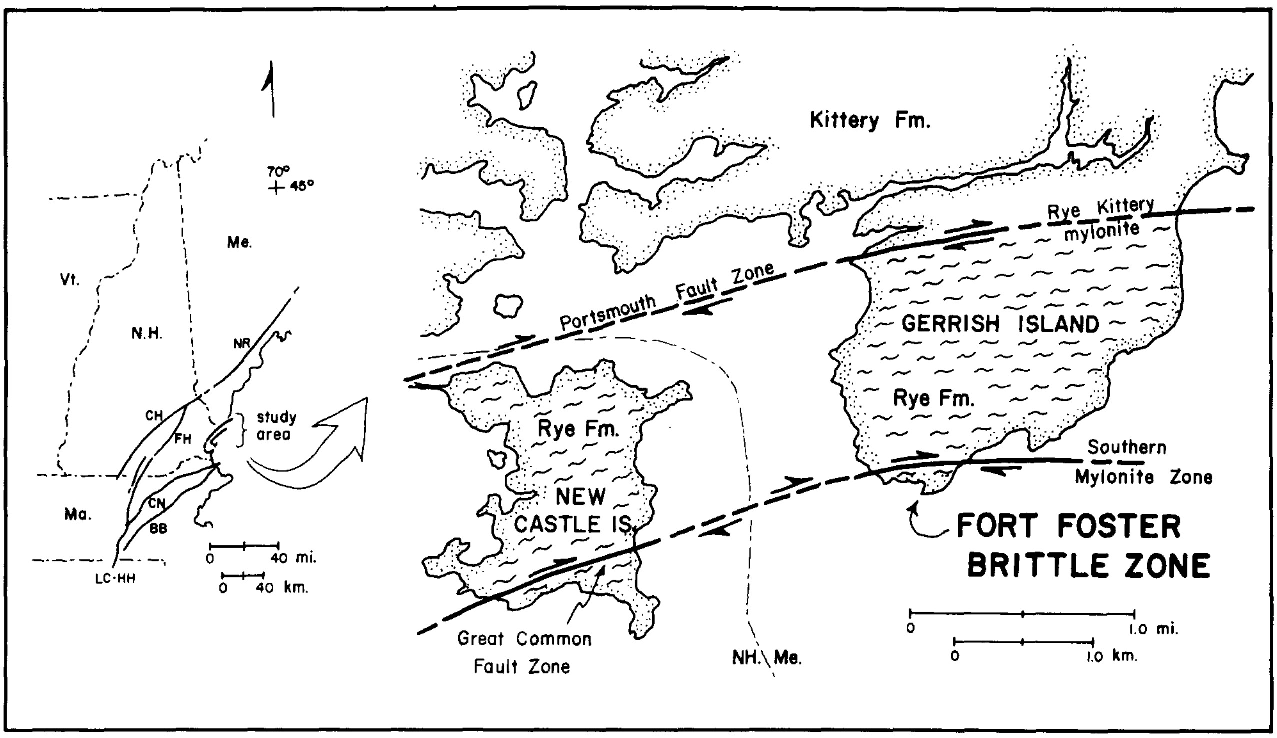

Fig. 1. Regional fault structures in coastal New England (largely late Paleozoic) in relation to fault structures in the Rye Formation of southernmost Maine and New Hampshire. The Fort Foster Brittle Zone is located within the Southern Mylonite Zone along the southeastern Gerrish Island shoreline. (NR—Nonesuch River; FH—Flint Hill; CH—Campbell Hill; CN—Clinton–Newbury; BB—Bloody-Bluff; LC–HH—Lake Char–Honey Hill Fault zones).

impure marbles as well as granitic gneisses and pegmatites associated with migmatization. Where highly strained, mylonitic gneisses, mylonites and ultramylonites occur. A poly-phase metamorphic history proposed by Carrigan (1984a,c) includes an early sillimanite-grade event associated with migmatization and a later andalusite event possibly associated with the early phases of mylonitization. The close association of the pseudotachylyte fault veins with the mylonitic units and in some cases the ductile deformation of these veins suggests that these brittle zone structures were developed at pressures and temperatures close to the brittle–ductile transition of these rocks. Regional relationships between the ductile deformation in the Rye Formation and the pseudotachylyte-bearing faults of the Fort Foster Brittle Zone at this point remain unclear.

The Rye Formation has developed a pervasive porphyroclastic mylonitic fabric with significant post-metamorphic concentration of strain into discrete zones of ultramylonite. These higher strain zones (Fig. 1) of fine-grained mylonite to ultramylonite delineate the Portsmouth Fault Zone at the Rye–Kittery Formation contact and the Great Common Fault Zone–Southern Mylonite Zone within the Rye Formation proper (Novotny 1969, Hussey 1980, Carrigan 1984a,b). Distinctive mesoscopic and microscopic structures and textures related to shear zone development (Simpson & Schmid 1983) are abundantly developed within the Rye Formation and indicate a dominant dextral strike-slip component to this phase of ductile deformation. These include asymmetric porphyroclasts, mica fish, oblique quartz grain-shape alignments and quartz *c*-axis orientations.

The Southern Mylonite Zone of Hussey (1980) at Gerrish Island hosts the brittle deformation (Fig. 2) that is the focus of this study. This mylonite zone consists of over a dozen discrete lithotectonic units from 2 to 30 m thick. These units include variably-sheared pelitic schists, amphibolites, gneisses and pegmatitic schists. The finer-grained mylonite units within the central zone of the mapped exposures (Fig. 2) are host to the brittle deformation associated with the Fort Foster Brittle Zone proper. These mylonitic host rocks contain hundreds, if not thousands, of pseudotachylyte-bearing slip surfaces. Pseudotachylyte slip surfaces can be found within most of the other units as well, although they are not as numerous.

FORT FOSTER BRITTLE ZONE

The Fort Foster Brittle Zone (Fig. 2) consists of a complex network of layer-parallel and obliquely-oriented (relative to the mylonitic fabric) strike-slip surfaces containing abundant pseudotachylyte and minor amounts of fault breccia (Figs. 2 and 3). The development of the pseudotachylyte generation zones in the duplex configuration is a characteristic kinematic pattern within the Fort Foster Brittle Zone. The pseudotachylyte-bearing duplexes are defined by pairs of layer-parallel slip surfaces (Figs. 3a–e) that structurally isolate the intervening host rock slab. The actual site of pseudo-

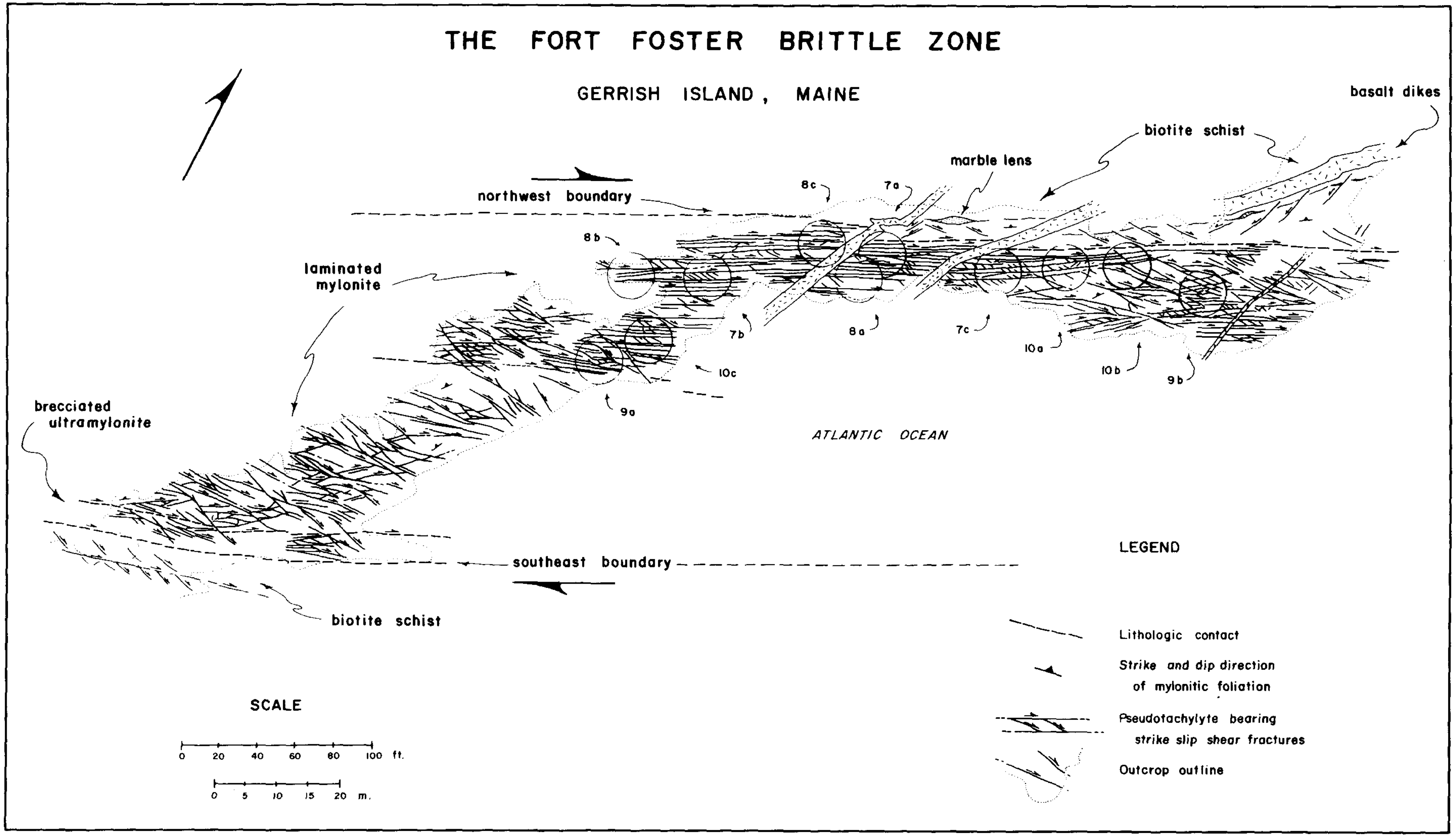

Fig. 2. The Fort Foster Brittle Zone at Gerrish Island, Maine, showing the pattern and distribution of pseudotachylyte-bearing strike-slip faults within the dominant mylonite unit. Numbered circles refer to more detailed fault configurations in Figs. 7–10. Map is a reduced version of an original 1:60 scale fault pattern map and a 1:120 scale lithology–structure map.

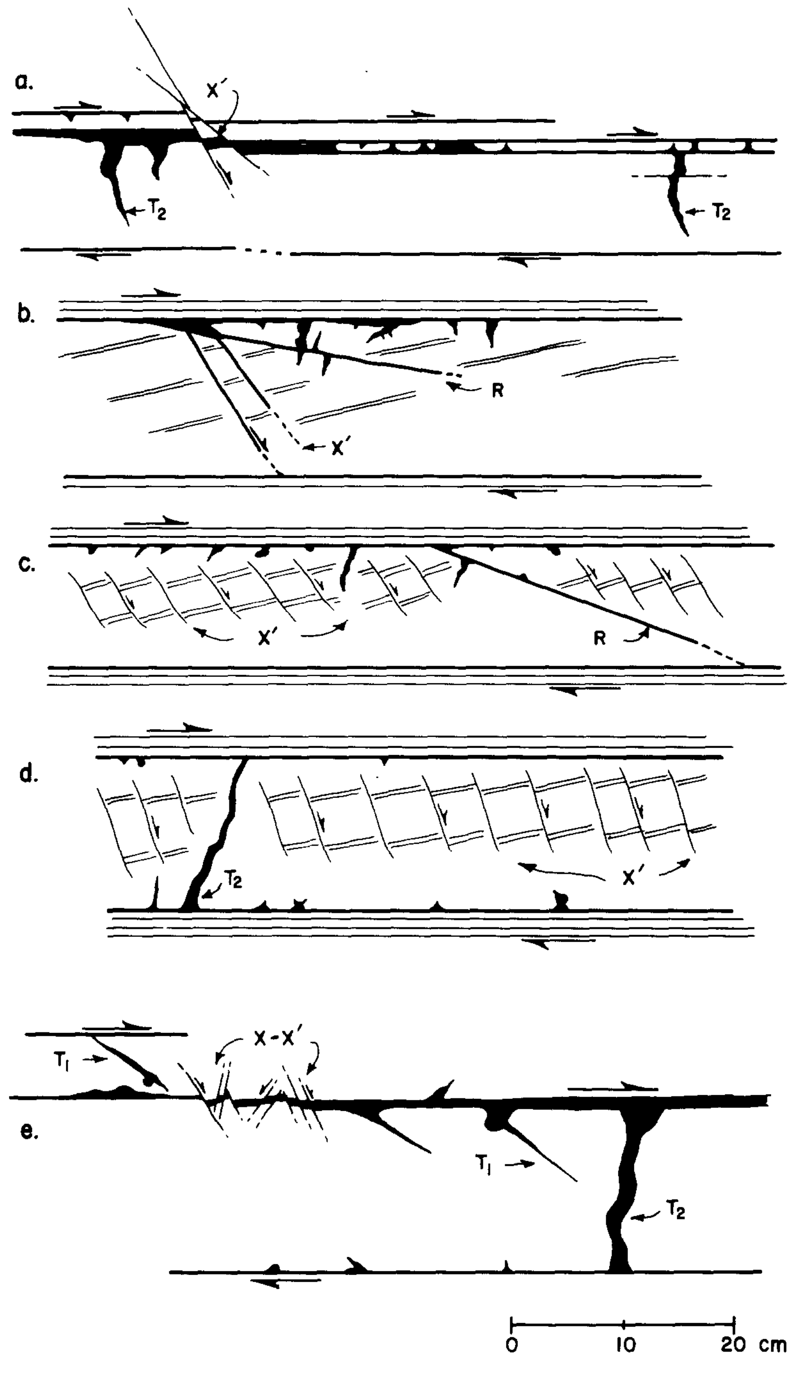

Fig. 3. Examples of pseudotachylyte generation zone configurations in the Fort Foster Brittle Zone exposures. (a) Coupled layer-parallel surfaces (Y-shears) with pseudotachylyte injection veins (black) (T_2 extension fractures) and later brittle offsets (X' dextral shears). (b) Rotated and truncated internal layering associated with R and X' dextral shears within pseudotachylyte generation zone. (c) Coupled layer-parallel slip surfaces showing injection veins and rotated internal slip surfaces (dextral X' shear set and a single R shear). (d) Pseudotachylyte generation zone with discordant injection vein (T_2 extension fracture) and rotated internal X' shear sets. (e) Coupled layer-parallel slip surfaces (Y-shears) showing various styles of injection veins (T_1 and T_2 tension fractures) and later brittle (X–X') offsets.

tachylyte generation is along the boundary surfaces of the decoupled fault slabs, particularly at local asperity contacts marked by cryptic seams of pseudotachylyte. Fault slabs in distinct duplex zones range from microscopic (<1 mm) to about 1 m in width. The overall structure of the 60 m wide Fort Foster Brittle Zone is also zonal in nature with strain concentration in layer-parallel slip surfaces along the northwest and southeast boundaries and with oblique slip surfaces in the interior of the zone. These long zonal fault structures are interpreted to represent a distinctive style of strike-slip duplexing (Woodcock & Fischer 1986), here termed the slab-duplex.

A plot of poles to measured shear fractures (Fig. 4a) distinguishes between the principal layer-parallel dextral slip surfaces, sinistral and dextral oblique shear fractures (at an angle to the mylonitic layering) and dextral lateral ramp structures. This same data set (Fig. 4b) yields a best-fit great circle representing the movement plane during this essentially plane-strain deformation and supports the kinematic interpretation of this brittle zone as nearly pure strike-slip in its present orientation. The pole to the movement plane for the deformation at 65°N40°W approximates the intermediate principal stress direction. A plot of poles to measured mylonitic layering (Fig. 4c) within this brittle deformation zone also shows a similar pattern. The spread of data points along the trace of the great circle reflects both clockwise and counterclockwise rotation of fault blocks within the movement plane during slip. The counterclockwise rotation is generally accommodated by slip on sets of oblique dextral shears. The clockwise rotation is developed as drag along some of the larger oblique dextral shear surfaces.

The pseudotachylyte occurs as thin concordant and discordant veins up to 2 cm in thickness along fault and fracture surfaces (Figs. 3a–e) and as the matrix to localized fault breccias. A single section of a layer-parallel fault vein reaches 4 cm in thickness locally. The longest discordant injection vein found is 35 cm in length and approximately 1 cm in width developed between two coupled layer-parallel pseudotachylyte-generating slip surfaces. Many of the coupled layer-parallel pseudotachylyte veins are often less than 1 mm thick and occur as cryptic seams in these exposures. The pseudotachylyte itself is generally a dark grey, fine-grained, glassy material. In thin section it appears as a reddish-brown, very fine-grained, birefringent matrix and contains a variety of wallrock xenoliths and xenocrysts as well as an abundance of randomly oriented feldspar microlites and spherulitic structures. The veins often exhibit a macroscopic flow layering defined microscopically by variations in matrix texture and xenolith concentration.

Observed displacements on internal shear fractures are quite variable and are generally on the order of a few centimeters to a few tens of centimeters. Displacements along some lateral ramp structures are generally 0.25–0.50 m or more. Some of the larger oblique dextral shears may show displacements in excess of 3.0 m.

Displacements for the principal layer-parallel slip surfaces are more difficult to determine due to the general lack of any cross-strike pre-existing marker layers, However, an empirical relationship found by Sibson (1975) between displacement and pseudotachylyte fault-vein width can be used to estimate the displacements involved. A reasonable estimate for typical vein width would be 2–5 mm corresponding to estimated displacements of 0.2–1.0 m per slip event. Detailed mapping and measurement is continuing to further quantify these initial estimates.

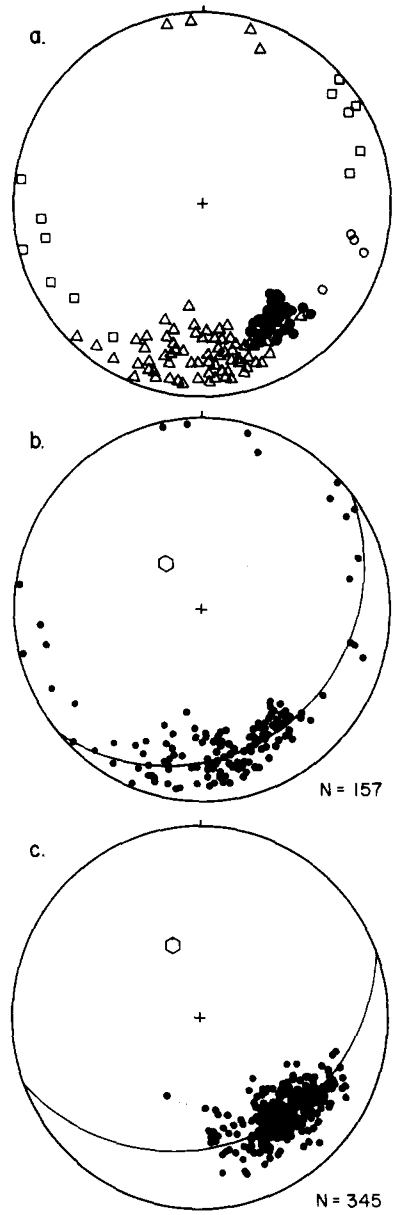

Fig. 4. Equal-area projection of planar structural data from the Fort Foster Brittle Zone. (a) Poles to shear fractures, with filled circles as layer-parallel dextral shears, open triangles as oblique dextral (X', R) shears, open squares as sinistral oblique (X) shears and open circles as dextral (P) shear ramps. (b) Best-fit great circle for poles to shear fractures as filled circles (same data as above). The pole to this great circle (hexagon) shows a near-vertical rotation axis for the brittle fault system approximating the intermediate principal stress direction. (c) Best-fit great circle for poles (filled circles) to the mylonitic fabric (S_m) showing a similar rotation axis (hexagon). Spread of data points along the great circle reflects the counterclockwise rotation of S_m in duplex structures and the clockwise rotation of S_m due to drag on larger dextral oblique shears.

ROLE OF DUPLEXING IN EN ECHELON FAULT GEOMETRIES

Structural duplexes are best known from thrust fault environments (Dahlstrom 1970, Boyer & Elliott 1982). Analogous extensional duplex structures have been described from rifted basin margins (Gibbs 1984). Recently, Woodcock & Fischer (1986) have applied the duplex concept and terminology to strike-slip fault systems where fault-bounded lenses and slabs represent the duplex structures. The duplex structures discussed here represent a particular rupture style developed between offset-overlapping en échelon strike-slip faults.

These offset-overlap zones have been described in terms of dilational and antidilational jogs (Sibson 1985) and compressive and tensile bridges (Gamond 1987) between the en échelon fault segments. The rupture of these bridge areas at restraining and releasing en échelon offsets during continued displacements leads to the formation of fault-bounded lenses and slabs that evolve as contractional–extensional duplexes. Duplex development in strike-slip faults may involve symmetric and asymmetric growth with thinning in the extensional, and thickening in the contractional duplexes. The high-angle orientation of near-vertical strike-slip faults relative to typical low-dip bedding anisotropies when compared to dip-slip systems, according to Woodcock & Fischer (1986), is a contributing factor to the braided, disorganized geometry of many mature strike-slip zones. However, the role of strongly anisotropic vertical mylonitic fabrics expected at seismogenic depths within mature fault systems in controlling the geometries was not assessed in their study.

The pseudotachylyte-bearing fault geometries observed within the Fort Foster Brittle Zone are interpreted as strike-slip duplex structures bounded by overlapping en échelon fault surfaces (Fig. 5) developed parallel to the prominent near-vertical mylonitic fabric within the Rye Formation. The development of these coupled fault structures appears to be dramatically enhanced in the anisotropic mylonitic host rocks leading to the development of the distinctive fault slab-duplex configurations. The overlapping layer-parallel slip surfaces create left- and right-stepping en échelon overlap zones (Fig. 5). The rupture of these en échelon overlap zones leads to the formation of the slab-duplex structures. The growth and internal deformation of these zones play a key role in accommodating displacement along the adjoining layer-parallel slip surfaces and represent a mechanism for displacement transfer between the coupled fault surfaces. The strong layer anisotropy within the overlap zone influences the internal stress orientations and related structural assemblages during deformation. Within the Fort Foster Brittle Zone an extremely complex sequence of fault slab duplex development is preserved where the internal structural configurations can offer valuable clues as to the details of this distinctive kinematic pattern.

FRACTURE TERMINOLOGY

The internal shear fracture systems observed within the Fort Foster Brittle Zone exposures, as an example of brittle fault development, are comprised of a variety of shear and tension fractures in a range of orientations. These fracture types include all of the shear and tension fracture orientations previously noted by Logan *et al.* (1979) and earlier investigators, as well as several new ones. A composite diagram of possible fracture types and orientations expected within a dextral fault zone along with their terminology is shown in Fig. 6. The resulting composite fracture configuration is considerably more complex but maintains an overall sense of

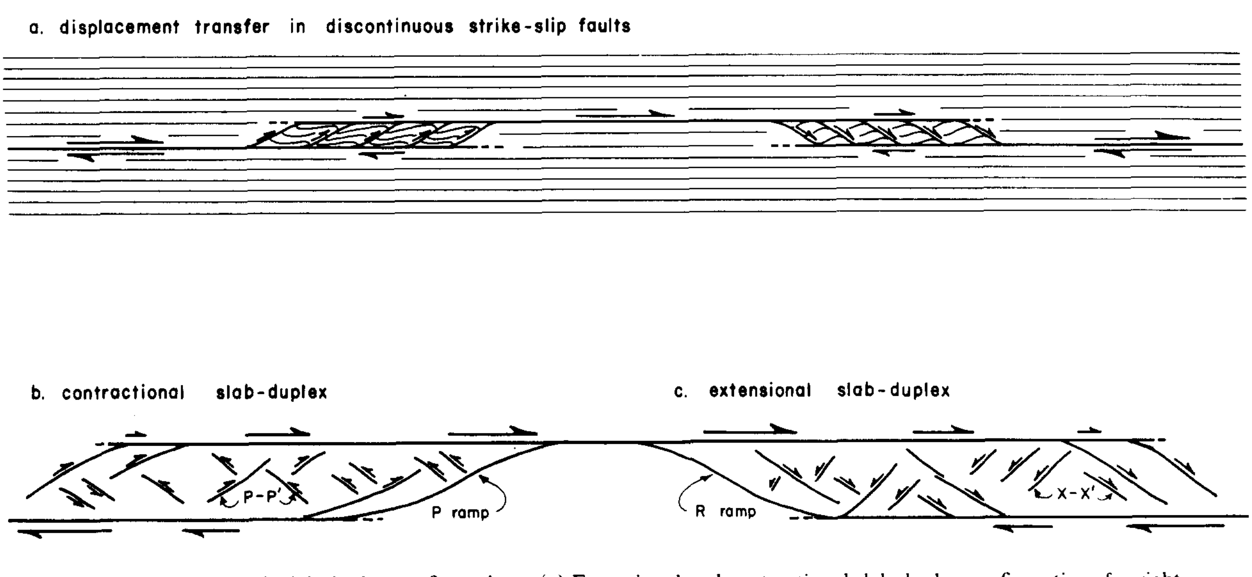

Fig. 5. Idealized fault slab-duplex configurations. (a) Extensional and contractional slab-duplex configurations for right- and left-stepping, respectively, en échelon, layer-parallel, dextral strike-slip surfaces in anisotropic rock. (b) Contractional slab-duplex configuration with leading and trailing (P^*) ramps and internal (P–P') conjugate shear fracture assemblages indicative of layer-parallel shortening. (c) Extensional slab-duplex configuration with leading and trailing (R or X') ramps and internal conjugate (X–X') shear fracture assemblage indicative of layer-parallel extension.

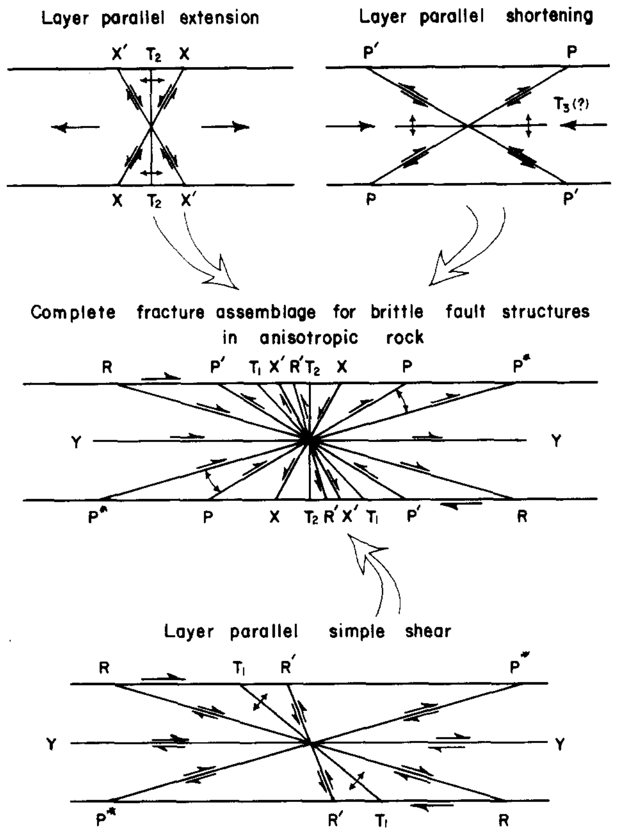

Fig. 6. Strain partitioning and shear fracture orientations within idealized brittle fault structures due to the dominant role of the mylonitic layer anisotropy. Components consist of fracture sets associated with layer-parallel extension (X', T_2, X), layer-parallel shortening (P, P', T_3) and dextral layer-parallel simple shear (R, T_1, R', P^*) that combine into a composite of potential fracture orientations expected in brittle fault structures within anisotropic rocks.

asymmetry relative to the shear zone boundaries and the sense of shear. The possible fracture types and orientations have been segregated into conjugate sets and related fractures that correspond to dextral simple shear and fault-parallel contraction and extension. This interpretation is very similar to the concept of strain partitioning, decoupling and the development of conjugate extensional crenulation cleavage as described by Platt (1984) for anisotropic pelitic rocks.

The typical Riedel shear fracture set (R, R') with oblique T_1 tension fractures (Fig. 6) is represented with the R shears dominating and the R' shears only locally developed, related to a layer-parallel dextral simple shear strain. A second set of conjugate shear fractures is also apparent (Fig. 6) that consists of the X fracture orientation of Logan *et al.* (1979) and its conjugate pair, here labeled X'. The X–X' shear fracture set accommodates layer-parallel extension relative to the near-vertical layer anisotropy of the host rocks. T_2 tensional fractures are associated with the X–X' shear fracture set and are orthogonal to the layer-anisotropy.

Shear fractures similar to the P shears (Fig. 6) of the Logan *et al.* (1979) array are typically developed as lateral ramps or splays off the layer-parallel fault structures. The lateral P-type ramp structures are often found in two orientations. These structural orientations (Fig. 6) form a third conjugate shear fracture set, the P–P' set (Tchalenko 1968, Mandl *et al.* 1977), developed in these exposures. Related conjugate fold and kink structures are also developed in accommodating layer-parallel shortening. Lower-angle P-shear ramps that link en échelon layer-parallel surfaces are here termed P^* to distinguish them from the conjugate P–P' shear fracture set at slightly higher angles typically developed within the slab-duplexes.

The Y shears (Fig. 6) as proposed by Logan *et al.* (1979) may be particularly important in the basic structure of the slab-duplex structures although they may be difficult to distinguish from the initial bounding surfaces. The propagation of new through-going layer-parallel slip surfaces, essentially Y shear fractures, would truncate any previously developed shear fractures and contribute to the apparent zone-within-zone arrangement of multiple slab-duplexes. The resulting structure is similar to the Y-slivers of gouge material described by Rutter *et al.* (1986) for exposed cataclastic fault zones.

The development of the individual fracture types and orientations within the slab-duplex structures depends on the configuration of the coupled layer-parallel dextral shear surfaces and the sense of displacement transfer. Left-stepping contractional duplexes (Figs. 5a & b) would develop the P–P' shear fracture sets with leading and trailing P^* or P shear fractures in accommodating layer-parallel shortening (Fig. 6). The right-stepping extensional duplexes (Figs. 5a & c) would develop the X–X' shear and T_2 tension fracture sets with leading and trailing R or X' shear fractures in accommodating layer-parallel extension (Fig. 6). Fault slabs between dextral layer-parallel shear surfaces may also develop the R–R' shear and T_1 tension fracture sets reflecting layer-parallel dextral simple shear (Fig. 6).

SLAB-DUPLEX GEOMETRY

The internal structural development within these slab-duplex zones was found to vary from intact, undamaged host rock slabs with no internal structure to total disruption in the formation of localized pseudotachylyte fault breccias. The coherent disruption of the internal fault slab within these duplex zones generally takes the form of an assemblage of shear fractures, minor tension fractures and asymmetric folds and kinks. The nature of the internal structures within each zone was found to be complex; orientation, sense of slip and intensity of minor fault development vary along strike.

The nature of the minor shear fracture assemblages developed within these zonal structures suggests that the decoupled fault slabs have undergone internal layer-parallel compression and tension during rupture related to the development of contractional and extensional slab-duplex structures. Several exposures demonstrate sequences of layer-parallel shortening followed by layer-parallel extension. Individual fault slabs also show a complex spatial distribution of compressional and tensional structural assemblages along the length of the

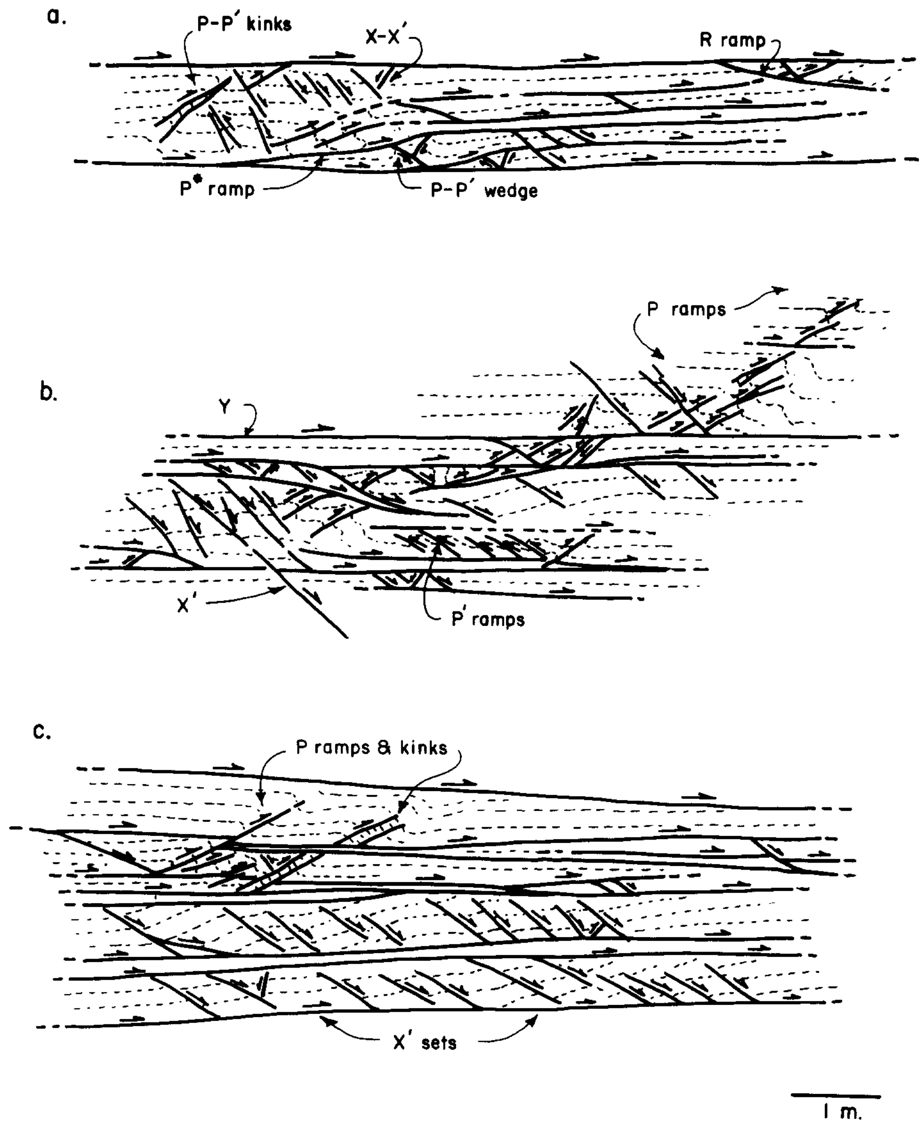

Fig. 7. Intricate fault geometries in layer-parallel pseudotachylyte generation zone configurations (see Fig. 2 for locations within the Fort Foster Brittle Zone). (a) Contractional ramp (P^*) structures, associated conjugate (P–P') fault and kink sets and minor dextral (R, X') slip surfaces. (b) Complex (P-type) ramp structure that cuts across the mylonitic layering with numerous (P–P') contractional shear sets. (c) Sets of coupled layer-parallel slip surfaces with low-angle (P^*) ramps showing spatial distribution of associated layer-parallel extensional (X') and contractional (P) shear fracture assemblages.

slabs. Figures 7–10 illustrate some of these geometric relations.

Layer-parallel extension within the slab-duplex zones is accommodated by several mechanisms (see Figs. 7c, 8c, 9a & b and 10b & c). These include the development of conjugate (X–X') fault arrays as well as pervasive sets of synthetic (R, X') or antithetic (X) minor faults. This extension has often resulted in significant thinning of the fault slab which in the extreme case leads to the localized formation of fault breccia with a pseudotachylyte matrix (Fig. 10c). Synthetic fault arrays are the most prominent, generally at lower angles to the anisotropy, intermediate between expected angles for typical R–X' shear surfaces. The fault surfaces often form listric-shaped and sigmoidal dextral shear surfaces that merge with the bounding principal layer-parallel slip surfaces. The development of the synthetic fault arrays is responsible for a prominent counterclockwise rotation of the intervening host rock blocks and their internal mylonitic fabric. Antithetic fault arrays are generally developed as high-angle minor shear fracture sets and can also effect a minor clockwise block rotation.

The larger oblique dextral shears (Figs. 9a & b and 10b) also accommodate extension and are more prominent in the central interior portions of the brittle deformation zone (Fig. 2) as a component of the overall duplex configuration. Most of the oblique dextral shears can also be shown to be sigmoidal in shape (Fig. 9a) becoming asymptotic to the dominant layer-parallel slip surfaces (Fig. 10b) where properly exposed. These fault surfaces may actually represent composite R–X'–R shears. The larger oblique shears typically have a more irregular internal structure in the absence of any anisotropic control on fracturing, contain more breccia and develop considerable drag on the mylonitic fabric. Displacements are variable, ranging to over 3 m of dextral

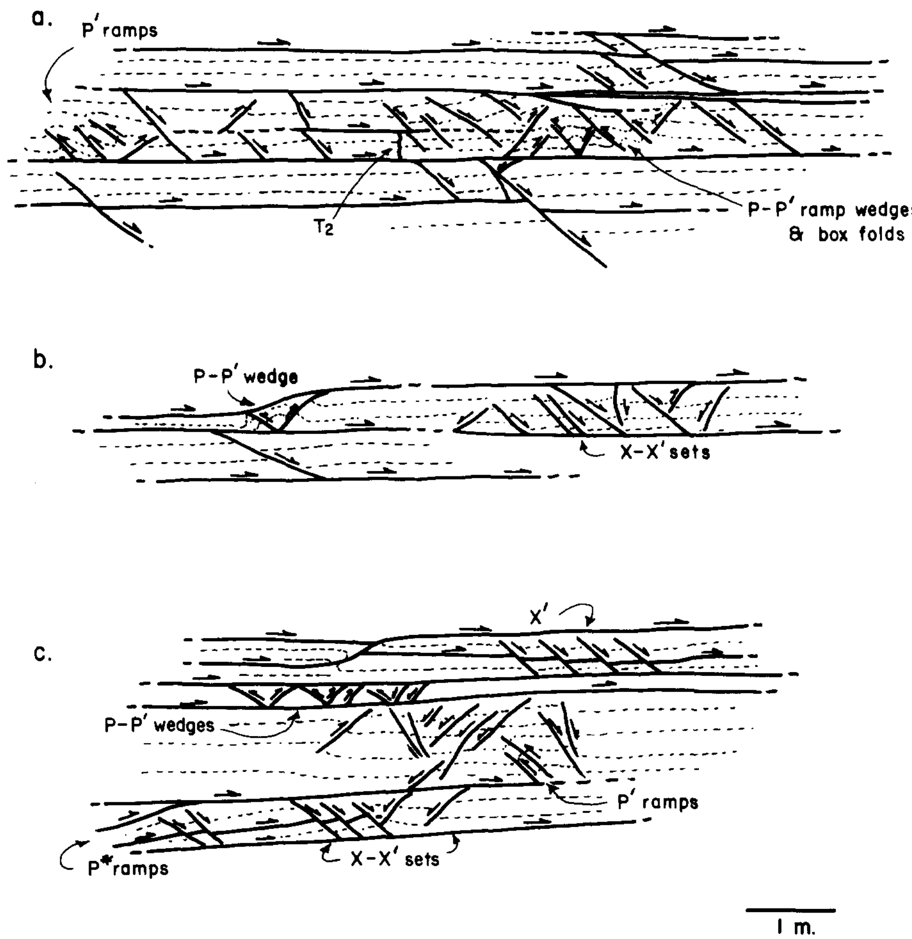

Fig. 8. Fault geometries in pseudotachylyte generation zone configurations (see Fig. 2 for locations within the Fort Foster Brittle Zone). (a) Conjugate contractional (*P–P'*) shear surfaces, box folds and wedge-shaped blocks decoupled along layer-parallel slip surfaces. (b) Wedge-shaped (*P–P'*) block at contractional (*P*-type) ramp in association with minor extensional (*X–X'* or *R*) shear fracture sets. (c) Complex interaction between layer-parallel extensional (*X–X'*) and contractional (*P–P'*) shear fracture configurations and low-angle (*P**) ramps.

offset. The larger oblique dextral shears are also responsible for the formation of traditional extensional duplex configurations (Gibbs 1984) as illustrated in Figs. 9(a) & (b).

Layer-parallel shortening in these slab-duplex structures is also accommodated by several different structural mechanisms (see Figs. 7, 8 and 10). These include the development of asymmetric folds, kink bands, box folds and discrete lateral ramp-type shear (*P**, *P–P'*) surfaces. The fold and kink structures are found in single sets and conjugate arrays (with axial planes and kink-band boundaries in the *P–P'* orientations) resulting from layer-parallel compression. Many of these compressional structures can be seen deforming earlier pseudotachylyte slip surfaces and are often cut and offset by younger, generally extensional (*X–X'*), slip surfaces. Imbrication of the fault slabs is also apparent on a small-scale, developing ramping horse structures in typical duplex configurations similar to structures found in thrust complexes. Lateral ramping along slip surfaces commonly occurs in two (*P–P'*) orientations in a conjugate configuration giving rise to distinctive wedge-shaped blocks (Figs. 7a and 8b).

An azimuth for each individual internal shear fracture was measured in a clockwise direction from the bounding layer-parallel slip surfaces using the original 1:60 scale base maps. The resulting orientation histograms for dextral and sinistral shear surfaces (Fig. 11) are considered a first order approximation of the fracture geometry as mapped in the field.

The orientation histogram for the dextral shear fractures (Fig. 11a) consists of two composite peaks. These peaks are distributed on either side of the orthogonal (90° orientation) to the bounding layer-parallel reference slip surfaces. The lower angle set (relative to the vertical layer-parallel slip surfaces) includes fractures representing the *R* and *X'* shear fracture sets with the *X'* set apparently dominating. Separate peaks at approximately 15° and 60° (expected initial orientations for *R* and *X'* shears) are not readily distinguishable on this diagram due to the prominent counterclockwise rotation of fault blocks and surfaces during slip. This rotation has shifted most of the initial *X'* shear fracture orientations from approximately 60° to lower angles of nearly 40° suggesting an average of 20° of counterclockwise rotation of the fault surfaces and the intervening host rock blocks. This correlates with the approximately 20° of counterclockwise rotation of measured mylonitic layering suggested from the stereoplot in Fig. 4(c). The situation is probably more complex, however, in terms

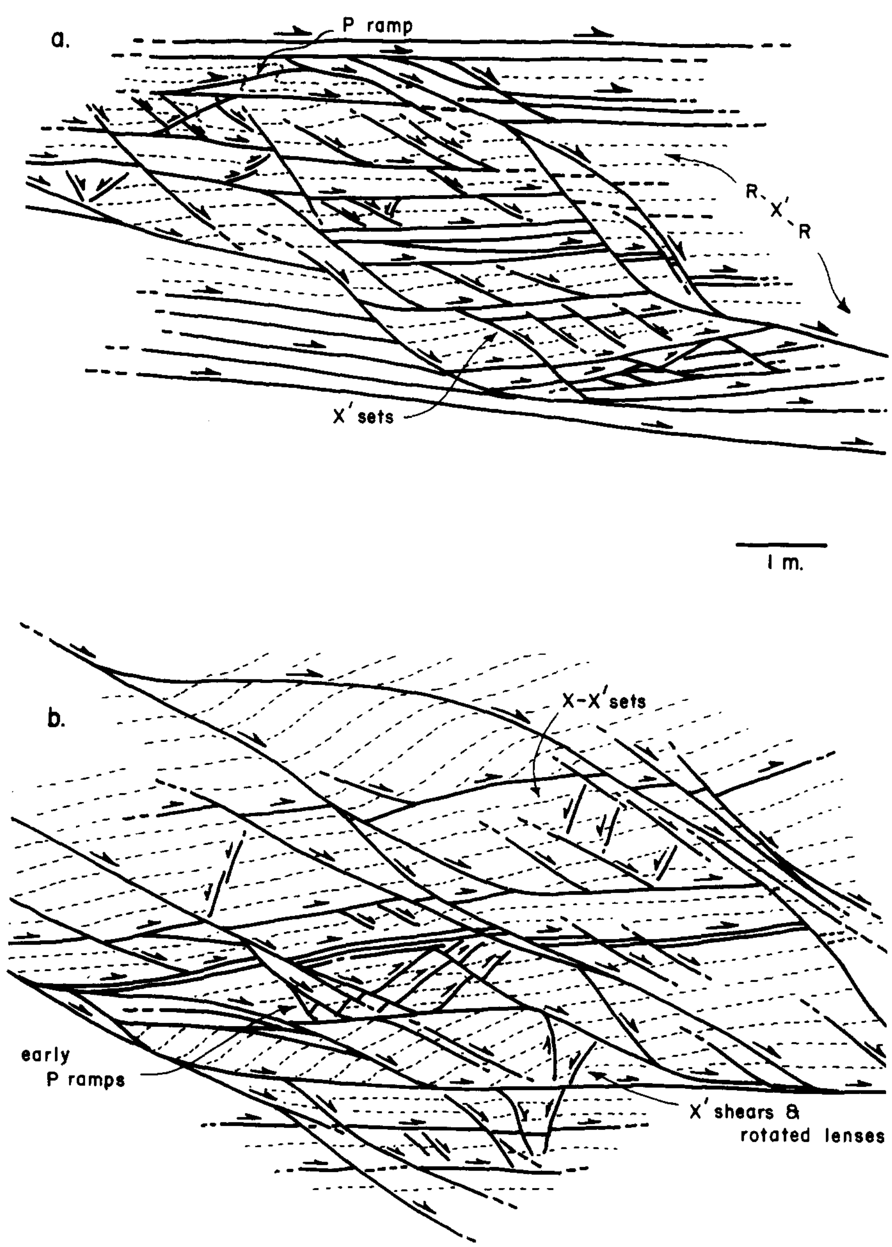

Fig. 9. Extensional duplex configurations (see Fig. 2 for locations within the Fort Foster Brittle Zone). (a) Larger-scale traditional extensional duplex structure showing asymmetric configuration, rotation of decoupled fault slivers and nature of sigmoidal composite (R–X'–R) shear surfaces. (b) Slightly more complex extensional duplex configuration utilizing (X') shear fracture orientations and exhibiting strong counterclockwise rotation of isolated fault blocks and lenses.

of varying stress orientations and degrees of decoupling in initiating these shear fractures. Many presumably X' shear fractures at lower angles than 60° show very little slip and resulting rotation. True low-angle R shears are developed as leading and trailing ramp structures between layer-parallel slip surfaces but represent only a small percentage of the total number of observed shear fractures.

The higher angle dextral shear fracture peak (Fig. 11a) shows a broad distribution of P-type shears with an apparent maximum at approximately 150°. This represents the ideal initial orientation of P shears resulting from layer-parallel compression. A smaller peak nearing 120° may represent the counterclockwise rotation (30°) of fault blocks and surfaces during slip. Orientations near 175° represent ramp structures (here termed P^*) as linking structures between overlapping layer-parallel slip surfaces.

The orientation histogram for the sinistral shear fractures (Fig. 11b) also consists of composite peaks with skewed distributions. The lower angle set includes the P' and R' shear fracture orientations. This portion of the diagram suggests a smaller peak at approximately 30° as the initiation angle for the P' shears and a larger peak near 45° possibly representing the clockwise rotation of the early formed P' shears to higher angles. True R' shears expected at approximately 75° appear to be rare.

The higher angle peak on this sinistral histogram represents only the X shear fracture set. The skewed asymmetric distribution also suggests an initial orientation near 120° with subsequent clockwise rotation of fault blocks and surfaces during sinistral slip, shifting the

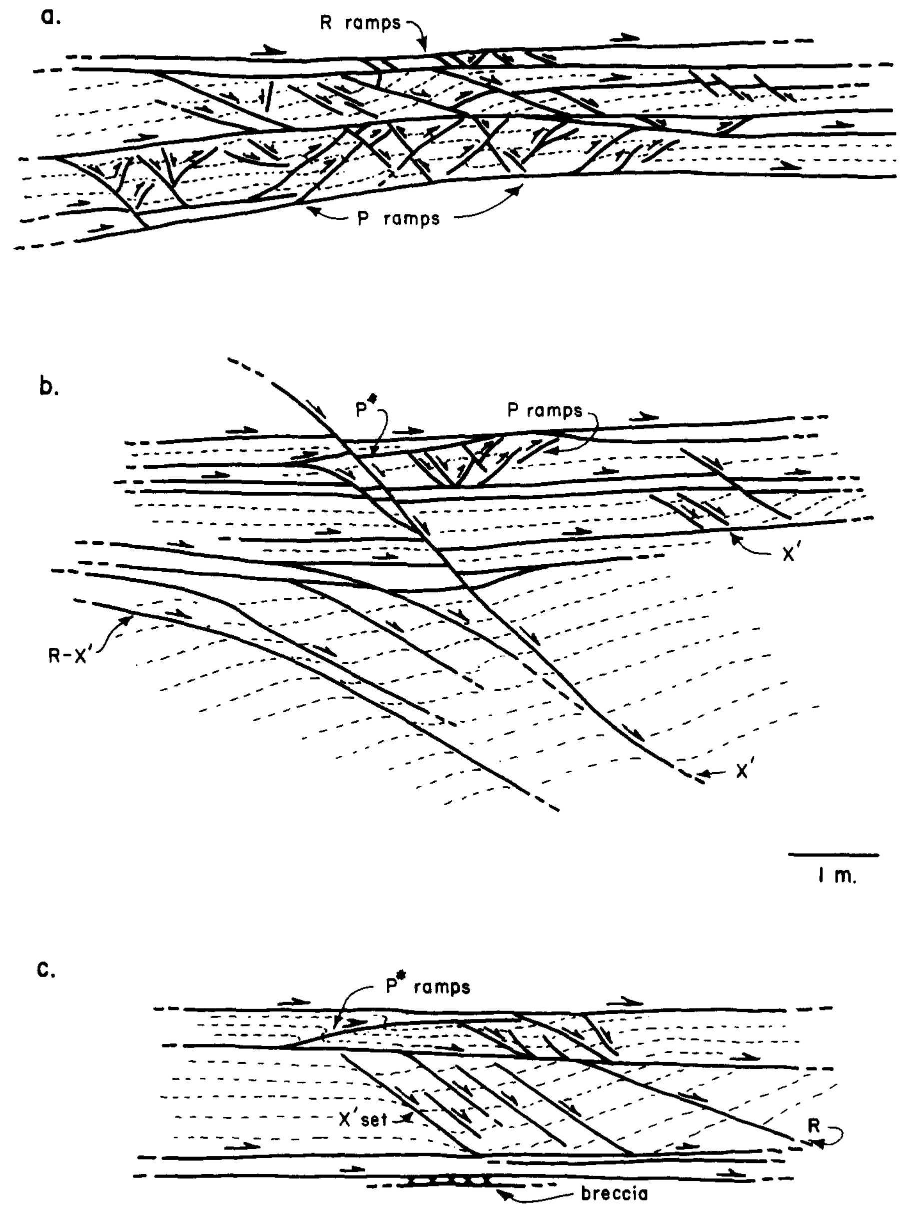

Fig. 10. Fault geometries in pseudotachylyte generation zone configurations (see Fig. 2 for locations within the Fort Foster Brittle Zone). (a) Slab extension (X'), shortening (P–P') and associated thinning–thickening of the decoupled fault slabs. (b) Pseudotachylyte generation zones showing localized contractional (P) shear fractures, associated slab thickening and interaction with strong oblique dextral (R, R–X', X') slip surfaces. (c) Zonal fault structures showing a contractional (P^*) ramp structure, extension (X') and counterclockwise rotation of internal fault blocks and the development of localized extensional pseudotachylyte breccias.

data distribution toward the higher peak at approximately 140°. This suggests approximately 20° of clockwise rotation during slip on the X shear fracture sets, corresponding with the 20° of counterclockwise rotation suggested by the dextral X' shear fracture histogram peaks.

The detailed geometric relations between the various shear fracture sets is of course dependent on the orientation of the principal stress directions both outside and within the developing slab duplexes. During rupture and decoupling of the fault slabs the principal stresses involved are expected to be quite complex and wildly fluctuating in both magnitude and orientation. This is evidenced by the close association of layer-parallel contractional and extensional shear fracture sets as well as their cross-cutting relations.

The internal geometry and kinematics of the slab-duplex development result from the interaction between shear fracture orientations modified by the influence of a prominent anisotropy. The role of an effective host rock anisotropy significantly affects the developing orientations and resulting kinematic patterns. Continuing research will attempt to clarify the geometric relations between the various shear fracture sets involved in this style of rupture.

REPORTED FAULT CONFIGURATIONS

The evolution of brittle fault zones has been simulated by numerous deformation experiments using clay (Riedel 1929, Morgenstern & Tchalenko 1967,

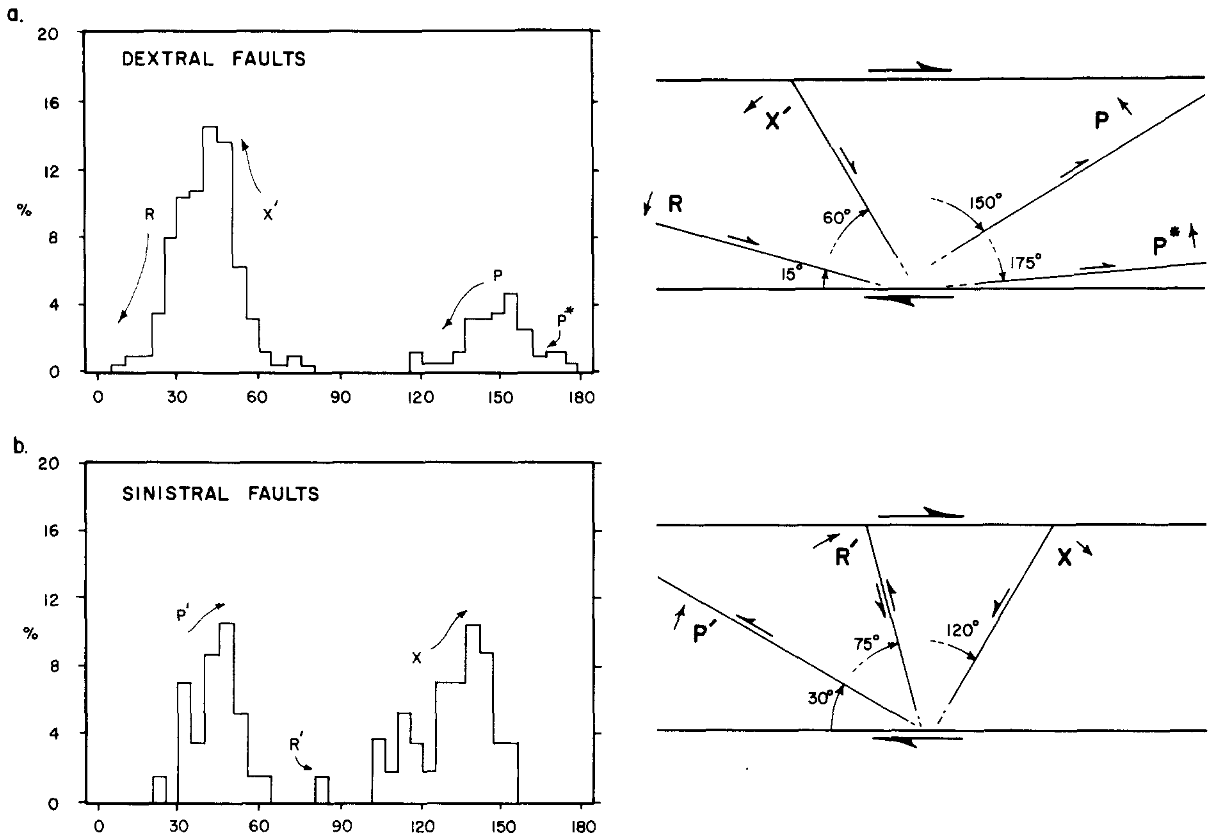

Fig. 11. Histograms of a preliminary orientation data set for the Fort Foster Brittle Zone. Fracture orientations measured clockwise from layer-parallel bounding slip surfaces. (a) Dextral shear histogram consists of a low-angle (5–75°) composite peak (R–X') dominated by X' shears, showing effects of counterclockwise rotation from initiation angle (60°) to lower angles (30–45°); and a less frequent peak at higher angles (120–180°) consisting of P^* ramps and P fracture sets which shows effects of counterclockwise rotation of P surfaces from initiation angles (150°) to new angles (120°) during slip. (b) Sinistral shear histogram consists of a low-angle peak (30–60°) dominated by P' shears and minor R' shears showing effects of clockwise rotation of P' surfaces from initiation angle (30°) to higher angles (45°) during slip; and a higher-angle peak (100–155°) consisting of only X shear fractures, showing effects of clockwise rotation from initiation angles (120°) to new angles (150°) during slip.

Tchalenko 1968, 1970, Harris & Cobbold 1985, Hempton & Neher 1986), sand (Jaeger & Gay 1974, Mandl *et al.* 1977, Naylor *et al.* 1986), fault gouge (Friedman *et al.* 1974, Byerlee *et al.* 1978, Logan *et al.* 1979) and rock (Donath 1961, Hoek 1964, Friedman & Logan 1970, Jackson & Dunn 1974, Engelder 1974, Bartlett *et al.* 1981, Friedman & Higgs 1982). Most of these experiments were concerned with the orientation and kinematic development of minor shear and tension fractures during deformation. Many of the reported experimental configurations, particularly the simulated gouge experiments, resemble the slab-duplexes discussed here, where distinctive structures have been developed between two adjacent rock surfaces.

Based on natural observations and experimental results the typical evolutionary pattern for brittle fault structures involves a number of different shear and extension fracture orientations, specifically the R, R' and P shears. Fault zone evolution (Fig. 12) usually begins with the development of en échelon R shears and minor conjugate R' shears. Continuing deformation results in linking of these early formed structures by P shears at low angles to the shear zone boundaries leading to the development of a through-going fault structure. The early en échelon R shears would develop contractional duplexes (Fig. 12b) while the later P shear sets would develop extensional duplexes (Fig. 12e) leading to decoupling.

Experiments by Logan *et al.* (1979) on simulated quartz fault gouge revealed the additional development of Y shears (fault-parallel) and X shears (high-angle to fault zone) during displacements as discussed above. Grocott's (1977, 1981) original descriptions of pseudotachylyte generation zones from western Greenland noted three characteristic internal shear fracture orientations (groups A, B and C). The group A and B shear fractures are interpreted as conjugate pairs generally accommodating extension within the zone similar to the X–X' shear fractures in this report. The group C fractures are contractional ramp structures similar to the P-shears of Logan *et al.* (1979).

Outcrop-scale examples of strike-slip duplexes abound in the geologic literature (see compilations by Woodcock & Fischer 1986) and are most helpful in evaluating the role of various shear fracture orientations in the kinematic development of these fault zones. Coupled parallel fault structures similar to the pseudotachylyte-bearing slab-duplexes have also been recently

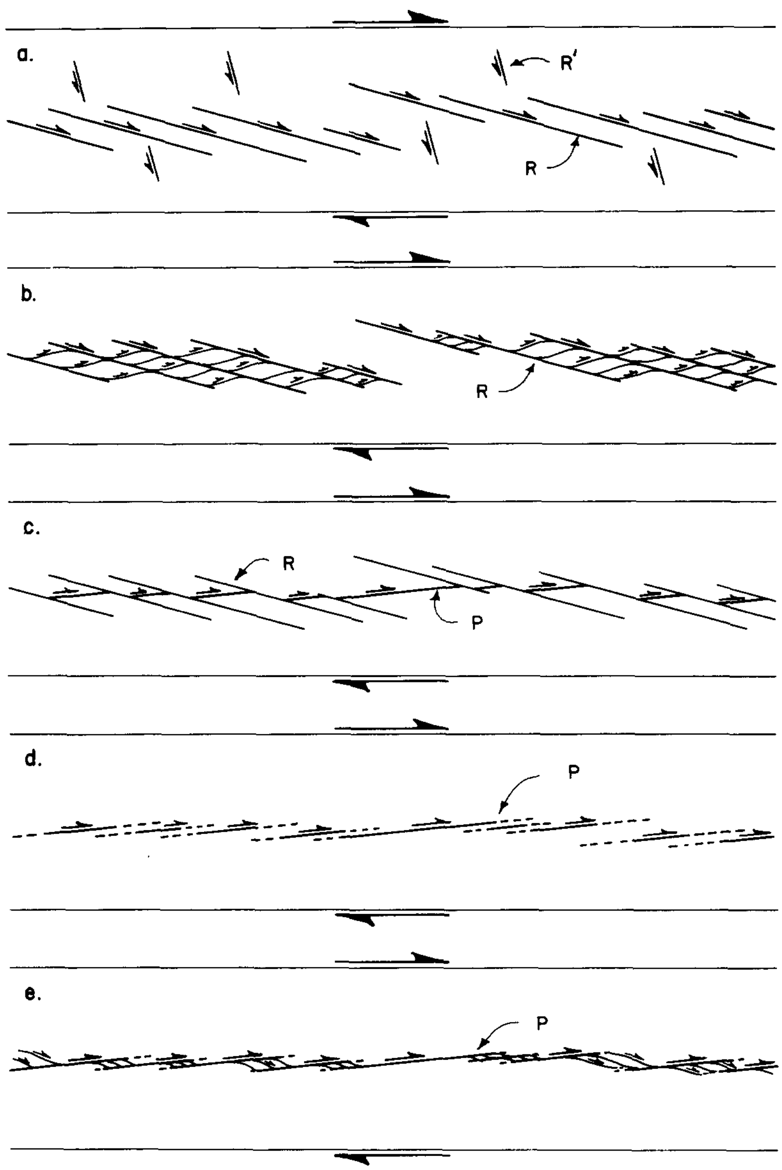

Fig. 12. Idealized structural evolution of brittle fault structures in relation to duplex development within interactive en échelon slip surfaces. (a) Initial left-stepping en échelon *R*-shear (and *R'*) configuration within dextral strike-slip fault zone. (b) Contractional duplex development in *R*-shear overlap zones. (c) *P*-shear development as a linking accommodation mechanism within the duplex overlap zones. (d) New *P*-shear orientations in a right-stepping en échelon configuration. (e) Extensional duplex development within *P*-shear overlap zones leading to a through-going fault structure.

described in granitic rocks by Segall & Pollard (1983) and Martel & Pollard (1986) and generally have high-angle internal shear and tension fractures. Similar strike-slip overlap structures have been described by Hedgecoxe & Johnson (1986), Dennis (1982) and Nicholson *et al.* (1986) with generally high-angle antithetic internal structural configurations. Granier (1985) had also described extensional 'horsetail' relay structures between en échelon fault terminations possibly similar to the overlap structures described here.

FAULT GEOMETRY AT DEPTH

Coupled en échelon fault structures represent a distinctive structural configuration found at all scales within the crust (Tchalenko 1970). The development of duplex structures as a kinematic pattern for linkage between coupled en échelon faults occurs in normal, reverse and strike-slip faults (Woodcock & Fischer 1986). The pseudotachylyte generation zones in strike-slip faults as slab-duplex structures are, however, unique in their development within the anisotropic mylonitic rocks that would dominate the brittle–ductile transition at the base of the seismogenic zone. The development of this style of faulting appears to be dramatically enhanced in anisotropic mylonitic host rocks.

The relationship between the typically en échelon geometry of surface faulting and rupture geometries at greater seismogenic depths may be reflected in a recent experimental sandbox study by Naylor *et al.* (1986). Their experiments were designed to model structure development in a cover sequence over a basement strike-slip fault. En échelon fault surfaces produced in their

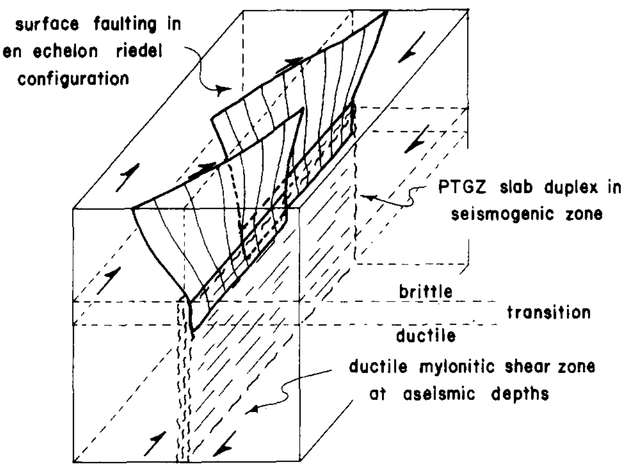

Fig. 13. Interpreted relationship between surface en échelon fault geometries and the pseudotachylyte-bearing slab-duplex structures, based on models by Sibson (1983; 1986) and experimental results of Naylor *et al.* (1986). Ruptures initiate at depth within the slab-duplex domain and propagate upward and outward into the typical en échelon surface geometries.

experiments (Fig. 13) are described as helicoidal in shape and were found to become more closely aligned and sub-parallel to the regional shear direction before merging into a single fault plane at depth. A possible influence of a prominent mylonitic anisotropy on the extension of surface geometry to seismogenic depths would be to merge the near-surface en échelon Riedel structures into an interactive system of essentially parallel, but non-coplanar slip surfaces due to the reactivation of the mylonitic foliation developed below and within the brittle–ductile transition. Repeated displacements result in the development of a mosaic of complex overlapping slab-duplex structures within the mylonitic rocks of the seismogenic zone similar to the observed systems of pseudotachylyte-bearing fault structures within the Fort Foster Brittle Zone in southern Maine.

RELATION TO EARTHQUAKE SOURCE ZONE MODELS

The Fort Foster Brittle Zone exposures are interpreted to represent a history of paleoseismicity in the development of a regional fault structure. Multiple earthquake rupture sequences are recorded and preserved. The intricate fault structures generating the pseudotachylyte represent the actual rupture mechanisms associated with this seismicity. These structures have been preserved in these exposures because of the small amounts of overall slip developed within this brittle zone. Continuing displacement which obliterates earlier-formed pseudotachylyte as well as the typical depth of formation within the seismogenic zone combine to make pseudotachylyte relatively rare. Most focal-depth rupture zones, therefore, are unexposed. Only a select few have been exhumed to the proper crustal level by uplift and erosion, thus permitting direct observation of the seismogenic structures (Sibson 1983).

Of importance to this study is the relationship, if any, between the pseudotachylyte-bearing slab-duplex structures and source zone models for earthquake generation. Currently, two earthquake source zone models have been proposed; the asperity model of Lay and Kanamori (Lay & Kanamori 1980, Kanamori 1986) and the barrier model of Das and Aki (Das & Aki 1977, Aki 1979, 1984).

A barrier is defined as an unbroken strong patch of rock that is left intact after through-going rupture propagation during a seismic event (Das & Aki 1977, Aki 1979). The velocity and acceleration of these ruptures would be controlled by the efficiency of the internal barrier deformation mechanisms. Barrier-type earthquakes are referred to as stress roughening and would lead to stress concentration in the unbroken zones resulting in a focused aftershock activity (Aki 1984). Extensional en échelon barriers may also play a role in stopping rupture propagation (Lindh & Boore 1981, Aki 1979, Sibson 1985).

An asperity is defined as a high strength patch along a freely-slipping fault surface that fails during a seismic event (Lay & Kanamori 1980, Kanamori 1986). This is modeled after indentation ploughing of asperities in experimental frictional sliding experiments (Engelder 1974, Scholz & Engelder 1976). Asperity-type earthquakes are referred to as stress smoothing and would involve total decoupling and shearing of the asperities during the main shock with foreshocks and pre-seismic slip defining the asperity (Aki 1984). It is important to note that a barrier of intact rock left after initial propagation of segmented en échelon shear fractures in the proper geometry will, with continued displacement, eventually impede slip on the adjoining fault segments as an asperity.

The pseudotachylyte-bearing slab-duplex structures have strong similarities to the barrier-asperity model for the earthquake source zone (Fig. 14). The initial offset-overlap zone between coupled layer-parallel shear surfaces in anisotropic rocks would represent an unbroken barrier structure left after the propagation of en échelon shear fractures associated with coseismic slip. Continued increments of displacement on the adjoining fault segments can be accommodated by duplex development, growth and internal deformation. Each duplex slab would be able to accommodate a limited amount of displacement by internal shear fracture mechanisms before complete failure as a ruptured asperity.

Barrier development has been modeled in terms of segmented colinear (coplanar in three dimensions) slip zones separated by zones of unbroken rock (Aki 1984). A more appropriate model in light of the present study might be the en échelon crack model of Segall & Pollard (1980) modified for significant overlap. It is the initial offset-overlap zone between en échelon faults with linkage leading to slab-duplex development that would represent the barriers and asperities in the current source zone models.

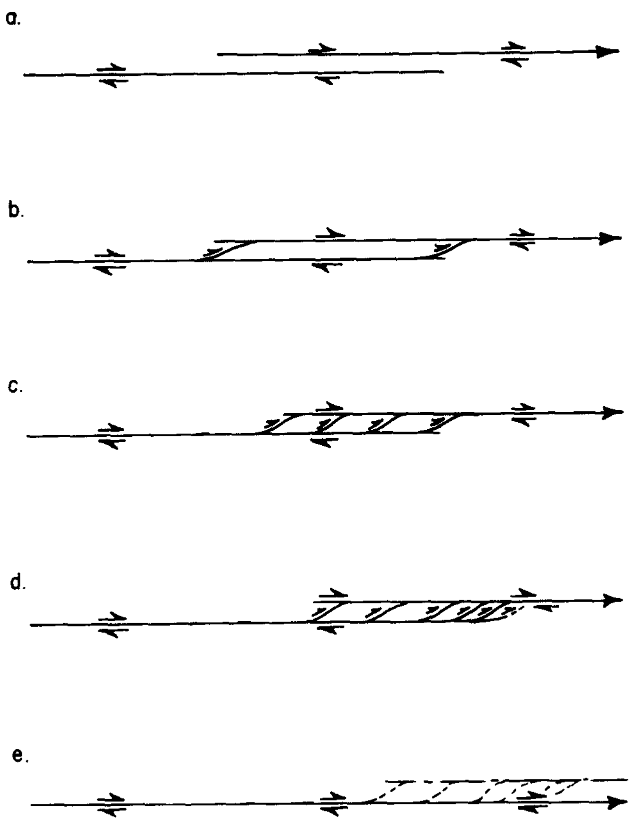

Fig. 14. Barrier-asperity sequence for the development of a contractional slab-duplex at a left-stepping offset-overlap zone within a dextral strike-slip fault: (a) initial offset-overlap zone as barrier; (b) decoupling of host rock slab; (c) internal imbrication; (d) asymmetric or symmetric growth of duplex structure; and (e) final rupture of slab-duplex as a binding asperity.

CONCLUSIONS

Rupture structures associated with the generation of pseudotachylyte in these exposures develop in a distinctive fault-bounded slab geometry that reflect the influence of a prominent mylonitic planar anisotropy at near-focal depths within a paleoseismogenic zone. The fault-bounded slabs are interpreted as duplexes and represent the style of linkage between en échelon layer-parallel fault segments. The formation, growth and internal deformation of these duplex structures plays a significant role in accommodating strain during slip on the adjoining fault segments.

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