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Late Acadian–Alleghenian transpressional deformation: evidence from asymmetric boudinage in the Casco Bay area, coastal Maine

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Abstract—Asymmetric competent-layer and foliation boudinage in the Casco Bay area of coastal Maine formed during regional F_2 hinge-parallel elongation and distributed dextral strike-slip movement. It consists of backward-rotated, oblique shear fracture boudinage and forward-rotated, extension fracture boudinage. Initially symmetric quartz-filled extension fractures were intermittently developed as boudin partings orthogonal to the prominent ductile stretching lineation, due to fault-related fluctuations in fluid pressure and tectonic stresses. Modification by concurrent non-coaxial deformation (related to dextral strike-slip movement) resulted in the clockwise rotation, sinistral slip and vein-parallel elongation reflected in the forward-rotated, asymmetric boudinage. Discordant planar pegmatite veins and variably-oriented boudinaged pegmatite sheets common in these exposures underwent a similar evolution. The development of this asymmetric boudinage is attributed to progressive brittle–ductile non-coaxial deformation related to orogen-parallel dextral transpression along the Norumbega–Nonesuch River strike-slip fault system during the later stages of the Acadian orogeny and subsequent Alleghenian deformation.

INTRODUCTION

BOUDINAGE, as the disruption and extension of competent layers during deformation, was originally defined by Lohest (1909), and later described by Cloos (1947), Ramberg (1955) and Rast (1956) from a variety of geologic settings. Renewed interest in the field relationships of boudinage in highly deformed metamorphic terrains (Hanmer 1984, 1986, Goldstein 1988, Lacassin 1988, Malavieille & Lacassin 1988) has focused on the use of asymmetric boudinage as strain and kinematic indicators for non-coaxial progressive deformation.

Hanmer (1984, 1986) has described the characteristics of asymmetric boudinage, pull-aparts and foliation fish, within the highly deformed rocks of the Grenville province where they have been modified by layer-parallel ductile shear. Types of asymmetric pull-aparts (Hanmer 1986) were distinguished by the sense of rotation of the competent layers and the sense of shear along the parting surfaces. Their distinctive asymmetric geometries enable their use as kinematic indicators for the sense of shear during the regional Grenville deformation (Hanmer 1986, Mawer 1987). The boudin classification of Hanmer (1986) and Waldron *et al.* (1988) as forward-rotated (Type I) extension fracture boudinage (Fig. 1a) and backward-rotated (Type II) shear fracture boudinage (Fig. 1b) is utilized in this study.

This report describes an array of symmetric and asymmetric boudin structures, some with new and distinctive features, developed in the deformed and metamorphosed rocks in the Casco Bay area of southern coastal Maine. With the aid of a shear-box experiment, the kinematic interpretation of these structures leads directly to previously unrecognized kinematic and tectonic implications for Acadian and Alleghenian deformation in the Mid- to Late Paleozoic.

GEOLOGIC SETTING

The present investigations in coastal Maine have focused on exposures of the highly deformed Casco Bay Group metasedimentary and metavolcanic rocks within and adjacent to Two Lights State Park in Cape Eliza-

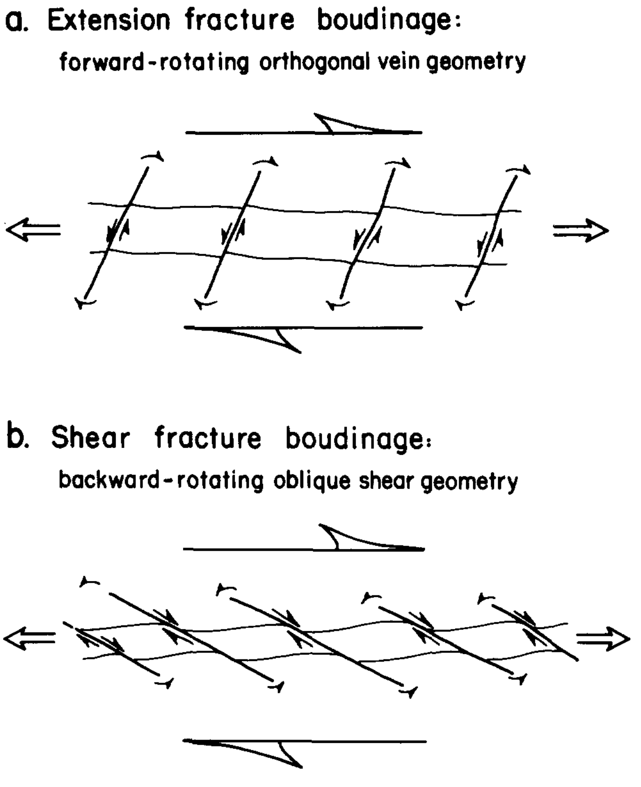

Fig. 1. Types of asymmetric boudinage discussed in the text formed under intermittent extension and layer-parallel dextral shearing. (a) Extension fracture boudinage with forward-rotating, orthogonal vein geometry (Type I). (b) Shear fracture boudinage with backward-rotating, oblique shear-band geometry (Type II).

beth, along Harpswell Neck in South Harpswell and in the Wolf Neck–Flying Point area in Freeport (Fig. 2). The Casco Bay Group (Hussey 1988), as part of the Coastal Lithotectonic Block, consists of interpreted stratigraphic sequences of medium- to high-grade metamorphic lithologies, such as metapelitic and metavolcanic schists and gneisses, marbles and amphibolites of uncertain Precambrian to Ordovician age. These lithologies have been deformed and metamorphosed during the Mid-Paleozoic Acadian orogeny and affected by Late Paleozoic strike-slip faulting. Regional structure (Hussey 1988) consists of an early recumbent fold phase (F_1) and a second, dominant phase of NE-trending, upright folds (F_2). The F_2 folds are considered to be syn-metamorphic and are cross-cut by the syn- to post-orogenic Late Devonian and younger intrusions (Osberg *et al.* 1989).

These Late Acadian structures and intrusions are, in turn, cut by what are generally considered to be post-metamorphic faults of Late Paleozoic to Mesozoic age (Hussey 1988), often associated with distributed retrograde chloritization. The dominant Late Paleozoic faults in coastal Maine (Fig. 2) are part of the Norumbega–Nonesuch River fault system (Wones & Stewart 1976,

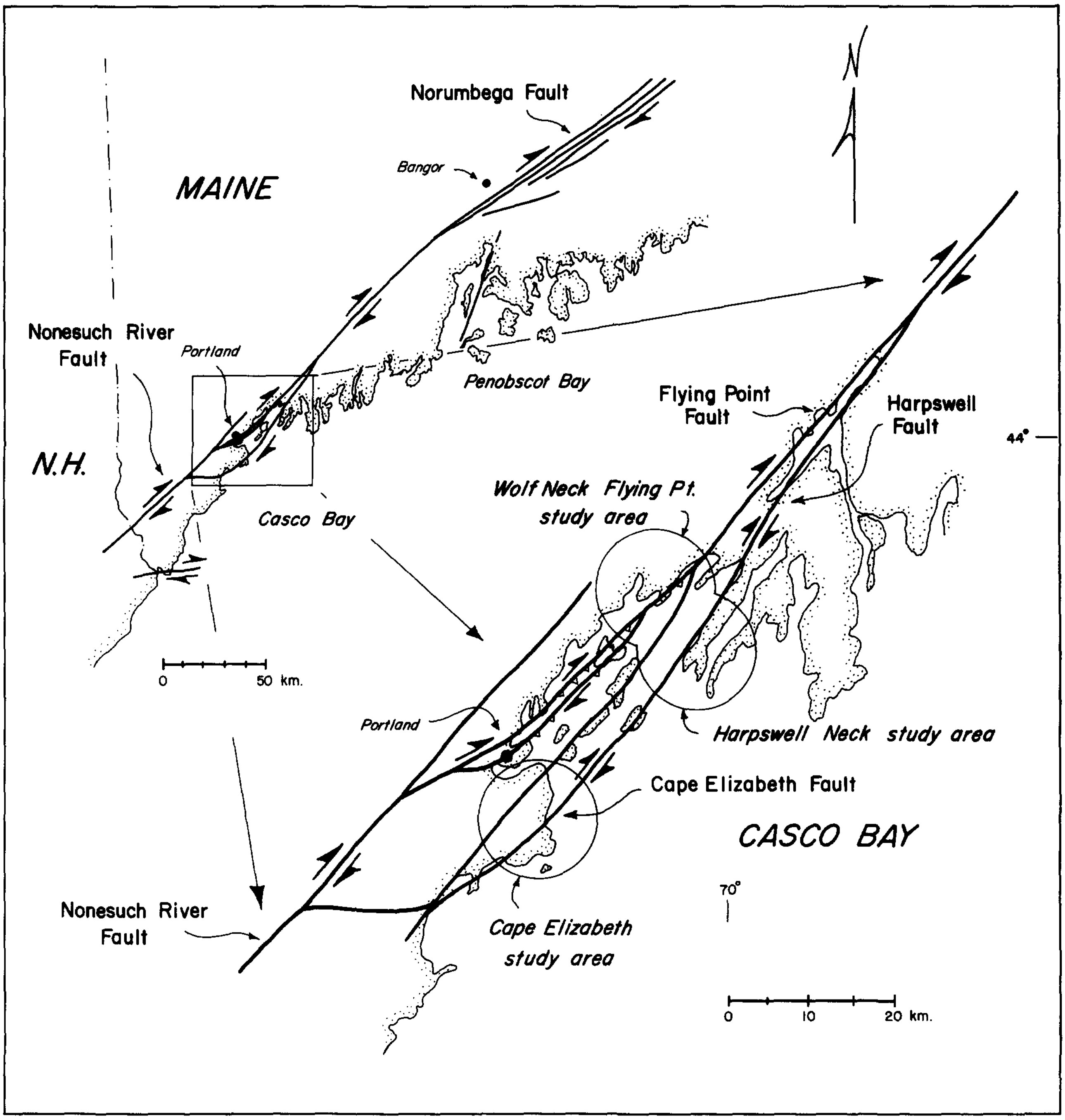

Fig. 2. Regional structure and location map for the Casco Bay area of coastal Maine, the major strike-slip fault segments and the localities discussed in the text in relation to the regional Norumbega–Nonesuch River fault system. (Modified after Osberg *et al.* 1985, Hussey 1988.)

Hussey & Newberg 1978, Osberg *et al.* 1985, Hussey 1988) that bounds the Coastal Lithotectonic Block on the northwest (Ludman 1991).

Mapped faults in the Casco Bay area, however, are poorly understood, being described simply as high-angle faults with a range of inferred displacements including normal dip-slip as well as both left- and right-lateral strike-slip (Hussey 1988). Preliminary field work for this study has shown that most of these faults are dextral strike-slip and constitute syn- to post-metamorphic ductile shear zones with later brittle reactivation. The structures in the Casco Bay area described in this paper are thought to have developed in association with these nearby shear zones. It will be shown that the ductile and brittle–ductile strike-slip history within this part of the Coastal Lithotectonic Block was more widespread than previously thought, distributed throughout the coastal lithologies and not strictly constrained to the mapped fault traces. The development of syn-metamorphic ductile stretching lineations parallel to F_2 fold hinges in an oblique relationship with a long-lived strike-slip fault system that persisted until the latest Paleozoic suggests that this regional shearing continued from the Late Acadian orogeny through the subsequent Alleghenian deformation.

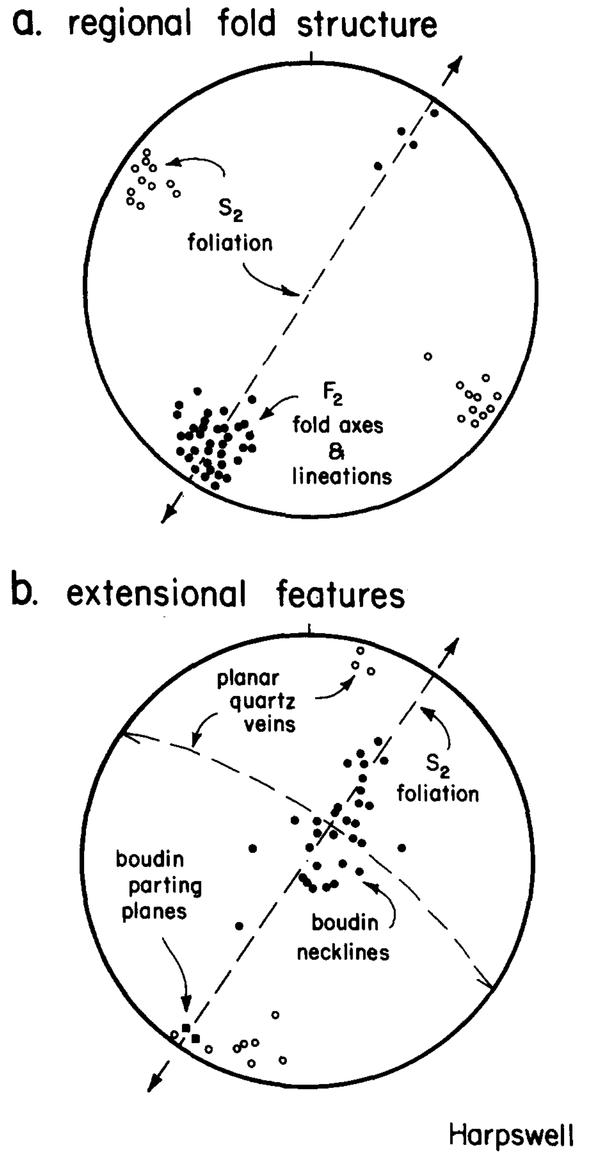

Fig. 3. Structural data from the Harpswell Neck area (Swanson *et al.* 1986) illustrating the geometry of upright F_2 folds, hinge-parallel elongation and related extensional features (arrows indicate extension direction). (a) Regional fold structures with gently SW-plunging F_2 fold axes, hinge-parallel stretching lineations and vertical foliation planes. (b) Boudinage structures with steeply-plunging scar-folds, lip-folds and neck lines, vertical boudin parting planes and late planar quartz veins orthogonal to the NE-trending near-vertical bedding/foliation and the gently SW-plunging elongation direction.

BOUDINAGE IN THE CASCO BAY AREA

The development of boudinage is a dominant characteristic of most of the lithologies in the Casco Bay area of coastal Maine. Boudinage in these exposures can occur as *competent-layer boudinage* involving relatively rigid metasedimentary layers or early quartz and pegmatitic veins in a less competent matrix. In more uniform lithologies, with little apparent competence contrast between layers, *foliation boudinage* is prominently developed. Both symmetric and asymmetric varieties of competent-layer and foliation boudinage occur. Asymmetric boudinage (Fig. 1) forms by the modification of initially symmetric structures (*extension fracture boudinage*) as well as by the evolution of initially asymmetric structures (*shear fracture boudinage*). In all cases, the bulk deformation responsible for the boudin generation and modification has a large dextral strike-slip component, where the distinctive asymmetry of the resulting structures can be used to determine the sense of shear. The combination of layer- and hinge-parallel elongation and layer-normal shortening with dextral strike-slip shearing makes this bulk deformation transpressional in nature.

Elongation direction

The rocks of the Casco Bay area exhibit a strong, NE-trending, subhorizontal, stretching lineation (L_2) that is parallel to the hinges of F_2 folds (Fig. 3a) and is expressed as syn-metamorphic elongate-mineral alignment and mineral aggregate elongation (Hussey 1971, Swanson *et al.* 1986). The NE-trending elongation direction is also reflected in the NW-trending planar quartz veins, boudin partings and steeply-plunging boudin necklines (Fig. 3b). This ductile stretching lineation is found within the gently-dipping (Cape Elizabeth area), moderately-dipping (Wolf Neck–Flying Point area) and steeply-dipping (Harpswell Neck area) beds about the F_2 folds and was probably formed under prograde upper greenschist to lower amphibolite metamorphic conditions as reported by Kaszuba & Simpson (1989) for similar lineations in the nearby Penobscot Bay area. It is important to note that this syn-metamorphic elongation direction is NE-trending, sub-horizontal and *parallel* to the Acadian orogenic belt. This is perpendicular to the typical NW–SE convergence direction (Osberg *et al.* 1989) interpreted for the Acadian deformation. The recognition of asymmetric boudinage structures related to this elongation direction provides valuable kinematic insight into the nature of orogenic movements during the Late Acadian and younger Alleghenian deformations.

Symmetric foliation and competent-layer boudinage

Symmetric boudinage in these exposures (Fig. 4) involves the formation of incipient partings, veins and mineralized partitions that define the boudin segments. Initial boudin partings in this area are typically orthogonal (i.e. symmetric) with respect to the layers undergoing elongation as a form of extension fracture boudinage (Fig. 4a). The initiation of these structures directly reflects the regional F_2 hinge-parallel extension throughout the Casco Bay area, with parting planes perpendicular to the elongation direction. Mineral assemblages within these extension fractures are feldspar, quartz, biotite and tourmaline in the Wolf Neck–Flying Point area, quartz, muscovite and minor garnet in the Harpswell area, and quartz, actinolite or quartz, calcite, chlorite and minor sulfides in the Cape Elizabeth area.

Continued layer-normal flattening and layer-parallel elongation modifies the geometry of the earlier-formed symmetric boudin structures. Dilation of the initial fractures deforms the parting fracture walls to form strongly tapered quartz-filled lenses (Fig. 4a), puckers, knots and 'stars' (Lacassin 1988). Collapse of the dilating fracture (Fig. 4b) leads to distinctive 'fishmouth' boudinage, in open- and closed-mouth varieties (Wegmann 1932, Ramsay 1967, fig. 3-44, Swanson & Pollock 1986) along with the formation of 'pseudofolds' at the boudin ends (Hambrey & Milnes 1975). In layered units where the competency contrast between the fractured layer and the surrounding host rock is high, little modification of the boudin ends occurs and the mineralized partition acquires a rectangular geometry. Continued ductile necking and stretching of the boudin segments about the mineralized quartz partitions (Fig. 4c) results in 'bone-shaped' boudins (Malavieille & Lacassin 1988).

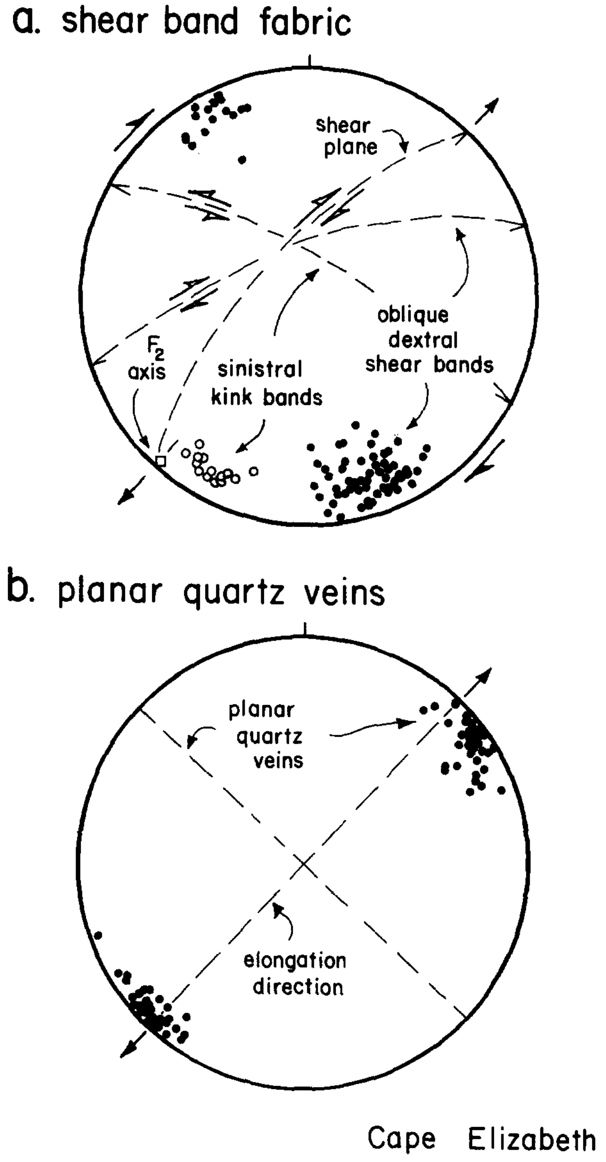

Fig. 5. Structural data from the Cape Elizabeth area showing (a) subhorizontal F_2 fold axis and regional shear plane with the oblique dextral shear bands and high-angle sinistral kink bands attributed to dextral strike-slip shearing, and (b) late undeformed planar quartz veins related to the final phase of F_2 hinge-parallel extension.

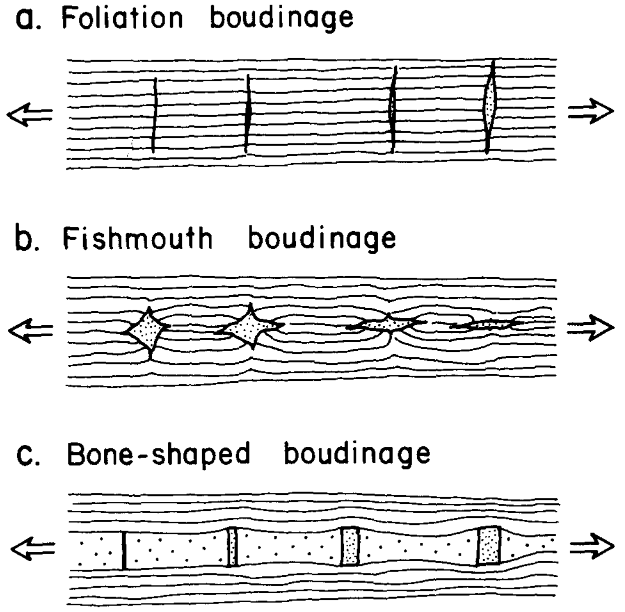

Fig. 4. Symmetric boudinage features with increasing elongation from left to right (arrows indicate extension direction). (a) Initiation and dilation of orthogonal vein partings for symmetric foliation boudinage. (b) Collapse of initial partings to form quartz stars and fishmouth boudins. (c) Continued layer-parallel elongation about initially rectangular boudins and quartz partition mineralization to form bone-shaped boudins.

While initial fracture lengths for partings in competent-layer boudinage are controlled by the layer thickness (1–20 cm), observed fracture lengths for typical foliation boudinage range from a few centimeters to several meters. Larger planar quartz veins in both the Harpswell Neck (Fig. 3b) and Cape Elizabeth (Fig. 5b) areas, 1–5 cm in thickness and tens of meters in length, are also orthogonal to the regional elongation direction.

In the Wolf Neck–Flying Point area, planar pegmatite intrusions up to several meters in width are developed perpendicular to this lineation direction as well. These quartz veins and pegmatite sheets are interpreted to represent a larger-scale foliation or competent-layer boudinage of entire formational units with ~10–20 m spacings between vein partings. They represent the youngest increment of extension in these rocks.

Asymmetric foliation boudinage—oblique shear band geometry

Initially asymmetric boudinage of the foliation, thin competent beds or older deformed foliation-parallel quartz veins (in F_2 limb outcrops) may develop directly as oblique (synthetic) shear fracture boudinage (Fig. 1b). This initially asymmetric boudinage is related to a meso-scale dextral oblique shear-band fabric (Figs. 5a, 6a and 8a & b) that is pervasively developed in these exposures, particularly in the Cape Elizabeth area, reflecting the non-coaxial component of the Late Acadian and/or Alleghenian deformation. In these exposures small-scale shear zones, 10 cm to 1 m in length and at low angles to the overall shear direction, cut the foliation and competent layers into doubly-tapered sigmoidal lozenges, lenses, pods or 'fish' (Figs. 6b & c and 8a,c,d & f) with a distinctly asymmetric geometry. These shear-band elements (Fig. 5a) modify existing fabrics and layering related to the F_2 folds and are similar to Riedel shears (R-shears) in strike-slip deformation. Associated with these oblique dextral shear fabrics and faults is an assemblage of NW-trending, near-vertical sinistral kink bands (Fig. 5a), 0.5–10 cm in width, but with one 40 m wide. These sinistral kinks occur at a high angle (65-85°) to the overall layer-parallel or hinge-parallel shear direction, and function as R'-shears in a conjugate relationship to the lower-angle oblique dextral R-shears that make up the shear band fabric. In the Two Lights area and adjacent exposures of the Cape Elizabeth Formation, larger-scale shear zones and distinct cataclastic fault segments, hundreds of meters in length, occur as an R-shear array with up to 10 m of displacement on individual faults. These fault structures represent a similar style of asymmetric foliation boudinage, but on a much larger scale. Oblique shears and fabrics are common along the F_2 hinge zones, but may give way to layer-parallel slip along F_2 limbs with a well-developed planar anisotropy, as suggested by experimental studies of Williams & Price (1990).

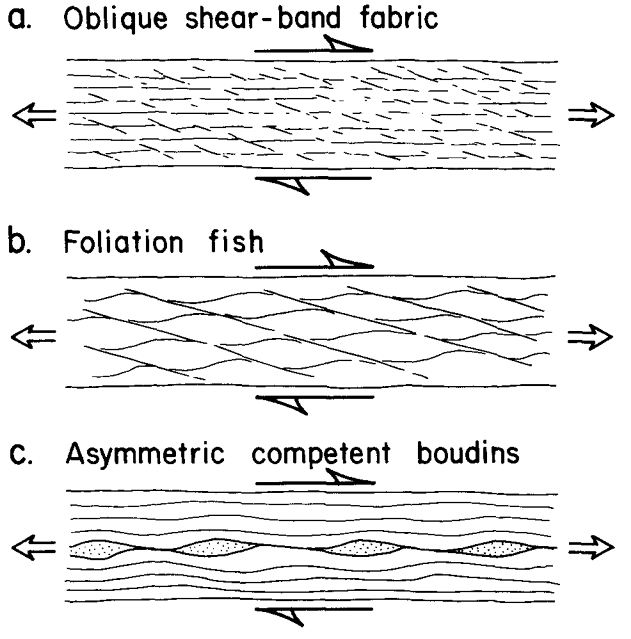

Fig. 6. Asymmetric shear fracture boudinage as (a) distributed dextral oblique shear band fabric, (b) oblique dextral shear zones and intervening foliation fish and (c) remnant asymmetric competent boudins.

This type of asymmetric boudinage is characterized by the counterclockwise or backward rotation of the competent layering and the intervening shear surfaces during development, a feature interpreted as being indicative of transpression (Ghosh & Ramberg 1976, Jordan 1991). Shear bands (White *et al.* 1980, Kelley & Powell 1985, Behrmann 1987) and related extensional structures such as asymmetric foliation boudinage (Platt 1979, 1984, Platt & Vissers 1980) in other deformed terrains have been useful as kinematic indicators of regional and localized shear deformation. The associated asymmetric backward-rotated boudinage structures are similar to the asymmetric extensional boudinage of Gaudemer & Tapponnier (1987); the Type IIa pull-apart structures of Hanmer (1986)—where preceded by some initial necking; the Type III asymmetric boudinage of Goldstein (1988)—where preceded by oblique extensional fracturing; and the antithetically-rotated shale pull-aparts of Jordan (1991)—where preceded by oblique shear fracturing. All of these asymmetric features evolve through backward rotation along the oblique shear surfaces during continued deformation, regardless of their origin.

Modified asymmetric boudinage—initial orthogonal vein geometry

Modified asymmetric boudinage in these exposures (Fig. 1a) results from the reorientation of symmetric competent-layer and foliation boudinage structures to asymmetric geometries. Reorientation involves the clockwise, forward-rotation of the initial orthogonal parting surfaces (Figs. 1a, 7 and 9a & b) during dextral shear. This rotation is accompanied by the development of sinistral antithetic slip along the mineralized parting surfaces between the boudin ends as well as by elongation parallel to the deforming quartz vein or parting surface (Figs. 9c & e). This modification is similar to the domino structures of Etchecopar (1977) and the Type-I asymmetric pull-aparts of Hanmer (1986). Further rotation of veins and partings to lower angles relative to the shear zone boundaries will result in continued elongation and the eventual development of dextral shear stresses along these lower-angle deformed veins (Figs. 9d & f). Various structures from several locations in the Casco Bay area will be described and

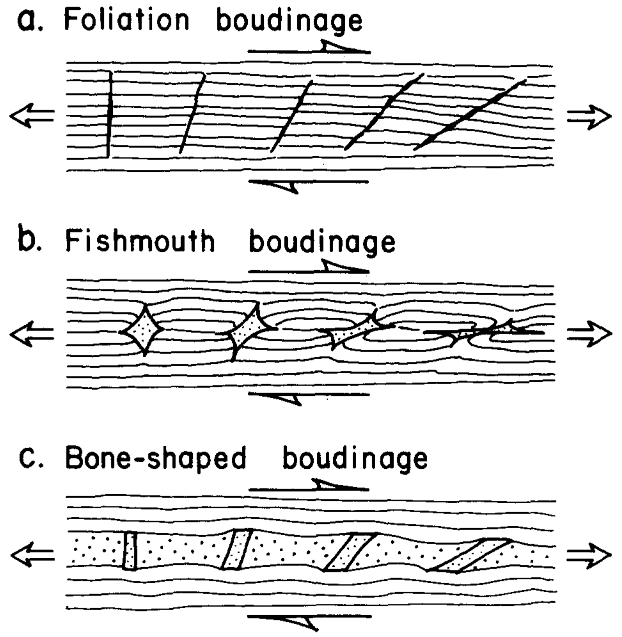

Fig. 7. Modified asymmetric boudinage features with increasing dextral shear strain from left to right. (a) Clockwise rotation and sinistral slip on initial orthogonal vein partings. (b) Modification and distortion of fishmouth boudinage during dextral shear. (c) Reorientation of rectangular mineral partitions in bone-shaped boudinage.

structural data presented to illustrate the nature of this progressive non-coaxial deformation.

Cape Elizabeth. The gently-dipping quartzites and phyllitic interbeds of the Cape Elizabeth Formation at Two Lights reflect NE-trending, flat-lying F_1 folds and only minor upright F_2 folds. The presence of an oblique shear-band fabric (Fig. 5a) as an initially asymmetric foliation boudinage and variably-oriented, quartz-filled, parting surfaces as modified asymmetric foliation boudinage suggest dextral shearing parallel to the F_1–F_2 fold axes, most likely associated with the nearby Cape Elizabeth fault zone (Fig. 2). The modified mineralized parting surfaces that define the foliation boudinage occur as cm-thick quartz veins, boudinaged sheets and mm-thick seams (Fig. 12) that are planar to sigmoidal, vary from 10 cm to 10 m in length and strike ~N45°W to N20°E with a consistent steep to moderate dip to the west. The youngest undeformed planar quartz veins, including the larger 10 m-scale veins (Fig. 5b) at ~N45°W, are interpreted to represent the initial parting surface orientation.

A stereonet plot of poles to these modified parting surfaces (Fig. 13a) defines a subhorizontal great-circle distribution with a near-vertical kinematic rotation axis for their clockwise reorientation in dextral strike-slip shearing. A plot of poles to measured segments of slightly-deformed, rusty quartz–calcite veins up to 10 m long (Fig. 13b), also defines a subhorizontal great-circle distribution with a similar kinematic rotation axis for the deformation.

Displacements along these boudin parting surfaces by sinistral slip during rotation are commonly 10–50 cm, with some up to several meters. They increase with the degree of rotation. Higher-angle veins and partings consistently crosscut the lower-angle surfaces (Fig. 12) reflecting their late appearance in the non-coaxial progressive deformation. The surfaces of the boudin sheets are commonly striated, indicating a consistent subhorizontal slip direction during rotation. Reorientation of slip striations during rotation also suggests (Fig. 13c) a similar horizontal great-circle distribution with a steeply-plunging rotation axis characteristic of strike-slip shear.

The reoriented meter-scale partings (Fig. 12) have also developed distinctive terminations and associated structures (Swanson 1989) related to the induced sinistral slip. 'Swordtail' tension fractures as arcuate to planar, tapered, quartz-filled gashes (Figs. 10a and 14a) are developed on the extensional side of the evolving slip surface terminations. Other termination structures consist of a 'fishmouth' termination (Figs. 10c and 14b) on the contractional side and 'kink-band' terminations (Figs. 10b and 14c) on the extensional side of the fracture tips. 'Swordtail–fishmouth' combinations (Fig. 1c) are also common. Modified 'swordtail' terminations (Fig. 10d) can be identified along the more evolved structures, with lower-angle tails where reoriented by continued dextral shear.

The rotation of the mineralized initial partings through non-coaxial deformation resulted in elongation, reflected in the typical quartz vein boudinage in these exposures. These quartz boudin sheets often exhibit pinch-and-swell type boudinage with steeply-plunging necklines (Fig. 9e). Reoriented veins may also show tapered tears at the boudin necklines due to this vein-parallel elongation (Fig. 9c). Rotation of the earliest quartz veins or boudin partings during continued shearing to low angles relative to the layer-parallel or hinge-parallel shear direction will eventually lead to the development of dextral vein-parallel shear. This is reflected in the development of localized asymmetric folding as minor open 'hook folds' (Gayer *et al.* 1978, Hudleston 1989), particularly at Spring Point on Cape Elizabeth. Forward-rotated modifications of the quartz vein boudins are also developed due to this vein-parallel dextral shear (Fig. 9d).

Harpswell neck. Similar reorientation and modification also affect initially symmetric boudinage features in the near-vertical beds and foliation planes at Harpswell Neck (Fig. 11) in association with the Harpswell Neck fault zone (Swanson *et al.* 1986). Asymmetric versions of the fishmouth (Fig. 11d) and bone-shaped boudins (Figs. 11a & b) can be observed (Swanson *et al.* 1986) where they have been modified by forward rotation during dextral shear. The blocky quartz-filled partitions, some up to 50 cm wide, between the bone-shaped boudins are often slightly asymmetric (Figs. 11a & b) with apparent clockwise rotation from the initial orthogonal orientation during dextral shear. They are similar to the modified bone-shaped boudins of Malavieille & Lacassin (1988). Asymmetric versions of the fishmouth boudinage described above can also be ob-

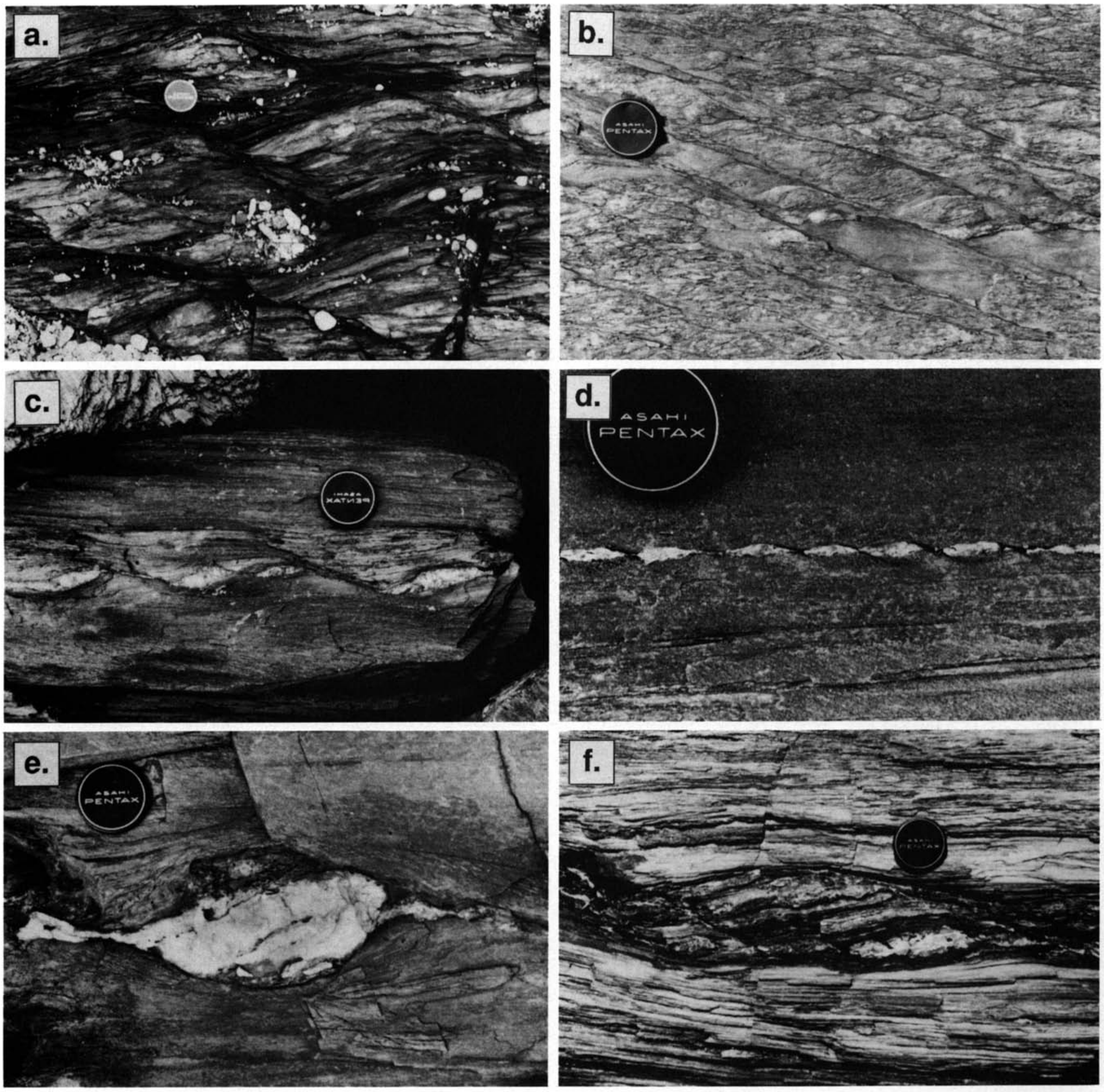

Fig. 8. Outcrop photographs of asymmetric shear band fabrics and asymmetric shear fracture boudinage from the Cape Elizabeth area (with dextral strike-slip shear plane left to right). (a) Dextral oblique shear-band fabric and modification of the intervening foliation. (b) Sporadic shear bands. (c) Interaction between a reoriented quartz vein and dextral shear bands to produce asymmetric quartz boudins. (d) String of tapered asymmetric quartz vein boudins where cross-cut by dextral shear bands. (e) Isolated asymmetric quartz boudin pod. (f) Lens of backward-rotated layering as asymmetric foliation boudinage.

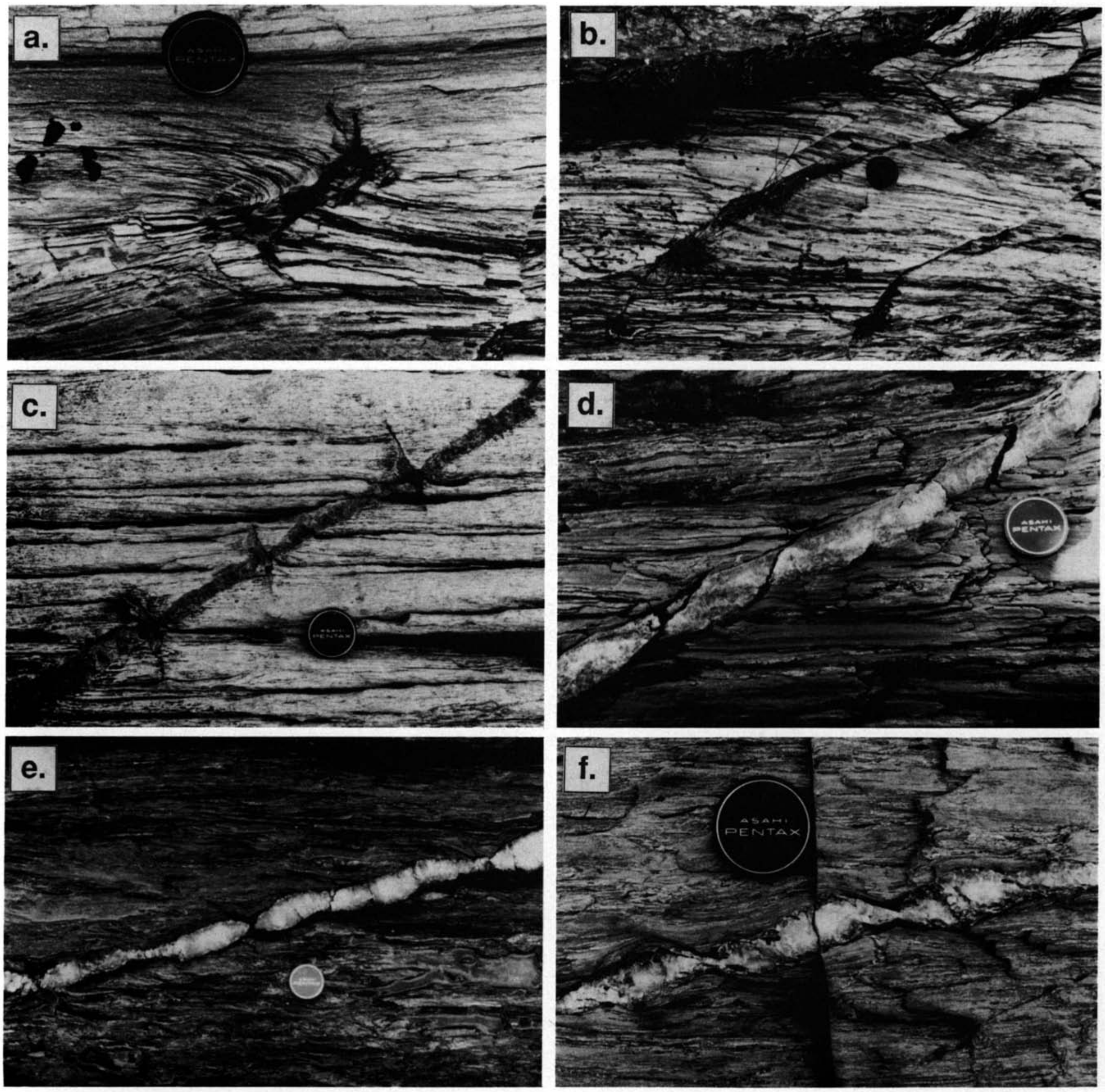

Fig. 9. Outcrop photographs from the Cape Elizabeth area (with dextral strike-slip shear plane left to right) showing: (a) sigmoidal boudin parting due to heterogeneous simple shear; (b) similar sigmoidal boudin partings after more severe reorientation; (c) reoriented quartz vein with vein-parallel elongation reflected in cross-cutting tapered partings; (d) reorientation of vein partings by forward rotation in vein-parallel dextral shear; (e) vein-parallel elongation by pinch and swell during reorientation; (f) asymmetric boudinage of a reoriented quartz vein by cross-cutting oblique shear band surfaces.

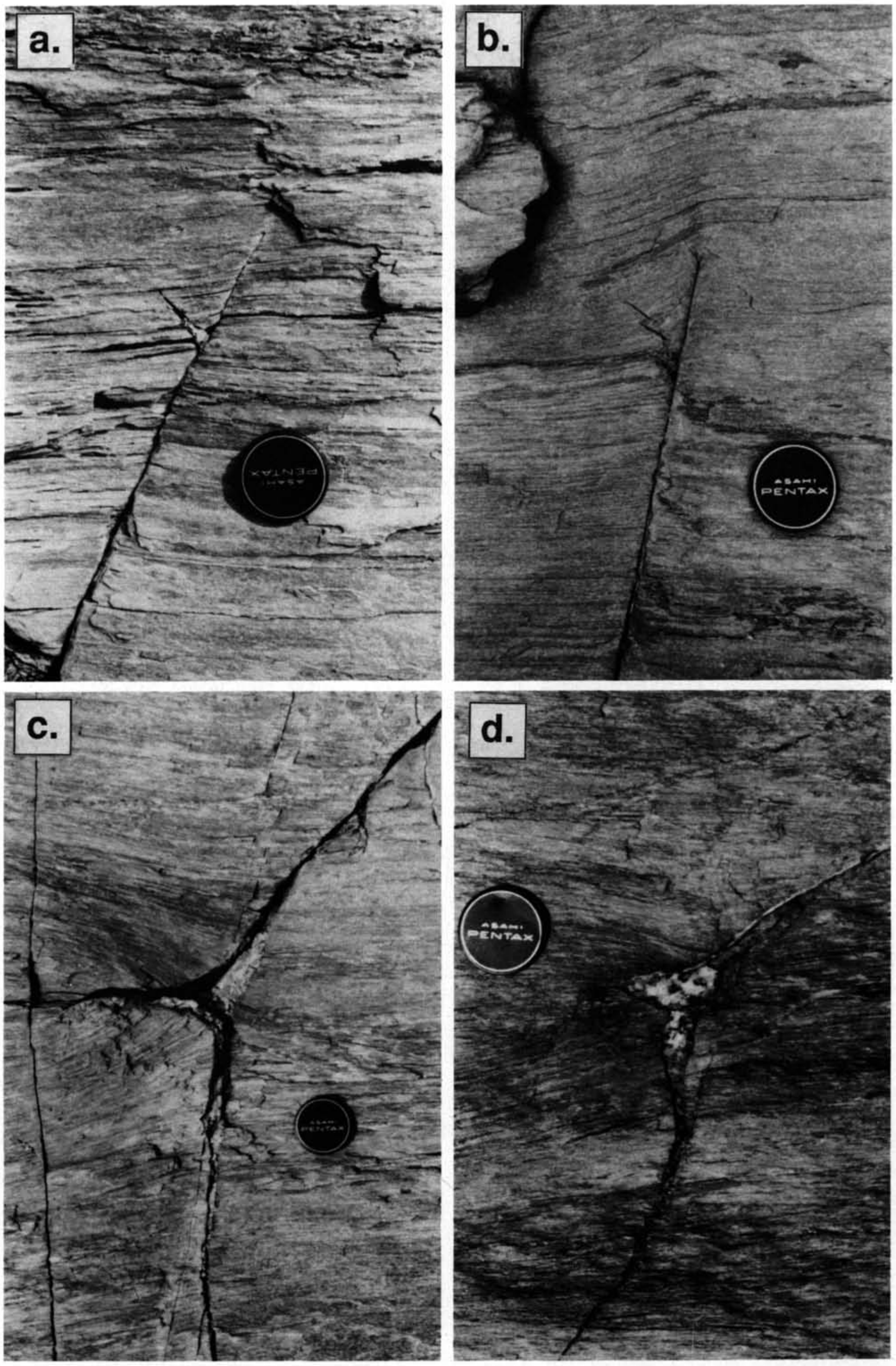

Fig. 10. Outcrop photographs of termination structures of reoriented extension fractures from the Two Lights exposures in the Cape Elizabeth area, where fractures have suffered clockwise rotation with sinistral slip within a dextral strike-slip shear couple. (a) Oblique gash veins as swordtail terminations. (b) Kink-band terminations. (c) Combination fishmouth–swordtail termination. (d) Similar fishmouth–swordtail termination modified by continued dextral strike-slip shearing.

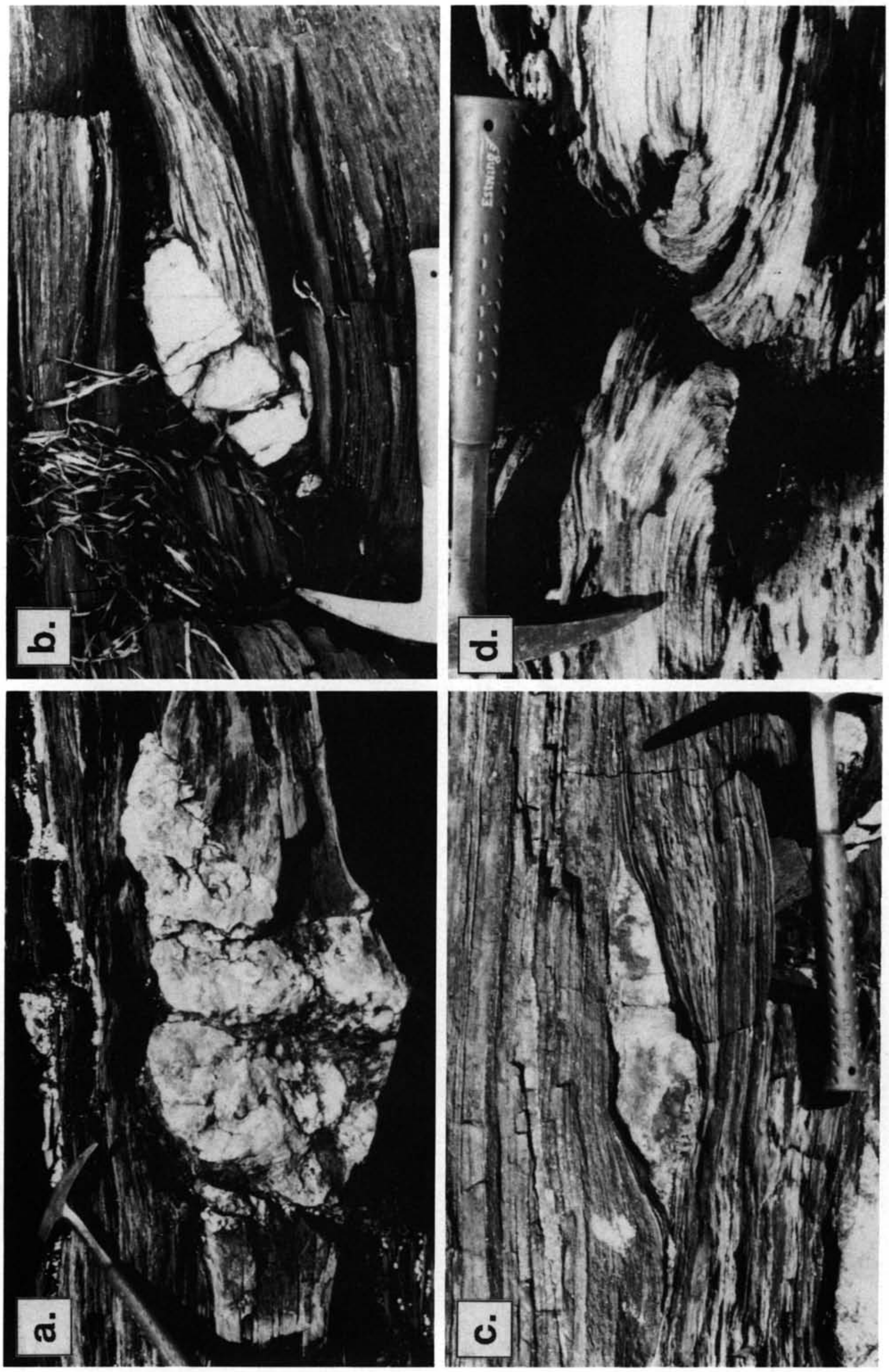

Fig. 11. Outcrop photographs of asymmetric boudin features from the Harpswell Neck area reflecting horizontal elongation and dextral shear parallel to layering (left to right in all photographs). (a) Asymmetric modification of bone-shaped boudins by dextral shear and clockwise rotation. (b) Further clockwise rotation of partition mineralization due to layer-parallel dextral shear. (c) Asymmetric quartz boudin as a remnant of a disrupted quartz vein cut by dextral layer-parallel slip. (d) Asymmetric fishmouth boudin pairs separated by an oblique sinistral slip surface (lower left to upper right) due to clockwise rotation during dextral layer-parallel shear. Note that the lower 'jaw' of the fishmouth on the left side of the photograph is missing.

served (Fig. 11d) where modified by clockwise, forward-rotation with sinistral slip along the collapsing parting surfaces (Fig. 7b).

Strings of quartz boudins at low angles to the foliation in the Harpswell exposures consist of individual asymmetric quartz pods with opposing tapered tails that anastomose into the near-vertical foliation planes. Offsets between quartz boudin pods to produce 'stair-stepping' geometries suggest dextral shear along the foliation. A similar asymmetry of recrystallized feldspar porphyroclasts in mylonites has also been interpreted in terms of dextral shear (Simpson & Schmid 1983). Some of these boudin strings with their stair-stepping geometries (Fig. 11c) remain slightly oblique to within a few degrees to the layer-parallel shear direction, indicating relatively high strain during non-coaxial progressive deformation.

Wolf Neck–Flying Point. Moderately-dipping strata in the Wolf Neck–Flying Point area display a gently NE-plunging stretching lineation and Z-shaped asymmetric quartz veins and intrafolial folds that provide evidence for layer-parallel dextral shear associated with the nearby Flying Point fault zone. Quartz-filled boudin parting surfaces, 10–20 cm in length, in the Goose Point area along the southeast Flying Point shoreline, exhibit a variety of orientations that suggest clockwise rotation during progressive deformation. The measured orientations of these quartz-filled partings (Fig. 15a) clearly illustrate the dextral shear nature of the non-coaxial deformation, similar to the situation in the Cape Elizabeth area. Poles to boudin parting surfaces define a great-circle distribution that marks a moderately-plunging kinematic rotation axis that is constrained within the inclined foliation and perpendicular to the NE-plunging stretching lineation (Fig. 15a).

A similar distribution of orientations is found for the varied pegmatite intrusions in this area as well. Pegmatite intrusions vary from 10 cm to several meter-thick planar discordant dikes to layer-parallel boudined sheets. Undeformed pegmatite dikes are generally perpendicular to the local stretching lineation in these exposures. Boudined pegmatite layers typically develop a gently NE-plunging stretching lineation (Fig. 15b) orthogonal to boudin necklines, quartz-filled partings and undeformed planar pegmatite veins. Several nearly-concordant pegmatite layers also display Z-shaped asymmetric folds. A stereonet plot of poles to pegmatite dikes and deformed pegmatite layers (Fig. 15b) shows that the pegmatite intrusions have also been affected by clockwise rotation during progressive ductile shearing constrained within the moderately-dipping lithologic layers.

DEFORMATION MODEL

The Casco Bay exposures exhibit evidence for both elongation with layer-normal shortening as well as dextral simple shear parallel to the F_2 hinge zones reflecting the transpressional nature of the deformation. Initially, orthogonal veins and partings were intermittently devel-

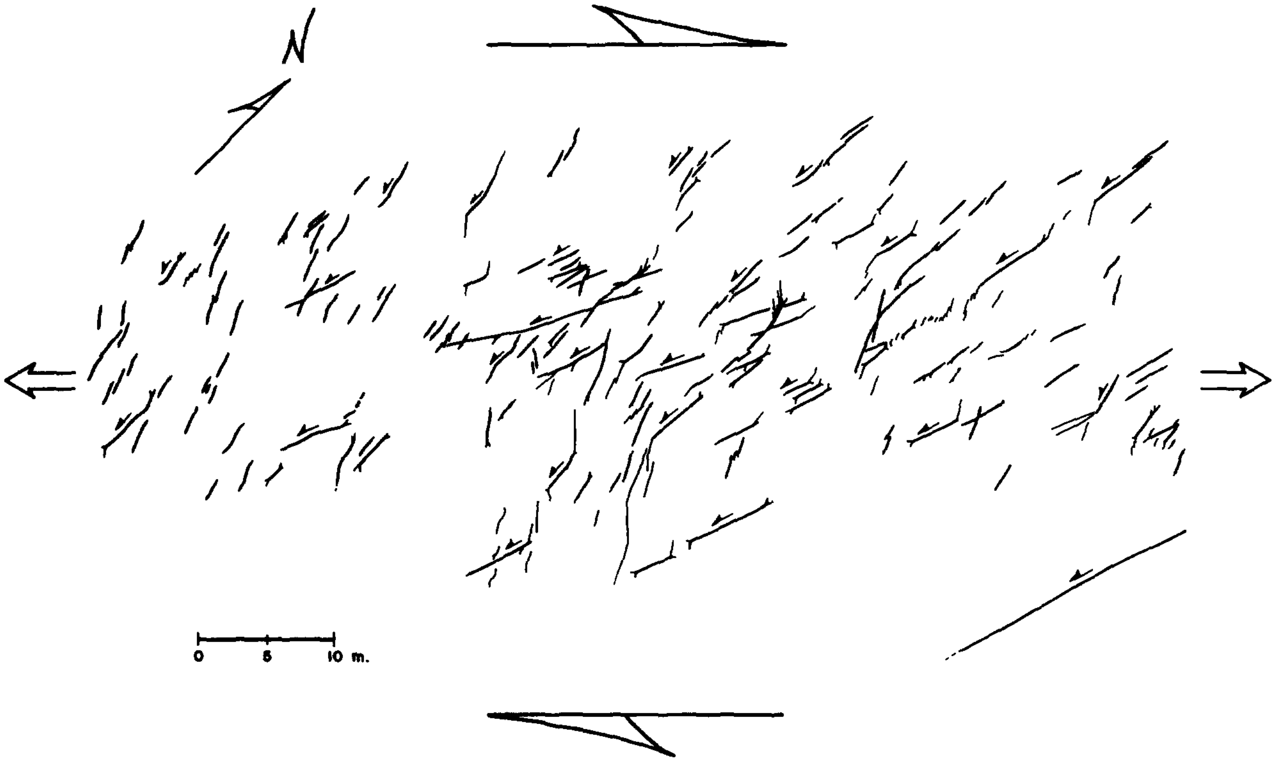

Fig. 12. Map section of an asymmetric foliation boudin field from the Two Lights exposures in the Cape Elizabeth area showing the scale and distribution of forward-rotating vein partings in dextral shear with clockwise rotation, sinistral slip and swordtail terminations. Note the variable orientations due to the intermittent initiation of orthogonal veins during shear, and the cross-cutting relations where younger higher-angle veins offset older lower-angle veins.

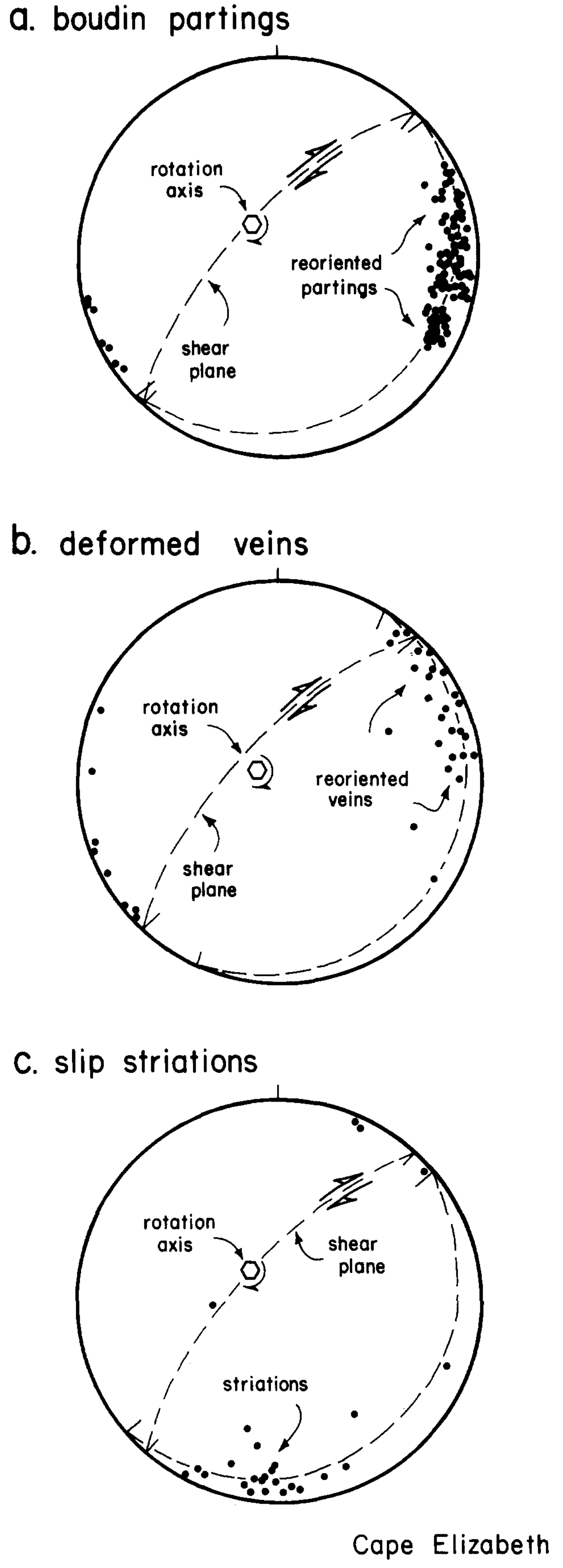

Fig. 13. Structural data from the Cape Elizabeth area showing great-circle distributions of: (a) poles to early quartz-filled boudin partings indicating clockwise rotation about a near-vertical kinematic rotation axis; (b) poles to deformed quartz–calcite vein segments reoriented in dextral shear; and (c) sinistral slip striations on boudined quartz sheets reoriented during clockwise rotation by dextral shear.

oped and then modified by forward-rotation during layer-parallel dextral simple shear as a component of this transpressional deformation. These forward-rotated boudinage features are also found to develop in conjunction with backward-rotated shear-bands that cut the foliation and competent layers into asymmetric shear fracture boudinage. Any deformation model must account for the contemporaneous development of both systems of boudinage as well as for the intermittent initiation of orthogonal rather than oblique veins and boudin partings during shear.

Orthogonal vs oblique initial vein models

In shear zones in isotropic materials, extension veins form oblique to the shear zone boundaries (Ramsay & Huber 1983, p. 50). In the Casco Bay area, however, extension veins were intermittently developed orthogonal to the layer-parallel shear planes as indicated by the progressive deformation sequence observed in the

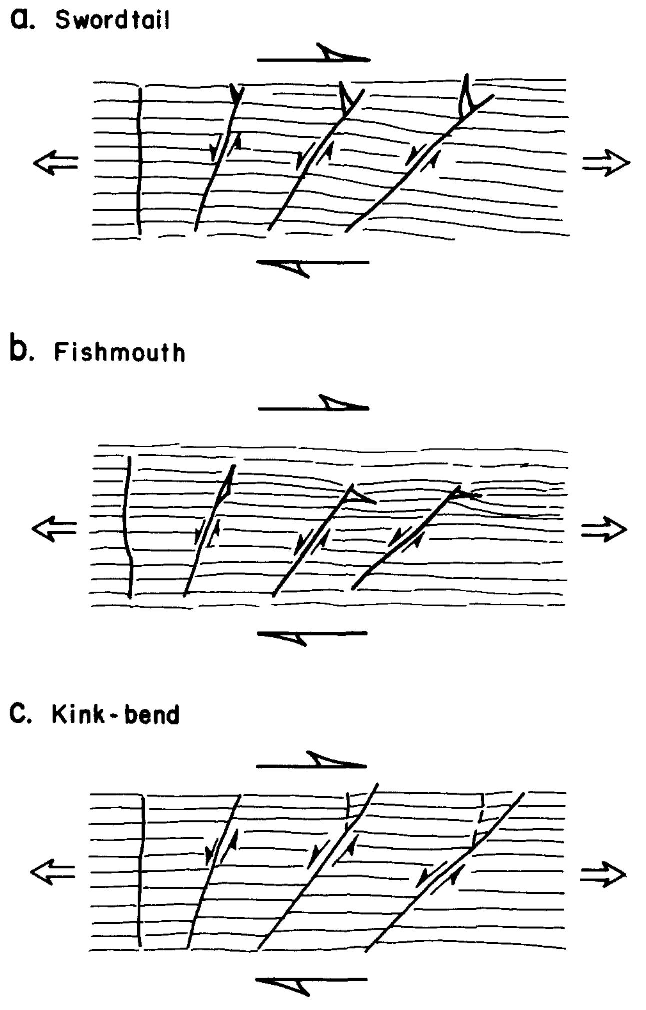

Fig. 14. Termination features on reoriented boudin parting surfaces found in the Cape Elizabeth area where fractures have suffered sinistral slip while undergoing clockwise rotation (left to right) within a dextral strike-slip shear couple. (a) Oblique gash vein on extensional side of fracture tip to form swordtail tension-fracture termination. (b) Collapse of contractional side of fracture tip to form fishmouth termination. (c) Kink-band termination on the extensional side of the fracture tip. Only single terminations are shown for graphical convenience.

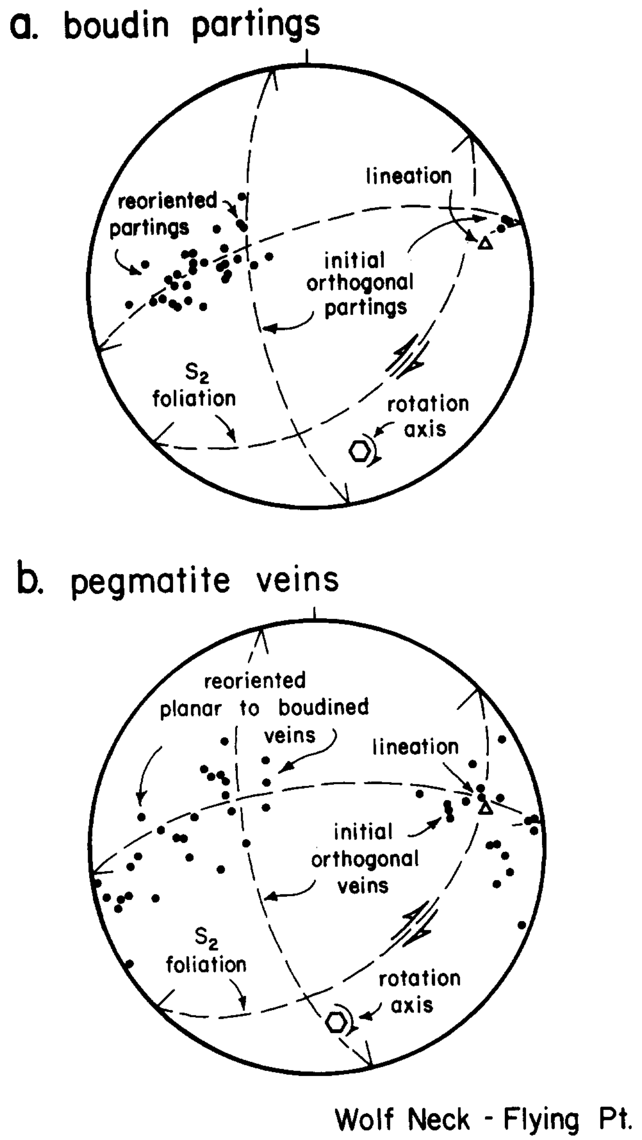

Fig. 15. Structural data from the Wolf Neck–Flying Point area showing: (a) a great-circle distribution of poles to quartz-filled boudin partings, indicating clockwise reorientation during dextral shear about a kinematic rotation axis constrained within the inclined foliation and perpendicular to the local elongation direction, and (b) similar reorientation of initially planar pegmatite veins orthogonal to the local elongation direction to deformed boudinaged pegmatite layers concordant to the foliation due to dextral shear with the kinematic rotation pole constrained within the inclined foliation.

Two Lights exposures, where the youngest undeformed veins are in this orthogonal orientation. The modification and continued growth of initially oblique veins in shear zones result in generally sigmoidal configurations, often with an initial phase of vein-parallel shortening prior to later elongation and boudinage (Maher 1987). The veins and boudin parting surfaces described from these exposures are clearly not the same, being derived from initially orthogonal fracture orientations which do not exhibit an early phase of vein-parallel shortening. Similar interpretations for the initially orthogonal orientation for boudin parting surfaces have also been reported by Hanmer (1984, 1986) and Malavieille & Lacassin (1988). Malavieille & Lacassin (1988) also incorporated the intermittent development of these orthogonal partings into their non-coaxial progressive deformation model.

The orthogonal initial orientation may be attributed to the influence of anisotropy in these deformed rocks and suggests a channelizing effect on the principal stress directions. However, the contemporaneous development of both layer-parallel shear and layer-parallel extension in the same layer does require a change or fluctuation in the orientation and magnitude of the principal stresses during the deformation.

Role of fluctuating fluid pressure

Repeated orthogonal extensional fracturing and quartz mineralization during regional shearing suggest an origin related to fluctuations in fluid pressure and tectonic stresses characteristic of the seismic faulting cycle. Transient high fluid pressures needed to trigger repeated tensional failure may be attributed to a tectonic origin through repeated cycles of dilatancy collapse following release of stored strain along nearby strike-slip faults. The clear spatial and temporal association of quartz vein arrays, ductile shearing and brittle pseudotachylyte-bearing cataclastic faults in the Two Lights exposures (Swanson in press) forms the basis of this preliminary seismo-structural model suggesting a prominent role for fluid pressure in, at least, the post-seismic period of this deformation cycle.

Periodic increases in fluid pressure associated with dilatancy collapse (Sibson *et al.* 1975, Sibson 1981, 1989) reduce the effective confining pressure (Phillips 1972) and, under little differential stress, will yield tensional, rather than shear failure, a likely condition for post-seismic periods adjacent to faults. These transient fluid pressures generated by post-seismic dilatancy collapse would result in the intermittent formation of symmetric foliation-boudin partings and planar quartz veins reflecting residual post-seismic stress configurations under little remaining differential stress. This would be related to the cyclic release of shear stress along the numerous fault splays throughout the Casco Bay area as part of the regional Norumbega–Nonesuch River fault system. Under regional transpression associated with the regional fault system this cyclic post-seismic stress configuration would be controlled by the layer-anisotropy and the coaxial component of the progressive deformation. This is the interpreted origin for the intermittent initiation of orthogonal boudin partings and quartz veins throughout the non-coaxial progressive deformation in these exposures.

Simulation in a simple shear machine

The style of deformation seen in these exposures can be effectively modelled using a card-deck simple-shear machine, similar to that used by Hanmer (1986) and Goldstein (1988). Such a device effectively distributes the simple shear deformation throughout a clay-cake specimen. The hand-driven device used in this study deforms a 50 × 25 cm clay cake, 2.5 cm thick, under simple shear and develops shear strains of ~1.2 during a single deformation cycle (Fig. 16). Higher strains are possible if the deformed block is removed from the box and reset within the initial configuration for a continued cycle of shear. It is designed to simulate the modification of initial extensional structures under dextral simple shear similar to model studies by Hudleston (1989) of veins in shear zones, but with orthogonal (as observed in these exposures) rather than oblique initial fractures.

Fractures, representing initial boudin parting surfaces were introduced (Fig. 16a) as cuts orthogonal to the overall shear direction to reflect the intermittent development of layer-parallel or hinge-parallel elongation. Once introduced, these fractures begin to rotate clock-

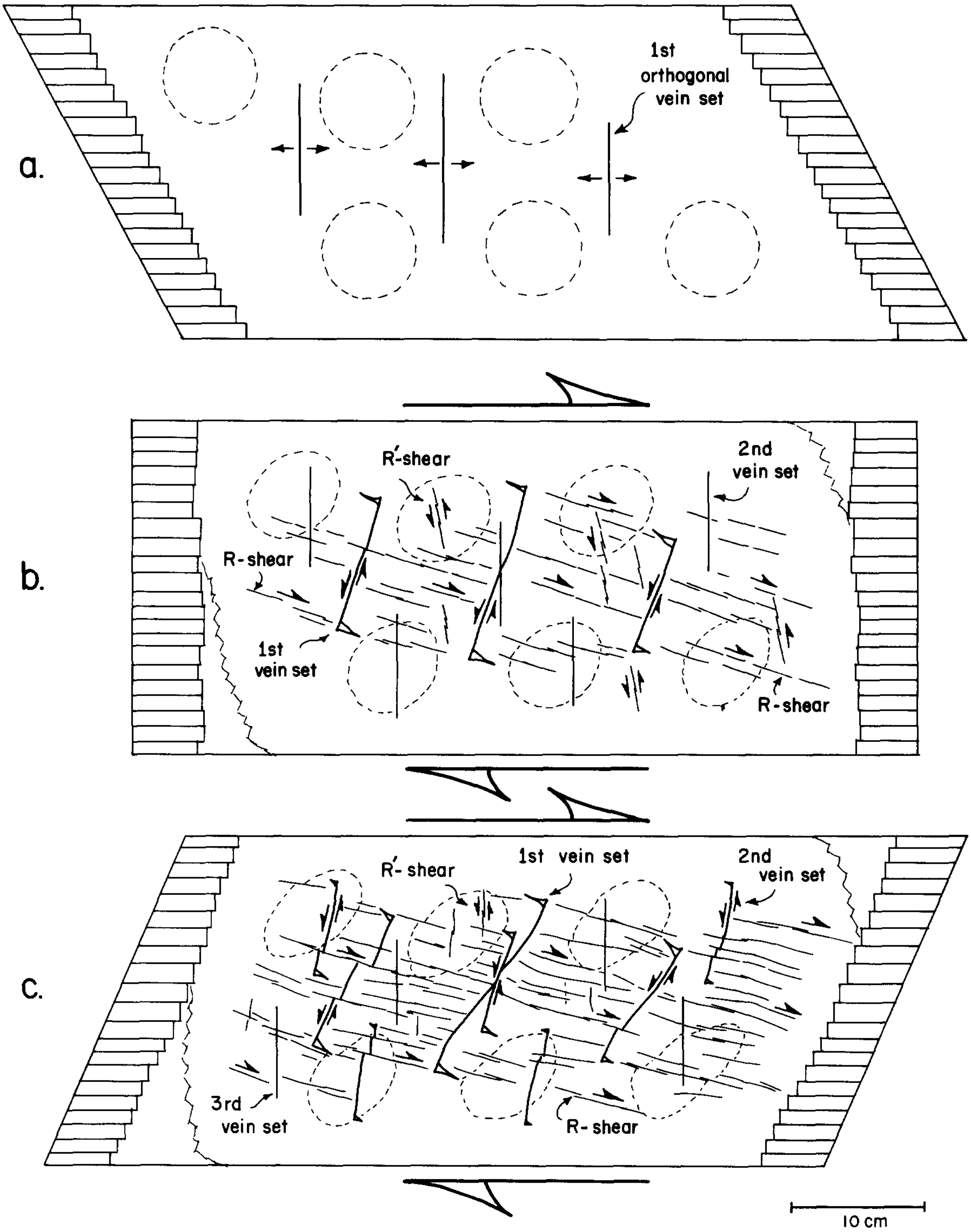

Fig. 16. Dextral deformation of a clay cake in a simple shear machine. (a) Initiation of a first vein set orthogonal to the overall shear direction reflecting intermittent elongation parallel to the shear plane. (b) Deformed first vein set after shear strain of ~0.6 with clockwise rotation, induced sinistral slip and tension gash terminations, as well as the development of an oblique dextral shear-band fabric (as *R*-shears) initiated at ~15° to the shear zone boundaries. A second undeformed vein set has initiated orthogonal to the overall shear direction, reflecting intermittent elongation parallel to the shear plane. (c) Deformed vein sets after shear strain of ~1.2 with clockwise rotation and sinistral slip, where the first vein set has suffered more angular shear and is cross-cut by the second, less deformed, vein set with sinistral offsets. The initiation of a third undeformed orthogonal vein set reflects intermittent elongation parallel to the shear plane.

wise under the imposed dextral simple shear (Fig. 16b). Sinistral slip along the fracture surfaces accompanies the rotation along with the development of distinctive oblique tears on the extensional side of the fracture tips similar to the swordtail termination structures. Successive sets of fractures (Fig. 16c) designed to simulate periodic stress fluctuations show lesser degrees of reorientation and induced sinistral slip reflecting their shorter duration in the developing strain field. Cross-cutting relations show the younger fracture sets as the active deformation mechanism with the older sets becoming inactive.

Deformation is also accompanied by the development of a prominent oblique dextral shear-band fabric (Figs. 16b & c) made up of small individual slip surfaces (R-shears), less than 1 cm in length initiated at ~15° to the shear zone boundaries. These shear-band surfaces were also found to increase in number, grow in length to several centimeters and suffer slight backward-rotation to ~8–12° before decoupling with progressive shearing (Fig. 16c). Minor sinistral R'-shears also developed (Figs. 16b & c) at ~75° to the shear zone boundaries in a conjugate relationship to the lower-angle R-shear fabric elements and suffer forward-rotation during the deformation. These R'-shears are similar to the NW-trending sinistral kink bands described above from the Casco Bay area.

These relatively simple experiments clearly demonstrate the formation of the forward-rotated boudin parting surfaces with their induced sinistral slip during rotation and the contemporaneous development of the oblique dextral shear band fabric. The successive initiation of populations of orthogonal fractures and their subsequent reorientation in response to the regional strain field can be shown to clock the accumulation of finite shear strain during progressive deformation.

DISCUSSION

Kinematic significance

Shear criteria on the meso- and micro-scales are now well defined for mylonitic shear zones (White *et al.* 1980, Simpson & Schmid 1983, Lister & Snoke 1984). Asymmetric boudinage in metamorphic rocks that have suffered more distributed ductile and brittle–ductile deformation can also be used as kinematic indicators (see Hanmer 1986) for determining the sense of shear during regional deformation. The use of asymmetric boudinage as a kinematic indicator in these exposures involves the recognition of essentially two distinct configurations; the forward-rotated orthogonal vein geometry as extension fracture boudinage (Fig. 1a) and the backward-rotated oblique shear-band geometry as shear fracture boudinage (Fig. 1b). Forward-rotated extension fracture boudinage has been described by Hanmer (1984, 1986), Mawer (1987) and Malavieille & Lacassin (1988) while backward-rotated shear fracture boudinage has been described by Hanmer (1984, 1986, Gaudemer & Tapponier (1987), Malavieille (1987), Marcoux *et al.* (1987), Mawer (1987) and Jordan (1991). Oblique shear band fabrics (White *et al.* 1980, Weijermars & Rondeel 1984, Behrmann 1987, Weijermars 1987) related to shear fracture boudinage can be attributed to non-coaxial progressive deformation most often associated with transpression. The potential ambiguity in the shear sense interpretation of asymmetric boudinage (Hanmer 1984, Goldstein 1988, Jordan 1991) may be avoided, at least in these exposures, with the recognition that the forward-rotated, antithetic shear planes in the modified extension fracture boudinage are typically mineralized and suffer vein-parallel elongation in contrast to the barren, backward-rotated, synthetic shear planes in the asymmetric shear fracture boudinage.

The contemporaneous development of both systems of boudinage in the Maine exposures described here has left a unique record of progressive non-coaxial deformation in the brittle–ductile regime. Based on the observed systems of asymmetries, this progressive deformation clearly contains a significant component of dextral strike-slip.

Sequence of boudinage types with progressive strain

The progressive deformation in these exposures illustrates the initiation, modification and final evolved geometries of the typical quartz vein boudinage (Fig. 17) found throughout the coastal Maine area. The larger meso-scale symmetric extension fracture boudinage of the foliation is defined by quartz-filled partings and larger planar veins orthogonal to the regional elongation direction (Fig. 17a). Modification of these symmetric veins by dextral shear along the foliation induces clockwise rotation, sinistral slip (Fig. 17b) and vein-parallel elongation during shear (Fig. 17c) to develop the meso-scale forward-rotated asymmetric foliation boudinage. The planar veins that fill the initial partings themselves respond to the vein-parallel elongation during rotation with the development of a second-order boudinage.

This second-order boudinage develops its own style of forward-rotated extension fractures with resolved dextral shear stress along the veins as well as backward-rotated asymmetric shear fractures through the interaction with oblique dextral shear-bands (Fig. 17d). Continued elongation and forward-rotation of the boudin string to near-parallelism (but still slightly oblique) with the F_2 limb layering along with backward-rotation of the shear-band surfaces will eventually lead to significant boudin separation (Fig. 17e) with the asymmetric tails and stair-step geometries commonly seen in these exposures.

Strain estimates

Using the progressive reorientation of initially orthogonal fracture surfaces during simple shear as a guide to the accumulation of finite strain, minimum shear strain estimates can be made for these exposures (Fig. 18). This assumes that the coaxial component of the defor-

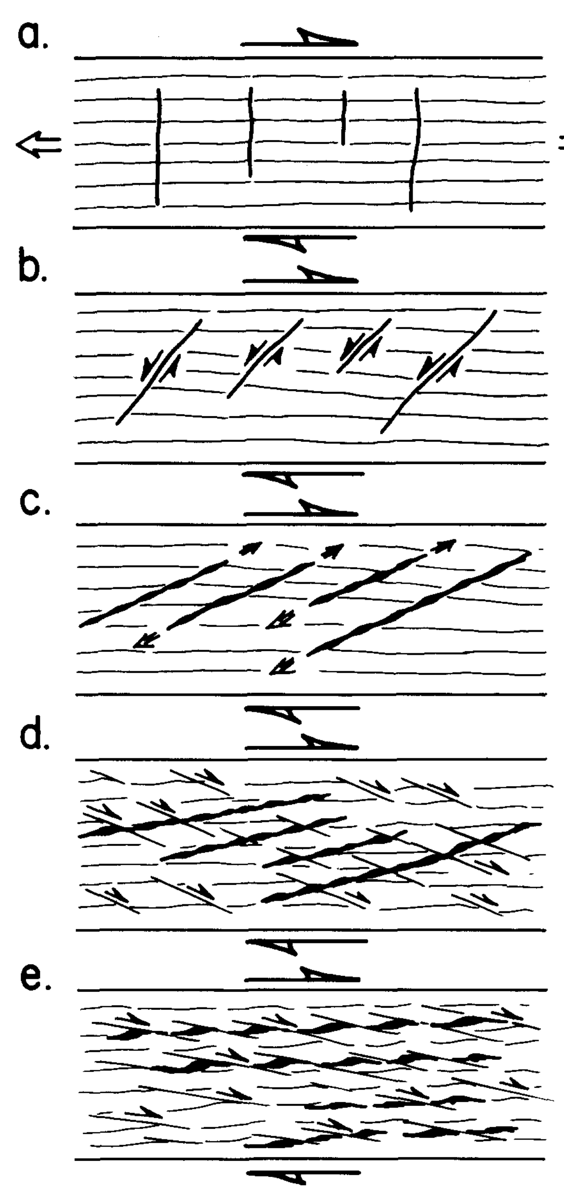

Fig. 17. Synopsis of Two Lights progressive deformation depicted in an evolutionary sequence of boudinage types. (a) Initial orthogonal vein partings as symmetric extension fracture boudinage reflecting intermittent layer-parallel elongation. (b) Clockwise rotation with sinistral slip as asymmetric forward-rotating boudinage under layer-parallel dextral shear. (c) Vein-parallel elongation during continued clockwise rotation. (d) Development of oblique dextral shear-band fabric. (e) Cross-cutting dextral shear bands produce strings of asymmetric backward-rotating quartz vein boudins at low angles to the layer-parallel shear plane.

mation contributed relatively little to the reorientation of the quartz veins and parting surfaces, a valid assumption considering the dominant dextral shear structures in these exposures. Estimation of this non-coaxial strain component is important as it indicates the magnitude of the strike-slip component of the regional ductile deformation.

Using the initial and final orientations for the oldest, most deformed veins at the lowest angles to the layer-parallel or hinge-parallel shear planes, the corresponding shear strain can be calculated using equations from Ramsay & Graham (1970) for the reorientation of lines in simple shear. The initial orthogonal orientation of the quartz veins in the Maine exposures relative to the shear direction reduces the equations to a simple calculation of shear strain, γ, from measured angular shear in the field (Fig. 18). Similar strain estimate techniques were used by Strayer *et al.* (1989) based on the reorientation of cross-cutting dikes and pegmatites in a deep crustal mylonite zone, again assuming a simple shear model.

The orientations of the oldest, most deformed quartz veins in these exposures relative to the layer-parallel or hinge-parallel shear direction range from ~22° in the Cushing Formation at Ft. Williams, to ~12° in the Cape Elizabeth Formation at Two Lights, to only a few degrees at Harpswell Neck. These orientations correspond to shear strains of ~2.5 (Cushing Formation), ~4.7 (Cape Elizabeth Formation) and ~10 (Harpswell Neck). Even lower-angle strings of quartz boudins in these exposures can be found, some nearly parallel to the layer-parallel shear planes, with even higher strains accommodated within the main parts of the ductile shear zones. This, then, is still only a conservative estimate of total angular shear strain in these exposures. For comparison, shear strains have been estimated at greater than ~15 for the development of banded mylonitic gneisses (Fossen & Rykkelid 1990) and greater than ~20 for refolding of mylonitic foliation (Skjernaa 1980).

If conservative shear strain estimates of ~5 for the Two Lights area are distributed over the 60 m width of these exposures it would represent ~300 m of previously unrecognized right-lateral ductile shear displacement. Although the regional distribution of these asymmetric

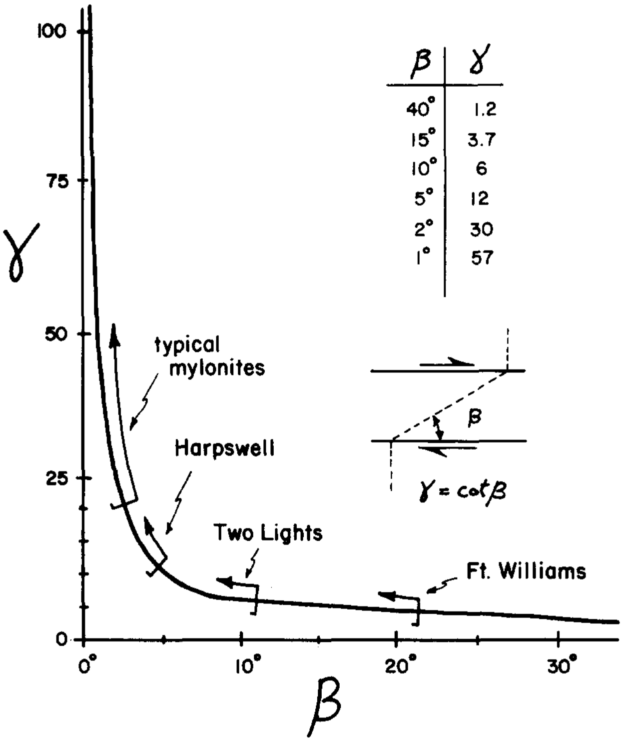

Fig. 18. Shear strain estimates, using Ramsay & Graham (1970) equations for initial orientations where cot $\beta = 0$, plotted on a shear strain, γ/β angle curve for reoriented veins and boudin partings in dextral simple shear from the Cape Elizabeth area (Two Lights and Fort Williams localities) and the Harpswell Neck area discussed in the text. Range for typical mylonites from Skjernaa (1980) and Fossen & Rykkelid (1990) included for comparison.

structures is not well known, they do appear to be ubiquitous throughout the Casco Bay area. If one assumes a relatively homogeneous distribution as a first order approximation throughout the exposed ~30 km width of the Casco Bay lithologies, a *rough* estimate of regional shear strain can be made. The conservative shear strain estimates made above would translate into ~150 km of ductile dextral strike-slip shearing. These order-of-magnitude strain estimates for ductile dextral shear indicate the importance and general magnitude of orogen-parallel shearing in the regional deformation of this area.

Tectonic implications

Kinematically, this assemblage of asymmetric boudinage structures reflects the development of significant NE-trending dextral strike-slip movement parallel to the regional F_2 hinge zones throughout the Casco Bay area. The distributed ductile dextral shear strain preserved within the rocks of the Casco Bay area has not been previously recognized and its implications have yet to be explored. Variable strain-related textural modifications, necking of competent units or entire formations resulting in out-of-sequence stratigraphic contacts (Swanson *et al.* 1986) and considerable along-strike translation of lithologic units related to this dextral shearing, for example, would be important considerations in any regional stratigraphic correlation.

Hinge-parallel elongation and orogen-parallel dextral shearing have never been considered in any structural or tectonic models (Bradley 1983, Hussey 1988, Osberg *et al.* 1989) for this part of the Northern Appalachians. Other tectonic areas world-wide that are typified by similar strong orogen-parallel, and fold hinge-parallel, ductile stretching lineations have also recently been interpreted or re-interpreted in terms of a significant orogen-parallel strike-slip component to the regional deformation (Gates 1987, Gates *et al.* 1988, Hudleston *et al.* 1988, Brown & Talbot 1989, Hansen 1989, Rajlich 1990). This type of deformation, with components of layer-normal shortening, layer-parallel elongation and layer-parallel simple shear is characteristic of transpressional orogens (Harland 1971, Sanderson & Marchini 1984). Alleghenian transpressional deformation, for example, has been recognized in the Southern Appalachians (Gates 1987, Gates *et al.* 1988) and in the Maritime Appalachians (Nance *et al.* 1988, Keppie 1989). Several suggestions have also been made in recent years that the development of dextral Acadian transpression in New England (Bradley 1988, Ferrill & Thomas 1988) may be due to oblique convergence but, so far, significant structural documentation has been lacking.

The recognition of a significant component of dextral strike-slip movement distributed throughout the rocks of the Casco Bay area as part of a regional transpressional deformation, then, has serious implications for tectonic modelling of the Acadian orogeny in northern New England and its relationship to Alleghenian deformation, particularly within the Coastal Lithotectonic Block in Maine. The orientation and distribution of major F_2 folds, strong hinge-parallel elongation and dextral shear in the Casco Bay area (Fig. 19) suggest a genetic relationship with the regional dextral strike-slip Norumbega–Nonesuch River fault system. Upright folds such as these F_2 structures are commonly developed oblique to regional strike-slip faults (Sylvester 1988) and can exhibit boudinage due to hinge-parallel elongation (Bürgmann 1989) particularly in transpressional regimes. The Casco Bay area also shows an apparent restraining bend in the mapped regional fault trace (see Osberg *et al.* 1985) with the development of numerous fault splays. Deformation related to dextral transpression along the fault (Fig. 19) and at this restraining bend is thought to have triggered the intense hinge-parallel elongation, dextral shearing and related asymmetric boudinage described in this report. This orogen-parallel strike-slip motion apparently developed as a wide zone of post-collisional ductile shearing, with later strain localization along segments of the regional fault system. The structures described here, then, appear to represent a progressive deformation that began with Mid- to Late Devonian synmetamorphic ductile shearing along with the formation of oblique F_2 folds during the Late Acadian orogeny. Dextral shearing continued through the later Paleozoic Alleghenian deformation to produce the overall pattern of hinge-parallel elongation and asymmetric boudinage associated with the regional dextral strike-slip fault system.

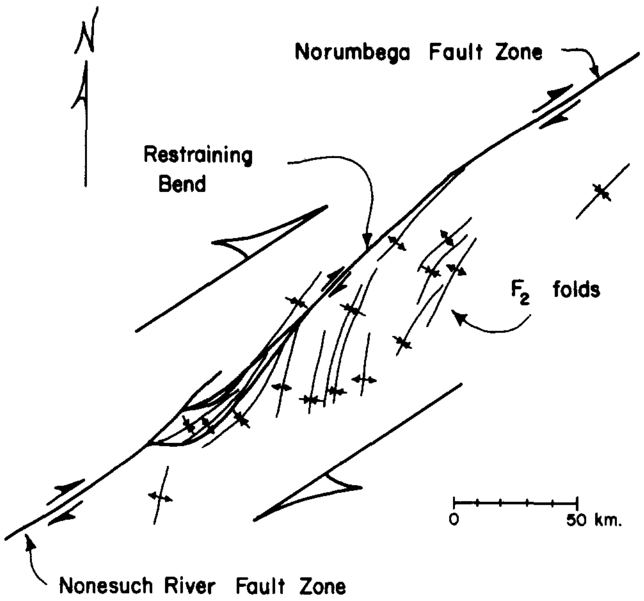

Fig. 19. Tectonic framework for the development of the oblique F_2 folds with axial stretching, boudinage and hinge-parallel ductile dextral strike-slip simple shear in association with a restraining bend in the Casco Bay area of the Norumbega–Nonesuch River fault system (modified after Osberg *et al.* 1985).

CONCLUSIONS

The examination of meso-scale structures in rocks of the Casco Bay area of coastal Maine has shown the development of asymmetric boudinage features which can be used as important kinematic indicators for regional non-coaxial deformation. Boudin partings and related quartz veins were intermittently generated orthogonal to the layer-parallel and fold hinge-parallel shear planes reflecting elongation along the regional horizontal stretching lineation. This is attributed to fault-related fluctuations in fluid pressure and tectonic stresses. These initially symmetric structures were then modified by forward rotation, sinistral slip and vein-parallel elongation through layer-parallel dextral strike-slip shearing.

The hinge-parallel elongation and dextral shear in these exposures is most likely related to dextral transpression along the regional Norumbega–Nonesuch River fault system and focused at a restraining bend in the Casco Bay area. Such a tectonic model is important for understanding the nature of the Acadian orogeny and subsequent Alleghenian deformation by recognizing a significant component of orogen-parallel shearing in relation to a regional strike-slip fault system in this part of the New England Appalachians.

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