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Evolution of a transcurrent fault system in shallow crustal metasedimentary rocks: the Norumbega fault zone, eastern Maine

ALLAN LUDMAN

Department of Geology, Queens College, Flushing, NY 11367, U.S.A. and Earth and Environmental Sciences Program, CUNY Graduate School, 365 Fifth Avenue, New York, U.S.A.

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Abstract—Differential exhumation in Maine exposes nearly half of the crustal profile of the Norumbega fault zone (NFZ), a major transcurrent fault zone of the Northern Appalachians. A large exposure of turbidites in eastern Maine records a multi-stage deformation history that provides insight into the epizonal evolution of the NFZ. Early deformation (Stage 1) involved episodic bed-parallel faulting with fluids playing a progressively smaller role. Strain was broadly distributed at the exposure but was localized by lithic anisotropy in pelitic layers. Little Stage 1 deformation occurred in the dominant wacke beds (by diffusive mass transfer); most took place in subordinate pelitic horizons by combined diffusive mass transfer and crystal plastic mechanisms. Later (Stage 2) activity was almost entirely brittle, producing isolated NE-trending faults and two deformation zones filled with cataclasite. The latter comprise complexly anastomosing fault strands with multiple slickenline generations indicating episodic faulting.

Regional-scale NFZ structures and history mirror those at outcrop scale. Late brittle faulting was superimposed on a broad region that had experienced largely ductile shearing, and the regional-scale brittle deformation was concentrated in three deformation zones characterized by anastomosing fault strands. It is the Stage 2 features that are mapped elsewhere in the Northern Appalachians as the Norumbega fault zone. © 1998 Elsevier Science Ltd.

INTRODUCTION

Attempts to understand regional-scale fault systems are commonly thwarted by the differences between their scale and complexity and those of the local and experimental studies from which much of our knowledge of faulting is derived. For example, fault systems in the relatively cold upper crust are characterized by low strain rates, but rates in laboratory studies must be many orders of magnitude faster in order to yield observable results, so experimentalists use high temperatures or easily deformed organic materials to obtain them. Regional-scale faults may transect a wide variety of lithologies with pre-existing or developing anisotropy (e.g. bedding, foliation, *S–C* fabrics), but experiments generally use homogeneous monomineralic or simple bimineralic media to reduce the number of experimental variables (e.g. Tullis and Yund, 1985, 1991). Similarly, local fault studies typically focus on homogeneous material such as granite (Gapais and Barbarin, 1986) or quartzite (Ord and Christie, 1984). High-angle faults pose another problem because they can span several crustal levels and different sets of conditions. Thus, shallow and deep segments of a single fault should yield very different information on timing, deformation mechanics, and the roles of fluids, phyllosilicates, and lithic anisotropy.

The Norumbega fault zone (NFZ) of the Northern Appalachians exemplifies this problem. It is a regional-scale strike-slip fault system (Fig. 1a), some of whose fault strands were shown by a seismic reflection profile to penetrate the entire crust steeply, cutting and displacing the Moho (Doll *et al.*, 1996). Differential erosion in Maine exposes the upper half of the NFZ (Fig. 1b) and allows comparison between its upper and mid-crustal levels.

This paper focuses on deformation of low-grade metasedimentary rocks in the Kellyland fault zone (KFZ), a hitherto undescribed upper-crustal strand of the NFZ in eastern Maine for which conditions during deformation are well constrained. The nature of the KFZ in the epizonal Deblois granite on strike to the southwest (Fig. 2) is described by Ludman and Gibbons (in press) and is summarized briefly below to compile the full KFZ history.

Methods

Part of the KFZ is spectacularly exposed in metasedimentary rocks below the Grand Falls of the St. Croix River at Kellyland (Fig. 2). Approximately 5500 m^2 of this exposure were mapped at a scale of 1:120 by plane table and alidade, and the geometry, mechanics, and sequence of faulting compared with regional-scale features to construct a model for the upper crustal portion of the NFZ. Nearly 200 oriented thin sections of the KFZ and adjacent strands of the NFZ were studied to determine deformation mechanics and sequence and sense of displacement.

REGIONAL SETTING

The Norumbega fault zone (NFZ) is one of the major fault systems of the Northern Appalachians. It extends at least 400 km from southern Maine to west-central New Brunswick, and possibly as much as 1200 km from

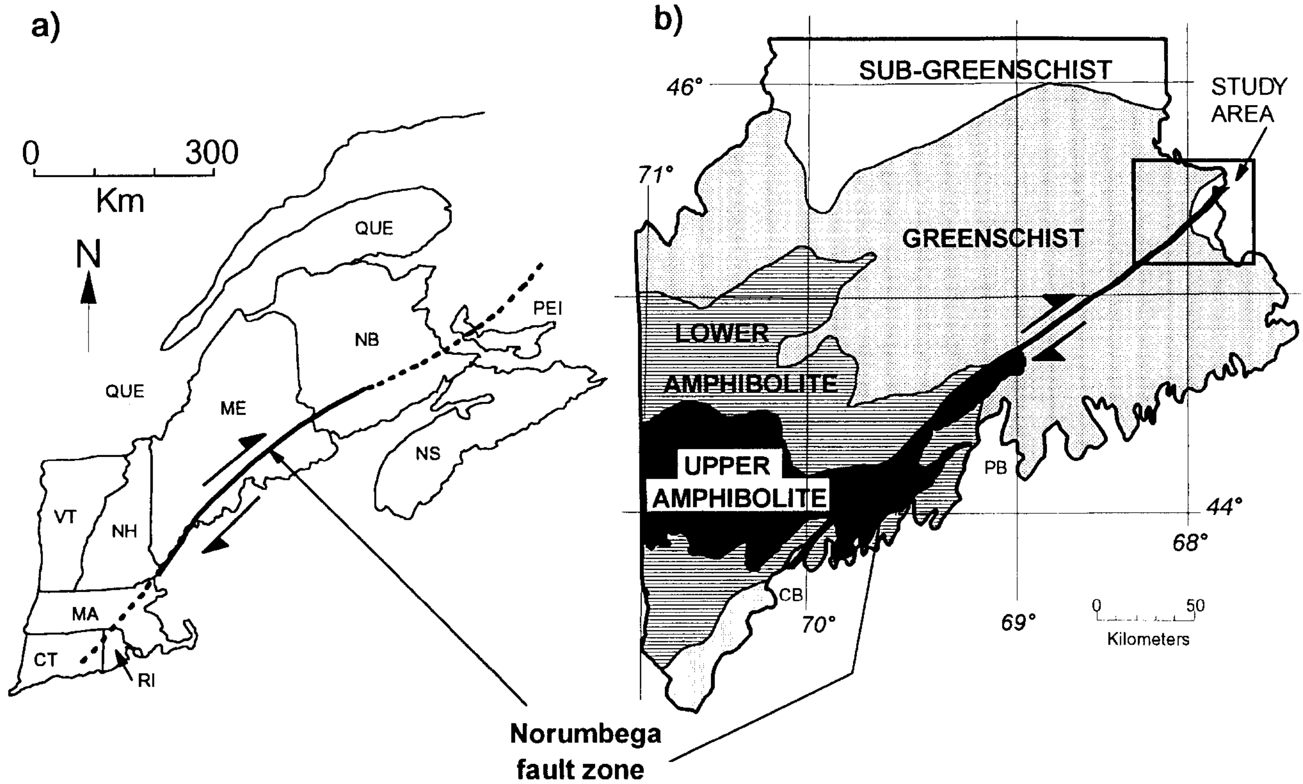

Fig. 1. Extent and metamorphic setting of the Norumbega fault zone. (a) Extent of the Norumbega fault zone in the Northern and Maritime Appalachians. Solid line = continuously mapped NFZ in Maine and New Brunswick (after Osberg *et al.*, 1985; McLeod *et al.*, 1994); dashed lines = inferred extensions into southern New England, New Brunswick, and the Gulf of St. Lawrence. (b) Regional metamorphic grade of rocks hosting the Norumbega fault zone in Maine (after Guidotti, 1985). Rectangle outlines area covered in this paper. PB = Penobscot Bay; CB = Casco Bay.

Connecticut to the Gulf of St. Lawrence (Fig. 1a), a distance comparable to the onshore length of the San Andreas fault zone. First described as a single fault in south-central Maine by Stewart and Wones (1974), the Norumbega *fault system* is now known to comprise numerous anastomosing faults and shear zones that span a width of at least 30 km in southwestern Maine (Swanson, 1992, 1994; Swanson and Carrigan, 1984), 25 km in south-central Maine (Newberg, 1986; Hussey *et al.*, 1986; West, 1993), and 35–40 km in easternmost Maine (this study). The NFZ possibly narrows to 5–10 km where it cuts large granitic plutons in east-central Maine (Hubbard *et al.*, 1995), but this may reflect the reconnaissance nature of mapping in that area. In eastern Maine, strain was concentrated in three 2–5 km wide brittle deformation zones (the Codyville, Waite, and Kellyland fault zones) separated by broad areas of much lower, inhomogeneously distributed strain (Fig. 2).

Differential exhumation along the NFZ exposes progressively shallower crustal levels from southwest to northeast (Fig. 1b), and faulting was coeval along the entire length of the system in Maine during the middle and late Paleozoic (Hubbard *et al.*, 1995; West, in press; Ludman *et al.*, in press). Previous detailed studies of the NFZ were restricted to south-central Maine, where amphibolite facies assemblages and ductile shear fabrics indicate mid-crustal faulting during or immediately after peak early Devonian regional metamorphism (Swanson, 1992; Hussey *et al.*, 1986; West, 1993). Until now, there have been no studies in the higher structural levels exposed in eastern Maine. This paper fills that gap by describing NFZ faulting at the Maine–New Brunswick border where faulting occurred at shallow crustal levels following very low-grade regional metamorphism and emplacement of large granite plutons (Ludman, 1991).

Eastern Maine and adjacent New Brunswick are underlain by a series of NE-trending lithotectonic belts containing rocks of Cambrian(?) through Early Devonian age (Fig. 2 inset; Ludman, 1986; Ludman and Hill, 1986; Ludman *et al.*, 1993; Fyffe *et al.*, 1988). In easternmost Maine, the NFZ is contained almost entirely within the late Ordovician–middle Silurian(?) Flume Ridge Formation of the Fredericton belt, although the northernmost NFZ fault zone (Codyville) separates the Fredericton and Miramichi belts. The Fredericton strata were tightly folded during mid-late Silurian times (West *et al.*, 1992) and intruded west of the study area by Devonian granites of the Bottle Lake complex and Deblois pluton, both of which are cut by the NFZ (Fig. 2). The Silurian (West *et al.*, 1992) Pocomoonshine gabbro–diorite intrudes the southern part of the Fredericton Belt and is also deformed by the NFZ. Lower and regional metamorphic grades characterize eastern Maine, regardless of the age or structural complexity of

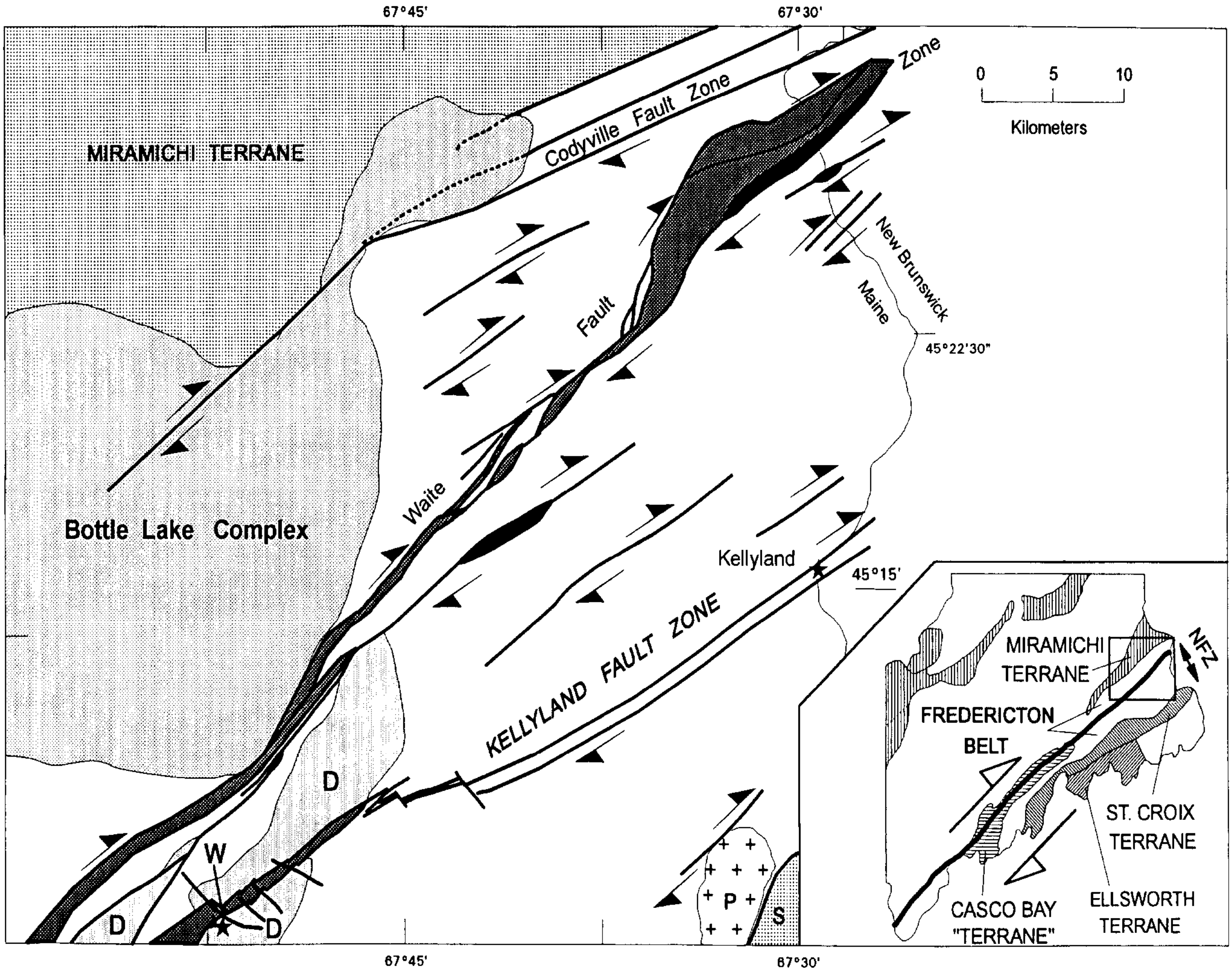

Fig. 2. Geologic setting of the Norumbega fault zone in eastern Maine. Inset shows lithotectonic framework of southern Maine and schematic representation of NFZ. Ruled patterns highlight pre-Silurian terranes. The NFZ is largely confined within the Fredericton belt. Simplified geologic map shows the three NFZ high-strain zones of eastern Maine and their relationships to major plutons. Black fill = post-Acadian (Pennsylvanian?) redbeds; dense stipple = mylonite in the Waite fault zone; white = Fredericton belt; gray fill = granitic rocks; + = mafic and intermediate rocks. S = St. Croix terrane, P = Pocomoonshine gabbro-diorite, D = Deblois pluton, W = Wabassus Mountain.

the strata (Guidotti, 1985). More intense metamorphism occurred only in contact aureoles surrounding the post-folding granites and gabbros (Ludman, 1986).

The Kellyland fault zone is the southernmost and, at this time, the best understood of the three NFZ deformation zones in eastern Maine. It is particularly well exposed in metasedimentary rocks below the Grand Falls of the St. Croix River at Kellyland, and in granite on Wabassus Mountain and adjacent hills, 50 km to the southwest along strike.

Physical conditions of faulting

Previous inferences of shallow-crustal conditions for KFZ and NFZ faulting in eastern Maine and adjacent New Brunswick (e.g. Hubbard *et al.*, 1995) are corroborated by this study and by Ludman's and Gibbons's (1995) examination of the KFZ in the Deblois pluton. Evidence concerning the role of fluids during faulting was obtained in this study and will be discussed below.

Lithostatic pressure. Lower greenschist and subgreenschist facies regional metamorphism in the Fredericton and adjacent belts in eastern Maine indicate burial to only shallow crustal levels from Cambrian through Carboniferous times, despite multiple orogenic pulses in Cambro–Ordovician (Penobscottian), middle Ordovician, mid–late Silurian, and Devonian (Acadian) times. Miarolitic cavities in the Devonian Bottle Lake and Lucerne plutons (Ayuso *et al.*, 1984; Wones and Ayuso, 1993) and contact metamorphic assemblages around the Deblois and Pocomoonshine plutons (Ludman *et al.*, 1989) constrain their emplacement to pressures of 150–250 MPa prior to the onset of NFZ faulting. All stages of KFZ faulting in eastern Maine thus occurred at depths no greater than 4–8 km, well above the brittle–ductile transition as described by Sibson (1982). This contrasts with the 400–500 MPa (13–17 km) estimated for initial faulting in the deeper NFZ segment in southwest Maine (West, 1995).

Temperature. The absence of regional metamorphic biotite from non-calcareous pelites in the Fredericton and adjacent belts constrains ambient temperatures prior to KFZ faulting to less than 350–400°C (Spear, 1993; Bucher and Frey, 1994). Biotite forms at even lower temperatures in ankerite-bearing metapelites and metawackes like those of the Flume Ridge Formation (Ludman, 1969; Spear, 1993), so that its absence suggests temperatures closer to 300°C. Comparable conditions were inferred for faulting in the Deblois granite from the contrasting ductile behavior of quartz and brittle behavior of microcline and albite (Ludman and Gibbons, 1995; in press). Initial deformation temperatures in the granite may have been as low as 275°C, based on deformation in quartz, microcline, and albite (J. Tullis, personal communication, 1996).

Lithic anisotropy. The KFZ at Kellyland is hosted by highly anisotropic metasedimentary rocks of the Flume Ridge Formation, a thick pile of fine to medium grained graywackes with subordinate siltstone, slate, and phyllite that was folded into near-vertical attitudes prior to KFZ faulting (Ludman, 1981, 1986, 1994). The wackes typically occur in massive beds from 25 cm to 3 m thick, but many grade into thin pelitic horizons, and some occur with pelite in thin, rhythmically alternating beds. Flume Ridge wackes make up most of the exposure ($\sim$85%) at Kellyland. They are variably calcareous (calcite $\pm$ ankerite) and contain abundant white mica and chlorite. Intercalated pelitic rocks were originally medium gray muscovite-rich shales or rusty-weathering black carbonaceous shales, but most have been converted to phyllonites during faulting. Bedding and more delicate primary features in the wacke such as cross-laminations and graded beds are well preserved.

THE KELLYLAND FAULT ZONE AT GRAND FALLS

About 85% of the Grand Falls exposure is underlain by chlorite-grade wackes with subordinate interbedded pelitic layers (ca. 14%). Felsite dikes, composite quartz–carbonate veins, quartz veins, and cataclasite amount to less than 1% of the outcrop but relationships among faults and these minor lithologies are the key to unraveling the detailed deformation sequence. The dikes and veins will therefore be described briefly here.

Eight small felsite dikes crop out at Grand Falls, seven in a swarm near the dam, the eighth near the northeastern limit of the mapped area. They are thin, ranging from 8 to 65 cm in width and, although partially dismembered by faults, are subparallel, trending slightly west of north. The felsites have been partially replaced by ferroan carbonate but thin sections reveal a cryptocrystalline aggregate of sutured quartz and feldspar typical of rhyolites and rhyodacites. The easternmost dike is homogeneous, but the others display a well-developed foliation defined by chlorite-rich patches where cut by some of the faults.

Two types of veins are present. Composite veins composed of coarse grained quartz and orange–brown weathering ferroan carbonate are the most abundant and occur in zones of massive metawacke in the western, central, and eastern parts of the map area. A few are zoned, with carbonate concentrated along vein/wacke contacts. Composite veins are 10–40 cm thick but typically pinch and swell where deformed by the faults. Fine grained quartz veins lacking carbonate are thinner (5 mm–5 cm) and less abundant volumetrically, but are found throughout the Grand Falls exposure. Cross-cutting relationships uniformly demonstrate that the quartz veins are younger than the composite veins.

All strata at Grand Falls strike within a few degrees of 020°and dip steeply to the northwest except in drag folds adjacent to faults. Graded beds and truncated cross-laminations indicate numerous facing reversals, revealing the presence of upright isoclinal folds. Figure 3 shows the distribution of faults identified during plane table mapping. For the sake of clarity, the attitude of bedding is indicated in Fig. 3 by only a few dotted reference lines.

Figure 4(a) summarizes the attitudes of more than 150 faults observed at Grand Falls, and Fig. 4(b) shows the attitudes of associated slickenlines. Most faults dip steeply and can be grouped into one of two major sets based on their trends. The most prominent set trends northeasterly (045–070°) and is shown by heavy solid lines in Fig. 3 and solid circles in Fig. 4. All observed faults of this group are depicted on Fig. 3 except for those too short to be mapped at that scale. Faults of the second set (thin solid lines in Fig. 3, solid diamonds in Fig. 4) are parallel to bedding (010–020°). These faults are found throughout the Grand Falls exposure and a few can be traced across most of the map area, but for clarity the bed-parallel faults are shown only where they visibly offset felsite dikes.

Northeast-trending faults

NE-trending faults are prominent at the Grand Falls outcrop, cutting beds, bed-parallel shear zones, dikes, and veins. These faults are filled with thin bands of fault rock ranging from fine-grained cataclasite to coarse fault breccia that are less resistant to erosion than unfaulted wacke. Differential weathering therefore gives them a pronounced topographic expression, reflecting at outcrop scale the regional lowland underlain by the KFZ, and highlighting the inhomogeneous distribution of this group of faults at Grand Falls.

Two subparallel brittle deformation zones, each containing numerous anastomosing fault strands, underlie

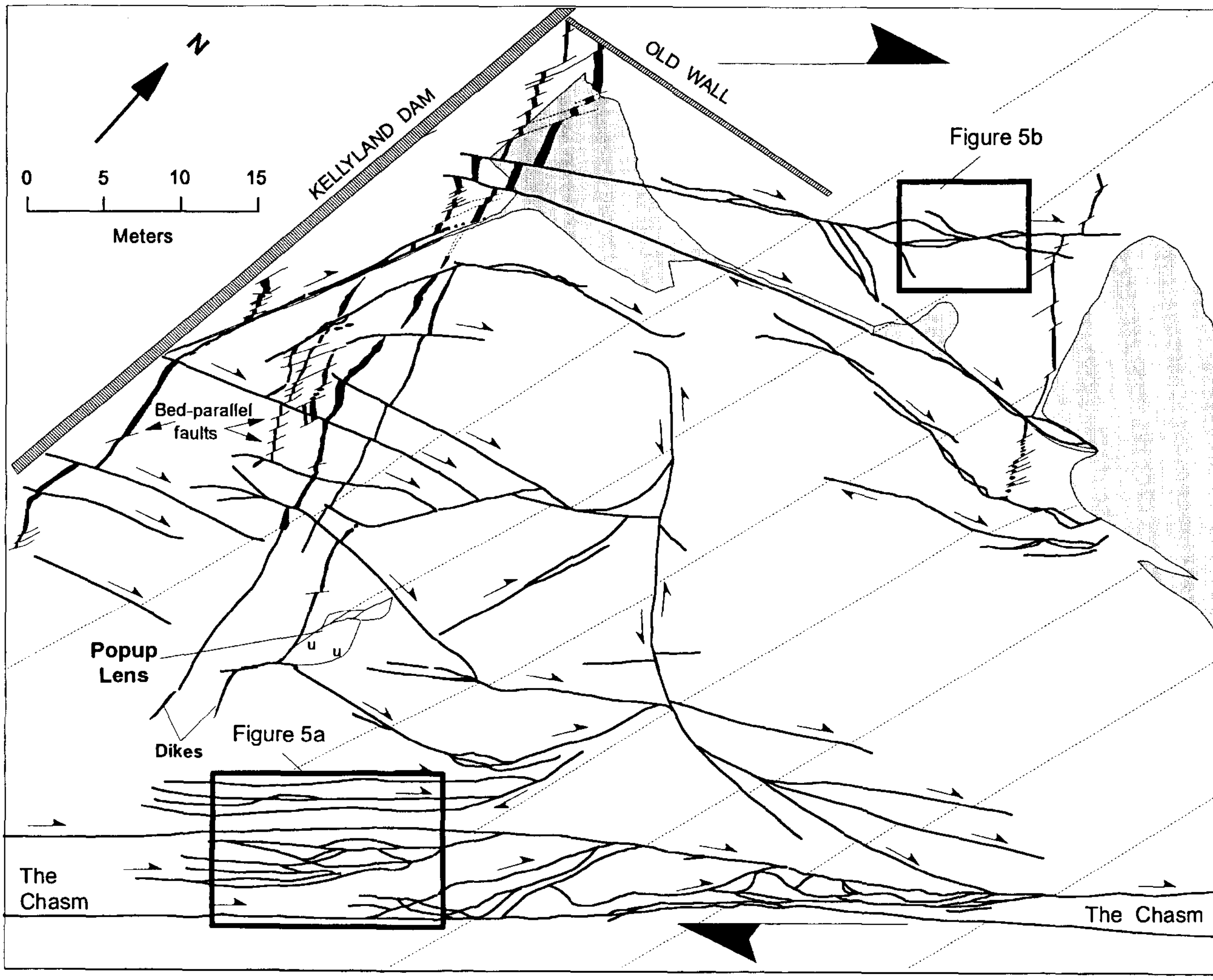

Fig. 3. Map of the Grand Falls exposure showing faults and dikes. Shading = pools of water below the dam. Dotted lines show schematic trace of bedding at exposure. Black fill = dikes; Heavy lines = NE-trending faults; Light lines = bed-parallel faults shown only where they offset dikes. All faults are dextral strike-slip unless otherwise indicated.

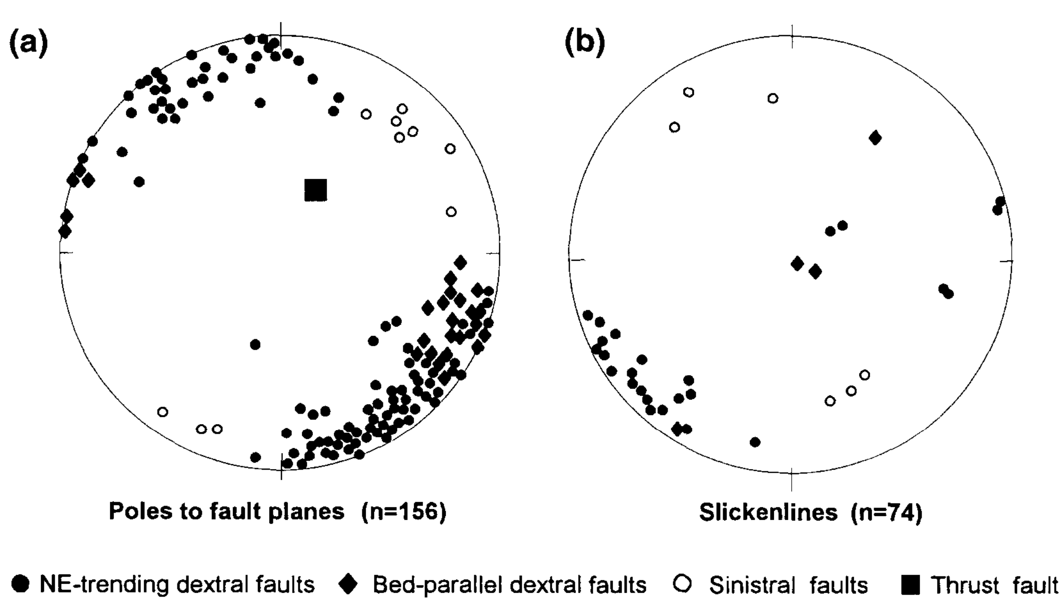

Fig. 4. Equal area stereonets (lower hemisphere) showing faults and slickenlines at Kellyland. (a) Poles to fault surfaces. (b) Slickenlines.

prominent NE-trending topographic lows at the exposure: a drainage channel in the northern part of the map area, and a large vertical-walled valley nearly 10 m wide and 8 m deep (the 'Chasm') at the southern edge (Fig. 3). These two relatively high strain zones are separated by a 45 m wide zone of weaker and more diffusely distributed strain in which narrow (1–5 cm) faults are spaced at approximately 3 m intervals. These isolated fault strands are also expressed topographically, as small erosional notches that cross bedding at moderate to high angles.

Several NE-trending faults can be traced across the entire study area, including some in the Chasm and a few of the isolated faults in the area of weaker strain. Others are short and either connect larger master faults or splay and terminate into areas of diffuse strain (Figs 3 & 5). Most NE-trending faults terminate along strike by splaying into horsetail terminations visible in both high-strain and distributed strain areas (Fig. 3, particularly at the west end of the Chasm). Some in the region of weaker strain, however, terminate by refracting into bed-parallel faults.

Faults in the region of weak strain are relatively straight for most of their length, curving slightly as they merge with larger-scale faults. Although the two high-strain zones are essentially linear in plan view, each comprises numerous curved fault strands that anastomose along strike to produce distinctive lensoid structures (Fig. 5). The Chasm provides enough relief to show that these strands anastomose vertically as well as along strike. This produces a 'tulip' structure (Fig. 6) made of lensoid masses somewhat longer (up to 4 m) parallel to strike than in their vertical dimension (up to 2 m). Similar but smaller lensoid structures occur in the smaller high-strain zone. Slickenlines associated with the NE-trending faults, including those on fault surfaces separating lenses in the tulip structure, are horizontal or plunge gently (Figs 4 & 6).

All earlier features are deformed into drag folds adjacent to the NE-trending faults, and the S-shaped folds shown in Fig. 5 are common where beds, bed-parallel shear zones, and groups of composite veins can be traced between two faults of this group. Beds and bed-parallel shear zones are dragged locally from attitudes at moderate angles to the NE-trending faults to subparallel orientations.

Fault motion and displacement. Ubiquitous drag folds and displaced beds, bed-parallel shear zones, and dikes all indicate dextral displacement along the NE-trending faults. Gently plunging slickenlines, abundant on polished fault surfaces, verify the dominantly strike-slip nature of fault motion. The few sinistral faults at Grand Falls are oriented NNW and are interpreted as antithetic R′ shears developed during this stage of faulting. Most occur in lenses in the two high-strain zones (Fig. 5a) and extend for only one or two meters before being truncated by or refracting into the dominant dextral faults. One prominent antithetic fault, however, dominates the central part of the map area (Fig. 3) and, like the Chasm, underlies a prominent steep-walled valley.

Dextral strike-slip displacement on the NE-trending faults can be measured directly from offset beds, dikes, and early composite veins. Offsets across individual strands in the zone of broadly distributed strain are typically small, ranging from a few centimeters to a meter. Offset of the most clearly defined marker horizons across the higher strain Chasm and drainage channel ranges from 3.3 to 3.7 m. Displacement:width values for faults in the zone of distributed strain, based on displacement of the dikes near the dam, range from 0.12 to 0.15, but d/w ratios for the higher-strain zones, based on stratigraphic displacement, are from 3.5 to 5 times greater (0.68–0.75 for the Chasm, 0.41–0.83 in the drainage channel). Thus, most deformation associated with NE-trending faults at Grand Falls was concentrated in the zones of higher strain, significantly less in the much broader areas of homogeneously distributed but weaker strain.

Episodic nature of NE-trending faults. Coarse fault breccia and finer-grained cataclasite (Fig. 7a, b) indicate dominantly brittle mechanisms for the NE-trending faults, as does the brittle response of all dikes and veins (Fig. 7c). Slickensided surfaces in the two high-strain zones contain as many as three distinct sets of slickenlines, suggesting multiple reactivation of individual fault strands. Most slickenlines plunge less than 10° to either the northeast or southwest, but a few moderate plunges (up to 25°) are also present on the walls of the Chasm. Relationships among the three groups of slickenlines are not preserved well enough to determine their sequence.

Bed-parallel (010–020°) faults

Bed-parallel faults and shear zones are ubiquitous at Grand Falls but their orientation makes them difficult to identify except where they offset felsite dikes or veins (Fig. 8). Where significant competence contrast exists, as at wacke–pelite contacts, shear zones parallel bedding and extend with little deviation along strike. Homogeneous zones of massive metawacke exhibit more variation, particularly just east of the dike swarm. There, steep to vertical faults define an anastomosing pattern that converts packages of thick metawacke beds into lenses elongated roughly parallel to bedding. The largest lenses, near the southwest corner of the map, are mappable at the scale of Fig. 3. In thinly intercalated sandstone/pelite sequences near the dam, strain is distributed diffusely within a few narrow anastomosing shear zones.

Strain is more commonly localized within pelitic layers and/or along wacke/pelite contacts, and nearly all pelitic layers have been converted to phyllonite. Massive wackes generally show little evidence of this deformation, except for the lenses just mentioned. Effects of bed-parallel faulting in thick wacke beds are generally confined to

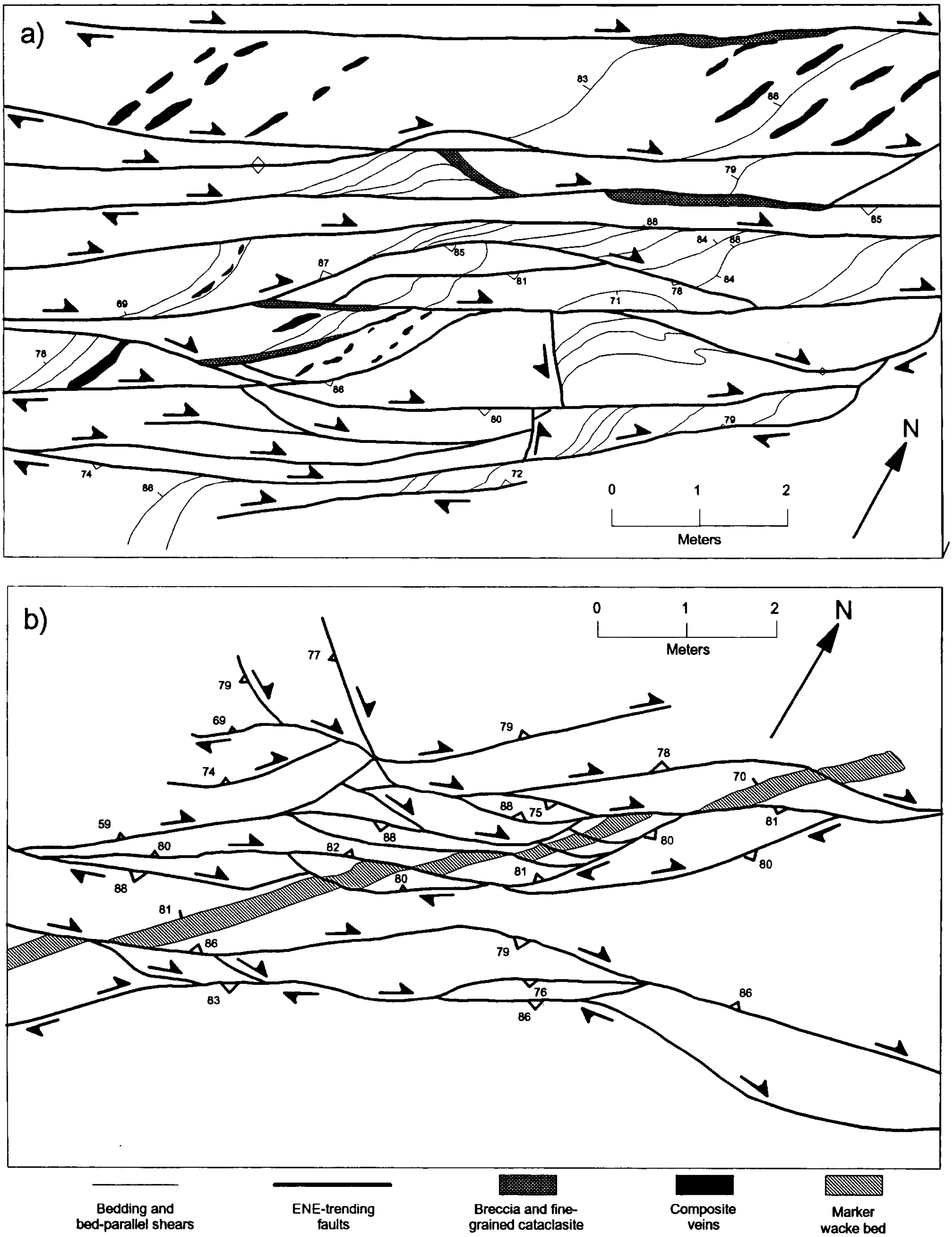

Fig. 5. Detailed maps showing anastomosing NE-trending faults in zones of relatively high strain at Kellyland. (a) Southwest end of the Chasm; (b) northeast part of exposure. See Fig. 3 for exact locations.

Fig. 6. View (southwest) along the Chasm showing lensoid tulip structure produced by vertically anastomosing Stage 2 faults. Slickenlines on fault surface at right indicate sub-horizontal motion along lens-bounding faults. Cataclasite on fault surface in right foreground shown in detail in Fig. 7(a). Vertical dimension is 5 m.

strongly cleaved zones up to 2 cm wide adjacent to pelite layers and to paper-thin pelitic partings between beds. The remainder of each wacke bed, some up to 2 m thick, shows no sign of this cleavage and thus no sign of the faulting.

Microstructures resulting from bed-parallel faulting are shown in Fig. 9. Most clasts in unfaulted wacke are moderately to well rounded. The low degree of ellipticity, small amount of insoluble residue, and poorly developed pressure-solution cleavage visible in Fig. 8(a) is typical of the *more intensely sheared* wackes, and is appropriate for the relatively low strain accommodated in the wacke at Grand Falls. *In situ* reprecipitation of quartz fibers or carbonate grains is uncommon, suggesting that the dissolved material was transported from the immediate source grains, perhaps to form the composite veins. This fabric indicates that bed-parallel faulting occurred in the wackes by diffusive mass transfer, a mechanism consistent with deformation at temperatures lower than 400°C (Rutter, 1983, 1985).

Deformation in the pelitic layers was quite different. Conversion of original shale beds to phyllonite and disruption of primary siltstone laminae (Fig. 8b) were accompanied by recrystallization of white micas and chlorite. The phyllonites vary in grain size. Most white mica and chlorite flakes are only slightly coarser than those of the unsheared pelites, but areas of particularly high strain contain muscovite with significantly increased grain size (up to 3 mm). These fabrics suggest that crystal plastic processes involving recrystallization and possibly intracrystalline glide and intercrystalline slip dominated the low-temperature shearing of the pelites. The presence of very fine grained, non-reflective opaque material on many foliation surfaces suggests that pressure solution of fine grained quartz also occurred in these horizons and that diffusive mass transfer was also a factor.

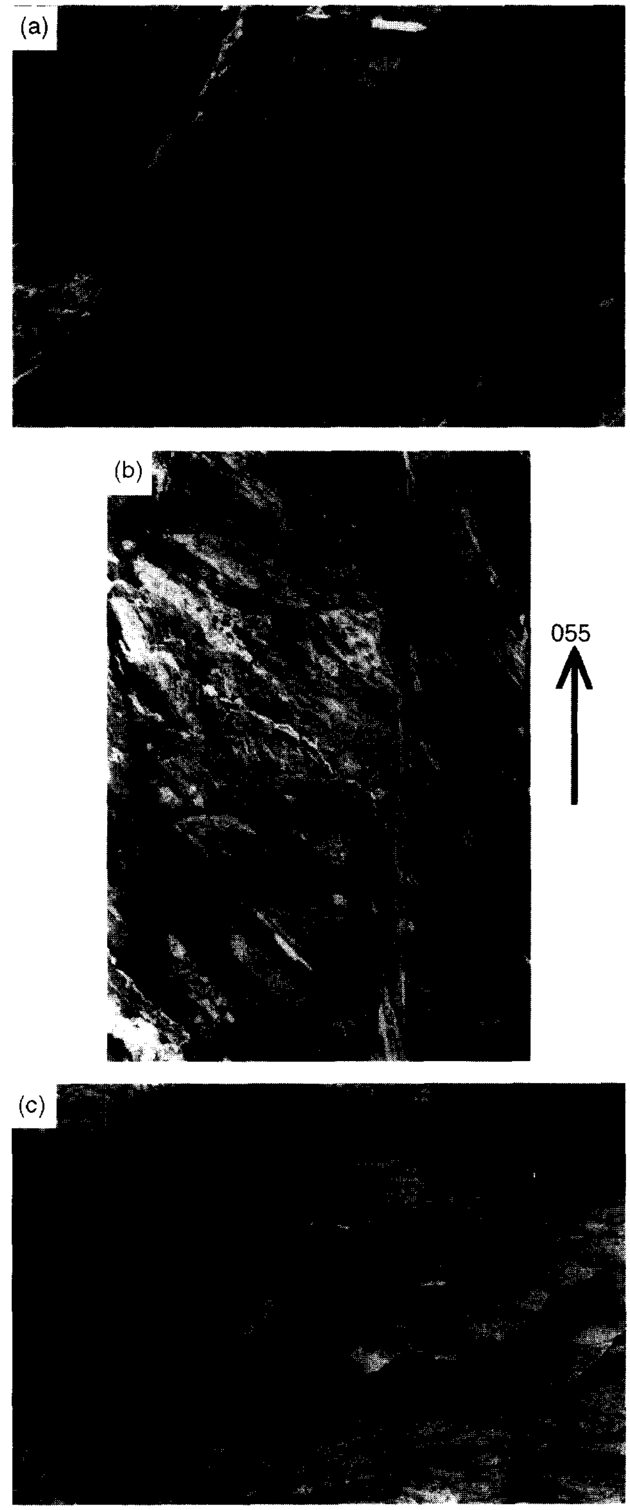

Fig. 7. Brittle features associated with NE-trending faults. (a) Coarse fault breccia on nearly vertical NW wall of Chasm with 1–5 cm angular fragments of wacke and pelite. Note sub-horizontal slickenlines. (b) View looking down onto fine-grained cataclasite filling fault at SW end of Chasm. Width of view is 2.5 m. (c) Map view of NE-trending fault (upper left to lower right) offsetting two felsite dikes and bed-parallel faults adjacent to Kellyland dam. Knife blade points 020°, parallel to dextral bed-parallel faults. Pen is oriented 050°.

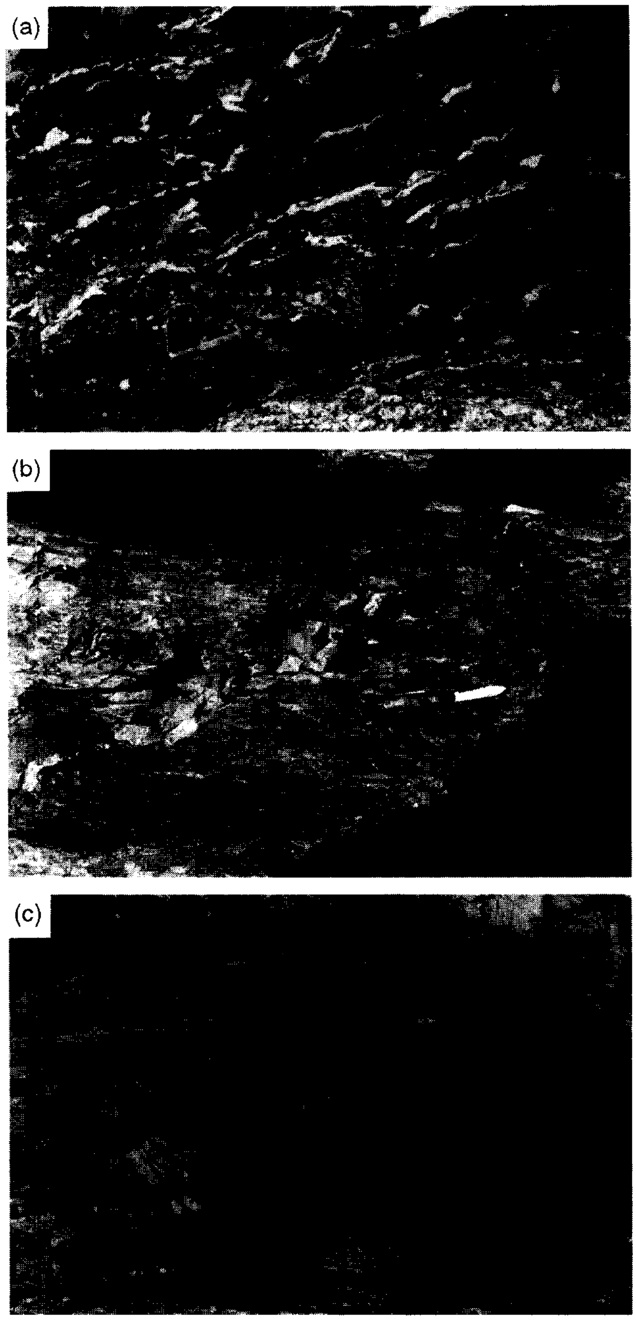

Fig. 8. Bed-parallel faults. (a) Composite quartz + ferroan carbonate veins boudinaged within thick-bedded wacke sequence; (b) felsite dike (gray) and quartz vein (light gray) cut by multiple bed-parallel faults (parallel to knife) in thinly interbedded pelite and wacke near dam; (c) almost complete dismemberment of felsite dike in same horizon. Black lines outline dike fragments offset dextrally by faults.

Foliated biotite flakes occur sparsely in phyllonites from zones of highest bed-parallel strain. Because no other biotite is present at Grand Falls—or anywhere else in the Fredericton belt other than in contact aureoles—this biotite is inferred to have been generated during faulting rather than during the regional metamorphism that preceded KFZ activity. The biotite-forming process is unclear, although extremely localized strain heating or the action of hot fluids are considered most likely.

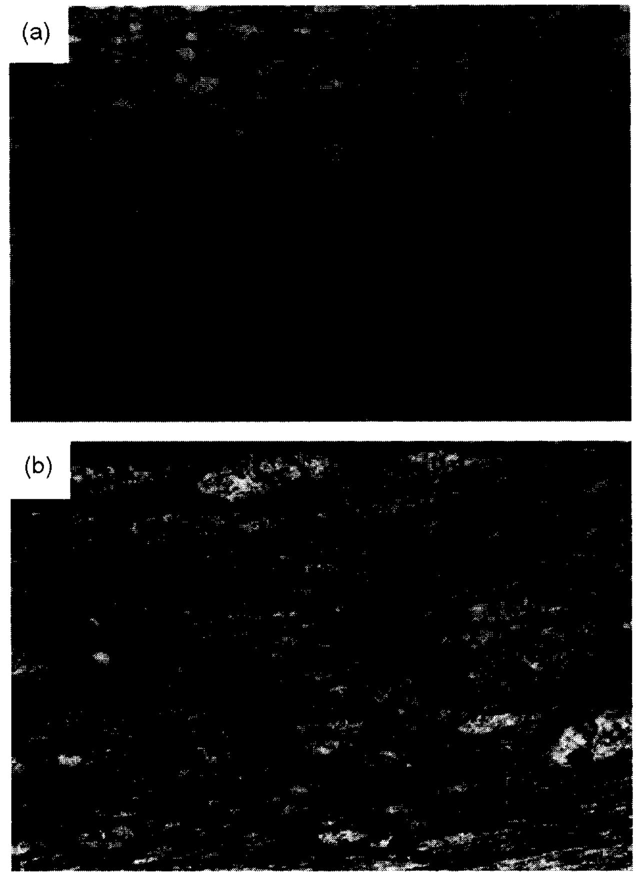

Fig. 9. Photomicrographs showing fabrics associated with bed-parallel shear zones. (a) Pressure-solution cleavage and deformed clasts in massive wacke. [Crossed polarizers; width of field 3.2 mm.]; (b) Phyllonitic fabric characteristic of thick pelite horizons. [Uncrossed polarizers; width of field is 3.2 mm.]

Fault motion and displacement. Their bed-parallel orientation makes it difficult to determine the sense of motion in some faults and shear zones, but abundant steeply plunging intrafolial drag folds and a few subhorizontal slickenlines (see Fig. 4) confirm the dominantly strike-slip motion. Rare asymmetric porphyroclasts derived from quartz veins, offset dikes and quartz veins (Fig. 7c), and asymmetric quartzofeldspathic lenses in phyllonite (Fig. 9) all indicate a dextral sense of motion.

Some high-angle dip-slip and thrust movements also occurred locally on these faults, but such displacements appear to have been minor compared with the dextral motion. Slickenlines and chlorite smears on surfaces bounding the largest lens in the wacke indicate vertical movement, suggesting that the lens 'popped up', probably as the result of local transpression. Transpression is also suggested by a low-angle, NE-trending thrust fault (Fig. 10a) that steepens upward and terminates in a bed-parallel fault just west of the easternmost dike. NW-over-SE thrusting is demonstrated by broad drag folds at the base of the upper plate (Fig. 10b).

Displacement:fault zone width (d/w) data from bed-parallel faults that offset the best-exposed dikes (Table 1)

Table 1. Dike offset in Stage 1 bed-parallel shear zones

Dike	Cumulative offest on bed-parallel faults (meters)	Cumulative width of fault zone (meters)	displacement/width ratio
1	17.4	9.14	1.90
2	25.6	18.0	1.42
3	22.9	13.1	1.75
4	7.13	16.1	0.44

1–3: Foliated dikes in pelite-rich horizon from swarm in western part of exposure.
4: Isolated dike intruding massive wackes in eastern part of outcrop.

confirm that more strain was accommodated in the pelites than in the wackes. d/w values from the three most continuous dikes are comparable, and all are significantly greater than those from the isolated dike to the east. This is attributed to the fact that the swarm cross-cuts a pelite-rich horizon, one in which bed-parallel shear strain was greater than in the massive wackes intruded by the isolated dike. Alternatively, the isolated dike might have intruded later than the swarm, but the parallelism of all dike–Flume Ridge contacts suggests emplacement in the same stress field, probably at the same time.

Episodic nature of bed-parallel faulting. Field relationships show that bed-parallel faults experienced several episodes of activity punctuated by emplacement of composite and quartz veins and intrusion of the dikes. KFZ deformation probably began before emplacement of the composite veins, creating tension fractures in massive wacke beds. Unlike the later dikes and quartz veins, however, all composite veins are now in positions subparallel to bedding (Fig. 8a). This deformation suggests bulk ductile behavior of the composite veins and host metawacke during early phases of bed-parallel faulting. Following emplacement and deformation of the composite veins, bed-parallel fault activity included the following.

(1) Emplacement of quartz veins/injection of dikes: in contrast to the composite veins, original quartz vein–Flume Ridge and dike–Flume Ridge contacts are well preserved and show no evidence of the ductile shearing that affected the composite veins. The nearly identical attitudes of the dikes and many of the quartz veins indicates stress-controlled emplacement, perhaps in extension fractures comparable to those envisaged as controlling earlier emplacement of the composite veins.

(2) Renewed (more brittle?) deformation: the dikes and quartz veins were then partially to completely dismembered by movement along the bed-parallel faults. Dikes and veins behaved brittlely, even within relatively thick pelite-rich horizons (Fig. 7c).

The contrasting ductile deformation of the composite veins and brittle behavior of the dikes and quartz veins could conceivably reflect their different mineralogies. Cross-cutting relationships, however, indicate that the quartz veins were injected later in KFZ history, suggesting that the different behaviors might also have been due to changed conditions during later phases of faulting.

DISCUSSION

Comparison of bed-parallel and NE-trending faults

The two sets of faults are distinguished by characteristics in addition to their different attitudes. Lithic anisotropy of the interbedded turbidites concentrated most strain during bed-parallel faulting into pelitic horizons, but was not a significant factor in determining the geometry or strain localization of the NE-trending faults. Deformation mechanisms were also different: bed-parallel faulting occurred by diffusive mass transfer, recrystallization of micas, and intercrystalline slip/glide resulting in production of phyllonites, whereas deformation on the NE-trending faults involved brittle comminution of grains to form cataclasite containing porphyroclasts of both wacke and pelite.

Their different compositions, volumetric abundances, and relationships with the two sets of faults suggest that the veins reveal the relative importance of fluids during faulting at Grand Falls. The change from early emplacement of composite veins during bed-parallel faulting to later monomineralic quartz veins indicates a change in fluid composition with time. If the volumetric abundance of the two vein types can be used as a measure of the amount of fluid in the rocks during faulting, the decrease in vein material with time suggests a progressively smaller role for the fluids during deformation. In this model, the almost complete absence of veins associated with NE-trending faults would imply the driest conditions—consistent with the more brittle nature of deformation.

Sequence of faulting

These differences, coupled with consistent cross-cutting relationships such as those shown in Figs 7 & 8, indicate that the NE-trending and bed-parallel faults represent separate phases of deformation. Figure 11 provides evidence that a strain-free interval of unknown duration separated bed-parallel and NE-trending fault-

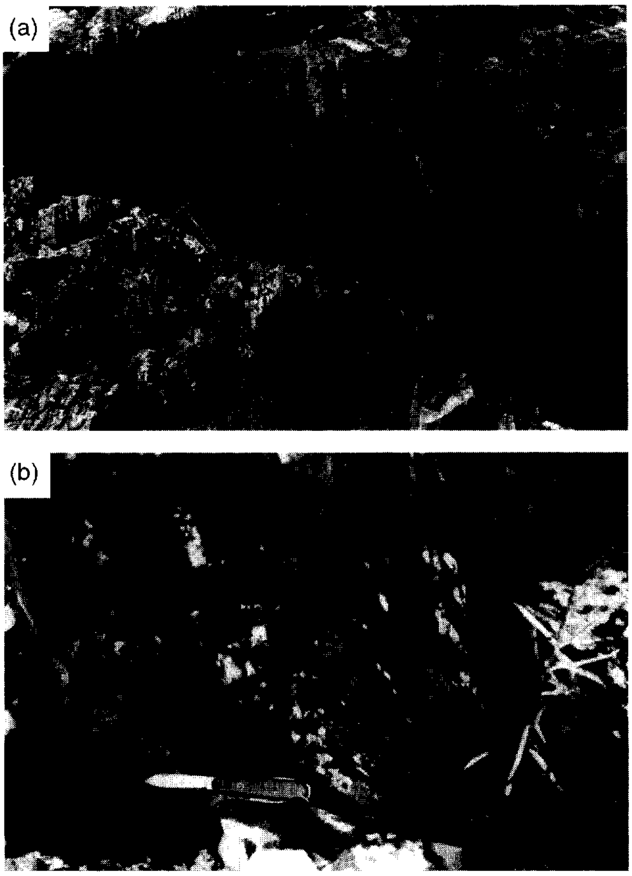

Fig. 10. Thrust fault associated with bed-parallel faults. (a) Hammer resting on thrust fault (view looking southwest). (b) Closeup of thrust showing drag folds in wacke beds at base of upper plate.

ing. Euhedral ferroan carbonate rhombs crystallized locally in fine-grained metasiltstone and incorporated inclusions that define a pre-existing foliation caused by bed-parallel faults (Fig. 11a). Similar euhedral rhombs grew across chlorite foliation in felsite dikes but did not incorporate inclusions. The euhedral nature of the rhombs, in lithologies otherwise characterized by strongly penetrative fault-generated foliations, indicates strain-free growth following bed-parallel faulting. The euhedral rhombs were subsequently deformed and their included foliation was rotated adjacent to NE-trending faults (Fig. 11b, c).

Cross-cutting relationships among faults, quartz veins, composite quartz + carbonate veins, and felsite dikes thus document a two-stage history at Grand Falls in which bed-parallel faults (Stage 1) preceded the NE-trending faults (Stage 2). Each of the stages comprised multiple episodes of activity. Figure 12 summarizes the sequence of fault events deduced from the Grand Falls exposure.

Timing of fault stages

Clarification of the relationships between the KFZ and the Deblois and Bottle Lake plutons (Ludman and Gibbons, 1995; in press) and recent dating of the Deblois granite at 383 ± 14 Ma (Ludman *et al.*, in press) yield some constraints on the timing and duration of faulting (see Ludman and West, 1994). At least *three* stages of dextral faulting have been observed in the Deblois pluton at Wabassus Mountain, 50 km southwest of Grand Falls. The two earliest sets of faults parallel and are equated with Stages 1 and 2 at Grand Falls (Ludman and Gibbons, 1995; in press). The maximum age for initiation of Stage 1 is thus 383 ± 14 Ma.

Stage 1 fabrics occur throughout the Fredericton belt north of the KFZ and in Deblois granite at Wabassus Mountain (see fig. 2; Ludman and Gibbons, 1995; in press), but are absent from the Bottle Lake complex just north of the Deblois. Only the Stage 2 NE-trending faults are found in the Bottle Lake. Its emplacement at approximately 380 ± 5 Ma (Ayuso *et al.*, 1984) is thus the minimum age for Stage 1. Considering the full time spans possible from these data, Stage 1 activity is constrained to as little as 3 Ma (between 383 and 380 Ma) and to as much as 22 Ma (between 397 and 375 Ma). $^{40}Ar/^{39}Ar$ dating of granite and cataclasite now under way is designed to refine this timetable.

Extrapolation to the Norumbega fault zone

The outcrop-scale features and relationships at Grand Falls described above are mirrored by regional-scale structures throughout most of the Fredericton belt. For example, Stage 1 phyllonites cut by Stage 2 faults characterize the Fredericton belt from the Pocomoonshine gabbro-diorite northward to the Miramichi terrane, and from the New Brunswick border westward to the Deblois and Bottle Lake plutons (see Fig. 2). Extrapolation from the Grand Falls exposure can thus yield an improved understanding of the evolution, extent, geometry, strain partitioning, and deformation mechanics of the shallow crustal segment of the NFZ.

Extent, geometry, and strain partitioning. The NFZ was previously portrayed in eastern Maine as two straight NE-trending fault strands about 1 km apart (Osberg *et al.*, 1985), but Stage 2 structures identical to those of Grand Falls and the KFZ have been identified throughout the Fredericton belt. The NFZ is therefore extended several kilometers across strike to the southeast and northwest of the faults shown on the most recent state geologic map, to a total width of about 40 km. The two faults mapped by Osberg *et al.* (1985) are now interpreted as part of the Waite fault zone.

Regional-scale mapping (Ludman, 1991) coupled with the detailed Grand Falls study suggests that Stage 2 strain was partitioned throughout eastern Maine in the same manner as at Grand Falls. Thus, the KFZ is one of three, 2–5 km wide, northeast-trending Stage 2 NFZ high-strain zones (Fig. 2). Each, like the Chasm, contains several individual fault strands and occupies a topographic low. Where bedrock exposures permit detailed

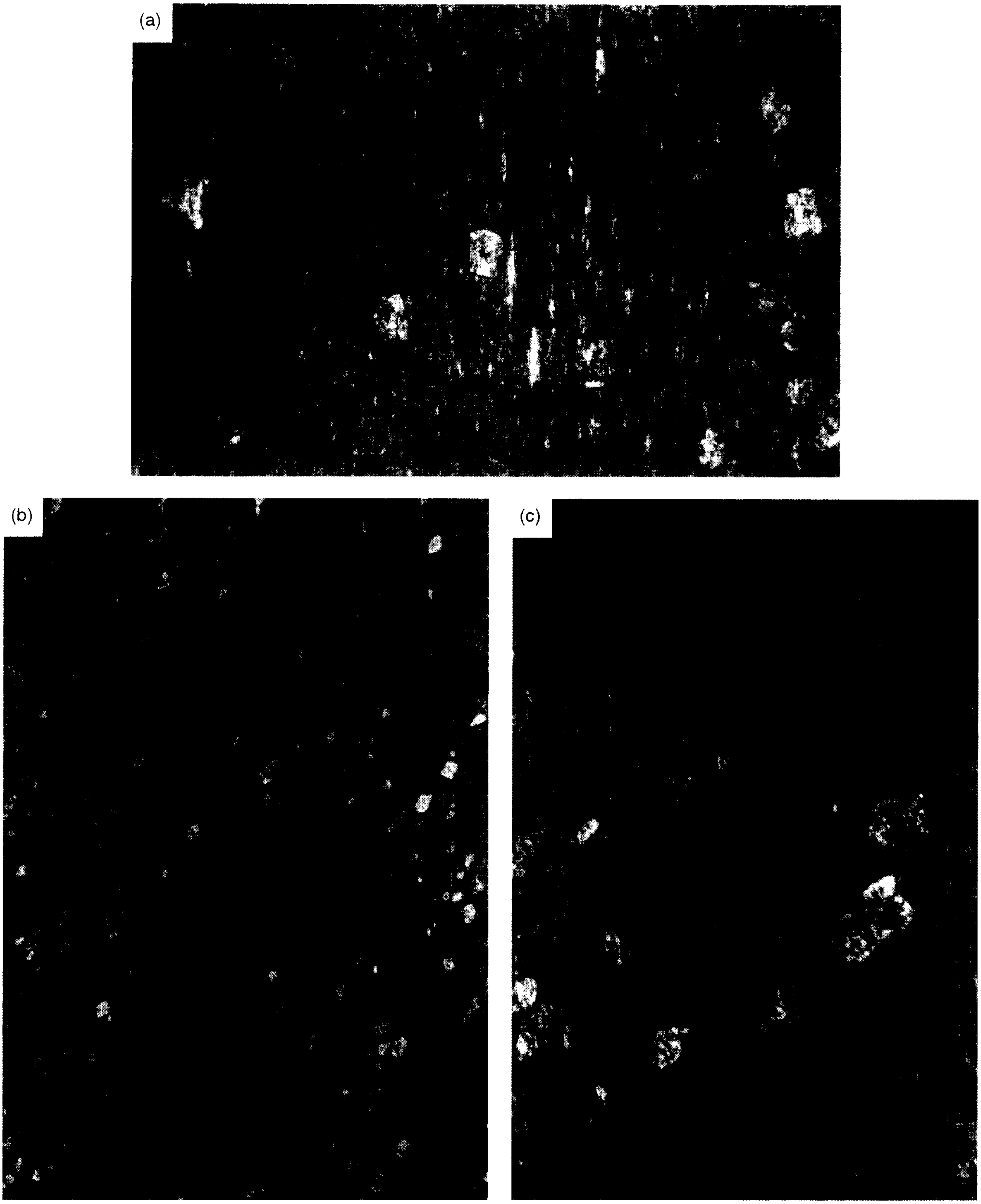

Fig. 11. Photomicrographs of horizontal surfaces showing evidence for a static, strain-free period separating bed-parallel and NE-trending faulting. Uncrossed polarizers. Direction toward top of all photomicrographs is 015°. (a) Euhedral ferroan carbonate rhombs overgrowing Stage 1 foliation in fine grained siltstone. Width of field = 3.2 mm; (b) Broad view of deformed rhombs showing effects of Stage 2 faulting. Width of field = 8 mm. (c) Close-up of deformed rhombs showing drag folds and rotation of foliation trains included in rhombs. Width of field = 3.2 mm.

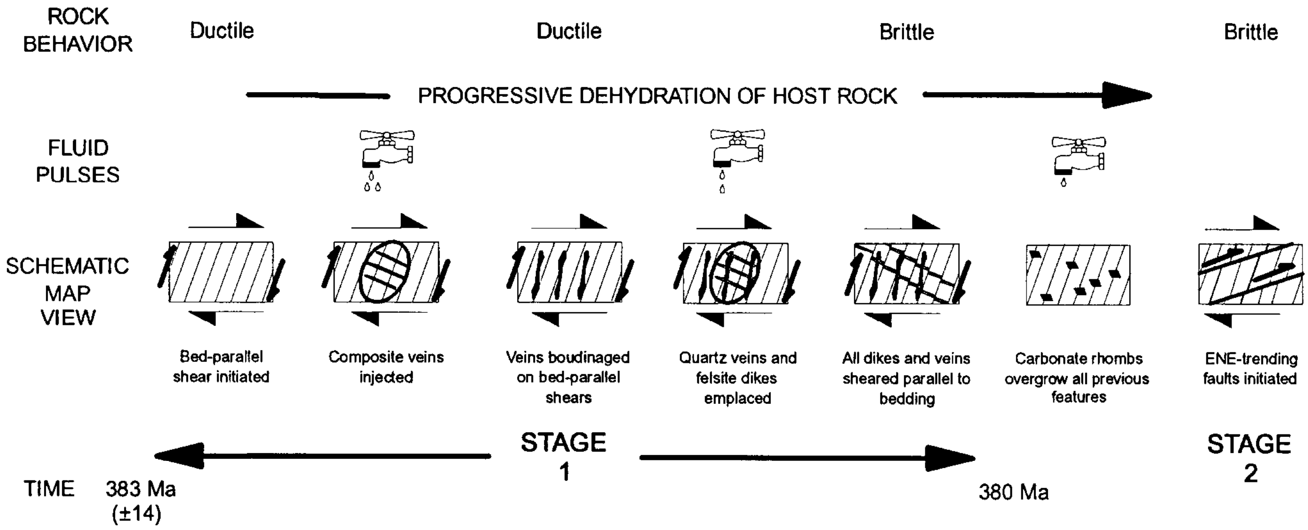

Fig. 12. Interpreted sequence of deformation events at Kellyland.

mapping, such as in the Waite fault zone, these faults clearly anastomose like those in the Chasm (see Fig. 2). As at Grand Falls, the regional zones of high Stage 2 strain are separated by broad areas of weaker strain in which beds and Stage 1 features are cut by only a few, widely spaced faults.

Dynamic metamorphism related to the NFZ. Biotite is generally present in the Fredericton belt only in unfoliated hornfels assemblages. The exception is along the Waite fault zone where a group of polydeformed, thinly laminated rocks crops out in which biotite and muscovite define a strongly-developed foliation (dense stipple in Fig. 2). These rocks were previously assigned an Ordovician (?) age (McLeod *et al.*, 1994), because their polydeformation and relatively high metamorphic grade differ sharply from the adjacent chlorite-grade late Ordovician-Silurian rocks of the Fredericton belt.

Biotite crystallization in Stage 1 faults at Kellyland suggests another possibility—that these rocks may have formed by biotite-grade dynamic metamorphism during early faulting. Chlorite-grade rocks displaying the same foliation and thin layering interfinger with the biotite-bearing varieties for about 40 km along strike in the Waite high-strain zone. Both biotite and chlorite-grade rocks display the paper-thin compositional layering and penetrative foliation characteristic of phyllonites or mylonites, and are here interpreted as the product of early (Stage 1) NFZ activity. Subsequent deformation of the foliation is attributed to multiple Stage 2 episodes and to even later faulting described by Ludman *et al.* (in press).

Displacement. Cumulative dextral displacement on the three Stage 2 high-strain zones was approximately 50 km, based on offset pluton/host rock contacts in the Kellyland, Waite, and Codyville fault zones (Ludman, 1995; Ludman *et al.*, in press), but total displacement in the broad regions of weak strain can not be measured directly. The Grand Falls exposure, located at the margin of the Kellyland fault zone, helps to estimate the effects of Stage 2 faulting in the zones of weak strain separating the three high-strain zones. Measured offsets and d/w ratios for the Chasm and drainage channel are much higher than those for the intervening area, suggesting that most of the displacement in the NFZ is concentrated in the three high-strain zones. Extrapolating from the Grand Falls data, only another 5–10 km of dextral offset is inferred for the broad areas separating the three fault zones in eastern Maine.

CONCLUSIONS

The Grand Falls exposure of the Kellyland fault zone is a small-scale model for the epizonal segment of the Norumbega fault zone in eastern Maine and western New Brunswick. Shallow-crustal evolution of the NFZ involved sporadic dextral strike-slip activity during which deformation became progressively more brittle. Strain during early activity (Stage 1) appears to have been broadly and relatively homogeneously distributed across the 40 km width of the NFZ. At this point in NFZ evolution, the competence contrast between wackes and pelites controlled shear zone geometry and localized most strain in pelitic layers and along bedding planes. Fluids played an important role in this early activity, facilitating diffusive mass transfer and intercrystalline slip, and yielding the most ductile behavior recorded in the metasedimentary rocks of eastern Maine during faulting.

Later events (Stage 2) largely ignored the lithic anisotropy in the well-bedded metasedimentary rocks of the Fredericton belt and in granites that had been strongly foliated during initial shearing. Stage 2 strain was strongly partitioned into three well-defined brittle deformation zones comprising several anastomosing faults. Fluids were less abundant and less significant than during early deformation, and both wacke and pelite behaved brittlely.

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