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Kinematic significance of sediment-filled fissures in the North Mountain Basalt, Fundy rift basin, Nova Scotia, Canada

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Abstract—Numerous sediment-filled fissures are present near the upper surface of the North Mountain Basalt (~202 Ma) of the Fundy basin, which formed during Triassic–Jurassic rifting. The fissures are infilled with the same clastic material comprising the basal parts of the overlying earliest Jurassic-age sedimentary formations, which accumulated less than 200 k y after the cooling of the basalt. Nearly all of the 1368 fissures measured in this study are planar to sub-planar and are sub-vertical (after correcting the basalt flows to paleo-horizontal). The fissures typically formed along preexisting columnar joints within the basalt. Northeast-striking fissures generally define a preferred orientation and commonly are wider than other fissures. The sediment-filled fissures therefore indicate earliest Jurassic-age NW–SE extension. This extension direction is consistent with that indicated by the NE-striking Shelburne diabase dike, the attitude of mesoscopic faults, and the geometry of the Fundy rift basin. Thus, sediment-filled fissures by themselves can serve as useful kinematic indicators and place tight constraints on the relative timing of extension.

INTRODUCTION

Fissures are fractures or cracks across which there is a significant separation of the wall rocks (Bates & Jackson 1980). If infilled with mineralized material, these fissures are called veins. Submarine fissures that become filled by sediment are termed neptunian dikes (Bates & Jackson 1980). The vast majority of neptunian dikes reported in the literature (see citations in Smart *et al.* 1988) occur within and are filled with carbonate rocks, but fill material consisting of sandstone and shale has also been described (Halstead & Nicoll 1971). The submarine fissures may be infilled by sediments transported through a network of cavities that connect to the seafloor (e.g. Wendt 1971, Bernoulli & Jenkyns 1974, Hsü 1983, Kerans *et al.* 1986, Winterer *et al.* 1991) or through the injection of soft sediments overlying the fissure-bearing unit (e.g. Robinson 1956, Castellarin 1965, Jeanbourquin 1985, Lehner 1991, Winterer *et al.* 1991). In some cases, fissures and neptunian dikes can be dated biostratigraphically using fossils recovered directly from the sedimentary infilling (e.g. Robinson 1956, Wendt 1971, Szulczewski 1973).

As most neptunian dikes occur within carbonate rocks, it is not surprising that dissolution is one mechanism responsible for void initiation and enlargement, commonly during a period of karst development (Halstead & Nicoll 1971, Schöll & Wendt 1971, Sturani 1971, Wendt 1971, Misik 1979, Palmer *et al.* 1980, Gonzáles-Donoso *et al.* 1983, Melendez *et al.* 1983, Vera *et al.* 1984, Wendt *et al.* 1984, Smart *et al.* 1988). Nonetheless, fracturing of the carbonates is generally regarded as the primary mechanism for void initiation. Fracturing is inferred to be caused by either tensional stresses (Wiedenmayer 1963, Schöll & Wendt 1971, Wendt 1971, Szulczewski 1973, Bernoulli & Jenkyns 1974, Misik 1979, Stanton 1981, Wood 1981, Gonzáles-Donoso *et al.* 1983, Vera *et al.* 1984, Wendt *et al.* 1984, Hancock 1985, Blendinger 1986, Smart *et al.* 1988, Lehner 1991) or gravity-sliding or slumping down tectonically produced slopes (Castellarin 1965, Füchtbauer & Richter 1983, Winterer *et al.* 1991) or both (Schlager 1969, Kerans *et al.* 1986). A tectonic origin for many neptunian dikes is suggested by a preferred orientation of the fractures (Halstead & Nicoll 1971, Schöll & Wendt 1971, Wendt 1971, Palmer *et al.* 1980, Stanton 1981, Vera *et al.* 1984, Blendinger 1986, Kerans *et al.* 1986, Lehner 1991) and by successive generations of dikes with the same orientation (Schöll & Wendt 1971, Wendt 1971) as well as repeated opening of the same dikes (Blendinger 1986).

In their review of neptunian dikes, Smart *et al.* (1988) suggested that the terrestrial equivalents of neptunian dikes be called fissure fills. Examples of non-marine fissure fills (e.g. Robinson 1956, Richter 1966, Jenkyns 1977, Olsen & Schlische 1990) are relatively rare and in some cases are associated with cave deposits (Halstead & Nicoll 1971). In this paper we describe abundant sediment-filled fissures that occur within continental basalt flows of the Fundy rift basin, Canada. Although the initial fracturing was related to differential cooling of the basalt flows and resulted in the formation of polygonal cooling joints which exhibit a wide range of orientations, the fissures that subsequently occupied the cooling joints exhibit a preferred orientation, and can thus be used as kinematic indicators of extension.

GEOLOGIC BACKGROUND

The Fundy basin of New Brunswick and Nova Scotia, Canada, is the northernmost exposed basin within the

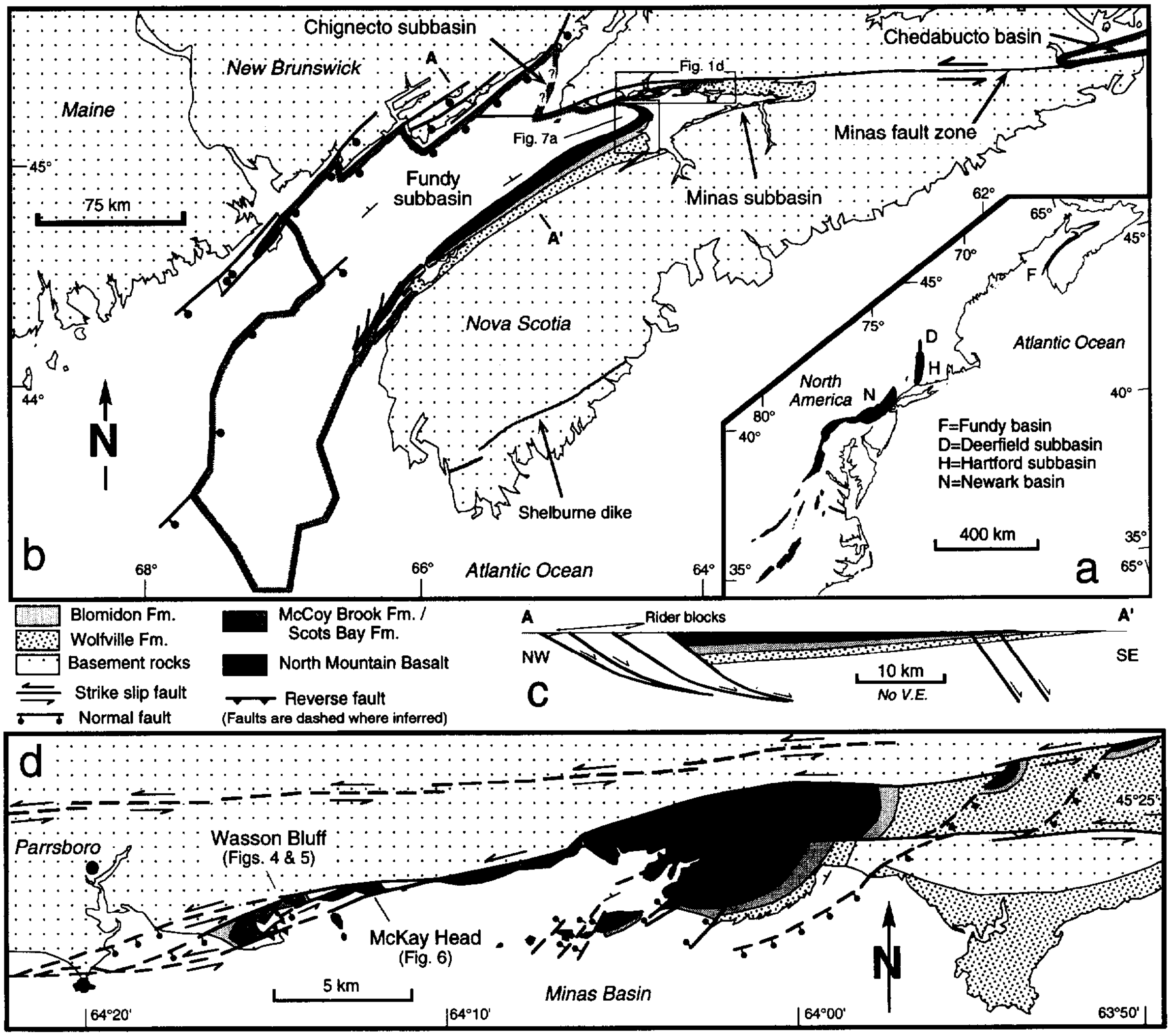

Fig. 1. (a) Triassic–Jurassic rift basins (black) of eastern North America. (b) Geologic map of the Fundy rift basin, New Brunswick and Nova Scotia, Canada. (c) Cross-section A–A′ through the Fundy subbasin illustrates the half-graben geometry that resulted from NW–SE extension along a NE-striking border fault system. (d) Geologic map of a part of the northern margin of the Minas subbasin. [Modified from Olsen & Schlische (1990) and Schlische (1990).]

eastern North American rift system that formed during continental rifting associated with the breakup of North America and Africa (Fig. 1a, Van Houten 1977). The basin consists of three subbasins: the NE-trending Fundy and Chignecto subbasins and the E-trending Minas subbasin (Fig. 1b, Olsen & Schlische 1990). Based on seismic reflection data, the Fundy subbasin is a large half graben in which the basin fill dips toward the SE-dipping border fault system (Fig. 1c, Olsen & Schlische 1990, Schlische 1990). The principal basin-bounding fault is submerged beneath the Bay of Fundy; splay faults bounding a series of exposed rider blocks (terminology of Gibbs 1984) along the New Brunswick coastline generally strike to the northeast and in some cases consist of reactivated Paleozoic thrust faults (Plint & van de Poll 1984, Brown 1986). The geometry of the Chignecto subbasin, also defined by seismic reflection data (Schlische 1990, Withjack *et al.* 1991), is that of a NW-tilted half graben. The geometry of both subbasins is consistent with NW–SE extension.

The Minas fault zone forms the northern boundary of the Minas subbasin (Olsen & Schlische 1990, Schlische 1990). This fault zone underwent dextral slip during Paleozoic time and marked the boundary between the Avalon and Meguma terranes (Keppie 1982). As a consequence of the NW–SE extension that produced predominantly dip slip along the NE-striking boundary faults of the Fundy and Chignecto subbasins, the E-striking Minas fault zone was reactivated as a left-oblique slip fault zone and formed the transtensional Minas subbasin (Keppie 1982, Olsen & Schlische 1990). The northern margin of the Minas subbasin consists of a network of NE-striking normal faults and E-striking sinistral faults that bound a series of small graben and half graben (Fig. 1d, Olsen & Schlische 1990). A number of these faults, including the Minas fault zone, experienced some post-rift structural inversion (Olsen *et al.* 1992, Withjack *et al.* 1992, in press). Seismic reflection data indicate that the Minas fault zone merges with the principal basin-bounding fault of the Fundy subbasin (Schlische 1990).

Strata of the Fundy basin are collectively known as the Fundy Group, which consists of five formations in Nova Scotia (see summary in Olsen *et al.* 1989). The Middle and Late Triassic-age Wolfville Formation is the oldest unit in the basin and consists predominantly of fluvial strata with subordinate eolian deposits. The overlying Blomidon Formation, which is Late Triassic and earliest Jurassic in age, is a mostly cyclical playa lacustrine deposit. The North Mountain Basalt consists of multiple quartz-normative tholeiitic lava flows (Stevens 1987, Puffer & Philpotts 1988). U/Pb isotopic dating of the basalt indicates that it crystallized at ~202 ± 1 Ma (Early Jurassic) (Hodych & Dunning 1992). The Shelburne dike of mainland Nova Scotia was emplaced penecontemporaneously with the North Mountain Basalt and is geochemically similar to it (Hodych & Hayatsu 1988). The northeasterly strike of this large dike indicates earliest Jurassic NW–SE extension. The Early Jurassic-age McCoy Brook Formation overlies the North Mountain Basalt in most parts of the basin, and consists of a wide range of deposits: fluvial, deltaic, lacustrine and eolian. The McCoy Brook Formation also contains extremely coarse-grained deposits with megaclasts of North Mountain Basalt; these are interpreted to have accumulated as talus deposits on the downthrown sides of syndepositional faults (Olsen *et al.* 1989, Olsen & Schlische 1990, Tanner & Hubert 1990). The Scots Bay Formation is a lateral equivalent of the McCoy Brook Formation and consists mostly of lacustrine deposits that fill a series of small sag basins developed on top of the North Mountain Basalt along the coast of Scots Bay (see Discussion).

Based on seismic reflection data and well information, all formations in the Fundy subbasin increase in thickness toward the border fault system, indicating that it was syndepositionally active (Fig. 1c, Olsen & Schlische 1990). Within the Minas subbasin, the same formations vary in thickness considerably over small areas, also indicative of strong tectonic control on sedimentation. Thus, both dip-slip and strike-slip margins were active penecontemporaneously (Olsen & Schlische 1990). In addition, all formations within the Minas subbasin are thinner than in the Fundy subbasin; thus, subsidence within the strike-slip-dominated Minas subbasin was less than in the dip-slip-dominated Fundy subbasin.

SEDIMENT-FILLED FISSURES

The highest concentration of sediment-filled fissures occurs near the contact between the North Mountain Basalt and the overlying sedimentary units, the McCoy Brook and Scots Bay Formations (Fig. 2a). Numerous fissures also have been observed at individual flow contacts, marked by highly vesicular basalt, within the North Mountain Basalt. Fissures are also locally more abundant near fault zones; a similar association has been noted elsewhere by Jenkyns (1977).

The fissures generally have planar to subplanar contacts that are moderately steeply to steeply dipping (Fig. 2b), depending on the attitude of the host basalt. Following Wendt (1971), these fissures would be classified as 'Q-Spalten', which are oblique to 'bedding'. In cross-section view, some steeply dipping fissures taper in width downward. Some of the largest fissures extend downward at least 3 m (Fig. 2b). At the very top of the North Mountain Basalt, subsidiary fissures have been observed to splay from the main fissures. At the Ross Creek study site (see discussion below), some structures superficially resembling sediment-filled fissures are oriented subparallel to the contact between the North Mountain Basalt and the Scots Bay Formation. These structures appear analogous to Wendt's (1971) 'S-Spalten'.

The most common arrangement of sediment-filled fissures in plan view consists of sets of fissures forming four- to six-sided polygons (Fig. 3). This geometry strongly suggests that many of the fissures occupy polygonal cooling joints within the basalt. Where such preexisting structural control exists, the length of the fissures in plan view is limited by the length of the cooling joint, generally 10–20 cm. Not all cooling joints are necessarily occupied by sediment-filled fissures, nor are all fissures restricted to preexisting cooling joints. For example, one fissure at Ross Creek is >20 m in length and has a nearly constant strike (Fig. 2c). As discussed in greater detail below, the width of a single continuous fissure is sometimes variable. For all fissures studied in Nova Scotia, the width ranges from <1 cm to 40 cm.

Fissure fills within the North Mountain Basalt consist mostly of red, reddish-orange, reddish-brown, reddish-purple and green massive sandstone and mudstone; no bedding or laminations were observed. The lithologies of the fissure fills are similar to those of the overlying McCoy Brook and Scots Bay Formations, which accumulated in fluvial and lacustrine environments in areas where the fissures are present. Some fissures also contain clasts of rounded to subrounded basalt, which were likely derived from the weathering of North Mountain Basalt and then transported into the open fissures. Other basalt clasts have planar edges and were presumably emplaced through spalling of wall rock within the fissure (Fig. 2c). Fissure fills at Wasson Bluff also contain clasts of igneous and metamorphic rocks derived from pre-Triassic rocks to the north of the Minas fault zone (Fig. 1d). These clasts are also present in debris flow deposits at Wasson Bluff (Tanner & Hubert 1990). At Ross Creek (see Fig. 7a), S-fissure fills are exclusively green in color and contain rare fossils (fish scales and molluscs), whereas Q-fissure fills are either red (more common) or green. Red and green fissure fills do not occur in the same general area, and the color differences might reflect different sources of sediment infill or different oxidation/reduction states as a result of fluid movement.

Many narrow (<3 cm) fissures are silicified and commonly contain chalcedony. Consequently, the fissure fills are more erosionally resistant than the surrounding basalt. This type of fissure fill preferentially occurs in fissures near flow contacts within the basalt but is also present in some fissures near the top of the basalt. The zeolite mineral chabazite (known locally as acadialite) is a common occurrence in many fissure fills and may have grown in voids unfilled by sediments. In places, the

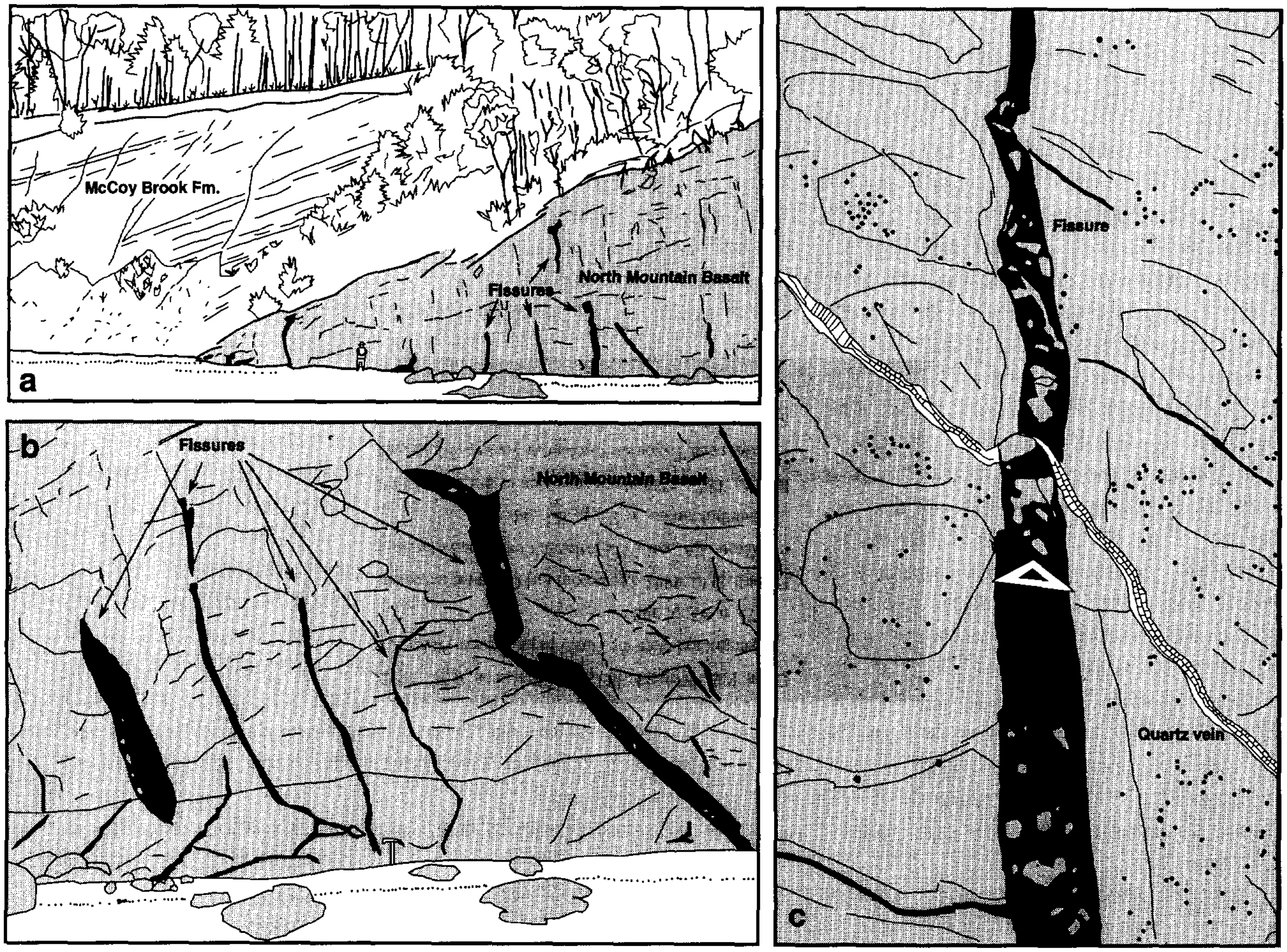

Fig. 2. (a) Contact between the North Mountain Basalt and McCoy Brook Formation at McKay Head (see Figs. 1d and 6a for location). The basalt contains subvertical sediment-filled fissures (shown in black for emphasis). Person for scale. (b) Close-up view of sediment-filled fissures (black) within the vesicular North Mountain Basalt (stippled) near the contact with the overlying McCoy Brook Formation at McKay Head. Some fissures taper in width downward. Hammer for scale. (c) Large sediment-filled fissure in the North Mountain Basalt at Ross Creek (see Figs. 1b and 7a for location). The E-trending fissure is 10–15 cm wide and more than 20 m long. Note the filled vesicles in the basalt (small black dots), located a few meters below the contact with the Scots Bay Formation (not shown). Note also the large blocks and clasts of basalt within the fissure fill. Some of the more angular clasts may be remnants of the wall rock. The fissure is cut by a vein striking 052° and dipping 73°SE. Triangle is 12 cm wide.

fissures are cut by generally NE-striking quartz veins (Fig. 2c).

KINEMATIC ANALYSIS

The attitudes of over 1300 sediment-filled fissures were measured at four study sites within the Fundy basin. Strike and dip of the fissure walls were recorded along with the maximum width of the fissure fill. In general, fissures <0.2 cm wide were not included in the survey, nor were cooling joints within the basalt that contained no sedimentary infill.

Wasson Bluff

Wasson Bluff is a 1.6 km-long stretch of continuously exposed rocks located approximately 5 km east of Parrsboro, Nova Scotia (Fig. 1d). This area is dominated by outcrops of the North Mountain Basalt and the overlying McCoy Brook Formation. East-striking strike-slip faults and NE-striking normal faults form the predominant structural motif (Fig. 4a, Olsen & Schlische 1990). Syndepositional faulting is indicated by paleotalus slope deposits, large slide blocks of basalt, and significant variations in thickness of units within the McCoy Brook Formation (Olsen & Schlische 1990).

At the western Wasson Bluff study area, the majority of the data on the sediment-filled fissures were collected from outcrop surfaces subparallel to the contact (075°, 37°S) between the North Mountain Basalt and the overlying McCoy Brook Formation. The fissures are thus well displayed in plan view, and many of them clearly occupy preexisting cooling joints within the basalt (Fig. 3a). The majority of the fissures are moderately to steeply dipping structures and generally dip to the north-northwest (Fig. 4b). If the lava flows are rotated to paleohorizontal, the majority of the fissures become more steeply dipping (Fig. 4c). As the original cooling joints likely formed subperpendicular to the cooling surface of the basalt, we conclude that fissure formation preceded significant tilting of the North Mountain Basalt.

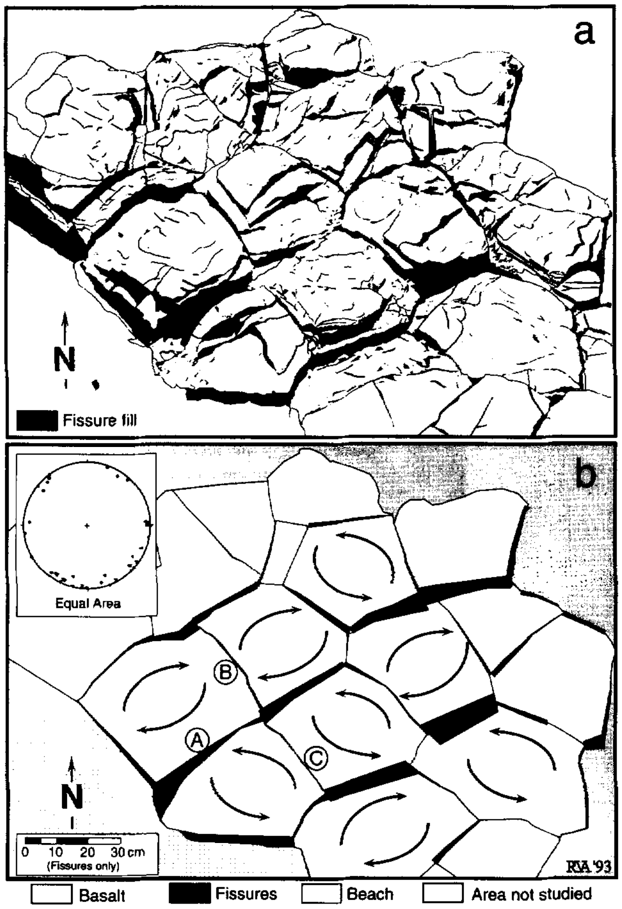

Fig. 3. (a) Outcrop sketch of polygonal cooling joints in the North Mountain Basalt at western Wasson Bluff (see Fig. 1d for location). Many of the joints have been reoccupied by sediment-filled fissures (gray stipple). The outcrop surface dips ~40° toward the reader, thus limiting the visibility of some of the fissures. Hammer for scale. (b) Schematic diagram of outcrop shown in (a). Fissure widths have been slightly exaggerated to show tapered geometry used to determine rotation sense of cooling columns. Circled letters refer to areas discussed in the text. Due to perspective, scale is only strictly valid for the fissures.

A wide range of strikes for the sediment-filled fissures is represented in Fig. 4(c). This variation is not surprising considering that the fissures occupied cooling joints which generally form a pentagonal pattern. Nonetheless, the Schmidt contour diagram of the poles to the fissures shows that generally NE-striking fissures predominate (Fig. 4d). Furthermore, the widest fissures tend to be NE-striking (Fig. 4c). These features are particularly prominent in the sketch shown in Fig. 3(a). Northeast-striking cooling joints within the basalt formed the widest fissures, whereas some NW-striking joints were never opened. The overall geometry of these structures strongly suggests NW–SE extension.

The sediment-filled fissures shown in Fig. 3 taper asymmetrically in width in plan view. On average, the width of a fissure in Fig. 3 increases from 1.5 cm at one end to 3.0 cm at the other, an increase of 100% (e.g. A in Fig. 3b). The plan-view arrangement of these tapering fissures can be used to determine localized displacements of the cooling columns: the narrow ends of the fissures indicate that adjacent columns converged, whereas the wide ends of the fissures point to a divergence of adjacent columns. The pattern of convergence or divergence for multiple fissures surrounding a given cooling column defines a rotation sense for that column (Fig. 3b). In two cases, adjacent columns have the same rotation sense, and the shared cooling joints are sheared and contain little or no sediment fill (B and C in Fig. 3b); note that these fractures are also subparallel to the inferred extension direction. In most cases, however, the rotation sense for one column is opposite that of an adjacent column, similar to a pair of watch gears. The rotations are perhaps the result of jostling associated with seismic shaking. Rotation likely occurred prior to infilling of the fissures because the narrow ends of the fissure fills show no evidence of contractional strain, nor do the wide ends of the fissure fills display evidence of post-filling extension.

As at the western study site, the data from central Wasson Bluff were obtained mainly from outcrop surfaces parallel to the contact (116°, 40°SW) between the North Mountain Basalt and the McCoy Brook Formation. Many of the fissures here also occupy preexisting cooling joints and thus the attitude of the fissures shows considerable scatter (Fig. 5a). Post-fissure formation tilting is again suggested by the increase in dip of the fissures after the lava flows are rotated to paleohorizontal. Once again, NE-striking fissures predominate (partially reinforced by an examination of fissure widths shown in Fig. 5a), suggesting a NW–SE extension direction (Fig. 5b).

McKay Head

Located approximately 2 km east of Wasson Bluff, the McKay Head region exposes virtually the entire thickness of the North Mountain Basalt (see Figs. 1d and 6a for location). The basalt rests conformably on Blomidon Formation, which is only a few meters thick and rests unconformably on Carboniferous strata. The top of the basalt is onlapped by McCoy Brook Formation (Fig. 2a). The majority of the sediment-filled fissures are found just below the upper contact of the basalt, which strikes ~015° and dips 30°NW. The fissures occur along wave-cut sea cliffs and are thus observed in cross-sectional view (Fig. 2b).

The sediment-filled fissures at McKay Head generally increase in dip following a 'bedding' correction (Figs. 6b & c), suggesting that they predated most of the tilting of the basalt. Fissure filling prior to significant tilting is also indicated by the following: the basal McCoy Brook Formation is subparallel to the upper surface of the basalt, and fissure filling and deposition of the lower McCoy Brook Formation were penecontemporaneous. Although a wide variety of orientations is represented at McKay Head, a preferred orientation (generally WNW-striking fissures) is evident in the data, particularly in the widest fissures (Fig. 6c) and in the contoured Schmidt plot of the poles to the fissures (Fig. 6d). A NNE–SSW extension direction is indicated.

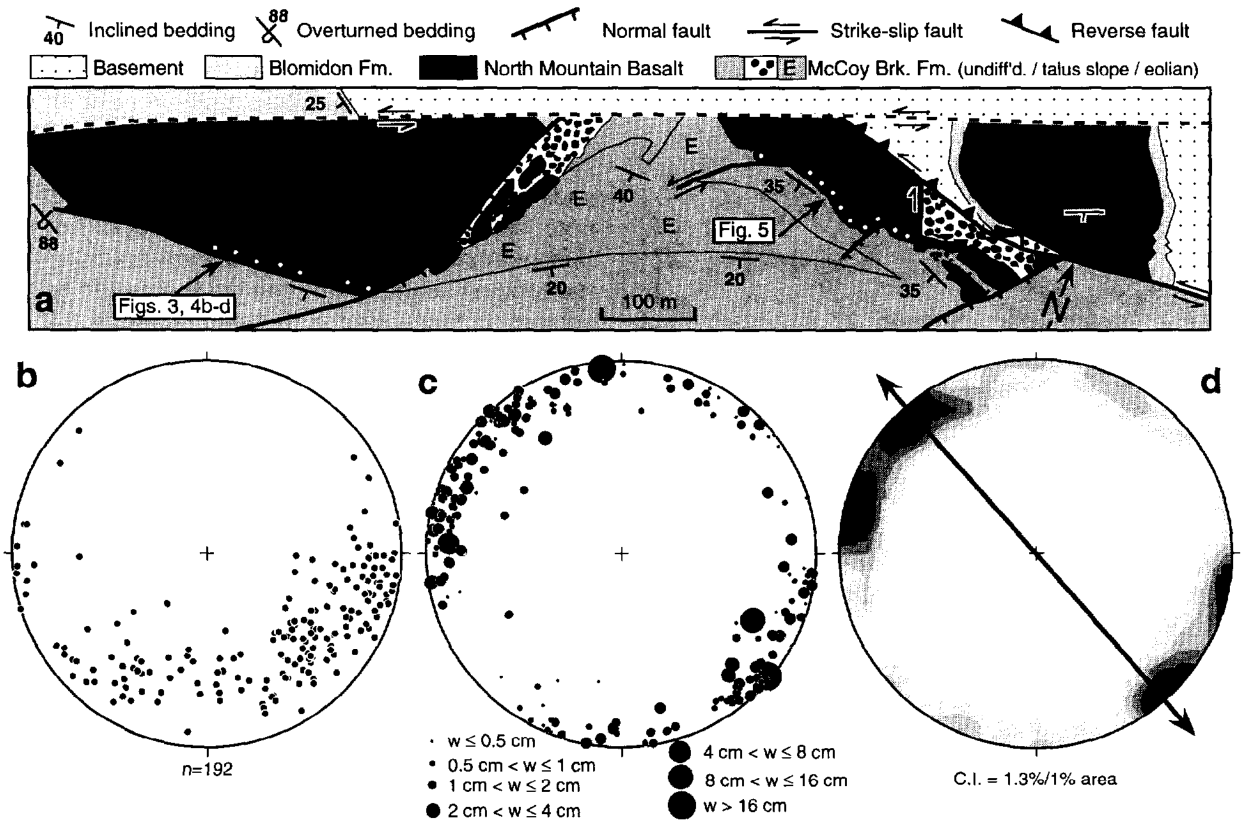
40 Inclined bedding
88 Overturned bedding
Normal fault
Strike-slip fault
Reverse fault
Basement
Blomidon Fm.
North Mountain Basalt
E McCoy Brk. Fm. (undiff'd. / talus slope / eolian)
25
88
E
40
35
Fig. 5
20
35
Figs. 3, 4b-d
100 m
N
a
b
n=192
c
· w ≤ 0.5 cm
• 0.5 cm < w ≤ 1 cm
• 1 cm < w ≤ 2 cm
● 2 cm < w ≤ 4 cm
● 4 cm < w ≤ 8 cm
● 8 cm < w ≤ 16 cm
● w > 16 cm
d
C.I. = 1.3%/1% area

Fig. 4.

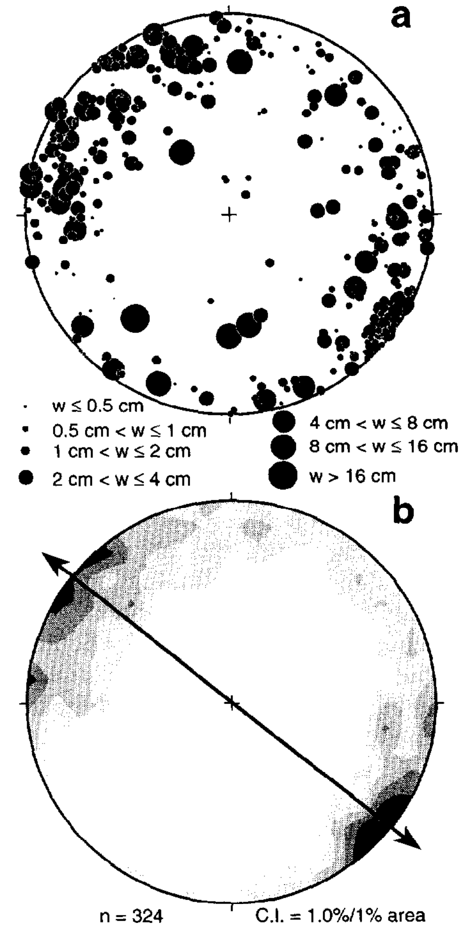
a
· w ≤ 0.5 cm
• 0.5 cm < w ≤ 1 cm
• 1 cm < w ≤ 2 cm
● 2 cm < w ≤ 4 cm
● 4 cm < w ≤ 8 cm
● 8 cm < w ≤ 16 cm
● w > 16 cm
b
n = 324
C.I. = 1.0%/1% area

Fig. 5.

Ross Creek

The largest number of sediment-filled fissures was found north of Ross Creek along the southeast shore of Scots Bay. This study area is located on the southeastern limb of a large, gently SW-plunging syncline thought to be related to post-rift basin inversion (Figs. 1b and 7a, Withjack *et al.* 1992, in press). The top of the lava flow at the study site generally dips gently to the north–northwest, but is locally warped into a series of small synclines, possibly collapse structures, that are filled with Scots Bay Formation (Fig. 7a, Stevens 1987, Olsen *et al.* 1989). No bedding correction was applied to the data discussed below because of the gentle dips (<5°) and variable dip directions associated with the NW-plunging folds.

Of all the study sites, the Ross Creek locality exhibits the most poorly defined preferred orientation of sediment-filled fissures. There are minor concentrations of NNW-striking and NNE-striking fissures, indicating ENE–WSW and WNW–ESE extension directions, respectively (Figs. 7c & d). A subset of the data collected from the northern part of the study area (on the limb of one of the collapse synclines) exhibits a much better defined concentration of poles to the fissures, indicating NW–SE extension (Fig. 7b). The fissures excluded from this subset were measured mainly from a broad anticlinal structure, which may have experienced localized axis-normal (NE–SW) stretching. Indeed, fissures found nearer the crest of the anticlinal structure strike predominantly to the northwest, whereas NE-striking fissures become more prevalent at structurally lower levels.

The formation of the collapse synclines and intervening anticlines, the filling of the collapse synclines, and the formation and filling of the fissures are penecontemporaneous because: (1) the Scots Bay Formation progressively onlaps the limbs of the collapse synclines; (2) the fill of the fissures is virtually identical to the Scots Bay Formation; and (3) the orientation of many of the fissures appears to have been influenced by localized NE–SW stretching in the crests of the broad anticlines between the collapse synclines. A large number of the fissures are cut by quartz-fiber veins (see Fig. 2c) that uniformly strike to the northeast, indicating post-fissure-filling NW–SE extension (Fig. 7d).

DISCUSSION

In spite of the wide range of fissure orientations resulting from their occurrence along cooling joints within the North Mountain Basalt, preferred orientations are clearly evident in the data from the two Wasson Bluff localities (Figs. 4 and 5), from McKay Head (Fig. 6), and in the subset of the Ross Creek study site (Fig. 7b). Furthermore, NW–SE extension is indicated by all but the McKay Head fissures, which may have been rotated as a consequence of dextral slip on the bounding fault zones during post-rift basin inversion (Fig. 6, Olsen *et al.* 1992, Withjack *et al.* in press). The same general extension direction is indicated by: (1) the NE-trending half-graben geometry of the Fundy and Chignecto subbasins and their NE-striking, predominantly dip-slip border fault systems (Fig. 1b); (2) the mosaic of E-striking sinistral and NE-striking normal faults along the northern region of the Minas subbasin (Fig. 1d, Olsen & Schlische 1990); (3) the pattern of small-scale faults at Wasson Bluff (Fig. 4a, Olsen & Schlische 1990); (4) NE-striking clastic dikes within the upper Blomidon Formation; (5) the NE-striking Shelburne diabase dike (Fig. 1b); and (6) the quartz-fiber veins at Ross Creek (Fig. 7d). We therefore suggest that the orientation of sediment-filled fissures in basalt may serve as a useful kinematic indicator in the absence of other structures. In addition to their orientation, the width of a fissure may provide useful kinematic information. As exemplified by the Wasson Bluff fissures (Fig. 3), the widest fissures clearly formed normal to the extension direction.

The fissures in the North Mountain Basalt were filled from above, although the exact mechanism of fissure filling is unknown. The uncertainty stems from the lack of sedimentary structures in the fissure fills and because most fissures were observed in plan view. At McKay Head (Fig. 2a), where the contact between fissure-bearing North Mountain Basalt and the overlying McCoy Brook Formation is well exposed, the apparent lack of deformed strata in the McCoy Brook Formation suggests that forceful injection is unlikely. Rather, the fissures were infilled by the same agents that deposited the overlying sedimentary units.

The sediment-filled fissures place tight constraints on the relative timing of the deformation. The fissures occupy cooling joints in the North Mountain Basalt, which crystallized at 202 ± 1 Ma (Hodych & Dunning 1992). In addition, the fissures are filled with sedimentary material that very closely resembles the basal McCoy Brook and Scots Bay Formations. Based on a variety of biostratigraphic, cyclostratigraphic and geochemical correlations of the Fundy basin stratigraphy with that of the Newark basin (Fig. 1a), Olsen *et al.* (1987) estimated that the basal McCoy Brook Formation in the Wasson Bluff area is <200 k y younger than the Triassic–Jurassic boundary, located within the upper

Fig. 4. (a) Geologic map of the Wasson Bluff area (see Fig. 1d for location), showing locations of sediment-filled fissures (white circles). Modified from Olsen & Schlische (1990). (b) Scatter plot of poles to fissures from the western part of Wasson Bluff in geographic coordinates. (c) 'Bedding'-corrected scatter plot of poles to fissures with width also indicated. The widest fissures are generally NE-striking. (d) Contoured Schmidt plot of data in (c). The fissures indicate a NW–SE extension direction.

Fig. 5. Attitude of sediment-filled fissures in the North Mountain Basalt near the central part of Wasson Bluff (see Fig. 4a for location). (a) 'Bedding'-corrected scatter plot of poles to fissures with width also indicated. (b) Contoured Schmidt plot of data in (a). The fissures indicate a NW–SE extension direction.

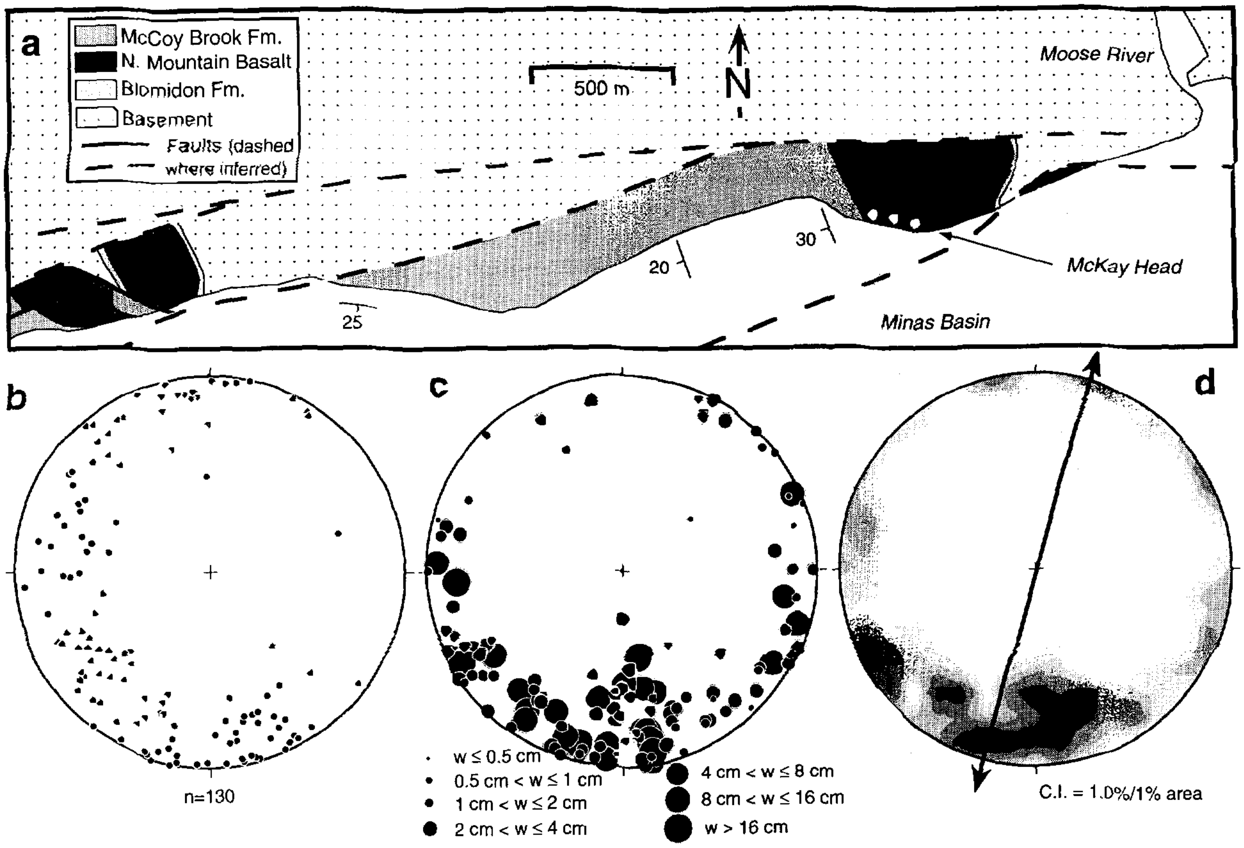
a
McCoy Brook Fm.
N. Mountain Basalt
Blomidon Fm.
Basement
Faults (dashed where inferred)
500 m
N
Moose River
20
30
25
McKay Head
Minas Basin
b
c
d
n=130
w ≤ 0.5 cm
0.5 cm < w ≤ 1 cm
1 cm < w ≤ 2 cm
2 cm < w ≤ 4 cm
4 cm < w ≤ 8 cm
8 cm < w ≤ 16 cm
w > 16 cm
C.I. = 1.0%/1% area

Fig. 6.

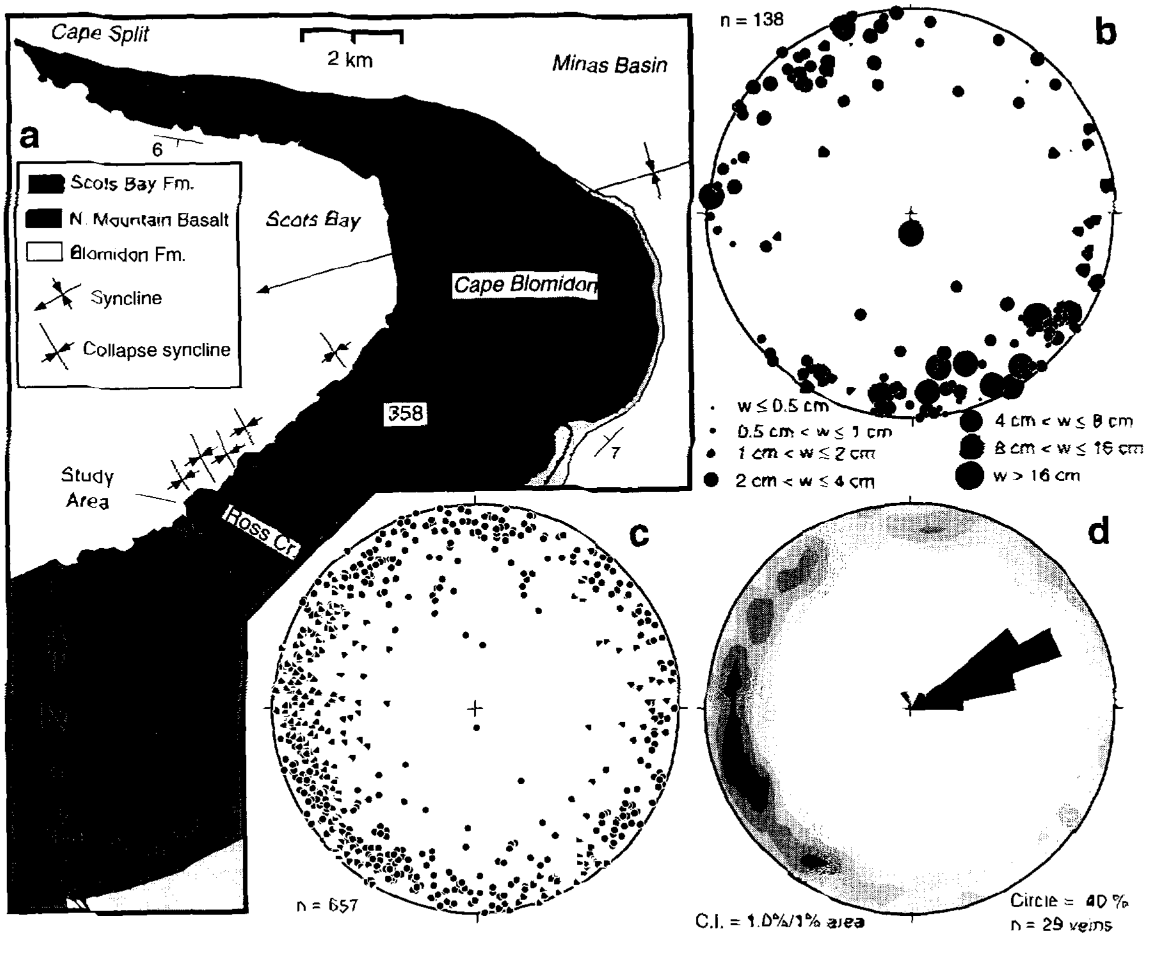
Cape Split
2 km
Minas Basin
a
6
Scots Bay Fm.
N. Mountain Basalt
Blomidon Fm.
Syncline
Collapse syncline
Scots Bay
Cape Blomidon
358
7
Study Area
Ross Cr.
n = 138
b
w ≤ 0.5 cm
0.5 cm < w ≤ 1 cm
1 cm < w ≤ 2 cm
2 cm < w ≤ 4 cm
4 cm < w ≤ 8 cm
8 cm < w ≤ 16 cm
w > 16 cm
c
n = 657
d
C.I. = 1.0%/1% area
Circle = 40 %
n = 29 veins

Fig. 7.

Blomidon Formation, <1 m below the North Mountain Basalt. The fissures therefore formed in the earliest Jurassic. Such precise relative dating is generally not available from more traditional structures like faults, joints and veins.

The deformation responsible for the fissures was a near-surface phenomenon. Other evidence for shallow-level deformation in the Fundy basin includes: (1) upward-widening fault zones containing sedimentary material within the fault breccia (Schlische 1990); (2) paleotalus slope deposits (Olsen & Schlische 1990, Tanner & Hubert 1990); and (3) unmineralized faults and hydroplastic slickensides (terminology of Laville & Petit 1984) within sedimentary rocks of the McCoy Brook Formation (Olsen & Schlische 1990).

Basalt-hosted sediment-filled fissures are not unique to the Fundy rift basin. Similar types of features have been observed in the Deerfield Basalt of the Deerfield subbasin (Olsen *et al.* 1989), the Hampden Basalt of the Hartford subbasin (adjacent to the border fault of the basin), and the Orange Mountain Basalt of the Newark basin (Fig. 1a). Sediment-filled fissures in the Newark basin occur on the limb of the Flemington syncline, which plunges northwestward to the adjacent Flemington intrabasinal normal fault. Fissures from this site have a preferred orientation and indicate NE–SW extension (R. W. Schlische & R. V. Ackermann, unpublished data).

SUMMARY AND CONCLUSIONS

(1) Within the early Mesozoic Fundy rift basin, sediment-filled fissures are common near the upper surface of the Early Jurassic North Mountain Basalt, near the tops of individual flows within the basalt, and adjacent to fault zones.

(2) The steeply dipping fissures have planar to sub-planar borders; range in width from a few millimeters to 40 cm; are filled with sandstone or mudstone that commonly contains sub-rounded basalt clasts; commonly occupy pre-existing cooling joints within the basalt; and, in some cases, taper in width downward.

(3) The fissures formed as a result of extension of the basalt and subsequent infilling from above; significant tilting of the basalt at most study sites post-dated fissure formation.

(4) At multiple study sites, the fissures indicate a preferred orientation, despite the wide variety of attitudes for the preexisting cooling joints. The extension direction indicated by the fissures at most of the study sites is northwest–southeast, which is consistent with mesoscopic and macroscopic structures within the Fundy basin. Thus, sediment-filled fissures by themselves may be useful kinematic indicators.

(5) The sediment-filled fissures in the Fundy basin constrain this near-surface deformation to the first 200,000 years of the Jurassic.

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Fig. 6. (a) Geologic map of the McKay Head area (see Fig. 1d for location), showing the location of sediment-filled fissures (white circles). (b) Scatter plot of poles to fissures in geographic coordinates. (c) 'Bedding'-corrected scatter plot of poles to fissures with width also indicated. (d) Contoured Schmidt plot of data in (c). The fissures indicate a NNE–SSW extension direction.

Fig. 7. (a) Geologic map of the Cape Blomidon region (see Fig. 1b for location). (b) Scatter plot of poles to fissures from northeast end of Ross Creek study area with fissure widths indicated. (c) Scatter plot of poles to all fissures in study area. (d) Contoured Schmidt plot diagram of poles shown in (c) along with rose diagram of strike of quartz veins.

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