PERGAMON

Journal of Structural Geology 23 (2001) 1067–1077

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Deciphering the Neoproterozoic history of the Hollow Fault, Avalon terrane, mainland Nova Scotia

J.B. Murphy[a,*], J.D. Keppie[b], J. Stacey[a], R. Trainor[a]

[a]*Department of Geology, St. Francis Xavier University, P.O. Box 5000, Antigonish, Nova Scotia, Canada, B2G 2W5*
[b]*Instituto de Geologia, Universidad Nacional Autonoma de Mexico, Mexico, D.F., Mexico*

Received 2 February 1999; accepted 25 July 2000

Abstract

Recognition and deciphering of the early history of fault zones is difficult because younger fabrics commonly overprint and obscure older ones. The Hollow–Greendale Fault system in the Avalon terrane of the northern Antigonish Highlands in mainland Nova Scotia has suffered many episodes of motion in the Paleozoic during development of the Appalachian orogen. Field relationship and petrographic observations indicate that its Neoproterozoic history is preserved as ca. 610 Ma NE- and NW-trending ductile shear zones within the Georgeville Group contact aureole of the intrusive syn- to late-tectonic Greendale Complex. Kinematic indicators within the NE-trending shear zone along the southwestern contact indicate dextral shear and are compatible with dextral shear indicators within the Greendale Complex and with the orientation of coeval regional F_1 fold structures within the Antigonish Highlands. The NW-trending shear zone along the northeastern contact represents either a step-over fault within a dextral shear zone or a zone of localized transpression associated with the emplacement of the Greendale Complex. Local preservation of Neoproterozoic shear zone fabrics within the Georgeville Group host rocks is attributed to the shielding effects of the proximal Greendale Complex, which acted as a rigid unit during Paleozoic deformation so that subsequent motion along the Hollow Fault was partitioned along the northeastern and southwestern contact of the complex. The Neoproterozoic history, combined with paleocontinental reconstructions, indicates that the Hollow–Greendale fault system was part of an important regional strike-slip fault zone within a volcanic arc regime along the periphery of Gondwana (Murphy et al., 1999a,b). © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Recognition and deciphering of the early history of faults is a major problem in orogenic belts because reactivation commonly obscures kinematic evidence of earlier movements. Faulting and reactivation have played major roles in the evolution of the Appalachian orogen in eastern North America (e.g. Williams et al., 1995) which involved the opening and subsequent closure of the Iapetus and Rheic oceans between Laurentia and Gondwana (Williams, 1979; Keppie, 1993; van Staal et al., 1996, 1998). Early Cambrian extensional faulting and passive margin development gave way to Late Cambrian convergence, Early Ordovician thrusting associated with foundering of the passive margin and ophiolite obduction, followed by Late Ordovician–Devonian thrusting and strike-slip tectonics associated with collisions between Laurentia and outboard terranes (including Avalonia) and finally Permo–Carboniferous terminal collision to form Pangea (Williams, 1979; Keppie, 1985; van Staal et al., 1998). A wealth of paleomagnetic, paleontological, geochemical and isotopic data indicate that Avalonia, which is the largest suspect terrane in the northern Appalachians, migrated from its original setting along the Gondwanan margin in the Neoproterozoic (Fig. 1a; O'Brien et al., 1983, 1996; Johnson and van der Voo, 1986; Murphy and Nance, 1989; Keppie et al., 1996), became accreted to Laurentia by the Late Ordovician (e.g. McKerrow et al., 1991; O'Brien et al., 1991, 1994; Cawood et al., 1994; Hodych and Buchan, 1994; Lin et al., 1994; van Staal et al., 1996) and subsequently was dispersed along the Laurentian margin by sinistral followed by dextral strike-slip faults between the Silurian and Late Carboniferous (Fig. 1b; Keppie, 1982; Nance et al., 1991; Hibbard, 1994; Holdsworth, 1994; Yeo and Ruixiang, 1987).

Each stage in the migration of Avalonia was accompanied by episodes of movement on NE-trending fault zones including the Hollow–Greendale fault system (Fig. 2; Murphy et al., 1999). In many parts of the Appalachians, later movements on fault zones have obscured evidence of older movements thereby hindering kinematic analysis of the early history of these fault zones (Williams et al., 1995).

---

* Corresponding author. Tel.: +1-902-867-2481; fax: +1-902-867-2457.
E-mail address: bmurphy@stfx.ca (J.B. Murphy).

PII: S0191-8141(00)00176-0

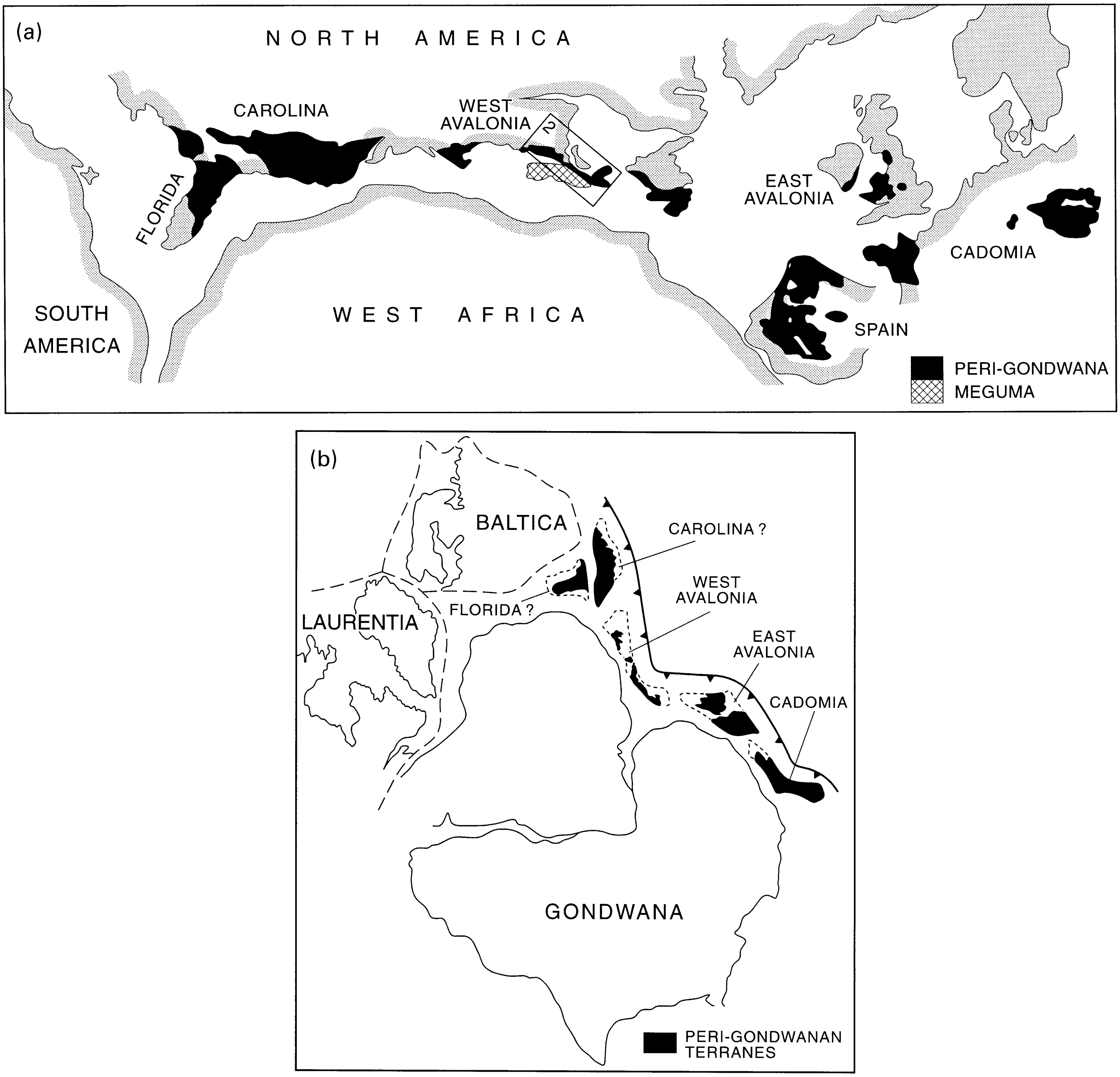


Fig. 1. (a) Map of the north Atlantic Borderlands in their pre-Mesozoic drift positions, showing the distribution of Neoproterozoic peri-Gondwanan terranes (modified from Strachan and Taylor, 1990). The portion of Avalonia in Atlantic Canada is identified as West Avalonia, the portion in Britain and Ireland is known as East Avalonia. Only areas where Cambrian overstep sequences occur are identified (see Keppie, 1985). Avalonian rocks in Maritime Canada occur in the rectangled area, and are shown in more detail in Fig. 2. (b) Proposed distribution of Neoproterozoic peri-Gondwanan terranes (modified from Nance and Murphy, 1996) in the Neoproterozoic reconstruction of Dalziel (1992).

In this paper, we document the Neoproterozoic kinematic history of the NE-trending Hollow Fault Zone that is preserved in host rocks adjacent to a syn- to late-tectonic plutonic complex known as the Greendale Complex in the Avalon terrane of mainland Nova Scotia. These data have special tectonic significance because the Hollow Fault is thought to be a major component of an arc to arc-transform fault system along the Gondwanan margin in the Neoproterozoic (Murphy and Nance, 1989; Murphy et al., 1999a,b). Subsequent (Paleozoic) movement along the Hollow Fault was deflected around the Greendale Complex, thereby facilitating preservation of these earlier fabrics in a “strain shadow” region within the host rocks. Such regions are critical in locating zones where older fabrics may be preserved in reactivated fault systems (see also Holdsworth et al., 1997).

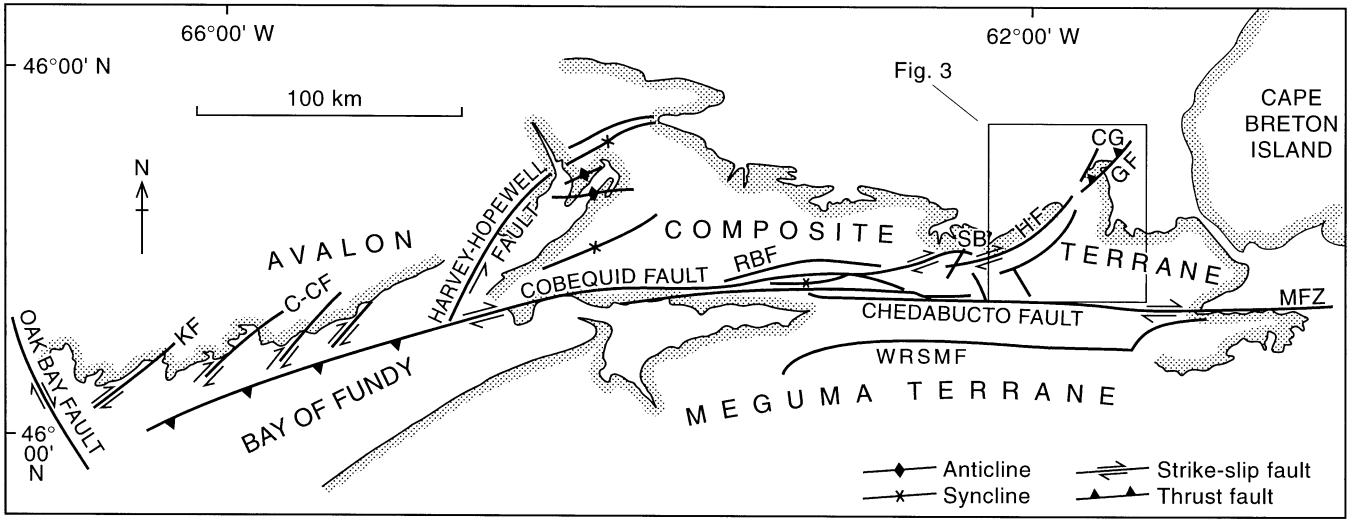
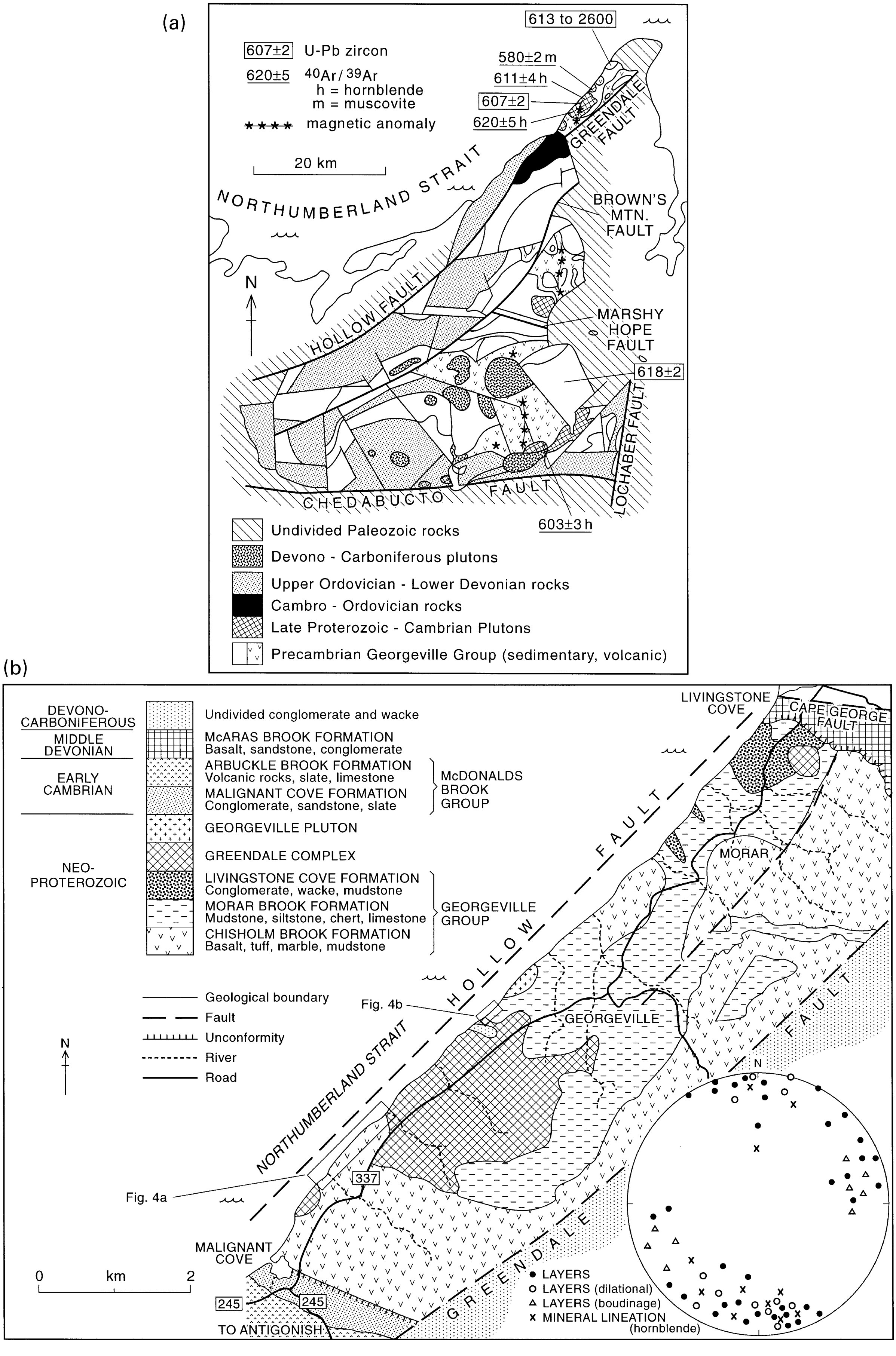


Fig. 2. Location of important fault systems within Avalonia and the linkage between these NE-trending faults and the E–W Minas Fault Zone (MFZ) along the Avalon–Meguma boundary represented by the Chedabucto Fault in mainland Nova Scotia and by thrusts (triangles) in the Bay of Fundy (modified from Keppie, 1982; Nance, 1987; St. Jean et al., 1993). HF—Hollow Fault; GF—Greendale Fault; RBF—Rockland Brook Fault; KF—Kennebacasis Fault; C–CF—Caledonia–Clover Hill Fault; WRSMF—West River St. Marys Fault. These fault systems were active at various times in the Paleozoic and Early Mesozoic. The rectangle shows the location of the Antigonish Highlands (for details see Fig. 3). The northernmost exposure of the Hollow–Greendale Fault system on mainland Nova Scotia is at Cape George (CG) and the system terminates in the Stel Basin (SB).


(a)
607±2 U-Pb zircon
620±5 40Ar/39Ar
h = hornblende
m = muscovite
★★★★ magnetic anomaly
20 km
N
613 to 2600
580±2 m
611±4 h
607±2
620±5 h
NORTHUMBERLAND STRAIT
GREENDALE FAULT
BROWN'S MTN. FAULT
HOLLOW FAULT
MARSHY HOPE FAULT
618±2
LOCHABER FAULT
CHEDABUCTO FAULT
603±3 h
Undivided Paleozoic rocks
Devono - Carboniferous plutons
Upper Ordovician - Lower Devonian rocks
Cambro - Ordovician rocks
Late Proterozoic - Cambrian Plutons
Precambrian Georgeville Group (sedimentary, volcanic)
(b)
DEVONO-CARBONIFEROUS
MIDDLE DEVONIAN
EARLY CAMBRIAN
NEO-PROTEROZOIC
Undivided conglomerate and wacke
McARAS BROOK FORMATION
Basalt, sandstone, conglomerate
ARBUCKLE BROOK FORMATION
Volcanic rocks, slate, limestone
MALIGNANT COVE FORMATION
Conglomerate, sandstone, slate
McDONALDS BROOK GROUP
GEORGEVILLE PLUTON
GREENDALE COMPLEX
LIVINGSTONE COVE FORMATION
Conglomerate, wacke, mudstone
MORAR BROOK FORMATION
Mudstone, siltstone, chert, limestone
CHISHOLM BROOK FORMATION
Basalt, tuff, marble, mudstone
GEORGEVILLE GROUP
Geological boundary
Fault
Unconformity
River
Road
N
0 km 2
LIVINGSTONE COVE
CAPE GEORGE FAULT
HOLLOW FAULT
MORAR
NORTHUMBERLAND STRAIT
Fig. 4b
GEORGEVILLE
FAULT
Fig. 4a
337
MALIGNANT COVE
245
245
TO ANTIGONISH
GREENDALE
N
● LAYERS
○ LAYERS (dilational)
△ LAYERS (boudinage)
x MINERAL LINEATION (hornblende)

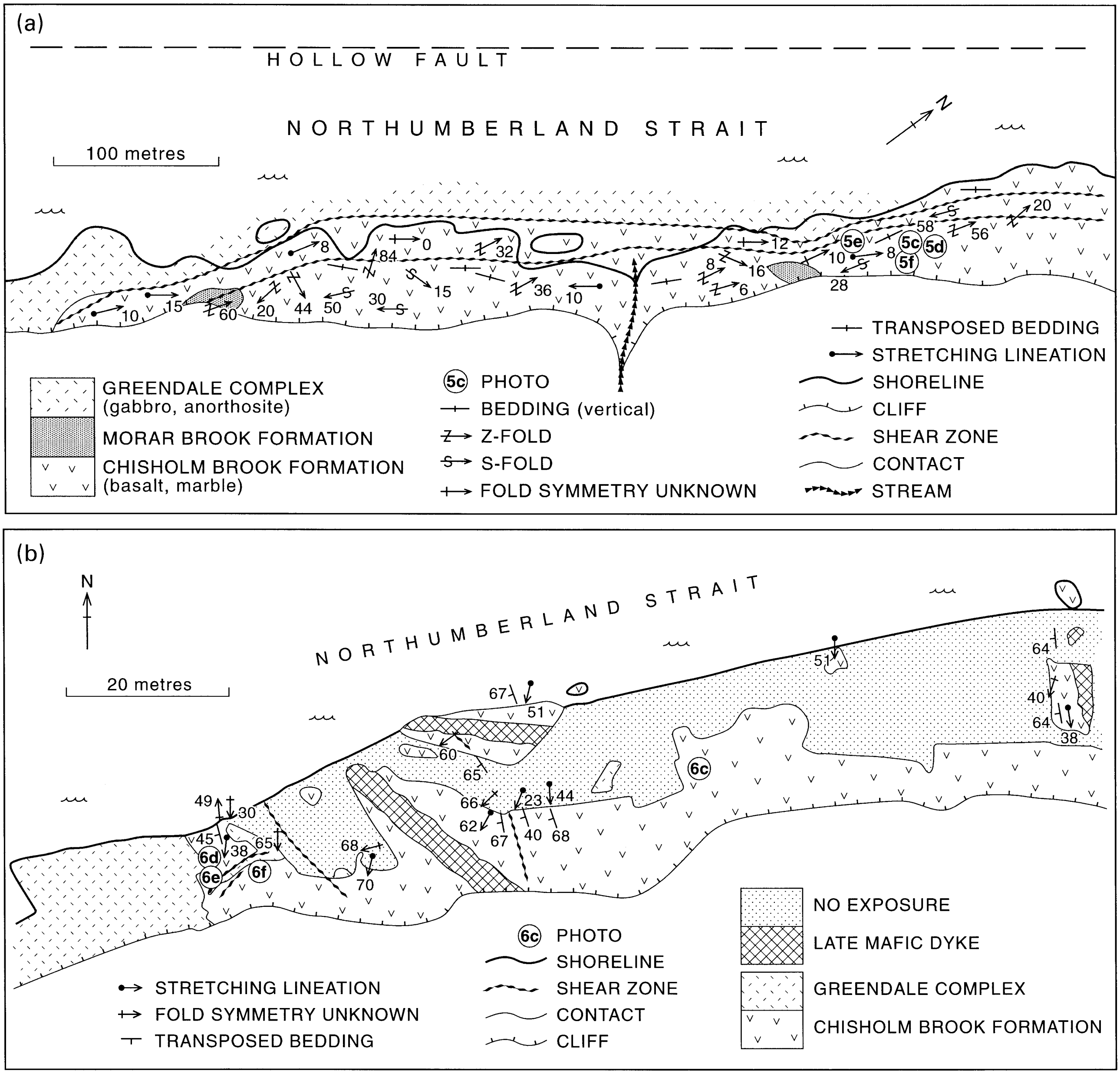
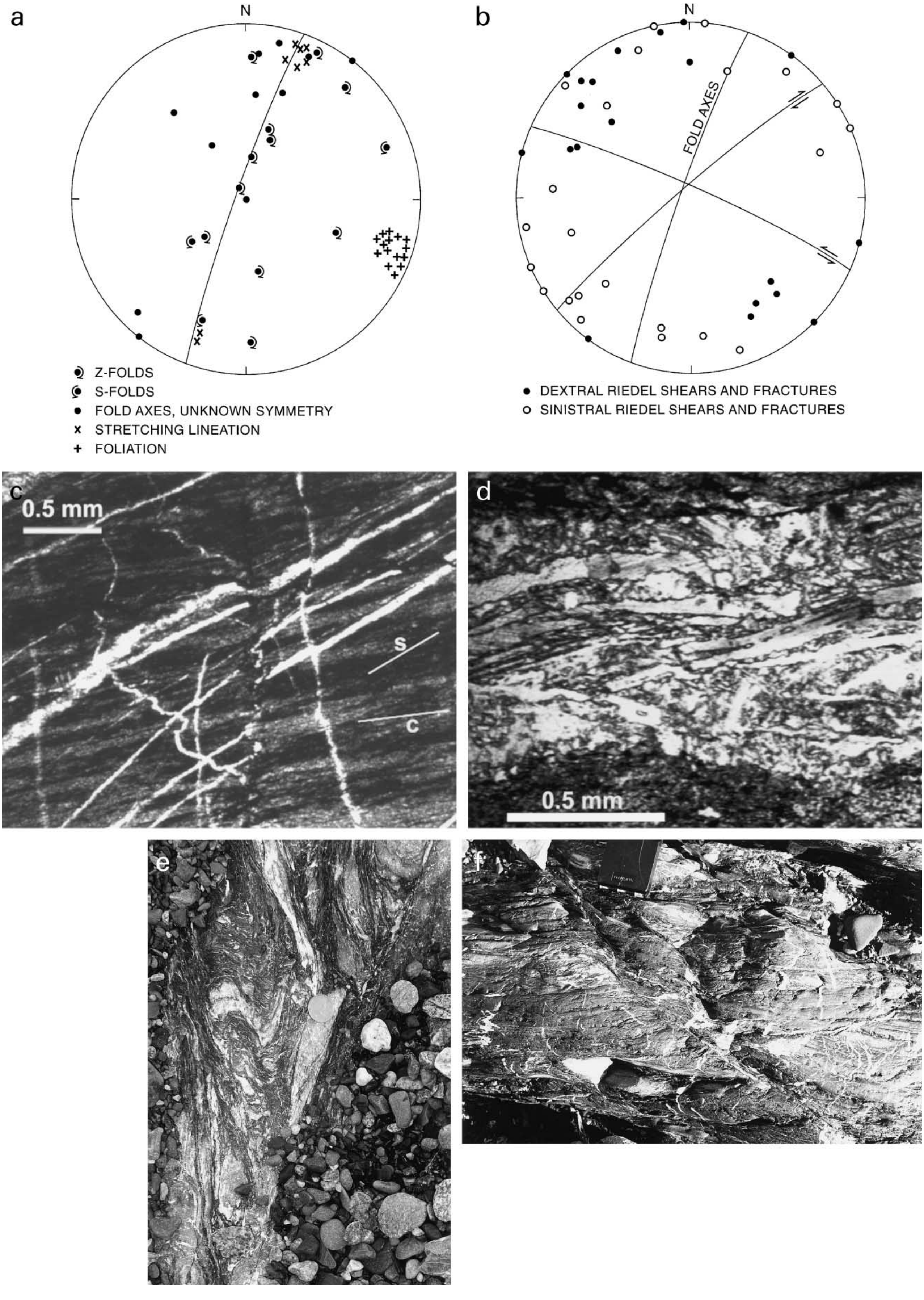


Fig. 4. Maps of the host rock Georgeville Group adjacent to: (a) the southwestern contact, and (b) the northeastern contact with the Greendale Complex. For locations see Fig. 3b.

2. Geological setting

Regional syntheses suggest that the Neoproterozoic rocks in the Antigonish Highlands are local representatives of widespread ca. 700–550 Ma arc to arc-transform sequence developed along the periphery of Gondwana (Murphy and Nance, 1989). The Antigonish Highlands are bounded to the northwest by the Hollow Fault, and to the south by the Chedabucto Fault (Fig. 3a,b; Murphy and Keppie, 1987; Murphy et al., 1991). The highlands are predominantly

Fig. 3. (a) Geological map of the Antigonish Highlands (after Murphy et al., 1991) showing the distribution of Late Precambrian and Paleozoic rocks (for location, see Fig. 2). Precambrian rocks belong to the Georgeville Group, Cambro–Ordovician rocks to the Iron Brook and McDonalds Brook Groups, Late Ordovician to Early Devonian rocks to the Arisaig Group (A) and undivided Paleozoic rocks represent various groups of latest Devonian–Carboniferous age. (b) Summary of the geology of the northern Antigonish Highlands, between the Hollow and Greendale faults, modified after Murphy et al. (1991). The inset shows an equal area stereoplot (from Murphy and Hynes, 1990) of structural data from the Greendale Complex. Many of the steeply dipping layers are dilational, strike E–W and have N–S hornblende mineral linetations. These layers are thought to have been emplaced along the extensional plane in the instantaneous strain ellipsoid in response to dextral shear on the Hollow–Greendale fault system. Other layers are thought to have been rotated towards the plane of flattening and commonly exhibit boudinage.


a
N
Z-FOLDS
S-FOLDS
● FOLD AXES, UNKNOWN SYMMETRY
× STRETCHING LINEATION
+ FOLIATION
b
N
FOLD AXES
● DEXTRAL RIEDEL SHEARS AND FRACTURES
○ SINISTRAL RIEDEL SHEARS AND FRACTURES
c
0.5 mm
s
c
d
0.5 mm
e
f

underlain by the ca. 618–610 Ma Neoproterozoic Georgeville Group which comprised of a ca. 4000 m succession of arc-related volcanic rocks overlain by a thick sequence of turbidites and which is bounded to the northwest by the Hollow Fault and to the south by the Chedabucto Fault. D_1 deformation of the Georgeville Group produced isoclinal N–S F_1 folds followed by upright N–S F_2 folds. Intrusion of ca. 610–605 Ma mafic to felsic plutonic complexes was syn- to late tectonic with respect to D_1 (Murphy and Hynes, 1990). The Greendale Complex is the most voluminous of these plutonic complexes. Exposed only in the northernmost highlands between the Hollow and Greendale faults, the complex predominantly consists of dykes of both mafic and felsic compositions (Murphy et al., 1997a,b). The abundance and orientation of dykes in the complex suggests that intrusion was associated with progressive and repeated extensional failure at the roof of the magma chamber during dextral shear along the Hollow–Greendale fault system (see Murphy and Hynes, 1990; Fig. 3b).

These Neoproterozoic rocks are unconformably overlain by Cambrian to Lower Ordovician rocks that are interpreted to have been deposited in a pull-apart basin generated by dextral strike-slip motion between the Hollow and Greendale faults (Keppie and Murphy, 1988). They were deformed in the Late Ordovician by thrusting associated with coeval sinistral movement along these faults during accretion of Avalonia to North America (Murphy et al., 1999). This deformation was localized in the centre of the basin and did not affect basal Cambrian units along the basin margin or the unconformably underlying Georgeville Group. The Late Ordovician to Early Devonian Arisaig Group unconformably overlies Neoproterozoic and Cambrian–Early Ordovician sequences and consists of bimodal volcanic rocks and interbedded continental clastics at the base, overlain by a thick sequence of marine siliciclastic rocks (Boucot et al., 1974; Murphy et al., 1991). This sequence is inferred to have been deposited during strike-slip motion of Avalonia along the Laurentian margin (Murphy et al., 1999).

During the middle Devonian to Late Carboniferous, episodic motion along the Hollow–Greendale fault system, reflecting regional dextral shear along the Avalon–Meguma terrane boundary, profoundly affected the depositional history and structural style of coeval rocks. The best examples occur: (i) in the Cape George along the northeastern margin of the Antigonish Highlands (Fig. 2) where Late Carboniferous transpression along the Hollow–Greendale fault system resulted in the development of a positive flower structure (St. Jean et al., 1993), and (ii) along the southwestern margin of the Antigonish Highlands where transfer of motion between the Hollow and Cobequid faults led to the Late Carboniferous development of a pull-apart basin (Fig. 2; Yeo and Ruixiang, 1987).

3. Neoproterozoic deformation in the Antigonish Highlands

3.1. The Hollow–Greendale fault system

Between the Hollow and Greendale faults in the northern Antigonish Highlands, the Georgeville Group consists of basalts and interbedded marbles of the Chisholm Brook Formation, overlain by mudstones and tuffaceous rocks of the Morar Brook Formation followed by turbiditic conglomerates and interbedded mudstones of the Livingstone Cove Formation (Fig. 3a,b). Recent U–Pb geochronological data indicate that the depositional age of the Georgeville Group is constrained between ca. 620–608 Ma. Zircons in rhyolites from the lowermost portion of the group yield crystallization ages of 618 ± 2 Ma (Murphy et al., 1997a) whereas the youngest detrital zircon in turbidites has an age of 613 ± 5 Ma (Keppie et al., 1998).

The Georgeville Group was regionally deformed by isoclinal and upright folds and metamorphosed to lower greenschist facies (chlorite grade) prior to the intrusion of the ca. Greendale Complex (Fig. 3a) which has yielded ages of 607 ± 2 Ma (U–Pb, titanite, Murphy et al., 1997a) and 611 ± 4 Ma ($^{40}Ar/^{39}Ar$, hornblende, Keppie et al., 1990). The limited time gap between deposition and intrusion of the Georgeville Group constrains the age of regional deformation to between 618–605 Ma. In general, throughout most of the Antigonish Highlands, this deformation produced only a weak cleavage which is parallel or subparallel to bedding, except in the hinges of rarely preserved F_1 folds (Murphy et al., 1991). However, recent detailed mapping in the vicinity of the Hollow Fault shows that an intense foliation is developed in two localities within the Georgeville Group host rocks adjacent to the contacts with the Greendale Complex (Figs. 3b and 4a,b). These localities have well developed stretching lineations, asymmetric augen predominantly defined by plagioclase porphyroclasts in the mafic rocks, C–S fabrics, sheath folds, and a transposed foliation that is axial planar to

Fig. 5. Structural features and data along the southwestern contact of the Greendale Complex. (a,b) Equal-area projections displaying the orientation and symmetry of small scale folds and poles to the predominant foliation (a) and shear and fracture surfaces (b); (c) photomicrograph showing intrusion and progressive rotation of calcite veinlets within a dextral strike-slip regime. Later veinlets intrude parallel to the plane of extension in the instantaneous strain ellipsoid (approximately perpendicular to the S fabric) within the field of shortening and so are folded. Earlier veinlets, although originally intruded within the field of instantaneous shortening are stretched as they are rotated towards parallelism with the S-fabric; (d) photomicrograph of a bedding-parallel calcite vein showing stretching lineation oriented parallel to the S-fabric in the outcrop; (e) moderately plunging fold with Z asymmetry with an axial plane oriented parallel to the S-fabric; (f) C–S fabrics displaying dextral kinematics, and a pronounced dextral shear (upper right to lower left) is interpreted as a synthetic Riedel shear. Locations of photographs are shown in Fig. 4a.

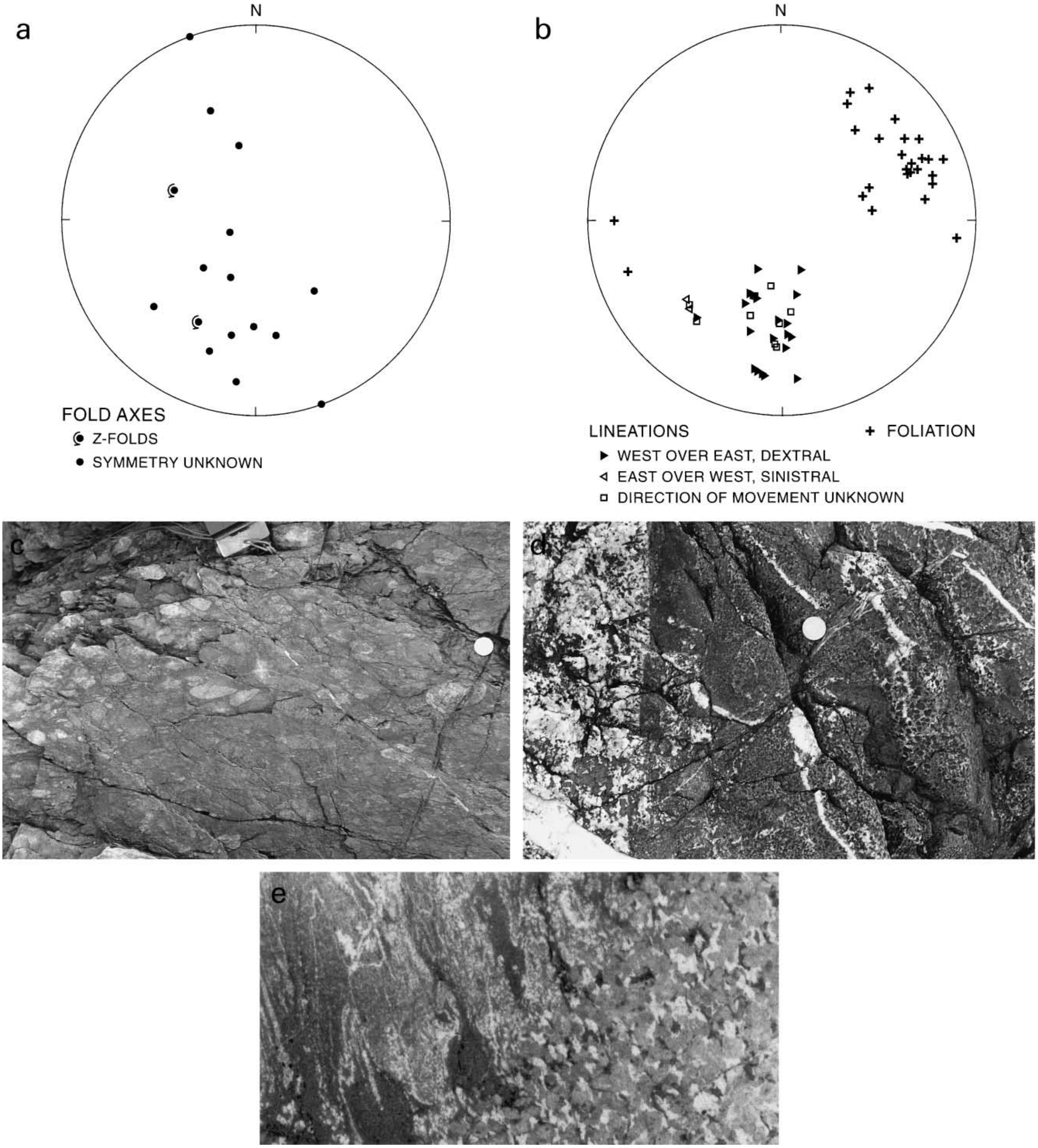


Fig. 6. Structural data and features along the northeastern contact of the Greendale Complex. (a,b) Equal area stereoplots showing: (a) orientation and asymmetry of fold axes; (b) mineral lineations with sense of shear determined from adjacent augen and poles to foliation planes adjacent to the northern contact of the Greendale Complex. (c) a relatively weakly defined fabric in volcaniclastic rocks along the northerneasternmost portion of the shear zone, (d) field photograph of the northeastern contact of the Greendale Complex showing contact metamorphic growth of hornblende (right) within the host rock basalts, (e) photomicrograph displaying sheared contact between host rock (left) and a Greendale Complex felsic dyke (right). The dyke intrudes across the contact between the complex and the host rock, and shows evidence of shear across its margin (field of view, 1 × 2 cm). Locations of photographs are shown in Fig. 4b.

locally developed “fold hooks”. These features indicate that the rocks underwent non-coaxial strain and are interpreted to represent the products of ductile shear zones. Regional studies show that Paleozoic deformation events were localized and did not significantly affect the underlying Georgeville Group rocks. This suggests that the present orientation of the shear zone fabrics in the study area reflects their Neoproterozoic orientation.

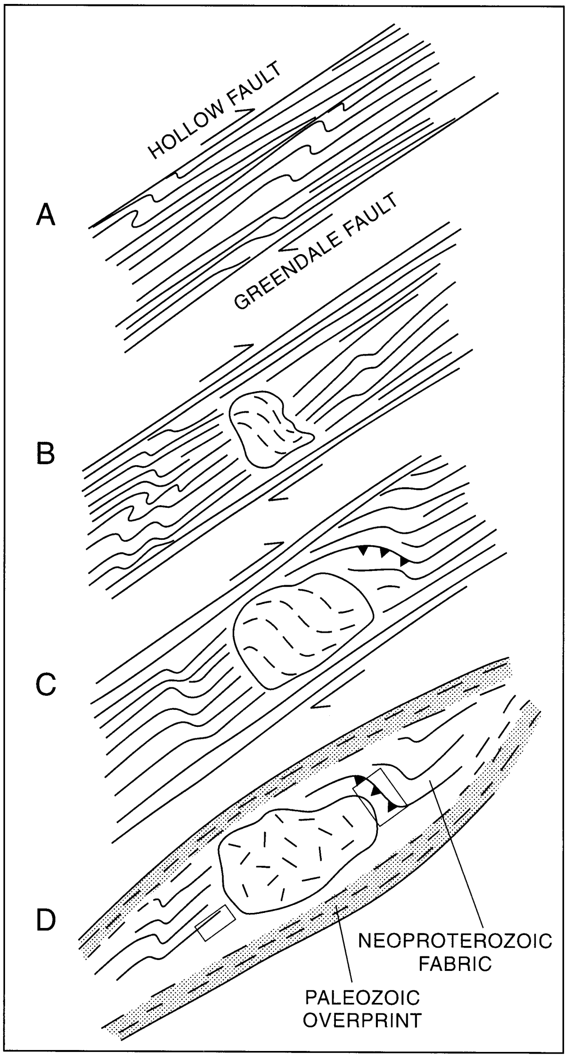


Fig. 7. Schematic diagram showing the development of shear zone fabrics in the Neoproterozoic, and their preservation in the Paleozoic. A, B and C reflect the ca. 610–605 Ma progressive development of the Hollow–Greendale dextral shear zone during system late-tectonic intrusion of the Greendale Complex (for an account of the origin and orientation of layering in the complex within a dextral shear regime, see Murphy and Hynes, 1990). Oblique dextral shear on the NNW shear zone near the northern coast may reflect folding during progressive dextral shear or strain softening and wedge during the intrusion of the Greendale Complex; D: Paleozoic deformation is partitioned to the north and south of the complex (see shaded region), and Neoproterozoic fabrics are locally preserved in strain windows. The rectangles show the inferred locations of the study areas in this regime.

In the southwestern area (Fig. 4a), the predominant foliation is subvertical and NE-striking, i.e. parallel to the Hollow Fault. The contacts between the basalt and marble host rocks to the Chisholm Brook Formation are transposed within the shear zone and are parallel to the predominant foliation (Figs. 4a and 5a). At the western end of this area, this foliation is truncated at the contact with the ca. 610–605 Ma Greendale Complex, indicating that shear zone deformation commenced prior to ca. 610 Ma. Local shears and fracture zones may be divided into NE-striking steep surfaces with dextral offset, and highly variable shear and fracture surfaces with sinistral offset (Fig. 5b). Abundant thin NW-trending carbonate veinlets developed within the basalt and marble host rocks are characterized by fibres oriented perpendicularly to the vein walls. These veinlets are cross-cut, offset and are rotated into the S-fabric indicating that their emplacement was coeval with shear zone deformation (Fig. 5c). Fibres within these veinlets are uniformly oriented, are essentially sub-horizontal to gently plunging either to the NE or SW, lie within the S-fabric and are interpreted to record the stretch direction within the shear zone (Fig. 5d). Fold hinge line orientations are variable, but together define a NNE-striking plane that is oriented counterclockwise with respect to the predominant foliation (Fig. 5a and e). Northeasterly plunging folds have Z-asymmetry (Fig. 5e), whereas SE-trending folds have variable symmetry. The variation in fold axis orientation and fold asymmetry is consistent with the presence of sheath folds. In most localities, S-foliation is oriented counterclockwise with respect to the predominant C-foliation (Fig. 5f).

The limited time interval between deposition and regional deformation of the Georgeville Group indicates that shear zone deformation was probably penecontemporaneous with respect to the development of the regional structures. The orientation of the stretching lineations, S–C fabrics, and sheath folds are consistent with dextral shear of a NE-striking shear zone. The variable orientation of the veinlets in Fig. 5c is consistent with formation normal to the instantaneous stretching direction within the field of shortening followed by progressive clockwise rotation towards the stretching direction in a dextral shear setting. The NE-striking shear and fracture surfaces are interpreted as synthetic Riedel shears. The origin of the variably-oriented surfaces with sinistral shear is less certain; they may represent an antithetic Riedel shear array that was rotated clockwise during progressive dextral shear.

Along the northeastern contact zone (Fig. 4b), the bedding is transposed into the foliation, strikes predominantly NNW, dips moderately to relatively steeply to the WSW, and contains a well developed stretching lineation that plunges moderately to the south (Fig. 6a). Kinematic data in this locality were predominantly obtained from feldspar augen and indicate oblique shear with reverse and dextral components (Fig. 6b). The shear zone is about 200 m wide and dies out gradually northeastwards where clasts in a volcanogenic sedimentary rock have a relatively weakly defined fabric (Fig. 6c). In contrast to the southern contact, the orientation of the transposed foliation is subparallel to the contact with the Greendale Complex and so map-scale cross-cutting relationships cannot be demonstrated. However, randomly-oriented contact metamorphic growth of hornblende in the wall-rock overprints the shear zone fabrics, indicating that the shear zones in the vicinity of the northern and southern contacts underwent similar deformational histories (Fig. 6d). On the other hand, late-stage felsic dykes that are cogenetic with respect to the Greendale Complex and intrude across the contact between the complex and the host rock, show evidence of shear across their contact with the host rocks and the presence of a weakly defined foliation (Fig. 6e) that is parallel to the predominant foliation in the host rock. This relationship indicates that the dykes were intruded into a host rock undergoing coeval shear.

3.2. Interpretation

The spatial association of intense shear zone deformation with the Hollow Fault contrasts with the relatively mild D_1 deformation elsewhere in the Antigonish Highlands and strongly suggests that the shear reflects motion along the Hollow Fault. Constraints on the kinematic history of the shear zone are derived from the fabrics in the two areas studied (Figs. 4 and 5) in addition to fabrics in the Greendale Complex, which indicate that final cooling of the complex was accompanied by dextral strike-slip motion on NE-trending shear zones (Murphy and Hynes, 1990; Murphy et al., 1997a,b). The N–S orientation of coeval regional F_1 and F_2 folds within the Georgeville Group is also consistent with an origin by dextral shear along the NE-trending faults in the Antigonish Highlands, including the Hollow–Greendale fault system (Murphy et al., 1991).

The southwestern contact has structures and kinematics that are consistent with a synthetic shear within a dextral shear regime. Field evidence from the northwestern contact indicates that the shearing of the host rock predates final emplacement of the plutonic complex, whereas geochronological data and kinematic data suggest the host rocks and the Greendale Complex were affected by either episodic or progressive dextral shear along the Hollow–Greendale fault system at about 610 Ma. The shear zone could represent either a synthetic dextral shear that was folded into its present NNW orientation (Fig. 7c,d) or a localized area of transpression associated with strain-softening that occurred during intrusion of the Greendale Complex (e.g. Paterson and Fowler, 1993). The dextral and reverse components of shear on the NNW-trending shear zone along the northeastern contact is inconsistent with a simple R' shear within a dextral riedel shear array. The dyke-like nature of the complex which indicates intrusion by wedging is consistent with the latter explanation. The contact metamorphic growth of hornblende reflects cooling of the complex and provides age constraints on Neoproterozoic shear zone activity.

4. Discussion

The Neoproterozoic evolution of the NE-trending Hollow–Greendale fault system is interpreted as a zone of distributed episodic dextral shear, in which slip is distributed among many faults and shear zones within and adjacent to the Greendale Complex. The limited time gap between the deposition and regional deformation of the Georgeville Group and the intrusion of the plutonic complexes is consistent with a strike-slip setting within the Neoproterozoic volcanic arc (Murphy et al., 1991). This dextral motion has been related to closure of a back-arc basin (Murphy et al., 1997b). Thus, the Hollow Fault Zone may represent an important fault system along the margin of Gondwana.

Given the evidence for repeated motions along the Hollow–Greendale fault system into the Paleozoic, one may ask why the Neoproterozoic fabrics were locally preserved. Preservation is attributed to the shielding effects of the Greendale Complex (schematically represented in Fig. 7) and is analogous to strain shadows adjacent to a rigid porphyroblast that are shielded from the regional stress. After final cooling and consolidation of the complex, strain associated with subsequent events was partitioned along the margins of the complex and Neoproterozoic structures are preserved in strain windows. This approach may aid in the search for preservation of older fabrics within reactivated shear zones.

Acknowledgements

We are pleased to recognize the important contribution of Paul Williams to the fields of structural geology and Appalachian tectonics. This research was supported by the Natural Sciences and Research Council of Canada (N.S.E.R.C.), by St. Francis Xavier University through the University Council for Research (to JBM) and the James Chair of Pure and Applied Sciences (to JDK) and Course Based Service Learning, and summer employment programs for students sponsored by the Nova Scotia and Federal governments. We are grateful to Cees van Staal, John Waldron and an anonymous reviewer who made insightful, constructive comments on the manuscript.

References

Boucot, A.J., Dewey, J.F., Dineley, D.L., Fyson, W.K., Hickox, C.F., MacKerrow, W.S., Ziegler, A.M., 1974. Geology of the Arisaig Area. Geological Society of America, Special Paper 139 p. 191.

Cawood, P.A., Dunning, G.R., Lux, D., van Gool, J.A.M., 1994. Timing of peak metamorphism and deformation along the Appalachian margin of Laurentia in Newfoundland: Silurian, not Ordovician. Geology 22, 399–402.

Dalziel, I.W.D., 1992. On the organization of American plates in the Neoproterozoic and the breakout of Laurentia. GSA Today, 2, 238, 240–241.

Hibbard, J., 1994. Kinematics of Acadian deformation in the Northern and Newfoundland Appalachians. Journal of Geology 102, 215–229.

Hodych, J.P., Buchan, K.L., 1994. Paleomagnetism of the Early Silurian Cape St. Mary's sills of the Avalon Peninsula of Newfoundland, Canada. EOS, Transactions, American Geophysical Union 75 (16), 128.

Holdsworth, R.E., 1994. Structural evolution of the Gander-Avalon terrane boundary: a reactivated transpression zone in the NE Newfoundland Appalachians. Journal of the Geological Society, London 151, 629–646.

Holdsworth, R.E., Butler, C.A., Roberts, A.M., 1997. The recognition of reactivation during continental deformation. Journal of the Geological Society, London 141, 73–78.

Johnson, R.J.E., van der Voo, R., 1986. Paleomagnetism of the late Precambrian Fourchu Group, Cape Breton Island, Nova Scotia. Canadian Journal of Earth Sciences 23, 1673–1685.

Keppie, J.D., 1982. The Minas Geofracture. In: St. Julien, P., Beland, J. (Eds.). Major Structural Zones and Faults of the Northern Appalachians. Geological Association of Canada, Special Paper 24. pp. 263–280.

Keppie, J.D., 1985. The Appalachian Collage. In: Gee, D.G., Sturt, B.A. (Eds.). The Caledonide Orogen: Scandinavia and Related Areas. Wiley, pp. 1217–1226.

Keppie, J.D., 1993. Synthesis of Paleozoic deformation events in the Canadian Appalachians. Geoligsche Rundschau 82, 381–431.

Keppie, J.D., Murphy, J.B., 1988. Anatomy of a telescoped pull-apart basin: an example from the Cambro–Ordovician rocks in the Antigonish Highlands, Nova Scotia. Maritime Sediments and Atlantic Geology 24, 123–138.

Keppie, J.D., Dallmeyer, R.D., Murphy, J.B., 1990. Tectonic implications of ^{40}Ar/^{39}Ar hornblende ages from Late Proterozoic–Cambrian plutons in the Avalon Composite Terrane in Nova Scotia, Canada. Bulletin of the Geological Society of America 102, 516–528.

Keppie, J.D., Dostal, J., Murphy, J.B., Nance, R.D., 1996. Terrane transfer between eastern Laurentia and western Gondwana in the Early Paleozoic: constraints on global reconstructions. In: Nance, R.D., Thompson, M.D. (Eds.). Avalonian and Related Peri-Gondwanan Terranes of the Circum North Atlantic. Geological Society of America, Special Paper 304, pp. 369–380.

Keppie, J.D., Davis, D.W., Krogh, T.E., 1998. U–Pb geochronological constraints on Precambrian stratified units in the Avalon Composite Terrane of Nova Scotia, Canada: tectonic implications. Canadian Journal of Earth Sciences 35, 222–236.

Lin, S., van Staal, C.R., Dube, B., 1994. Promontory–promontory collision in the Canadian Appalachians. Geology 22, 897–900.

McKerrow, W.S., Dewey, J.F., Scotese, C.R., 1991. The Ordovician and Silurian development of the Iapetus Ocean. In: Bassett, M.G., Lane, P., Edwards, D. (Eds.). The Murchison Symposium. Special Papers in Paleontology, 44, pp. 165–178.

Murphy, J.B., Keppie, J.D., 1987. The stratigraphy of the late Precambrian Georgeville Group, Antigonish Highlands, Nova Scotia. Maritime Sediments and Atlantic Geology 23, 49–61.

Murphy, J.B., Nance, R.D., 1989. Model for the evolution of the Avalonian–Cadomian belt. Geology 17, 735–738.

Murphy, J.B., Hynes, A.J., 1990. Tectonic control on the origin and orientation of igneous layering: an example from the Greendale Complex, Nova Scotia. Geology 18, 403–406.

Murphy, J.B., Keppie, J.D., Hynes, A.J., 1991. Geology of the Antigonish Highlands. Geological Survey of Canada, Paper 89-10, 114.

Murphy, J.B., Hynes, A.J., Cousens, B.L., 1997. Tectonic influence on Late Proterozoic Avalonian magmatism: an example from the Greendale Complex, Antigonish Highlands, Nova Scotia. In: Sinha, A.K., Whalen, J.B., Hogan, P. (Eds.). Magmatism in the Appalachians. Geological Society of America Memoir, 191, pp. 255–274.

Murphy, J.B., Keppie, J.D., Davis, D., Krogh, T.E., 1997b. Regional significance of new Neoproterozoic igneous units in Avalonian rocks of northern mainland Nova Scotia, Canada. Geological Magazine 134, 113–120.

Murphy, J.B., Keppie, J.D., Nance, R.D., 1999a. Fault reactivation within Avalonia: plate margin to continental interior deformation. Tectonophysics 305, 183–204.

Murphy, J.B., Keppie, J.D., Dostal, J., Nance, R.D., 1999b. Neoproterozoic–Early Paleozoic evolution of Avalonia and Cenozoic. In: Ramos, V., Keppie, J.D. (Eds.). Laurentia–Gondwana Connections before Pangea. Geological Society of America, Special Paper 336, pp. 243–256.

Nance, R.D., 1987. Dextral transpression and Late Carboniferous sedimentation in the Fundy coastal zone of southern New Brunswick. In: Beaumont, C., Tankard, A.J. (Eds.). Sedimentary Basins and Basin-Forming Mechanisms. Canadian Society of Petroleum Geologists, Memoir 12, pp. 363–378.

Nance, R.D., Murphy, J.B., 1996. Basement isotopic signatures and Neoproterozic paleogeography of Avalonian–Cadomian and related terranes in the circum North Atlantic. In: Nance, R.D., Thompson, M.D. (Eds.). Avalonian and Related Peri-Gondwanan Terranes of the Circum North Atlantic. Geological Society of America Special Paper, 304, pp. 369–380.

Nance, R.D., Murphy, J.B., Strachan, R.A., D'Lemos, R.S., Taylor, G.K., 1991. Late Proterozoic tectonostratigraphic evolution of the Avalonian and Cadomian terranes. Precambrian Research 53, 41–78.

O'Brien, S.H., Wardle, R.J., King, A.F., 1983. The Avalon Zone: a Pan-African terrane in the Appalachian orogen of Canada. Geological Journal 18, 195–222.

O'Brien, S.J., O'Brien, B.H., O'Driscoll, C.F., Dunning, G.R., Holdsworth, R.E., Tucker, R., 1991. Silurian Orogenesis and the NW Limit of Avalonian Rocks in the Hermitage Flexure, Newfoundland Appalachians. Geological Society of America, Abstracts with Program 23, p. 109.

O'Brien, B.H., O'Brien, S.J., Dunning, G.R., Tucker, R.D., 1994. Episodic reactivation of a Late Precambrian mylonite zone on the Gondwanan margin of the Appalachians, southern Newfoundland. Tectonics 12, 1043–1055.

O'Brien, S.J., O'Brien, B.H., Dunning, G.R., Tucker, R.D., 1996. Late Proterozoic Avalonian and related peri-Gondwanan rocks of the Newfoundland Appalachians. In: Nance, R.D., Thompson, M.D. (Eds.). Avalonian and Related Peri-Gondwanan Terranes of the Circum North Atlantic. Geological Society of America, Special Paper 304, pp. 9–28.

Paterson, S.R., Fowler Jr, T.K., 1993. Reexamining pluton emplacement mechanisms. Journal of Structural Geology 15, 191–206.

Strachan, R.A., Taylor, G.K. (Eds.), 1990. Avalonian and Cadomian rocks of the North Atlantic. Blackie & Sons, Glasgow, UK.

St. Jean, J.A.R., Nance, R.D., Murphy, J.B., 1993. Tectonic significance of Late Paleozoic deformation, Cape George Peninsula, Nova Scotia. Atlantic Geology 29, 27–42.

van Staal, C.R., Sullivan, R.W., Whalen, J.B., 1996. Provenance and tectonic history of the Gander Zone in the Caledonide–Appalachian orogen: implications for the assembly of Avalon. In: Nance, R.D., Thompson, M.D. (Eds.). Avalonian and Related Peri-Gondwanan Terranes of the Circum North Atlantic. Geological Society of America, Special Paper 304, pp. 347–368.

van Staal, C.R., Dewey, J.F., MacNiocaill, C., McKerrow, W.S., 1998. The Cambrian–Silurian tectonic evolution of the Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. In: Blundell, D.C., Scott, A.C. (Eds.). Lyell: the Past is the Key to the Present. Geological Society of London, Special Publication 143, pp. 199–242.

Williams, H., 1979. Appalachian orogen in Canada. Canadian Journal of Earth Sciences 16, 792–798.

Williams, P.F., Goodwin, L.B., Lafrance, B., 1995. Brittle faulting in the Canadian Appalachians and the interpretation of seismic reflection data. Journal of Structural Geology 17, 215–232.

Yeo, G.M., Ruixiang, G., 1987. Stellarton Graben: an upper Carboniferous pull-apart basin in northern Nova Scotia. In: Beaumont, C., Tankard, A.J. (Eds.). Sedimentary Basins and Basin-forming Mechanisms. Canadian Society of Petroleum Geologists, Memoir 12, pp. 299–310.