Tectonic significance of the northeastern Gander Zone, Newfoundland: an Acadian ductile shear zone

SIMON HANMER

Department of Geology, Dalhousie University, Halifax, N.S., Canada B3H 3J5

Received March 18, 1980
Revision accepted July 22, 1980

Penetrative deformation and granite intrusion in the northeastern Gander Zone, Newfoundland, represent a progressive Acadian event. Interference between ductile, strike-slip shearing along the southeastern margin of the Appalachian orogen and the emplacement of syntectonic granite diapirs results in the formation of a vertical, northeast–southwest strike-slip ductile shear zone where granites come to outcrop and a ductile strike-slip thrust zone where granites are absent at the surface. Sinistral movement along the vertical shear zone is compatible with recent palaeomagnetic models for the Appalachians and the British Caledonides. The constraints that the geologic model places on the symmetry of the Appalachian orogen in Newfoundland and the definition and extrapolation of the Gander tectonostratigraphic zone are discussed.

Introduction

The Appalachians of Newfoundland constitute a Central Mobile Belt underlain by oceanic crust, bounded to the northwest by the Precambrian rocks of the Humber Zone and to the southeast by the Avalon Zone. The latter is presumed to be underlain by continental crust (H. Williams 1964, 1979; Williams et al. 1972, 1974). The southeastern margin of the Central Mobile Belt in immediate contact with the Avalon Zone is defined as the Gander Zone (Williams et al. 1972, 1974). Apart from the elaboration and application of plate tectonic theory to the northern Appalachians (see Williams 1979 for detailed review and bibliography), three major themes have dominated geological thought with respect to the southeastern margin of the orogen: (a) the symmetrical nature of the orogen (Williams 1964); (b) the definition and extrapolation along strike of tectonostratigraphic zones (H. Williams 1976; Williams et al. 1972, 1974); (c) the presence or absence of Lower Palaeozoic or Precambrian basement within the Gander Zone (Jenness 1963; Kennedy 1975, 1976; Kennedy and McGonigal 1972; Blackwood 1977a, b, 1978; H. Williams 1978, 1979; Williams et al. 1972). Moreover, recent palaeomagnetic data have given rise to speculative models for the Appalachians and the British Caledonides that imply that large-scale sinistral transcurrent movement occurred along the length of the orogen during the Devonian–Carboniferous (e.g., Irving 1979).

The present contribution, based upon recent fieldwork in the northeastern Gander Zone and the fresh perspective that this work has shed upon published data of other workers, attempts (a) to present a coherent model of progressive Acadian deformation and syntectonic, diapiric emplacement of granites in the northeastern Gander Zone; (b) to show that deformation in the Gander Zone is compatible with recently proposed palaeomagnetic models for the Appalachians and the British Caledonides; and (c) to support the suggestion of others that the Central Mobile Belt of the Newfoundland Appalachians is asymmetrical.

The northeastern Gander Zone

Detailed reviews of the Newfoundland Appalachians are given by other authors and will not be duplicated here (e.g., H. Williams 1979; Williams et al. 1972, 1974; Kennedy 1975, 1976). Briefly, convergence of the northwestern and southeastern forelands, presently identified with the Humber and Avalon Zones, resulted in a contraction of the Late Proterozoic—Lower Palaeozoic Iapetus Ocean and southeastward-directed subduction of oceanic crust. Closure of the Iapetus during the Lower to Middle Ordovician was accompanied by destruction of the northwest foreland margin and northward-directed obduction of oceanic crust, i.e., the Taconic Orogeny. Although subjected to relatively mild deformation during the Acadian and Variscan Orogenies, the Taconic structures of northwestern Newfoundland...
land have not been profoundly modified by these later events. To the southeast, however, the orogenic history of the Central Mobile Belt has been the focus of much debate. Guided by the notion of a symmetrical orogenic belt, and on the basis of lateral variation of structural sequence, some workers have identified Precambrian basement, a Late Precambrian to pre-Middle Ordovician orogeny (the Ganderian), and subsequent minor Acadian reworking, all within the Gander Zone (Kennedy 1975, 1976; Kennedy and McGonigal 1972). Others consider the main deformation and metamorphism of the southeastern margin to be Acadian, but propose southeasterly obduction of ocean crust beginning in Lower to Middle Ordovician times and terminating during the Acadian (Pickerill et al. 1978; Pajari et al. 1979). Yet other workers have insisted upon the absence of true oceanic crust in this part of Newfoundland and, more particularly, on the asymmetrical nature of the northern Appalachians (Strong et al. 1974a; Stevens et al. 1974), although their objections appear to have gone unanswered.

Much detailed work (cited below) has been undertaken both in the field and in the laboratory on rocks of the northeastern Gander Zone and adjacent parts of the Central Mobile Belt (Davidsville Group, Fig. 1). The present consensus accepts the Gander Zone as an accreted continental rise prism or clastic sedimentary wedge (H. Williams 1964; Kennedy 1975), although Strong et al. (1974a) and Colman-Sadd (1980) consider it to represent a behind-arc basin, at least in its western part.

When considering the geology of this part of Newfoundland it is indispensible to take into account that of the immediately adjacent Davidsville Group (Fig. 1; Tables 1, 2).

Previous work

Details of the local geology and comprehensive reviews of previous work in the northeastern Gander Zone and the Davidsville Group have been published by Jenness (1963), Kennedy and McGonigal (1972), Blackwood (1977b), Pickerill et al. (1978), Jayasinghe (1978), Pajari and Currie (1978), and Pajari et al. (1979). These and other above cited authors have divided the rocks into four units: the Hare Bay gneiss, Square Pond gneiss, and the Gander Group, all of which constitute the Gander Zone (sensu stricto), and the Davidsville Group (Table 1, Fig. 1). The contacts between the different units are locally variable, but the three Gander Zone divisions appear to be metamorphic, lateral equivalents of one another (Blackwood 1978) and, at least locally, pass conformably into the Davidsville Group (Blackwood 1978; Pajari et al. 1979). To the east and north the country rocks are cut by quartz diorites, biotite megacrystic granites, biotite–muscovite granites, and leucogranites. Rb/Sr whole-rock isochron data on some of the granites suggest a range of ages of emplacement from 420 ± 20 to 332 ± 42 Ma (Blenkinsop et al. 1976; Bell et al. 1977, 1979), and K/Ar data from micas suggest comparable ages for at least some of the quartz diorites (Wanless et al. 1965, 1972). The southeastern limit of the Gander Zone is determined by the Dover Fault (Younce 1970), marked by a 300-500 m wide belt of mylonites and protomylonites (Blackwood and Kennedy 1975).

Deformation within the Gander Zone and the Davidsville Group is complex and laterally variable, even within a given unit. On the basis of geometry, style, and orientation workers have attempted to erect polyphase structural sequences characteristic of each of the mapping groups (Table 2). In general, structural complexity increases from the Davidsville towards the Hare Bay gneiss and is accompanied by increasing grade of regional metamorphism (Jenness 1963; Blackwood 1978). The attitude of planar structures varies systematically across the area from upright in the Davidsville Group (west of Gander, Kennedy and McGonigal 1972) to subhorizontal in the central part of the Gander Group (east of Gander, Kennedy and McGonigal 1972) to upright again in the Square Pond and Hare Bay gneisses (Jenness 1963).

The emplacement of granitic plutons, although generally assigned an Acadian age, is also described in terms of a sequence of distinct events (Jayasinghe and Berger 1976; Blackwood 1977b; Jayasinghe 1978). The granites have been divided by these and other authors (e.g., Dickson 1974; Strong et al. 1974b; Blackwood 1977a,b) into individual biotite megacrystal granites, muscovite–biotite granites, and several small leucogranite bodies, some of which are shown in Fig. 1.

Recent detailed work on the ultrabasic rocks, volcanioclastic debris flows, and minor lavas near the base of the Davidsville Group has interpreted them to be a south-easterly obducted ophiolite suite overlain by ophiolitic olistostromes (Pickerill et al. 1978; Pajari et al. 1979). For these authors, obduction began within the Central Mobile Belt during the Lower Ordovician and final emplacement coincided with the peak of Devonian regional metamorphism and granitoid intrusion.

In order to establish some degree of perspective, the above summary can be reduced to the skeletal framework upon which the rest of this article will be based (Fig. 1). A "Flat" Belt of greenschist facies metasediments characterized by a subhorizontal schistosity passes to the northeast and southeast into a "Steep" Belt of metasediments, para- and orthogneisses, migmatites, and intrusive Acadian granitoid rocks characterized by steep to vertical foliations and banding.
FIG. 1. Generalized geological map of the northeastern Gander Zone. Biotite megacrystic granite (1); North Pond - Business Cove granite (2); quartz diorite (3); Davidsville Group (4); Gander Group (5); Square Pond gneiss (6); Hare Bay gneiss (7); amphibolite–tonalite gneiss occurrences (8). Windmill Bight section (W.B.); Valleyfield section (V); Islands section (I); Indian Bay section (I.B.); Hare Bay section (H.B.). Location of area studied with Gander Zone (black) is at top right. Foreland blocks (Humber Zone (A); Avalon Zone (C)) and Central Mobile Belt (B) in Newfoundland are shown at top left. F: Flat Belt; S: Steep Belt. Numbers refer to localities mentioned in text.
TABLE 1. Main divisions of the northeastern Gander Zone

<table>
<thead>
<tr>
<th>NW</th>
<th>Davidsville Group*</th>
<th>Gander Group†</th>
<th>Square Pond gneiss‡</th>
<th>Hare Bay gneiss‡</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal or subbasal ultrabasic rocks and basaltic volcanioclastics overlain by olistostromes, greywacke turbidites, semipelites, and pelites</td>
<td>Semipelitic and psammatic metasediments with minor pelite and intraformational conglomerate</td>
<td>Psammitic, semipelitic, and minor pelitic paragneiss</td>
<td>Tonalite orthogneiss and migmatites with some metasediment and minor amphibolite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: Regional metamorphic grade generally increases from northwest (lower greenschist facies) to southeast (upper amphibolite facies).
†Blackwood and Kennedy (1975).
‡Blackwood (1977a,b).

TABLE 2. Published polyphase structural sequences for the major lithological units of the northeastern Gander Zone

<table>
<thead>
<tr>
<th>Davidsville Group* (NE)</th>
<th>Davidsville Group† (SW)</th>
<th>Gander Group† (SW)</th>
<th>Gneisses‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complex polyphase pattern similar in appearance to that of gneisses</td>
<td>Single upright cleavage</td>
<td>D3—tight SE facing folds</td>
<td>D5—crenulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D2—isoclinai folds facing</td>
<td>D4—&quot;cataclastic&quot; event and localized shear zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SE: axial planar main schistosity</td>
<td>D3—early transposed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D1—local and weak</td>
<td>D2—schistosities</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D1—coaxial folding and refolding</td>
</tr>
</tbody>
</table>

NOTES: Structural complexity increases from northwest to southeast and, with respect to the Davidsville Group, from southwest (the Flat Belt) to the northeast. No correlations are here implied across the table.
†Jasasinghe and Berger (1976), Blackwood (1977b), Jasasinghe (1978).

The Flat Belt

Along the Trans-Canada Highway, east of Gander, a single subhorizontal layer-parallel schistosity or cleavage, carrying a variably developed, penetrative north-east–southwest mineral alignment lineation, is folded about centimetre- to metre-scale isoclinal folds. The fold axes are generally parallel to the constantly oriented lineation or are locally strongly curved through 90° within their own subhorizontal axial planes. Where curvature is extreme (≈ 180°), sheath or eye folds (Quinquis et al. 1978; Mukhopadhyay and Sengupta 1979) result, wherein the shear axis is parallel to the lineation (Figs. 2, 3). The long axes of boudins (Kennedy 1975) and a mild crenulation lineation are also parallel to the lineation. The long axes of quartz pressure shadows on pyrite grains (Fig. 3b) lie in the mineral lineation direction, oblique to the cleavage planes, and indicate the orientation of the maximum extensional strain X (Ramsay and Graham 1970) of the incremental strain ellipsoid (Spry 1969, p. 247; Choukroune 1971; Elliott 1972; Wickam 1973; Durney and Ramsay 1973). The orientation of the long axes of the boudins, parallel to the lineation (Fig. 3d), suggests that they have rotated into this direction and confirms the mineral lineation as the X direction of the finite strain ellipsoid (Quinquis et al. 1978) (Figs. 2, 3).

The consistent sense of obliquity of the pressure shadows with respect to the cleavage planes (X–Y plane of the finite strain ellipsoid X = Y = Z, Ramsay and Graham 1970) is suggestive of noncoaxial, rotational strain. This structural association is identical to that described elsewhere by workers who have shown that it results from progressive simple shear along the deforming anisotropy (cleavage) (Bryant and Reed 1969; Hobbs et al. 1976, pp. 285–288; Rhodes and Gayer 1977; Bell 1978; Quinquis et al. 1978; G. Williams 1978). According to these authors, the fold axes initiate at a high angle to the stretching lineation (Fig. 3a). With increasing strain, the folds become progressively noncylindrical as the axes rotate towards the X direction. During rotation the folds amplify and tighten and new folds progressively initiate at high angles to X. From the variably noncylindrical nature of the folding and pressure shadow criteria, Quinquis et al. (1978), working in northwestern France, deduce that deformation there was continuously noncoaxial and,
Fig. 2. Eye or sheath fold in Gander group metasediments. The fold axes and mineral alignment lineation are perpendicular to the section in which concentric cleavage planes are visible. The axial plane of the sheath structure is subhorizontal. See Fig. 3a.

from inclusions within metamorphic garnets, that it was continuously rotational. They further state that "the simplest kind of progressive deformation, that is at once continuously non-coaxial and progressively rotational, is a progressive simple shear" (Quinquis et al. 1978, p. 44). Following this line of reasoning, the isoclinal folds of the Flat Belt initiated with northwest-southeast oriented axes that have rotated into their present position. A major component of simple shear along the deforming cleavage planes accompanied the deformation and, from the sense of pressure shadow obliquity, corresponded to southwestward directed overthrusting. Note that the isoclines are coaxially refolded by open upright folds.

To the northwest the Flat Belt steepens down towards the Davidsville Group with which it is generally in faulted contact (Currie and Pajari 1977). The steepening of the belt may be attributed to movement along the fault (Pajari and Currie 1978). To the southeast the Flat Belt turns up into the Steep Belt.

The Steep Belt

For descriptive convenience, the country rocks of this belt are considered in two parts: the Square Pond gneiss and northeastern Gander Group; and the Hare Bay gneiss (Blackwood 1977b). The intrusive rocks will be considered separately. Note that, in general, the deformation in these rocks is so variable in nature and complexity as to preclude simple outcrop–outcrop correlation (cf., Talbot 1979). Any labelling of structures is artificial and for ease of reference only. The terms "earlier" and "later" are used here to refer to increments of strain at the local outcrop scale only, without implying larger scale correlation.

Square Pond gneiss and Gander Group

The following evidence suggests that ductile deformation of these rocks is characterized by a major component of progressive simple shear along the layering.

Dominatedly psammitic and semipelitic metasediments are deformed by several sets of structures, essentially comprising at least one layer-parallel schistosity, which is (are) deformed by at least one set of isoclinal folds. The axes of the isoclines are generally parallel to a well-developed consistently subhorizontal to gently plunging, penetrative mineral alignment lineation (Fig. 4a). The long axes of boudins, themselves containing isoclinal folded internal foliations, now lie parallel to the lineation. Isoclinal fold axes are commonly curved through 90° within their own axial planes and thereby intersect the mineral lineation (e.g., between Thwart and Northwest Ponds, location 1 of Fig. 1).

The composite, layer-parallel structures are locally deformed by crenulation cleavages and associated folds. There is no evidence to indicate relative age relationships between the crenulations. They are often axial planar to upright, horizontal folds whose axes are parallel to the subhorizontal lineation or strongly curved through 90° within the associated crenulation cleavage planes. Locally the folds are oblique to the lineation and therefore deform it. Furthermore, even in the absence of later crenulations and of marked lithological variation, layer-parallel foliations are locally mylonitic (e.g., Alleys Pond, location 2 in Fig. 1) or are anomalously
planar in layer-parallel zones some hundreds of metres in width. These zones of relatively high strain imply the existence of local strain gradients across the strike and a major component of simple shear along the layering (Cobbold 1977).

**Hare Bay gneiss**

From the present study, the southeastern margin of this division comprises a belt of amphibolite and tonalite gneiss adjacent to the Dover Fault, flanked to the west and north by volumetrically important, protomylonitic granite orthogneiss with migmatite and relatively minor metasediment. The significance of the restricted occurrence of the amphibolite–tonalite assemblage is unclear.

Fine-grained banded amphibolite gneiss is best exposed along the Hare Bay section (south shore of Lockers Bay, Fig. 1) and contains metre sized slices of semipelite. Metagabbroic textures are locally preserved in shear-bounded pods. The gneiss is protomylonitic to mylonitic and commonly carries 2–50 mm diameter epidote porphyroclasts. Amphibolite gneiss is included as internally foliated blocks within a leucocratic tonalitic host. The alignment of inclusions passes into a continuous banding within layer-parallel zones of protomylonitic and mylonitic amphibolite–tonalite gneiss several hundreds of metres wide.

Granitic orthogneiss is best exposed in the Windmill Bight and Valleyfield sections (Fig. 1), where augen gneiss, protomylonite, and mylonite are apparently
FIG. 4. (a) Subhorizontal, northeastward trending mineral alignment lineation (crosses) and poles to generally upright foliation (open circles) in country rocks of the Steep Belt. (b) Similarly oriented structures in the Steep Belt granites. Note, however, the steeply plunging mineral alignment (circled crosses) from the Newport-Cape Freels granite contact. Discrete minor, conjugate shear planes and zones cut the granite foliation at approximately 30° (solid circles). The sample shown here is not representative: in the field the set of shear planes oriented north–south are markedlynumerically dominant.

derived from a biotite megacrystic granite protolith, which is still preserved in shear-bounded low-strain pods and bands. These rocks were previously described as migmatites and paragneisses (Jayasinghe 1978), but the presence of all the intermediate lithologies, from foliated granite to mylonite, suggests that they record the heterogeneous deformation of a granite parent mate-
ial. Large rafts of migmatite do, however, occur within the orthogneiss (e.g., east end of Windmill Bight section). The linear and planar elements of the folded and foliated migmatite are parallel to those of the host orthogneiss.

Migmatites are best exposed along the Indian Bay section (Fig. 1; Jayasinghe 1978) where high-grade banded varieties pass into inhomogeneous nonbanded varieties (metatexite and diatexite, respectively, of Mehnert 1968). The metatexites comprise alternating bands of foliated biotite–quartz restite, biotite–garnet melasome, and isotropic coarse-grained leucosome. Pods of paleosome carry an internal foliation or banding, locally folded concordantly to the external migmatite banding. Other migmatites occur as large rafts within the protomylonite augen orthogneiss, e.g., along the Valleyfield section (Fig. 1) where they are associated with rafts of psammitic and semipelitic metasediment. Passing eastwards along the section, these rocks and the host orthogneiss become protomylonitic and highly planar and develop a pronounced internal structural concordance. Discordant relationships are, however, locally preserved within 10 m scale low-strain pods of psammitic enclosed by the mylonitic foliation of the bounding metasedimentary material.

The following observations suggest that deformation of these rocks is heterogeneous and associated with layer-parallel simple shear. Deformation is highly variable. Nevertheless, the high proportion of mylonitic rocks is a salient feature. In general, the more intense the strain, the simpler the apparent structural sequence in a given outcrop. In the simplest case, e.g., in mylonitic rocks, a penetrative, planar, layer-parallel foliation carries a consistently subhorizontal to gently plunging, penetrative mineral alignment lineation (Fig. 4a). Locally, nests of tight to isoclinal, upright, horizontal folds deform the foliation and show the same relationship to the lineation as that already described for the rocks to the northwest. Sheath folds are locally developed, e.g., in the migmatites of the Indian Bay section and the metasediments at Valleyfield (Fig. 1). More complex coaxial refolding is generally restricted to the multilayer lithologies, i.e., metasediments and migmatites. No relative age significance is attached to locally complex structural sequences since fold axis—lineation relationships are identical to those in outcrops of more simply folded foliations. For example, the preservation of complex refolding and cross-cutting relationships in shear-bounded pods in the Valleyfield section has been interpreted to represent folded paleosome within postfolding migmatite (e.g., Jayasinghe 1978). Since the rocks both within and outside of the pods are deformed metasediments, the pods represent low-strain zones within the mylonitic rocks; i.e., the lateral variation in apparent structural complexity reflects lateral variation or hetero-
geneity of the finite strain rather than the relative ages of the rocks.

Throughout the area, all of the above structures are cut by a set of conjugate, discrete, vertical shears, centimetres or tens of metres in length. Although symmetrically disposed at about 30° to the locally dominant foliation, those of sinistral offset make up approximately 90% of all occurrences. In the migmatites of the Indian Bay section (Fig. 1) isotropic leucosome, identical to that of the metatexites, fills and welds many such shears and cross-cuts the migmatitic banding. Mobile leucosome was therefore present within the migmatites throughout the deformation history of the Hare Bay gneiss.

Steep Belt granites

The granitoid rocks of the Steep Belt (Fig. 1) and elsewhere in northeastern Newfoundland have been studied in close detail (Jenness 1963; H. Williams 1968; Dickson 1974; Strong et al. 1974b; Strong and Dickson 1978; Blackwood 1977b; Currie and Pajari 1977; Pickering et al. 1978; Jayasinghe 1978, 1979; Jayasinghe and Berger 1976). Only the structure of the eastern granites has been examined here (see Blackwood 1977b and Jayasinghe 1978, 1979 for detailed petrographic descriptions).

From Fig. 1, the North Pond—Business Cove two-mica ± garnet, locally megacrystic granite is surrounded by extensive outcrops of biotite megacrystic granite. The Deadman’s Bay and Newport granites are generally isotropic, whereas the other biotite megacrystic granites and part of the two-mica granite are foliated. Leucogranite ± garnet occurs as small, scattered outcrops. Apart from the presence or absence of an internal foliation, the essential character of the biotite megacrystic granites is fairly constant and may be summarized as follows. In any of the plutons, the main body of coarse megacrystic granite is cut by sheets of fine- to medium-grained two-mica granite in which biotite is the dominant mica, and garnet and 1 cm megacrysts of K-feldspar are locally present. Sheets of leucogranite (± muscovite ± garnet) usually cut the two-mica granite sheets but the reverse relationship is also seen. The granite suite is commonly cut by muscovite ± garnet ± tourmaline aplites and pegmatites. Sheets of all the above lithologies intrude the country rocks. The absence of a unique emplacement sequence at the outcrop scale is reflected at the regional scale since the North Pond—Business Cove two-mica granite both cuts and is itself cut by biotite megacrystic granite (Jayasinghe and Berger 1976; Jayasinghe 1978).

The following account of deformation within the biotite megacrystic granites draws heavily from personal field observation of the Cape Freels granite but, in the main, is also applicable to the other foliated biotite megacrystic granites. The evidence suggests that the foliation in the granites is subparallel to the direction of maximum simple shear, and that deformation was contemporaneous with subsolidus cooling of the granites.

The penetrative foliation of the main granite is variable in the intensity of its development across strike. Where the foliation is most marked, it passes to varying degrees into deformed intrusive sheets of two-mica leucogranite. The orientation of the sheets with respect to the host rock foliation is variable and, in general, the sheet—foliation angle decreases as the internal fabric in the sheets increases in intensity (see also Jayasinghe 1976). All permutations may be present in a single, limited outcrop and, therefore, sheet orientation with respect to the host rock foliation is in great part related to the proportion of the finite strain that they have undergone. The sheets were, therefore, emplaced during the development of the host rock foliation.

The foliation in the biotite megacrystic granites (Fig. 4b) is commonly expressed as an alignment of polycrystalline quartz leaves, biotite aggregates, and feldspar megacrysts or aggregates derived from them. Locally it passes into foliation-parallel bands of promylonite and mylonite up to several hundreds of metres in width. Where a penetrative mineral alignment is visible within the foliation planes, it is subhorizontal to gently plunging (Fig. 4b). On surfaces perpendicular to the foliation and parallel to the lineation, two sets of planes are seen in the intrusive granite sheets: a planar mineral alignment fabric is cut and deflected into 1 cm spaced, continuous, discrete shear planes (Fig. 5). These structures correspond to S and C planes, respectively, (Berthé et al. 1979a, b) where S planes correspond to the X—Y plane of the finite strain ellipsoid and C planes correspond to planes of contemporaneous maximum shear strain. Following these authors, field observation of the intrusive sheets shows that the concentration of C planes increases and the C—S angle decreases with progressive increments of strain. Progressive rotation of S planes towards the C plane orientation conforms to well-established models of simple shear in rocks (Ram-
Fig. 6. A discrete shear plane, oriented at 30° to the main biotite megacrystic granite foliation (Cape Freels granite). While cutting (and dextrally offsetting?) two K-feldspar megacryst fragments, the shear plane is clearly cross-cut by the megacryst on the left.

say and Graham 1970; Berthé et al. 1979b). Note that the C planes are continuous with the biotite megacrystic granite foliation. As in the country rocks, then, the association of mylonitic bands, across-strike strain gradients, and C and S planes indicates a major component of simple shear along the foliation planes (Cobbold 1977; Berthé et al. 1979b).

The foliation planes within the granites are cut by discrete conjugate shears identical to those affecting the country rocks (D5 in Table 2; Fig. 4b). The following observations demonstrate that the conjugate shears, the intrusive granite sheets, and the main granite foliation were all formed or emplaced during subsolidus cooling and crystallization of the biotite megacrystic granites.

(a) Strong and Dickson (1978) have shown that the growth of the K-feldspar megacrysts does not represent major alkali metasomatism from an external source. Indeed, they have been variously interpreted as autosomatic porphyroblasts (Blackwood 1976) and as phenocrysts (Jayasinghe 1978).

(b) K-feldspar megacrysts overgrow the margins of intrusive granite sheets within the biotite megacrystic granites (see also Blackwood and Kennedy 1975).

(c) Figure 6 shows one of the postfoliation shears both cutting across and being cut and welded by K-feldspar megacrysts.

(d) Decussate or poorly aligned, subeuhedral megacrysts commonly occur within a matrix of well-aligned quartz aggregates and matrix feldspars. On polished surfaces, larger, sub- to euhedral megacrysts are occasionally seen to overprint the foliated matrix.

Granite–country rock relationship

Contacts of the North Pond–Business Cove two-mica granite (Fig. 1) and of the foliated biotite megacrystic granites with the country rocks are generally sheeted and intrusive. At the outcrop scale the main or individual sheet contacts may cross-cut structures in the adjacent country rocks. However, the following observations suggest that the deformation and emplacement of most, if not all, of the granites were contemporaneous with most, if not all, of the deformation of the country rocks.

(a) Noting the evidence for simple shear strain in both foliated granites and country rocks, cleavage–schistosity trajectories have been drawn for the area using both published and new data (Fig. 7). They approximate the trace of the X–Y plane of the finite strain ellipsoid. The resultant pattern reveals that there are three major trajectory orientations and that the trajectories pass in continuity from the country rock into the granites making a small angle with the contacts. Trajectories are concen-
FIG. 7. Cleavage trajectories, approximate to the trace of the $X/Y$ plane of the finite strain ellipsoid drawn on a simplified geological base map. Undifferentiated country rock (a); undifferentiated granite (b). The trajectories delineate three main orientation directions: north–south, north–northeast, and east–northeast, corresponding to three directions of major simple shear along the foliation planes. Isotropic biotite megacrystic Newport granite does not contain such trajectories and truncates those of the country rocks and foliated granites. The trajectories pass across lithological contacts from country rock into granite. Note the concentric configurations and triangular patterns at and to the southwest of A, discussed in text.
FIG. 8. Schematic representation of strain gradients in country rocks adjacent to isotropic North Pond granite (location 1 of Fig. 1). In psammites (s) a progressively developed layer-parallel crenulation cleavage (bold dashes) progressively transposes an earlier fabric (fine line) in the western limb of the major synform and is itself completely transposed (bold lines) in the eastern limb into an upright crenulation cleavage (dashes) adjacent to the granite. There are therefore two strain gradients present: one associated with earlier strain increments and the other with later strain increments. In detail, the contact of the isotropic granite (and its associated intrusive veins) cross-cut all the structures yet acts as the focus for the strain gradients. The granite is therefore syntectonic. p = semipelite. Horizontal length 2.4 km. No vertical scale.

Tric about the granite A and describe a pronounced loop, concentric with the granite contact to the southwest of A. They also described two triangular configurations adjacent to the concentric elements. It is suggested that a third triangular pattern to the northwest of A is presently masked by the adjacent isotropic biotite megacrystic granites. The elements of the triangular configurations are parallel to adjacent granite margins and pass in continuity into the regional trajectory pattern. Identical structures are described from granite terrains elsewhere (Ledru and Brun 1977; Brun et al. 1976; Brun and Pons 1979; Hammer 1978; Hammer and Vigneresse 1980; Hamner et al. 1981). As explained by these authors, the concentric pattern results from expansion of diapiric granites during emplacement. Each triangular configuration is related to three simultaneously expanding granite margins (Brun et al. 1976). In the light of this, consider the following field observations. To the southwest of the North Pond two-mica granite (location 1 of Fig. 1), a kilometre scale, southeastward verging subhorizontal synform exhibits an increasing strain gradient towards the granite margin (Fig. 8). Gently westward dipping away from the margin and only present in the semipelites, the axial planar crenulation cleavage becomes moderately to steeply dipping at the granite contact where it transposes most of the earlier layer-parallel structure in the psammites. As mentioned above, the layer-parallel structures are frequently composite and therefore associated with varying degrees of transposition (see also Blackwood 1977b). A transposition gradient is visible along the same North Pond contact traverse where a layer-parallel crenulation cleavage in the psammites clearly transposes earlier fabrics before the later cleavage becomes a penetrative feature in the same rocks. Thus both earlier and later strain gradients respond to the presence of the same granite contact. Isotropic, undeformed veins of the granite, which intrude and cross-cut the country rock structures, indicate that the granite is syntectonic to both earlier and later increments of strain. Furthermore, the margins of both the North Pond two-mica granite (e.g., between Northwest and Rocky Ridge Ponds, location 3 of Fig. 1) and the biotite megacrystic granites (e.g., between Southwest and Parsons Ponds, location 4 of Fig. 1) are locally gently to moderately dipping, suggesting that exposure lies within or close to the roof of the plutons. The dominant planar and linear structures of the adjacent country rocks, which as already discussed may represent either earlier or later increments of strain, depending on the local geology, are parallel to both the planar and linear structures within the granites. In other words, the country rock anisotropy is gently inclined. These rocks, however, are part of the Steep Belt, an area characterized by upright foliations. Combined with the evidence for granite expansion during emplacement provided by the trajectory patterns in Fig. 7, the field evidence suggests that granite emplacement and expansion are genetically related to and thereby contemporaneous with the earlier and the later increments of strain in the country rocks.

(b) The isotropic Newport granite (Figs. 1, 7) cuts all the adjacent foliated rocks at both the outcrop and map-
following preliminary conclusions may be drawn. Furthermore, the length of this contact is characterized by an anomalously steeply plunging mineral alignment lineation within the foliated granite (Fig. 4b). Angular relationships between the lineation, the foliation, and the post-foliation shears are identical to those pertaining when the regional lineation is horizontal. This observation conflicts with the superposition of a local strain associated with the emplacement of a post-tectonic granite (Blackwood 1977b; Jayasinghe 1978; Bell et al. 1979) and is more reasonably interpreted in terms of the interference of the local strain field about a radially expanding diapir with contemporaneous regional strain in the Cape Freels granite.

**Discussion**

Each of the units of the northeastern Gander Zone and the intrusive granites examined here have undergone deformation characterized by a major component of simple shear. Cursory examination of the northeastern Davidsville Group suggests a similar strain regime. Within the Flat Belt and the granites and mylonitic rocks of the Steep Belt, simple shear occurred along the locally dominant foliation planes. From the subhorizontal, northeast–southwest orientation of the mineral alignment lineation throughout the study, simple shear operated along strike (Ramsay and Graham 1970). The Flat Belt, therefore, represents a subhorizontal ductile shear zone or southwestward directed “strike–slip thrust” in the sense of Bayer and Matte (1979). Within the Steep Belt, Jayasinghe and Berger (1976) have reported two discrete strike–slip ductile shear zones affecting granites and Younce (1970) has recognized the Dover Fault as a strike–slip feature. I suggest that the entire Steep Belt is a vertical, strike–slip ductile shear system comprising three dominant, mutually interacting, contemporaneous shear zones (Fig. 7): (a) a regional 035° orientation; (b) an 015° shear zone centered upon the exposed margin of the Cape Freels granite; and (c) the 075° Dover Fault direction. These three directions are reflected within the rocks of the Steep Belt at all scales down to the thin section level. They correspond to the main anisotropy (foliation) of both the granites and the country rocks and to the post-foliation shears common to both. Although further work is necessary (and is in progress), the following preliminary conclusions may be drawn.

(a) From the foliation trajectories of Fig. 7 and the microstructural criteria of Berthé et al. (1979a, b), planes oriented at 015° have accommodated sinistral shear strain.

(b) From microstructural criteria, planes oriented at 075° have accommodated dextral shear strain.

(c) From the observations detailed above, planes oriented at 035° have also accommodated a major component of sinistral shear strain.

(d) The three sets of shear planes correspond geometrically to \( R, R', \) and \( P (015°, 075°, \) and \( 035°, \) respectively) of a set of riedel shears produced during progressive deformation within an 035° trending sinistral shear zone (Morgenstern and Tchalenko 1967; Tchalenko 1970). Local complication results from “riedel-within-riedel” structure (Tchalenko 1970), e.g., in the Locker’s Bay and Cape Freels granites.

Echoing Currie and Pajari’s (1977) caution that “the age of intrusion must be defined with extreme care,” I consider “emplacement” to mean the period from the first detectable thermal and mechanical influence of an intrusive body through to the moment of final intrusive movement relative to the country rocks. In this context, the contemporaneity of both earlier and later increments of strain in the country rocks and granite emplacement and the “syn-cooling” and consolidation deformation of the granites themselves indicate that all of the Steep Belt granites are syntectonic with respect to all of the deformation of the belt. Available radiometric evidence is not unequivocal (cf., Bell et al. 1979), but tends to indicate that the granites and therefore the deformation of the Steep Belt are of Acadian age (sensu lato, 420–? Ma: note that Bell et al.’s (1979) 332 ± 42 Ma age for the Newport granite does not allow precise definition of the end of deformation). Indeed, many of the country rocks constituting the southeastern side of the Steep Belt are themselves protomylonitic orthogneisses derived from a protolith that, in the present author’s opinion, resembles the intrusive biotite megacrystal granites. Furthermore, (a) the granites rose as expanding diapirs into the Steep Belt rocks; (b) the Flat Belt turns up into the Steep Belt; and (c) the regional metamorphic grade increases towards the southeast. I, therefore, propose that during the Acadian (sensu lato) Orogeny the northeastern Gander Zone may have been a ductile strike–slip thrust along the southeastern margin of the Central Mobile Belt. A thermal anomaly at depth, attributed to crustal thickening (Strong 1977) for which the strike–slip thrusting itself might provide a likely mechanism, resulted in the production of granitic melts, which rose diapirically into the eastern and northern parts of the thrust. Interaction between the horizontal southwestward directed thrust displacement and the vertical diapiric movement resulted in a steepening up of the ductile thrust to produce the sinistral Steep Belt (Fig. 9a). The Flat Belt is intruded by post-tectonic biotite megacrystal granite (Gander Lake granite, R. F. Blackwood, personal communication, 1979) associated with a classical, high-level metamorphic contact aureole (hornfels) with-
overlie still hidden syntectonic granites below the pre-

The Flat Belt itself may represent an anomalous zone

dient and to the production of granite melts (cf., Strong

end of the deformation history most conveniently.

rocks would accommodate itself to the rising, expanding

contribute to the northwest-southeast metamorphic gra-

in which the tectonic foliations are entirely obliterated.

Clearly, an accurate age fix on this granite would delimit

An alternative model, however, cannot be excluded.
The Flat Belt itself may represent an anomalous zone

within an overall vertical ductile shear zone and may

overlie still hidden syntectonic granites below the present

level of exposure. Regional strain in the country rocks

would accommodate itself to the rising, expanding

granite roofs and the resultant foliation would take on a

flat-lying attitude (Fig. 9b). In this model, shear heating
due to movement along the shear zone may possibly

contribute to the northwest-southeast metamorphic gradient

and to the production of granite melts (cf., Strong

1980).

In Newfoundland, the Acadian events outside of the

Gander Zone are nowhere as intense as those considered

in the model presented here (e.g., Williams et al. 1972;

H. Williams 1979) and to propose that the Acadian

Orogeny in Newfoundland represents major strike-slip

movement along the southeastern margin of the Appala-

chian Orogen is out of keeping with the generally ac-

cepted context of Appalachian–Caledonian geology.

Therefore, attempts to define and correlate the Gander

Zone along the length of the orogen (e.g., Williams et

al. 1972, 1974; H. Williams 1975, 1978, 1979) should

take account of the salient structural aspects of the Gan-

der Zone, especially in the light of recent evidence for
deformation associated with a major component of sim-

ple shear in its southwestern extension in Newfoundland

(e.g., Chorlton 1979). I propose that the definition and

extrapolation of the Gander Zone based upon the sup-

posed existence of pre-Acadian or Precambrian base-

ment be treated with caution. I would suggest that a

more fruitful future definition should take account of the
dominant strain regime rather than simply the nature of
the rocks affected.

This account is incomplete in that it takes no account

of the proposed southeastward obduction of at least part

of the Davidsville Group (e.g., Pickerill et al. 1978;
Pajari et al. 1979). However, the strike-parallel tectonic
transport proposed here constrains the obduction to a

pre-Acadian time slot.

Finally, the model of the structural and intrusive his-
tory of the northeastern Gander Zone presented here is

compatible with certain larger scale, published models

for the Appalachians and the British Caledonides. In

terms of timing, style, and transport direction, models

for the structural geology of the northwestern margin of

the Central Mobile Belt are in striking contrast to the

geology of the southeastern margin (see H. Williams

1979, for detailed bibliography). This implies that the

Appalachian Orogen in Newfoundland is markedly

asymmetrical in nature as suggested by Strong et al.

(1974a) and Stevens et al. (1974). Moreover, the sinis-

tral strike–slip movement along the Steep Belt provides

tangible geological support for the paleomagnetic mod-
els of major sinistral offset within the Appalachians and

the British Caledonides during the Devonian and the

Carboniferous (Morris 1976; Kent and Opdyke 1978,

1979; Piper 1979; Roy et al. 1979; Van der Voo et

al. 1979; Scotese et al. 1979). According to these authors,
major sinistral transcurrent movement occurred between

south Britain, New England, and the Canadian Mari-
times relative to stable cratonic North America. Morris

(1976) proposed that the motion was all pre-Upper De-

vonian in age. Kent and Opdyke (1978) subsequently

proposed that major movement ceased in Upper Carbon-
iferous times. Scotese et al. (1979) and Van der Voo et

al. (1979) consider Devonian and post-Upper Devon-

ian transcurrent movement, respectively. In the absence

of a post-Silurian ocean in the northern Appalachians

(H. Williams 1979), one would expect to find geological

evidence of such large-scale motion. The northeastern

Gander Zone apparently provides such evidence and

may have accommodated a major component of the

paleomagnetically predicted movement during Devon-

ian and Lower Carboniferous (420–330? Ma) time. As it

may only represent one of a possible array of such shear

zones and did not function during the Upper Carbonifer-
ous, other likely sites should be examined within the

Appalachians for possible Devonian–Carboniferous ver-
tical ductile shear belts.

Conclusions

Penetrative deformation in the northeastern Gander

Zone corresponds to Acadian sinistral shear along the


Acknowledgements

I wish to express my thanks to D. F. Strong for initiating me into the mysteries of the geology of Newfoundland and to A. R. Berger for my introduction to the Gander Zone. I also thank N. R. Jayasinge, H. Williams, S. Colman-Sadd, R. F. Blackwood, G. K. Muecke, and R. A. Jamieson for critically reading and improving the manuscript and for stimulating discussion. Finally, I acknowledge Dalhousie University for a Killam Post-Doctoral Fellowship during the course of this work and financial support from A. R. Berger (Natural Sciences and Engineering Research Council grant A8532) during field work.


BÉRIO, D., CHOUKROUNE, P., and JEGOUZO, P. 1979b. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican Shear Zone. Journal of Structural Geology, 1, p. 31-42.


HANMER


