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DISPLACEMENT HISTORY OF THE NORTHERN ARM FAULT, AND ITS BEARING ON THE POST-TACONIC EVOLUTION OF NORTH-CENTRAL NEWFOUNDLAND

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ABSTRACT

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The Northern Arm Fault is a northeast trending late Paleozoic fault which, together with the Reach and Cape Ray Faults, separates the Exploits and Botwood tectonstratigraphic zones of Newfoundland. Kinematic indicators reveal a dextral strike slip sense of motion. Although previous studies have suggested that the Northern Arm-Reach Fault system represents the suture marking the former position of an ocean which closed during the Devonian Acadian Orogeny, the presence of identical pre-Acadian lithologies and similar deformation histories on either side of the fault suggest otherwise. Alternatively, we suggest that the Northern Arm Fault system represents a major wrench zone, which developed within the Taconic- and Acadian-modified margin of North America in response to oblique subduction of the oceanic tract between North America and Gondwana. Analysis of Silurian sedimentary and volcanic sequences of the Botwood and Windsor Point Groups, which occur in right-steps along this fault system, suggests that they formed in pull-apart basins during an earlier episode of strike slip faulting. We relate this phase of motion to oblique subduction of the Acadian Ocean beneath North America during the Silurian and early Devonian, leading to the Acadian Orogeny.

INTRODUCTION

Most workers now agree that the Taconic Orogeny in Newfoundland was the result of a collision in Ordovician times between the ancient east-facing (present coordinates) passive margin of North America and a magmatic arc

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over an east-dipping subduction zone (Stevens, 1970; Nelson and Casey, 1979; Williams, 1979; Casey and Kidd, 1981; Dewey *et al.*, 1983). Despite the fact that it is usually regarded as the main deformation episode to have effected the Northern Appalachians, there is comparatively little agreement on the cause of subsequent Acadian orogenesis, during Devonian times. Was it due to intraplate shortening within the Dunnage Terrane (e.g. Williams 1978, 1979, 1980; Colman-Sadd 1982), or was the Acadian Orogeny the result of a second collision, between the Avalon Terrane and the Taconic-modified North American margin (e.g. Dewey, 1969; McKerrow and Ziegler, 1972; Dewey *et al.*, 1983). Even among workers who favor the latter alternative, there is considerable disagreement on the location of the suture and the plate geometry which led to collision (cf. McKerrow and Cocks, 1977, 1980; Stouge, 1980a, b, c; Arnott *et al.*, 1985; Neuman, 1984; Rowley, 1983).

In Newfoundland, a protracted history of strike-slip faulting adds to the problems of interpreting post-Taconic tectonics and paleogeography. The Northern Arm Fault separates the Ordovician magmatic arc rocks of the Exploits Terrane from Silurian terrestrial and shallow marine clastics of the Botwood Group in central Newfoundland (Williams *et al.*, 1972; Dewey *et al.*, 1983). It has been correlated with the Noel Pauls and Cape Ray Faults to the south (McKerrow and Cocks, 1977; Brown, 1973, 1977); together these faults transect the island of Newfoundland (Fig. 1). Based on the limited amount of paleontological data available at the time, McKerrow and Cocks (1976, 1977) suggested that this fault system might mark the Acadian Ocean suture in Newfoundland (to avoid confusion resulting from misuse of the term Iapetus, we refer to the postulated ocean which closed during the Acadian Orogeny as the Acadian Ocean, and that which closed during the Taconic Orogeny as the Taconic Ocean). Recently, other workers have (1) followed the original suggestion of McKerrow and Cocks (e.g. Arnott *et al.*, 1985; McKerrow and Cocks, 1980), (2) doubted that the faunal evidence requires a suture zone in this area (Stouge, 1980a, b, c), (3) suggested that the Northern Arm-Reach Fault system is a relatively late orogenic feature with only minor associated displacements (Karlstom *et al.*, 1982; Williams, 1984), or (4) placed the Acadian suture along the Gander River Ultramafic Belt which lies well to the east of the Northern Arm Fault System (Rowley, 1983; Kusky, 1985). Here, we present evidence that the Northern Arm Fault is a major dextral strike slip fault active after the Acadian Orogeny, and that the fault system may also have been active earlier, during Silurian times, localizing the formation of pull-apart basins. Our model requires that the Acadian suture lies to the east of the Northern Arm Fault System, and a likely candidate is the prominent belt of ophiolitic slivers lying along the Gander River-Carmanville Ultramafic Belt.

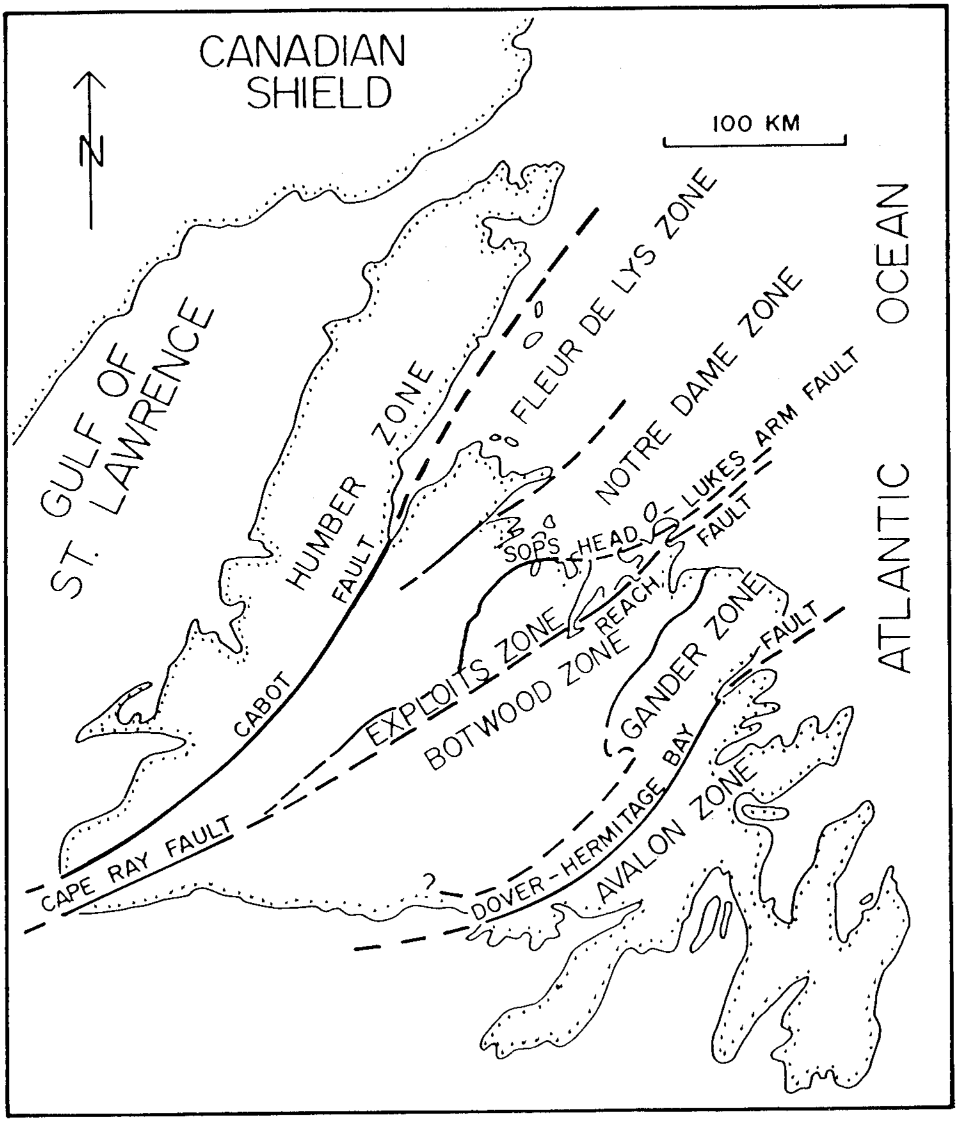

Fig. 1. Outline map of Newfoundland showing tectonostratigraphic zones as defined by Dewey *et al.* (1983). The Northern Arm-Reach-Cape Ray Fault system separates the Exploits and Notre Dame Zones from the Botwood zone.

STRUCTURAL ANALYSIS OF THE NORTHERN ARM FAULT

1. *Map scale*

In an effort to better understand the sense, timing and significance of Paleozoic strike slip faulting in the Northern Appalachians, we have analyzed a particularly well exposed portion of one of these faults, the Northern Arm segment of the Reach-Cape Ray System, which separates the Exploits and Botwood tectonstratigraphic zones within the Dunnage Terrane of central Newfoundland (Williams *et al.*, 1972; Dewey *et al.*, 1983). Geologic investigations of the Exploits Zone (Fig. 1) have suggested that it represents the back-arc side of the Taconic island arc which collided with North America in medial Ordovician times (Dean, 1978; Nelson, 1979; Kusky, 1985). Tectonic interpretations for the Botwood Group (which is part of the Botwood Zone: compare Figs. 1 and 2) are not so soundly based, but suggestions for its origin include (1) a "cratonized" terrestrial environment later preserved in fault bounded belts (K. Currie, pers. comm.,

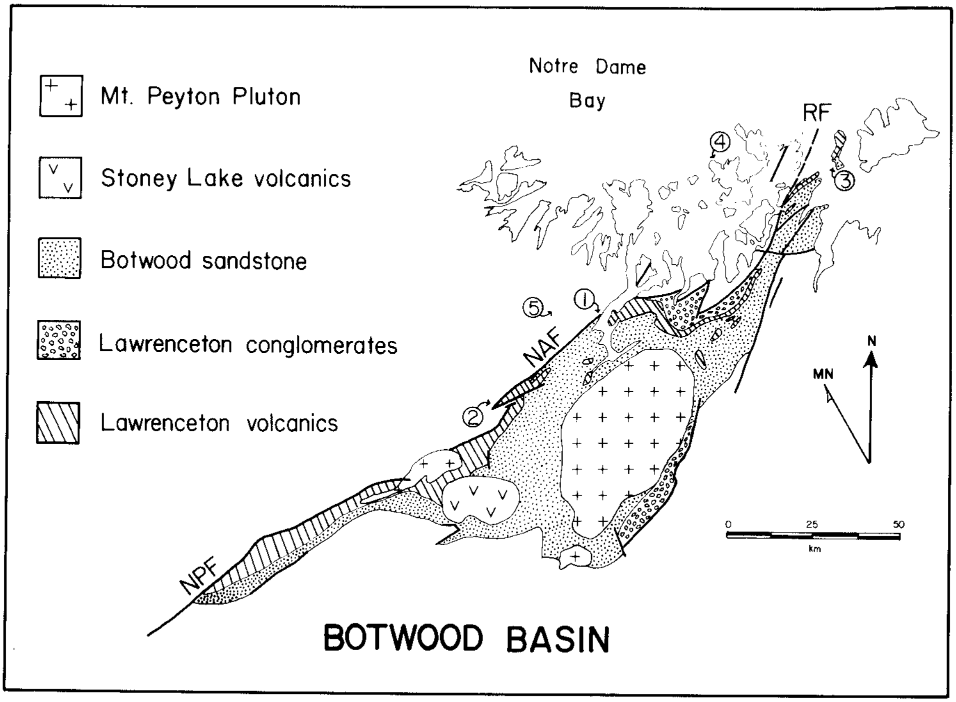

Fig. 2. Generalized geological map of north-central Newfoundland showing the relationships between the Northern Arm, Reach, and Cape Ray Faults, and the distribution of rock types in the Silurian Botwood Basin. Map drawn after Williams (1967) and Karlstrom *et al.* (1982).

1986), (2) deposits from the melting of an oceanic slab which was subducted in the Caradocian (Dean, 1978), and (3) deposition in an actively subsiding trough (Williams, 1967; Eastler, 1969). The Northern Arm Fault forms a pronounced topographic lineament extending from the Bay of Exploits to Red Cliff Overpass on the Trans-Canada Highway, approximately 8 km west of Grand Falls (Fig. 2). Outcrops from the Northern Arm of the Bay of Exploits area (10 km north of Botwood on Route 32; 1 on Fig. 2) were selected for structural analysis because numerous road, quarry and shoreline exposures offer an excellent cross section through the fault zone. Surfaces of variable orientation are available for observation in this relatively well exposed area, minimizing any statistical bias in the measurements.

At Northern Arm (locality 1 on Fig. 2), the fault strikes N45E and is approximately vertical; it displays a zone of complex structure approximately 25 meters wide within which lozenges of both the Ordovician mafic lavas of the Exploits Zone and the Silurian micaceous sandstones of the Botwood Zone appear intimately sheared together. Mafic lavas of the Exploits Zone belong to the Wild Bight Group (Espenshade, 1937; Williams, 1962) and contain a lower greenschist facies assemblage consisting of chlorite + actinolite + albite + epidote + quartz +/− pumpellyite (Franks, 1974; Nelson, 1979; Kusky, 1985). Micaceous sandstones of the Botwood Zone are assigned to the Wigwam Formation of the Botwood Group (Dean, 1978, after Williams, 1962); these are typically cross-laminated and contain quartz + detrital muscovite + hematite, giving the rocks an orange-red color (Williams, 1967). Small scale structures within this complex fault zone are described below and indicate right-lateral shear along the Northern Arm Fault.

2. *Slickenside Surfaces*

Deformation associated with the Northern Arm Fault is distributed in a diffuse zone approximately 1 km wide and is manifested in the country rocks as an increase in abundance of slickensided fault surfaces toward the main fault plane (Fig. 3). Green chlorite commonly coats these surfaces and in places comprises the slickenline fiber material. Since many of the fibrous slickensides contain steps, they may be used as kinematic indicators following the interpretation that the steps face in the direction of movement of the opposite block (Durney and Ramsay, 1973; Hancock, 1985). Most of these slickenlines are subhorizontal and occur on subvertical planes (Fig. 4) indicating that at least the latest phase of movement on the Northern Arm Fault was strike slip in character. However, a few relict slickenlines plunge

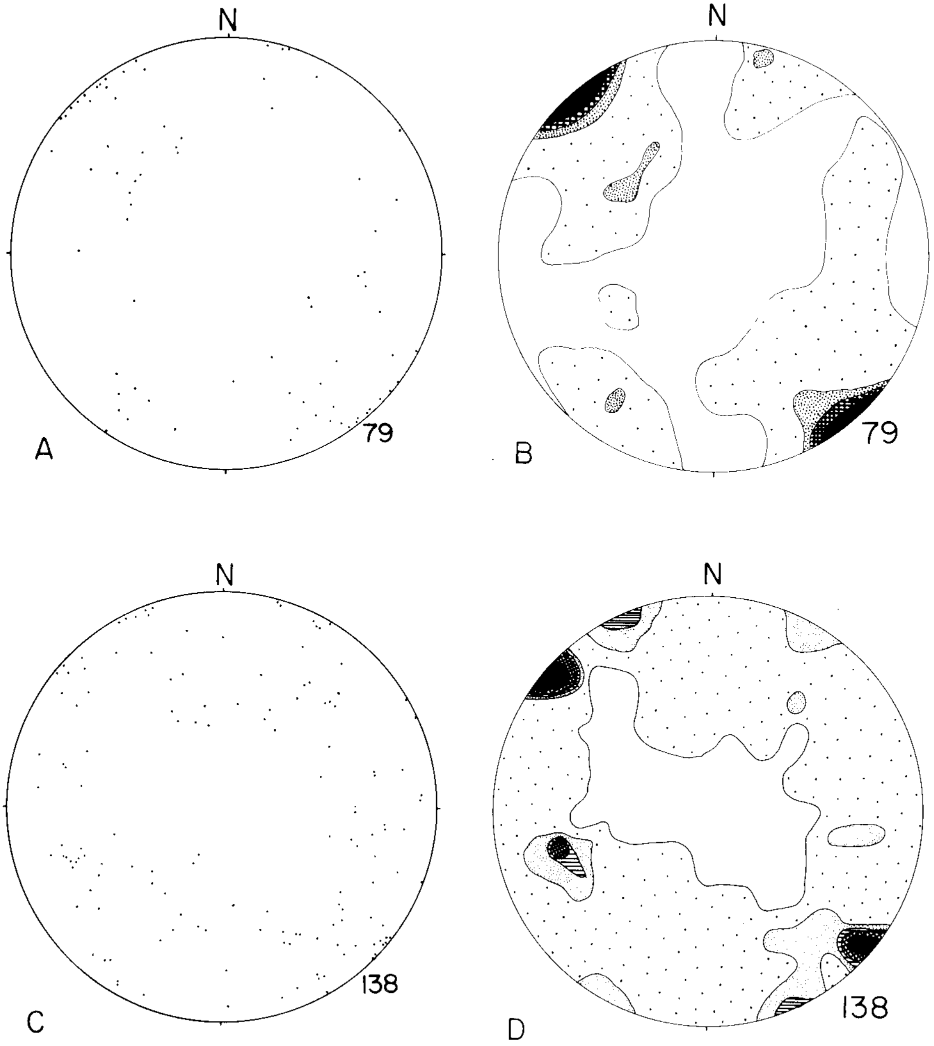

Fig. 3. Lower hemisphere equal area projections showing the orientation of fracture surfaces (A) north of and (C) south of the Northern Arm Fault. (B) is a contoured (1, 4, 7, and 10 %) version of (A) and (D) is a contoured (1, 4, 7, 10, and 13 %) version of (C).

steeply (45–90) and are typically overprinted by subhorizontal slickenlines. These palimpsest slicks suggest a more complex history of movement, possibly including early thrusting. Because strike slip faults commonly have thrust, normal, and/or rotational components of movement associated with them (e.g. Hancock and Barka, 1981; Wilcox *et al.*, 1973; Reading, 1980), the simplest interpretation, and the one suggested here, is that all of the slickenlines are the result of the same progressive deformation episode.

Figure 5 shows the orientations and general locations of all fault surfaces with slickenside steps from which the sense of shear could be deduced (22 % of total). Two sets of faults with opposing senses of shear are apparent; a northeast trending set with dextral displacement, and a northwest trending sinistral set. The northeast trending faults are by far the more prominent and are parallel to the trace of the main fault zone (Fig. 5); the less numerous northwest trending set strikes at a high angle to the main fault.

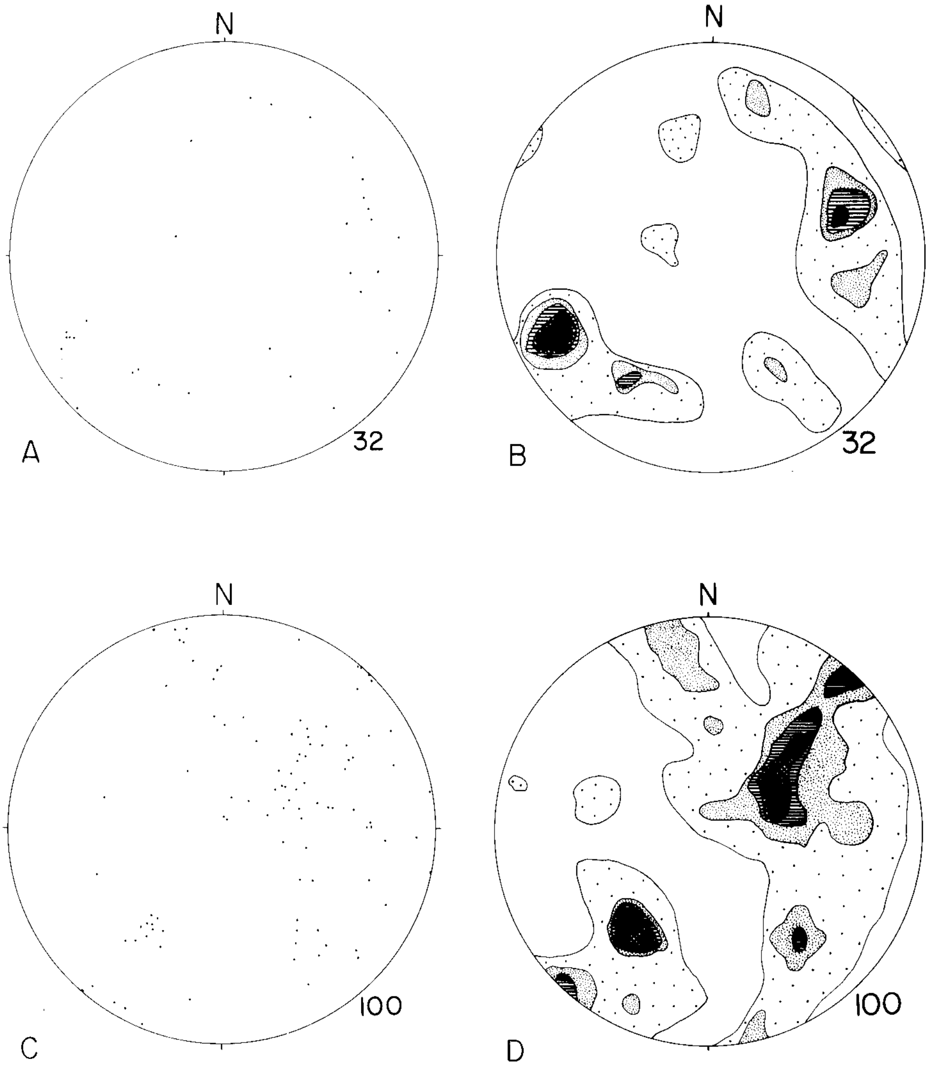

Fig. 4. Lower hemisphere equal area projections showing the orientations of slickenline fibers from (A) north of the fault, while (C) shows the same from south of the fault. (B) is a contoured (1, 3, 5, 7, and 9 %) version of (A) and (D) is a contoured (1, 2, 3, 4, and 5 %) version of (C).

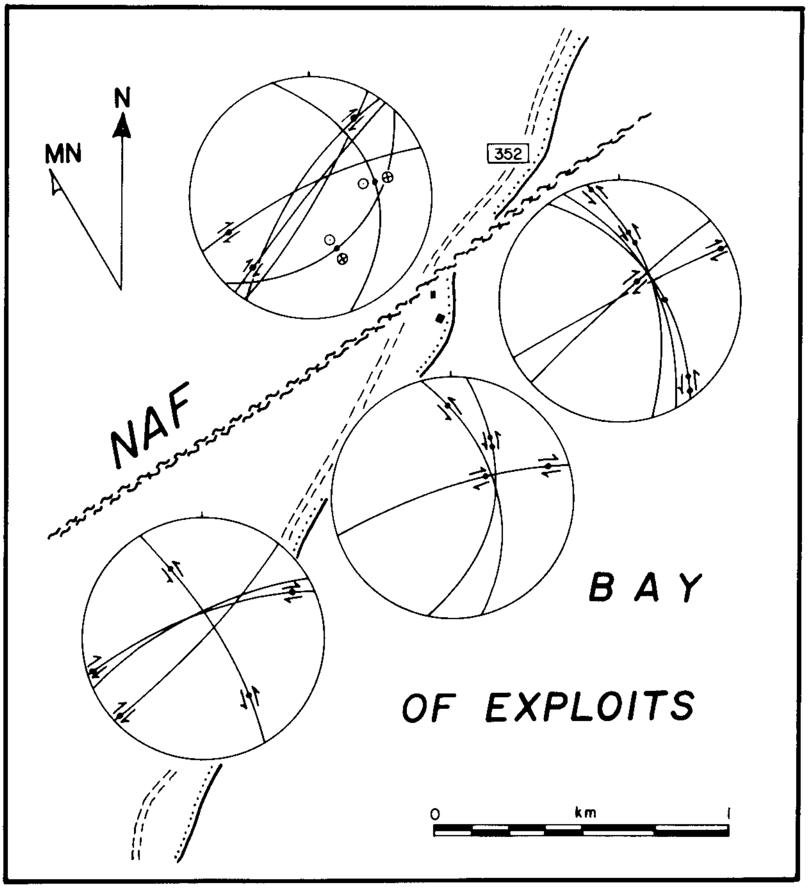

Fig. 5. Diagramatic map of the Northern Arm Fault Zone showing the orientation of fault surfaces from which the sense of shear can be deduced using the stepping directions of slickensides. Faults with right-lateral offsets are sub-parallel to the main fault trace, while those exhibiting left-lateral displacements strike at a high angle into the main fault. These are interpreted as a Reidel/Antireidel fracture set.

These two fault sets are oriented in the predicted R1 and R2 Riedel shear directions (synthetic and antithetic faults of Harding, 1974) of a dextral wrench zone and are therefore interpreted as such. The attitude of a few fault surfaces deviate considerably from the vertical, and contain thrust slickenlines, suggestive of flower structure.

3. *Fault Gouge Foliation*

Within the Northern Arm Fault Zone, thin (<5 cm), anastamosing zones of fault gouge wrap around lozenges of Wild Bight and Botwood Group lithologies. Gouge at an exceptionally good outcrop in the quarry 10 km north of Botwood on Route 32 (locality 1 on Figure 2), exposed by the floods of 1983, possesses three distinct color zones which are separated by thin layers of clay minerals oriented parallel to the shear zone boundaries. The layer closest to the orange Wigwam Sandstone closely reflects its color, while the layer flanking the Wild Bight Group volcanics is a darker red. Between these is a layer which exhibits hues transitional between both, presumably representing a "mixing zone." The predominant constituent of

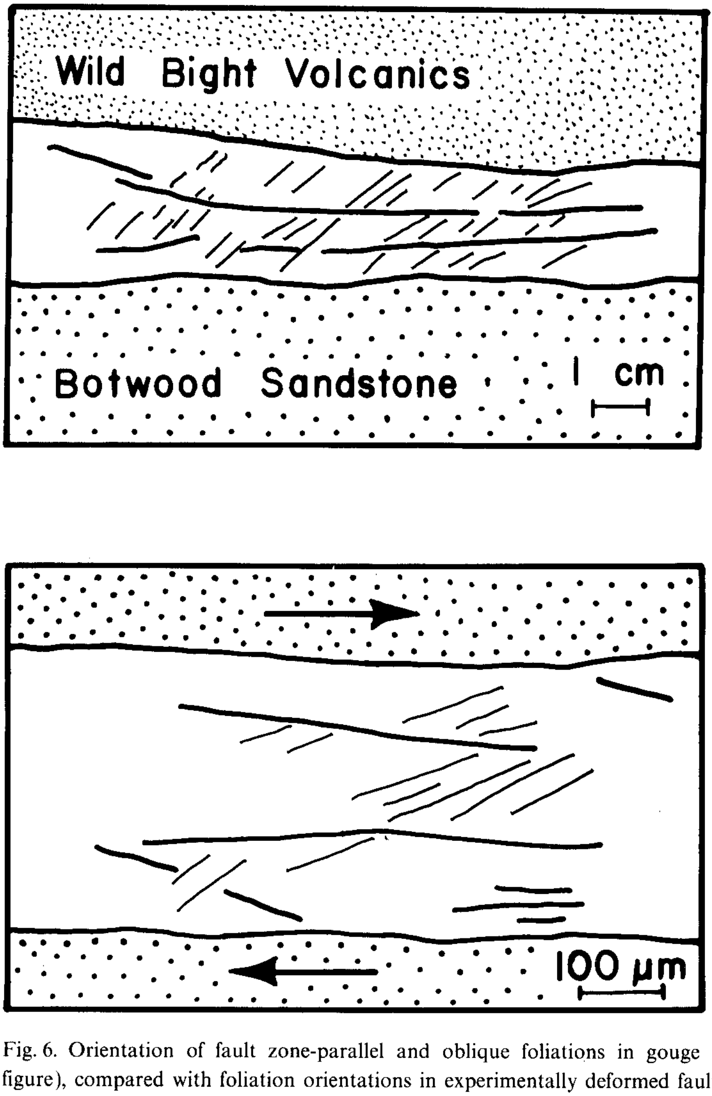

Fig. 6. Orientation of fault zone-parallel and oblique foliations in gouge from Northern Arm (top figure), compared with foliation orientations in experimentally deformed fault gouge (bottom figure) of Logan *et al.*, (1981).

the fault gouge is fine grained (<2 mm) granulated quartz. Phyllosilicates with preferred orientation define the fault gouge foliations. Several authors (e.g. Engelder, 1974a; Engelder *et al.*, 1975; Paterson, 1978) have suggested that as sliding on fault gouge zones increases, the rounding of the contained quartz grains also increases, and the mean size of these particles decreases. These features, together with the width of the gouge zones along the Northern Arm Fault (several cm each), suggest that large amounts of displacement were accomodated along them. However, complications arise in attempting to quantify displacements because of other possible influences, including normal load and the amount of water present (Paterson, 1978; Okubo and Dieterich, 1984; Steirman, 1984).

Two distinct foliation orientations occur within the fault gouge zone: the first, defined by sparsely distributed phyllosilicates, forms a mean angle of 42 degrees with the shear zone boundary while the second, defined by phyllosilicates concentrated in planes, is typically parallel to the boundary (Fig. 6). Several models exist which adequately explain the presence and orientation of these foliations. Logan *et al.* (1981) experimentally deformed gouge from the San Andreas Fault Zone under various applied conditions. Comparison of the orientation of foliations developed in their experiments (right lateral shear) with those observed in the gouge zones along the Northern Arm Fault reveals a striking similarity (Fig. 6). Logan *et al.* (1981) attributed the orientation of foliations to the alignment of clay particles along R1 and R2 Reidel shears. If the foliations in the Northern Arm Fault gouge zone had a similar origin, then their orientations indicate that it is a right lateral strike slip fault.

4. *Feather Joints*

Feather joints constitute a prominent structure in the rocks around the fault gouge zones (Fig. 7). Although several differently oriented sets of feather joints exist, the most numerous strikes to the northeast and consistently forms dextral steps in the walls of the fault gouge zones; these feather joints are therefore interpreted as pinnate fractures (e.g. Hancock, 1985). Comparison of the Northern Arm pinnate fractures with those of recent faults with known offset, as well as with other experimentally formed pinnate fractures (Cloos, 1932; Hobbs *et al.*, 1976; Quidong and Peizhen, 1984) reveals that the acute angle formed by the intersection with the main fault invariably points in the direction of movement of the block containing the pinnate fracture (Hobbs *et al.*, 1976). Hancock (1985) has suggested that pinnate fractures may contain the σ_1 paleostress trajectory. The orientation of pinnate fractures indicates right-lateral motion along the Northern Arm Fault.

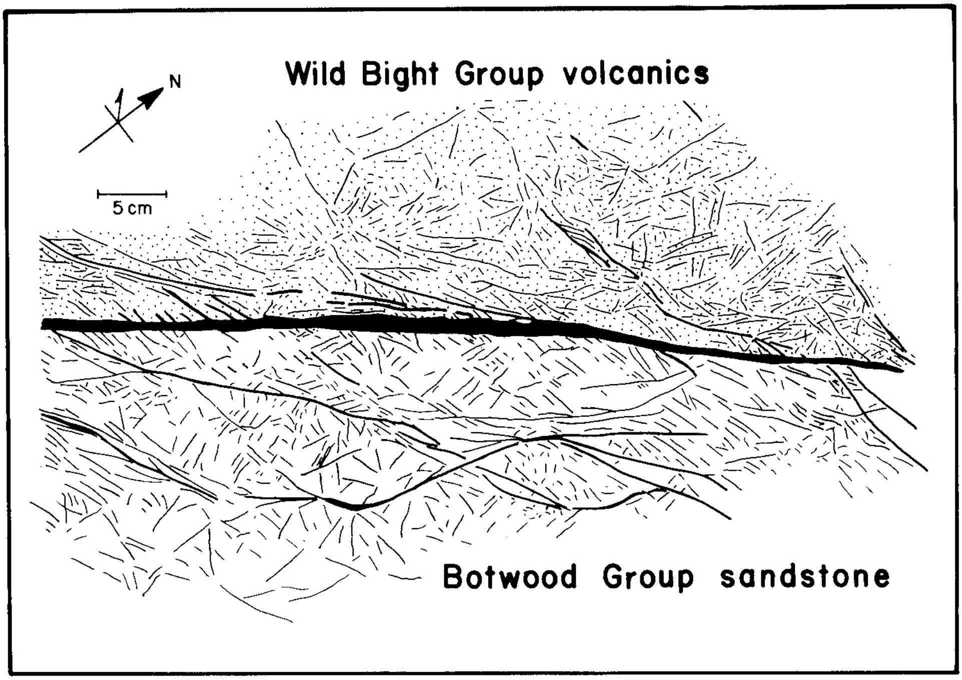

Fig. 7. Sketch of numerous fracture surfaces which surround a fault gouge zone (black) separating mafic volcanics of the Wild Bight Group from the Botwood Sandstone.

5. *Extensional Veins*

Several arrays of an echelon veins were noted from the vicinity of the Northern Arm Fault. They are typically calcite-filled and planar in habit. Veins indicate extension normal to their walls and compression parallel to their traces. Therefore, if the poles to the walls of the veins are plotted on an equal angle net which has been divided into quadrants using the orientation of the fault as one boundary (Fig. 8a), all of the poles should plot in two opposite quadrants which were in extension during their formation (assuming one generation of vein formation). Rispoli (1981) has shown that the maximum compressive stress lies parallel to the long axis of tension gashes. The principal compressive stress which resulted in the formation of these veins must therefore lie in the quadrants in which the poles to veins do not occur. When the component of stress parallel to the main fault is resolved onto the fault plane it will reveal the sense of displacement that was concurrent with vein formation. This plot is analogous to a first motion plot and is here colloquially named a "last motion plot" (Fig. 8b). The result from the Northern Arm extensional veins is compatible with this hypothesis and indicates right-lateral motion along the fault.

TIMING OF MOVEMENT ALONG THE NORTHERN ARM FAULT

1. *Post-Acadian Movement*

In several places, the Northern Arm Fault (or its along-strike continuations) cuts structures formed during the Devonian Acadian Orogeny: (1) On New World Island (locality 4 on Fig. 2), folds effecting Silurian strata are truncated by the fault, but similar structural trends on either side of the fault suggest minor dextral offset (Karlstrom *et al.*, 1982), (2) the fault cuts the Hodges Hill Pluton, which is similar to other Newfoundland plutons dated as mid Devonian (Bell *et al.*, 1977; Dallmeyer *et al.*, 1983a; see also Dallmeyer *et al.*, 1983b). These observations indicate that at least the latest phase of movement on the Northern Arm Fault occurred in late- or post-Devonian times, although some evidence, discussed below, suggests that major displacements probably occurred earlier, during Silurian times.

The age of structures recording movement along the Northern Arm Fault is thus late Devonian or possibly Carboniferous. Numerous tectonic models for strike slip faulting of this age in the Appalachians have recently been advanced, particularly in light of the suggestion that large (2000 km) sinistral displacements may have occurred during the Carboniferous (Kent and Opdyke, 1978; Van der Voo and Scotese, 1981). Re-analysis of major late Paleozoic high angle faults in the Appalachians shows almost exclusive dextral motion (Bradley, 1982, 1984; Gates *et al.*, 1986) although a few sinistral faults of minor significance are known (an example is the northeast trending fault through the center of New World Island; locality 4 on Fig. 2). Subsequent analysis of the critical paleomagnetic data has revealed that they actually do not require any displacement (Kent and Opdyke, 1985; Irving and Strong, 1984; Bradley, 1984).

Tectonic models which have been proposed to explain the widespread occurrence of late Paleozoic dextral strike slip faulting in the Appalachians include (1) oblique convergence and subduction between North America and an oceanic plate between Africa and the Acadian-modified margin of North America (Snoke and Secor, 1983; Bradley, 1984), (2) continental escape following Acadian collision (Arthaud and Matte, 1977; Lefort and Van der Voo, 1981), (3) counterclockwise rotation of Africa with respect to North America during the Carboniferous (McKerrow and Ziegler, 1972; Arthaud and Matte, 1977). The first hypothesis requires the formation of a

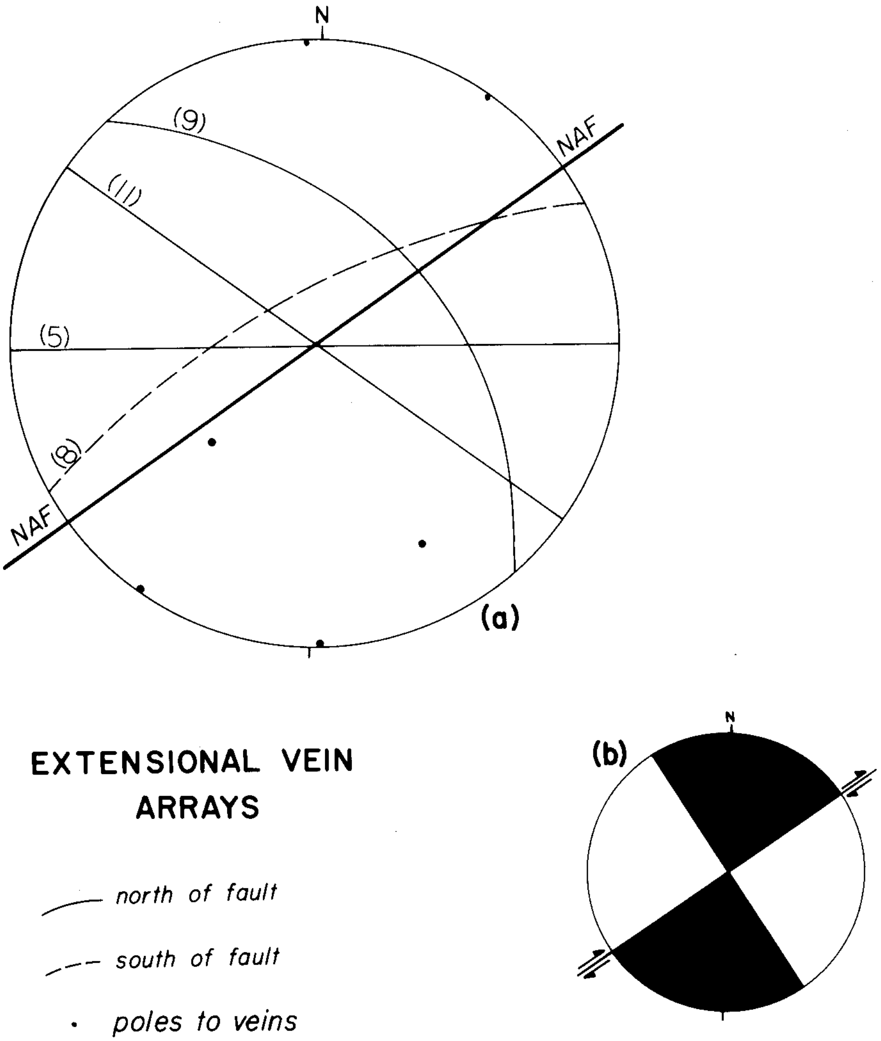

Fig. 8. Orientation of extensional en echelon vein arrays from north of (solid lines) and south of (dashed line) the Northern Arm Fault. Poles to these planes fall into two opposite quadrants defined by the fault plane: (b) is a "last motion plot" and shows compressional quads (shaded) containing poles to vein arrays, and extensional (unshaded quads).

new subduction zone on the eastern side of the collided Avalonian fragment. We favor the oblique subduction hypothesis over the continental escape model because the later implies different senses of offset along strike (e.g. Gates *et al.*, 1986; cf. Burke and Sengor, 1985), and it cannot explain the longevety (more than 100 Ma) of dextral displacements in the Appalachians. The counterclockwise rotation of Africa with respect to

North America model predicts displacements larger than those observed (Gates *et al.*, 1986) and so the oblique subduction hypothesis is favored here.

2. *Pre-Acadian Movement and the Origin of the Botwood Basin*

In old mountain belts such as the Appalachians, where the role and significance of strike slip faulting is becoming increasingly more appreciated, it is indeed a challenge to separate the significance of strike-slip faults from other tectonic features. Our analysis of the Northern Arm Fault shows clearly that it is a major dextral strike slip fault, and preliminary analyses by us and other workers of the Reach Fault suggest a similar situation (Williams, 1984; C. Elliott, pers. comm., 1986; J. Urai, pers. comm., 1985). Because of the difference in strike between the Northern Arm and Reach Faults, which form a complicated right step in a dextral strike slip fault system (Fig. 2), any simultaneous dextral motion along them would, by geometric arguments, lead to the formation of a pull-apart basin (e.g. Mann *et al.*, 1983). The age of any volcanics and sediments in such a basin should date the timing of movement along the faults.

Rocks of the Silurian Botwood Group occupy a rhomboidal outcrop area bounded on the west by the Northern Arm Fault and its extensions, and by several other faults on the east (Fig. 2). Dean (1977, 1978) and Livacarri (1980) have recognized some graben structures in the region of mismatch between these two faults, in the location and orientation (e.g. Harding, 1974) expected for pull-apart formation. Geometric aspects of the Botwood outcrop belt thus superficially resemble the pull-apart model; a more detailed look at its internal stratigraphy and structure is therefore warranted.

The basal section of the Botwood Group (Lawrenceton and correlative North End Formation from the Change Islands), contains a large amount of subaqueous and mainly subaerially-erupted volcanics (Williams, 1967; Eastler, 1969) which are strongly bimodal in silica content (Dean, 1978). The lavas are typically vesicular and red, purple, or green in color. We have observed pillow lavas with bedded interstitial red sandstone. Sediments in the lower section of the Botwood Group are typically immature and include conglomerates containing fragments of sandstone and lavas; some of the sediments locally exhibit dessication structures including mud cracks and raindrop impressions (Eastler, 1969). The presence of caliche breccias containing large volcanic fragments demonstrates subaerial erosion of rocks deposited under water.

Volcanics and immature sedimentary rocks from the lower section of the Botwood Group are overlain by a thinner, finer grained, entirely sedimentary section (Wigwam Formation) that outcrops over a larger area than the basal section (Fig. 8). Rocks of the Wigwam Formation, which is correlated with the South End Formation (Eastler, 1969) of the Change Islands (locality 3 on Fig. 2) are red to gray cross-laminated sandstones containing abundant detrital muscovite. These micaceous sandstones differ markedly in provenance from the older sandstones of central Newfoundland. Mud cracks and ripple marks are common, and local erosional unconformities are present (Eastler, 1969). Paleontological data including the presence of favositid corals, stromatoporids, crinoids, gastropods, and cephalopods indicate that some Botwood strata were deposited in a shallow marine basin (Berry and Boucot, 1970). The depositional environment was thus shallow marine and/or subaerial for both the upper and lower parts of the Botwood Group, with a larger derital contribution from uplifted basin margins during deposition of the lower sections. Even more important is the inference that stratigraphic relationships in the Botwood Group demonstrate deposition in a tectonically unstable area. The environment fluctuated between subaerial and shallow marine conditions, and the local angular unconformities suggest that the depositional basin was broken into several independently rotating or subsiding blocks.

Because these stratigraphic features are so characteristic of rocks deposited in pull-apart basins (cf. Reading, 1980; Mann *et al.*, 1983; Hempton, 1983), and the Botwood Group rocks are contained within a right step in a right-lateral strike fault system, we suggest that they do indeed represent an extensional basin formed during movement along the Northern Arm-Reach Fault system. The Botwood Group has yielded numerous shelly faunas assigned to the Llandoverian and early Wenlockian (Dean, 1978), although one suspect graptolite suggests a possible Ludlovian age (Twenhofel and Shrock, 1937; Twenhofel, 1947; Kay, 1969; Eastler, 1969; Williams, 1967; Berry and Boucot, 1970). Extrusive rocks of the Stoney Lake Volcanics have yielded a U/Pb (zircon) age of 430 Ma (Llandoverian; no error quoted, K. Currie, pers. comm., 1986). The Mount Peyton Pluton, which intrudes the Botwood Group (Fig. 2), has yielded some rather dubious K-Ar ages (not recalculated) of 410 Ma (Ludlovian) and 423 Ma (Llandoverian) (Williams, 1964); isotopic work using more recent techniques needs to be done to verify these interesting dates. If the pull-apart origin for the Botwood Group proves correct, then the above ages constrain the timing of basin formation. However, this early to middle Silurian age of strike slip faulting and pull-apart sedimentation disagree with the observation that the Northern Arm-Reach Fault system cuts structures (e.g. folds) and a pluton (Hodges Hill Batholith) which are believed to be mid Devonian in age.

In the New Bay Pond area just to the northwest of the Northern Arm

Fault study area (locality 5 on Fig. 2), two generations of northeast trending dextral strike slip faults are recognized (Kusky, 1985). The younger of these fault sets is eactly parallel with the Northern Arm Fault and cuts all other structures in the area, but the older, slightly more northerly trending set is locally intruded by mafic dikes probably related to the Devonian Hodges Hill Pluton (Fig. 9). This older set involves sediments as young as Ashgillian (or possible Llandoverian), demonstrating that Silurian or early Devonian dextral wrench faulting occurred in the region.

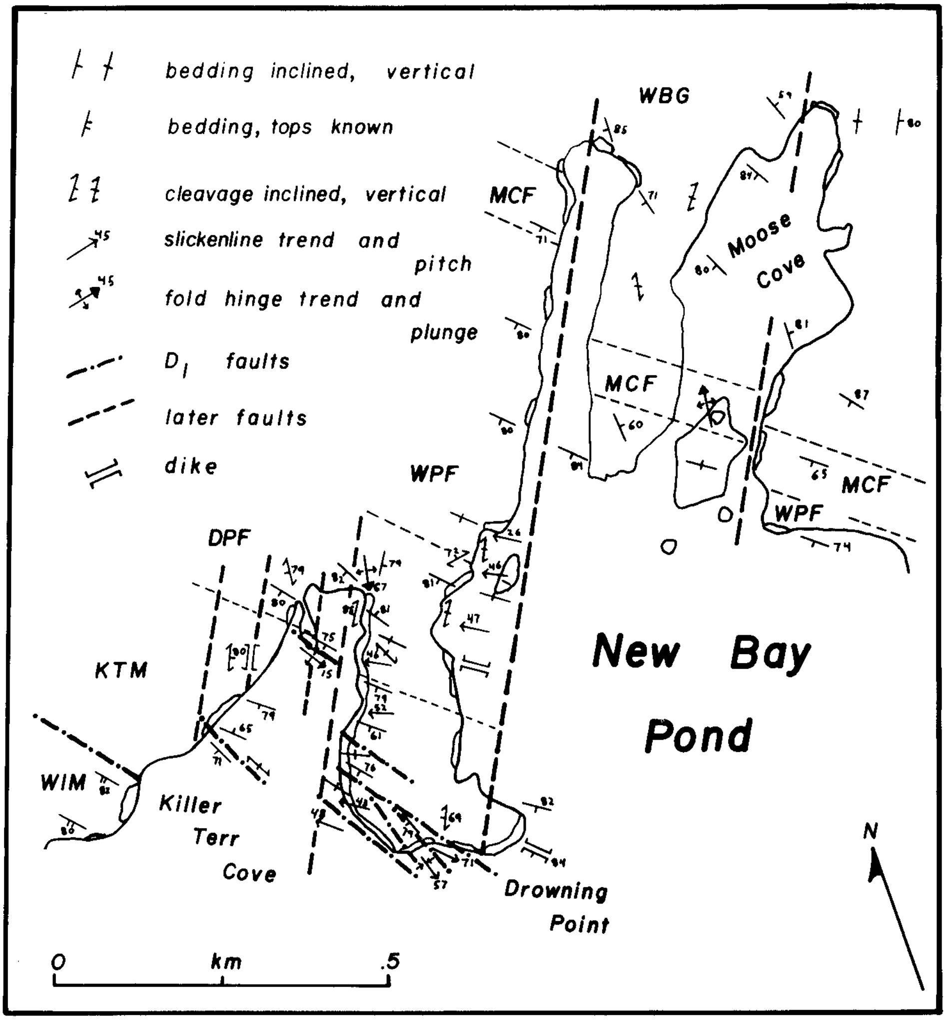

Fig. 9. Map of the New Bay Pond area (locality 5 on Fig. 2) showing northeast trending dextral strike slip faults which are locally intruded by dikes of the Devonian Hodges Hill Pluton.

We believe that these relationships indicate that there was indeed significant Silurian strike slip faulting in central Newfoundland but that movement continued, or was re-initiated along the Northern Arm Fault system after the Acadian Orogeny. Thus, although the Botwood Group is believed to represent deposition in a pull-apart basin, the structures now preserved along the Northern Arm Fault are significantly younger.

OBLIQUE CLOSURE OF THE ACADIAN OCEAN

Most workers presently accept the premise that the Taconic Orogeny was the result of the collision of an east facing passive margin of North America with an exotic island arc terrane (e.g. Stevens, 1970; Williams, 1979; Dewey *et al.*, 1983 and references therein). Recent studies have show that this collision did not mark the end of convergence between the North American Craton and the remaining, open part of the Acadian Ocean. A series of back-thrusts in central Newfoundland (Dean and Strong, 1977; Nelson, 1979; Kusky, 1985; Elliott, 1985) have been related to Ashgillian-Llandoverian compression, shortening the Taconic modified margin of North America on a series of westward dipping thrust planes (Kusky, 1985; Kusky and Kidd, 1985a, b). Thrusting is here suggested to have marked the beginning of an arc-polarity reversal event, in which pre-Taconic subduction towards the east was succeeded by post-Taconic subduction towards the west (Fig. 10). Continuous pre-Taconic through Acadian convergence between North America and Avalon is implied by the rapid reversal of subduction polarity during Ashgillian/Llandoverian times. Arc polarity reversal events are not uncommon in the geologic record but, rather, seem to be the norm following a passive margin-island arc collision (Burke *et al.*, 1984). A modern example is the eastern Banda arc which has collided with the northern shelf of Australia; here, the Flores thrust marks the initiation of a new subduction zone, on the back side of the arc, with a polarity reversed from that prior to the collision with Australia (Johnson and Jacques, 1980; Silver *et al.*, 1983).

Evidence discussed above suggests that beginning in Llandoverian times, Newfoundland was being sliced apart by dextral strike slip faults of which the Northern Arm-Reach system is but one proposed example (others include those bounding the Springdale and White Bay (Sops Arm Group of Lock, 1969) Groups, which are believed to be similar in origin to the Botwood Group: Williams, 1967; Dewey *et al.*, 1983). The change from backthrusting tectonics and molassic sedimentation (Ashgillian to Llandoverian Goldson conglomerate) to strike slip tectonics and rift sedimentation could be marked by the first eruption of Lawrenceton volcanics dur-

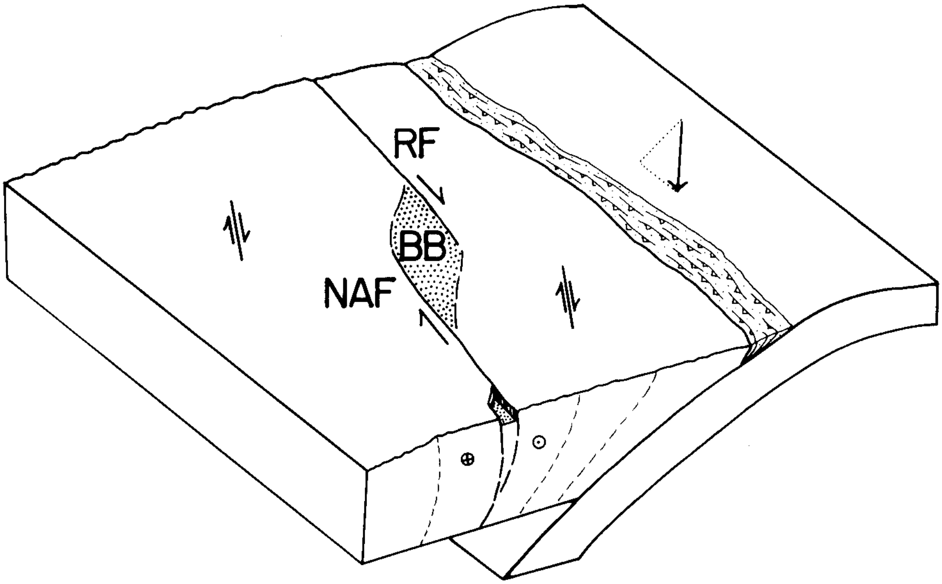

Fig. 10. Schematic block diagram showing the Northern Arm Fault (NAF) and the Reach Fault (RF) as a major arc-parallel wrench which accomodated at least part of the oblique component of convergence between the Taconic modified margin of North America and the remaining, open part of the Acadian Ocean. The Botwood Basin (BB) is suggested to be a pull-apart formed as a result of the mismatch between these related faults.

ing the Llandoverian. Alternatively, the Lawrenceton volcanics could be first melts from the new Benioff Zone. Because this transcurrent faulting episode was concurrent with the inferred closure of the Acadian Ocean and occurred above a zone of westward-directed subduction, we suggest a causal relationship: the precursor to the present Northern Arm-Reach Fault system developed in accomodation of the oblique component of convergence between the Taconic modified margin of North America and the remaining, open part of the Acadian ocean (Fig. 9). The Silurian paleogeography is thus envisioned to have strongly resembled a California borderland-type margin (Kidd *et al.*, 1977). A remarkably similar post medial Ordovician to Devonian tectonic evolution has been recognized from the Southern Uplands of Scotland e.g. Weir, 1979; Leggett *et al.*, 1982). Wrench faulting of arc terranes is common above zones of oblique subduction; well-known modern examples include the western coast of North America (Atwater, 1970; Coney, 1978), New Zealand (Lewis, 1980; Sporli, 1980), and the western Sunda arc (Fitch, 1972). In the latter example, the island of Sumatra is being sliced apart by major arc-parallel strike slip faults which accomodate the shear component of motion between the

Australian and Asian plates. A general model of this phenomenon has been described by Dewey (1980).

Rocks of the Windsor Point Group (Brown, 1975, 1976, 1977; Chorlton and Dingwell, 1981; Chandler and Dunning, 1983) occur in a narrow belt along the Cape Ray segment of the Northern Arm-Reach-Cape Ray Fault system (Fig. 1). Included is a lower sequence of bimodal mafic and silicic volcanic rocks, conglomerates, and other "rift-type" rocks, and an upper sedimentary sequence (Chorlton and Dingwell, 1981). Dates from the Windsor Point Group include a U/Pb (zircon) age of 430+/−4 Ma (Llandoverian; Chandler and Dunning, 1983) from the lower, volcanic rich sequence, and an Emsian (early Devonian) age inferred from the fossiliferous upper sedimentary section (Chorlton and Dingwell, 1981; Dorf and Cooper, 1943). The lower volcanic rich section is very much like the lower Botwood Group, including red conglomerates and sandstones. Because these rocks occur in a minor right step in the Cape Ray Fault, we suggest that they too may have been deposited in a pull-apart basin along the Northern Arm-Cape Ray fault system. The Llandoverian age of the lower Windsor Point Group is the same as that of the lower Botwood Group, suggesting that these two basins formed during the same wrenching interval. Along strike in the Gaspe, regional relations suggest that the Taconic modified North American margin may also have been cut by dextral strike slip faults during the Silurian (Bradley, 1983) and Devonian (Bourque and St. Julien, 1984).

IMPLICATIONS FOR THE LOCATION OF THE ACADIAN OCEAN SUTURE

Our model for the post-Taconic tectonic development of central Newfoundland is at variance with some other tectonic models which place the Devonian Acadian suture within our continental borderland (McKerrow and Cocks, 1977, 1980; Arnott *et al.*, 1985). Several independent lines of evidence indicate that the Northern Arm Fault system does not mark the position of the Acadian Ocean suture:

(1) Correlative Late Ordovician-Early Silurian clastics lie on both sides of the Northern Arm-Reach Fault System, and locally underlie the Botwood Group (Dean, 1977, 1978; Williams, 1967; Livacarri, 1980; Dewey *et al.*, 1983; Karlstrom *et al.*, 1982).

(2) Rocks on either side of the Northern Arm-Reach Fault have experienced similar deformation histories and early structures show a general continuity across this fault zone (Karlstrom *et al.*, 1982; Williams, 1984).

(3) Ordovician and Silurian rocks from the eastern Botwood Zone (sensu

Dewey *et al.*, 1983) are generally similar to the strata of the Exploits Zone, except that they appear to represent a more distal environment (Kusky, 1985).

Thus, we interpret the Northern Arm Fault system not as the Acadian suture, but merely as a major strike slip system which formed within the post-collisional Taconic island arc, in response to the oblique closure of the Acadian Ocean (Fig. 9). The suture must therefore lie further to the east.

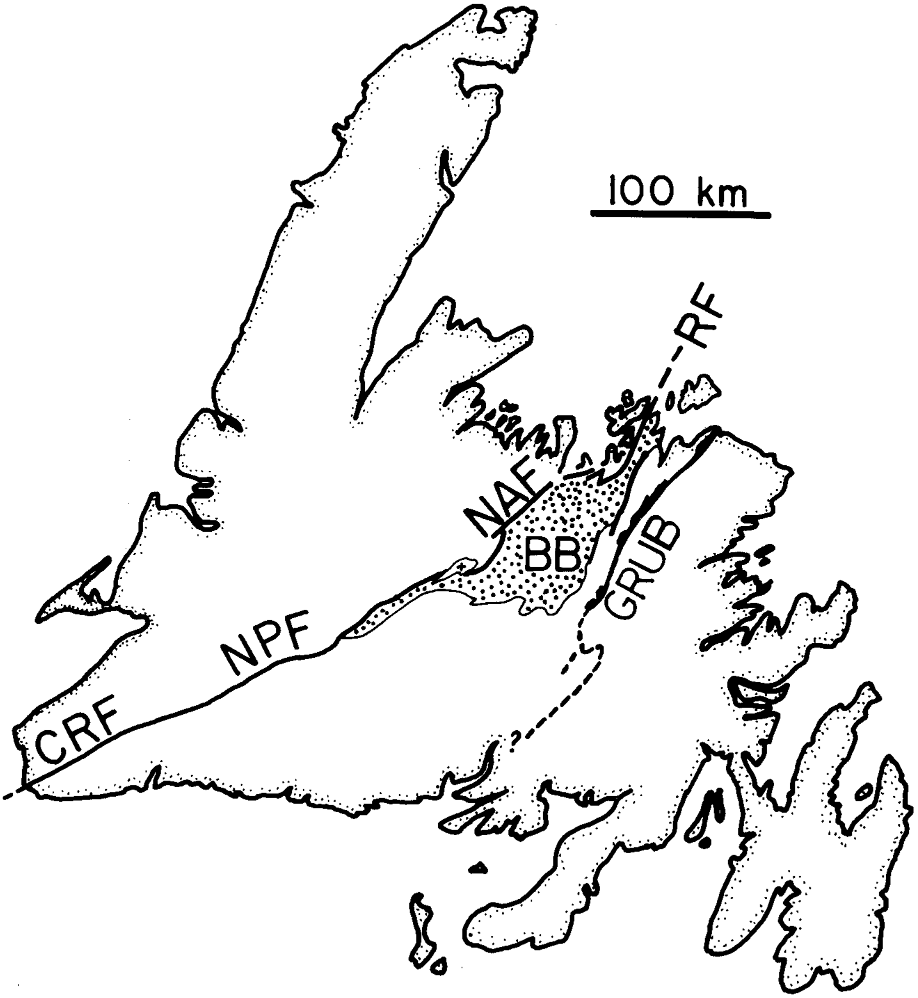

Fig. 11. Map of Newfoundland showing the Gander River Ultramafic Belt (GRUB) in relation to the Northern Arm Fault (NAF), Reach Fault (RF), Noel Pauls Fault (NPF), Cape Ray Fault (CRF), and the Silurian Botwood Basin (BB). The Gander River Ultramafic Belt is suggested to be the Acadian suture.

Sutures are recognized by zones of complex structure, locally containing ophiolitic slivers, which separate zones of different stratigraphic, structural and paleontologic histories (Dewey, 1977). A discontinuous band of highly-deformed ultramafic rocks, the Gander River Ultramafic Belt (Fig. 11), separates the distinct Dunnage and Gander Terranes (Williams, 1979; Williams and Hatcher, 1982). Gravity surveys (Miller and Weir, 1982) show that these dismembered bodies within the Gander River Ultramafic Belt (GRUB) penetrate to deep crustal levels. Structural relationships within the GRUB are rendered obscure by the scarcity of outcrop, although recent work has shown that it consists of an imbricate series of thrust sheets (Blackwood 1978, 1979, 1980, 1981, 1982; Miller and Weir, 1982), and that the ultramafic bodies are ophiolitic slivers (Kennedy and McGonigal, 1972; Pajari and Currie, 1978; Pickerill *et al.*, 1978; Pajari *et al.*, 1979; Currie *et al.*, 1980; Wonderley and Neuman, 1984). The GRUB is correlated, in a loose sense, with the overlying Carmanville ophiolitic melange on the North coast of Newfoundland (Pajari *et al.*, 1979), and its extends inland along an ill-defined arc to southwestern Newfoundland (Dewey *et al.*, 1983; Williams and Hatcher, 1982). Rocks of the Davidsville Group (Kennedy and McGonigal, 1972) structurally overlie the Carmanville melange and occur as isolated klippen on the Gander Zone (Wonderley and Neuman, 1984; Miller and Weir, 1982), suggesting considerable overthrusting of the Gander Zone by the Botwood Terrane. Although all relationships are not yet clear, most workers agree that the Gander Terrane (on the east side of the GRUB) represents a continental margin prism formed on the Avalonian side of the Acadian Ocean (cf. Williams, 1964b, 1979; Kennedy, 1975; Kennedy and McGonigal, 1972; Dewey *et al.*, 1983). We suggest that rocks to the west of the "base" of the GRUB, including the Davidsville Group, were accreted within the Acadian Ocean. If this interpretation is proven correct by subsequent work, then the Acadian suture will have to be re-defined as the Gander-Carmanville ophiolitic melange belt and its extensions to the southwest.

Most previous workers have not regarded the GRUB as the Acadian suture because ophiolitic clasts in the lower Ordovician Davidsville Group were taken to indicate that obduction of the Gander River ophiolites occurred during lower Ordovician times. We do not consider ophiolitic clasts on the ocean floor to be exclusively indicative of ophiolite emplacement, and suggest that their presence may be the result of other sea-floor processes, such as movement on a transform fault. Furthermore, the emplacement-related Carmanville melange has a Caradocian matrix, giving a maximum age of obduction. Blackwood (1981, 1982) has suggested that thrusting along the GRUB began in post-Ordovician times, and continued through the Silurian and Devonian. In terms of our model, this thrusting

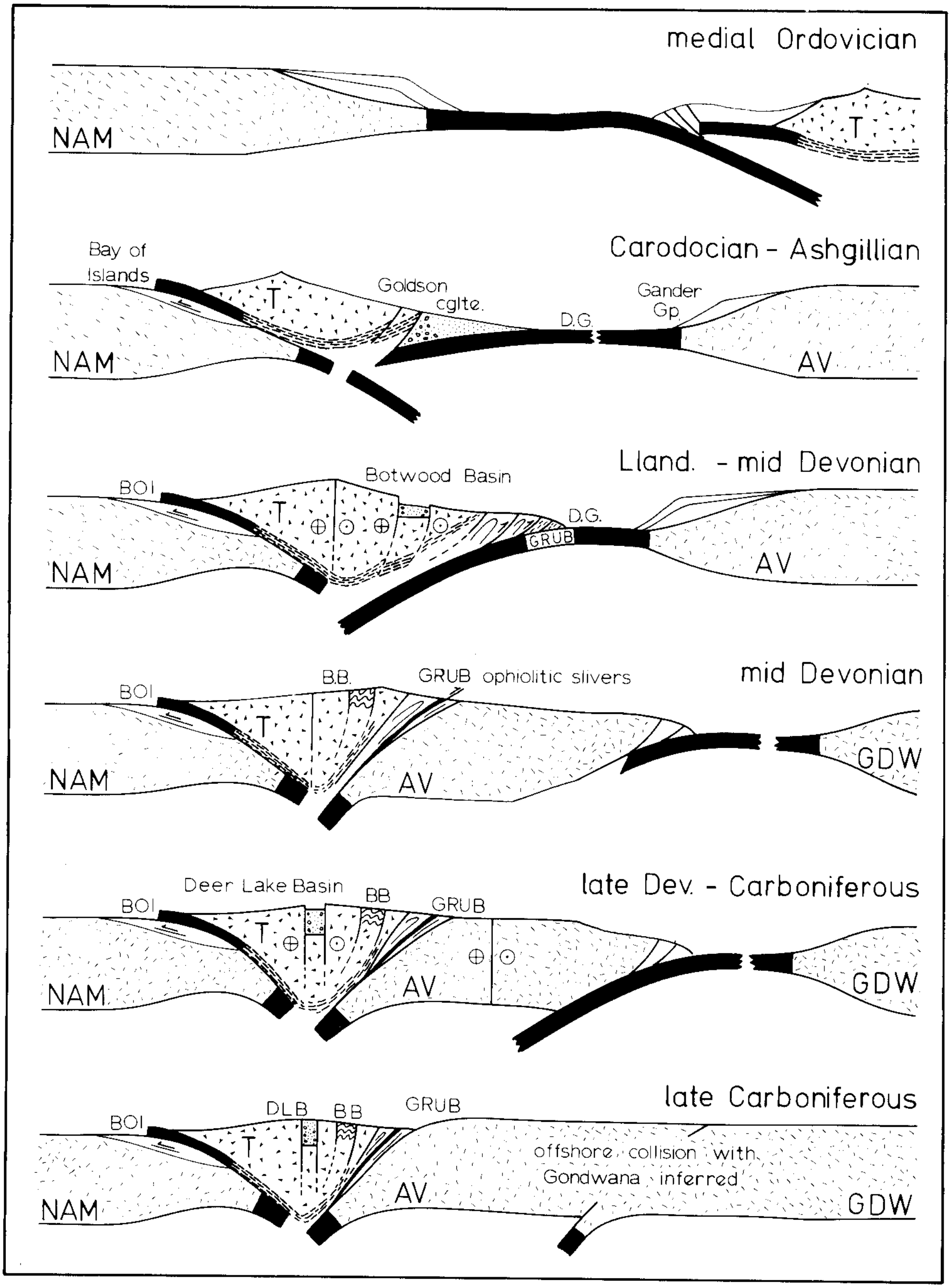

Fig. 12. Schematic diagrams showing the proposed post-Taconic tectonic evolution of Newfoundland. Note particularly the pull apart basins which form along the modified North American continental margin in response to oblique subduction. See text for details.

would be coincident with the oblique closure of the Acadian Ocean, with obduction finally occurring during the Devonian Acadian Orogeny.

SUMMARY AND CONCLUSIONS

As a summary (Fig. 12), we suggest that after the medial Ordovician Taconic collision, the formation of a new post-Taconic subduction zone on the east side of the accreted Taconic island arc allowed continuation of convergence between North America and Avalon. The Llandoverian to mid Devonian formation of numerous strike slip faults with associated pull-apart basins (the Botwood Basin being one example) above this young subduction zone suggests that convergence was oblique. Continued oblique convergence led to the collision of the Avalonian fragment with North America and the consequential Acadian Orogeny in mid Devonian times. The late Paleozoic strike slip fault system in the Appalachians, with which the latest phase of motion on the Northern Arm Fault is associated, is suggested to have had a similar origin; a post collisional subduction zone developed on the eastern margin of the Avalonian Terrane, and, as before, accomodated the continued oblique convergence between the Acadian-modified margin of North America and Gondwana. Numerous pull-apart basins (such as the Deer Lake Basin) are associated with this phase of dextral wrenching. Migration of subduction zones away from cratonic regions is widely recognized as a mechanism of continental growth, and it also allows convergence to continue between continental masses after the accretion of intervening island arcs. A similar sense of oblique convergence in the Northern Appalachian throughout the later half of the Paleozoic might suggest that only continent-continent collisions significantly effect relative velocities of the global plate mosaic.

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