

The western end of the Avalon Zone in southern New Brunswick

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The western end of the Avalon zone of southern New Brunswick displays a history extending from middle Proterozoic to Triassic time. About 620 Ma magmatism above a Late Precambrian subduction zone emplaced volcanic rocks and plutons into an orthogneiss-platformal sequence basement which had been modified by mafic intrusion and thermal metamorphism about 780 Ma. About 565 Ma a bimodal sheeted dyke complex accompanied by bimodal volcanism and high-level granite was emplaced into a major mylonite zone during minor spreading or transtension. Shallow water clastic marine sediments accumulated during Cambro-Ordovician time. From Silurian to mid-Devonian, the northwestern part of the zone subsided along steep faults which served as conduits for bimodal igneous activity. Strong Carboniferous deformation along the Bay of Fundy affected the interior of the terrane only slightly, if at all. Acadian and Taconic orogenies had little effect on this region, which acted as a relatively stable crystalline block during the Paleozoic. The exposed rocks may form a "welt" on continuous basement of similar character, which disappears north-westward beneath younger formations by down-stepping on faults, and south-eastward beneath over-riding allochthons.

La terminaison occidentale de la zone d'Avalon au sud du Nouveau-Brunswick montre une histoire s'étalant du Protérozoïque moyen au Trias. Vers 620 Ma le magmatisme au-dessus d'une zone de subduction emplaça des roches volcaniques et des plutons dans un socle à orthogneiss et séquence de plate-forme qui avait été modifié vers 780 Ma par une intrusion mafique et un métamorphisme thermal. Vers 565 Ma un complexe bimodal de "sheeted dikes", accompagné d'un volcanisme bimodal et d'un granite de niveau élevé, s'emplaça au sein d'une zone importante de mylonite au cours d'une faible expansion ou transtension. L'Ordovicien vit l'accumulation de sédiments clastiques d'eau peu profonde. Du Silurien au Dévonien moyen, la portion nord-ouest de la zone s'abaissa le long de failles à forts pendages qui agirent comme conduits pour une activité ignée bimodale. Une forte déformation carbonifère le long de la Baie de Fundy n'eût guère d'effet sur l'intérieur de la lanrière. Les orogénèses acadienne et taconique n'eurent qu'un effet quelconque sur cette région qui forma un bloc cristallin relativement stable au cours du Paléozoïque. Les affleurements peuvent constituer un "renflement" sur un socle continu de même facture qui disparaît vers le nord-ouest sous les formations plus jeunes par abaissement sur des failles et vers le sud-est sous les allochtones chevauchants.

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INTRODUCTION

Massifs of Late Precambrian volcanic and sedimentary rocks intruded by plutons of similar age, and locally overlain by Cambrian strata with an Acado-Baltic fauna, fringe much of the Atlantic coast of North America (Fig. 1). This assemblage of units constitutes an "Avalonian terrane" (compare Williams and Hatcher, 1983). The relations of these massifs with each other and with surrounding rocks remain obscure because of complex internal dissection by faults and disappearance of many of the critical boundaries beneath Devonian-Carboniferous sedimentary basins. In particular, the nature of basement to Avalonian terranes and the extent of the terranes beneath surrounding younger rocks remain uncertain. The western end of the Caledonia block, an Avalonian terrane in southern New Brunswick (Fig.

2), exposes unequivocal basement to the late Precambrian rocks and contact relations with surrounding units which permit much of the Paleozoic tectonic history to be reconstructed. This region can, therefore, serve as a testing ground for a variety of theories on the origin and development of Avalonian terranes.

DESCRIPTION OF UNITS

The stratigraphy of the western part of the Caledonia block has been discussed in detail elsewhere (Helmstaedt, 1968; Garnett, 1973; Rast *et al.*, 1976; Wardle, 1977; Donohoe, 1978; Ruitenberg *et al.*, 1979; Currie *et al.*, 1981; Currie and Nance, 1983; Currie, 1984, 1986, 1988; McCutcheon and Ruitenberg, 1987; Tanoli, 1987). The oldest rocks form a narrow rib of mesocratic, migmatitic quartz-plagioclase-hornblende±biotite

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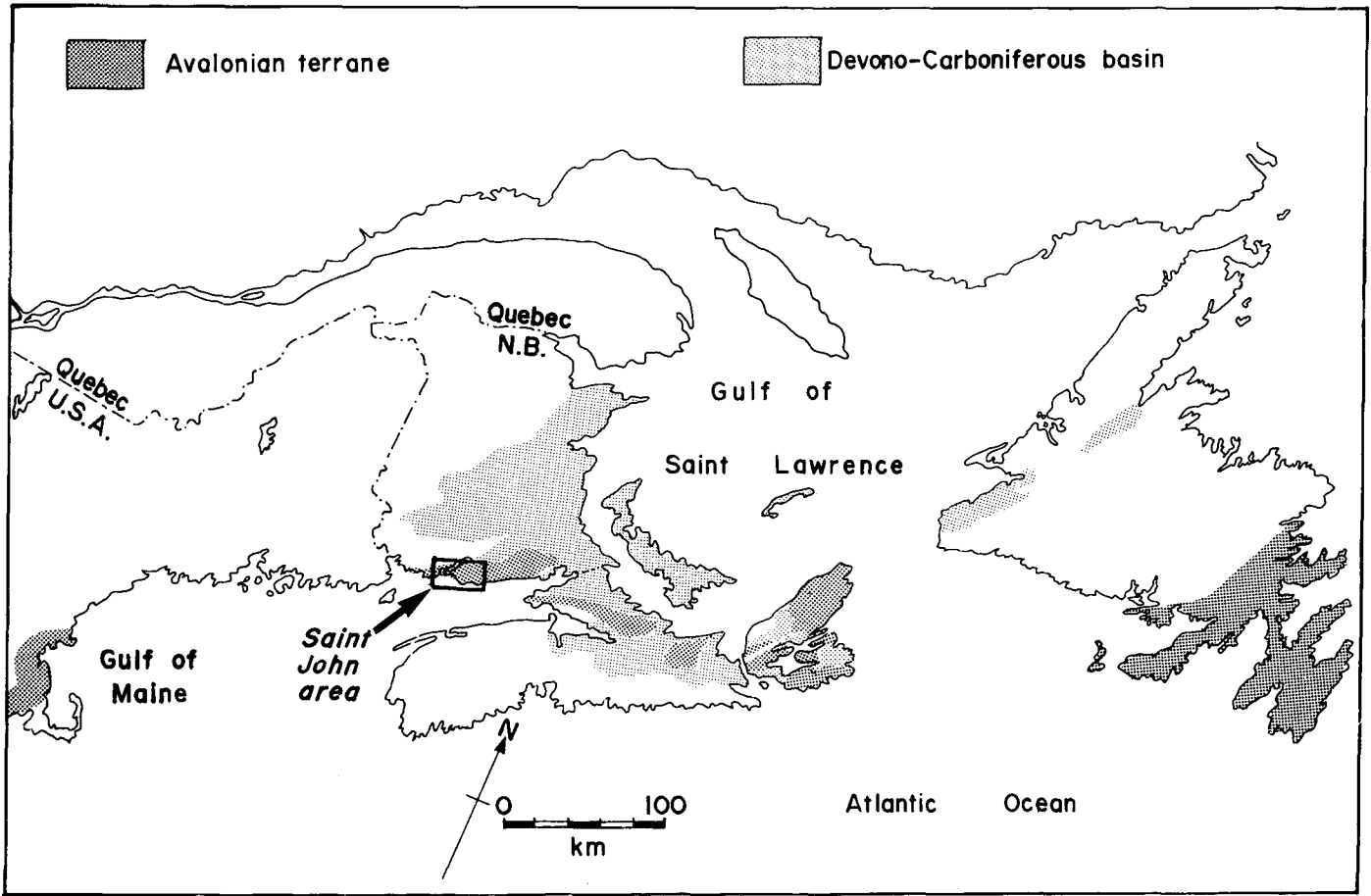


Fig. 1. Avalonian terranes in the northern Appalachians. The area covered by Figure 2 is marked with a box.

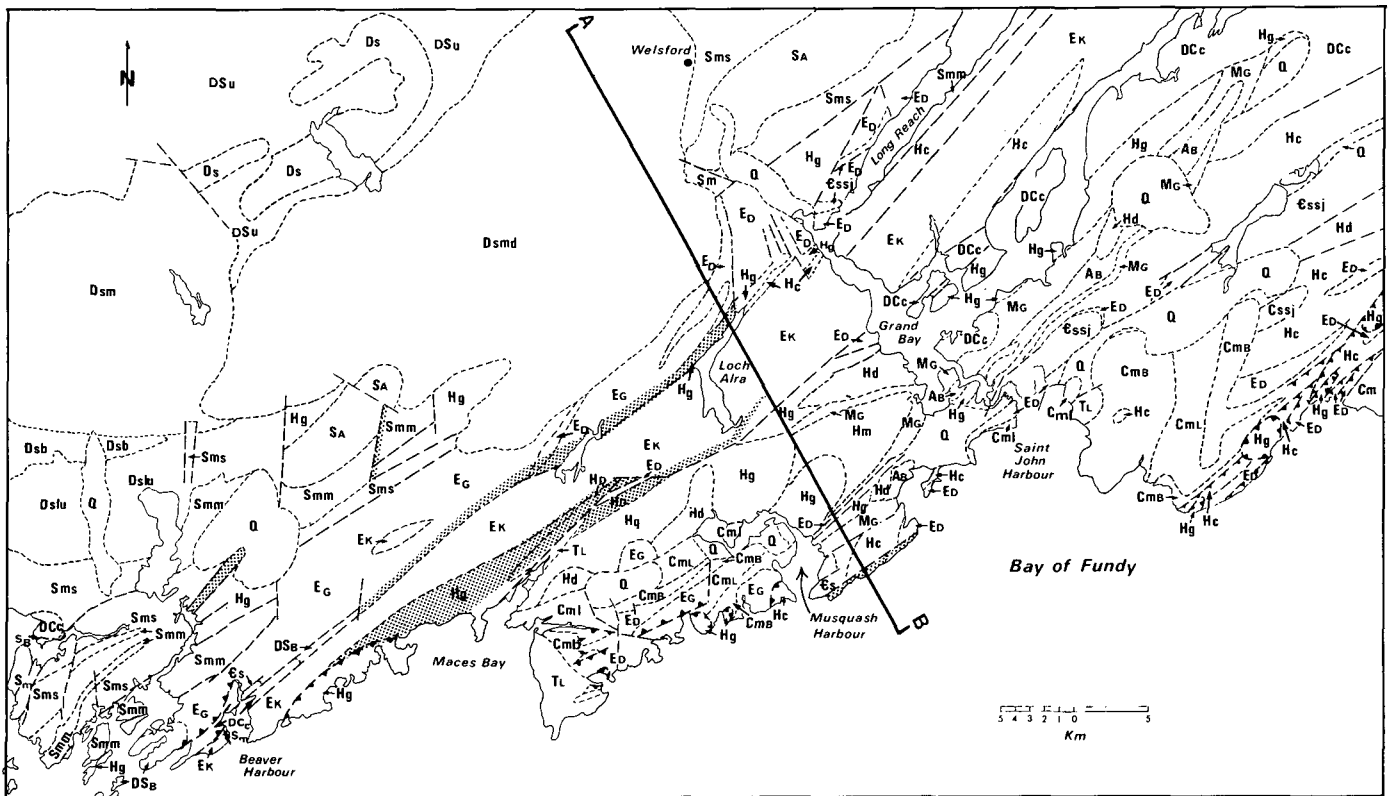


Fig. 2. Geological map of the western end of the Avalon terrane in southern New Brunswick.

Legend for Figure 2

QUATERNARY

Q till, moraine, outwash, glacio-marine deposits

TRIASSIC

T_L LEPREAU FM.; brown conglomerate, red sandstone and siltstone

LATE CARBONIFEROUS

C_M MISPEC GP.; LANCASTER FM. grey litharenite, pebble conglomerate, black siltstone (L); BALLS LAKE FM. red siltstone and shale with conglomerate lenses, basal caliche and limestone (B)

LATE DEVONIAN TO CARBONIFEROUS

DC_c red conglomerate, green to tan sandstone with conglomerate lenses, includes KENNEBECASIS FM., PERRY FM., and BEAVER HARBOUR FM.

DEVONIAN

D_s SAINT GEORGE BATHOLITH; MOUNT DOUGLAS PLUTON, biotite granite and porphyry with rapakivi feldspar, aplite dykes (md); pink seriate biotite granite with tuffite veins, LAKE UTOPIA PLUTON (lu) and MAGAGUADAVIC PLUTON (m); gabbro, diorite and granodiorite (BOCABEC COMPLEX (b))

SD_u undivided Silurian and Devonian strata north of the Saint George batholith, includes QUEEN BROOK FM., WAWEIG FM., and PISKAHEGAN GP.

LATE SILURIAN

S_A riebeckite granite, felsite, porphyry, aplitic amphibole granite, minor mafic phases. (WELSFORD and JAKE LEE MOUNTAIN plutons)

SILURIAN AND EARLY DEVONIAN

S_B BLACKS HARBOUR BEDS; deformed red conglomerate and siltstone (may be Late Devonian in part)

S_M MASCARENE GP. (includes EASTPORT FM. equivalents); amygdaloidal basalt, tuff, rhyolite, minor siltstone and limestone (m) (includes LONG REACH FM.); rhythmically banded siltstone and shale, massive siltstone and sandstone, minor limestone, locally interbedded with volcanics (s) (includes JONES CREEK FM.)

CAMBRIAN AND LOWER ORDOVICIAN

C_s SAINT JOHN GP., green sandstone and siltstone, basal red-beds and conglomerate, upper black shale (sj); BUCKMAN CREEK BEDS, basalt and rhyolite flows and tuff, reddish siltstone and conglomerate (bc)

EOCAMBRIAN (~565 Ma)

E_D red feldspathic sandstone and tuff, conglomerate (s); ignimbrite, felsite and porphyry (f); basalt (b)

E_G red-stained granodiorite to granite, commonly leucocratic and aplitic; quartz-feldspar porphyry (g); gabbro and melagabbro (u)

E_K KINGSTON COMPLEX, bimodal sheeted dykes, basalt, rhyolite, foliated amphibolite and felsite; minor amounts of Coldbrook Group.

LATE PROTEROZOIC (~620 Ma)

H_g GOLDEN GROVE SUITE; hornblende diorite(d), hornblende-biotite granodiorite biotite granite, megacrystic granite. Rocks epidotized and chloritized, commonly with abundant enclaves and/or comingling textures.

H_c COLDBROOK GP., mainly andesitic to rhyolitic volcanic fragmental rocks, subordinate basaltic flows, minor conglomerate and rhythmically banded grey siltstone and sandstone: equivalent mafic and salic schists

PROTEROZOIC (~780 Ma)

H_M MARTINON FM., black turbiditic siltstone with cherty lenses, minor debris flows, intercalated basaltic flows and sills

P_d tonalite, diorite, amphibolite, foliated and cut by numerous mafic dykes

MIDDLE PROTEROZOIC

M_G GREEN HEAD GP., marble, locally stromatolitic, quartzite, minor pelite


EARLY PROTEROZOIC (?)

A_B BROOKVILLE GNEISS, dioritic to tonalitic gneiss and migmatite, commonly chloritized and mylonitized

----- geological contact

----- fault, high angle or transcurrent

▼▼▼▼ thrust fault, teeth on thrust block

 mylonite zone

gneiss (Brookville gneiss, unit A_B on Fig. 2) diapirically emplaced into its surroundings as a plastic solid (Currie *et al.*, 1981). The Green Head Group (unit M_G) of buff to grey, locally stromatolitic, marble, quartzite and minor pelitic schist was mobilized along the contact with the Brookville gneiss, complexly structurally interleaved with it, and raised from chlorite to sillimanite grade (Wardle, 1977). The age of gneiss emplacement with its high temperature deformation and attendant deformed mafic dyke swarm (Fig. 3) appears to be fixed by 780-820 Ma Pb-U ages on zircon from deformed dioritic gneiss (Olszewski and Gaudette, 1982). The protolith ages remain uncertain. Hofmann (1974) estimated an age of 1000-1500 Ma for stromatolites of the Green Head Group.

Turbiditic siltstones and debris flows of the Martinon Formation (unit H_M) rest unconformably on the Green Head Group (Fig. 4) west of Grand Bay. The Martinon Formation, which contains a significant component of basalt sills and flows, occurs mainly as cusped synformal enclaves between large plutons, for one of which Olszewski *et al.*, (1980) reported an age of 615 Ma by Rb-Sr isochron. The age of the Martinon Formation remains uncertain. S.R. McCutcheon (personal communication, 1988) pointed out that the lithology and stratigraphy resemble those of the Burin Group of Newfoundland which has been dated at 762 Ma (Krogh *et al.*, 1988).

The calc-alkaline, arc-related (Fig. 5, see also McCutcheon in Ruitenberg *et al.*, 1979) Coldbrook Group (unit H_C) in the Saint John area consists of abundant intermediate, commonly fragmental volcanic rocks, including lahars and ignimbrites, subordinate basaltic flows, locally pillowed, and minor sedimentary rocks, mainly rhythmically banded siltstones, with minor conglomerate and sandstone. A suite of elongate dioritic to grano-

dioritic I-type plutons (Golden Grove suite, unit H_G , Hayes and Howell, 1937) may be cogenetic with the Coldbrook Group, although the two units are rarely seen in close proximity except across faults. Golden Grove plutons typically exhibit cognate enclaves of felsic and mafic rocks with textures varying from net-veining and agmatitic, to spectacular mixing textures. Watters (1987) reported a preliminary Pb-U age on zircon of 625 ± 15 Ma for the pluton at Cape Spenser. Stukas (1978) reported similar ages for volcanic rocks south of the Long Reach (630-640 Ma by $^{40}\text{Ar}/^{39}\text{Ar}$). Rocks of the Coldbrook Group, Golden Grove suite and Martinon Formation exhibit a pervasive prehnite-pumpellyite to greenschist facies metamorphism.

The youngest Precambrian rocks in southern New Brunswick comprise a bimodal sheeted dyke complex (Kingston complex, unit E_K), high-level granitoid plutons (unit E_G), and a bimodal volcanic-red bed suite (unit E_D). The Kingston complex, with a strike length of more than 100 km and a width of 3 to 6 km, consists mainly of alternating salic and mafic dykes (Fig. 6). The central part of the complex is at greenschist facies (Leger, 1986) but the grade declines toward the margins, which are marked by major mylonite zones. Relict igneous textures persist through much of the complex. Leucocratic, equigranular red granodiorite to monzogranite bodies (unit E_G) characterized by strong radiometric signature (Shives, 1986) form lenticles within the Kingston complex and equant plutons outside it. Two of these bodies gave Pb-U zircon ages of 565 ± 8 Ma (Currie, 1987, 1988). Red tuffaceous siltstone and conglomerate associated with basalt and rhyolite porphyry flows (unit E_D) occur north of the Kingston complex and also along the Fundy coast. The basalts chemically resemble the Coldbrook Group, but show some transition toward within-plate chemistry (Fig. 5). These strata underlie the Cam-

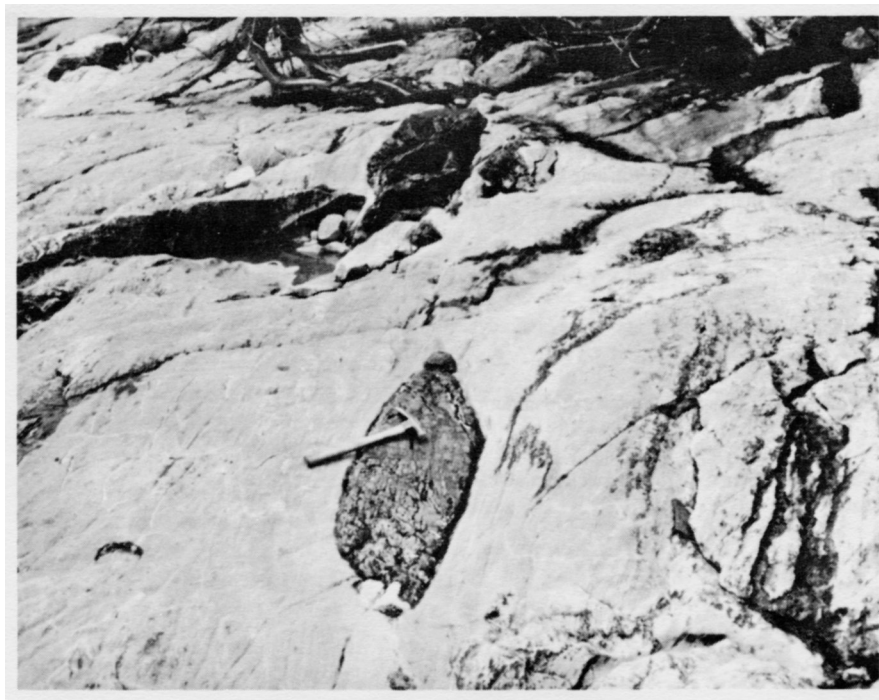


Fig. 3. Mafic dyke dismembered by mobilized Green Head marble, shore of Musquash Harbour. Note rootless isoclinal fold in marble. Hammer is 35 cm long.



Fig. 4. Proximal debris flow in Martinon Formation, southeast of Grand Bay, with clasts derived almost entirely from marble of the Green Head Group. Note the cusped shapes of clasts resulting from pressure solution effects. Hammer is 35 cm long.

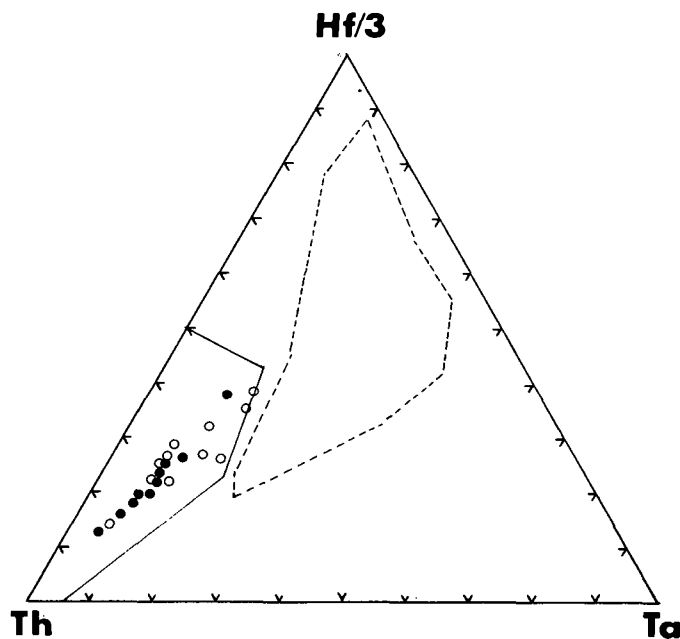


Fig. 5. Th-Hf-Ta data for volcanic rocks of the Coldbrook Groups and Eocambrian strata. Solid circles - Coldbrook Group; open circles - Eocambrian strata. Field enclosed in solid line corresponds to calc-alkaline rocks from destructive plate margins (Wood, 1980). Note that both Coldbrook and Eocambrian volcanics are calc-alkaline, but the latter are displaced toward the MORB field (dashed line). INAA data from samples collected and analysed by G.N. Eby.

brian Saint John Group with only slight angular discordance, suggesting that the Eocambrian rocks and the basal Cambrian Ratcliffe Brook Formation of the Saint John Group may form a single stratigraphic "package."

Two types of Lower Cambrian to Lower Ordovician strata (unit C₂) occur. The Saint John Group, a transgressive barrier-bar complex of sandstone and siltstone (Tanoli, 1987) lies unconformably upon the Coldbrook Group. It now appears mainly in down-dropped fault slices. At the head of Beaver Harbour a sequence of ignimbrite, vesicular basalt, lapilli tuff, tuffaceous siltstone and calcareous siltstone capped by red siltstone with volcanic cobbles rests unconformably on the Kingston complex and an Eocambrian(?) granite. The lapilli tuff yielded middle Cambrian (*P. beneti* zone) fossils (Helmsteadt, 1968). Thin tuffaceous beds in the Saint John Group may be equivalent to this volcanic sequence.

Silurian to Devonian sedimentary and volcanic strata fringe the northwestern margin of the Precambrian rocks. The upper part of this sequence in the Passamaquoddy Bay area has generally been correlated with the Eastport Formation of Maine (Pickerill *et al.*, 1978; Donohoe, 1978; Van Wagoner and Faye, 1988), but stratigraphy and nomenclature of lower strata ("Mascarene Group") remain unresolved. Northeast of the Mount Douglas pluton (Fig. 2, Unit D_{smd}) McCutcheon and Boucot (1984) considered basalt, tuff and siltstone of the Long Reach Formation to be conformably overlain by siltstone of the Jones Creek Formation. As Llandovery fossils occur in the former and Pridolian fossils in the latter, the two formations span

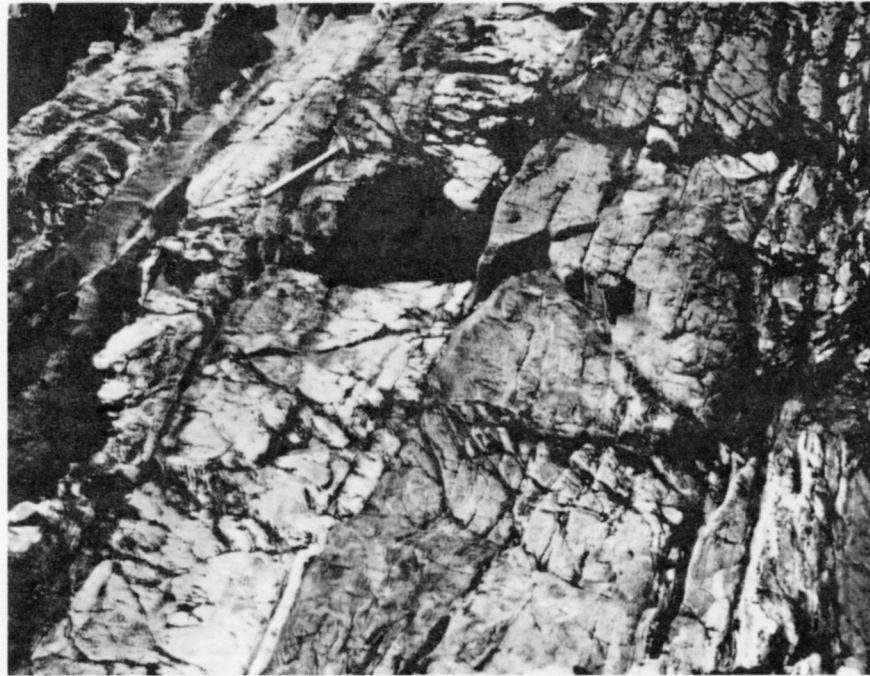


Fig. 6. Sheeted bimodal dykes, Kingston complex, Beaver Harbour. Hammer at centre left is 35 cm long.

Wenlock and Ludlow time. Currie (1987) found basalt and siltstone interbedded northwest of Grand Bay, suggesting that relations between the Long Reach and Jones Creek formations may be more complex than envisaged by McCutcheon and Boucot (1984). Southwest of the Mount Douglas pluton a shallow marine-littoral Silurian section, Llandoverly in age at the base, faces consistently to the northwest (Donohoe, 1978), and passes north into interbedded sedimentary and volcanic rocks that are Pridolian near the top, or even of Gedinnian age (Van Wagoner and Faye, 1988). Unconformity between Silurian and Precambrian rocks has not been directly observed, but abundance of dykes in the Precambrian granites and granitic cobbles in the Silurian volcanic rocks (Fig. 7) prove a hidden unconformity.

The "Saint George batholith" comprises five plutons of Silurian to Devonian age. High level alkaline to peralkaline granite (unit S_A) occurs in a linear belt which is interrupted by the Mount Douglas pluton. Volcanic strata correlative to the granite form part of the Pridolian Jones Creek Formation (Payette and Martin, 1987). The early Devonian Bocabec complex comprises sheets of gabbro grading to granodiorite and has yielded a Rb-Sr isochron age of 403 Ma. The Lake Utopia and Magaguadavic plutons consist of coarse biotite granite of Middle Devonian (~380 Ma) age. Late Devonian coarse-grained to megacrystic biotite granite of the Mount Douglas pluton (360-370 Ma by ^{40}Ar - ^{39}Ar , M.J. McLeod, 1987, personal communication, 1988) has cut all older units. The Mount Douglas pluton intruded both Silurian strata and Precambrian granite on its south side. Gravity modelling by Thomas and Willis (in press) suggests that the Bocabec complex is a thin sill, not more than a few hundred metres thick, whereas the granitic rocks of the Lake Utopia, Magaguadavic and Mount Douglas plutons form a sheet some 6 km thick overlying Paleozoic strata and possibly Precambrian

basement. The lack of minor intrusions around the south side of the Saint George batholith is striking. Only the Eagle Lake stock (Ruitenberg, 1969) may be correlative.

Carboniferous strata northwest of the Kingston complex comprise little deformed red sandstone and conglomerate of the Kennebecasis, Perry and Beaver Harbour formations (units DC_c) which are locally derived clastic sequences deposited in fault troughs. The lower parts of these formations are Late Devonian in age (Hayes and Howell, 1937; Alcock and Perry, 1960), whereas the upper parts may be as young as Westphalian (Currie, 1984). The Blacks Harbour member of the Perry Formation, as defined by Schluger (1973), consists of deformed red siltstone-sandstone sequences with abundant caliche horizons and coarse conglomerate intervals which occur in several fault troughs southeast of the Mascarene Group. Alcock and Perry (1960) considered the Perry Formation to be little deformed and to contain debris of Devonian granites. The beds in question obey neither criterion, do not correlate well with the rest of the Perry Formation, and may be significantly older, possibly lower Devonian to upper Silurian in age and equivalent to part of the upper Mascarene Group. The rocks are shown separately on the map under the name Blacks Harbour beds at the suggestion of N. Rast (personal communication, 1988).

Southeast of the Kingston complex, the Mispic Group (in the sense of Currie and Nance, 1983) represents an alluvial fan complex fed from the southeast (unit C_M). The lower (proximal) Balls Lake formation, resting unconformably on Coldbrook and Saint John Groups and Golden Grove suite, consists of red siltstone with conglomerate lenses, and basal caliche-rich layers with a local basal, black stromatolitic limestone. The upper (distal) Lancaster Formation consists of pale grey lithic arenite with thin black, plant-bearing, siltstone layers. The Mispic



Fig. 7. Mafic volcanic of the Mascarene Group packed with granite debris, woods road 18 km north of Beaver Harbour. Hammer is 35 cm long.

Group is mainly of Westphalian age, although the range in age may be from Visean to Stephanian (Currie and Nance, 1983).

Chocolate-coloured conglomerate and red siltstone of the Triassic Lepreau Formation (unit T_1) occur in several small, fault bounded troughs along the Bay of Fundy. A large thickness of Triassic rocks has been detected by oil exploration just off-shore in the Bay of Fundy.

DEFORMATION OF THE WESTERN END OF THE AVALON ZONE

The structures of the rocks of the western part of the Avalonian terrane have been the subject of much work by students and staff at the University of New Brunswick (Helmsteadt, 1968; Garnett, 1973; Brown, 1972; Rast and Grant, 1974; O'Brien, 1976; Wardle, 1977; Rast *et al.*, 1978; Donohoe, 1978; Parker, 1984; Leger, 1986), and by Ruitenberg and co-workers for the New Brunswick Geological Survey (Ruitenberg *et al.*, 1973; Ruitenberg *et al.*, 1977; Ruitenberg and McCutcheon, 1982). Interpretation of observations made in these studies has proven quite controversial because of difficulty in establishing the age of deformation and correlating these ages from one fault panel to another.

Regionally developed, systematic folding has proved difficult to detect. In the Saint John area pre-Coldbrook ductile deformation of the Brookville gneiss and Green Head Group (Fig. 3) cannot reliably be distinguished from younger deformation (Nance, 1982), although relations between Brookville gneiss and Green Head Group prove at least some deformation about 780 Ma. Late Precambrian deformation of the Coldbrook Group and older rocks has not been proved on a regional scale (O'Brien, 1976; Wardle, 1977), although deformation about 620 Ma is

demonstrated where the Martinon Formation occurs as hornfelsed and migmatized synclinal keels between dated plutons.

Traditionally most folding was assigned to the Ordovician Taconian and Siluro-Devonian Acadian orogenies (Helmsteadt, 1968; Garnett, 1973; Wardle, 1977; Donohoe, 1978; Ruitenberg *et al.*, 1979), although the evidence was at best slender and circumstantial (see Wardle (1977) for a careful discussion). Since the pioneering work of Rast and Grant (1974) and Rast *et al.* (1978), most workers assign a Carboniferous age to strong folding and thrusting along the Bay of Fundy (Currie and Nance, 1983; Parker, 1984; Nance and Warner, 1986; Caudill and Nance, 1986; Watters, 1987). Major folding of the Saint John Group resembles folds in nearby Carboniferous rocks in style and orientation (Currie, 1984). Minor folds in fault slivers of the Saint John Group appear to be related to faults (Wardle, 1977) known to exhibit Carboniferous movement. No metamorphism or plutonism of Taconian or Acadian age can be demonstrated south of the Kingston complex (Currie, 1984, 1986). Radiometric ages quoted by Helmsteadt (1968) and Stukas (1978) in support of an Acadian event suffered both from inherent unreliability (K/Ar on actinolite and Ar/Ar on plagioclase) and poor internal consistency.

Donohoe (1978) described polyphase Acadian folds and cleavage in the Saint George area. He also noted that the Silurian section has a consistent northwesterly facing direction. These observations are probably better explained by local fault-related deformation, rather than large-scale systematic folding. Penetrative cleavage of several ages occurs across the belt, but the trends of these cleavages are diverse. In many cases the cleavage is demonstrably of Carboniferous or younger age, for example where it cuts Carboniferous rocks. In some cases a Precambrian age can be demonstrated, for example where uncleaved Cam-

brian rocks sit unconformably on the Kingston complex.

Numerous northeast-, north- and northwest-trending faults cut the terrane. Indeed it would hardly be an exaggeration to describe the whole region between the Long Reach and the Bay of Fundy as a high-strain zone. Most recognizable faults belong to one of four groups, namely (a) old ductile faults (mylonite zones), (b) steeply-dipping northeast-trending brittle faults, (c) steeply-dipping north- to northwest-trending brittle faults, (d) gently to moderately south- or north-dipping brittle-ductile faults.

Old mylonite zones fringe both sides of the Kingston complex from Beaver Harbour to Loch Alva. Mylonitization is

intense in granitoid rocks (Fig. 8) but weak or absent in mafic dykes of the Kingston complex, which locally cut the mylonite at a high angle (Fig. 9). The mylonites nowhere cut Phanerozoic strata, but a sliver of unmylonitized fossiliferous Silurian rocks has been downdropped into mylonitic granite on New River. Greenschist-facies metamorphism affects dykes, mylonites and granites, but not overlying Cambrian strata. Stratigraphic evidence strongly suggests that mylonitization occurred in late Precambrian time. The mylonite zones end abruptly at Loch Alva.



Fig. 8. Mylonitic granite, gravel pit near Lepreau. Note the mylonitic banding and horsetailing of the host. Hammer is 35 cm long.



Fig. 9. Mylonitic granite cut by little deformed dyke of the Kingston complex. The contact is marked by a narrow white contact aureole at the hammer point. Same locality as Figure 8.

Most kinematic indicators suggest dextral motion in the mylonite zones (Leger, 1986), but small-scale sinistral indicators occur locally within the Kingston complex. The mylonite zone and Kingston complex both exhibit a very consistent, northeast-trending, steeply plunging lineation. The scale of motion is uncertain because there are no precise markers of appropriate age. However plutons of identical age and petrography occur on opposite sides of the zones. Shearing appears to have dissected a magmatic suite, rather than juxtaposing unrelated suites. Movement, therefore, appears likely to have been in the tens, rather than thousands, of kilometres. Garnett and Brown (1973) and Rast and Currie (1976) showed that the mylonite zone on the north side of the complex does not mark the northwestern boundary of Precambrian rocks (Fig. 10), and this point has been emphasized by recent Pb-U zircon age determinations which demonstrate that late Precambrian granite extends up to the Mount Douglas pluton (Currie, 1988).

Steeply dipping northeast-trending brittle faults tend to follow the older mylonite zones, but locally cut them at a low angle. East of Loch Alva where the mylonite zones are absent or inconspicuous, the faults form anastomosing breccia zones following the margins of the Kingston complex, and including out-of-sequence fault blocks. In some cases latest motion on these faults can be dated by emplacement of undeformed igneous rocks across the faults. These data indicate a considerable range of ages from early Silurian to Mississippian. Geophysical modelling suggests significant high-angle displacement on some of these faults (Thomas and Willis, in press; Spector and Pichette, 1980). A northwest-side down motion totalling nearly 11 km has been deduced beneath the Mount Douglas pluton. Farther south, Helmsteadt (1968) and Garnett (1973) deduced only small displacements of a few tens of meters in Phanerozoic time, producing small grabens. To the southeast, Gupta (1975) deduced a kilometre-scale down-drop of the southeastern side on the Green Head-Coldbrook boundary. This pattern suggests systematic uplift of the exposed Avalonian rocks relative to their surroundings.

Little detailed work has been done on the north- to northwest trending features. The Oak Bay fault west of the mapped area shows late sinistral movement (Stringer, 1982). A series of small-scale exposed faults northwest of Grand Bay show alternating sinistral and dextral motions with a significant normal component. A very strong linear feature parallel to these faults runs from Grand Bay to Welsford. The orientation of this lineament relative to the northeast-trending structures suggests a Riedel shear pattern. The dominant northeast-trending shear zones are thought to be dextral (Leger, 1986). Therefore sinistral motion is predicted on the Grand Bay lineament, and overall east-west compression. A very strong north-trending lineament runs from the north end of Loch Alva to Welsford. Major mylonite zones end abruptly against this lineament. Perhaps the Loch Alva-Welsford-Grand Bay triangle represents some kind of gigantic kink band.

Moderate- to low-angle faults occur along the Bay of Fundy. This Carboniferous deformation has been extensively described (Rast and Grant, 1974; Rast *et al.*, 1978; Currie and Nance, 1983; Parker, 1984; Nance and Warner, 1986; Watters, 1987). For the present purpose it suffices to note that whatever the significance of the deformation off-shore, it affects only a thin skin of the Avalon terrane on-shore. Along the Bay of Fundy, older mylonite zones have been partially overprinted by Carboniferous deformation (Rast and Dickson, 1982), but this effect extends only a few kilometers inland. Similarly Triassic extension, presumably related to opening of the Atlantic Ocean may truncate the Avalon zone offshore, but onshore produces only minor grabens.

STRUCTURAL SYNTHESIS

The termination of the Avalon terrane in southern New Brunswick can be understood in semi-quantitative fashion from recent mapping and geophysical results. The oldest configuration deducible from present evidence (Fig. 11a) has the metasedimentary shelf-type sequence of the Green Head Group resting on

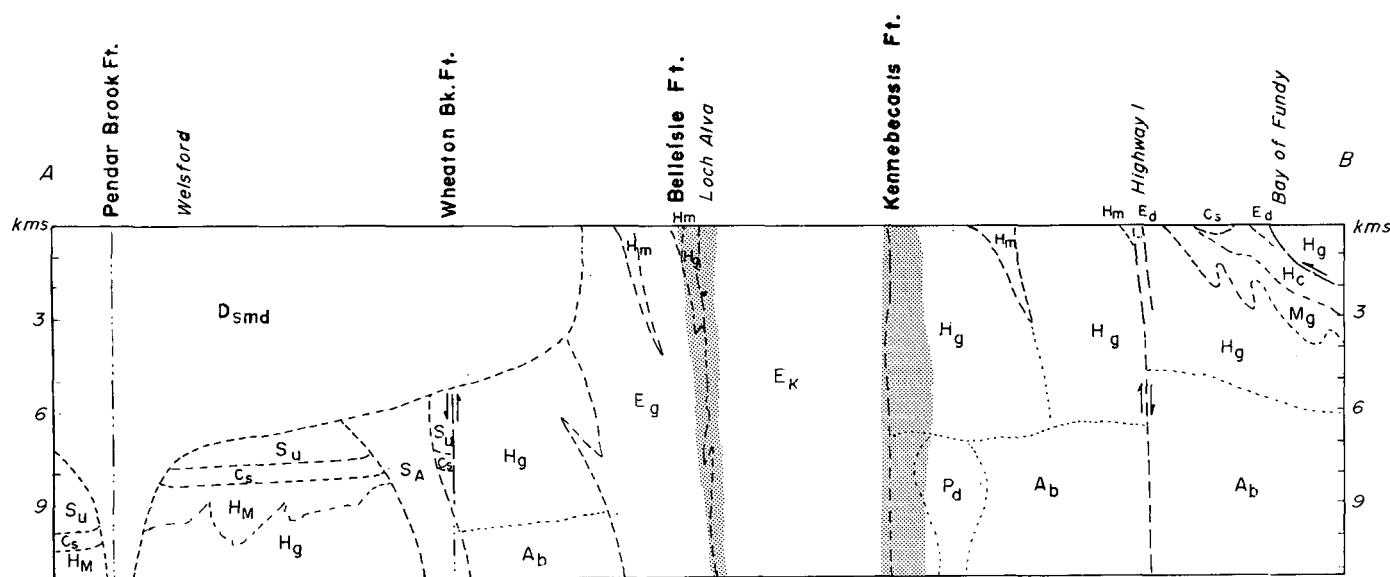
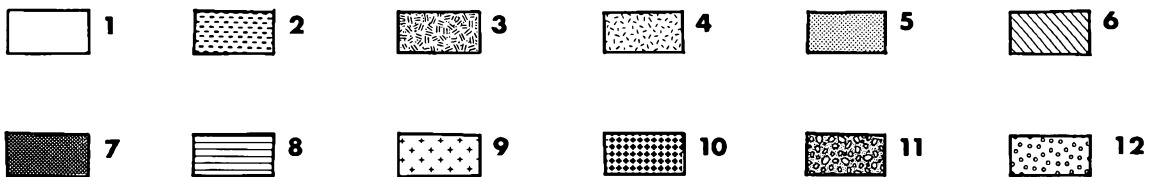
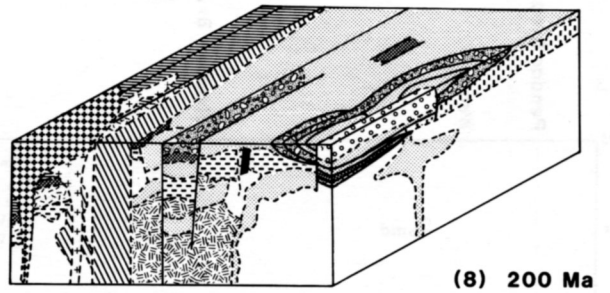
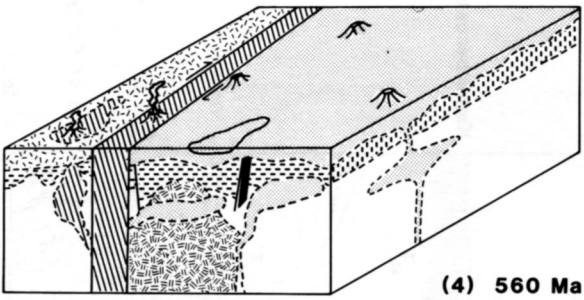
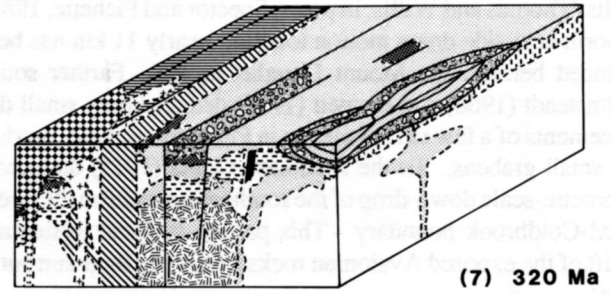
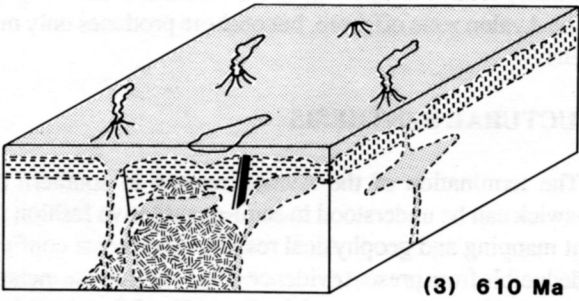
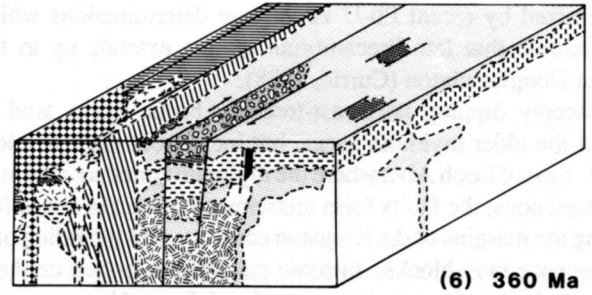
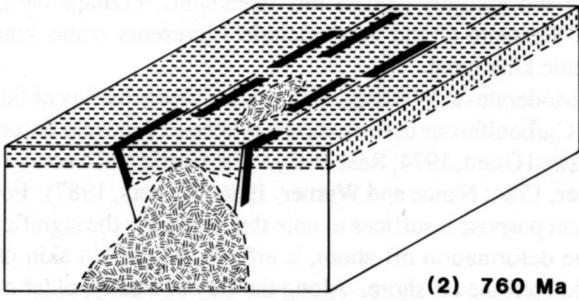
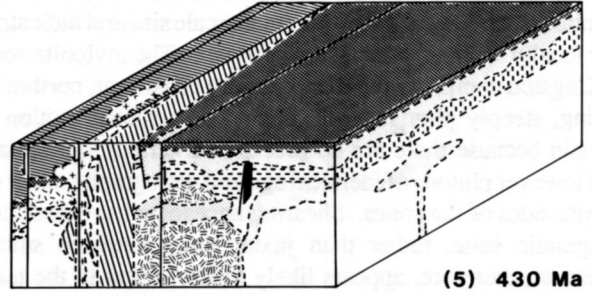
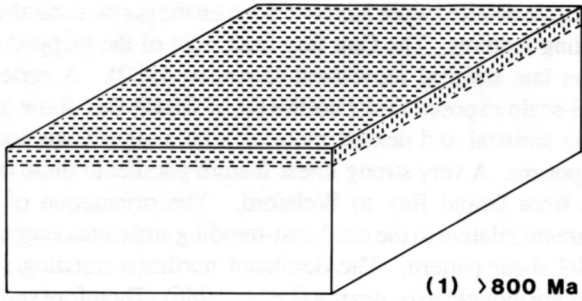


Fig. 10. Partly schematic cross-section across the Avalon zone in southern New Brunswick. The legend is the same as Figure 2. Vertical and horizontal scales are the same. Data beneath the Mount Douglas batholith from Thomas and Willis (in press).



Brookville gneiss. Like other similar sequences in the Cobequid Highlands (Bass River complex, Gaudette *et al.*, 1983) and Cape Breton Island (George River Group, Lowland Brook syenite (Barr *et al.*, 1987)) the lithologies and age constraints are suggestive of the Grenville province of the Canadian Shield. About 780 Ma (Fig. 11b) emplacement of dioritic plutons and mafic dykes was accompanied by high-temperature, low-pressure metamorphism. High-temperature, low-pressure metamorphism in Cape Breton Island (Jamieson, 1984) has been dated at 701 Ma (Gaudette *et al.*, 1985). Gabbro of oceanic affinity in Newfoundland (Strong and Dostal, 1980) gave an age of 762 Ma (Krogh *et al.*, 1988). The significance of these ages is not understood at present, but a tensional event with upwelling of mafic magma, possibly locally generating oceanic crust seems reasonable. About 620 Ma (Fig. 11c) subduction-related arc volcanism emplaced the Coldbrook Group and associated plutons. Northwest-directed subduction could have built an arc on Grenville basement, but microcontinents left after an earlier event, as envisaged for example by O'Brien *et al.* (1983), would do as well. Presence of a Pan-African event on Canadian shores (O'Brien *et al.*, 1983) is not surprising as the continents were assembled at this time and Africa probably juxtaposed with Atlantic Canada (Worsley *et al.*, 1984).

Before 565 Ma (Fig. 11d) transcurrent motion, possibly the result of oblique convergence, developed the mylonite zones typical of the western Caledonia block. A tensional phase indicated by emplacement of the dyke complex generally post-dated shearing, and may have marked the opening of the "Iapetus Ocean" as suggested by Rast (1979).

During Cambrian and Ordovician time, the western Caledonia block was a rigid, relatively high-standing region, but by early Silurian time (Fig. 11e) the northwestern part of the block began to subside along faults. These brittle faults roughly paralleled nearby older ductile shear zones, but in most cases the trends and positions of the two types of faults can readily be distinguished. Both mafic, mantle-derived magma and salic magma with a large crustal component, as indicated by isotope signature (Bevier, 1988), leaked up the faults over an extended period of time, suggesting not only persistent down-faulting, but also a major upwelling of mantle at this site. This process culminated with emplacement of late granite of the Saint George batholith (Fig. 11f), which according to gravity modelling (Thomas and Willis, in press) is best interpreted as a sheet about 6 km thick, beneath

which both the Paleozoic supracrustal section and probable Precambrian basement extend far to the northwest.

Carboniferous deformation (Fig. 11g) in the context of the Avalon block was entirely superficial, as were effects of the tensional break-up during Triassic opening of the Bay of Fundy (Fig. 11h).

DISCUSSION

Most penetrative deformation of the western Caledonia block appears to be of Late Precambrian or Carboniferous age. Major deformation of Late Precambrian age occurred in three distinct pulses. The oldest seems to have been an abortive spreading episode about 780 Ma. Subduction-related magmatism of unknown polarity occurred about 620 Ma. Stratigraphic considerations and isotopic dating suggest that latest Precambrian shearing and plutonism formed a successor to subduction. This episode ended with dyke emplacement, possibly related to opening of the Iapetus Ocean. The analogy to post-Devonian history of the region is strikingly close. The three-fold division and diverse character of the late Precambrian rocks, which have also been found in other terranes (O'Brien and Knight, 1988) shows that the definition of Avalonian terrane needs to be sharpened.

The western part of the Caledonia block formed a stable crystalline mass lying near sea level from Cambrian to early Silurian time. From early Silurian to Late Devonian the northwestern part of the terrane was flexed and faulted downward, with major uprise of mantle material and magma generation. There is no evidence for regional Ordovician or Devonian penetrative deformation. Taconic/Acadian dichotomy seems not so much inadequate as irrelevant in this region. Proven Taconic deformation lies far to the west. Acadian deformation, metamorphism and plutonism affected a deep trough of sedimentary rocks northwest of the Saint George batholith, but had little effect on the crystalline rocks. This relation implies that the batholith occupies a position where the basement became relatively weak, possibly due to thinning, or to break-up by faulting.

The geometry and timing of the basement culmination represented by the Caledonia block resemble those predicted by van Staal (1987) for the "fore-arc" bulge formed by peripheral loading of a slab subducted westward during the Acadian orogeny. Explanations of Avalonian terranes have tended to as-

Fig. 11. Structural cartoons of the development of the western end of the Avalon zone in southern New Brunswick.

1 - Brookville gneiss and other basement rocks; 2 - Green Head Group; 3 - deformed amphibolitic dykes and plutons; 4 - Martinon Formation; 5 - Coldbrook Group and correlative plutons; 6 - Kingston complex and correlatives; 7 - Cambro-Ordovician sedimentary rocks; 8 - Silurian strata (Mascarene Group and correlatives); 9 - Peralkaline granite; 10 - Mount Douglas granite; 11 - Carboniferous clastic rocks; 12 - Triassic clastic rocks.

- (a) >800 Ma. Shelf sequence (Green Head Group) lies on basement
- (b) 760 Ma. Tensional break-up, dyking, high heat flow with metamorphism and emplacement of diapiric gneiss
- (c) 610 Ma. Arc magmatism, eruption of the Coldbrook Group and emplacement of large calc-alkaline plutons
- (d) 560 Ma. Mylonitization due to oblique closure followed by transtension, dyking and minor plutons
- (e) 430 Ma. After shallow water clastic sedimentation during Cambro-Ordovician, faulting and bimodal magmatism begins
- (f) 360 Ma. Major granite emplacement, end of down-faulting and flexing
- (g) 320 Ma. Carboniferous overthrusting affects the Avalonian terrane only superficially
- (h) 200 Ma. Triassic tensional break-up, sedimentation has only minor effect within the Avalonian terrane

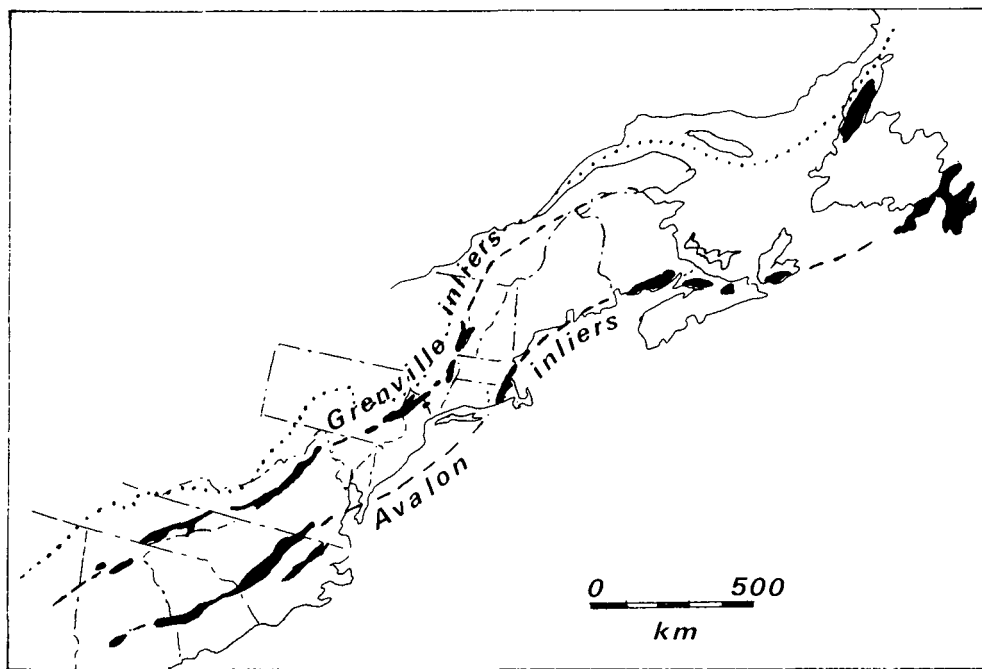


Fig. 12. Major basement inliers in the northern Appalachians. Inliers shown in solid black. Broken lines show trend of Grenville and Avalon inliers. Dash-dot lines show political boundaries. Dotted line marks the edge of the Appalachian orogen. Note the approximately symmetrical disposition of Avalon and Grenville inliers. The plot of Grenville inliers is from Hatcher (1983).

sume, implicitly or explicitly, sharp boundaries, and little extension beyond their known exposure (compare Williams and Hatcher 1983; Keppie, 1984; O'Brien *et al.*, 1983). However evidence is steadily accumulating for a much wider distribution of Avalonian rocks in the sub-surface. Gravity data by Thomas and Willis (in press) suggest the southern New Brunswick Avalonian terrane could extend many kilometres to the northwest of its exposed edge. Both stable isotope (Bevier, 1988) and detailed age dating evidence (Roddick and Bevier, 1988) suggest Avalonian basement to the Miramichi highland of New Brunswick. In Cape Breton Island, Jamieson *et al.* (1986) showed that the characteristic three-fold division of Avalonian igneous activity continued from the classic Avalon terrane of the southeast across the metamorphic and plutonic rocks of the western highlands. Avalonian ages and lithologies have been found on the south coast of Newfoundland (Dunning *et al.*, 1988) and "Pan-African" ages occur in western Newfoundland in transported slices (Williams *et al.*, 1985; van Berkel and Currie, 1988). A reasonable case can now be made that Avalonian basement extends, perhaps discontinuously, from its surface exposure northwest to the Iapetus suture, although this basement must be heterogeneous across strike as a result of Taconian and older plate tectonic process, and considerably modified in regions like western Cape Breton Island and northeastern Maine where it was affected by extensive subsequent plutonism and metamorphism. On this model, exposed Avalonian terranes represent an uplifted welt of basement, analogous to the chain of Grenvillian terranes on the west side of the Appalachians (Hatcher, 1983). The symmetry of these two types of Precambrian inlier is quite striking (Fig. 12). Once again the insight of Williams (1964) that the Appalachians form a symmetrical two-sided system has proved remarkably prescient.

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