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Résumé de l'article

Autour de Saint John, la laniere avalonienne englobe un socle de gneiss tonalltlque qu'est venu recouvrlr un tegument metasedimentaire a cachet neritique. Ces unites sont recoupees et recouvertes par des complexes volcano-plutoniques d'age tardl-proterozoique emplaces en trols etapes. On pmgMHnmP mafique et des gllssements synsedimentaires sous-marins ont rechauffe et remobilise les rocbes preexlstantes 11 y a environ 770-830 Ma. Des venues magmatlques calco-alcallnes, en grande partie subaeriennes et associees a une falble sedementation sous-marine, ont prls place autour de 600 Ma. Le volcanlsme basaltique et la sedimentation volcanlclastlque eocambrlens ont debouche sur une sedimentation cambro-ordovlcienne. Les rochea siluriennes se limltent a une ecaille bordee par des falllea alors que les rocbes devoniennes font defaut. On apport detrltlque grossler a eu lieu pendant la deformation au Carbonlfere et au Trlaslque.

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The Stratigraphy And Structure Of The Avalonian Terrane Around Saint John, New Brunswick

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The Avalonian terrane around Saint John exhibits basement of tonalitic gneiss veneered by a shelf type metasedimentary sequence. These units are intruded and overlain by volcanic-plutonic complexes of Late Proterozoic age emplaced in three stages. Mafic magmatism accompanied by submarine slumping heated and remobilized older rocks about 770-830 Ma. Calc-alkaline magmatism, mainly subaerial with minor submarine sedimentation occurred about 600 Ma, and subsequently Eocambrian basaltic volcanism and volcaniclastic sedimentation passed into Cambro-Ordovician sedimentation. Silurian rocks occur only as a fault-bounded slice and Devonian rocks are absent. Coarse clastic rocks of Carboniferous and Triassic age accumulated during deformation.

Major deformation and metamorphism occurred in Late Proterozoic time, but most mappable structures appear to be of Carboniferous age. Carboniferous deformation resulted mainly from transcurrent motion on curved or stepped faults which locally produced spectacular thrust allochthons.

Comparison of the Saint John terrane with other Avalonian terranes suggests that some of the Avalon tectonostratigraphic zone is floored by basement of Grenvillian aspect. The western side of this zone was strongly affected by Late Ordovician-Early Silurian magmatism which reflects the amalgamation of this zone with more westerly zones. These observations suggest that Avalon terranes may be of relatively local, rather than exotic, origin, and suggest a history involving repeated breakup and rewelding of a continental edge.

Autour de Saint John, la lanière avalonienne englobe un socle de gneiss tonalitique qu'est venu recouvrir un tégument métasédimentaire à cachet néritique. Ces unités sont recoupées et recouvertes par des complexes volcano-plutoniques d'âge tardi-protérozoique emplacés en trois étapes. Un magmatisme mafique et des glissements synsédimentaires sous-marins ont réchauffé et remobilisé les roches préexistantes il y a environ 770-830 Ma. Des venues magmatiques calco-alcalines, en grande partie subaériennes et associées à une faible sédementation sous-marine, ont pris place autour de 600 Ma. Le volcanisme basaltique et la sédimentation volcaniclastique éocambriens ont débouché sur une sédimentation cambro-ordovicienne. Les roches siluriennes se limitent à une écaille bordée par des failles alors que les roches dévoniennes font défaut. Un apport détritique grossier a eu lieu pendant la déformation au Carbonifère et au Triasique.

Une déformation et un métamorphisme importants furent présents au tardi-Protérozoique bien que la plupart des structures cartographiques semblent être d'âge carbonifère. La déformation carbonifère est liée surtout faux coulissages affectant des failles courbes ou en gradins ce qui, par chevauchement, a produit localement des allochtones spectaculaires.

La comparaison entre la lanière de Saint John et d'autres lanières avaloniennes suggère que la zone tectonostratigraphique d'Avalon repose en partie sur un socle d'aspect grenvillien. L'amalgamation de celle-ci avec d'autres zones plus à l'ouest y a imprimé son cachet sur le flanc ouest comme en fait foi un magmatisme prononcé tardi-ordovicien ou éo-silurien. De ces observations, on conclut que les lanières d'Avalon seraient d'une origine relativement locale et non pas exotique et que leur histoire serait inféodée au jeu répété du morcellement et de la restauration de la marge continentale.

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INTRODUCTION

The Saint John region exhibits Late Precambrian volcano-sedimentary strata, Late Precambrian plutons of dioritic to granitic composition, a faunally distinctive Cambrian section, and sparse to absent Middle Ordovician to Middle Devonian deposition, deformation and intrusion. A discontinuous chain of similar terranes (Williams and Hatcher 1983, Keppie 1984) separated by Devono-Carboniferous sedimentary basins (Fig. 1) forms the Avalon tectonostratigraphic zone of the Canadian Appalachians (Williams 1978, 1979). Among these Avalonian terranes, the Saint John region is of particular interest because of the broad range in age and lithology of the exposed rocks, and because of the unusually good exposure of both margins of the terrane.

Geological investigations have been carried on around Saint John for more than 150 years, but the basic outlines of the geology were established by Hayes and Howell (1937) and Alcock (1938). Recent re-mapping by Wardle (1977), Currie *et al.* (1981), Currie and Nance (1983), Currie (1984, 1985, 1986) and McCutcheon and Ruitenberg (1984) has substantially changed the understanding of many of the units. This contribution reviews the present understanding of the stratigraphy and structure of the Saint John region based on current geological mapping.

DEFINITION OF STRATIGRAPHIC UNITS

An easily recognized, mappable stratigraphy has proved difficult to establish in the Saint John region due to pervasive but heterogeneous deformation and alteration, which cause the same unit to locally exhibit very

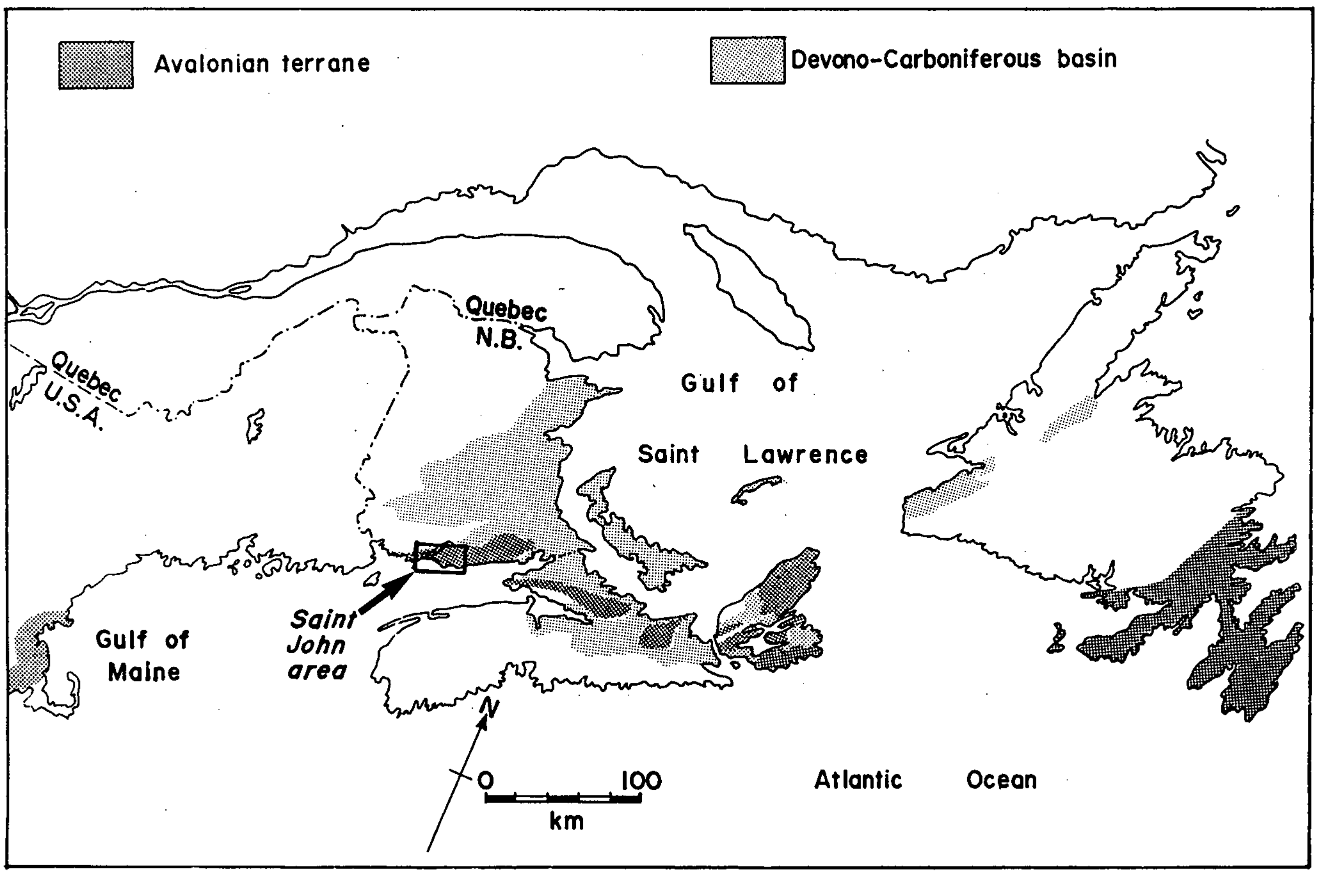

Fig. 1. Location of the Saint John region (boxed) relative to Avalonian terranes (shaded) and Devono-Carboniferous basins in the northern Appalachians (stippled).

diverse appearances, and to the occurrence of very similar lithologies at quite different places in the stratigraphic column. Criteria must therefore be developed to distinguish lithologically similar units. A stratigraphic column which has proven to be successful in recent mapping is shown in Fig. 2 together with the resulting map.

The Brookville gneiss (map unit Ab) forms a narrow northeast-trending, uplifted strip of mesocratic quartz-plagioclase-hornblende+/-biotite gneiss locally containing schlieren, patches and nebulous enclaves of biotite granite gneiss and muscovite-tourmaline pegmatite. Wardle (1977) and Olszewski and Gaudette (1982) assumed the Brookville gneiss to be a more highly metamorphosed equivalent of the platformal metasedimentary rocks of the Green Head Group (map unit Hgh) intruded by mantle-derived tonalitic

LEGEND

TRIASSIC
Tl LEPREAU FORMATION; chocolate-brown torrential conglomerate
----- unconformity -----
CARBONIFEROUS MISPEC GROUP (units Cl and Cbl)
Cl LANCASTER FORMATION: grey lithic arenite, black siltstone shale
----- gradational contact -----
Cbl BALLS LAKE FORMATION: Red siltstone with polymict conglomerate
----- unconformity on Hca and older units -----
Ck KENNEBECASIS FORMATION; red to brown conglomerate and sandstone.
----- unconformity -----
DEVONIAN
Dmd MT. DOUGLAS PLUTON; pink porphyritic rapakivi biotite granite
----- intrusive contact to He, Sw and Sjc -----
SILURIAN
Sw WELSFORD PLUTON: riebeckite granite and felsite
----- intrusive contact -----
Sjc JONES CREEK FORMATION; grey-green siltstone
----- tectonic contact -----
Slr LONG REACH FORMATION: basalt; minor siltstone
----- tectonic contact -----
CAMBRO-ORDOVICIAN
COsj SAINT JOHN GROUP: mainly grey-green siltstone and sandstone.
----- disconformity -----
EOCAMBRIAN
Ed red tuff, sandstone, amygdaloidal basalt
----- unconformity -----
HADRYNIAN
Hk KINGSTON COMPLEX; salic and mafic dykes
---- relations uncertain, possibly gradational ----
COLDBROOK GROUP (Hca, Hcb)
Hca andesite, rhyolite lahars, ignimbrites, minor sedimentary rocks
-- relations uncertain --
Hcb mafic flows
GOLDEN GROVE SUITE (He, Hg, Hd)
He rhyolite porphyry, alaskite
--- gradational contact ---
Hg granite, granodiorite, hornblende dominant
--- gradational contact ---
Hd diorite, quartz diorite
--- intrusive contact ---
Hu gabbro, ultramáfics
----- intrusive contact -----
Hm MARTINON FORMATION; turbidites, debris flows, basalt sills
----- unconformity (?) -----
HELIKIAN (?)
Hgh GREEN HEAD GROUP; marble, quartzite, pelitic schist
----- mobilized unconformity -----
APHEBIAN (?)
Ab BROOKVILLE GNEISS; tonalitic gneiss, agmatite, migmatite
drift covered area
highly deformed area
high angle brittle fault
thrust fault
mylonite zone

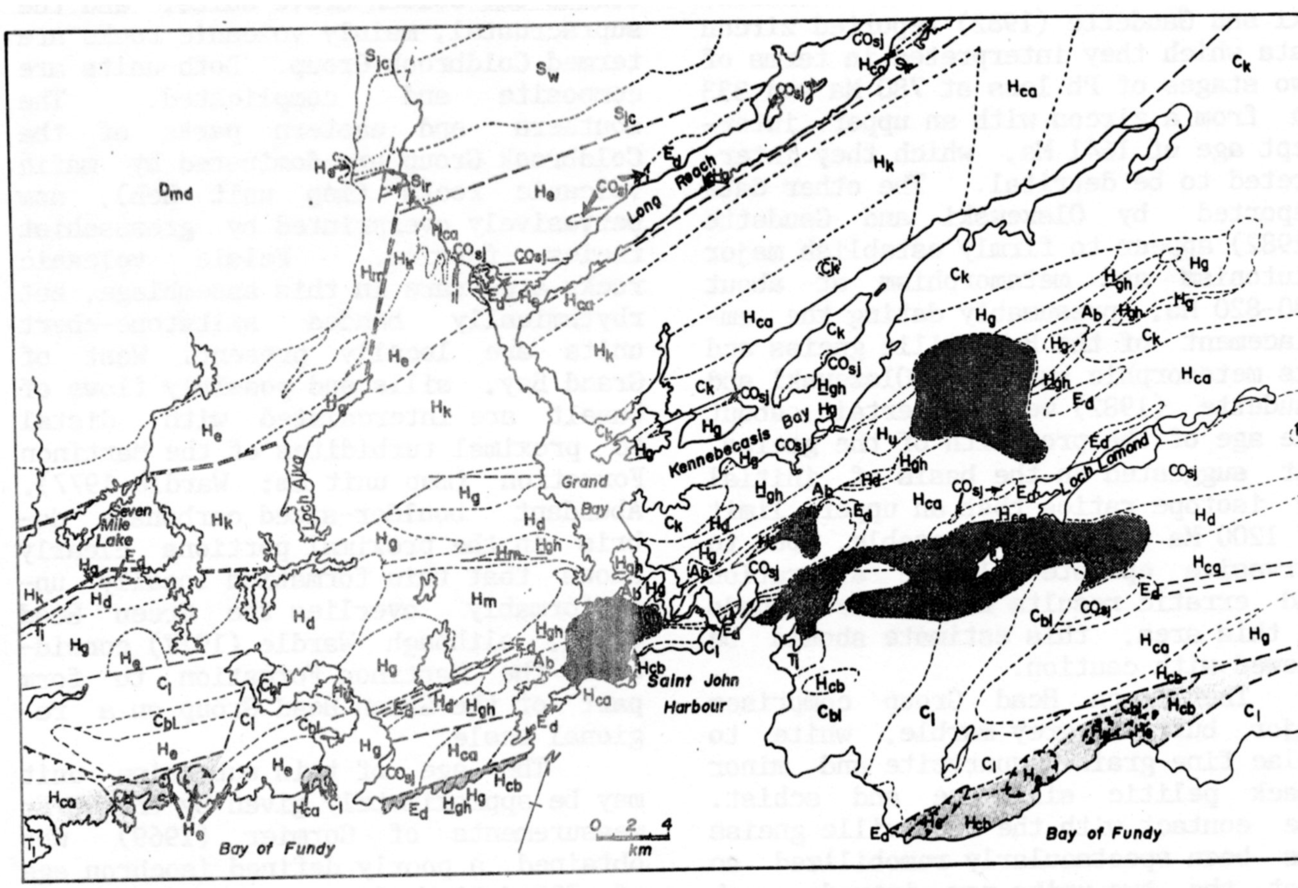

Fig. 2. Simplified geological map of the Saint John region. Main sources of information are as follows: Currie 1985, 1986, McCutcheon and Ruitenberg 1984, McCutcheon 1984, Wardle 1977, Alcock 1938, 1959, Hayes and Howell 1937.

rocks at about 770 Ma. This seems improbable because (a) the Brookville gneiss is generally tonalitic in composition, in contrast to the quartzite- and carbonate-rich compositions of the Green Head Group, (b) the Brookville gneiss is pervasively migmatized and remobilized (Fig. 3) but recognizable Green Head lithologies have never been identified in the migmatites, and (c) the Green Head Group contains sillimanite around the Brookville gneiss but elsewhere is at greenschist facies (Wardle 1977, Currie *et al.* 1981), suggesting that the Brookville gneiss arrived as a hot mass from a deep-seated source. The age of the protolith of the Brookville gneiss remains uncertain, but these considerations suggest that parts of this protolith are substantially older than the Green Head Group. Radiometric age determinations on the Brookville gneiss have given ambiguous results. Olszewski and Gaudette (1982) reported zircon data which they interpreted in terms of two stages of Pb loss at 780 Ma and 333 Ma from a zircon with an upper intercept age of 1641 Ma, which they interpreted to be detrital. The other data reported by Olszewski and Gaudette (1982) appear to firmly establish major plutonism and metamorphism at about 780-820 Ma, presumably dating the emplacement of the Brookville gneiss and its metamorphic aureole. Olszewski and Gaudette (1982) were uncertain about the age of the protolith of the gneiss, but suggested on the basis of initial Sr isotope ratios that an upper limit of 1200 Ma would be reasonable. Due to pervasive epidote-chlorite alteration and erratic results from Rb/Sr methods in this area, this estimate should be viewed with caution.

The Green Head Group comprises major buff to grey marble, white to lilac fine-grained quartzite and minor black pelitic siltstone and schist. The contact with the Brookville gneiss has been spectacularly remobilized so that the two units now intrude each other. Marble and in places quartzite occur as dyke-like masses throughout the Brookville gneiss and in adjacent plutons. The marble locally shows complex patterns of flowage which have boudined dykes (Fig. 4). Because of the ubiquitous flowage, an internal stratigraphy for the Green Head Group cannot be successfully mapped, although readily recognizable lithologies of the group form valuable stratigraphic markers. The age of deposition of the Green Head Group is not well constrained, but estimates by Hofmann (1974), on the basis of stromatolites locally preserved in little-deformed enclaves, suggest possibly 1000-1500 Ma, approximately contemporaneous with lithologically similar rocks of the Grenville Supergroup of Ontario and Quebec.

Like most Avalonian terranes, outcrop in the Saint John region consists largely of Late Precambrian rocks. Plutonic rocks of this age are termed the Golden Grove suite, and the supracrustal, mainly volcanic rocks are termed Coldbrook Group. Both units are composite and complicated. The southern and eastern parts of the Coldbrook Group are dominated by mafic volcanic rocks (map unit Hcb), now pervasively overprinted by greenschist facies fabrics. Felsic volcanic rocks are rare in this assemblage, but rhythmically banded siltstone-chert units are locally present. West of Grand Bay, sills and possibly flows of basalt are intercalated with distal to proximal turbidites of the Martinon Formation (map unit Hm; Wardle 1977). Abundant boulder-sized carbonate debris in the proximal portions clearly shows that this formation locally unconformably overlies the Green Head Group, although Wardle (1977) considered the Martinon Formation to form part of the Green Head Group on a regional scale.

The age of this submarine unit may be approximately given by the Rb/Sr measurements of Cormier (1969) who obtained a poorly defined isochron age of 725+/-80 Ma (converted to current decay constants) for the Coldbrook Group. The isochron was controlled by

Fig. 3. Reactivated Brookville gneiss, Shamrock Park, Saint John. The original (?) gneiss can be seen in the lower right and as rafts surrounded by a pale grey tonalitic intrusive, interpreted to be anatectic, which has broken two ages of basic dykes (dark blocks). Scale is 1 m long.

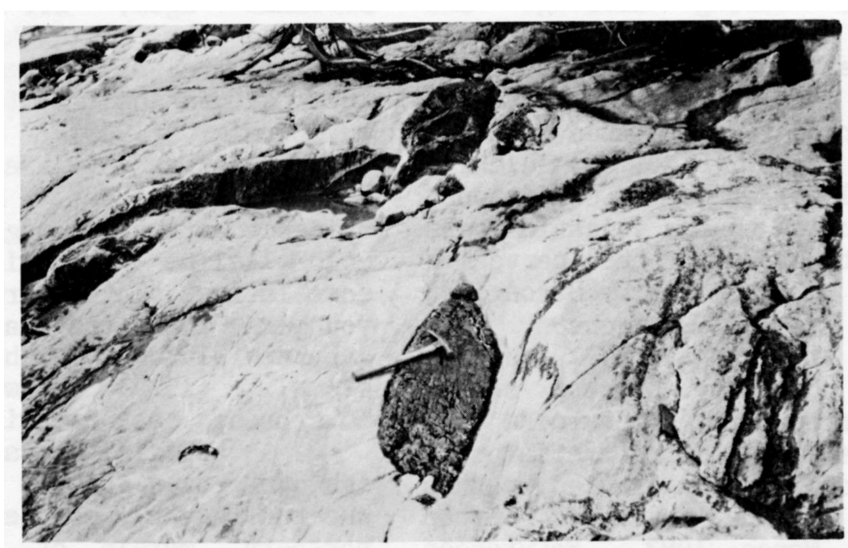

Fig. 4. Basalt dyke (unit Hc b) boundined in Green Head marble. Note complex small folds in marble.

the Rb-poor samples, that is mafic volcanic rocks.

The oldest parts of the Golden Grove suite consist of tonalitic, dioritic and gabbroic to ultramafic, locally layered, suites (map unit Hu) which are abundantly veined by younger, more felsic material. The ages of the gabbroic and ultramafic bodies are unknown, but Olszewski and Gaudette (1982) have shown that emplacement of contorted quartz diorite associated with mobilization of the Brookville gneiss probably occurred within the range 770-830 Ma. Field mapping and (fragmentary) isotopic dating suggest an early phase of mafic igneous activity. Although the presently observed volume of this material is relatively small, mobilization of the Brookville gneiss suggests that much larger scale intrusion and introduction of heat may have occurred at depth.

The Coldbrook Group consists mainly of intermediate to felsic flows, ignimbrites, and volcanic fragmentals, some of them laharic (Fig. 5). Locally this material (map unit Hca) shows well preserved primary textures, but greenschist-facies assemblages and moderate to strong cleavage are pervasive. The presence of lahars and ignimbrites suggests that this volcanic activity was mainly subaerial, although minor intercalated, graded cherty sedimentary rocks (Fig. 6) clearly demonstrate local submarine conditions. Chemical studies of the volcanic rocks are difficult because of the pervasive alteration, but studies by Strong *et al*. (1979) and by McCutcheon (in Ruitenberg *et al*. 1979) suggest calcalkaline chemistry. Strong *et al*. (1979) referred to the rocks as Carboniferous, but current opinion is that the volcanic rocks studied by them form part of the Coldbrook Group (Currie and Nance 1983, McCutcheon 1984).

Southwest of Saint John along the Bay of Fundy and along the Long Reach volcanic rocks of this type can be seen to grade to dioritic to alaskitic plutons (map units Hd and Hg). Most of this plutonic suite appears to have been emplaced at very high to sub-volcanic levels, and transitions from intrusive to volcanic features can be observed in many localities. Large dioritic plutons exhibit remarkably complex cuspate internal contacts (Fig. 7) suggesting coexisting magmas. Many of the plutons form rather homogeneous hornblende-dominant quartz diorite to granite bodies, locally with megacrystic feldspar. Where such plutons are emplaced in Brookville gneiss, they show gradational, migmatitic contacts, whereas elsewhere the contacts are sharp and hornfelsed. Alaskitic plutons, generally quartz-feldspar porphyries, are characteristic of the Saint John region. Like the other plutons they are pervasively epidotized. This alteration may be the reason for the extraordinarily diverse results obtained in dating these plutons. The most plausible ages appear to be the Rb-Sr isochron age of 615 Ma reported by Olszewski *et al*. (1980), and possibly the composite Rb-Sr isochron age of 526 Ma reported by Poole (1980). The many younger K/Ar and Rb/Sr ages reported, including Devonian ages, for example that reported by Olszewski and Gaudette (1982), are almost certainly due to later alteration, as first pointed out by Cormier (1969). Current work on zircon dating of these plutons may clarify their age. At present the evidence strongly suggests that the calc-alkaline volcanic rocks and correlative plutons are significantly younger than the mafic lavas and gabbroic plutons, although Ruitenberg *et al*. (1979) showed them to be interbedded east of Saint John.

A special class of hypabyssal igneous rocks forms a large, bimodal sheeted dyke complex within the northern margin of the Saint John terrane (Kingston complex, map unit Hk). This dyke swarm was noted by Rast (1979) 70 km southwest of Saint John, where it has a northeasterly trend, and is essentially entirely composed of mafic dykes. In the Seven Mile Lake

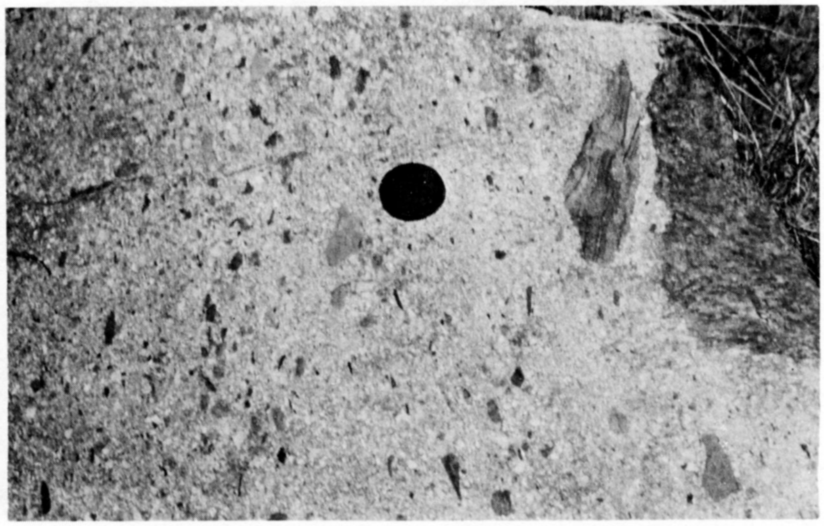

Fig. 5. Rhyolite (white) and basalt (black) fragments in a dark silty matrix (upper Coldbrook Group). The strong foliation is partially tectonic, but probably reflects original preferred orientation.

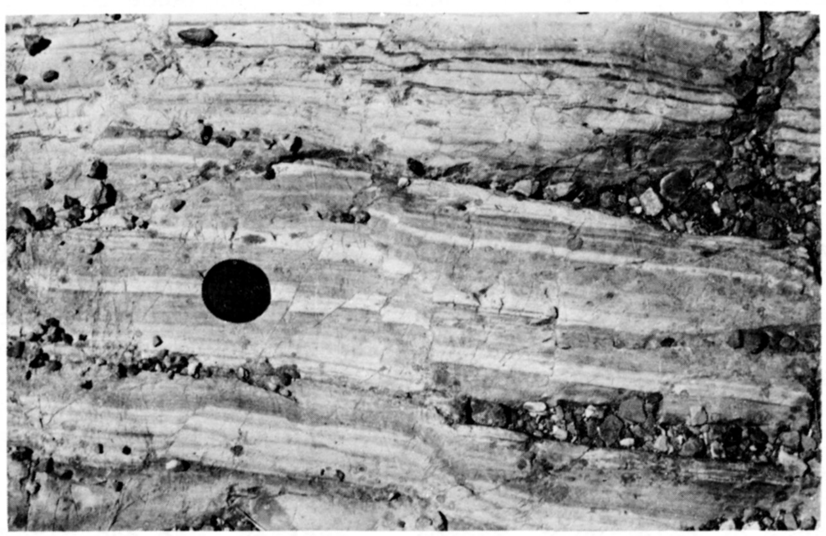

Fig. 6. Laminated, graded cherty siltstone from the Coldbrook Group. Lens cap is 6 cm in diameter.

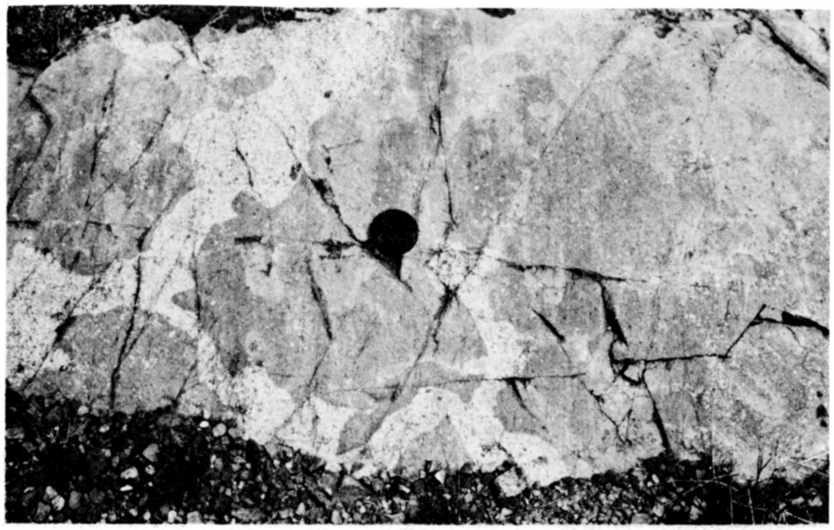

Fig. 7. Complex cuspate internal contacts between diorite (dark) and granodiorite (light) suggestive of coexisting magmas in the Lepreau Pluton (map-unit Hd). Note the fine grained (dark) margin of the basic material.

area the trend is still northeasterly, but about 15-20 percent of the dykes are of salic rocks. The strike of the dikes changes abruptly to north-south near Loch Alva, although the boundaries of the unit continue northeast. The dyke trend remains generally north-south in a diamond-shaped region at least 40 km in extent in a northeast-southwest direction by 10 km in extent along dyke strike, although the trends in the north-east part of the map area become more diverse. In the Loch Alva - Grand Bay - Long Reach area the complex consists of alternating felsite and microdiorite dykes 1 to 20 m in width, with some rare fault slivers of Green Head Group, Coldbrook volcanic rocks and Golden Grove suite. Some of the mafic dykes contain patches of relatively coarse, idioblastic hornblende reminiscent of appinitic texture. The transition from northeasterly to northerly trends of the dykes coincides approximately with the transition from mafic to bimodal compositions.

Currie (1984) and Tanoli *et al.* (1985) defined and described a sequence of volcanogenic redbeds, and basalts (map unit Ed) which are younger than the Coldbrook Group but older than the Cambro-Ordovician Saint John Group. The abundance of volcanogenic detritus (rhyolite and basalt cobbles, feldspar crystals) distinguish this unit from the Ratcliffe Brook Formation, the basal unit of the Saint John Group, and from the Carboniferous Balls Lake Formation with which it has been confused in the past. The local abundance of red cobble to boulder conglomerates with cobbles entirely derived from the Coldbrook Group, as well as a generally lower degree of deformation, suggests a local unconformity between the Coldbrook Group and the Eocambrian section. Judging from the primary volcanic textures and the sedimentology of the red beds, this Eocambrian section was deposited almost entirely subaerially. The disposition of this unit in narrow, fault-bounded slivers suggests that it may have accumulated in local rift valleys.

Hayes and Howell (1937) subdivided the Cambro-Ordovician Saint John Group (map unit COsj) in great detail on the basis of paleontology, but their units cannot be used for mapping, as they admitted. For mapping purposes it is convenient to subdivide the group into basal Ratcliffe Brook Formation (rusty to grey, muscovitic sandstone and pebble conglomerate, with 1 cm layers of sandstone containing feldspar crystals), Glen Falls Formation (white quartz-pebble conglomerate, with a very distinctive tourmaline-rich top), and the upper part of the group, consisting of grey green sandstones and black shale and siltstone. Pickerill and Tanoli (1985) have demonstrated that this upper part can be divided into six mappable formations which have a very consistent lithology over the whole area of outcrop of the group. From the Glen Falls Formation upward the Saint John Group consists of a marine transgressive sequence indicating gradual submergence. The Ratcliffe Brook Formation more closely resembles the underlying Eocambrian section which accumulated under quite different conditions.

The Saint John Group and the Eocambrian section contain sparse, generally northeast-trending, gabbroic dykes and minor intrusions. These dykes have a characteristic brownish colour and ophitic texture permitting an easy distinction from older altered basaltic dykes, assumed to be of Late Proterozoic age, which are abundant in the Green Head and Coldbrook Groups. The age of the dykes in the Saint John Group is not known, but they have not been observed in the Carboniferous section, and are here tentatively correlated with the Silurian Long Reach Formation (map unit Slr), which forms a narrow belt of feldspar-phyric, locally amygdaloidal basaltic lavas with minor interbedded grey-green feldspathic arenite and limestone which contains Llandovery to Wenlock fossils (Berry and Boucot, 1970). The contacts of the Long Reach Formation against other units of the Saint John terrane are commonly faulted, but feldsparphyric basaltic dykes in the Coldbrook Group adjacent to the Long Reach Formation are thought to be correlative to the Long Reach Formation.

Other Silurian and Devonian units shown in Fig. 2 do not form part of the Saint John terrane, but lie in the Mascarene-Nerepis belt, or zone 4b of Ruitenberg *et al.* (1977). The Jones Creek Formation (map unit Sjc) of siltstone and pelitic siltstone contains an abundant Pridoli fauna (Berry and Boucot 1970). The hornfelsed, sill-infested character of the Jones Creek Formation makes a striking contrast to the lithologically similar Saint John Group which completely lacks granitoid intrusions. The Welsford complex (map unit Sw) consists of high-level riebeckite granite with marginal felsite and porphyry. Extrusive rhyolitic phases of the Welsford complex are intercalated with the Jones Creek Formation, and show the Welsford complex to be of Silurian age. The Mount Douglas pluton (map unit Dmd) consists of quartz and plagioclase-phyric biotite granite. The central part contains rapakivi feldspars up to 3 cm across riddled with fine inclusions of matrix minerals. Marginal phases are much finer grained, but granophyric or chilled phases are rare. The Mount Douglas pluton gave a Rb-Sr isochron age of 345 Ma (L. R. Fyffe, personal communication, 1984).

The Carboniferous stratigraphic section in the Saint John region has provoked controversy for more than a century. The northern part of the section, the Kennebecasis Formation (map unit Ck) consists of locally derived red to brown conglomerate and sandstone of Fammenian to Westphalian age (Currie 1984). The Kennebecasis Formation is a distal equivalent of several formations in the Moncton Basin to the northeast (Pickerill *et al.* 1985). The southern part of the section, traditionally termed the Mispec Group consists of the Balls Lake and Lancaster Formations (Currie and Nance 1983). The Balls Lake Formation (map unit Cbl) lies unconformably upon the Coldbrook Group. The basal part of the formation commonly contains red caliche nodules or locally black, stromatolitic limestone (Parleeville Formation of McCutcheon, 1984). The lower part of the Balls Lake Formation contains a pale green sandstone-siltstone sequence, whereas the upper part consists mainly of red siltstone and shale with characteristic conglomerate intercalations. The Lancaster Formation (map unit C1) gradationally overlies and overlaps the Balls Lake Formation. The formation consists of pale grey to almost black lithic sandstone with pebble conglomerate lenses and black fossiliferous strata. The Lancaster Formation is of Westphalian age, but the formation becomes younger from northeast to southwest, passing from Westphalian A to D in a distance of about 30 km (see Currie and Nance 1983 for references). The Mispec Group represents an alluvial fan complex fed from the southeast, with the Balls Lake Formation forming essentially subaerial proximal to mid-fan deposits and the Lancaster Formation forming distal alluvial deposits (Currie and Nance 1983, Caudill and Nance 1986).

Chocolate-coloured conglomerate and red siltstone of the Triassic Lepreau Formation (map unit Tl) occur in various small outliers in the Saint John region (Alcock 1938, 1959) and large amounts of Triassic sedimentary rocks have been detected by drilling for oil just off-shore in the Bay of Fundy.

STRUCTURE OF THE SAINT JOHN REGION

Recognizable deformation in the Avalonian rocks around Saint John appears to be mainly of Precambrian and Carboniferous ages. Field mapping and isotopic dating (Currie *et al.* 1981, Olszewski and Gaudette 1982) imply intense deformation and metamorphism about 770-830 Ma in the Brookville gneiss and Green Head Group, here presumed to have been related to emplacement of mafic to ultramafic plutons at this time. Nance (1982) found that the intensity of concurrent remobilization erased systematic evidence of older deformations, although relict older structures are quite common. The younger part of the Coldbrook Group apparently exhibits calc-alkaline volcanism and plutonism suggestive of arc-type. Available isotopic evidence suggests magmatism at about 600 Ma. I assume that at some appropriate depth such phenomena should be accompanied by deformation and metamorphism. However, only greenschist and lower grade metamorphism has been recognized in the Coldbrook Group, presumably because appropriate erosional levels are not exposed. Late Proterozoic faulting may be significant in the Saint John region, but the evidence (as discussed below) is equivocal because of later movements on the faults.

The presence of lower Paleozoic deformation (Taconic and/or Acadian) in the Saint John region is generally assumed. Wardle (1977) reviewed the evidence and found it to be slender and circumstantial. He believed that isotopic dates, specifically those of Helmstaedt (1968) and Stukas (1978), suggested lower Paleozoic orogeny, and that fabrics in the Saint John Group not found in Carboniferous rocks proved lower Paleozoic deformation. However the methods used by Helmstaedt (1968) and Stukas (1978) did not give reliable values (K/Ar on actinolite, and resetting of $^{40}Ar/^{39}Ar$ ages in plagioclase), and the dates likely reflect partial updating during a Carboniferous event. Wardle (1977) pointed out that deformation of the Saint John Group was closely related to fault movements. Current studies (Leger and Williams 1986) have found no evidence for pre-Late Devonian movement on these faults. The possibility of Taconic and/or Acadian deformation remains open, but at present there is little or no evidence for such deformation, and most observations seem better explained by Carboniferous deformation.

The map pattern in the Saint John region (Fig. 2) is dominated by northeasterly trending strips of rock produced by a combination of faulting and folding. South of the Kingston complex, Carboniferous deformation (Fig. 8) appears to be mainly a response to dextral transcurrent motions. Zones of strong deformation, steeply dipping en echelon folds slightly overturned to the northwest and cores of plutonic rocks all step to the right. Zones of strong deformation tend to follow the shore of the Bay of Fundy, then pass inland along coves where they end abruptly in festoons of small allochthons with subhorizontal bases. These thrust allochthons were first regarded as evidence of major regional overthrusting (Rast and Grant 1973, Rast *et al.* 1978), but more recent work suggested that they are flower structures, small scale thrust blocks produced at flexures in a transcurrent fault (Nance and Warner 1986). Among the lines of evidence leading to this conclusion are the following: (i) The lithologies in the allochthons can all be identified as derived from their immediate surroundings (Currie 1984, 1986). (ii) The grade of metamorphism in the allochthons and their surroundings is low, reaching chloritoid grade only in a small region on the shore of the Bay of Fundy, and garnet grade over an area a few hundred meters across. (iii) The allochthons are associated with the termination or flexure of strong deformation zones. (iv) Thrusting takes place in both directions almost contemporaneously (Currie and Nance 1983), suggesting that thrusting cannot be due to regional directed stress, but rather results as a byproduct from a stress field without strong horizontal compression. One observation not satisfactorily explained by the locally derived, small allochthon model is the pervasive presence of gently dipping cleavage in Carboniferous rocks east of Saint John harbour, even in rocks which otherwise show little deformation. Currie and Nance (1983)

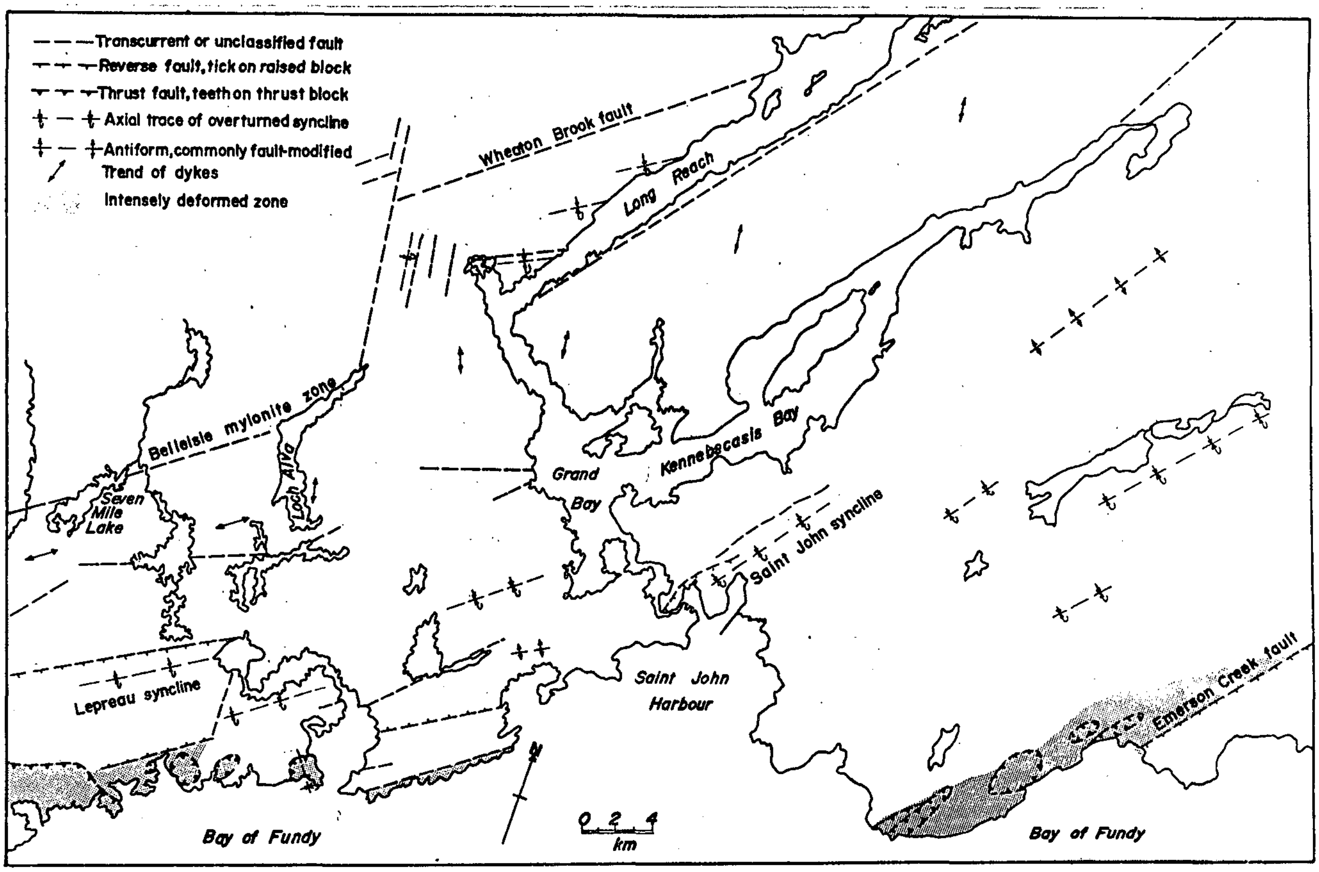

Fig. 8. Major structures in the Saint John region. Major folding and latest fault movement is Carboniferous in age, but many of the faults may have a significant pre-Carboniferous history.

suggested that this might be due to over-riding of this terrane by a large, easterly derived allochthon now completely eroded away. Some support for this idea has been provided by seismic reflection surveys in the Gulf of Maine which suggest that the dextral Cobequid Fault system (Keppie 1982) in this area becomes a low angle thrust (D. B. Stewart, personal communication 1986), as required by the change in direction of the fault system in the Saint John region. Study of thrust faulting in the Saint John region is of considerable economic interest since Au mineralization occurs in silicified zones associated with strong deformation in the sole of thrusts. Mapping of the mineralization on a regional scale (McCutcheon 1984, Ruitenberg 1984) clearly shows an association between thrust deformation and silicified zones, presumably due to circulation of fluids in the cataclastic zones.

Two, or locally three, periods of roughly coaxial folding can be identified in Carboniferous rocks. The style of folding, its scale and associated metamorphism appear to be essentially identical in the Saint John Group and Mispec Group, suggesting a possible Carboniferous age for deformation of the Saint John Group. Sedimentological evidence (Caudill and Nance 1986) shows that deformation commenced during deposition of the Westphalian Mispec Group.

The northern margin of the Saint John terrane lies along a well defined fault (Wheaton Brook fault, see Currie 1984, 1986 for discussion of the field evidence) which is truncated by the Mount Douglas pluton. Fold keels along the fault in the Long Reach area appear to show an en echelon pattern in a sinistral sense. The axes of these fold keels have a markedly more easterly trend than those south of Kennebecasis Bay. Despite this evidence for sinistral movement, local kinematic indicators quite consistently indicate latest dextral movement. To the northwest of Grand Bay the rocks have been reduced to a multitude of small fault slivers, some not more than 10 m across which trend north, northwest and northeast. One possible explanation for this configuration could be an extended history of movement along the northern boundary of the Avalon zone. Sinistral movement in Late Precambrian time would produce spreading across the old fault segment extending north from Loch Alva. Such spreading could provide a mechanism for producing a north-trending sheeted dyke complex in this region, and by an appropriate adjustment of the spreading rate could produce a bimodal dyke swarm by injection of mantle and crustal derived melts. On this mechanism the width across strike of the dyke complex could provide an estimate of the strike slip on the fault during formation of the Kingston complex. This mechanism also could explain the abrupt change in strike of dykes in the region of Lock Alva. Following this reasoning the configuration of the Saint John Group outliers along the Long Reach suggests continued sinistral motion in post-Cambrian time. The dextral motion which now masks all else may be of Carboniferous age, as the fault is well known to cut Carboniferous strata (Garnett and Brown 1973). This whole line of reasoning depends on an extended movement history for the northern boundary of the Avalon zone, which is supported at present only by circumstantial evidence. Clear evidence for such a history is a major objective of further field work.

The central part of the Saint John terrane is dominated by northeast-trending faults and high strain zones. Dip slip, reverse and thrust movements can be identified locally. Some of these faults may have large displacements, as discussed by Wardle (1977), but the size and age of the displacements are in most cases unknown. The general stratigraphic coherence of the Saint John terrane suggests that the movements did not produce large aggregate displacements across the terrane.

DISCUSSION

The Late Proterozoic volcanic section in the Saint John region appears to be built on older crystalline basement. The zircon age (1641 Ma) obtained by Olszewski and Gaudette (1982) from the Brookville gneiss resembles zircon ages from the Grenville province of central Labrador (Nunn *et al.* 1985), where such ages exhibit only a weak to nonexistent overprinting by the 1000 Ma ages thought to be typical of the Grenville (Currie and Loveridge 1985). The lithology of the Green Head Group resembles that of the Grenville Group of southern Ontario and Quebec, and the ages of these successions appears to be comparable. Basement of Grenvillian affinity (one or more of massif anorthosite, Middle Proterozoic shelf-type sediments, 900-1200 Ma radiometric dates) has now been proved or strongly indicated in the Cobequid Highlands (Gaudette *et al.* 1983), western Cape Breton Highlands (Currie 1983, Jamieson *et al.* in press) and in the Goochland terrane of Maryland (Farrar 1984). A significant part, perhaps most, of the Avalon zone may be underlain by basement of Grenvillian aspect.

The three-fold division of Late Proterozoic magmatism observed in the Saint John region suggests diverse tectonic environments at this time. The early phase of abundant mafic magmatism may reflect rifting and spreading as first suggested by Rast (1979). The later calc-alkaline magmatism suggests association with arc-type magmatism and subduction. The Eocambrian section clearly represents rifting of completely cratonized material. The three-fold division of Late Proterozoic magmatism has been shown to be a circum-Atlantic phenomenon in terranes of Avalon type (Jenkins 1984). The youngest two of his divisions (600 and 560 Ma) correspond very well with Canadian experience, but his oldest (650 Ma) seems too young. Mafic magmatism of 700-800 Ma has now been documented in Newfoundland (Krogh *et al.* 1983) and Cape Breton Island (Gaudette *et al.* 1985) as well as in the Saint John area. The younger intermediate to felsic volcanic rocks have been widely interpreted in western Europe as resulting from an ensialic island arc associated with the major Cadomian orogeny (see Rast 1980 for review). An Eocambrian section, including bimodal volcanics, has been recognized in the Boston basin (Kaye and Zartman 1980). The tectonic significance of the three-fold division of Late Proterozoic igneous rocks is presently speculative, but an interpretation in terms of rifting followed by closure and renewed rifting seems reasonable.

Modest subsidence of the Saint John region in Cambro-Ordovician time permitted a marine incursion. However during Silurian and Devonian time the region appears to have been land which underwent relatively little deformation or intrusion (compare Berry and Boucot 1970, McKerrow and Zeigler 1971). The Cambro-Ordovician section around Saint John contains the characteristic Acado-Baltic fauna thought to typify terranes which lay on the southeast side of the Iapetus Ocean in Lower Paleozoic time (McKerrow and Cocks 1977). However terranes with such faunas are by no means uniform. Murphy *et al.* (1982) describe a sequence in the Antigonish Highlands, otherwise a fairly typical Avalonian terrane, containing major amounts of volcanic rocks. Furthermore this terrane exhibits significant Silurian deposition and magmatism. An even more striking contrast is seen between the Saint John terrane and the adjacent Mascarene-Nerepis belt (Ruitenberg *et al.* 1977), which also contains an Acado-Baltic fauna in a volcanic-dominated Cambrian sequence, as well as massive amounts of Ordovician volcanic rocks. Late Proterozoic rocks are thought to be present in this belt, but definitive evidence has proved difficult to obtain.

Northwestern Cape Breton Island

exhibits the typical Avalonian three-fold division of Late Proterozoic plutons (Jamieson *et al.* in press), but also displays abundant Silurian magmatism and high-grade Devonian metamorphism. A similar terrane (Putnam-Nashoba block) lies west of the typical Avalonian terrane of the Milford-Dedham block in Massachusetts (Zartman and Naylor 1984). If the presence of Cambrian Acado-Baltic faunas and the characteristic three-fold division of Late Proterozoic magmatic rocks are accepted as valid criteria of Avalonian terranes, then such terranes apparently show a northwestward progression from "classical" Avalonian terranes which exhibit a purely sedimentary Cambrian section and little or no Silurian deposition and magmatism, through terranes with Cambrian and Ordovician volcanism and Silurian magmatism, to terranes with extensive Ordovician-Silurian plutonism and strong Devonian metamorphism. Such a sequence would be compatible with an unstable northwestern margin to a continentally-cored Avalon terrane. Given the generally accepted framework of Appalachian geology, the major Ordovician-Silurian magmatic event and subsequent Devonian metamorphism could reasonably be correlated with the amalgamation of the Avalonian terranes to America.

Major deformation of the Saint John terrane by dextral transcurrent movements began in Carboniferous or earlier time. Following the reasoning outlined above, it seems probable that this motion produced a reshuffling of an existing continental margin, rather than addition of major exotic

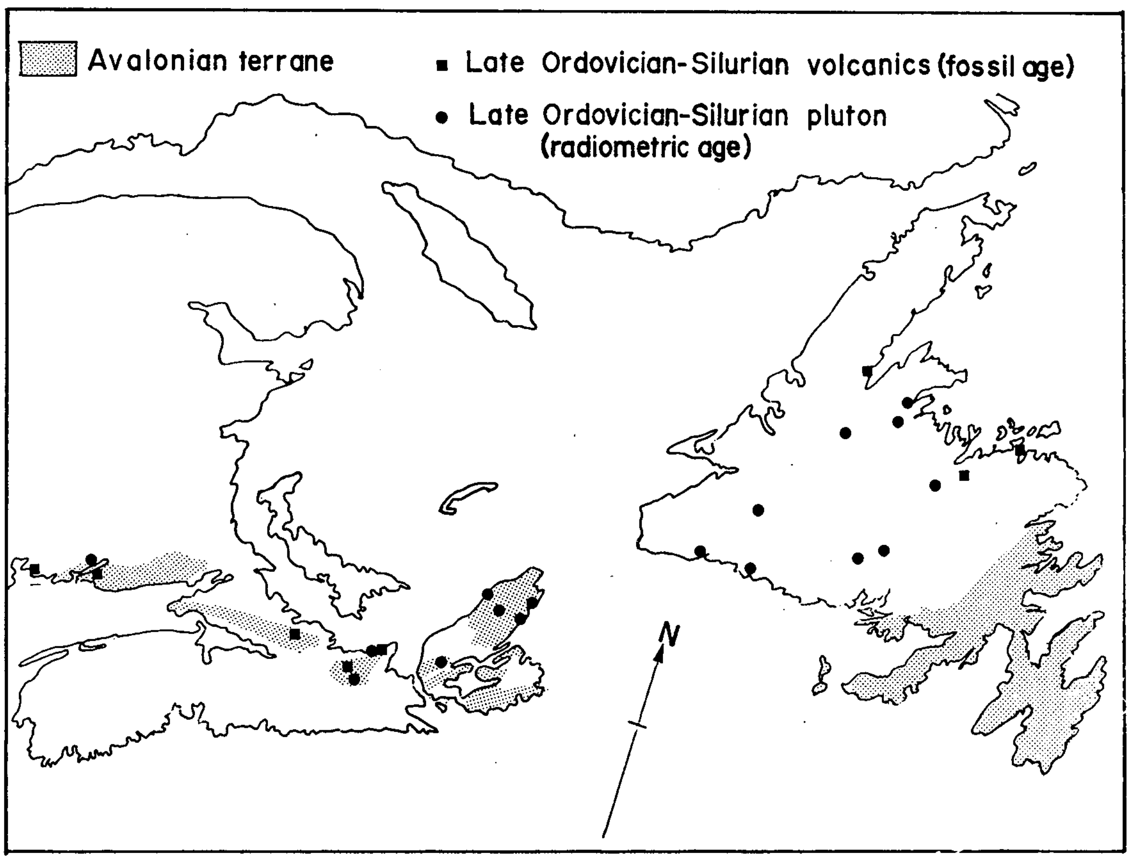

Fig. 9. Upper Ordovician-Lower Silurian volcanic (open circles) and plutonic (closed circles) rocks in the northeastern Appalachians. Note that Silurian magmatism crosses zone boundaries, including the Avalon zone. (After Currie *et al.* 1986).

fragments. Although latest movement in the Saint John region is consistently right-hand, there are numerous hints of older left-hand motion. The extent of reactivation of old faults by subsequent motions has been very little studied in Avalonian terranes. The Saint John region suggests that it deserves more detailed consideration.

According to many current models, Avalonian terranes are exotic to North America and arrived in Devonian or later time, perhaps from Africa (O'Brien *et al.* 1983) or South America (Keppie 1984). The Saint John region suggests a possible North American origin for the terrane, and relatively early (re)accretion to the

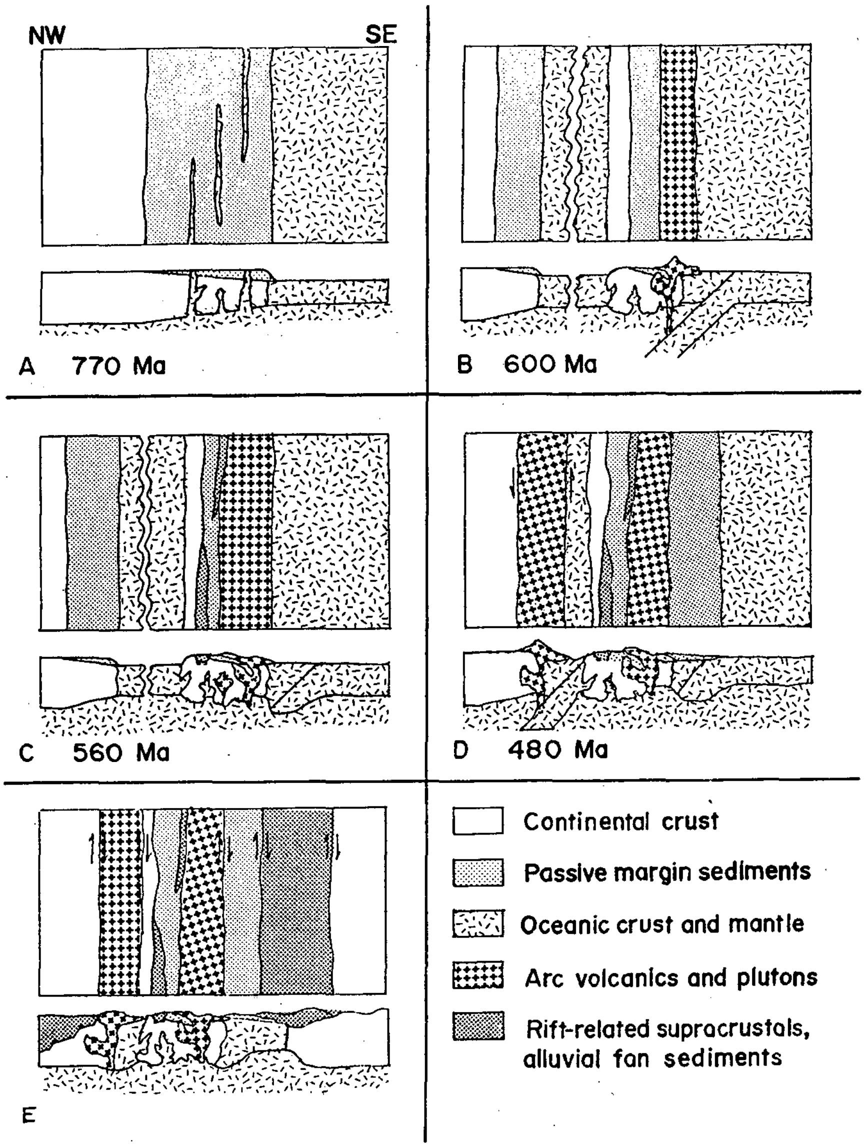

Fig. 10. Cartoon of a possible development of Avalon terranes by break-up of the continental edge of North America.
(a) Rifting of a passive continental margin about 750-800 Ma, accompanied by emplacement of mafic magma.
(b) Closure by subduction of a marginal sea with an assumed left-lateral component about 600 Ma.
(c) Rifting of the continental margin about 580 Ma with subsequent development of a passive margin.
(d) Closure of a marginal sea (Iapetus) by subduction about 480 Ma with assumed right-lateral component.
(e) Post-Ordovician right-lateral displacement.

continent. Basement to Avalonian terranes has been identified in the Saint John area, Cape Breton Island and the Cobequid Highlands. In all cases the ages and lithologies of the basement are compatible with derivation from the Grenville province of the Canadian shield. Late Proterozoic magmatism in the Avalonian terranes suggests spreading followed by reclosing accompanied by ensialic arc-type magmatism. Major Late Ordovician-Silurian magmatism strongly suggests Avalonian terranes were linked to North America by that time (Fig. 9). These points suggest a possible origin involving a Late Proterozoic breakup and rewelding of the American continental margin, followed by a Cambro-Ordovician breakup and rewelding and subsequent dextral transcurrent motions. Fig. 10 shows in cartoon form the ideas involved in such a scenario. A possible modern analogue might be Japan, which contains an old Asian continental core, and could be rewelded to Asia by subduction of the Japan Sea. In the present state of field mapping and laboratory studies all such models must be considered highly speculative, but the wider the range of models considered, the higher the probability that the correct explanation will be considered.

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