TECTONOSTRATIGRAPHIC EVOLUTION OF THE AVALON TERRANE IN SOUTHERN NEW BRUNSWICK, CANADA

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Un ejemplo único de sucesión de edad Proterozoico a Triásico del Terreno de Avalon, en los Apalaches septentrionales, aflora entre las fallas dextrales de Belleisle y Cobequid-Chedabucto, en el sur de New Brunswick, Canadá. El basamento tonalítico del Proterozoico Medio, movilizado diapíricamente (Gneis de Brookville), y su cobertera carbonatada-clástica (Grupo de Green Head) están recubiertos discordantemente (?) por brechas de colapso y turbiditas carbonatadas (Formación Martinon), que se interpretan como un registro del colapso de una plataforma ensiálica. Un acontecimiento tectonotérmico del Proterozoico Superior (c. 800 Ma), posiblemente asociado a un plutonismo ultramáfico-máfico, puede haber acompañado a este colapso, atribuyéndose provisionalmente a extensión del arco interno con separación cortical durante la subducción inicial del Océano Cadomiense (?). En este episodio podría haberse formado corteza suficiente como para explicar el desarrollo de plutonismo granítico calcoalcalino (Suite de Golden Grove) y vulcanismo bimodal cogenético (Grupo de Coldbrook) durante la etapa de subducción del Proterozoico terminal (c. 600 Ma). La polaridad de la subducción hacia el noroeste actual es la que mejor se adapta a los datos disponibles, apoyando el desarrollo de esta porción de terreno de Avalon sobre el basamente norteamericano. El emplazamiento de un complejo bimodal de diques (Kington) dentro de la zona milonítica penecontemporánea (Pocologan) a lo largo del margen noroccidental del terreno, sugiere una transtensión intra-arco del Precámbrico Superior. Las capas rojas volcanogénicas y rocas volcánicas bimodales del Precámbrico terminal (Eocámbrico), podrían anunciar el comienzo del Océano Japeto y pasar con una discordancia poco importante a las areniscas y lutitas Cambro-Ordovícicas (Grupo de Saint John) que representan una secuencia sobreimpuesta a la historia Precámbrica del Terreno de Avalon. Estas últimas contienen faunas de mar somero de tipo Atlántico y registran la reinstauración de la plataforma tras una discordancia con ruptura (?). El atraque de Avalon en Norteamérica tras el cierre del Japeto podría haber ocurrido ya durante la Fase Tacónica. Sin embargo, las unidades silúricas y devónicas se encuentran ausentes o son alóctonas y las fases Tacónica y Acadiense no han sido aún demostradas. Las capas rojas carboníferas y la estructura principal registran una compresión dextral del Paleozoico Superior (Alleghéniense) según fallas que en la actualidad definen los límites de terrenos del Avalon. Las capas rojas triásicas registran la apertura de la Bahía de Fundy con el rifting inicial del actual Océano Atlántico.

Palabras clave: Terreno de Avalon, New Brunswick, Canadá, Apalaches Septentrionales, Precámbrico Superior, Tectonoestratigrafía, Cadomiense, Arco interno, Fauna Acado-báltica, Japeto, Tectónica de placas.

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A unique Proterozoic to Triassic record of the Avalon terrane in the Northern Appalachians is exposed between the dextral Belleisle and Cobequid-Chedabucto faults of southern New Brunswick, Canada. Diapirically mobilized mid-Proterozoic tonalitic basement (Brookville gneiss) and its carbonate-clastic cover (Green Head Group) are ?unconformably overlain by carbonate slump breccias and turbidites (Martinon Formation) that are interpreted to record the collapse of an ensialic platform. A Late Proterozoic (~800 Ma) tectonothermal event, possibly associated with ultramafic-mafic

plutonism, may have accompanied this collapse and is tentatively attributed to back-arc extension and crustal separation during initial subduction of the ?Cadomian ocean. Sufficient oceanic crust may have formed at this time to account for the development of calc-alkaline granitoid plutonism (Golden Grove suite) and co-genetic, bimodal volcanism (Coldbrook Group) during its latest Proterozoic (~600 Ma) subduction. Subduction polarity towards the present northwest best accommodates the record and supports the development of this portion of the Avalon terrane on North American basement. Emplacement of a bimodal (Kingston) dike complex within the penecontemporaneous (Pocologan) mylonite zone along the terrane's northwestern margin suggests Late Precambrian intra-arc transtension. Latest Precambrian («Eocambrian») volcanogenic redbeds and bimodal volcanics may herald the inception of the Iapetus ocean and pass with minor unconformity to Cambro-Ordovician sandstones and shales (Saint John Group) that represent an overlap sequence to the Precambrian history of the Avalon terrane. The latter bear shallow-marine, Atlantic-realm fauna and record platform re-establishment following a ?break-up unconformity. Ihe docking of Avalon to North America after closure of Iapetus could be as early as the Taconian. However, Silurian and Devonian units are absent or allochthonous and Taconian and Acadian events have yet to be demonstrated. Carboniferous redbeds and the region's major structure record Late Palaeozoic (Alleghanian) dextral transpression on faults that now define Avalon terrane boundaries. Triassic redbeds record the opening of the Fundy Basin with initial rifting of the present Atlantic ocean.

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In the Northern Appalachians of New England and Atlantic Canada, the Avalon terrane forms a distinctive tectonostratigraphic belt (Fig. 1) that is defined principally by the presence of volcanic-sedimentary sequences and co-genetic granitoid plutons of the late Precambrian (circa 600 Ma) Avalonian cycle, and Lower Palaeozoic platformal successions containing Acado-Baltic (Atlantic-realm) trilobite fauna (O'Brien *et al.* 1983; Rast and Skehan 1983; Nance 1986a). Traditionally considered as one of five tectonostratigraphic zones within the Northern Appalachians (e.g. Williams 1978, 1979), Avalon constitutes the largest Appalachian suspect terrane and extends discontinuously from offshore eastern Newfoundland to southeastern Massachusetts and possibly the Carolinas (Williams and Hatcher 1982, 1983). Potential correlatives of the Avalon terrane occur outside the Appalachian orogen in the Caledonides of southern Britain (Rast *et al.* 1976), the Cadomian massifs of western and central Europe (Rast 1980), and the Pan-African belts of northwest Africa (Pi-

qué 1981; O'Brien *et al.* 1983; Rast and Skehan 1983).

In southern New Brunswick, Canada (Fig. 2), an instructive segment of the Avalon terrane is exposed in the vicinity of Saint John. The succession, which rests on sialic basement of Middle Proterozoic (Helikian) age (Brookville gneiss), includes Mid-to-Late Proterozoic platform carbonates and clastics (Green Head Group); Late Proterozoic (mid-Hadrynian?) carbonate conglomerates and siltstones (Martinon Formation), and mafic to ultramafic intrusives; Latest Proterozoic (Late Hadrynian) calc-alkaline granitoid rocks (Golden Grove suite), a co-genetic volcanic-volcaniclastic assemblage (Coldbrook Group), and a bimodal dike complex; an unnamed «Eocambrian» volcanic-sedimentary sequence; and Cambro-Ordovician sandstones and shales bearing Atlantic-realm fauna (Saint John Group). Younger units include fault bound basalts and sandstones of Silurian age, and Late Devonian, Carboniferous and Triassic redbeds. The following review pro-
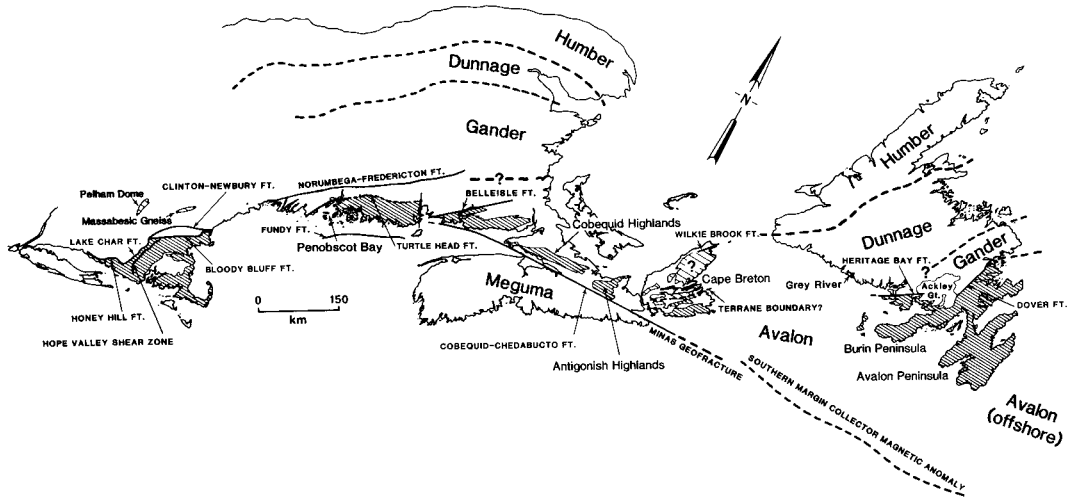
Fig. 1.–Distribution of the Avalon terrane (broad-shaded where uncertain) and major terrane boundary faults in the Northern Appalachians (from Nance 1986a, modified after Zen 1983). Zone boundaries from O'Brien *et al.* (1983); Collector Anomaly from Haworth and Lefort (1979); and Fundy Fault from Ballard and Uchupi (1975).

vides brief descriptions of these units, summarizes present knowledge and uncertainties in the geology of this region, and outlines a tentative tectonic model for the Precambrian to Early Palaeozoic evolution of this portion of the Avalon terrane (Nance, 1987a).

UNIT DESCRIPTIONS

MIDDLE PROTEROZOIC (HELIKIAN) ELEMENTS

The tonalitic BROOKVILLE GNEISS (*H*b; Fig. 2) has traditionally been considered both
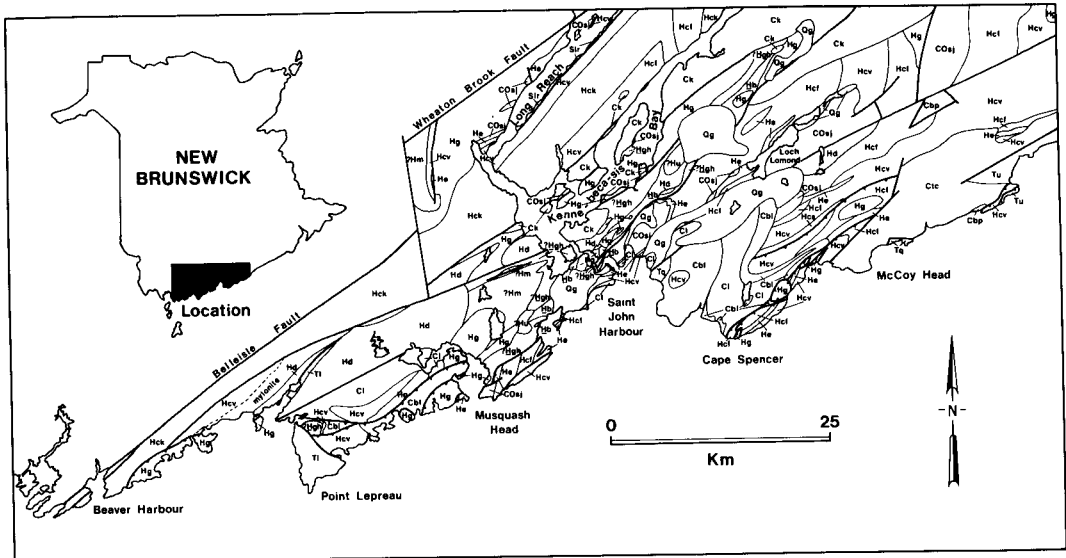

Fig. 2.–Geology of the Saint John region, southern New Brunswick (modified from Hayes and Howell 1937; Alcock 1938; Rast *et al.* 1978; Wardle 1978; Ruitenberg *et al.* 1979; Currie *et al.* 1981; Currie and Nance 1983; Currie 1984, 1986a; McCutcheon 1981a, 1984; Parker 1984; Ruitenberg 1984; and Nance and Warner 1986). See Table I for legend and unit descriptions.

TABLE I.–Legend and unit descriptions (modified after Currie 1984; 1986a, b)

QUATERNARY

Qg   Glacial drift, boulder till, stratified fluviolacustrine sand and gravel
—unconformity—

TRIASSIC

Tu   UNDIFFERENTIATED: brick-red conglomerate and alluvial and eolian sandstone of the
Echo Cove, Quaco and Honeycomb Point Formations
Tq   QUACO FORMATION: red to brown conglomerate and minor sandstone
Tl   LEPREAU FORMATION: reddish brown conglomerate, sandstone and mudstone
—unconformity—

CARBONIFEROUS

Ctc   TYNEMOUTH CREEK FORMATION: red pebbly sandstone and siltstone
—relations uncertain, probably correlative—
Cbl   BALLS LAKE FORMATION: red conglomerate, sandstone, siltstone and shale
—gradational contact—
Cl   LANCASTER FORMATION: grey lithic arenite and quartz-pebble conglomerate
—relations uncertain, probably correlative—
Cbp   BOSS POINT FORMATION: grey sandstone, quartz conglomerate and siltstone
—relations uncertain, probably unconformity—
Ck   KENNEBECASIS FORMATION: red-brown conglomerate, sandstone and siltstone
—unconformity—

SILURIAN OR YOUNGER

SDd   gabbro, diabase and augite porphyry dikes
—intrusive contact (to COsj)—

SILURIAN

Slr   LONG REACH FORMATION: basalt flows, minor calcareous siltstone and shale
—relations unknown, probably tectonic—

CAMBRO-ORDOVICIAN

COsj SAINT JOHN GROUP: Lower Cambrian maroon sandstone and conglomerate, white quartzite and
grey sandstone; Middle to Upper Cambrian grey sandstone, siltstone and shale; Upper Cambrian to
Lower Ordovician black shale
—unconformity or disconformity—

HADRYNIAN

He   «EOCAMBRIAN» red feldspathic sandstone, tuff, conglomerate and basalt
—disconformity—
Hkc   KINGSTON COMPLEX: alternating felsic and mafic dikes
—intrusive contact—
Hc   COLDBROOK GROUP: (f) tuff, agglomerate, lahars; (v) basalt and rhyolite flows; (s) siltstone
and chert
—probably co-genetic—
Hg   GOLDEN GROVE SUITE: hornblende granodiorite, hornblende-biotite granite, leucogranite,
quartz porphyry, epidote alaskite
—intrusive contacts—
Hd   GOLDEN GROVE SUITE: diorite, monzonite, minor gabbro, mixed plutonics
—relations uncertain, probably intrusive—
?Hu   altered and metasomatized gabbro, hornblendite and ultramafics
—relations uncertain, probably intrusive—
?Hm   MARTINON FORMATION: carbonate conglomerate and grey to black siltstone
—probable unconformity—

HELIKIAN

?*H*gh GREEN HEAD GROUP: grey to buff marble, grey-white quartzite, black pelite
—probable mobilized unconformity—
*H*b   BROOKVILLE GNEISS: hornblende/biotite tonalitic gneiss and migmatite

a member of the Golden Grove suite (Hayes and Howell 1937) and a high-grade, migmatized portion of the upper Green Head Group (Rast *et al.* 1976; Wardle 1978). More recent investigations, however, view this unit as an older, ductily remobilized and partially melted basement to the Green Head platform (Currie *et al.* 1981; Currie 1983, 1986a; Nance, 1987a). The tonalitic, quartz-plagioclase-hornblende/biotite gneiss (fig. 3a) has been metamorphosed to amphibolite facies (Wardle 1978) and includes relict mafic dikes, and enclaves of biotite granite gneiss and tourmaline pegmatite that apparently developed through in-situ anatexis (Currie *et al.* 1981). The age of the Brookville gneiss, however, remains controversial and existing radiometric data is problematic. In a preliminary isotopic study of the unit, Olszewski and Gaudette (1982) obtained zircons of detrital morphology that yielded an original age of 1641 Ma with Pb-loss events at 780 Ma and 370 Ma, and a single metamorphic zircon that yielded an essentially concordant age of 814 Ma. Metamorphic zircons from a quartz diorite gneiss considered to be ductily remobilized basement by Wardle (1978) and included in the Brookville gneiss by Currie *et al.* (1981), have yielded ages of 827 Ma and 333 Ma. Rb/Sr whole-rock data for both gneisses support a metamorphic event at circa 800 Ma and, on the basis of initial ratio, suggest that the original age of the Brookville gneiss is unlikely to exceed 1,200 Ma (Olszewski and Gaudette, 1982). Based on field relations, however, Currie *et al.* (1981) and Currie (1983, 1986a) have interpreted the earlier (1641 Ma) age to be that of the Brookville protolith.

Contact relations between the Brookville gneiss and adjacent Green Head Group are extremely complex with dike-like projections of gneiss invading the Green Head Group and ductily mobilized Green Head marbles and locally sillimanite-bearing metaclastics incorporated in the gneiss (Currie *et al.* 1981). The exceptionally steep thermal gradient adjacent to the gneiss implied by the predominantly greenschist facies Green Head Group, coupled with their contrast in composition, has been taken to indicate emplacement of the gneiss through hot gneissic diapirism (Wardle 1978; Currie *et al.* 1981). Such an origin may be supported by the multidirectional,

steeply plunging and polyphase nature of the gneissic folding. The development of these ductile contact relations appears to have accompanied regional metamorphism at ~800 Ma. However, reactivation of the basement has apparently occurred on a repeated basis. An earlier episode of partial melting may be reflected in the enclaves of biotite granite gneiss (Currie *et al.* 1981), and later alteration is likely to have accompanied the Late Precambrian emplacement of the Golden Grove plutons which show broad migmatitic aureoles in the Brookville gneiss and narrow hornfelsic aureoles in the Green Head Group (Currie 1983, 1986a). Still younger partial melting that reactivated the Late Precambrian plutons to produce marginal metasomatic aureoles may be synchronous with the development of the unfoliated enclaves of tourmaline pegmatite. A slightly discordant zircon age of 466 Ma, obtained from these pegmatites by Olszewski *et al.* (1980), was taken by Currie *et al.* (1981) and Nance (1982) to imply a significant period of Late Ordovician («Taconian») partial melting. Yet this episode does not appear in the isotopic results of Olszewski and Gaudette (1982) where the younger Pb-loss events appear to correspond to Acadian emplacement or isotopic resetting of granitoid members of the Golden Grove suite. However, given the degree of alteration of these rocks, the available age data should be viewed with considerable caution. Continued basement uplift as a result of brittle displacement occurred at least into Carboniferous time (Currie 1983), as re-flected in the antiformal distribution of major units in which the basement core is flanked across high-angle faults to the northwest and southeast by successively younger rocks (Fig. 2).

The metasedimentary GREEN HEAD GROUP (?*H*gh; Fig. 2) is informally subdivided into two formations (Leavitt 1963). The lower, Ashburn Formation comprises a thick (~3,700 m) carbonate-clastic succession of orthoquartzites, color-banded marbles, massive dolomites, minor meta-siltstones and pelitic schists (Fig. 3b). The overlying Martinon Formation comprises a homogeneous (~1,800 m), clastic assemblage of massive grey sandstones, siltstones, greywacke and orthoquartzite (Wardle 1978) with a prominent, basal carbonate-pebble conglomerate horizon (Fig.
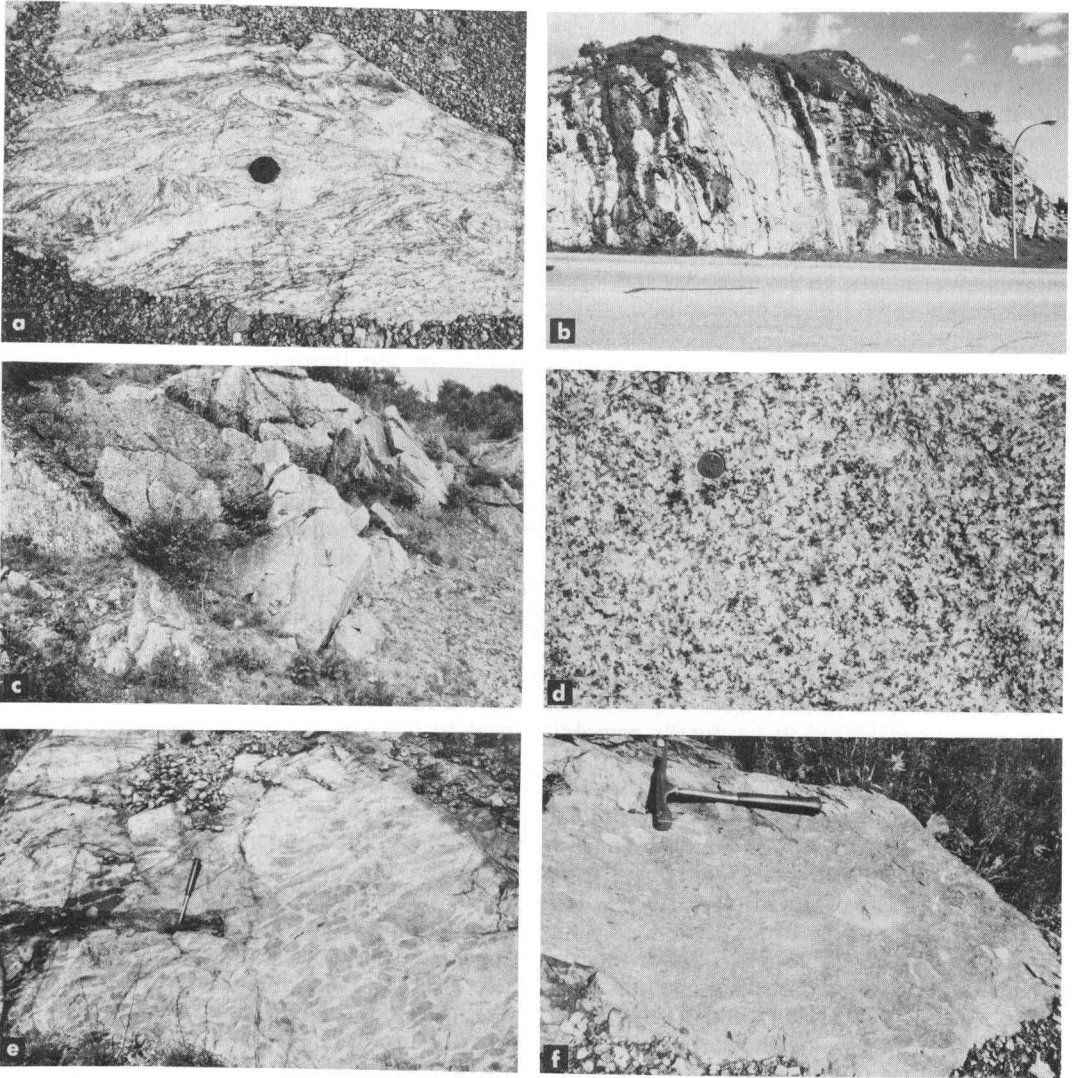
Fig. 3.—Representative field exposures of (a) the Brookville gneiss, (b) carbonates of the Green Head Group, (c) the basal, carbonate slump breccia of the Martinon Formation, (d) a ?mid-Hadrynian meta-gabbro (Duck Lake pluton), (e) acid-basic magma mixing within a granitoid body of the Golden Grove suite, and (f) a lahar within the Coldbrook Group.

3c). With the exception of its contacts with the Brookville gneiss, where sillimanite-bearing pelitic assemblages are locally developed, the bulk of the Green Head Group lies within the greenschist facies as demonstrated by the co-existence of dolomite + quartz in carbonates and muscovite + chlorite ± biotite in clastics (Wardle 1978; Nance 1982). However, stable assemblages are commonly those of the retrograde metamorphism of higher grade phases that, at least in part, define contact metamorphic aureoles around late Precambrian plutons of the Golden Grove suite. Several generations of cross-cutting mafic dikes and occasional felsic dikes (that are probably feeders to the overlying Coldbrook Group) similarly show low-grade metamorphic assemblages.

Within the Ashburn carbonate-clastic succession, Wardle (1978) defined three formations, namely a basal, predominantly clastic Lilly Lake Formation; a largely carbonate Drury Cove Formation; and an uppermost, heterogeneous Narrows Formation comprising minor conglomerates, calcareous pelites and carbonates which locally contain the ?Neohelikian stromatolite *Archaeozoon acadiense* (Hofmann 1974). Wardle (1978) interpreted this stratigraphy as reflecting depositional environments that evolved from a stable carbonate shelf to basinal slope conditions in the Narrows Formation, and thence to basinal sedimentation deepening to the west or southwest in the Martinon Formation. However, polyphase deformation within the Green Head Group has been strongly heterogeneous such that strain during the earliest phases was largely accommodated by ductile flow in the carbonates, while the clastics responded by boudinage and the development of a weak, bedding-subparallel cleavage (Nance 1982). As clastic units under these conditions show little lateral continuity, and color-banding in the carbonates is deformational and hence an unreliable guide to bedding, attempts to erect a detailed stratigraphy for the carbonate-clastic succession may be of dubious validity. However, an overall upward-deepening succession seems likely. The age of this inhomogeneous deformation is uncertain but it is probably a composite fabric with co-planar components as old as the mid-Hadrynian. Subsequent deformations that produced upright folds sequentially oriented northeast-southwest and east-west (Wardle 1978; Nance 1982), may have accompanied the retrogression that partly reset Brookville gneiss zircon ages during the Acadian (Olszewski and Gaudette 1982).

LATE PROTEROZOIC (HADRYNIAN)
ELEMENTS

The MARTINON FORMATION (?Hm; Fig. 2), which unconformably (Leavitt 1963) or gradationally (Wardle 1978) overlies the Green Head Group, differs from the underlying carbonate-clastic succession in lithology, sedimentology and structural style, and is considered a separate unit by Currie (1984,

1986b). If so, its age is uncertain although it is cut by granitoid plutons of the Golden Grove suite (Currie 1984) and is overlain with approximate conformity by the Coldbrook Group (Currie 1986b). However, the stratigraphy of the formation, in which basal slump breccias of Green Head carbonate (Fig. 3c) are overlain by turbiditic sandstones and siltstones, appears to record the abrupt subsidence, slumping and structural disruption of the Green Head platform. This break-up and collapse of a pre-existing platform has been taken to herald the circa 800 Ma tectonothermal event during an episode of back-arc extension (Nance, 1986a, 1987a). If so, deposition of the Martinon Formation may be penecontemporaneous with the emplacement of small MAFIC-ULTRAMAFIC PLUTONS (?Hu; Fig. 2) comprising locally cumulate amphibolites and gabbros (Fig. 3d). These post-date the Green Head Group but record the amphibolite facies metamorphism characteristic of the mid-Hadrynian tectonothermal episode.

The bulk of the GOLDEN GROVE SUITE of Hayes and Howell (1937) occupies a narrow belt associated with the Brookville gneiss (Fig. 2) and termed the «central plutonic core» by Currie *et al.* (1981). This late Hadrynian calc-alkaline suite comprises a diverse assemblage of small, granitic to dioritic plutons (Hg, Hd; Fig. 2) that intrude all previously described units and are preserved as pebbles in the basal Cambrian Ratcliffe Brook Formation (Currie *et al.* 1981; Currie 1984). Compositional changes within and between these plutons are gradational but range from alaskite and granodiorite to tonalite and hornblende diorite (Ruitenberg *et al.* 1979) and show widespread evidence of complex, acid-basic magma mixing (Fig. 3e). Pluton contacts are commonly sharp with respect to the Green Head Group, in which retrograded andalusite-bearing contact aureoles are developed, but gradational, hybridized and metasomatic with respect to the Brookville gneiss, where their margins tend to be potassic and megacrystic (Currie *et al.* 1981; Currie 1986a). In addition, many plutons show evidence of cataclasis and recrystallization, and all are cut by mafic dikes of several generations. Available K/Ar data generally yield anomalously young, Taconian or Acadian ages for the plutons (Leech *et al.* 1963; Wanless *et al.* 1973),

but their absence as intrusions into the Cambro-Ordovician Saint John Group and the high initial strontium ratio of the Musquash Harbour granite (Olszewski and Gaudette 1982), suggest that the ages have been metamorphically reset during remobilization. Ruitenberg et al. (1979) therefore favoured a Late Precambrian to Early Palaeozoic age for the Golden Grove suite which is supported by a questionable «composite» Rb/Sr age of 526 Ma (Poole 1980) and a recent zircon age of 550 Ma (K. L. Currie, pers. comm. 1986) from a granite body at Musquash Harbour (Fig. 2). However, plutonism was likely to have been protracted, as is suggested by two recently determined ages of 598 ± 18 Ma (whole-rock Rb/Sr) and 598 ± 27 Ma (K/Ar, hornblende) from a granitic pluton in the Caledonian Highlands (Barr 1987), and a zircon age of 625 ± 15 Ma (Watters 1987) from a granite at Cape Spencer (Fig. 2). The existence of locally gradational contacts between plutonic and volcanic rocks demonstrates that the plutonism was cogenetic and largely coeval with units of the Coldbrook Group (Currie 1986a, b).

Volcanics and volcanogenic sediments of the COLDBROOK GROUP (Fig. 3f) extend from a type area immediately east of Saint John (Hayes and Howell 1937; Alcock 1938) some 100 Km to the northeast (Giles and Ruitenberg 1977; Ruitenberg et al. 1979). Within this region, Giles and Ruitenberg (1977) described three distinct volcanic belts, namely an Eastern Belt lying outside the area of Fig. 2 and characterized by intensely deformed mafic and felsic flows, tuffs, volcanogenic sediments and thick arkosic sandstones and conglomerates; a Central Belt on the south flank of the «central plutonic core», comprising weakly deformed felsic and lesser mafic flows, coarse lithic tuffs, volcanic breccia and minor volcanogenic conglomerates; and a Western Belt lying north of the core, composed of flows and tuffs that resemble those of the Central Belt but are more intensely deformed.

Currie (1984, 1986a, b) similarly distinguishes the Coldbrook Group (Hc; Fig. 2) south of the central plutonic core from the KINGSTON COMPLEX (Hkc; Fig. 2) to the north. The latter, however, comprises a major mafic to bimodal dike complex (O'Brien 1976) which defines a linear zone up to 10 Km across strike that extends over 200 Km from Moncton (Rast 1979) to Campobello Island on the U.S. border (Helmstaedt 1968). Intruded into volcanics of the Coldbrook Group and granitoid bodies of the Golden Grove suite, the complex comprises from 40 % to 100 % dikes (Fig. 4a). These trend northeast-southwest and are predominantly mafic in southwestern portions of the belt (Beaver Harbour swarm of McLeod 1979 and Rast 1979) but trend north-south and show alternating basaltic to dioritic and rhyolitic to microgranitic compositions farther northeast (Currie 1984). The absence of these dikes in the overlying Eocambrian and Lower Palaeozoic successions supports the late Precambrian emplacement age proposed by Rast (1979).

Within the Late Precambrian volcanic succession, Currie (1984) further identified a culminating sequence of feldspathic sandstones, volcanogenic conglomerates, felsic tuffs and basalt flows (Fig. 4b) that disconformably underlies the basal Cambrian Ratcliffe Brook Formation. Currie referred to this sequence as «EOCAMBRIAN» (He; Fig. 2) to emphasize its intermediate age between the Late Precambrian Coldbrook Group and the lithologically similar Ratcliffe Brook Formation. Previously mapped with the Coldbrook Group, the Saint John Group or the Carboniferous, criteria for the differentiation of this unit have been presented by Tanoli et al. (1985).

The thickness of the Coldbrook Group is uncertain since a firm stratigraphy has yet to be established due to problems of correlation. However, individual sections in the Central Belt and broad correlation of arkosic sediments in the Eastern Belt suggest it approximates 10,000 m (Giles and Ruitenberg 1977; Ruitenberg et al. 1979). The basement to the Coldbrook succession is widely held to be the Green Head Group although firm stratigraphic evidence is lacking as contacts are everywhere faulted (Giles and Ruitenberg 1977). Nevertheless, a Late Precambrian age for the Coldbrook Group is indicated by its cogenetic relationship with respect to the Golden Grove suite and its locally unconformable relationship with respect to overlying Lower Cambrian strata, and is supported by several as yet rather unsatisfactory radiometric estimates (e.g. Rast 1983). The most widely quoted of
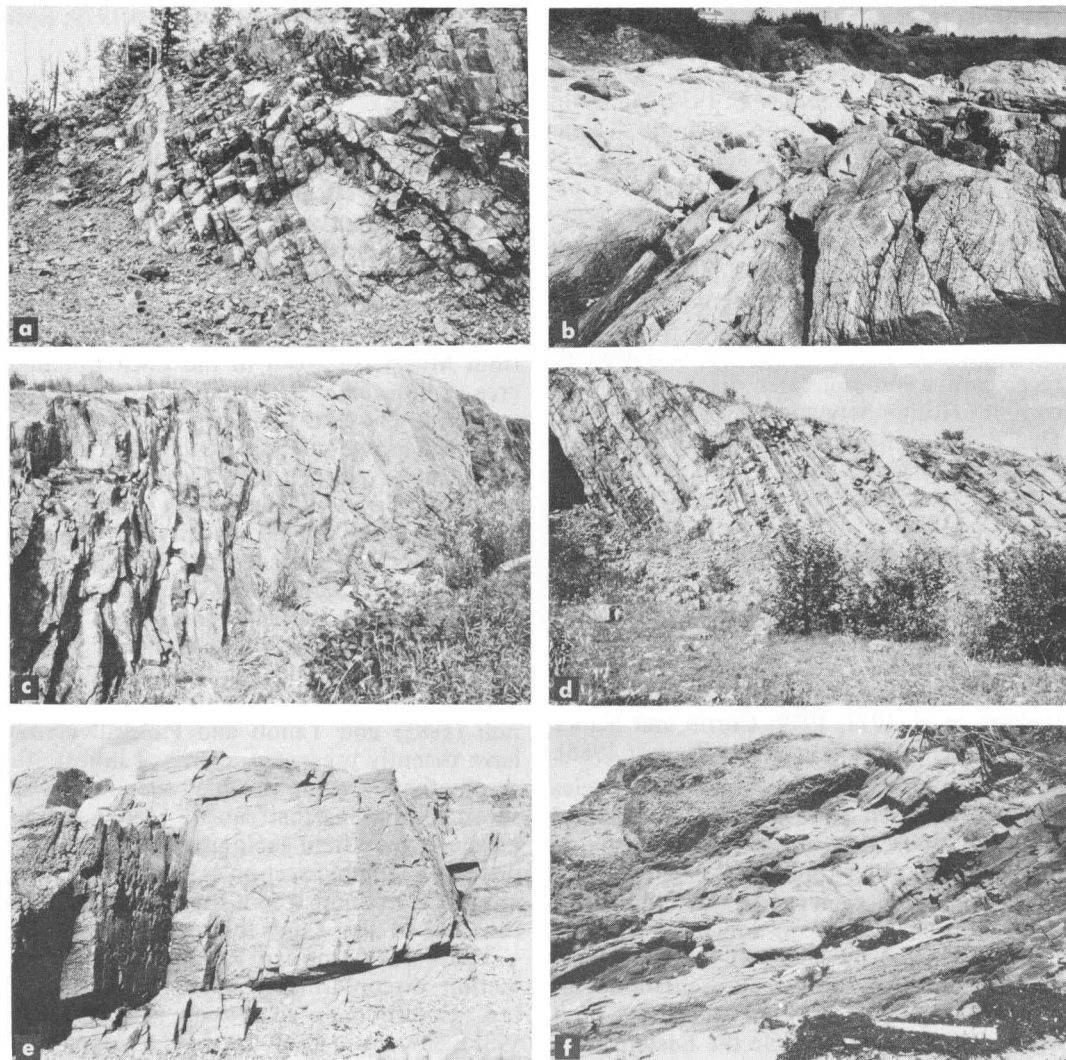
Fig. 4.—Representative field exposures of (a) the bimodal Kingston dike complex, (b) the Pocologan mylonite zone, (c) volcanogenic redbeds and basalt (to right) of the «Eocambrian» succession, (d) alternating sandstones and shales of the Saint John Group (King Square Formation), (e) conglomerates and sandstones of the Balls Lake Formation, and (f) conglomerates, sandstones and mudstones of the Lepreau Formation.

these is a recalculated Rb/Sr age of 776 Ma (Cormier 1969) which suggests a temporal relationship between the Coldbrook volcanics and the mid-Hadrynian tectonothermal event. However, Rb/Sr determinations range from 460 to 830 Ma (Rast 1983) and are hence unreliable. A pair of questionable Ar/Ar determinations (Stukas 1977, in Rast 1983) that yielded ages of 630 and 640 Ma, lie closer to the

age range of Late Precambrian Avalon volcanics in Newfoundiand with which the Coldbrook Group is commonly correlated (e.g. O'-Brien *et al.* 1983).

Deformation of the Coldbrook Group varies greatly in style, intensity and age but has yet to be examined systematically. Metamorphic assemblages, often only partially developed, are of greenschist grade or lower

(Ruitenberg *et al.* 1979). Polyphase deformation in the Western Belt (Kingston complex) includes penetrative elements of probable Acadian age (Ruitenberg *et al.* 1979) but is dominated by a 2 Km-wide, mylonitic shear zone (Fig. 4c) that extends southwestward to the Bay of Fundy at Pocologan (Rast and Currie 1976; Rast and Dickinson 1982). The polyphase deformation associated with the Pocologan mylonite zone records significant dextral displacement that was penecontemporaneous with the emplacement of the parallel Kingston dike swarm since mylonitization affects earlier but not later dikes within the complex (Ruitenberg and McCutcheon 1982). Hence, mylonitization is likely to be of Late Precambrian age. In contrast, deformation within the Central Belt is mild, and penetrative fabrics are largely absent (Ruitenberg *et al.* 1979). Along the Bay of Fundy coast, however, units of the Coldbrook Group, the Kingston dike complex and the «Eocambrian» succession have been strongly influenced by polyphase thrusting and strike-slip faulting of Late Palaeozoic age (e.g. Rast *et al.* 1978; Ruitenberg *et al.* 1973, 1979; Currie and Nance 1983; Parker 1984; Nance and Warner 1986).

On the basis of demonstrable facies changes between the Eastern and Central Volcanic Belts that suggest their temporal equivalence, Giles and Ruitenberg (1977) have proposed a palaeogeographic model for the Coldbrook Group in which the Central Belt, dominated by subaerial flows, volcanic breccias and lithic tuffs, represents a northeast-trending belt of volcanic centers built upon sialic basement, while the Eastern Belt, dominated by waterlain tuffs and volcanogenic sediments, represents deposition to the southeast along the edge of a continental margin or an intracratonic basin. Giles and Ruitenberg (1977) favour an intracratonic rift as the tectonic setting for these volcanics but note that their bimodal chemistry might also reflect the ensialic arc environment favoured by Rast *et al.* (1976). The latter setting is also supported by their calc-alkaline affinities (Rast *et al.* 1984) and their co-genetic association with the granitoid plutons of the Golden Grove suite. The somewhat younger tholeiitic to calc-alkaline, Beaver Harbour (Kingston) dike complex of the Western Belt has been interpreted to record the Late Precambrian

opening of the Iapetus ocean (Rast 1979; Rast and Dickson 1982).

CAMBRO-ORDOVICIAN ELEMENTS

Discontinuously flanking the Coldbrook Group northwest and southeast of the «central plutonic core», the Cambrian to Lower Ordovician (Arenig) SAINT JOHN GROUP (COsj; Fig. 2) comprises basal redbeds overlain by fining-upward grey beds (Fig. 4d). The succession occupies a narrow belt extending from Musquash Head to the Loch Lomond area, and occurs in scattered outcrops in Kennebecasis Bay and the Long Reach (Fig. 2). Here the group has been reported to contain abundant volcanics (McCutcheon 1981a; Greenough *et al.* 1985) although Currie (1984) assigned these to the underlying «Eocambrian» succession. Hayes and Howell (1937) subdivided the Saint John Group into eleven, essentially biostratigraphic formations but for mapping purposes only four lithostratigraphic units have usually been distinguished (e.g. Wardle 1978; Currie 1984). Pickerill and Tanoli (1985) and Tanoli and Pickerill (1988) have recently presented a revised lithostratigraphy for the group in which they recognize seven formations that can be readily distinguished by the field geologist. The most complete stratigraphic section is preserved in the city of Saint John where the group occupies the core of the Saint John syncline.

The basal Cambrian Ratcliffe Brook Formation disconformably overlies redbeds of the «Eocambrian» succession (Tanoli *et al.* 1985) or volcanics of the Late Precambrian Coldbrook Group (Hayes and Howell 1937; Patel 1975; McLeod and McCutcheon 1981) and comprises purple to grey conglomerates, sandstones, siltstones and shales that locally contain trace fossils (Patel 1976). Thickness estimates range up to 285 m (Pickerill and Tanoli 1985) while interpretations of depositional environment range from continental and deltaic (Patel 1973) to alluvial, lagoonal and shallow marine (Tanoli and Pickerill 1988). A basal, alluvial fanglomerate unit containing quartzite and minor deformed volcanic clasts (McCutcheon *et al.* 1982) is formally included in the Radcliffe Brook Formation (Hayes and Howell 1937) but may be better assigned to the underlying «Eocambrian» succession. The

Radcliffe Brook Formation is overlain by white orthoquartzites and quartz-pebble conglomerates of the Glen Falls Formation. These have an exposed thickness of 5 m to 15 m and are interpreted as the remnants of a barrier island system (Tanoli and Pickerill 1988).

The succession continues with a largely Middle Cambrian, *Paradoxides* and *Agnostus*-bearing, grey sandstone-shale, marine shelf sequence (Tanoli and Pickerill 1988) that includes both the Hanford Brook and Forest Hills Formations of Pickerill and Tanoli (1985) with a maximum combined thickness of 58 m. The Forest Hills Formation is equivalent to the Fossil Brook and Porter Road Formations of Hayes and Howell (1937). Hayes and Howell's (1937) Hastings Cove Formation, which was included in the Forest Hills Formation by Pickerill and Tanoli (1985), has since been allocated to the overlying King Square Formation on the basis of sedimentology (Tanoli and Pickerill 1988). Lithologies in the shallow marine, Forest Hills Formation represent a mud-dominated shelf sequence characterized by thinly interbedded, grey feldspathic sandstones and semi-calcareous shales with minor lenses of fossiliferous biosparite limestone. In the vicinity of the Long Reach and Beaver Harbour (Fig. 2), McCutcheon (1981a) and Greenough *et al.* (1985) have assigned mafic and bimodal volcanic rocks to the Lower to Middle Cambrian. However, given the structural complexities of these areas, the continental rift environment to which these volcanics are tentatively attributed, and the absence of similar rocks in the type sections of the Saint John Group, these volcanics are more reasonably allocated to the underlying «Eocambrian» succession as mapped by Currie (1984).

The upper Middle Cambrian to Lower Ordovician succession consists of basal, wave– and storm-dominated grey shales and sandstones overlain by a deep marine shelf sequence of monotonous black, calcareous shales bearing *Olenus, Dictyonema* and *Tetragraptus* (Tanoli and Pickerill 1988). The succession includes the King Square Falls, and Reversing Falls Formations of Pickerill and Tanoli (1985) which are respectively equivalent to the Hastings Cove and Agnostus Cove Formations; the Black Shale Brook and Narrow

Formations; and the Navy Island and Suspension Bridge Formations of Hayes and Howell (1937); the combined thickness is approximately 530 m.

Like the underlying Coldbrook Group, deformation in the Saint John Group varies greatly in style and intensity while the metamorphic grade is low. Within the Saint John syncline, the polyphase (post-Arenig) structural sequence is closely analogous to that of the adjacent Green Head Group with an axial planar, muscovite-chlorite cleavage sequentially deformed about northeast-southwest and east-west fold axes (Wardle 1978; Nance 1982). At Musquash Head (Fig. 2), deformation is again polyphase but is largely, if not entirely, of late Palaeozoic age (Nance 1986b). In the vicinity of Loch Lomond, however, units of the Saint John Group are commonly flat-lying and deformation and metamorphism are very weakly expressed.

SILURIAN AND YOUNGER ELEMENTS

The mid-Silurian LONG REACH FORMATION (Slr; Fig. 2) forms a narrow, fault-bound slice along the eastern shore of the Long Reach where it comprises locally amygdaloidal basaltic lavas with minor felsic volcanics and intercalated feldspathic arenites and fossiliferous limestones (McCutcheon 1981a; Currie 1984). Interbedded siltstones contain a penetrative fabric that is presumed to be of Acadian age. North of the Long Reach, correlatives of the formation have been interpreted to rest unconformably on the Saint John Group and, northwest of the Wheaton Brook Fault (Fig. 2), are conformably overlain by Late Silurian sandstones and siltstones of the Jones Creek Formation (McCutcheon 1981a). If this is the case, the Long Reach Formation would represent a mid-Silurian overlap sequence since the Wheaton Brook fault marks the northeastern limit of the Avalon terrane in southern New Brunswick (e.g. O'Brien *et. al.* 1983). However, Currie (1984, 1986b) concluded that the critical exposures north of the Long Reach represent units of the «Eocambrian» succession underlying the Cambrian sequence. If so, the Long Reach Formation would represent an exotic, fault-bound sliver incorporated in the northwestern tectonic boundary of the Avalon ter-

rane. The relationship of the formation to rocks on either side of this boundary is consequently unclear.

The presence of Acadian plutons in southern New Brunswick is suggested by several Late Silurian to Early Devonian K/Ar ages from granitoid bodies of the Golden Grove suite (Ruitenberg et al. 1979). However, these erratic results probably reflect metamorphic resetting of older intrusive ages as suggested by the high initial ratio of the Musquash Harbour pluton which has yielded an Rb/Sr whole rock age of 392 ± 55 Ma (Olszewski and Gaudette 1982). Currie (1984) considered all the granitic rocks of the Saint John region to be of Late Precambrian age with the exception of the Mount Champlain pluton north of the Wheaton Brook Fault which cuts the late Silurian Jones Creek Formation. Rast (1979, 1983) similarly finds little evidence for major post-Precambrian intrusion southeast of Wheaton Brook-Belleisle Fault. However, a set of broadly north-northeast trending diabase dikes (SDd; Fig. 2), that cut the Saint John Group southeast of the «central plutonic core» but have yet to be reported in the Carboniferous section, are presumably of Silurian or Devonian age (Currie 1984).

The Carboniferous stratigraphy of the Saint John region has long been problematic although two lithologic successions are commonly distinguished (Rast et al. 1978; Wardle 1978; Ruitenberg et al. 1979; Currie and Nance 1983; Nance 1986b, 1987b). North of the «central plutonic core», largely undeformed redbeds of the KENNEBECASIS FORMATION (Ck; Fig. 2) rest with a pronounced unconformity on older rocks. Southeast of the core, in contrast, Carboniferous sandstones and conglomerates of the BOSS POINT, LANCASTER, BALLS LAKE and TYNEMOUTH CREEK FORMATIONS (Cbp, Cl, Cbl and Ctc; Fig. 2) are strongly influenced by polyphase deformation of late Palaeozoic (Alleghanian) age (Rast and Grant 1973; Ruitenberg et al. 1973).

The Kennebecasis Formation comprises red conglomerates, arkoses and siltstones that are locally derived (Currie et al. 1981) and are likely to represent alluvial to fluvial sedimentation within fault-bound, strike-slip basins (Nance 1985). The formation, which has yielded fossils of Latest Devonian to Early Mississippian age (Hayes and Howell 1937), is generally assigned to the Lower Mississippian (Wardle 1978). However, clasts of late Mississippian limestone reported from Kennebecasis conglomerates by Currie (1984), suggest that it spans a considerable portion of Carboniferous time.

South of the «central plutonic core», the Carboniferous stratigraphy of the Saint John region was formerly subdivided into three formations, namely the West Beach, Balls Lake and Lancaster Formations, although complete disagreement has historically existed with respect to their succession (Hayes and Howell 1937; Alcock 1938; Wardle 1978; Ruitenberg et al. 1979). Currie and Nance (1983), Parker (1984) and Caudill and Nance (1986), however, substantiated the stratigraphy of Wardle (1978) and showed that the bimodal, ?calc-alkaline volcanics (Strong et al. 1979), volcaniclastics and volcanogenic sediments of the West Beach Formation are unconformably overlain by pink conglomerates and sandstones of the Balls Lake Formation (fig. 4e) that grade both laterally and vertically into grey, lithic arenites of the Lower Pennsylvanian Lancaster Formation. However, Currie and Nance (1983) further established a lithologic correlation between the West Beach Formation and the «Eocambrian» succession and hence proposed its removal from the Carboniferous stratigraphy. West of Musquash Head (Fig. 2), McCutcheon (1981b, 1984) has demonstrated the presence of a basal, discontinuous cryptalgal limestone in the Carboniferous section which he assigned to the Visean to Namurian PARLEEVILLE FORMATION. Where present, the unit rests unconformably on «Eocambrian» or Coldbrook Group volcanics and is overlain by redbeds of the Balls Lake Formation (Currie 1986b). Northeast of McCoy Head (Fig. 2), the sandstones and conglomerates of the Boss Point and overlying Tynemouth Creek Formations (Plint and van de Poll 1982, 1984) show striking lithologic similarities to the Lancaster and Balls Lake Formations and are likely to be their respective equivalents (Nance 1987b).

Sedimentation within the Balls Lake and Lancaster Formations records the transition from alluvial fan through braided stream to meandering stream environments that developed in response to the uplift of a wrench-re-

lated thrust complex to the southeast during a Westphalian stage of Alleghanian deformation (Caudill and Nance 1986, Nance 1986b). Wrench-related sedimentation has also been proposed for the time-equivalent but largely undeformed fluvial and alluvial sediments of the Boss Point and Tynemouth Creek Formations (Plint and van de Poll 1982, 1984) and is recorded in the development of syntectonic sedimentary structures (Plint 1985). Continued deformation along the Bay of Fundy shore involved thrusting, backthrusting and strike-slip displacements and was associated with Late Palaeozoic transpression on the Cobequid-Chedabucto fault (Mosher and Rast 1984; Nance 1986b, 1987b; Nance and Warner 1986). As a result, highly deformed, southerly portions of the Carboniferous stratigraphy overrode their mildly deformed and essentially autochthonous equivalents to the north (Nance 1985) along a thrust that has been considered to define the «Variscan front» in southern New Brunswick (Rast and Grant 1973).

Southwest of Saint John, entirely allochthonous units of the Balls Lake and Lancaster Formations are involved in major overturned structures of regional extent (Rast *et al.* 1978) and are associated with both dextral wrench faults synthetic to the Cobequid system (Nance 1986b) and granites that have yielded Carboniferous K/Ar ages (Ruitenberg *et al.* 1979; Rast 1983). However, these ages are likely to reflect metamorphic resetting since the granites are lithologically identical to those of the Golden Grove suite and have recently yielded zircon ages of 550 Ma (K. L. Currie, pers. comm. 1986) and 625 Ma (Watters 1987). Illites from a gold-bearing alteration zone associated with Late Palaeozoic thrusting at Cape Spencer (Fig. 2) have yielded Ar/Ar ages of 274 ± 1 Ma and 283 ± 1 Ma (Watters 1987).

Carboniferous and older units are locally overlain unconformably by redbeds of Triassic age. Undeformed and poorly indurated conglomerates and sandstones containing northwesterly derived boulders (Currie *et al.* 1981) occur on the east side of Saint John Harbour. These have been tentatively correlated (Alcock 1938) with conglomerates of the Triassic QUACO FORMATION (Tq; Fig. 2) which, further to the northeast, separates allu-

vial redbeds of the HONEYCOMB POINT FORMATION from red to green fluvial sandstones of the ECHO COVE FORMATION (Tu; Fig. 2). Southwest of Saint John, reddish-brown conglomerates, sandstones and mudstones (Fig. 4f) of the mildly deformed but presumed Triassic LEPREAU FORMATION (Tl; Fig. 2) attain a minimum thickness of 3,000 m (Stringer and Lajtai 1979). These Triassic fluvial and alluvial sequences record graben sedimentation during initial rifting of the present Atlantic Ocean (Nadon and Middleton 1984) which locally involved extensional reactivation of Late Palaeozoic thrusts (Plint and van de Poll 1984; Nance 1987b).

Extensive deposits of unconsolidated gravels, boulder till and stratified sands of Pleistocene to Recent age (Qg; Fig. 2) blanket large areas of bedrock and locally attain a sufficient thickness that mapping of bedrock geology becomes impractical (Ruitenberg *et al.* 1979; Currie *et al.* 1981).

DISCUSSION AND INTERPRETATION

As one of the five tectonostratigraphic zones recognized in the Northern Appalachians (Fig. 1) by Williams (1978, 1979), the Avalon terrane has been traditionally distinguished on the basis of its pre-Silurian evolution and has been interpreted in terms of the creation and destruction of a Late Precambrian-Early Palaeozoic Iapetus ocean. Thus the Humber zone records the development and destruction of the western miogeocline of Iapetus floored by Grenvillian basement, while the Dunnage zone preserves vestiges of Iapetus and its island arc, remnant arc and backarc sequences. The Gander zone has been interpreted to contain elements of the active eastern margin of Iapetus (Kennedy 1976; Williams 1978, 1979; Colman-Sadd 1980) but is defined largely on its structural and metamorphic style; closely resembles the Dunnage zone in age and lithology; and lacks proven Grenvillian basement, rift related magmatism and a passive margin history (Williams and Hatcher 1983). However, relationships of the more easterly Gander, Avalon and Meguma zones to the Iapetus cycle are uncertain since the zones are structurally uncoupled and show no demonstrable connection to the an-

cient North American miogeocline. More recent treatments of the Appalachian orogen have consequently viewed these and other zones in the southern Appalachians and Europe as a mosaic of suspect terranes (Keppie 1981; Williams and Hatcher 1982, 1983; Zen 1983; Keppie 1985; Keppie *et al.* 1985) that lie west of the eastern miogeocline of Iapetus preserved in the Scandinavian Caledonides, the Mauritanides of west Africa and possibly Morocco (Williams 1984).

Within the Avalon terrane, the existence of two distinct tectonothermal events at 750-800 Ma and 550-630 Ma (O'Brien *et al.* 1983; Rast and Skehan 1983; Nance 1986a) further demonstrates its distinctive tectonostratigraphic evolution relative to that of the Iapetus cycle and implies a composite Precambrian history that has been likened to the Pan-African belts of northwest Africa (Piqué 1981; O'Brien *et al.* 1983). Assembly of this Avalon composite terrane may therefore correspond to the circa 600 Ma Avalonian orogeny and must have occurred prior to the widespread development of Cambro-Ordovician overlap sequences that bear distinctive Atlantic-realm fauna (Williams and Hatcher 1982, 1983; Keppie *et al.* 1985). Cambro-Ordovician faunal contrasts (Cocks and Fortey 1982; Neuman 1984) and recently determined paleomagnetic discrepancies (Johnson and Van der Voo 1985; Van der Voo and Johnson 1985) suggest considerable separation of the Avalon terrane from cratonic North America and place the terrane at high paleolatitudes in the Lower Palaeozoic. However, paleomagnetic evidence for the position of the Avalon terrane with repect to North America is poorly constrained for the Late Precambrian (e.g. Morel and Irving 1978; Piper 1982; Scotese 1984) and remains inconclusive for much of the Palaeozoic (Kent and Opdyke 1978, 1979; Spariosu and Kent 1983; Scotese *et al.* 1984). As a result, the nature and location of Avalon's Late Precambrian development, and the mechanism and timing of its final accretion to the remainder of the Appalachian orogen, remain far from certain.

Proposed settings for the Late Precambrian evolution of the Avalon terrane have historically ranged from a pre-Iapetus, ensialic island arc (Rast *et al.* 1976) to an aborted rifting event, possibly related to the opening of the Iapetus ocean (Strong *et al.* 1978). More recent models have favoured the former interpretation. Keppie (1982), Dostal *et al.* (1984) and Keppie *et al.* (1985), for example, have interpreted the Late Precambrian development of the Avalon terrane in Nova Scotia in terms of a cratonic island arc (Cape Breton terrane), an interarc basin (Antigonish terrane) and a remnant arc (Cobequid terrane). The product of the subduction of a major ocean lying to the southeast, these were assembled during the Avalonian orogeny to produce the Avalon composite terrane. Rast and Skehan (1983) similarly suggested that the Avalon terrane originated as a microcontinental arc and was separated from North America by a back-arc basin and from West Africa by the Late Precambrian Cadomian ocean. They further suggest that the arc developed as a volcanic carapace on both continental and oceanic basement derived from the fragmentation of an African supercontinent at 800-850 Ma. Closure of the Cadomian ocean and back-arc basin at 600-650 Ma respectively produced the Cadomian (II) and Avalonian orogenies and accreted Avalon to the North American and West African cratons. O'Brien *et al.* (1983), in contrast, have proposed a Pan-African origin for the Avalon terrane in which rifting of pre-Pan-African basement during the interval 800-1000 Ma initially produced ensialic basins that subsequently underwent partial melting and high grade metamorphism during the period 750-800 Ma due to ductile spreading of the lower crust and local crustal separation. Closure of these basins through limited subduction and collision during the interval 570-630 Ma resulted in the production of Late Precambrian volcanic assemblages and the Avalonian orogeny, and terminated with the intrusion of granitoid bodies and the deposition of marine-to-terrestrial clastic sediments.

As a test of these models, the tectonostratigraphic record of southern New Brunswick is particularly instructive since it provides one of the most complete histories of Avalon's Precambrian evolution. Although the contacts between units are commonly faulted and the original relationships in many areas are far from certain, the names, lithologies and proposed tectonic settings for major units of the southern New Brunswick Avalon terrane are summarized in Fig. 5 in the form of an interpretive tectonostratigraphic succession.

With respect to establishing tectonic models, the resolution of three aspects of this tectonostratigraphy is essential, namely the age and cratonic provenance of the continental basement to the Avalonian succession; the nature and tectonic setting of the mid-Hadrynian tectonothermal event; and the nature and tectonic setting of the Late Hadrynian Avalonian orogeny and the transition from a Late Precambrian magmatic arc setting to an Early Palaeozoic stable shelf.

The basement age of the Avalonian succession is controversial (e.g. Zen 1983) although both West African (O'Brien *et al.* 1983; Rast and Skehan 1983) and North American (Currie 1986a) provenances have been proposed. The former is supported by the close similarities in the Precambrian evolution of the Avalon terrane and that of the Pan-African belts of Morocco (Piqué 1981) and the Mauritanides (Dallmeyer and Villeneuve 1987). However, model age constraints based on the low initial strontium ratio of the Brookville gneiss, suggest a maximum protolith age of 1,200 Ma (Olszewski and Gaudette 1982). Although of questionable validity, such an age for the Brookville gneiss would not be inconsistent with the development of the Green Head platform on Grenvillian (circa 1,100 Ma) basement, as was proposed by Currie (1986a). In support of this, Currie (1986a) has further pointed out the lithological similarities and comparable successions between the Green Head Group in New Brunswick and the Grenville Group of southern Ontario and Quebec. Recently determined Grenville ages from northern Cape Breton Island (Barr and Raeside 1986; Barr *et al.* 1987) also place the Grenvillian and Avalonian belts in relatively close proximity and might support Currie's (1986a) proposal that the tectonostratigraphic evolution of the Avalon terrane in southern New Brunswick involved the repeated break-up and rewelding of a North American continental edge. However, if the Grenvillian orogeny was the product of continental collision (e.g. Moore *et al.* 1986) that in any way involved the North American and West African cratons, as was originally suggested in the southern Appalachians by Hatcher and Odom (1980), the distinction between these two provenances loses much of its significance since the subsequent development of platformal
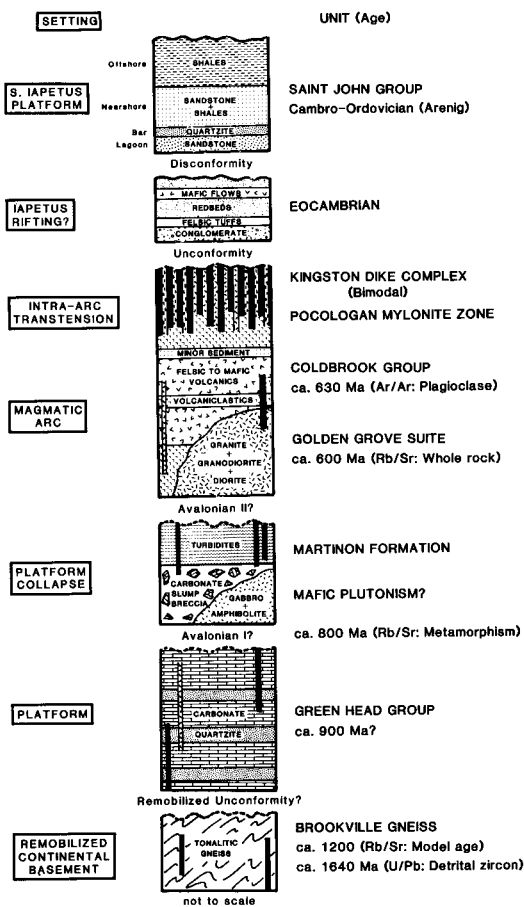

Fig. 5.–Interpretive, Precambrian to early Palaeozoic tectonostratigraphic column for the Avalon terrane in southern New Brunswick (from Nance 1987a).

conditions recorded at the base of the Avalonian succession could have readily occurred on both cratonic blocks. In view of these uncertainties and the limited data base presently available, any comment concerning the nature of the Avalonian basement should be treated with caution until better geochronological constraints are established for the Brookville gneiss.

The mid-Hadrynian (circa 800 Ma) tectonothermal event in southern New Brunswick remains poorly understood and loosely constrained, but has been tentatively associated with the apparent break-up and collapse of the Green Head platform recorded in the Marti-

non Formation; the high-grade, ductile mobilization of original basement-cover relations; and the emplacement of locally cumulate, mafic to ultramafic plutons (Nance, 1987a). The proposed scenario is compatible with the model of mid-Hadrynian rifting presented by O'Brien *et al.*(1983), based on relationships in the Burin Peninsula of Newfoundland (Fig. 1). Here carbonate slump breccias similar to those of the Martinon Formation conformably underlie oceanic basalts of the Burin Group (Strong *et al.* 1978) with a crystallization age of circa 760 Ma (Krogh *et al.* 1983). However, although the depositional age of the Green Head Group is uncertain, tectonostratigraphic relationships in southern New Brunswick imply that the Green Head platform was already well established by the mid-Hadrynian. In contrast to O'Brien *et al.*'s (1983) model, therefore, the development of platformal conditions must have preceded, and was presumably unrelated to, the mid-Hadrynian rifting event. If so, a case could be made for the break-up a pre-existing platform and the diapiric mobilization of its basement during a period of rifting and high heat flow. Such conditions have been proposed to reflect an extensional back-arc setting (Fig. 6) which developed during mid-Hadrynian (Avalonian I) subduction of the (?Cadomian) ocean that, before, had passively bordered the Green Head platform (Nance, 1987a). The Burin Group, which rests on clastics derived from a subaerial acid volcanic terrain (Strong *et al.* 1978), might then be reinterpreted as the the product of a back-arc marginal basin rather than small, intracratonic ocean basin envisioned by O'Brien *et al.* (1983).

Evidence of Late Hadrynian (circa 600 Ma) subduction within the Avalon terrane is more compelling and forms a common theme in tectonic models for this period of Avalon's evolution (e.g. O'Brien *et al.* 1983; Rast and Skehan 1983; Keppie *et al.* 1985). In southern New Brunswick, the evidence includes widespread calc-alkaline plutonism (W. L. Dickson, pers. comm. 1986) recorded in granodiorites of the Golden Grove suite, and the co-genetic, if largely bimodal, volcanism represented by the Coldbrook Group. Although Giles and Ruitenberg (1977) favoured an intracratonic rift setting for the Coldbrook Group, an ensialic arc environment (Rast *et al.* 1976) is

more compatible with the Golden Grove suite and, following the reasoning of O'Brien *et al.* (1983), has been interpreted as reflecting limited (Avalonian II) subduction (Fig. 6) due to closure of the marginal basin proposed for the mid-Hadrynian (Nance, 1987a).

Parallel and adjacent to the Belleisle fault (Fig. 2), which forms the northwestern boundary of the Avalon terrane in southern New
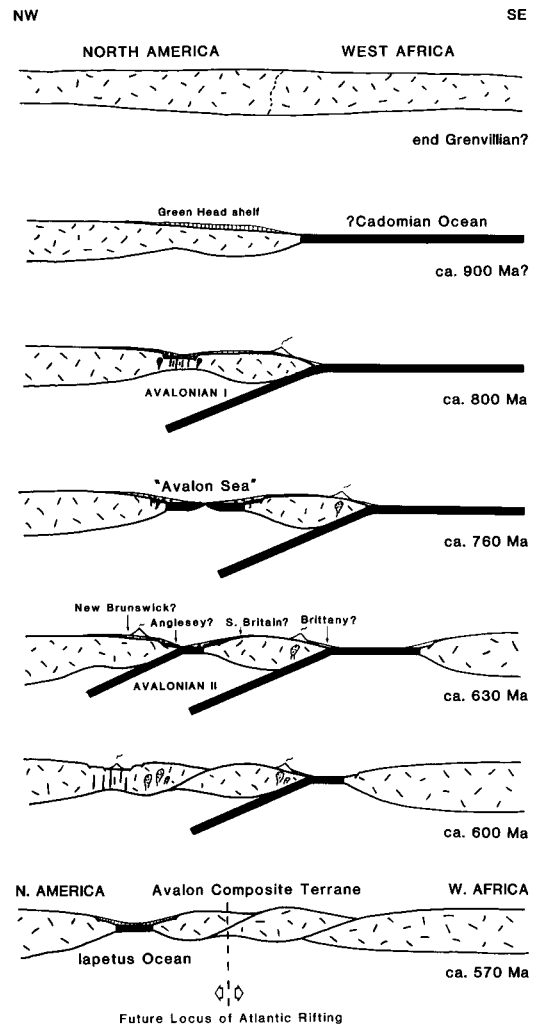

Fig. 6.—Schematic plate tectonic model for the Precambrian to Early Palaeozoic evolution of the Avalon terrane in southern New Brunswick and its possible relationship to the Avalonian (Cadomian) development of southern Britain and Brittany (From Nance 1987a).

Brunswick, units of the Coldbrook Group and the Golden Grove suite are locally affected by temporally and spatially associated zones of intense mylonitization and dike injection that may be unconformably overlain by the «Eo-cambrian» succession (K. L. Currie, pers. comm. 1986) and are absent in the Cambro-Ordovician Saint John Group. Deformation within the Pocologan mylonite zone records significant dextral shear while the Kingston (Beaver Harbour) complex records penecon-temporaneous crustal extension and the em-placement of bimodal dikes, the mafic mem-bers of which display continental tholeiitic af-finity (W. L. Dickson, pers. comm. 1986). Clo-sure of the marginal basin proposed for the Late Precambrian may therefore have been accomplished by oblique subduction which, during the collisional stage responsible for the Avalonian II orogeny, led to local transten-sion (Fig. 7a, b) within or adjacent to the mag-matic arc (Nance, 1987a).

The post-tectonic redbeds and bimodal vol-canics of the overlying «Eocambrian» succes-sion, which probably include the «Cambrian» continental rift basalts described by Gree-nough *et al.* (1985) and may be broadly con-temporary with the youngest (circa 550 Ma) granites of the Golden Grove suite, could then be interpreted as the product of rifting (Fig. 7c) that heralded the onset of platformal conditions (fig. 7d) recorded in the Cambro-Ordovician Saint John Group (Nance, 1987a). Furthermore, since the Acado-Baltic fauna of the Saint John Group is widely considered to reflect its Lower Palaeozoic position on the southeast margin of the Iapetus ocean (e.g. Cocks and Fortey 1982; Neuman 1984), the «Eocambrian» succession may also record the initial rifting of this ocean in the back-arc re-gion of the Late Precambrian Avalon terrane. A pattern therefore emerges whereby local transtension associated with the Avalonian II orogeny was followed by more widespread (and possibly oblique) extension that led to the back-arc opening of the Iapetus ocean and the development, following a break-up disconform-ity, of a Cambro-Ordovician overlap sequence.

Assembly of the Avalon terrane with North America following closure of the Iapetus ocean is of uncertain timing. Late Ordovician (470 Ma) pegmatitic sweats in the Brookville gneiss (Olszewski *et al.* 1980) have been taken

ca. 630 Ma

A. COLDBROOK GROUP
GOLDEN GROVE SUITE

B. KINGSTON DIKE COMPLEX
POCOLOGAN MYLONITE ZONE

C. EOCAMBRIAN SUCCESSION
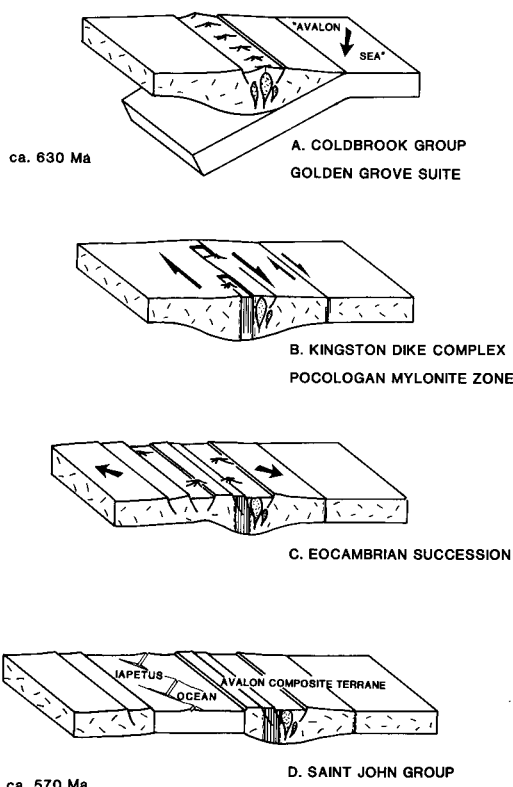
D. SAINT JOHN GROUP

ca. 570 Ma

Fig. 7.—Preliminary plate-tectonic detail of the late Pre-cambrian to early Palaeozoic arc-platform transi-tion in the Avalon terrane of southern New Brunswick (from Nance 1987a).

to indicate locally elevated temperatures of broadly «Taconian» age (Currie *et al.* 1981; Nance 1982). However, such an event does not appear in the subsequent isotopic results of Olzsewski and Gaudette (1982) which, ins-tead, suggest a significant period of Devonian metamorphism and isotopic resetting. Never-theless, the presence of a belt of Late Ordo-vician to Early Silurian (430±15 Ma) bimodal volcanic and plutonic rocks, that straddles the northwestern boundary of the Avalon terrane from north-central Newfoundland to southern New Brunswick, has been interpreted to re-flect the amalgamation of the Avalon terrane and North America (Currie 1986a, Currie *et al.* 1986) and would require the accretion of the Avalon to more westerly terranes by early Si-lurian time. Widespread Late Devonian and

Carboniferous redbeds form an overlap sequence with adjacent terranes but are locally involved in significant, Late Palaeozoic deformation. The present position of the Avalon terrane is consequently a function of Late Palaeozoic dextral displacements on faults that now define the Avalon terrane boundaries. Undeformed Triassic redbeds, which unconformably overlie the Carboniferous succession, record the opening of the Fundy Basin during initial rifting of the Atlantic ocean.

SUMMARY AND CONCLUSIONS

Between the dextral Belleisle and Cobequid-Chedabucto faults of southern New Brunswick, Canada, a unique record of the Avalon terrane is exposed that spans the interval mid-Proterozoic to Triassic. Ductily mobilized tonalitic basement of probable Helikian age is represented by the Brookville gneiss and is overlain by platform carbonates and quartzites of the Green Head Group. The Martinon Formation, which follows the platform succession with probable unconformity, comprises turbidites and slump breccias of Green Head carbonate and may be broadly contemporary with minor mafic-ultramafic plutonism and amphibolite facies metamorphism of mid-Hadrynian (circa 800 Ma) age. Late Hadrynian (circa 600 Ma) granitoid plutonism and co-genetic volcanism, respectively recorded in the calc-alkaline Golden Grove suite and the largely bimodal Coldbrook Group, immediately predate the development of the bimodal Kingston dike complex and the penecontemporaneous Pocologan mylonite zone which represent a local manifestation of the Avalonian orogeny adjacent to the terrane's northwestern boundary. Latest Hadrynian («Eocambrian») volcanogenic redbeds and mafic volcanics of continental rift affinity pass with minor unconformity into Cambro-Ordovician sandstones and shales of the Saint John Group which bear shallow-marine, Acado-Baltic fauna and represent an overlap sequence to Avalon's Precambrian development. Silurian basalts incorporated within the Belleisle fault zone are likely to be allochthonous while Devonian units are restricted to minor Fammenian molasse at the base of the Carboniferous succession. Carboniferous redbeds developed in response to Late Palaeo-

zoic dextral transpression on terrane boundary faults while underformed Triassic redbeds record the opening of the Fundy Basin during the initial rifting of the present Atlantic.

The tectonostratigraphy of the Avalon terrane in southern New Brunswick is interpreted to record the latest Helikian (?) development of an ensialic carbonate-clastic platform whose mid-Hadrynian (circa 800 Ma) break-up and local metamorphism occurred in response to back-arc extension and crustal separation associated with initial (Avalonian I) subduction of the ?Cadomian ocean that had formerly bordered passively the carbonate-clastic platform. The development of a late Hadrynian (circa 600 Ma) ensialic arc and its subsequent subjection to bimodal dike emplacement and mylonitization during the Avalonian II orogeny is attributed to oblique subduction and transtensional closure of this marginal basin. A subduction polarity towards the present northwest best accommodates the record and may indicate the development of this portion of the Avalon terrane on North American basement. The post-tectonic «Eocambrian» succession is then interpreted to reflect the initial rifting of the Iapetus ocean and, following a break-up unconformity, the re-establishment of a platform during the Cambro-Ordovician. Docking of the Avalon terrane to North America following closure of Iapetus could be as early as the Taconian. However, its present position with respect to adjacent terranes reflects significant, Late Palaeozoic dextral movements on faults that now define the Avalon terrane boundaries.

At present, however, tectonostratigraphic interpretation of the Avalon terrane in southern New Brunswick remains speculative since it is critically dependent on questionable radiometric data. Thus the mid-Hadrynian tectonothermal event is based on several ~800 Ma age determinations, none of which are individually satisfactory. Although similar ages have also been found in other areas of the Northern Appalachian Avalon terrane (see Nance 1986a for a review), recent results from the Avalon terrane of the Cobequid Highlands (Fig. 1) may question their validity (Nance and Murphy 1988). Here, ductile shear on basement-cover contacts, which appears to have occurred in an extensional setting under conditions of high heat flow, is interpreted to

have heralded the development of a possible back-arc basin. Relations are therefore similar to those of the mid-Hadrynian event but, in the Cobequid Highlands, are attributed to sinistral transtension at circa 630 Ma, based on available age data (Gaudette *et al.* 1984). If this isotopic data (rather than that of the Brookville gneiss) is substantiated, and a cor- relation can be established between the otherwise similar tectonostratigraphic succession of southern New Brunswick and the Cobequid Highlands, what has here been interpreted as occurring in sequence (Fig. 6) would become broadly contemporaneous and the region may, instead, trace the evolution of a Late Precambrian back-arc basin.

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