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Article abstract

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In Part 1 the effects of the faults are systematically outlined over five time intervals beginning in the late Precambrian (Hadrynian), continuing through parts of the Ordovician, Silurian, Devonian and Carboniferous and ending in the Triassic. The relationships of various generations of faults to depositional environments in contemporaneous basins and the regional structural setting are documented.

In Part 2 evidence concerning the nature of the major faults and fault zones is presented. Properties peculiar to the southern New Brunswick structures are their repeated association with volcanic rocks, their distinction as narrow zones of stratigraphic and structural discontinuity and their persistant control on the manifestation of stresses associated with repetitive orogeny. Interpretions of the faults are proposed which identify them as long~lived, mechanically weak, dislocation zones in the lithosphere (i.e."deep-faults").

THE PERSISTANCE AND LONGEVITY OF FAULTS IN THE CRUSTAL EVOLUTION OF SOUTHERN NEW BRUNSWICK

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Examination of the structural and stratigraphic sequences in southern New Brunswick indicates that the area evolved under the influence of a series of major faults. Relatively localized faulting persisted for at least 450 to 500 Ma.

In Part 1 the effects of the faults are systematically outlined over five time intervals beginning in the late Precambrian (Hadrynian), continuing through parts of the Ordovician, Silurian, Devonian and Carboniferous and ending in the Triassic. The relationships of various generations of faults to depositional environments in contemporaneous basins and the regional structural setting are documented.

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INTRODUCTION

Southern New Brunswick provides an excellent geological section across the eastern margin of the northern Appalachians. There, unique to other regional cross-sections, the stratigraphic and structural successions clearly indicate the presence and partial superposition of three Paleozoic foldbelts (*i.e.* the Taconic, Acadian and Variscan). The Precambrian basement to these foldbelts is itself a fragmented portion of a much larger late Proterozoic orogenic belt which has not yet been formally named despite being well distributed around the North Atlantic (Rast *et al* 1976, Strong, in press).

In the northern Appalachians the northwestern limit of this late Proterozoic (Hadrynian) orogenic belt as well as its inferred basement is concealed within the Acadian Orogen (Williams, in press). In the Caldonides the syn- and post-orogenic rocks of the Hadrynian belt swing into central Europe after leaving southern Britain (*e.g.* the American Massif) and cease to become a fundamental element of the Appalachian-Caledonian system. For example, in Norway, the eastward directed thrusts of the Caledonian front bring Lower Palaeozoic rocks directly over the 1 b.y. and older rocks of the Baltic Shield. In New Brunswick a fault-bordered segment of the late Proterozoic orogenic belt forms a basement to the Acadian Orogen on its southeastern margin just as the Grenvillian orogenic belt does along its northwestern one. In the south of the province it can be demonstrated that block faults, imposed on the region during the Hadrynian as a late stage orogenic feature, remain intermittently active throughout the deposition of the overlying succession of Palaeozoic and Mesozoic rocks.

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In western, central and northern New Brunswick such fault patterns cannot be recognized. There major tectonostratigraphic and tectonometamorphic zones are mapped and described as a series of regional, northeasterly trending fold structures. Six major anticlinoria and synclinoria have been proposed (Poole and Rodgers 1972, and Fig. 1) and attributed to the Acadian Orogeny. Like their continuation in Maine and New England (*cf* Rodgers 1970), some of the regional fold structures are internally complex and refold minor and major folds of earlier orogenic cycles. In general, however, the rank of Acadian regional metamorphism is low, permitting the observation of the older structural and metamorphic patterns.

During the Acadian deformation the rocks in the aforementioned area were folded in paratectonic style and shortened but the original depositional basins were not destroyed. In some regions the present position of the cores of anticlinoria coincides with proposed zones of topographic relief during the deposition of the strata unconformably overlying the rocks in the cores (*e.g.* Miramichi Anticlinorium, Fig. 1). Likewise, contacts on the limbs of certain synclinoria may not differ significantly from the positions of margins of basins. As a result, the concept of strike belts (*cf* Rodgers 1970) can be applied to the distribution and description of rock units throughout most of the province. However, an analysis of the succession of rocks in southern New Brunswick indicates a different descriptive terminology must be employed due to the role of faulting in the development of the stratigraphic sequence and the positioning of basins and highlands.

The pre-Carboniferous rocks in southern New Brunswick to the southeast of the Belleisle fault system (Fig. 1) are included in a heavily faulted structure known as the Kennebecasis Bay anticlinorium (Rodgers 1970, p. 137). The anticlinorium comprises the southernmost structural unit in the province (Fig. 1). It is, however, usually divided into several regional fault blocks mainly of Carboniferous or Permian age - the Kingston and Caledonian uplifts and their south-

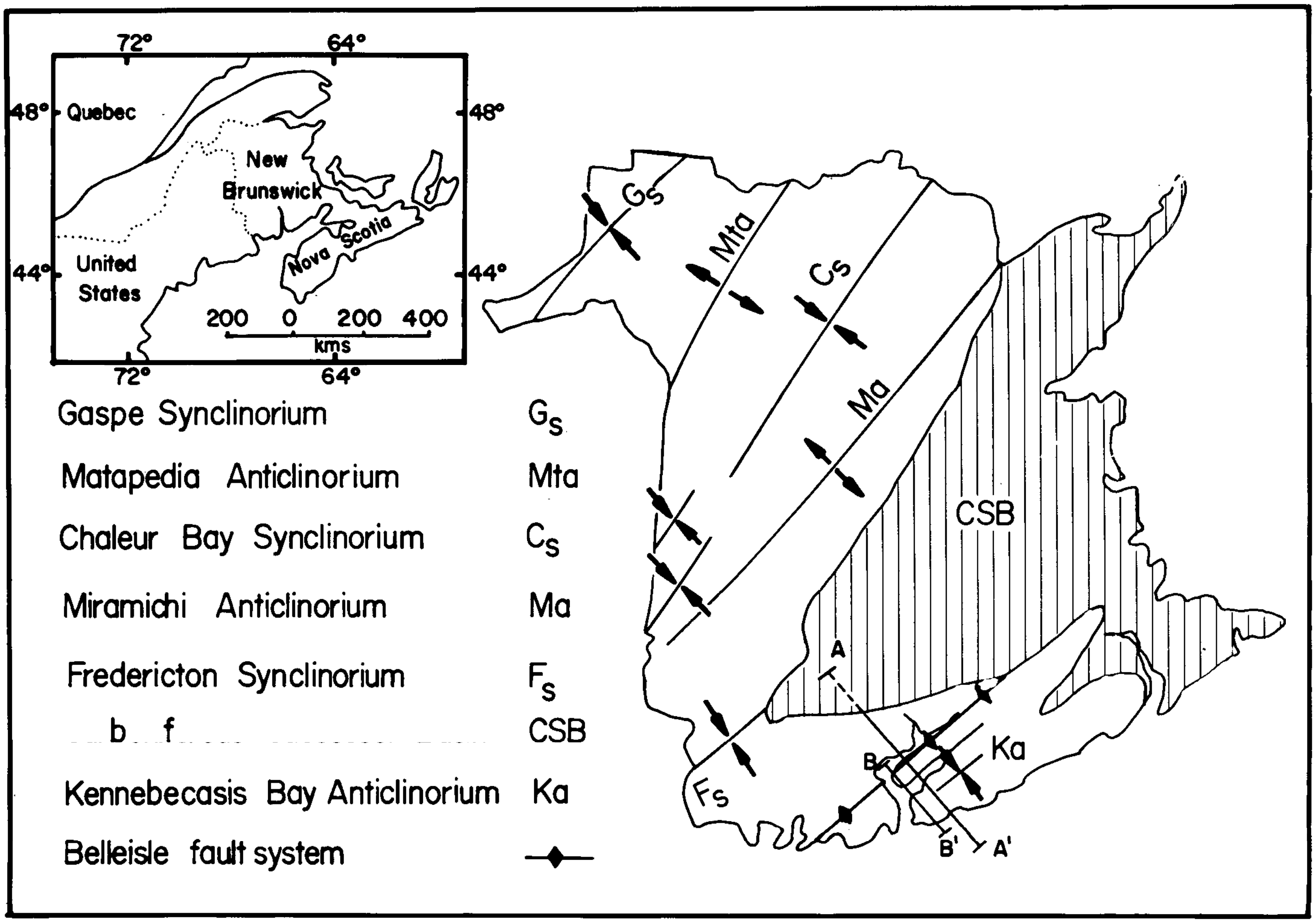

FIG. 1 Map depicting the regional structure of New Brunswick (modified from Poole and Rodgers, 1972). Cross-sections AA' and BB' are illustrated in Figures 2 and 3 respectively.

westerly extensions being the most notable. The southeastern limb of the anticlinorium is either obscured by the Bay of Fundy or overthrust by much later structures belonging to the Variscan thrust belt. To the northwest it is faulted against the southeastern limb of the Fredericton synclinorium and a series of smaller scale structures which occupy positions between the aforementioned anticlinorium and the synclinorium (*e.g.* Paleozoic Deformed Belt of Ruitenberg *et al* 1973b). These smaller structures have not generally been named but include the Saint David's Dome (Ruitenberg 1967) of Charlotte County and the North Mountain Uplift (Grant 1971) of Saint John County. Figure 2 illustrates a representative structural cross-section across the major tectonic features in the area considered.

PART 1

RELATIONSHIPS OF PRECAMBRIAN, PALEOZOIC AND MESOZOIC STRATA IN SOUTHERN NEW BRUNSWICK

Rocks in southern New Brunswick range in age from the Precambrian to the Triassic and have been affected by several episodes or orogeny. In this paper data presented in the following sections have been summarized and only the major points of relevance are discussed, although most of the regionally significant references have been cited.

In southern New Brunswick the late Precambrian volcanic and sedimentary rocks of the Coldbrook Group are the most extensive (approximately 8,000 km^2) and important in any interpretation by virtue of the fact that they form much of the effective basement to the Paleozoic rocks. In the following pages, therefore, most regional relationships are discussed relative to the Coldbrook Group.

PRECAMBRIAN ROCKS

Relationships between the Greenhead and Coldbrook Groups

The Precambrian succession in southern New Brunswick is comprised of two major stratigraphic units known as the Greenhead and Coldbrook groups. The outcrop area of the Greenhead Group is extremely small relative to the Coldbrook Group (Potter *et al* 1968) and the former is in contact with the latter for only 20 km. The Greenhead Group occupies the faulted core of the Kennebecasis Bay anticlinorium

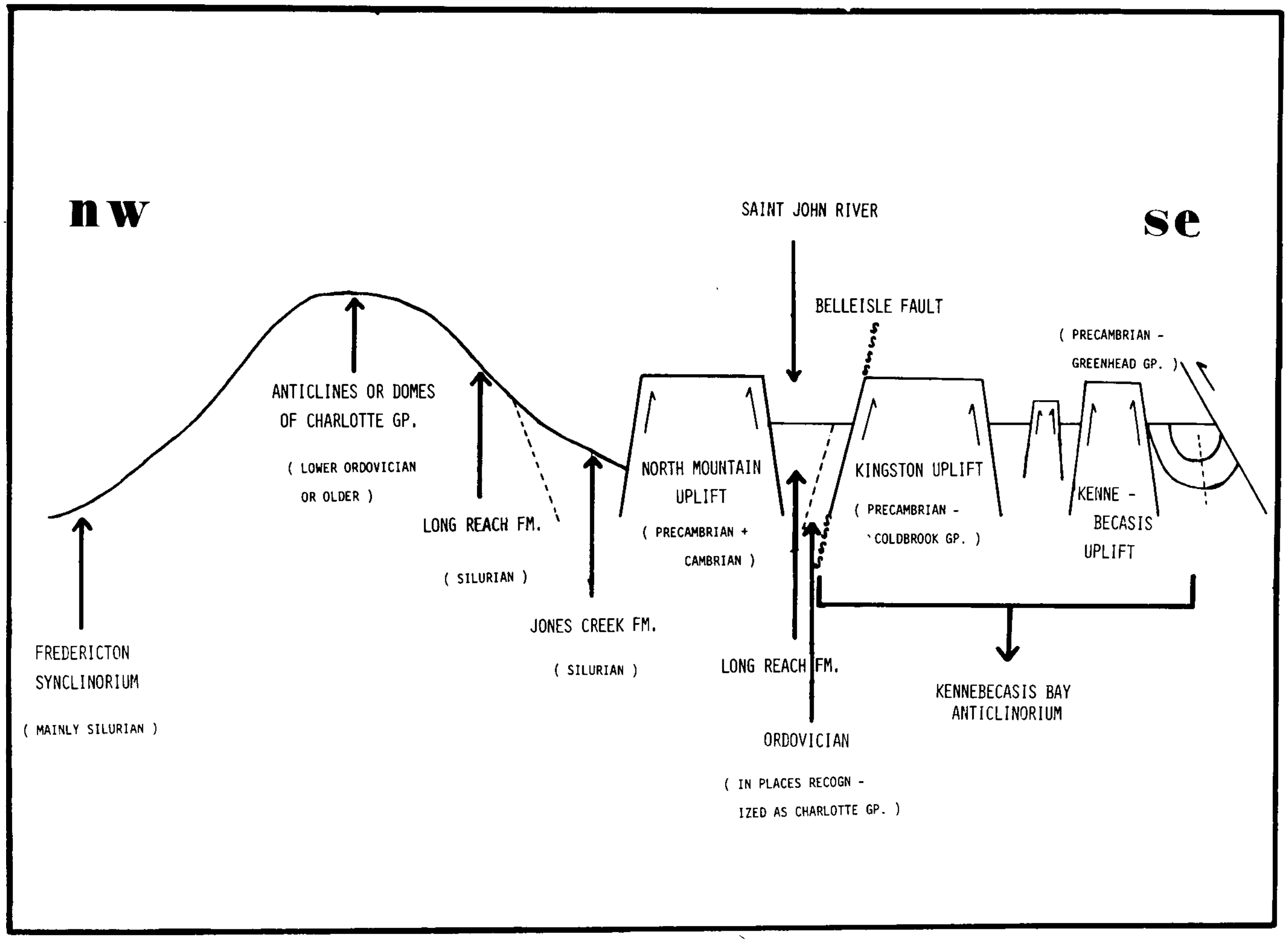

FIG. 2 Schematic cross-section of southern New Brunswick from Fredericton to Saint John illustrating the major structural features discussed.

(Fig. 2 and 3) and can be considered to occur in a tectonic window through the widespread Coldbrook Group.

Limestones, quartzites and argillites compose most of the Greenhead Group. Although they are ubiquitously tectonized, the state and degree of deformation and recrystallization varies considerably over certain areas (Leavitt 1963, Wardle 1977). On the basis of stromatolites Hofmann (1974) suggested a probable Neo-Helikian age for the deposition of the group.

The structurally overlying Coldbrook Group is essentially comprised of acidic and basic lavas and pyroclastic rocks although it is very heterogeneous. In some sections it contains volcanic and associated suites of high level intrusive rocks (O'Brien 1976); whereas, in others a mixture of volcanic and shallow water sedimentary rocks predominate (Ruitenberg *et al* 1973a; Giles and Ruitenberg 1977). No continuous sections have been described which show the vertical stratigraphic passage from the volcanic rocks in the intrusive belts to the volcanic and sedimentary rocks in the areas of redbed deposition. This may imply that such regions developed with some autonomy and possibly in separate fault blocks. The age span of the Coldbrook Group is presently unknown but it is probably mid to late Hadrynian (Fairbairn *et al* 1966, Cormier 1969).

The contact of the Greenhead and Coldbrook groups is everywhere tectonic. There are abrupt structural, metamorphic and magmatic contrasts between the groups across their contacts (O'Brien 1976, Map 3). Several phases of deformation, high grade metamorphism and sny- to post-kinematic intrusion locally affect the Greenhead Group but do not transgress the contact with the Coldbrook Group. Most Coldbrook rocks, excepting massive, structureless units, display the same generations of fold structures as the overlying Cambrian rocks. The Greenhead metasediments, however, contain pre-Cambrian folds and fabrics (Wardle 1977). As a result, the Greenhead Group is considered to be structurally older than the tectonically adjacent Coldbrook Group. Although it is uncertain if all Coldbrook rocks lie with angular unconformity on the Greenhead Group, it is highly probable that the latter forms a basement to the local Coldbrook sequence. The deformation and metamorphism in the Greenhead Group predate the accumulation of at least some of the volcanic rocks at the level that they are exposed in the Kingston and Caledonian uplifts.

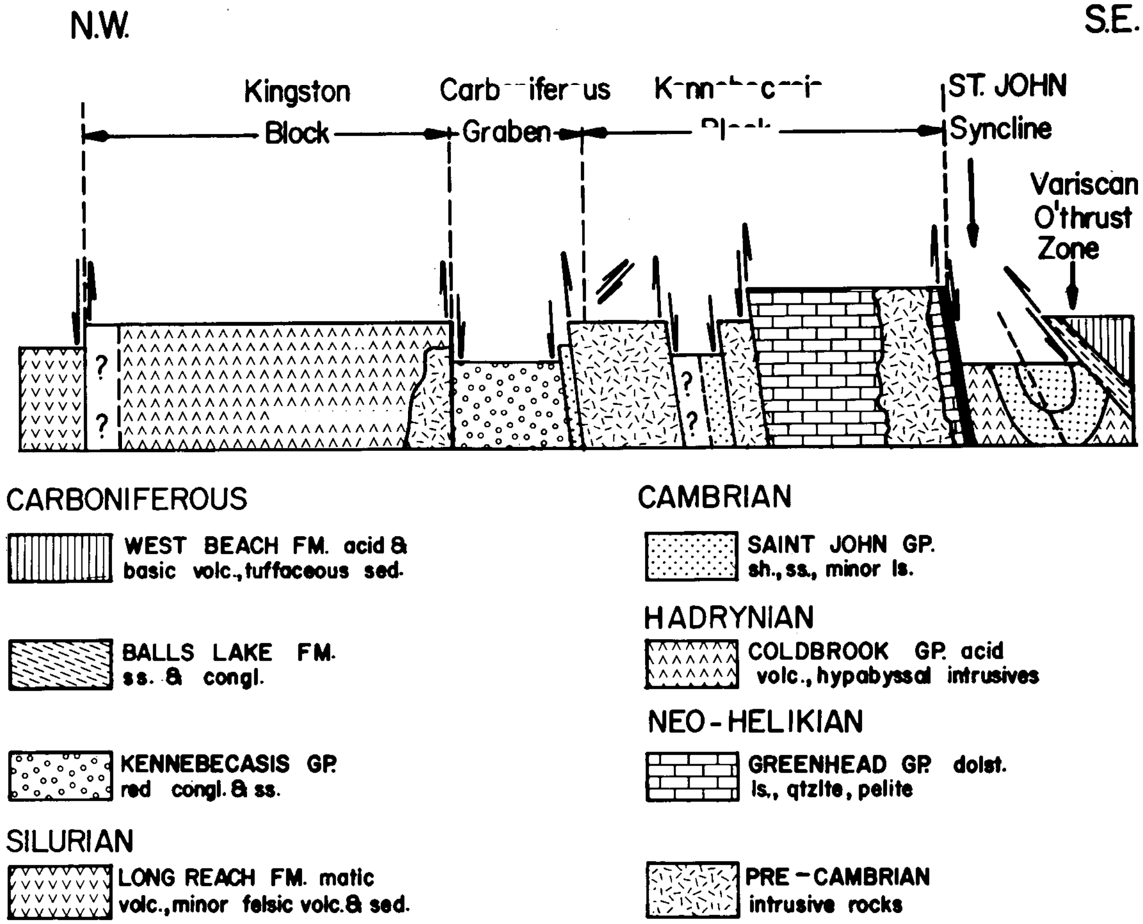

FIG. 3 Geological section across the Kennebecasis Bay anticlinorium (Figure 2).

The age of the tectonism of the Greenhead Group as well as that of its regional correlatives (Rast *et al* 1976) is presently controversial (*e.g.* Wiebe 1972, 1973, Helmstaedt and Tella 1973). However, detrital clasts of foliated Greenhead Group lithologies are found in overlying Lower Cambrian strata (I. Patel, pers. comm. 1975). In southern New Brunswick the deformation of the Greenhead Group must have occurred between Neo-Helikian and late Hadrynian time.

Gupta (1975) examined the fault boundary separating the Greenhead and Coldbrook groups and other major faults in the region by means of aeromagnetic and gravity data. From geophysical evidence he found that some faults were deep and extended 18 to 20 km beneath the 18 to 30 km surface. He suggested the boundary fault terminated in rocks of probably very mafic composition and that in the greater Saint John area and northeast it may have had a throw of the order of 6 km. Recent work has shown that this fault as well as several others in the Kennebecasis Bay anticlinorium (Fig. 3) had their earliest movements in pre-Lower Cambrian, probably late Hadrynian time (Wardle and O'Brien 1973, O'Brien 1976).

PALEOZOIC ROCKS

Relationships between platformal Cambro-Ordovician strata (Saint John Group) and the Coldbrook Group.

In southern New Brunswick platformal sedimentary rocks of Lower Cambrian to Lower Ordovician age are in contact with a variety of rock groups occurring in both the Kennebecasis Bay anticlinorium and smaller scale structures to the immediate northwest (Fig. 2) but not beyond. The sequence, locally known as the Saint John Group (Hayes and Howell 1937), contains the earliest dated Cambrian rocks and the most complete and best documented Cambro-Ordovician succession in New Brunswick. Lower Ordovician strata (Poole 1970) also occur in the southern part of the province in the upper portions of the dark argillite division of the Charlotte Group, whilst its lower portions probably extend downwards into the Cambrian. The Charlotte Group, however, is generally flyschoid and its paleogeographic relationships with the platformal Saint John Group are unknown due to a zone of faulting (Farnett 1973) which generally separates the groups (*e.g.* MacKenzie 1964b).

The Saint John Group begins with continental redbeds (Ratcliffe Brook Formation) and is succeeded by quartzite (Glen Falls Formation) and then shales with less sandstone and minor limestone (Hanford Brook and succeeding formations). The group does not contain any volcanic rocks with the exception of some rare beds of lapilli tuff (Helmstaedt 1968) and it is not intruded or metamorphosed by any plutonic rocks. A few intermediate to basic dykes (*i.e.* the augite porphyrites of Hayes and Howell, 1937, p44) can be observed within the Cambrian however.

A basal redbed succession of variable thickness can be observed to unconformably overlie the Coldbrook Group in several locations on the southeastern limb of the Kennebecasis Bay anticlinorium (the Caledonian uplift). In other locations within the structure as well as in the North Mountain Uplift (Grant 1971) minor faults, shear zones or Quaternary cover distort or hide what are most probably erosional and, with the Greenhead Group, angular unconformities.

The Cambrian exposures have marked regional significance since not only do they rest unconformably upon the Precambrian but none of the complex magmatic sequences in the Coldbrook or Greenhead groups can be recognized within the Paleozoic rocks. The Saint John Group belongs to a much larger belt of platformal sedimentary rocks along the eastern side of the Appalachians which are thought to be essentially shallow marine strata (Williams *et al*, 1972, p.201). Thus the Precambrian-Cambrian boundary in a large portion of southern New Brunswick represents a time when a distinctive phase of Greenhead deformation, metamorphism and plutonism and a subsequent period of Coldbrook constructive volcanism and associated intrusion ceased and new, entirely different conditions began.

Faults of late Precambrian age bear an interesting relationship to the beds at the base and lower portion of the Cambrian series. The facies of the Lower Cambrian (Patel 1975) is remarkably constant over the various post-Lower Carboniferous fault blocks in the Kennebecasis Bay anticlinonium and the North Mountain Uplift (Figs. 2 and 3). Also noteworthy is the fact that the transport direction is always from the north to the south (Patel 1973). It is, therefore, reasonable to assume that there was little topographic relief during Lower Cambrian transgression relative to the surface of the Coldbrook Group when the Coldbrook redbeds filled certain areas, while other areas were being actively eroded. Although faulted, the presence of Greenhead-Cambrian contacts on Kennebecasis Island (MacKenzie 1964a) does seem to indicate that the Cambrian once rested upon the Greenhead Group since the faults are minor and the Cambrian is autochthonous. In such cases the Precambrian-Cambrian boundary would be a marked angular unconformity. It seems Greenhead and Coldbrook rocks occurred in separate fault blocks that were eroded and reduced to a common base level prior to Lower Cambrian transgression. Lower Cambrian basal conglomerates contain foliated Greenhead and unfoliated Coldbrook fragments in the same horizon. The dispostion of these pre-Lower Cambrian, post-Hadrynian fault blocks is uncertain; however, it may be that they did not significantly differ from the present post-Lower Carboniferous configuration.

Relationships between the Coldbrook Group and Rocks of Middle Ordovician to Uppermost Silurian-Lowermost Devonian Age

The fault blocks which comprise the Kennebecasis Bay anticlinorium (Figs. 1 and 3) are devoid of any strata spanning the time from the Middle Ordovician to the Lowermost Devonian. In southern New Brunswick such rocks can, however, be found to the northwest of the faulted limb of the Kennebecasis Bay anticlinorium (Fig. 3) or, in other words, within and to the northwest of the Belleisle fault zone. They are represented by the sedimentary and volcanic rocks of the Long Reach and Jones Creek formations, the pale argillite divisions of the Charlotte Group and successions of unnamed greywackes and slates which extend northwards to the vicinity of Fredericton (Poole 1970, p 265 and Fig. 2). Poole states that these rocks range in age from probable middle to late Ordovician, in the case of the so-called pale argillite division, and to Ludlow, in the case of the Fredericton greywackes. Regionally they occur on the southeast limb of the Fredericton synclinorium (Figs. 1 and 2) and in the smaller structures to the south. The complexly interfingered rocks of the Long Reach and Jones Creek formations (Boucot *et al* 1966, Smith 1966, Porter 1973) are thought to represent shelf deposits; whereas, the Fredericton greywackes to the north are generally considered to be turbidites of the deep basin. In southwestern New Brunswick around the Saint David's Dome (Ruitenberg 1967) and southwards to Passamaquoddy Bay Silurian strata are well displayed and are thought to extend upwards into the Lowermost Devonian (Pickerill and Pajari 1976). Younger Devonian rocks (the Perry Formation) are found in the Passamaquoddy Bay area but they rest with an important angular unconformity upon the older beds.

The rocks to the southeast of the Kennebecasis Bay anticlinorium are not exposed in southern New Brunswick. However, in Nova Scotia, middle to late Ordovician and Silurian rocks most probably occur in a southerly thickening basin called the Meguma Trough (*cf* Poole 1967, 1976). The Halifax Formation of the Meguma Group is, in part, Tremadocian (Taylor 1967) and is, though not everywhere, conformably succeeded by the White Rock, Kentville and New Canaan formations. Middle to late Ordovician rocks may be represented in the White Rock Formation (Poole 1970, p244 and 268) and Ludlow strata can be found in the Kentville and New Canaan formations.

Thus it appears that Ordovician and Silurian rocks are confined to basins or troughs on either side of the Kennebecasis Bay anticlinorium (*i.e.* the Kingston and Caledonian uplifts). In the anticlinorium, relatively thin Lower Ordovician (Arenigian) black slates and argillites can be found in the Charlotte and Saint John groups of southern New Brunswick and the Halifax Formation of Nova Scotia. It is thought that this widespread deposition of black slate represents the drowning of the Cambrian platform.

The Lower Ordovician and older rocks, which now form the Kennebecasis Bay anticlinorium, did not remain submerged for any length of time (*i.e.* the effect of Taconic Orogeny) because throughout the Middle and Upper Ordovician the area formed a continuous landmass (Berry 1968). McKerrow and Zeigler (1971) state that during the Lower Silurian (Llandovery) the area was still a landmass but that a shelf and deeper water basin had developed to the northwest. Boucot (1969) also suggested that the area was an Early Llandovery landmass but that by the Late Llandovery a volcanic belt had formed to the northwest presumably on continental crust. This offshore volcanic belt persisted till at least Ludlow time (Boucot 1969). In southwestern New Brunswick it was active until the Gedinnian (Pickerill and Pajari 1976).

A very narrow zone separates the Arenigian and older rocks of the anticlinorium from the Ordovician and Silurian rocks to the northwest. This zone across which significant stratigraphic breaks occur is also the zone in which the Belleisle fault system (*e.g.* Garnett 1973, Garnett and Brown 1973) is developed. Movement along some of the constituent faults of the system has been prolonged. The latest displacements offset Lower Carboniferous rocks (MacKenzie 1964). However, in the same area, Lower Carboniferous strata rest with an angular unconformity on rocks which have been deformed in a Lower Paleozoic, presumably Acadian (*cf* Brown 1972) orogeny. Several workers have postulated that movements on certain faults in the Belleisle system have occurred in pre-, syn- and post-Acadian time (Garnett 1973, Wardle and O'Brien 1973; Rast and Grant 1974). MacKenzie (1964) thought that the primordial Belleisle fault in the Long Reach area was active in the Silurian and acted as a channel for magma. The present author has recognized composite dikes of diabase and rhyolite porphyry intruding Silurian rocks in the Long Reach area.

The total absence of Middle Ordovician to Lowermost Devonian strata to the southeast of this zone of faulting suggests than an hiatus or lacuna occurred during those times. Siluro-Devonian and post-Lower Carboniferous movements along the fault system have been summarized. It may be that the evidence of the hiatus is suggestive of even earlier movements. Movement may have been initiated in Middle Ordovician time in a narrow area across which deposition ceased, only to become subsequently the site of repeated fault reactivation.

The Ordovician and Silurian strata to the northwest of the inferred highlands of Arenigian and older rocks illustrate signs of deposition in or near a tectonically unstable area. Lateral facies changes are very common (Smith 1966) and have largely hindered the development of a reliable stratigraphic succession. Tectonic control of volcanism and sedimentation with associated uplifting may be evidenced in the Silurian deposits of the Long Reach Formation (O'Brien 1976). Similar conclusions have been reported by Gates (1969) from the Coastal volcanic belt of Maine.

Relationships between Lower Carboniferous rocks and the Coldbrook Group

In southern New Brunswick Lower Carboniferous rocks are in contact with and overlie the rocks of the Coldbrook Group for large areas (Potter *et al* 1968). Denudation and tectonic uplift had been such that by the latest Devonian and earliest Carboniferous the rocks of the Coldbrook Group formed the marginal landmasses for a series of Lower Carboniferous basins (Van de Poll 1972, Hacquebard 1971, 1972). During the Carboniferous the Coldbrook Group was intimately involved in both the tectonic and sedimentary history of the uplifts of Kennebecasis Bay anticlinorium. The variability in the nature of the contacts between Lower Carboniferous rocks and the Coldbrook Group is noteworthy.

In several locations around Kennebecasis Bay, Lower Carboniferous redbeds with reworked limestone and caliche horizons rest with angular unconformity on the Coldbrook and Greenhead groups and their associated plutonic rocks. These unconformities are commonly found near the margins of local graben; however, the majority of the Carboniferous successions are found within the structures. Sediments are poorly sorted and show features indicative of penecontemporaneous, thixotropic deformation. The rocks also illustrate signs of tectonic or bottom instability. For example, ancient talus slope deposits (Grant 1971) have been described from the Lower Carboniferous along the Coldbrook contact on the Southeastern side of the Kingston Uplift (Figs. 2 and 3). The Lower Carboniferous in the Kennebecasis Bay area is regionally representative of at least part of the Lower Carboniferous elsewhere in southern New Brunswick. It seems that the Coldbrook Group rocks of the Kingston and Caledonian uplifts occurred as a series of belts of alternating positive and negative areas some of which were bounded by reactivated faults.

Sometime after its deposition but before the late Triassic, the unconformable cover of Carboniferous strata above the rocks of the Kennebecasis Bay anticlinorium was subjected to varying degrees of deformation. Sny- and post-depositional faulting, especially evident in a series of major northeast striking faults, is a typical feature of most of the outcrop area of the Lower Carboniferous strata (*eg* Belt 1968). The disposition of the Lower Carboniferous in Figure 3 demonstrates the nature of the Lower Carboniferous sedimentary basins. During the early stages of deposition of Lower Carboniferous strata some faults were moving and the fault bordered areas subsequently became the sites of the thickest accumulation of Lower Carboniferous rocks. However, while many graben structures were formed, some were abortive and others never received Carboniferous deposits (O'Brien 1976).

To the south of the aforementioned area intensely cleaved and deformed Carboniferous rocks occur in a relatively narrow belt. The folded belt is a part of a larger zone in Maritime Canada, which has been variously interpreted as a mobile belt (Poole 1967), a zone underlain by salt dome piercement structures (Van de Poll 1972) and an overthrust zone related to an orogenic front (Rast and Grant 1973). The deformed zone occurs along the southeast margin of the Kennebecasis Bay anticlinorium and does not cross the older structural grain. Within the zone Carboniferous formations as well as several of the rock groups in the anticlinorium have been penetratively deformed together.

In summary, it appears that the Precambrian and Lower Paleozoic rocks in the anticlinorium are involved with Carboniferous strata in two distinct ways. To the north of the overthrust belt the Coldbrook Group, amongst others, forms the basement and walls of fault-controlled Lower Carboniferous basins. The Carboniferous faults may be reactivated "basement" faults. They appear to have controlled sedimentation locally although many have had much later movements. To the south within the deformed belt the pre-Carboniferous rocks in the anticlinorium simply appear as some of the stratigraphic elements in the overthrust zone. The variation in the type of tectonic mobilization of the pre-Carboniferous basement is probably a signature of the presence of an orogenic thrust front (*cf* Rast and Grant 1973).

MESOZOIC ROCKS

Relationships between Triassic and Precambrian-Paleozoic Rocks

The predominantly Precambrian rocks of the Kennebecasis Bay anticlinorium have been repeatedly fault reactivated and, as has been demonstrated, were a prominent paleogeographic feature during Lower and Upper Paleozoic time. During the Mesozoic (in the Trias) the region, then a part of the stabilized New Brunswick Appalachians, may have continued to play a significant role in the development of the local Triassic successions (Klein 1962).

Triassic redbeds are found in several locations along the present shoreline of the Bay of Fundy and extend under the waters of the bay. They occur in grabens or in thick successions on the limbs of monoclines (*eg* Stringerand Wardle 1973). The base of the Triassic redbeds can be observed at West Quaco Head (Hayes and Howell 1937) and Martin Head (Ruitenberg *et al* 1976). In both cases Triassic red sandstones lie with angular unconformity on a variety of older rocks (O'Brien 1976). At West Quaco Head Triassic limestones, marls and sandstones are involved in a double unconformity (Hayes and Howell 1937, pl 20). There undated pl. 20 volcanic rocks are overlain with an erosional unconformity by Lower Carboniferous limestone, caliche and conglomerates. These rocks are, in turn, overlain with angular unconformity by the Triassic rocks. Locally erosion associated with the development of the Triassic unconformity denudes the Lower Carboniferous unconformity. Limestone, caliche and redbeds comprise the base of both the Triassic and Lower Carboniferous successions.

At Martin Head, some 30 km northeast along the shore of the Bay of Fundy, Triassic redbeds similar to those at Quaco Head are faulted against Precambrian rocks. However, near the margin of the Triassic fault block, relicts of limestone and caliche are preserved. Nearby the same limestone is conformably overlain by diagnostic Lower Carboniferous evaporites. The basal limestone and caliche rest with angular unconformity on Precambrian schists. Thus Lower Carboniferous unconformities, involving similar strata near the base, occur in at least two localities uniquely situated below a Triassic unconformity and near the margins of Triassic graben.

The presence of unconformities some 30 km apart is noteworhty as they are restricted to a very narrow zone. Appreciable thicknesses of Triassic rocks are not found inland from the outcrops along the Fundy shoreline although locally they young in that direction They do not occur as outliers on the Precambrian and Paleozoic rocks in the anticlinorium. In places, where the unconformable base of the Trias is found very near the graben margin, it seems as though the strand line during deposition subsequently became a fault border. In this sense the Trias has developed in a similar manner as the Lower Carboniferous to the north. In fact, it is interesting to note that the aforementioned pre-Triassic unconformities involve Lower Carboniferous strata.

The Triassic successions are thousands of metres thick and great volumes of sediment have been locally eroded (Klein 1962). Erosion and denudation, however, have probably been aided by localized faulting and uplift. For example, in the Quaco Bay area the Triassic section youngs and thickens very rapidly away from the unconformities on West Quaco Head. Hinge lines or strand lines seem to have developed along old lines of weakness in the sub-Triassic and sub-Carboniferous basement.

Thus movement on some of the fault blocks in the Kennebecasis Bay anticlinorium may have persisted into the Mesozoic. As such this continually fault reactivated crustal block may have played an active role during periods of extension and rifting along the continental margin during the earliest stages of the opening of the present day Atlantic Ocean.

Summary of Contact Relationships

The evolution and development of the major stratigraphic and tectonostratigraphic units in southern New Brunswick have been generalized and summarized pictorially in Figure 4.

In Neo-Helikian time (Fig. 4a) algal limestones and orthoquartzites of the Greenhead Group formed a platformal cover to a cratonic basement which may or may not be exposed in southern New Brunswick. Prior to the extrusion of late Hadrynian volcanic rocks, the metasedimentary rocks of the Greenhead Group were highly deformed, metamorphosed and intruded by a variety of plutonic rocks (Fig. 4b). The zone of deformation and more significantly metamorphism is very narrow and the metamorphic isograds are very steep. Migmatite gneisses are thought to represent highly metamorphosed parts of the Greenhead Group (R.J. Wardle *in* Wardle and O'Brien 1976).

In the late Hadrynian (Fig. 4c) the volcanic rocks of the Coldbrook Group were extruded and, in some regions, were interstratified with, and overlain by thick shallow water sedimentary deposits. Block faulting and epizonal (locally sub-volcanic) granite intrusion were broadly contemporaneous and occurred in different fault blocks than those in which the thick sedimentary successions were being deposited. Basic dykes and sills also intruded the Coldbrook Group at this time.

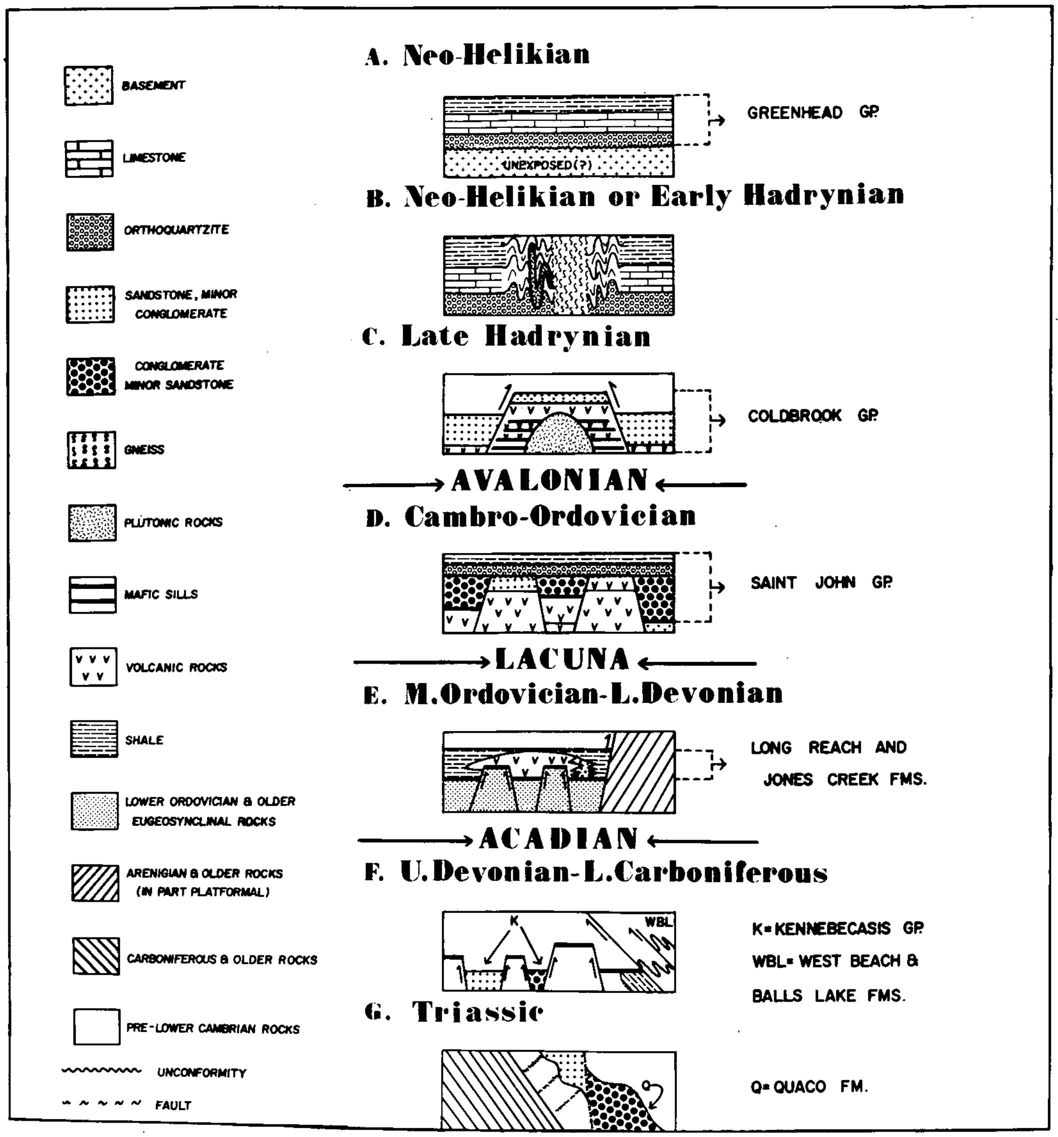

FIG. 4 Chart summarizing the crustal evolution of southern New Brunswick from the Neo-Helikian to the Triassic.

In earliest Cambrian time redbeds of variable thickness filled topographic irregularities in the block faulted surface of the Coldbrook Group. The base of the redbed sequence rested with varying degrees of disconformity on the latest Hadrynian volcanic and sedimentary rocks (Fig. 4d). A later widespread transgression over the entire area started with an orthoquartzite and was succeeded by the shallow water, platformal deposition of sandstones, shales and minor limestones. By the lowest Ordovician, time deeper water deposits were widely distributed over the regional although only relics now remain.

In the area now occupied by the Kennebecasis Bay anticlinorium, the period between the lowest Ordovician and the upper Devonian is represented by an hiatus. Elsewhere in the Canadian Appalachians in zone H (Williams *et al* 1972, p. 184) hiatuses are also common. In Arisaig, Nova Scotia the hiatus occurs between the Lower Ordovician (Arenig) and Upper Ordovician (Ashgillian). This phenomenon has been interpreted as a Taconic Lacuna.

Strata ranging in age from Middle Ordovician to lowermost Devonian only occur to the northwest of the Kennebecasis Bay anticlinorium in southern New Brunswick. There the strata lie with an angular unconformity (Cumming 1967) on Lower Ordovician and older rocks. It is apparent that the zone or line between the area involved in the Taconic Orogeny and the area recording a Taconic lacuna is narrow, if not sharp. This zone or line about which penetrative deformation ceases also coincides with a zone or line, immediate northwest of which facies changes in Silurian rocks are common. To the southeast of this line or zone no Middle Ordovician to lowermost Devonian rocks occur. One possible explanation is that this zone separates an uplifted block of Arenigian and older rocks to the southeast from a continually fault-activated shelf or basin to the northwest. Facies changes may be related to localized vertical uplift on the shelf (Fig. 4e).

There is no stratigraphic record of deposition in the Kennebecasis Bay anticlinorium after the lowermost Devonian and prior to the Upper Devonian. The widespread Acadian Orogeny occurred during these times.

In the Upper Devonian and Lower Carboniferous faults were, in some places, reactivated along old lines of weakness in the Coldbrook and Greenhead groups. Lower Carboniferous deposits filled small graben some of which were fault controlled (Fig. 4f). To the southeast of the zone of vertical faulting and sedimentation, overthrust zones related to an orogenic front carry polyphase deformed Carboniferous and Precambrian rocks over relatively undeformed rocks of the same age to the north. The thrust front approximately parallels the trend of the older uplift.

In the Triassic (Fig. 4g) unconformities developed at the base of redbed successions near the margins of large monoclines or a graben. The positions of the unconformities and the faults bordering the graben may be linked to areas in which similar processes were active in the Upper if not Lower Paleozoic.

PART 2

FAULTING AND CRUSTAL EVOLUTION IN SOUTHERN NEW BRUNSWICK

INTRODUCTION

An analysis of the data summarized in Part 1 clearly indicates that the rocks in southern New Brunswick have not subsided and been buried like the geosynclinal rocks in the rest of the province. Instead, for lengthy periods in the Lower and Upper Paleozoic, the area did not receive any deposits and probably provided detritus to the surrounding regions. In the late Precambrian and parts of the Paleozoic and Mesozoic, sedimentation and volcanism were largely terrestrial in origin. It seems quite apparent that faulting has persisted for a long time in a relatively localized area of the province. The writer has interpreted some of the faults or fault zones in southern New Brunswick as "deep faults" (*cf* Khain 1972) because of their longlived, fundamental affect on the depositional and tectonic evolution of the region. Recent geophysical studies have not been extensive enough to determine the presence, attitude or depth of such inferred structures, although data compiled by Gupta (1975) suggests that steeply dipping faults extend downwards to at least the lower crustal levels. In other areas where deep faults have been identified from combined geophysical methods, they have been found to extend downwards to the Mohorovicic discontinuity (*e.g.* Beranek and Dudek 1972).

In the following discussion the evidence for "deep faults" is documented and interpretations of their role in the crustal evolution of the area are suggested. The writer has concentrated on the effects of such faults on rocks within the supracrustal region only and has not endeavoured to link these features to models explaining the crustal evolution of the area by deeper-seated plate motion and interaction (*cf* Schenk 1971, Rast *et al* 1976).

REGIONAL SETTING

Most of the major faults in southern New Brunswick belong to a larger system of dislocations which can be traced from the coast of east-central Maine through southern New Brunswick, Cape Breton Island and western Newfoundland to Ireland and Scotland. In North America the system is referred to as the Cabot fault system (*cf.* Wilson 1962); whereas, it is known as the Great Glen Fault (Kennedy 1946) in the United Kingdom. In most locations along its outcrop the latest movements offset either Devonian or Carboniferous rocks. In offshore areas Mesozoic strata have been affected (Flinn 1969). However, recent studies have demonstrated that certain faults in the system have had a long history and played an active role in the development and subsequent deformation of the rocks which abutt them. Their effect has been realized in the deep seated crustal levels in Scotland (Powell 1976) and western Newfoundland (Brown 1973) and, in the supracrustal regions, in coastal Maine (Stewart 1974, Stewart and Wones 1974) and southern New Brunswick (O'Brien, this paper).

There is little doubt that the Cabot-Great Glen fault system and its ancestral precursors have had some fundamental control in the siting of orogenic movements in the Appalachian-Caledonian belt. The post-Carboniferous displacements along the system cross the trend of the orogenic belt from its northwestern margin in the United Kingdom through Newfoundland (*cf* Williams *et al*, 1970, Brown and Coleman - Sadd 1976) to its southeastern margin in Maritime Canada and Maine. In contrast, throughout its early development in the Precambrian and lowermost Paleozoic, belts of mylonite or zones of simple shear belonging to the primordial system, were the main controlling factors in the evolution of the rocks on or near what was later to become the opposing continental margins of the Iaepetus (Harland and Gayer 1972) Ocean.

ASPECTS OF THE MAJOR FAULTS OF SOUTHERN NEW BRUNSWICK

Volcano-Plutonic Belts

Faulting and fault reactivation have had a major role in controlling the amount of volcanic rocks and their repeated occurrences throughout the stratigraphic sequence in southern New Brunswick. The volcanic and associated sedimentary and intrusive rocks of the region can be regarded as an evolving (?) volcanic-plutonic belt of the type described by Ustiyev (1969). The southern New Brunswick belt is typical of such belts in that throughout most of its history it never subsided like the mio and eugeosynclinal rocks about it, despite the fact that it did change from a platformal (Cambrian) to an intrageosynclinal (M. Ordovician - L. Devonian) area.

Another characteristic feature of the southern New Brunswick belt is its direct relation to a system of major faults. Khrenov and Bukharov (1973) have described such a zone of faults that define a marginal suture about the North Asian craton. There distinct volcano-plutonic belts have formed in different epochs along the along system. Volcanism initiated in the Middle Proterozoic and continued intermittently in the Devonian, Mesozoic and Cenozoic. In southern New Brunswick faulting with or without associated volcanism and intrusion has also occurred throughout several intervals. Such activity started in the Hadrynian and continued in the Silurian, Lower Carboniferous and late Triassic.

Facies Changes

In the discussion of the relationship between the Coldbrook Group and the rocks of Middle Ordovician-Lowermost Devonian age (Part 1), a line or narrow zone was identified acorss which not only stratigraphic but structural breaks occurred. The line or zone, interpreted as a fault(s), separated an area involved in the Taconic orogeny from an area which recorded a Taconic lacuna. At a later date the former area was affected by syn-depositional faulting, while the latter remained in area of high relief.

Chikov (1967) noted that deep-seated faults could be recognized as zones of discontinuity. The discontinuity could be found in both the structure and stratigraphy of the area he discussed. He stated that the zone of discontinuity is distinguished by not only being very long but also very narrow. The structural variation across a given deep fault was usually documented for a given orogenic period. Stratigraphic and paleontological facies changes also occurred across buried or, at the time, partially buried deep faults. If an analogy can be made between the line or zone of discontinuity in southern New Brunswick and those of Chikov (1967), then some of the faults bordering the Kennebecasis Bay anticlinorium may be deep rooted.

Superposition of Orogenic Belts and Rifts

In southern New Brunswick orogenic cycles involving compression and subsequent distension spanned at least 450 to 500 Ma from the Precambrian to the Mesozoic. In all cases repetitive orogeny has produced a superposition of tectonic features on various scales.

Deep faults manifest themselves as major dislocations in the crust. In some regions these dislocation zones develop early in the history of an orogenic area and control the trends of younger orogenic belts as well as the site of much later rifting and associated magmatism (*e.g.* DeSwardt *et al* 1965). In southern New Brunswick, faults which were active during the development of parts of the Precambrian (Fig. 3, Fig. 4c) were reactivated in younger orogenies. These major faults must have exerted some form of control that persisted from one orogeny to another. For example, regional trends for the Taconic and Acadian orogenies are invariably parallel in southern New Brunswick, whereas, in the central part of the province the trends display an angular discordance. To further the point, the New Brunswick the Carboniferous thrust front and related fabrics are generally parallel to the older Appalachian structural grain (Rast and Currie 1976). In other regions, however, the Carboniferous thrust front crosses the trend of the basement rocks (Riding 1974, p. 126). It should also be noted that some of the fault zones continued to be activated long after southern New Brunswick had largely been stabilized. During the late Triassic, tholeiitic basalts erupted in rifts or taphrogenic troughs bordered by reactivated faults.

It must be emphasized that regions typified by deep faults can be expected to behave uniquely and sometimes differently to orogenic movements that originate in the upper mantle or lower crust. Because such faults are restricted to specific zones of weakness in the lithosphere and because they remain as zones of weakness throughout long periods of crustal evolution, they cannot remain mechanically linked to the mantle for any length of time (Watterson 1975). However, the forces which reactivate deep fault zones are external to the lithosphere and contain vectors of horizontal displacement. Thus, plate tectonic processes affecting either a part or the whole of an orogen may be expressed uniquely and continuously along deep fault zones in an evolving lithosphere.

Repetitive Orogeny and Rising Crustal Blocks

The culminating Acadian orogeny in the Appalachian fold belt and the "Variscan" orogeny in the Maritime fold belt can be strongly contrasted in southern New Brunswick. The widespread Acadian Orogeny not only affected the rocks in the area considered but most of the rocks in the north and central parts of the Appalachian Mountains (Rodgers 1970, Williams *et al* 1972). It involved substantial crustal shortening accompanied by regional metamorphism and granite intrusion. In southern New Brunswick these effects have been documented (Brown 1972, Brown and Helmstaedt 1970, Fyffe 1971, Cherry 1976); however, unlike other parts of the province syn- and late-deformational faulting has played an important role (Garnett 1973).

The effects of the Carboniferous orogeny have only been identified in southern New Brunswick and then only along the southern limb of the Kennebecasis Bay anticlinorium. As was previously documented in Part 1, there is a fundamental variation in the mechanics of the Carboniferous deformation across a thrust front which is parallel to the older uplifts. In a similar setting in the Hercynian belt of Algeria, Collomb and Donzeau (1974) have demonstrated that renewed movement on Precambrian basement faults occurred during the compressive stages of Variscan orogeny and resulted in the development of some of the structures and flexures in the region. They also stated that such faulting is usually found in areas where the compression has produced little crustal shortening, low pressure metamorphism and an abundance of acid volcanic supracrustal rocks. This is exactly the case in southern New Brunswick. There, the supracrustal portions of deep faults seem to have had a function in the manner in which Carboniferous compressive forces were released.

In the time elapsing between the Devonian (Acadian) and the Carboniferous (Variscan) orogenies, the supracrustal rocks in southern New Brunswick were elevated to an even higher crustal level. In fact, it seems that the Variscan overthrust front does not significantly differ from the position of the Lower Carboniferous shoreline. Shallow water, well sorted, carbonaceous sandstones and acid volcanic rocks are thrust over red fanglomerates and conglomerates which rest unconformably upon the scoured Precambrian basement. More significantly, it appears that, with time, faulting took on a more fundamental role as the rocks rose to successively higher crustal levels and the effects of compressive forces were increasingly manifested in the brittle field.

CONCLUSIONS

1. In southern New Brunswick there is evidence of two, regionally significant episodes of Precambrian deformation. The earliest episode is associated with an ubiquitous, penetrative deformation and localized high grade metamorphism (Greenhead-type). The later episode (Coldbrook type) resulted in the development of regional block faults. The precise dating of these deformations is presently unknown and there is no certainty that a significant time gap separates the tectonic events. Faults belonging to the later episode of deformation are chiefly responsible for the uplift of the Greenhead schists against the Coldbrook Volcanics.

2. Throughout the Paleozoic and into the Mesozoic, the rocks of the Kennebecasis Bay anticlinorium and, to some extent, the rocks to their immediate northwest were intermittently affected by faulting. Many of the faults were reactivated along old lines of weakness in the Precambrian basement. The faults and fault zones not only controlled the type of sedimentation but the positions of highlands and the depositional limits of basins. For example, in the late Hadrynian, the Coldbrook Group was extensively block faulted - a pattern regionally developed in Atlantic Canada as a late stage orogenic feature. However, by the Lower Cambrian, the region had changed from a late stage orogenic to a platformal area. In fact, in the Lowermost Ordovician, vast areas of New Brunswick and Nova Scotia would have been blanketed by graptolitic muds. Southern New Brunswick, however, was not to subside or, for that matter, become anorogenic. From the early Middle Ordovician to the Lowermost Devonian renewed faulting, especially along the Belleisle fault zone, played an important role in the configuration of the paleogeographic and paleotectonic zones. The heavily faulted sub-Carboniferous and sub-Triassic basements influenced the structural as well as stratigraphic development of the Upper Paleozoic and Mesozoic rocks.

3. Major faults and fault zones persisted in localized areas throughout several periods between the late Proterozoic and early Mesozoic. Typically they are represented by notable, very narrow lineaments (Naing 1976). The faults are also associated with an abundance of supracrustal volcanic and related rocks. Variations in the regional structure and depositional facies of rocks are often quite sharply defined by their presence and they are, in part, responsible for the superposition of tectonic features on local and regional scales. The region in and around the fault zones is characterized by the repetition and not the cyclicity of geological events. In southern New Brunswick "deep faults" are presently observed at an erosional surface in the supracrustal region. The geological evidence would suggest that, while the area has been intermittently rising since the early Middle Ordovician, it has always occupied the upper crustal levels since the late Precambrian.

4. It seems that faulting played a central role in the crustal evolution of southern New Brunswick. Throughout several orogenic cycles faults remained active and were important features in both the syn- and post-orogenic stages. During compression they acted as sites where strain was inhomogeneously dissipated - an effect which gained increasing importance with time. In periods of deposition preceding orogeny, volcanic eruptions along or in the fault zones were predominantly associated with isostatic uplift, while the surrounding areas subsided and became buried in the geosyncline proper. The persistence and longevity of the Kennebecasis Bay anticlinorium as an intrageosynclinal zone is, then, directly related to the presence of consanguineous faults.

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