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**Critical Readers**

*W.H. Poole*
*I. Harris*

**Author's Address**

*Department of Geology*
*Kochi University*
*Akebono-cho 2-5-1*
*Kochi, 780 Japan*

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## Foreword

Dr. Shigeki Hada came to the Atlantic Geoscience Centre from Kochi University, Japan, in October 1975, to commence tenure of an 18 month visiting Fellowship sponsored by the National Research Council of Canada. Because of Dr. Hada's prior experience in the geology of island arc regions in Japan and Southeast Asia, his studies here focussed in part upon the relationships of the volcanic zones within the Appalachian orogenic belt in Newfoundland. The fruits of his endeavours include the structural and restored sections of the Newfoundland Appalachians and the stratigraphic and tectonic correlation chart for that region which accompany this report.

## CONTENTS

# PRE-CARBONIFEROUS EVOLUTION OF THE NEWFOUNDLAND APPALACHIANS


### Abstract

*A synthesis of the stratigraphic and tectonic characteristics of the Newfoundland Appalachians and a proposed model to account for the pre-Carboniferous evolution of this part of the orogenic belt are presented.*

*The lithology and apparently great thickness of metasedimentary rocks of the Fleur de Lys Supergroup strongly suggest sedimentation on an Atlantic-type continental margin and the existence of the proto-Atlantic (Iapetus) Ocean during Hadrynian time. This ocean was probably initiated about 800 Ma ago by rifting and breakup of a North American-European supercontinent. Oceanic lithosphere produced during the spreading-expanding phase of the proto-Atlantic was consumed by subduction which started in late Hadrynian or earlier times. Subduction started first on the east side of the ocean and gave rise to volcanism and metamorphism at the margin of the Avalon subcontinent.*

*In latest Hadrynian time, a new, small-scale spreading centre at the western margin of the proto-Atlantic Ocean produced ophiolite complexes of mainly Cambrian age, followed in late Cambrian-early Ordovician by westward dipping subduction of the proto-Atlantic oceanic plate beneath this newly created oceanic microplate. Volcanism occurred along the ancient continental shelf and rise during the early stages of these developments, with the extrusion of plateau basalts and diabase dykes in latest Hadrynian time. Subduction resulted in the eruption of island arc-type volcanic rocks, which directly overlie the Cambrian ophiolites, and in the imbrication of an accretionary complex (including the Dunnage Mélange) at the lower trench slope on the eastern side of the island arc.*

*Detachment and obduction of the Cambrian ophiolite complex began, at the latest, in the Early Ordovician. Movement of the detached sheet of Cambrian oceanic crust and mantle onto the eastern margin of the North American continent presumably resulted from a combination of convergent plate motion and an unusually steep geothermal gradient in the newly created oceanic plate. Early Paleozoic deformation and metamorphism affected the continental rise sediments and may have resulted from overthrusting of the thick and hot detached ophiolite sheet. An exogeosynclinal basin developed on the craton and accommodated a thick succession of easterly derived flysch in the east grading to black shale in the west. Tectonically stacked slice assemblages of a variety of sedimentary, volcanic and plutonic rocks moved into the exogeosyncline by gravity sliding in the Middle Ordovician. After the final emplacement of the ophiolites in mid-Middle Ordovician, subduction became inactive beneath the island arc. Rejuvenation of the subduction zone, however, is indicated by the development of mature island arc-type volcanism in the early Silurian. Closure of the proto-Atlantic Ocean was completed in the Middle Devonian when the Avalon subcontinent collided with the North American continent and fringing island arc.*



### Résumé

*On présente une synthèse des caractéristiques stratigraphiques et tectoniques des Appalaches de Terre-Neuve et on propose un modèle pour expliquer l'évolution pré-carbonifère de cette partie de la zone orogénique.*

*La lithologie et, apparemment, la grande épaisseur des roches métasédimentaires du supergroupe Fleur de Lys, suggèrent une sédimentation sur une marge continentale de type Atlantique et l'existence d'un océan proto-Atlantique (Iapetus) au cours de l'Hadrynien. Cet océan a probablement pris naissance il y a environ 800 Ma par la fracturation et la rupture d'un supercontinent nord-américain-européen. La lithosphère océanique, produite au cours de la phase écartement-expansion du proto-Atlantique, a été absorbée par une subduction qui a commencé à la fin de l'Hadrynien ou plus tôt. La subduction a d'abord commencé sur le côté est de l'océan et a donné naissance à un volcanisme et à un métamorphisme sur la marge du subcontinent d'Avalon.*

*A l'Hadrynien terminal, un nouveau centre d'expansion, de petite envergure, a produit dans la marge occidentale de l'océan proto-Atlantique des complexes ophiolitiques, principalement d'âge Cambrien. Puis, vers la fin du Cambrien-début de l'Ordovicien, s'est produite une subduction plongeant vers l'ouest de la plaque océanique proto-Atlantique au-dessous de cette microplaque océanique nouvellement créée. Un épanchement volcanique, avec extrusion de basaltes de plateau et de dykes de diabase, s'est produit le long du plateau et du glacis continentaux anciens, au cours des premières étapes de ces développements, à l'Hadrynien terminal. La subduction a eu comme résultat l'éruption les ophiolites cambriennes, et l'imbrication d'un complexe d'accroissement (comprenant le Dunnage Mélange) à la partie inférieure du fossé, sur le côté est de l'arc insulaire.*

*Le détachement et l'obduction du complexe ophiolitique du Cambrien a commencé, au plus tard, à l'Ordovicien inférieur. Le mouvement de la nappe détachée de la croûte et du manteau océaniques du Cambrien, sur la marge orientale du continent nord-américain a comme origine, estime-t-on, une combinaison d'un mouvement convergent des plaques et un gradient géothermique inhabituellement fort dans la plaque océanique nouvellement créée. Les déformations et les métamorphismes du Paléozoïque inférieur ont affecté les sédiments du glacis continental et peuvent avoir comme origine le chevauchement de la nappe ophiolitique épaisse et chaude, détachée. Un exogéosynclinal s'est développé sur le craton, à l'est il s'y est accumulé une succession épaisse d'un flysch dérivant de l'est, qui passe graduellement à l'ouest à un schiste argileux noir. Des assemblages de roches sédimentaires, volcaniques et plutoniques, empilés tectoniquement par tranches, se sont déplacés par gravité au cours de l'Ordovicien moyen dans l'exogéosynclinal. Après le placement final des ophiolites, au milieu de l'Ordovicien moyen, la subduction devient inactive au-dessous de l'arc insulaire. Cependant, la réjuvénation de la zone de subduction est indiquée par le développement d'un volcanisme de type arc insulaire parvenu à maturité au début du Silurien. La fermeture de l'océan proto-Atlantique s'est terminée dans l'Ordovicien moyen, lorsque le subcontinent d'Avalon est entré en collision avec le continent nord-américain et l'arc insulaire marginal.*

## INTRODUCTION

The Appalachian Orogenic Belt consists of Paleozoic and Hadrynian sedimentary, volcanic, metamorphic and plutonic rocks. It extends 3300 km along the Atlantic seaboard of eastern North America from Newfoundland to Alabama. If the continents are assembled according to their early Mesozoic fit, the Appalachians are contiguous with the Caledonian Orogen of Ireland, Britain and Scandinavia, and with the Paleozoic orogenic belts of southwestern Europe and western Africa.

The island of Newfoundland lies at the northeastern extremity of the Appalachian System and offers one of the most complete cross-sections of the orogen. Williams (1964) emphasized the two-sided nature of the System in Newfoundland, with the central part of the orogen being symmetrical, bounded both on the northwest and on the southeast by Precambrian rocks overlain by Lower Paleozoic platformal deposits. The rocks of Newfoundland range in age from Precambrian to Carboniferous. They are overlain in most places by unconsolidated Pleistocene glacial deposits. The submerged offshore extensions of the orogenic belt are covered by Mesozoic and Cenozoic sediments of the Atlantic continental shelf.

Wilson (1966) postulated the existence of an Early Paleozoic proto-Atlantic Ocean, and, on the basis of facies and faunal distributions, suggested that the rocks of the Avalon Peninsula in eastern Newfoundland (Fig. 1) may be a remnant of an ancient Afro-European continent which collided with a North American continent more than 350 Ma ago. When the continents later rifted apart and the present Atlantic Ocean was formed, the rupture took place in a new locality and the Avalon rocks remained welded to the North American continent. Based on these considerations, Dewey (1969) and Bird and Dewey (1970) proposed their revolutionary plate tectonic model for the evolution of the Appalachian-Caledonian orogenic belt. These and subsequent authors who have described the tectonics of the Newfoundland Appalachians agree that the development of the orogen involved the birth, evolution and death of a late Precambrian-Paleozoic proto-Atlantic Ocean.

This paper summarizes the tectonostratigraphic development of the Newfoundland Appalachians from the Hadrynian to the Devonian, and presents a model for the evolution of the Newfoundland Appalachians in terms of contemporary concepts of plate tectonics. Similar models have been proposed by Dewey (1969), Dewey and Bird (1970, 1971), Bird and Dewey (1970), Williams et al. (1972, 1974), Kennedy (1975), Poole (1976), and others. This paper focuses attention on post-Late Hadrynian and pre-Silurian developments, when the proto-Atlantic Ocean presumably had started to close and a volcanic arc gradually developed above a northwest-dipping subduction zone.

The structural cross-sections (Fig. 2-4) that form the basis of this paper were compiled in large part from maps and reports of the geology of the coastal area of northeastern Newfoundland. Figure 2 is a composite cross-section of the entire Newfoundland Appalachians and shows the general distribution, principal lithologies and age relationships of the rocks. This paper involves the synthesis of a large amount of stratigraphic and structural data which are summarized in a tectono-stratigraphic correlation chart (Table 1).

### *Acknowledgments*

The author wishes to express his sincere gratitude to W.H. Poole, I.M. Harris, and A.C. Grant of the Geological Survey of Canada for their constant guidance and encouragement and for numerous stimulating discussions, to Professor Harold Williams of Memorial University of Newfoundland for consultation, and to all of these people for critically reading the manuscript. Special thanks are due to L.P. Purcell, J.A. Wade, and other members of the Atlantic Geoscience Centre of the Geological Survey of Canada who gave instructive advice in the laboratory and continued encouragement for this study. The author is most grateful to the late Professor W.D. Brückner and Professor M.M. Anderson of Memorial University of Newfoundland and to B.F. Kean and R.F. Blackwood of the Newfoundland Department of Mines and Energy for providing guidance in the field. The author is deeply indebted to Professor Jiro Katto and other members of the Geology Department, Kochi University, for their co-operation and support during his absence. This paper relies almost entirely upon the published literature. The author apologizes if through oversight he has failed to acknowledge any of the numerous publications that are pertinent to the contents of this report.

## GEOLOGY

The Newfoundland Appalachians were divided into three belts (Williams, 1964), which have been referred to as the Western Platform (Kay, 1967), the Central Paleozoic Mobile Belt (Williams, 1964), and the Avalon Platform (Kay and Colbert, 1965). The three belts are subdivided into a number of zones on the basis of contrasting stratigraphy and structural style. Williams et al. (1972) designated the zones, from west to east, by the letters A to H (Fig. 1). Later, the zones were named according to well-known geographic localities (Williams et al., 1974). The most easterly zone of the Appalachian Orogenic Belt (Zone I), has been recognized only in Nova Scotia.

The zonal subdivisions of Williams et al. (1972) are followed in this paper although small revisions have been made to the zone boundaries in several areas. Zone A

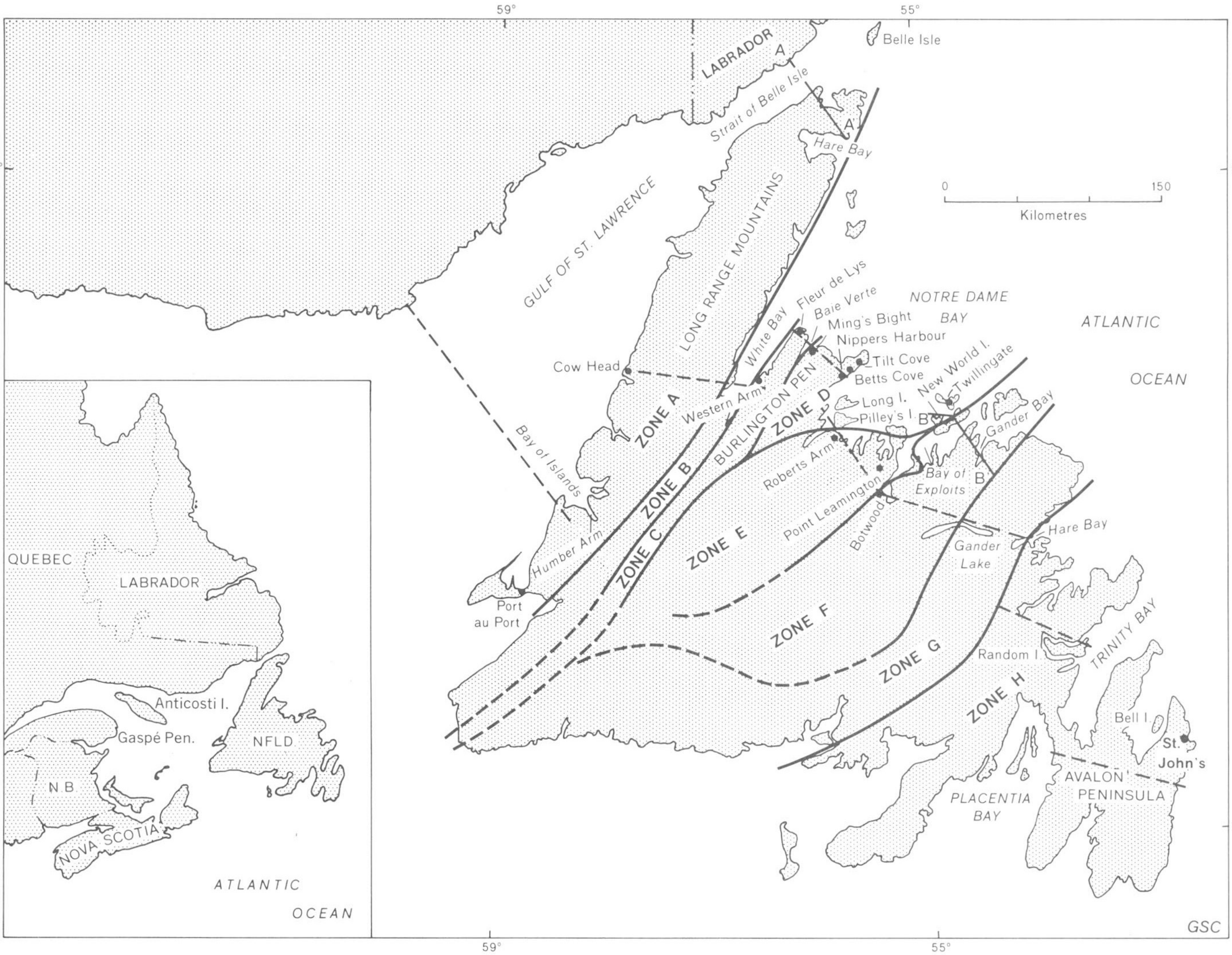


*Figure 1. Zonal subdivisions of the Newfoundland Appalachians based on contrasting stratigraphy and structural style and showing places referred to in the text. Dashed lines show the location of composite cross-section of Figure 2 and solid lines show those of Figures 3 and 4.*

corresponds to the Western Platform and Zone H to the Avalon Platform or Avalon Zone. The intervening zones occur within the Central Paleozoic Mobile Belt.

### *Zone A*

This zone includes a Grenvillian basement overlain by Hadrynian to Lower Cambrian clastics, Middle Cambrian to Middle Ordovician carbonates, and allochthonous and neo-autochthonous strata. The clastics (conglomerate, quartzite and shale) are westerly-derived and are generally coarsest in the west (Bradore Formation of the Labrador Group) and finest in the east (Kippens Group). The Labrador Group includes thin limestone beds (Forteau Formation). The sequence onlaps towards the west and thickens towards the east.

The Grenvillian basement rocks are cut by diabase dykes and locally are overlain by plateau basalts of the Lighthouse Cove Formation. The Lighthouse Cove Formation is intercalated with Upper Hadrynian to lowermost Cambrian clastics in the east (Williams and Stevens, 1969) (Fig. 3). Bird and Dewey (1970), Dewey and Bird (1971), Strong and Williams (1972), and Williams and Stevens (1974) have discussed the significance of the lavas and dykes in terms of continental rifting and the initiation of an early Paleozoic ocean (proto-Atlantic Ocean of Wilson, 1966; Protacadic Ocean of Kay, 1973; Iapetus Ocean of Harland and Gayer, 1972). Strong and Williams (1972) correlated the lavas and associated sediments of the Lighthouse Cove Formation with those of the Catoctin Formation in Virginia because of their similar geological setting. The former rocks, however, have been radiometrically dated at 605 Ma by the $^{40}Ar/^{39}Ar$ method (Stukas and Reynolds, 1974a) whereas the latter have been dated at 820 Ma by zircons (Rankin et al., 1969). Pringle et al. (1971) obtained an average whole rock K-Ar age of 805 Ma for the Newfoundland dykes, but this age is probably invalid in view of the fact that Stukas and Reynolds (1974a) found excess radiogenic argon in those rocks. Strong (1974) observed consistent chemical differences between the diabase dykes and the plateau lavas in Newfoundland. Emplacement of mafic volcanic rocks of the Lighthouse Cove Formation and the associated diabase dykes may have accompanied or immediately preceded the creation of oceanic crust during a small scale spreading or a spreading-like process in the pre-existing proto-Atlantic Ocean. This problem is discussed in the section that describes Zone C.

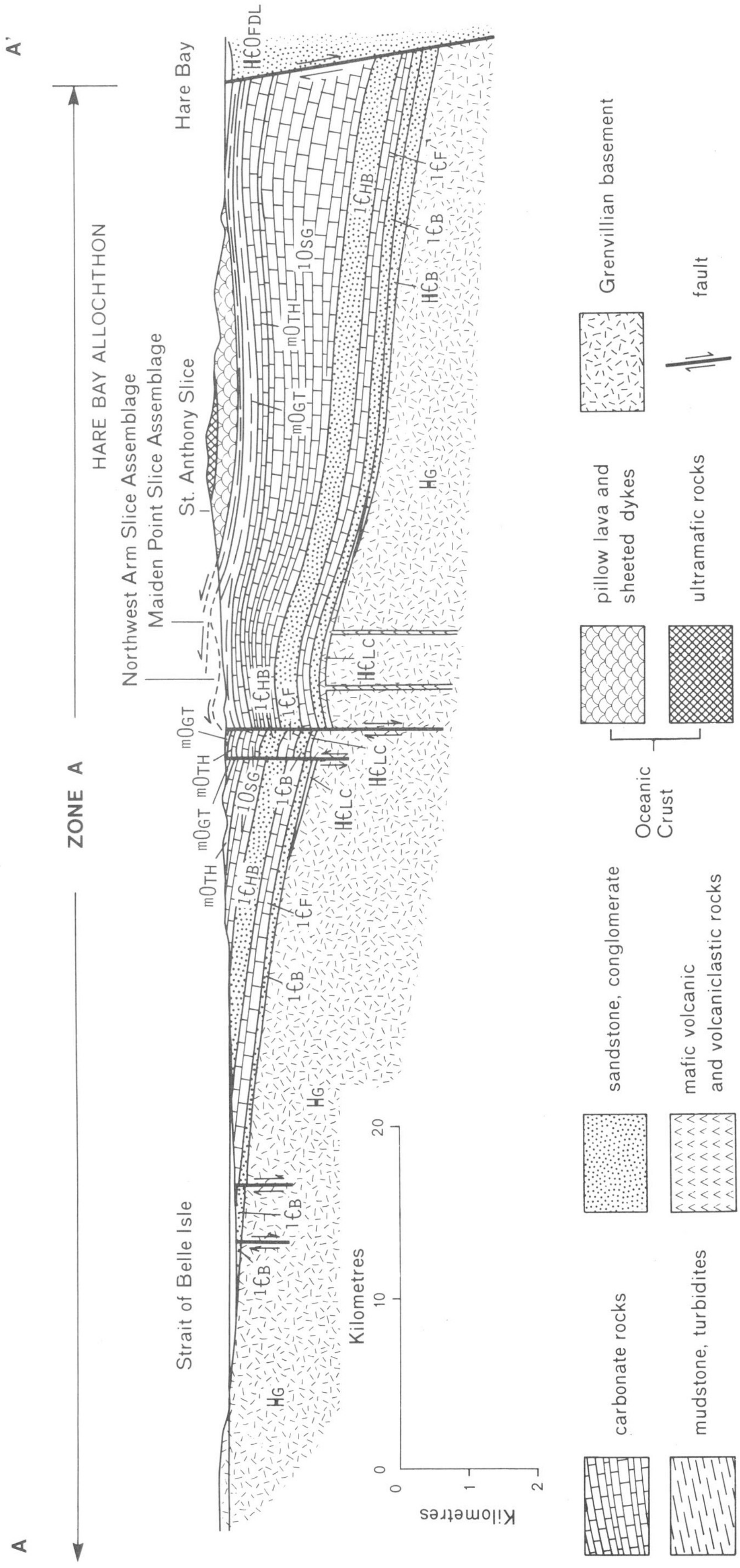


*Figure 3. Structural cross-section of Zone A in Strait of Belle Isle and the Hare Bay area. Location of section shown on Figure 1. The formations are identified in Table 1.*

A sequence of eastward-thickening carbonate rocks, ranging in age from the Middle Cambrian to Middle Ordovician, disconformably overlies the lower clastic sequence. The carbonates accumulated in a shallow water environment, comparable to the present-day Bahama Banks (Rodgers, 1968; Stevens, 1970; Fåhraeus, 1974). The upper part of the carbonate sequence is the early Middle Ordovician Table Head Formation, which disconformably overlies the Lower Ordovician carbonates. The lower part of the Table Head Formation is marked by rubbly-weathering limestone and carbonate flysch (Stevens, 1970). An apparently abrupt change in deposition from shallow water limestone to deep water rubbly limestone is attributed to the collapse of a stable continental margin which ultimately resulted in the emplacement of allochthons of oceanic crustal rocks from the east in the early Middle Ordovician (Stevens, 1970). The limestone is gradationally overlain by graptolitic shale in the upper part of the Table Head Formation. A thick succession of easterly derived flysch, which gradationally succeeds the graptolitic shale, transgressed westward in advance of rocks being transported from the east.

The allochthons and associated mélange overlie the Table Head Formation. The stratigraphy, structure and petrology of the allochthons in western Newfoundland have been studied by various authors (Brückner, 1966; Tuke, 1968; Stevens, 1970; Church and Stevens, 1971; Smyth, 1971; Williams, 1971, 1973; Williams and Malpas, 1972; Williams and Smyth, 1973; Williams et al., 1973). The results of these investigations have been summarized and interpreted by Williams (1975) and Williams et al. (1977). Williams (1975) has demonstrated that the allochthons are made up of fault-bounded "slices" and "slice assemblages" of diverse lithology and ages, as shown in Table 1. The table also shows the inferred origin and tectonic setting of each of the major slices and slice assemblages. In each allochthon, the lower structural slices consist of sedimentary rocks of the continental slope. The highest structural slice in each case consists of ophiolitic rocks, which have been interpreted as oceanic crust and upper mantle. The allochthons originated mainly in Zone D, and a description of them is deferred to the section on that zone. The transported slices are typically underlain by shaly mélanges which

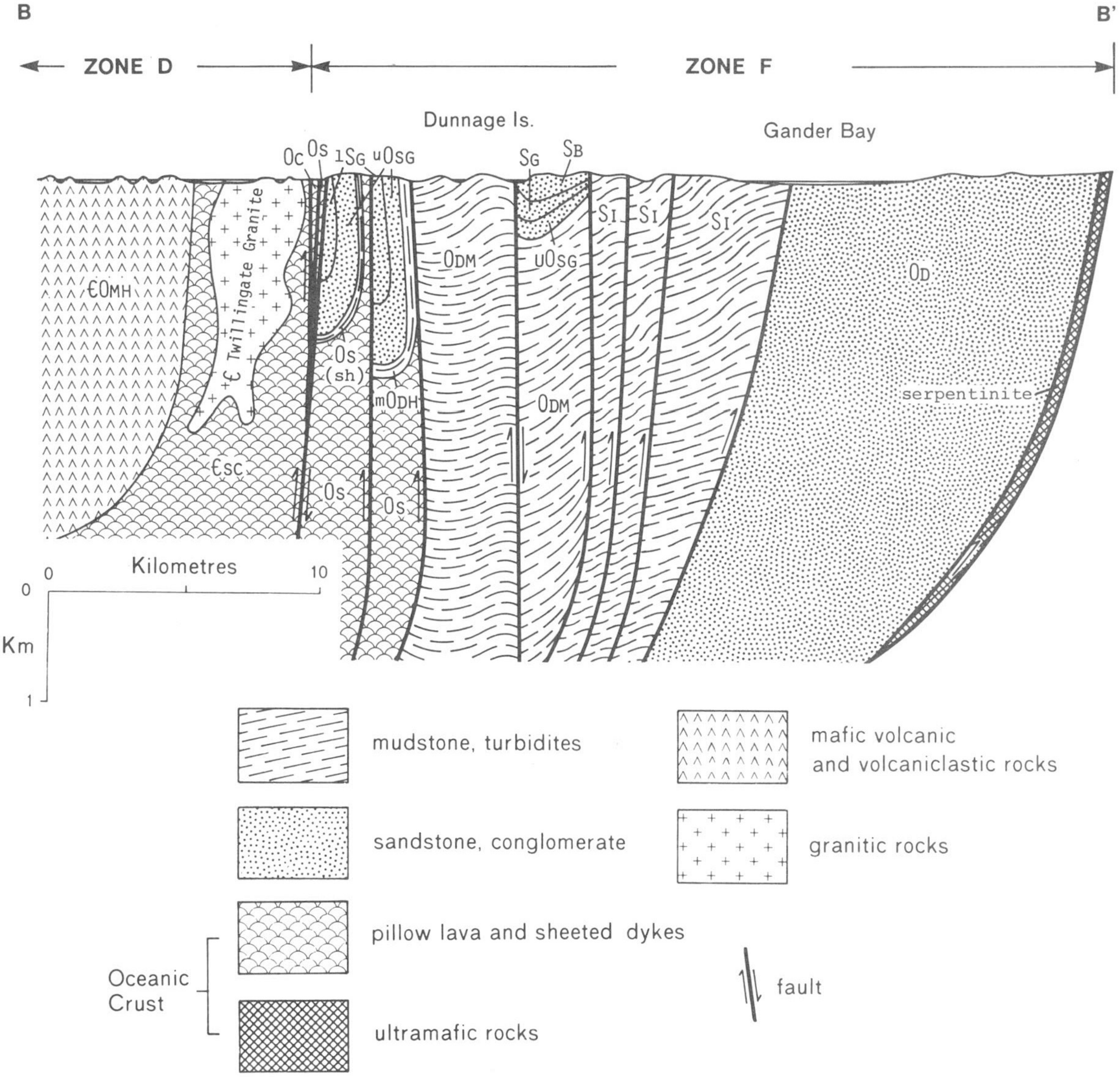


***Figure 4.*** *Structural cross-section of Zones D and F in the Twillingate and Gander area. Location of section shown on Figure 1. The formations are identified in Table 1.*

contain sedimentary, volcanic, and plutonic fragments. The structurally-stacked allochthons moved into Zone A by gravity sliding, at least in the later stages of transport (Brückner, 1975; Rodgers and Neale, 1963).

The neoautochthonous Long Point Formation (Middle Ordovician) unconformably overlies the Humber Arm Allochthon (Rodgers, 1965) and is probably unconformably overlain by terrestrial sediments of the Silurian-Devonian Clam Bank Formation. Farther to the west, in the Gulf of St. Lawrence (Anticosti Island), black shale of the Macasty Formation (Upper Ordovician) interrupted the carbonate deposition which had started in the Early Ordovician. The shale was probably derived from the southwest in association with the emplacement of the allochthon in Gaspé Peninsula. Widespread carbonate deposition resumed in the Late Ordovician and persisted throughout the Silurian and Early Devonian.

In western White Bay, immediately to the east of the Long Range Peninsula, the boundary between Zones A and B is marked by the Doucers Valley Fault Complex defined by Lock (1972). The Coney Arm Group (Lock, 1969, 1972), which outcrops immediately to the west of the fault complex, is lithologically similar to the continental shelf deposits of the lower clastic and middle carbonate sequences in the Gulf of St. Lawrence. The shelf-edge or slope deposits of the Cow Head Group of the Humber Arm Allochthon may have been derived from a site immediately to the east of the present outcrop of the Coney Arm Group (Lock, 1972).

***Zone B***

Whereas Zone A is characterized by continental shelf deposits and Zone C is characterized by continental rise deposits (Stevens, 1970; Williams et al., 1972), the rocks of Zone B represent continental slope deposits. The striking limestone breccias that occur in the Cow Head Group and the Cooks Brook Formation of the Humber Arm Allochthon in Zone A probably were deposited originally immediately to the east of the Doucers Valley Fault Complex (Lock, 1972). These rocks are best described as shelf-edge or slope deposits. For the purpose of this paper, "continental slope" is characterized by the deposition of limestone breccias which presumably were derived from mass wastage of shelf-edge carbonates. Limestone breccias are also present in the

Fleur de Lys Supergroup of Zone C, but they represent a perhaps more distal facies (i.e., continental rise deposits) than the limestone breccias and associated sediments of the allochthons (Bursnall and de Wit, 1975).

Most of Zone B in the White Bay area comprises Silurian volcanic rocks, volcaniclastic rocks and shallow-water sedimentary rocks, and Carboniferous sedimentary rocks. Because outcrops of pre-Silurian rocks are scarce, the pre-Silurian history is difficult to determine. However, if the original sites of the Humber Arm Slice Assemblage of the Humber Arm Allochthon and the Northwest Arm and Maiden Point Slice Assemblages of the Hare Bay Allochthon lie in Zone B as the author favours in this paper, then the geology of Zone B may be explained as follows:

The thick clastic units of the Summerside and Maiden Point formations are correlative and are Hadrynian to Early Cambrian in age (Williams, 1975). Both formations are lithologically similar to the Bateau Formation of Zone A, though much thicker and more variable in lithology than the Bateau Formation. Both the Maiden Point and Bateau formations are cut by diabase dykes similar to those that fed the flows of the Lighthouse Cove Formation. These clastic units (including the Lower Cambrian? Irishtown Formation) presumably are relatively shallow water deposits.

The lower clastic units of the Humber Arm Allochthon are overlain by a middle unit composed of thin bedded shale and limestone with prominent limestone-breccia beds (Cooks Brook Formation) and shale (Middle Arm Point Formation) ranging in age from Middle Cambrian to Early Ordovician. The Cow Head Group, which contains spectacular examples of limestone breccia, is a coarser equivalent of the Cooks Brook Formation (Williams, 1975). An easterly derived quartzofeldspathic flysch sequence containing sparse ophiolite detritus (Blow-Me-Down Brook Formation) forms the upper division. The easterly derivation of these flyschoid sediments in the early Middle Ordovician is related to the destruction of the previously stable continental margin by obduction of oceanic crustal rocks. The slice assemblages of the transported rocks in this stage were made up of volcanic and plutonic rocks which correspond to the oceanic crust and the upper part of the mantle and metamorphic rocks. The westwardly emplaced allochthon eventually overrode and incorporated the flyschoid sequences. Tectonically stacked sequences of these slice assemblages were finally emplaced together with the underlying sedimentary sequences as a discrete allochthon into Zone A by gravity sliding.

Williams (1977a) recently identified another allochthon at Coney Head in western White Bay and named it the Coney Head Complex. It consists of a variety of granitic rocks and mafic intrusive rocks, and it correlates, in part, with the Little Port slice assemblage of the Humber Arm Allochthon. The Coney Head Allochthon occurs in fault contact with the autochthonous, mainly carbonate sequence of Zone A, and is unconformably overlain by the Silurian Sops Arm Group.

### *Zone C*

Zone C is characterized by continental rise deposits (Stevens, 1970; Williams et al., 1972). The boundary between Zones B and C is designated herein as the Hampden Fault, which was defined by Lock (1972), although the original transition from continental slope to rise undoubtedly was not this abrupt. The eastern boundary of Zone C in the Burlington Peninsula is herein drawn at the Baie Verte Lineament, which was defined by Williams et al. (1977) as a zone of discontinuous mafic-ultramafic complexes that trend northeastward through the central portion of the peninsula. In contrast, Williams et al. (1972) included all of the Burlington Peninsula in Zone C, with the exception of a small coastal area in the vicinity of Nippers Harbour and Snooks Arm on the east side of the peninsula. Church (1969) correlated the rocks on both sides of the Baie Verte Lineament and subdivided them into western and eastern divisions of the Fleur de Lys Supergroup. Williams et al. (1977), however, recently suggested that this implied correlation of rocks and structures across the lineament was erroneous, at least in part, and emphasized the contrasting stratigraphy and structure on either side of the lineament. De Wit (1974) reported outcrops of Grenvillian basement rocks in the western division, and hence this area is continental. Miller and Deutsch (1976) suggested on the basis of geophysical data that the rocks of the eastern division differ from those of the western division in that oceanic crustal rocks of Zone D-type are probably present at depth in the eastern division. DeGrace et al. (1976) and Williams et al. (1977) also concluded that rocks which originated as oceanic crust probably underlie the eastern division. All these lines of evidence suggest that Zone C should be restricted to the west side of the Baie Verte Lineament.

According to the reinterpretations cited above, Zone C is composed of the Fleur de Lys Supergroup (White Bay and Harbour sequences of Kennedy, 1971) and the Birchy Schist Group (Bursnall and de Wit, 1975). The Fleur de Lys Supergroup consists of mainly polydeformed psammitic to semi-pelitic schists metamorphosed to greenschist and amphibolite facies (Kennedy, 1971). The Birchy Schist Group consists of basic schists interlayered with psammitic and pelitic schists (Bursnall and de Wit, 1975).

The Fleur de Lys Supergroup unconformably overlies a Precambrian orthogneissic and paragneissic basement complex which has been considerably remobilized during the tectono-metamorphic event that affected the Fleur de Lys Supergroup (de Wit, 1974). The Fleur de Lys metasediments surrounding the elongate area of basement outcrops form a large "outwards-younging" domal structure (Bursnall and de Wit, 1975). The basal part of the Fleur de Lys Supergroup is characterized by metaconglomerates of probable fluviatile origin (de Wit, 1974). The conglomerates are succeeded by a thick and monotonous sequence of metaclastic rocks. Both the metasediments and the basement complex are cut by mafic dykes that have been metamorphosed to amphibolite facies in the cover rocks and to eclogite facies in the basement rocks (de Wit and Strong, 1975). These authors correlated the mafic rocks with the diabase dykes and the plateau lavas of the Lighthouse Cove Formation of Zone A. A relatively thin metaclastic-metacarbonate succession overlies the metaclastic sequence. The carbonate-rich horizons have been described as the distal correlatives of parts of the Cow Head Group (Bursnall and de Wit, 1975) and other limestone-breccia beds of continental slope deposition.

The lithology and apparently great thickness of the Fleur de Lys Supergroup are consistent with deposition in a rift zone and, later, on an Atlantic-type continental margin during successive stages of continental breakup and seafloor spreading. The Atlantic-type continental margin has been discussed by many authors (Dewey and Bird, 1970; Falvey, 1974; Jansa and Wade, 1974; Beck and Lehner, 1974). The basal metaconglomerates correspond to terrestrial sediments that accumulated during the rifting phase and the overlying metasediments may be equated to sediments that accumulated on the newly-formed continental margin of the spreading proto-Atlantic Ocean. The succeeding metaclastics and metacarbonates probably represent sediments that accumulated on the continental rise during Middle-Late Cambrian to Early Ordovician times.

Various authors have interpreted the mafic dykes and plateau lavas in Zones A and C as having formed in an environment of continental rifting, distension, and separation during the inception of the proto-Atlantic Ocean (Dewey, 1969; Dewey and Bird, 1970; Bird and Dewey, 1970; Williams et al., 1972; Strong and Williams, 1972). In an attempt to reconcile the geology of the western proto-Atlantic Ocean and of the Avalon zone, I propose that the initiation of the proto-Atlantic Ocean predated the extrusion of these mafic volcanic rocks (dated as 605 Ma by Stukas and Reynolds, 1974a), for the following reasons: (1) In Zone C, a large volume of marine clastics accumulated before the emplacement of mafic volcanic rocks. If these clastics were deposited on an Atlantic-type continental margin, as seems probable, the margin must have existed for a considerable time before the extrusion of the mafic volcanics. (2) Hadrynian volcanism and metamorphism in Zones G and H are best explained in terms of an active continental margin, i.e., the tectonic history of Zones G and H necessitates that the proto-Atlantic Ocean was already extensively developed by late Hydrynian time. Consequently, the mafic dykes and plateau lavas in Zones A and C are herein interpreted as the products of tensional stresses that ultimately led to the development of new oceanic crust within or marginal to a pre-existing Hadrynian ocean. This new oceanic crust is presumed to have developed as a result of a small-scale spreading or spreading-like process in the manner described by Miyashiro (1975).

Based on a detailed geological survey, Williams et al. (1977) and Williams (1977b) recently have described the Birchy Complex as an assemblage of metamorphosed mafic volcanics, interlayered pelitic and psammitic schist, and ophiolitic mélanges with ultramafic and gabbroic blocks, various types of clastic sedimentary blocks, and locally marble blocks. They concluded that the Complex resulted from transport of Lower Ordovician or older ophiolitic complexes across undeformed Fleur de Lys strata producing a structurally imbricated assemblage which was later multiply deformed and metamorphosed. Thus most greenschists of the Birchy Complex are in slide contact with the Fleur de Lys metasediments.

The interlayering of basic schists with psammitic and pelitic schists observed locally in the Birchy Complex may be an original property of these rocks. Interlayering of sediments and volcanic rocks occurs at the boundary zone between continental crust and oceanic crust in the present Atlantic Ocean (Jansa and Wade, 1974; J.A. Wade, personal communication, 1976). Pelitic and psammitic rocks of the Birchy Complex may be a distal part of the Fleur de Lys Supergroup and the basic schist originally may have been volcanic rocks emplaced during the initial spreading of the proto-Atlantic Ocean. If so, the age of part of the Birchy metavolcanics probably is Hadrynian. The rocks have undergone the full sequence of deformation and metamorphism that characterizes the Fleur de Lys Supergroup, and they were complexly imbricated while the oceanic crust was obducted. At that time, a part of the obducted oceanic crust was accreted in the form of mélanges and ophiolitic assemblages, and probably equivalent rocks were incorporated into the allochthon as a structural slice (Old Man Cove slice of the Humber Arm Allochthon).

***Zones D and E***

Zone D occupies the area between the east side of the Baie Verte Lineament (including the mafic and ultramafic rocks of the lineament) and the Chanceport-Lobster Cove Fault. Zone E, to the south, is bounded on the east by the Northern Arm Fault (Dean and Strong, 1976a). Towards New World Island, Zone E pinches out between Zones D and F (Fig. 1, 4). The Chanceport-Lobster Cove Fault is a major east-west lineament that has been interpreted as an Acadian structure (Church, 1969; Williams et al., 1972; Dean and Strong, 1977). As the stratigraphy and tectonic setting of the Cambro-Ordovician rocks on either side of the fault are much the same, Zones D and E are described together.

Numerous studies of the volcanic rocks and mafic and ultramafic rocks have shown that island arc volcanic piles were gradually built upon pre-existing oceanic crust (Church and Stevens, 1971; Marten, 1971; Upadhyay et al., 1971; Smitheringale, 1972; Strong, 1973, 1977; Strong and Payne, 1973; Kean and Strong, 1975; Norman and Strong, 1975; DeGrace et al., 1976; Williams and Payne, 1975; Dean and Strong, 1976a-h).

The well-known Betts Cove Complex (Upadhyay et al., 1971) of western Notre Dame Bay consists of a basal ultramafic member, a poorly developed gabbro member, a sheeted dyke complex, and overlying pillow lavas. The general sequence of lithological units compares well with that of other ophiolites in the world and the group has been interpreted to represent a segment of oceanic crust and mantle. Pillow lavas of ophiolitic affinity are common in Zone D, e.g., parts of the Lushs Bight Group and the Sleepy Cove Formation of the Moretons Harbour Group. It is interesting that Miyashiro (1975) suggested that the Lushs Bight Group probably formed in an island arc setting, because it contains volcanic rocks of both calc-alkalic and tholeiitic series.

Typical ophiolitic rocks are also known along the Baie Verte Lineament (Church, 1969; Church and Stevens, 1971; Bird and Dewey, 1970; Norman and Strong, 1975; Kennedy, 1975; Bursnall and de Wit, 1975; Williams et al., 1977). The stratigraphy and structure of the area are the subject of conflicting interpretations and some classical terms are therefore abandoned, following the suggestions of Neale et al. (1975) and Williams et al. (1977). The terminology adopted by Williams et al. (1977) is followed in this report. The ophiolite and its volcanic cover along the Baie Verte Lineament are referred to the Advocate Complex and the Point Rousse Complex. The Advocate Complex has a steep foliation in most places and it is cut by numerous steep shear zones that repeat its rock units. It is composed mainly of ultramafic and mafic rocks. Sheeted dykes, pillow lavas, slate and slaty mélange are also present in the complex. The Point Rousse Complex is made up of several distinct structural blocks with their tectonic boundaries marked by foliated ultramafic rocks. It represents a full sequence of oceanic crustal rocks and some mantle materials. These rocks range in vertical sequence from interlayered ultramafic and gabbroic rocks to sheeted dykes overlain by pillow lavas and volcanic sediments (Norman and Strong, 1975).

The volcanic and volcaniclastic rocks that outcrop between the Baie Verte Lineament and the Betts Cove Complex are presumed to be underlain at depth by rocks which originated as oceanic crust (Miller and Deutsch, 1976; DeGrace et al., 1976; Williams et al., 1977). The existence of oceanic crustal rocks in Zone E has also been documented recently through detailed geological mapping (South Lake Ophiolite, Dean and Strong, 1976b).

The Bay of Islands Complex and the St. Anthony Complex constitute the structurally highest slice of the Humber Arm and Hare Bay allochthons respectively in Zone A (Williams, 1975). The Bay of Islands Complex includes the complete ophiolite suite of rock units from ultramafic rocks, through gabbros and sheeted dykes, to mafic pillow lavas. As well, the Complex includes a metamorphic aureole at its base and sedimentary rocks at its top. The St. Anthony Complex consists of ultramafic rocks that occur at the stratigraphic base of ophiolite suites, and an underlying metamorphic aureole. These rocks are comparable to the ophiolites of the Burlington Peninsula and Notre Dame Bay. Church and Stevens (1971) suggested that the ophiolites of the Betts Cove Complex, the Baie Verte Lineament and western Newfoundland were once a continuous sheet of oceanic lithosphere before disruption during emplacement.

The Twillingate Granite has intruded mafic volcanic rocks of the Sleepy Cove Formation of the Mortons Harbour Group. Three contrasting interpretations concerning the origin and possible tectonic significance of the Twillingate Granite and Sleepy Cove volcanics have been proposed: (1) The granite and volcanic rocks are a remnant of an older continental basement generally unrelated to surrounding Ordovician volcanic rocks (Williams and Malpas, 1972; Williams et al., 1972, 1974); (2) The granite and volcanic rocks are integral parts of a single arc complex, and the lowest part of the volcanic pile may possibly represent oceanic crust (Strong and Payne, 1973; Williams et al., 1976); and (3) The granite and volcanic rocks represent a remnant arc that is surrounded by volcanic rocks of a younger arc (Williams and Payne, 1975). These views need revision, at least in part, because geochemical studies have shown that the mafic rocks of the Sleepy Cove Formation are typical oceanic tholeiites rather than island arc volcanic rocks associated with plate subduction (Dean and Strong, 1976d).

The author proposes that the Twillingate Granite is an integral part of the original oceanic crust, of which the Sleepy Cove Group is representative. The general occurrence of leucocratic rocks within ophiolitic assemblages has been mentioned by numerous authors (Reinhardt, 1969; Moores and Vine, 1971; Davies, 1971; Coleman and Peterman, 1975; Coombs et al., 1976; and others). Such rocks have been reported from present-day spreading ocean ridges as well (Aumento, 1969; Miyashiro et al., 1970). These leucocratic rocks are characterized by an extremely low potassium content (Aumento, 1969; Coleman and Peterman, 1975). The Twillingate Granite shows this characteristic (Williams and Payne, 1975) and is comparable to "oceanic plagiogranite" as described by Coleman and Peterman (1975). A similar geological interpretation is possible for the Little Port Complex of the Humber Arm Allochthon and granitic rocks of the Coney Head Allochthon, which are remarkably similar to the Twillingate Granite in mineralogy, texture, chemistry and geological setting (Williams and Payne, 1975; Williams, 1975, 1977a).

Evidence for the age of the ophiolitic complex in Zones D, E and A is indirect and inconclusive, but a Cambrian or Early Ordovician age is favoured by most authors. Stukas and Reynolds (1974b) reported an $^{40}Ar/^{39}Ar$ age of 495 ± 5 Ma for the Brighton Gabbro which has intruded and therefore provides a minimum age for the Lushs Bight Group in the Pilley's Island region. Zircon ages determined for the Twillingate Granite and granitic rocks of the Little Port Complex are 510 and 508 Ma respectively (Mattinson, 1975; Williams et al., 1976). The ophiolites intruded by these rocks, therefore, are probably late Cambrian in age, if the interpretation given above for the origin of the Twillingate Granite and granitic rocks of the Little Port Complex is correct. Ophiolitic rocks of the Betts Cove Complex are directly overlain by Lower Ordovician (Arenig) sediments. Black shale interlayered with pillow lavas and other volcanic rocks of the Cape Onion Formation in the Hare Bay Allochthon contains Tremadocian (Early Ordovician) graptolites (Williams, 1971). In consideration of this evidence, it is concluded that the ophiolites and leucocratic rocks represent oceanic crust primarily of late Cambrian age which developed at a spreading centre near the western margin of the proto-Atlantic.

The ophiolitic rocks are conformably overlain by volcanic and volcaniclastic rocks which range in age from Early to Middle Ordovician. Early Ordovician fossils were found in the Snooks Arm Group at Betts Cove (Snelgrove, 1931) and in the Western Arm Group of the Little Bay area (MacLean, 1947), and Middle Ordovician fossils have been reported from the Cutwell Group in the Long Island area (Williams, 1962; Strong and Kean, 1972). The Moretons Harbour Group, excluding the Sleepy Cove Formation, the Wild Bight Group, which overlies the South Lake Ophiolite Complex (Dean and Strong, 1976b), the lower part of the Exploits Group, and the Roberts Arm Group[1] are all correlated on the basis of lithologic similarities with the fossiliferous Lower and Middle Ordovician volcanic and sedimentary sequences mentioned above. The volcanic rocks of these groups include calc-alkaline rocks and are considered to represent a thick Lower to Middle Ordovician island arc sequence built upon the Cambrian oceanic crust (Strong and Payne, 1973; Kean and Strong, 1975; Strong, 1977).

The Baie Verte Lineament is bordered to the east by metamorphosed mafic volcanics of the Pacquet Harbour Group and psammitic schist of the Mings Bight Group. These are followed farther east by the Cape Brulé Porphyry and dominantly felsic volcanic rocks of the Cape St. John Group. No major stratigraphic and structural breaks have been recognized between the Mings Bight, Pacquet Harbour and Cape St. John groups (DeGrace et al., 1976). Traditionally, the Mings Bight Group has been correlated with the Fleur de Lys Supergroup on the basis of their lithologic similarities and structural history. On structural grounds, the three groups – Mings Bight, Pacquet Harbour, and Cape St. John – were recognized as the eastern division of the Fleur de Lys Supergroup (Church, 1969). These correlations, however, are presently untenable, at least in part, because an unconformable relationship between the presumed Lower Silurian Cape St. John Group and the Lower Ordovician Snooks Arm Group has been described by Neale et al. (1975) and DeGrace et al. (1976). Miller and Deutsch (1976), DeGrace et al. (1976) and Williams et al. (1977) concluded that ophiolitic rocks underlie the Cape St. John Group. The present author assumes the age of the ophiolites to be Cambrian. If this is so, both the Mings Bight and Pacquet Harbour groups may be Ordovician in age and the Pacquet Harbour Group may be partly equivalent to the Snooks Arm Group. The psammitic sediments of the Mings Bight Group may have been shed from the seaward side of the allochthon as it was being emplaced, just as the quartzofeldspathic flysch of the Blow-Me-Down Brook Formation of the Humber Arm Allochthon probably accumulated in front of the advancing allochthon before being incorporated into it. Poole (1976) assumed that detritus from the assembling slices was carried seaward to be deposited upon ophiolitic rocks such as those of the Snooks Arm Group.

The presence of Upper Ordovician rocks in Zone D has not been confirmed, although the upper part of the Pacquet Harbour Group is possibly of this age in view of the fact that

[1] The age of the Roberts Arm Group is debatable; on the basis of stratigraphic evidence, Dean and Strong (1976f) concluded that the age was Late Ordovician to Silurian, but recent Rb-Sr age determinations by the Geological Survey of Canada on the Roberts Arm volcanics and the granite which cuts them give Middle or possibly Late Ordovician dates (Bostock et al., 1979).

no major stratigraphic break has been recognized between that group and the overlying Silurian sequence. In Zone E, island arc volcanic rocks are overlain by graptolitic black shale of Caradocian age. The shale is succeeded locally by the Upper Ordovician Sansom Greywacke and in other localities by mafic volcanic rocks (Frozen Ocean Group) (Dean and Strong, 1976a,b,c). The Sansom Greywacke is overlain by volcanic and volcaniclastic rocks in the central part of Zone E (Cottrells Cove Group) (Dean and Strong, 1976c,e) and coarse clastic rocks of the Goldson Group at the eastern margin of Zone E. The volcanic rocks of the Cottrells Cove Group are calc-alkaline in nature (Strong, 1973, 1977). The Sansom Greywacke and the Goldson Group also outcrop extensively in Zone F of New World Island. The detritus composing the groups was derived from a source area to the northwest (Horne, 1970). It may be inferred from these considerations that Zone D was mainly undergoing erosion during the Late Ordovician, and that the resulting detritus was supplied to Zones E and F, where it became interlayered with volcanic rocks.

An extensive belt of mainly subaerial volcanic rocks of Early Silurian age (Cape St. John, Mic Mac, and Springdale groups) extends from Zone D on the Burlington Peninsula to the western side of Zone E. DeGrace et al. (1976) described the calc-alkaline nature of the volcanic rocks of the Cape St. John Group. Within the Springdale Group, the dominantly volcanic basal part is overlain by red conglomerate and sandstone of the upper part (MacLean, 1947; Kalliokoski, 1953). It thus appears that the island arc was in a mature state of development in Early Silurian time, that subaerial volcanism was predominant and that terrestrial deposits accumulated in depositional sites within the island arc system.

### *Zone F*

Zone F occupies the area between the Northern Arm Fault (Dean and Strong, 1976a) and the belt of mafic and ultramafic rocks between the Gander and Davidsville groups to the southeast. The mafic and ultramafic rocks are included in Zone F. The northwestern boundary is marked by the northwestern limit of Dunnage Mélange along the Bay of Exploits and by the Chanceport-Lukes Arm Fault on New World Island.

Numerous workers have attempted to unravel the stratigraphy and tectonic history of the structurally complicated area of New World Island (Williams, 1963, 1964; Williams and Hibbard, 1976; Harris, 1966; Kay, 1967, 1970, 1972, 1975; Kay and Eldredge, 1968; Horne, 1969, 1970; Dean and Strong, 1976d). The well-known Dunnage Mélange (Kay and Eldredge, 1968; Horne, 1969; Kay, 1972, 1976; Williams and Hibbard, 1976) consists of laminated argillite containing an extraordinary assortment of sedimentary and mafic volcanic clasts and exotic blocks of predominantly pillow lava and greywacke up to hundreds of metres long. Dewey (1969) suggested that this mélange represents a deposit which is characteristic of an oceanic trench and subduction zone. This concept has been followed by authors who maintained that a subduction zone dipped northwestward beneath the Paleozoic Central Mobile Belt (Bird and Dewey, 1970; Dewey and Bird, 1970; Horne, 1970; Kay, 1972, 1973; Williams, 1975; Williams et al., 1972, 1974; Williams and Payne, 1975; Williams and Hibbard, 1976; Poole, 1976). I attribute much of the complicated stratigraphy and structure of Zone F to this northwest-dipping subduction.

The Ordovician rocks that lie between the Chanceport-Lukes Arm Fault and the Dunnage Mélange have been referred to as the Summerford and Chanceport groups, and those that lie southeast of the Dunnage Mélange as the Campbellton Sequence. These units have the following characteristics in common: (1) The predominant rock-types are mafic volcanic rocks, siliceous argillite and chert, and sandstone. (2) The sedimentary successions locally coarsen upwards. (3) The strata are commonly steeply dipping and consistently north-facing or isoclinally folded. (4) Repetition of strata across deeply dipping faults is common. (5) A thin unit of highly deformed black shale occurs at the base of some groups (Strong and Payne, 1973). The Summerford Group consists of a complex succession of mafic volcanic and sedimentary rocks. The geology of these rocks is characterized by repetition of the sequence across steeply dipping faults, by lithologic variation from area to area, by isoclinal structure, and by a general coarsening-upward succession of sediments (Horne and Helwig, 1969; Horne, 1970). Fossils range in age from Tremadocian to Llandeilian (Lower to Middle Ordovician) (Kay, 1967; Horne, 1970; Bergström et al., 1974). Strong and Payne (1973) gave the name 'Chanceport Group' to approximately 3 km of pillow lavas and sedimentary rocks exposed in an area bounded by the Chanceport Fault to the north and the Lukes Arm Fault to the south on Moreton's Harbour Peninsula of New World Island. The sequence is steeply dipping and consistently north-facing. The repetition of mafic volcanic rocks and sedimentary rocks in the succession suggests the existence of steep faults. The age of the group is uncertain. The Campbellton Sequence is characterized by mafic volcanic rocks, and siliceous argillite with manganiferous chert and sedimentary rocks (Kay, 1975). Kay (1975) considered the Campbellton Sequence as probably of oceanic origin, perhaps ocean floor that was being subducted in the trough in which the Dunnage Mélange was formed. The age of the sequence is uncertain.

The Summerford Group is overlain by the Sansom Greywacke and the Goldson Formation, ranging in age from Late Ordovician to Early Silurian. The Dunnage Mélange is directly overlain by the Caradocian (Middle Ordovician) shale of the Dark Hole Formation, which is in turn overlain by the Sansom Greywacke and Goldson Formation. The Sansom Greywacke and Goldson Formation are composed of turbidites that were derived from the northwest, presumably from the island arc terrane of Zones D and E (Horne, 1970).

The Indian Islands Group lies to the east of the Dunnage Mélange and contains Early Silurian fossils. This group consists mainly of siliceous argillite, sandstone, and conglomerate. Highly sheared slate and phyllite are the most common rock-types of this group (Baird, 1951; Williams, 1964). These rocks consistently differ in lithology and structure from those of equivalent age in adjacent areas (i.e., the Goldson and Botwood formations).

The strata of Zone F described above are assigned to two main assemblages. One assemblage is composed of relatively unmetamorphosed and weakly deformed turbidites (Sansom Greywacke and Goldson Formation). The other consists of sheared and steeply dipping strata of varied lithology, and includes the Dunnage Mélange and the Indian Islands Group. The rocks of the latter assemblage are restricted in distribution to narrow belts bounded by steeply-dipping faults, whereas the strata of the turbidite assemblage extend over a wider area. Steeply-dipping faults are numerous and the present author suggests that many of them originated before deposition of the turbidite assemblage, and were reactivated after the turbidites were deposited. The structural and sedimentary characteristics of each assemblage indicate that they may represent an accretionary complex and sediments of the mid-slope terrace, respectively, in an arc-trench gap (Dickinson, 1971a) as described by Karig and Sharman (1975), Moore, J.C. and Karig (1976), and Moore, G.F. and Karig (1976).

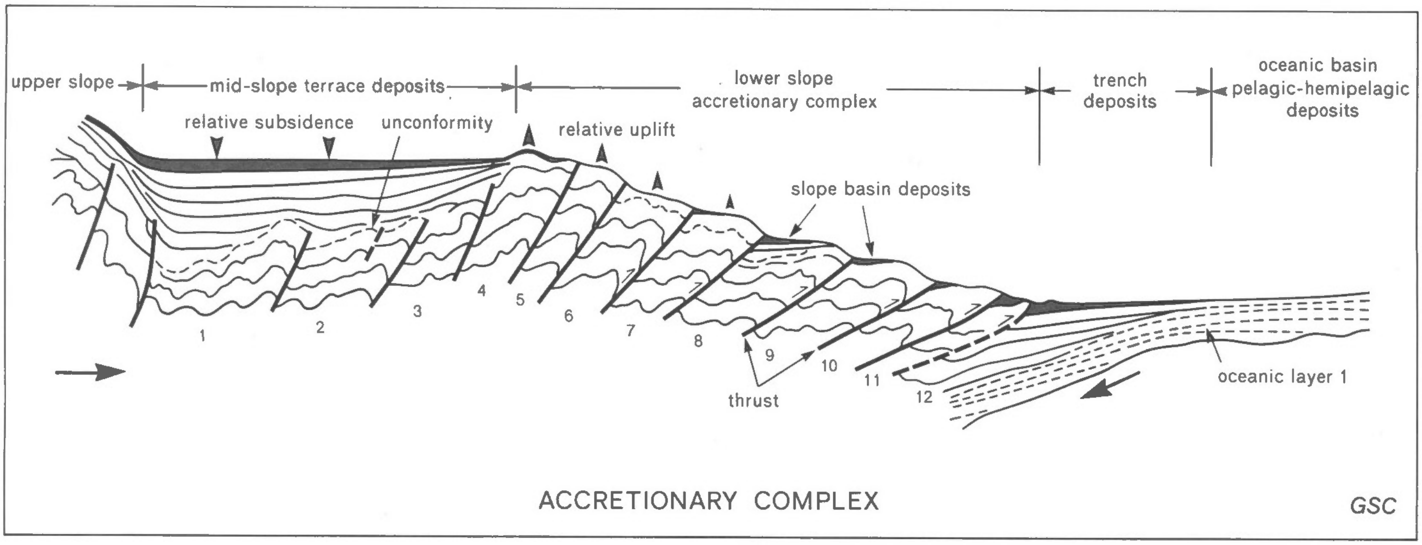


***Figure 5.*** *Evolutionary model for the frontal part of the arc-trench gap (Kanmera, 1976). Numbers indicate relative age of thrust slices and black areas show the youngest deposits.*

Seely et al. (1974), Karig and Sharman (1975), and Kanmera (1976) have proposed models for the evolution of a trench margin. It is generally agreed that abyssal sediments and parts of the oceanic crust are stripped off the downgoing oceanic plate during subduction and accreted, together with trench sediments, in fold or thrust packets to the base of the lower trench slope. The accretionary complex imbricated to the lower trench slope eventually may form a linear ridge, although this zone of uplift does not extend far behind the trench slope break. A progressively enlarging body of sediments is commonly ponded behind this ridge as described by Karig and Sharman (1975) (Fig. 5). Moore, J.C. and Karig (1976) have proposed that this type of sedimentary assemblage is associated with the Shikoku subduction zone of southwestern Japan, along the Nankai Trough where the Philippine Sea plate is underthrust beneath the Asian plate. The accretionary complex is characterized by a coarsening-upward sequence of trench and abyssal sediments and by isoclinal folds and fracture cleavage, despite the Quaternary age of the complex.

In central Newfoundland, the Sansom Greywacke and Goldson Formation may correspond to sediments of the mid-slope terrace, and the Summerford Group, Chanceport Group, Campbellton Sequence, Dunnage Mélange, and Indian Islands Group may correspond to the accretionary complex. If this is the case, the mafic volcanic rocks and siliceous argillite and chert which overlie or are intimately associated with the mafic volcanic rocks may be equated with oceanic layer 1 and part of layer 2. The Dunnage Mélange may once have been located at the trench-slope break (Dickinson, 1973) or outer ridge (Den and Yoshii, 1970).

The eastern half of Zone F is occupied by the Davidsville Group which consists of slate and greywacke with minor mafic volcanic rocks. The Group contains Middle Ordovician fossils and was considered by Kennedy and McGonigal (1972) to unconformably overlie the Gander Group of Zone G. A mélange occurs at the contact between Zones F and G (Blackwood and Kennedy, 1975), and it has been suggested that this mélange is similar in origin to the Dunnage Mélange (Williams et al., 1974). Probably the Davidsville Group originally accumulated on the continental margin of the Avalon subcontinent and the source area lay to the east in Zones G and H. In time, the Davidsville strata were accreted to the complex of rocks on the eastern side of Zone F. This could have taken place during a late structural phase, when the proto-Atlantic Ocean had entirely closed. Presumably, the mélange developed tectonically at or near the boundary zone between the Davidsville and Gander groups, where the latest surface of imbrication movement was located. According to this reasoning, the belt of mafic and ultramafic rocks also represents a mélange in which a piece of oceanic crust was incorporated tectonically into the thrust zone. If this is the case, a stratigraphic gap is assumed to occur between the Davidsville Group and the Gander Group[1].

After the development of the mélange, the mainly terrestrial Botwood Group filled a relatively narrow trough on the site of the former proto-Atlantic, between the former island arc of Zones D and E and the continent or subcontinent represented by the rocks of Zones G and H.

### *Zone G*

Zone G occupies the area between the belt of mafic and ultramafic rocks and the Dover Fault (Blackwood and Kennedy, 1975). The zone is characterized by a basement gneiss complex of possible Helikian age, overlain by polydeformed metasedimentary rocks of the Gander Group. The zone is also distinctive for the existence of a variety of granitic intrusive rocks of various ages (Kennedy and McGonigal, 1972; Blackwood and Kennedy, 1975).

[1] Recent work by Pickerill et al. (1978) and Parjari and Currie (1978) clarified the detailed lithology and the nature of the Davidsville Group, and indicated that an unconformity may not exist between the Gander and Davidsville groups and that the two groups may be partly age equivalent. The latter authors suggested that the source area of the Davidsville sediments lay to the west (i.e., the island arc of Zones D and E). Their description of the lithology of the Davidsville Group strongly suggests that the Group includes trench-fill deposits and rocks of the accretionary complex. If this is the case, the Davidsville Group is also comparable to the assemblage of the Summerford Group, Chanceport Group, Campbelton Sequence, Dunnage Mélange and Indian Islands Group, and the entire area of Zone F corresponds to an ancient arc-trench gap.

The Bonavista Bay Gneiss Complex (Blackwood and Kennedy, 1975) consists of quartzofeldspathic, mafic and granitoid gneisses. The Gander Group consists of a thick sequence of dominantly quartzofeldspathic and semipelitic metasedimentary rocks. Kennedy (1976) suggested that this Group represents a continental slope-rise succession. Geological relations in Zone G indicate that these rocks were deformed prior to the Middle Ordovician. The Hadrynian Musgravetown Group and correlatives of Zone H contain fragments of various kinds of foliated rocks (Jenness, 1963; Kennedy, 1976) and detrital muscovite and garnet (Papezik, 1972; Poole, 1973), indicating that metamorphic rocks existed nearby during the Late Hadrynian. By extrapolation, the rocks of the Gander Group were probably deformed and metamorphosed at the same time as these pre-Musgravetown rocks.

### *Zone H*

Zone H is separated from Zone G by the Dover Fault (Blackwood and Kennedy, 1975). Zone H is about 200 km wide in onshore eastern Newfoundland, to which an additional 500 km can be added if most of the Grand Banks of Newfoundland are included (the Virgin Rocks on the Grand Banks, 160 km southeast of St. John's, Newfoundland, consist of probable Hadrynian rocks (Lilly, 1966)). The geology of the northern and eastern parts of this zone has been described by a number of workers (e.g., Rose, 1952; Hutchinson, 1953, 1962; Jenness, 1963; McCartney, 1967; McCartney et al., 1966; Hughes and Brückner, 1971; King et al., 1974).

King et al. (1974) discussed the geology of the Avalon Peninsula in terms of three major assemblages, which developed successively in fundamentally differing paleogeographic settings. The lower assemblage comprises terrestrial and marine mafic tó felsic volcanic rocks, closely related volcanic sedimentary rocks, and felsic plutonic rocks consanguineous with felsic volcanics. The middle assemblage consists of thick detrital sequences predominantly composed of debris derived from rocks of the lower assemblage. The upper assemblage unconformably or disconformably overlies the other two and comprises a sequence of orthoquartzites disconformably overlain by sequences of mudstone, limestone, shale and sandstone. The two lower assemblages are assigned an Hadrynian age and the upper assemblage ranges in age from the latest Hadrynian to Early Ordovician. Hughes (1970) and Hughes and Brückner (1971) proposed that the volcanic rocks, the Holyrood granitoid pluton and the marine volcanic sediments formed in a series of calc-alkalic volcanic island environments. This interpretation has been disputed, however, on the grounds that at least some of the volcanic rocks are mildly alkaline and that the Holyrood granitoid pluton of the calc-alkaline suite appears to be genetically unrelated to the volcanic rocks (Papezik, 1970, 1972; Strong and Minatidis, 1975). Papezik (1970, 1972), Strong (1977), and Strong and Minatidis (1975) alternatively suggested a post-orogenic block-faulting environment of the "basin and range" type. This model implies that the volcanism in Zone H was that of an active continental margin and was associated with a tensional tectonic condition in a continental area.

The volcanic and volcaniclastic rocks of the lower assemblage were metamorphosed soon after their accumulation, especially in the western part of the zone. Metamorphic detritus derived from these rocks was supplied to the middle assemblage of thick clastics.

## TECTONIC MODEL

Since Dewey (1969) and Bird and Dewey (1970) proposed their revolutionary plate tectonic model for the evolution of the Appalachian-Caledonian orogenic belt, various models have been proposed for the development of the Newfoundland Appalachians (Stevens, 1970; Dewey and Bird, 1971; Church and Stevens, 1971; Williams et al., 1972, 1974, 1977; Williams and Stevens, 1974; Williams and Payne, 1975; Strong et al., 1974a,b; Strong, 1977; Kennedy, 1975; Poole, 1976; DeGrace et al., 1976; and others). These authors produced models with certain features in common: (1) They delineated a former mobile belt that was flanked by two continental margins (the ancient continental margin of eastern North America and that of the Avalon subcontinent as defined by Williams and Stevens (1974)). (2) They hypothesized the existence of a proto-Atlantic Ocean between the two continental blocks, at least during late Hadrynian and early Ordovician times. This ocean was initiated by continental rifting, distension and separation. (3) They postulated that a volcanic arc developed in the oceanic area from the Early Ordovician onward.

The models also include important differences: (1) Although it is generally agreed that an island arc existed at least in Ordovician time as a result of subduction processes, two alternative models regarding the polarity of subduction have been proposed. Bird and Dewey (1970) identified the Dunnage Mélange as a trench deposit on the east side of the island arc volcanic rocks, and on this basis inferred that the subduction zone dipped west or northwest. Church and Stevens (1971), however, concluded that the subduction zone dipped toward the east or southeast, and that ophiolites were emplaced on the Western Platform as a result of the underthrusting of the western continental margin beneath oceanic lithosphere. Their interpretation is supported by both the geochemistry of the igneous rocks and the present distribution of mineral deposits (Strong et al., 1974a,b). (2) In view of the conflicting interpretations, the nature of the oceanic basin represented by the ophiolites of the Western Platform and the Central Paleozoic Mobile Belt is uncertain. The ophiolites might have originated in a series of small marginal ocean basins separated by an island arc or arcs from the main proto-Atlantic Ocean (Dewey and Bird, 1971; Kennedy, 1975), or they may represent the remnants of a single obducted sheet of the proto-Atlantic oceanic crust and mantle (Church and Stevens, 1971).

A schematic representation of the model proposed by the present author is given in Figure 6. In addition to this figure, restored sections showing the tectonic development and structural relationships of western Newfoundland are presented in Figure 7. The model incorporates the common features mentioned above and adopts the interpretation that a westward-dipping subduction zone existed during latest Cambrian to Early Silurian times in relation to the eruption of island arc volcanic rocks in the Central Paleozoic Mobile Belt. The proto-Atlantic Ocean existed during Hadrynian (ca. 750 Ma ago) to Early or Middle Silurian times. Ophiolites in Zones A, D and E have originated by a spreading-like process in the proto-Atlantic Ocean in Cambrian time.

### *Hadrynian*

The volcanism and metamorphism in Zones G and H during Hadrynian time are regarded as evidence that the proto-Atlantic Ocean existed to the west of the Avalon subcontinent as early as Hadrynian. Drake et al. (1959) have pointed out striking analogies between the morphology and crustal structure of the present-day North Atlantic continental margin and Kay's (1951) restored section for the Northern Appalachians. Dietz (1963) and Dietz and Holden (1966) proposed a model for the present Atlantic-type margin and suggested that the modern Atlantic "miogeocline" is the precursor of a miogeosyncline like the ancient lower

Paleozoic Appalachian example. Similar reconstructions for the Appalachian orogenic belt were later proposed by Bird and Dewey (1970), Dewey and Bird (1970, 1971), Stevens (1970), and Williams and Stevens (1974). The present author supports the conclusion that the proto-Atlantic Ocean had Atlantic-type continental margins before it started to close.

The Fleur de Lys Supergroup, which consists of a thick sequence of mainly continental margin metasediments, strongly suggests an Atlantic-type continental margin as the setting for their accumulation. Therefore, the North American continent and Avalon subcontinent (a part of the European-African continent) are assumed to have been continuous before the initiation of the proto-Atlantic ocean. To the northwest of the Newfoundland Appalachians, the North American craton consists of schists, gneiss, granulite, granite, anorthosite, marble, etc., of Archean to Helikian age, which were deformed, metamorphosed, intruded, and uplifted and eroded during the Grenvillian orogeny (ca. 1000 Ma). Grenvillian rocks are exposed within Zones A, B and C. The nature of the continental basement of the Avalon subcontinent is uncertain, although the gneiss terrane of Zone G has been suggested to represent Grenvillian basement rocks which probably occur at depth beneath much of Zones G and H (Kennedy and McGonigal, 1972).

In Hadrynian time, the North American-European supercontinent began to distend along the axis of the future Appalachian orogenic belt. This stage of development may be compared to the tectonic evolution of the Red Sea, as described by Hutchinson and Engels (1970, 1972). Major domal uplift along the axial rift (Fig. 6a and 7a) was succeeded by the generation of a major flanking fault system (Fig. 6b and 7b). Block subsidence along successive flanking faults resulted in the deposition of coarse clastic sediments, comprising mostly terrestrial facies. The basal metaconglomerates of the Fleur de Lys Supergroup in Zone C may have been deposited in this type of setting (Fig. 6c and 7c). Dewey and Bird (1970) regarded the thinning and subsidence of continental crust during rifting to be the result of crustal stretching. Falvey (1974), however, proposed that such thinning and subsidence is a result of the crust and lithosphere being affected by thermal processes. Falvey's interpretation is followed in this paper.

The sea transgressed over the continental margin of eastern North America following continental separation, and clastic sediments such as the psammitic and pelitic rocks of the lower Fleur de Lys Supergroup were deposited on a newly formed continental shelf. The depositional area included Zones B and C, and in latest Hadrynian time gradually extended into Zone A (Fig. 7e, f).

Fine grained metasediments of the Birchy Schist Complex possibly are a distal facies of the sediments of the lower Fleur de Lys Supergroup. These metasediments are locally interlayered with mafic volcanics which may have been generated at, or near, the accreting plate margin (Fig. 7c). New oceanic crust was produced during a spreading phase of the proto-Atlantic Ocean in the Hadrynian (Fig. 6d). The thick clastic wedge of the Fleur de Lys Supergroup accumulated on the continental margin of eastern North America during this period. The psammitic and pelitic schists of the Gander Group in Zone G may also represent sediments of equivalent age that accumulated on an Atlantic-type continental margin on the western side of the Avalon subcontinent (Fig. 6d).

The timing of the initial rifting and continental separation is uncertain in the Newfoundland Appalachians. The flood basalts and diabase dykes of the Lighthouse Cove Formation have been correlated with similar rocks of the Catoctin Formation in the southern Appalachians (Strong and Williams, 1972). This correlation, however, may not be adequate because of the age difference between these formations (zircons from the Catoctin Formation yielded an age of approximately 820 Ma, Rankin et al., 1969). The exact thickness of the Fleur de Lys Group is not known, although a thickness of 30 000 feet has been estimated (e.g., Williams and Stevens, 1974). This thickness roughly compares to that of the sedimentary succession of the modern Atlantic continental margin in eastern North America. In the case of the present North Atlantic, volcanic activity associated with continental distension took place about 200 Ma ago, whereas the initiation of continental drift began approximately 30 Ma later (Jansa and Wade, 1974). In general, initial rifting and the associated emplacement of mafic volcanic rocks typically precede the development of oceanic crust by approximately 50 Ma (cf. Huchinson and Engels, 1972; Falvey, 1974). If an age of about 800 Ma is assumed for continental distension in the Newfoundland Appalachians, then the actual separation of the continental crust took place about 750 Ma ago. Deposition of the Fleur de Lys Supergroup presumably continued for about 250 Ma, in view of the probability that destruction of the Atlantic-type continental margin in eastern North America started, at the latest, in Early Ordovician time.

In Zone H, a thick pile of volcanic rocks erupted in the "basin and range" type block-faulting environment of the Late Hadrynian (Papezik, 1970, 1972; Strong and Minatidis, 1975). Scholz et al. (1971) expanded upon the idea of Karig (1970, 1971a,b) and suggested that the "basin and range" province represents an ensialic interarc basin which is of extensional origin. In the Basin and Range province, the early stages of volcanism are characterized by intermediate composition calc-alkaline lavas with large volumes of associated silicic ash-flow tuffs of island arc type (Lipman et al., 1971), and that of the later stage is characterized by an abrupt change to basaltic volcanism associated with the "basin and range" type normal faulting (Christiansen and Lipman, 1972). Therefore, the volcanic rocks and the associated volcaniclastic rocks of Zone H may have been generated in an active continental margin under conditions of tensional tectonics. These rocks, however, were metamorphosed and deformed soon after their accumulation, particularly in the western part of the zone (Love Cove Group). Detritus, derived mainly from the volcanic and volcaniclastic rocks, accumulated in a thick clastic sequence unconformably above the older rocks. These clastics were unconformably overlain, in turn, by stable platform-type sediments during the latest Hadrynian. On the other hand, the thick sediments of Zone G were strongly affected by a metamorphic event which probably is correlative with that which affected the Love Cove Group in Zone H judging from the metamorphic detritus in the Hadrynian Musgravetown Group (Kennedy, 1976).

This type of tectonic evolution, in which tensional tectonics and volcanism are followed by metamorphism, may be the same as that proposed by Nakamura (1969) for the geological development of the Green Tuff Region of Japan. The Japan Sea side of the Japanese islands is characterized by thick volcanic and sedimentary piles that resulted from subsidence and subsequent submarine volcanism in Miocene time. This geologic province is referred to as the Green Tuff Region because the volcanic and volcaniclastic rocks show a greenish colour as a result of alteration. Subsidence occurred along faults trending parallel to the present island arc. The principal volcanism was preceded by the development of these faults. In addition to the thick piles of volcanic and pyroclastic rocks that accumulated during the early stage of development, several thousand metres of clastic sediments were later deposited during basinal subsidence. Welded tuff has been recognized in areas that were uplifted during later stages of volcanism (Fujita, 1972; Ichikawa et al., 1972).

The geological setting of Zone H is analogous to that of the Green Tuff Region. The geological development of Zones G and H, in terms of Nakamura's model, is explained as follows: In Late Hadrynian, a subduction zone was initiated dipping southeastward beneath the western margin of the Avalon subcontinent, which at that time was located on the east side of the proto-Atlantic Ocean (Fig. 6e). The ocean may have reached its maximum width at that time. The subduction process generated compressive stresses close to the subduction zone but these stresses gradually gave way to tensional tectonics farther from the subduction zone (Matsuda and Uyeda, 1971; Sleep and Toksöz, 1971). Deep-seated fissures developed in the area of tensional stress. The volcanic rocks of Zone H emanated along such fissures, through tensionally attenuated continental crust (Fig. 6e). At the same time, a change of tectonic conditions from a stable Atlantic-type condition to a compressional condition in the continental margin caused the deformation and metamorphism of the rocks of both the Gander Group and presumably the underlying continental basement of Zone G. Deformation and metamorphism resulted in shortening of the area. The western edge of the Avalon subcontinent, in contact with the subduction zone, started to be destroyed and to be incorporated into a subduction zone. As a result, the original area of tensional tectonics in Zone H slowly migrated relatively westward into an area in which compressional tectonics prevailed (Fig. 6f). This type of situation, i.e., the destruction of a continental margin and dragging of continental crust into a subduction zone, was discussed by Nakamura (1969) as a model for the evolution of the margin of the Japan trench in northeast Japan.

Deformation and metamorphism continued in Zone G and the western part of Zone H until Late Hadrynian time. Volcanism may have changed from basin and range-type to island arc-type in these areas. Plutonism was very active in Zone G and was intimately related to the metamorphism. The Holyrood Granite intruded the Harbour Main Group of volcanic and volcaniclastic sequences in Zone H (Fig. 6f). This cycle of deformation, metamorphism and plutonism has been referred to as the Avalon Orogeny in Zone H (Lilly, 1966; Rodgers, 1967, 1972; Poole, 1967; Poole et al., 1970; Hughes, 1970) and the Ganderian Orogeny in Zone G (Kennedy, 1975, 1976).

Following the Avalonian and Ganderian disturbance, Zone G was uplifted and Zone H became a stable area of platformal sedimentation. The platformal sedimentation in Zone H continued until Early Ordovician time. The author assumes some stratigraphic gap(s) between the Gander Group (Hadrynian?) and the Davidsville Group (Middle Ordovician) across the intervening belt of mélange and mafic and ultramafic rocks. It is therefore difficult to trace the development of the margin of the Avalon subcontinent later than Hadrynian and to determine whether this stable Early Paleozoic platform represents a cessation of subduction, although no major geological event is evident in eastern Newfoundland until the Acadian Orogeny.

In latest Hadrynian time, major changes affected the Atlantic-type continental margin on the western side of the proto-Atlantic Ocean. Continental tholeiite and associated diabase dyke swarms accumulated in Zone A and also became interlayered in the continental margin sediments of Zone C (Fig. 6f and 7f). These events are attributed to the initiation of a small-scale spreading or spreading-like process which created new oceanic crust in Cambrian time. Lower Paleozoic carbonatites and alkaline intrusions along the north shore of the St. Lawrence River and the Labrador coast (Doig and Barton, 1968; Doig, 1970) are interpreted as resulting from the same episode.

### *Cambrian*

Following the extrusion of tholeiitic plateau lava of the Lighthouse Cove Formation and intrusion of the associated diabase dykes in the latest Hadrynian, new oceanic crust probably developed at or near the continental margin during the Cambrian (Fig. 6g), which is supported by the following observations. As previously noted, the ophiolite suites represented in Zones D and E, and in the allochthons of Zone A probably were produced in Cambrian time. Leucocratic rocks intimately associated with oceanic crust are represented by the Twillingate Granite and granitic rocks of the Little Port slice assemblage of the Humber Arm Allochthon and possibly the Coney Head Allochthon. These intrusive rocks may represent "oceanic plagiogranite" that differentiated from magma at the new spreading centre. The Twillingate Granite and granitic rocks of the Little Port slice assemblage are remarkably similar in mineralogy, texture, chemistry, geological setting and isotopic age, although those outcrops are now about 250 km apart. The zircon ages for the Twillingate Granite and granitic rocks in the transported Little Port slice assemblage are 510 and 508 Ma respectively (Mattinson, 1975; Williams et al., 1976). Assuming that the Little Port slice assemblage was emplaced by obduction, it originally may have been situated in the northwesternmost part of the newly formed oceanic crust. The Twillingate Granite, on the other hand, is located near the easternmost outcrop of ophiolites. These phenomena are satisfactorily explained if both the Twillingate Granite and granitic rocks of the Little Port slice assemblage originated, at the latest, in Late Cambrian time by differentiation at the spreading centre of the newly developing Cambrian seafloor, perhaps in the earliest phase of a spreading-like process, and then became separated and moved to the east and west respectively, with continued spreading. Such leucocratic rocks may have developed during a period of slow spreading rates (Moores and Vine, 1971; Coleman and Peterman, 1975).

The development of new oceanic crust presumably was initiated in the western periphery of pre-existing Hadrynian oceanic crust (Fig. 6f, g). A few remnants of older oceanic crust, such as that represented by part of the Birchy Schist, may have existed to the west of the new oceanic crust, and the rest of the older oceanic crust migrated to the east.

Lower Cambrian clastic sediments transgressed westward to directly overlie Grenvillian basement on the Lower Paleozoic Atlantic-type continental margin of eastern North America, and the deposition of the Fleur de Lys Supergroup continued on the continental rise (Fig. 7f). In the continental shelf area of Zone A, deposition of thick carbonate rocks, which overlie Lower Cambrian clastics, began during Middle-Late Cambrian time (Fig. 7g). A carbonate bank was established at the shelf edge. Seaward of the carbonate bank of Zone A, sediments of Zone B were deposited on the continental slope. The characteristic sedimentary facies of Zone B are limestone and some breccias that were derived from the bank edge. The area of the continental rise is represented by Zone C. This pattern of continental-margin sedimentation (carbonate bank, slope breccia, and continental rise deposits) lasted from the Middle-Late Cambrian to Early Ordovician.

### *Ordovician*

The ophiolites of Zones D and E are directly overlain by an island arc assemblage of mafic volcanic and volcaniclastic rocks of Early Ordovician age. This occurrence of island arc volcanic rocks suggests a reversal of plate motion from divergence to convergence in the zone of the western margin of the proto-Atlantic Ocean. The tectonic setting of this island arc was much the same as that of some of the island arcs of the present-day western Pacific region. Miyashiro (1975) noted that the ophiolite complex of Yap in the

Izu-Mariana Arc appears to be a piece of oceanic lithosphere which had existed before the initiation of the island arc suite of rocks in this locality. Shiraki and Maruyama (1976) extended this explanation and demonstrated that preceding the development of Yap, small-scale spreading was initiated in pre-existing oceanic crust, and as a result, new oceanic crust was formed. Soon after its formation, the new and hot oceanic crust became uncoupled from the pre-existing oceanic crust. The older oceanic lithosphere then began to be subducted beneath the new oceanic lithosphere and in due course the island arc developed above the subduction zone. The island arc volcanic rocks of Zones D and E are of both tholeiitic and calc-alkalic series (Strong, 1973, 1977; Strong and Payne, 1973; Kean and Strong, 1975; Norman and Strong, 1975; DeGrace et al., 1976). Kushiro (1975) established through his experimental work that the presence of $H_2O$ would cause the generation of calc-alkalic andesite magmas, and suggested that $H_2O$ would be supplied from the subduction zone by the decomposition of hydrous minerals such as amphibole, mica and chlorite. If the island arc volcanic rocks of Zones D and E developed in this manner, it is possible that the subduction zone was initiated as late as Early Ordovician (Fig. 6h). The time-lag between subduction and volcanism has been calculated to be 14 Ma in the Green Tuff Region in Japan. During such a time-lag, volatile elements may have accumulated from the subducted plate in the low-velocity layer (Horikoshi, 1975). Therefore it is likely that subduction in western Newfoundland was initiated in latest Cambrian time.

As previously noted, two contrasting interpretations have been proposed regarding the polarity of this subduction zone. Church and Stevens (1971) suggested that the emplacement of the ophiolite sheets in Newfoundland may reflect an early phase in the closing of a proto-Atlantic Ocean by underthrusting of the North American plate eastward along an easterly or southeasterly dipping subduction zone. Coleman (1971), however, noted that obduction zones in general tend to be characterized by a complete lack of volcanic activity and by a shallow seismic zone that dips oceanward. In this context, it is not necessary that obduction occur combined with subduction, although the combination appears to provide a plausible mechanism for ophiolite obduction. Strong et al. (1974a, b) supported the hypothesis of an east-dipping subduction zone on the basis of a uniform increase in the potash content of granitic rocks across Zones F, G and H. Their conclusion, however, should be viewed in the light of the following considerations. (1) Their samples were collected from granitic rocks of mainly Middle Devonian age, although they also included granites of other ages, such as the Holyrood Granite of Late Hadrynian age. By the Middle Devonian, however, the proto-Atlantic Ocean was probably closed. Therefore the chemistry of the granites does not necessarily relate to the volcanic activity of Ordovician time. (2) Most of their samples were collected from Zones G and H, whereas most of the island arc volcanic rocks now occur in Zones D and E. This implies either that the volcanic arc developed in the geological framework of Zones G and H, or that the proto-Atlantic Ocean was a marginal sea or a small ocean as suggested by Church and Stevens (1971). The former case is unlikely in view of the nature of Zone F, where there is a great discontinuity across the trace of the subduction zone. The latter is not consistent with the probability that appreciable oceanic crust was consumed during the development of the island arc. (3) The samples possibly include granitic rocks of various origins. The Twillingate Granite, which has an extremely low potash content, is explained as an oceanic plagiogranite by the present author. (4) The volcanism of Zone B in the Early Silurian is not consistent with a subduction zone dipping eastward from the western side of Zone D. On the contrary, Bird and Dewey (1970) inferred that the subduction zone dipped west on the basis of the nature of the Dunnage Mélange. This author suggested above that Zone F consists of an accretionary complex formed in an oceanic trench at a subducting margin, and mid-slope terrace sediments on a "basement" of accretionary complex material. If this is so, the subduction zone that dipped northwest beneath Zones D and E was initiated in the future site of Zone F. It is further suggested that oceanic crust that was produced in Hadrynian time started to subduct, at the latest, in Early Ordovician time, beneath oceanic crust which was created in Cambrian time. It may be speculated that the old, cold and dense (Hadrynian) oceanic crust was readily underthrust beneath the new and hot (Cambrian) oceanic crust during an early phase of the closing of the proto-Atlantic Ocean. With continued subduction, island arc volcanism became very active in Zones D and E. Zones A, B, and C and the northwestern sides of Zone D became an area of trapped marginal ocean behind an island arc (Fig. 6h).

In front of the island arc, fault-bounded slices (accretionary complex) composed of trench sediments, abyssal sediments and oceanic crustal rocks were gradually added to the lower trench slope as subduction proceeded (Summerford Group, Chanceport Group, Dunnage Mélange and Campbellton Sequence). Fragments of green rocks in this accretionary complex were derived from ocean crust of Hadrynian age. Zone F slowly evolved as an area between the trench and active volcanoes (the arc-trench gap of Dickinson, 1971a) (Fig. 6i). Zone F is in striking contrast to the continental margin of Zones G and H in Late Hadrynian time, where a part of the continental margin material was destroyed and dragged into the subduction zone.

During the period that subduction was in progress to the east of the island arc, new (Cambrian) oceanic crust was being obducted to the west onto the continental margin of Eastern North America (Fig. 6h, i, 7h, i). Armstrong and Dick (1974) considered that a necessary condition for the formation of a major overthrust sheet in an orogenic belt is an unusually steep geothermal gradient such as is now observed in only two tectonic settings – behind volcanic arcs and over mid-ocean rises and continental rift zones. In such circumstances, the boundary between brittle and ductile behavior, when considered in the context of geological time, occurs at very shallow depth. During a period of compressive stress, the near-surface brittle rocks may be readily detached from the underlying ductile rocks to form a thrust sheet. The present author applies this concept to the evolution of the allochthons in Newfoundland. The necessary condition of a steep geothermal gradient presumably was realized in the region of newly created (Cambrian) oceanic rocks. The region was subjected to tensional tectonics during the development of the new oceanic crust, but compressional tectonic forces related to subduction and directed from the east became dominant at latest in Early Ordovician time. It is likely that this transition of tectonic conditions triggered the detachment of the future allochthon from the underlying mantle when subduction was initiated. If this is the case, then subduction may have been initiated in latest Cambrian time. The stratigraphic evidence regarding the inception of obduction is uncertain. Metamorphic amphiboles from the metamorphic aureole of the allochthon have yielded an isotopic age by $^{40}Ar/^{39}Ar$ spectra of 460 Ma (Dallmeyer and Williams, 1975). Black shale interlayered with mafic volcanic rocks in the Cape Onion Formation of the Hare Bay Allochthon contains Tremadocian graptolites (Williams, 1971).

Church and Stevens (1971) and Church (1972) reported the presence of high-pressure mineral assemblages (spinel-lherzolite) in the basal part of the peridotite unit in the allochthons. A narrow, high-temperature metamorphic aureole, which occurs at the stratigraphic base of the transported ophiolite suites in the highest structural slices, was interpreted to be the result of obduction and initial transport of hot solids (Church and Stevens, 1971; Church, 1972; Williams and Smyth, 1973). The aureoles were stamped upon essentially undeformed and unmetamorphosed supracrustal rocks that lay at or near a continental margin (Williams and Smyth, 1973). The metamorphic grade of the aureoles decreases structurally downward and away from the overlying ultramafic rocks, resulting from downward decreasing temperature from the hot overthrust sheet. Judging from the thickness of ophiolites represented by the Bay of Islands Slice Assemblage, detachment occurred at a depth of approximately 10 km (Williams and Stevens, 1974) (Fig. 6h).

The detached sheet of oceanic crust and mantle began to move onto the continental margin not later than the earliest Ordovician. If the above model for the detachment is accepted, obduction would most probably have occurred mainly along the western margin of the belt of new oceanic crust and the eastern continental margin of North America (Fig. 6h). Almost all the transported rocks of western Newfoundland have lithic analogues in central Newfoundland, and the tectono-stratigraphic elements of the North American continental margin have been preserved in Zones A, B and C. It is most probable that the island arc was developed on the western margin of the proto-Atlantic Ocean. Widespread calc-alkaline volcanism in Zones D and E indicates that a large volume of the descending plate was consumed during the Ordovician to the Devonian. In view of these relationships, the author rejects the hypothesis of large scale easterly or southeasterly dipping underthrusting of the continental margin of eastern North America and its adjacent oceanic crust beneath oceanic lithosphere now represented by the ophiolites in Zones D and E.

The Advocate Complex, which is composed mainly of mafic and ultramafic rocks, was dislodged from the detached sheet and left in the root zone of obduction (Baie Verte Lineament (Fig. 7j). The Little Port slice assemblage was separated from the upper part of the detached oceanic crust and became preserved as a tectonic slice assemblage in the Humber Arm Allochthon (Fig. 7h). During movement of the detached oceanic crust and mantle, the Fleur de Lys Supergroup and the Birchy Schist were strongly affected by metamorphism. This metamorphism resulted from overriding by the thick and hot overthrust sheet, and by the associated lateral compressional stresses. The Old Man Cove slice, which is considered to be a fragment of the Birchy Schist, was stacked along with the Bay of Islands and Little Port slice assemblages (Fig. 7i).

Shortening and thickening of the continental crust occurred at the continental margin. The advance of the overriding sheet was accomplished not only by compressional tectonic forces, but also by crustal shortening in the area, because the overriding sheet was not confined by the surrounding rock bodies. The advance of the detached sheet was accompanied by subsidence of the continental margin and the resulting basin accommodated the deposition of a thick succession of easterly derived flysch in the east, and black shale in the west. Ophiolitic mélange formed in front of and beneath the advancing sheet of ophiolite complexes. These facies belts transgressed farther into Zone A as the allochthon advanced. The carbonate bank edge migrated westward and the earlier continental shelf limestones were covered by the flysch and shale (Fig. 7h, i).

Continuous compression from the east induced décollement in the detached sheet at Betts Cove. The Betts Cove Ophiolite Complex and the Snooks Arm Group of island arc volcanic and volcaniclastic rocks were thrust against the rocks of the Pacquet Harbour Group (Fig. 7i). The overthrusting was accompanied by the metamorphism of the Mings Bight and Pacquet Harbour groups. These groups were again affected by deformation during the Acadian Orogeny in Devonian time. Adjacent rocks of the Cape Brulé Porphyry and the Cape St. John Group (Lower Silurian?) were affected only by the Acadian Orogeny but not by the earlier, Ordovician diastrophism.

The rocks of the detached sheets acquired an anticlinal form as they overrode the continental margin, and continued compression from the east caused steep thrusts in the eastern flank of the anticline at the future site of the Point Rousse complex (Fig. 7h, i). The same kind of thrust may have originally bounded the Bay of Islands slice assemblage and Little Port slice assemblage. Eventually, the movement of the detached sheet stopped, possibly because the shortening of the area reached a critical amount. At this time, the frontal part of the tectonically stacked slice assemblages started to override flysch and mélange of Zone B (Fig. 6i and Fig. 7i). Isostatic adjustment and uplift took place in Zones B and C after the crust first had been depressed and thickened by the movement of the overriding detached sheet. This caused the separation of the detached sheet in Zones B and C from the root zone (Zones D and E) at the Baie Verte Lineament. The Point Rousse Complex was emplaced in its present position at this time. The disrupted and detached sheet in Zones B and C then slid by gravity into Zone A, along with the lower structural slice assemblages of the allochthon which were composed predominantly of clastic sedimentary sequences of Zone B (Fig. 7i). The timing of the gravity sliding of the allochthon is between graptolite zones **Didymograptus bifidus** (Llanvirnian) and **Nemagraptus gracilis** (Llandeilian) (Bergström et al., 1974).

The metamorphism, deformation and emplacement of the overthrust sheet of oceanic crust and mantle onto the continental margin of eastern North America during latest Cambrian to early Middle Ordovician time has been designated as the Taconian Orogeny (Poole, 1967). This orogeny was caused by contraction of a marginal sea area behind an island arc as a result of the convergence of the oceanic plates of the proto-Atlantic Ocean by northwest-dipping subduction.

In the western part of Zone A (Anticosti Island area), continental shelf conditions persisted from Cambrian to mid-Silurian (Wenlockian) and possibly later. Even the emplacement of the allochthon in the east did not interrupt these platformal conditions in the western part of Zone A, although a Llandeilian disconformity is present farther east (i.e., in western Newfoundland). Shallow water sediments of the neoautochthonous Long Point Formation were deposited unconformably above the allochthon in the Middle and Late Ordovician. Uplift and erosion of Zones B and C occurred more or less simultaneously.

Caradocian dark shale blanketed large parts of the area represented by Zones E and F. Deposition of this shale coincided approximately with the final movement of the allochthon during the Middle Ordovician. Strong (1977) suggested that subduction and volcanism ceased during deposition of the shale. He distinguished a period of early arc volcanism and a period of late arc volcanism, separated by a Middle Ordovician (Caradocian) black shale unit. During the Late Ordovician, large parts of Zone D were undergoing erosion. The resulting detritus was shed southeastward into Zones E and F, and much of it was ponded behind a ridge which formed as a result of the imbrication and partial uplift of the accretionary complex of Zone F.

### *Silurian and Devonian*

In Early Silurian time volcanism became active in Zones D, E and F, and even in Zone B (Fig. 6k). These areas subsided in latest Ordovician and earliest Silurian times and marine shallow-water sediments unconformably onlapped part of the former land area that had developed during the Middle and Late Ordovician. Subaerial volcanics accumulated in

Zone B and in the western part of Zone D, whereas submarine volcanism prevailed in Zone E in earliest Silurian time, but later gave way to subaerial volcanism. Both acidic and mafic volcanic rocks are represented.

Miyashiro (1974) described the regular and secular changes in the composition of volcanic rocks that take place during the evolution of an island arc by advancing accumulation of volcanic and volcaniclastic rocks. In an island arc, the proportion of calc-alkaline series rocks increases with progressive thickening of continental-type crust. This is accompanied by an increase in the proportion of felsic volcanic rocks and by an increase in the average percentage of $SiO_2$ in all of the volcanic rocks. These geochemical attributes are well developed in the Lower Ordovician to Lower Silurian, island arc volcanic rocks of Zones B, D and E.

By the Middle Devonian, the proto-Atlantic Ocean was completely closed when the eastern North American continent, including the island arc of Zones D and E, and the arc-trench gap area of the western half of Zone F, collided with the western Avalon subcontinent (Fig. 61). This collision resulted in the Acadian Orogeny, which is characterized by tight, upright folds, and which was accompanied by subvertical faults and granitic intrusion across the entire Appalachian belt. The effects of this orogeny were particularly severe in the zone where the island arc is sutured to North America (Zone C and the western side of Zone D) and to the Avalon subcontinent (Zones F and G). On the eastern side of Zone F, the Davidsville Group, which originally was deposited on the margin of the western Avalon subcontinent, was added to the accretionary complex of the arc-trench gap during the final phase of collision. A tectonic mélange and a belt of mafic and ultramafic rocks were emplaced between Zones F and G at this time. These mafic and ultramafic rocks may be relicts of the ancient oceanic crust which had developed in Hadrynian time.

## CONCLUDING REMARKS

In recent years, the continental margins have been the subject of increasing attention because of their fundamentally great geological significance. Modern continental margins can be basically classified as Atlantic-type or Pacific-type (Dewey and Bird, 1970; Beck and Lehner, 1974; Heezen, 1974; and others) depending on whether they have experienced a relatively long period of stability (Atlantic-type) or whether they have undergone active tectonism during later geological times (Pacific-type) (Heezen, 1974).

It has long been recognized in North America that orogenic belts represent deformed ancient continental margins. The ancient continental margins of both eastern North America and the Avalon subcontinent had developed as typical Atlantic-type continental margins during the spreading-expanding phase of the proto-Atlantic Ocean. These margins underwent collapse and extensional tectonics followed by regional subsidence. These stable continental margins, however, were modified to Pacific-type continental margins once closing of the proto-Atlantic Ocean started. According to plate-tectonic concepts, Pacific-type continental margins are zones of collision and consumption of the oceanic plate. Mitchell and Reading (1969), Dewey and Bird (1970) and Dickinson (1971b) have discussed the transformation of types of continental margins by shifting patterns of plate motions. Pacific-type continental margins would include two broad types: a) Andean- (Mitchell and Reading, 1969) or Cordilleran-type (Dewey and Bird, 1970) margins on which a magmatic arc is bordered by a trench with consumption of lithosphere from the oceanic side, and b) island arc-type margins (Mitchell and Reading, 1969) where the arc-trench system is separated from the continent by a marginal sea. The ancient continental margin of the Avalon subcontinent was of the former type, at least in late Hadrynian time. The ancient continental margin of eastern North America was characterized by the latter type from Late Cambrian to Silurian times. The arc-trench system of eastern North America was initiated in an oceanic region rather than by back-arc spreading at the continental margin, and the areas between the island arc and the continent were developed as a trapped marginal sea.

Small-scale collision between the North American continent and the island arc took place during latest Cambrian to Middle Ordovician times and Cambrian ophiolites composed of oceanic crust and mantle were partly obducted onto the continental margin of eastern North America. The Taconian Orogeny resulted from these events. The eastern margin of the North American continent, which was fringed by an island arc, collided with the Avalon subcontinent not later than Middle Devonian time, resulting in the complete closure of the proto-Atlantic Ocean. The Acadian Orogeny resulted from this event.

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