Geoscience Canada

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Volume 26, Number 2, June 1999

URI: https://id.erudit.org/iderudit/geocan26_2art01

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Williams, H., Dehler, S. A., Grant, A. C. & Oakey, G. N. (1999). Tectonics of Atlantic Canada. *Geoscience Canada*, *26*(2), 51–70.

Article abstract

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An understanding of the North Atlantic Ocean and its continental margins provides insights into the nature of lapetus and the evolution of the Appalachian Orogen. Likewise, an understanding of lapetus and the Appalachian Orogen raises questions about Uranus and the development of the Grenville Orogen. Modern tectonic patterns in the North Atlantic may have been determined by events that began before 1000 m.y.

# ARTICLE

## Tectonics of Atlantic Canada

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### SUMMARY

The tectonic history of Atlantic Canada is summarized according to a model of multiple ocean opening-closing cycles. The modern North Atlantic Ocean is in the opening phase of its cycle. It was preceded by an early Paleozoic Iapetus Ocean whose cycle led to formation of the Appalachian Orogen. Iapetus was preceded by the Neoproterozoic Uranus Ocean whose cycle led to formation of the Grenville Orogen. The phenomenon of coincident, or almost coincident orogens and modern continental margins that relate to repeated ocean opening-closing cycles is called the Accordion Effect.

An understanding of the North Atlantic Ocean and its continental margins provides insights into the nature of Iapetus and the evolution of the Appalachian Orogen. Likewise, an understanding of Iapetus and the Appalachian Orogen raises questions about Uranus and the development of the Grenville Orogen. Modern tectonic patterns in the North Atlantic may have been determined by events that began before 1000 m.y.

### RÉSUMÉ

L'histoire tectonique de la portion atlantique du Canada est présenté comme la résultante d'une série d'ouvertures et de fermetures océaniques. Selon ce modèle tectonique, l'Atlantique nord moderne serait actuellement dans sa phase d'ouverture. Au début du Paléozoïque, le cycle précédent de l'océan Iapétus a engendré l'orogène des Appalaches. L'océan Iapétus a été précédé au Néoprotérozoïque par l'océan Uranus, dont le cycle d'ouverture-fermeture a engendré l'orogène de Grenville. Le phénomène de coïncidence ou quasi-coïncidence du profil des diverses orogènes et des marges continentale modernes qui correspond aux multiples cycles d'ouvertures-fermetures se nomme l'effet accordéon.

La connaissance de l'océan Atlantique nord et de ses marges continentales permet d'appréhender certaines caractéristiques de la nature de l'océan Iapétus et de l'orogène appalachien. De même, une connaissance de l'océan Iapétus et de l'orogène appalachien suscite des pistes de questionnement sur l'océan Uranus et l'orogène de Grenville. Les profils de l'océan Atlantique nord actuelle pourrait bien être le résultat d'événements qui auraient débuté il y a environ 1 000 Ma.

### INTRODUCTION

Four thematic maps of Atlantic Canada, digital and in colour at 1:3,000,000, summarize the features of the region from central Labrador to the Bay of Fundy and offshore. These maps are tectonic assemblage (Williams and Grant, 1998), physiography (Macnab and Oakey, 1999), magnetic (Oakey and Dehler, 1998), and gravity (Dehler and Roest, 1998). Page size reductions are used as illustrations in Figures 2, 3, 4 and 5, respectively, and this written account is intended to complement the map presentations.

The region comprises two collisional orogens and a modern continental margin (Fig. 1). From northwest to southeast, the collisional orogens are the Grenville (1300-950 Ma) and the Appalachian (600-300 Ma) surrounded seaward by the Atlantic continental margin (250-0 Ma). The Grenville and Appalachian orogens are parallel for their entire lengths of more than 3000 km in eastern North America. Likewise the Atlantic continental margin parallels the Appalachian Orogen, except northeast of Newfoundland and Labrador. There, a bifurcation of the mid-Atlantic spreading axis transgresses both the Appalachian and Grenville orogens and separates Greenland from eastern North America. This circumstance provides complete cross sections of the truncated Grenville and Appalachian orogens in solid wave-washed cliff exposures.

The early Paleozoic ocean ancestral to the Atlantic and whose closing led to the Appalachian Orogen is called Iapetus (Harland and Gayer, 1972), mythical Greek father of Atlantis. The late Precambrian ocean ancestral to Iapetus, whose closing led to the Grenville Orogen, is called Uranus, a new name after the mythical Greek father of Iapetus and grandfather of Atlantis. The phenomenon of repeated, coincident cycles of ocean opening and closing *viz.* opening and closing of Uranus, opening and

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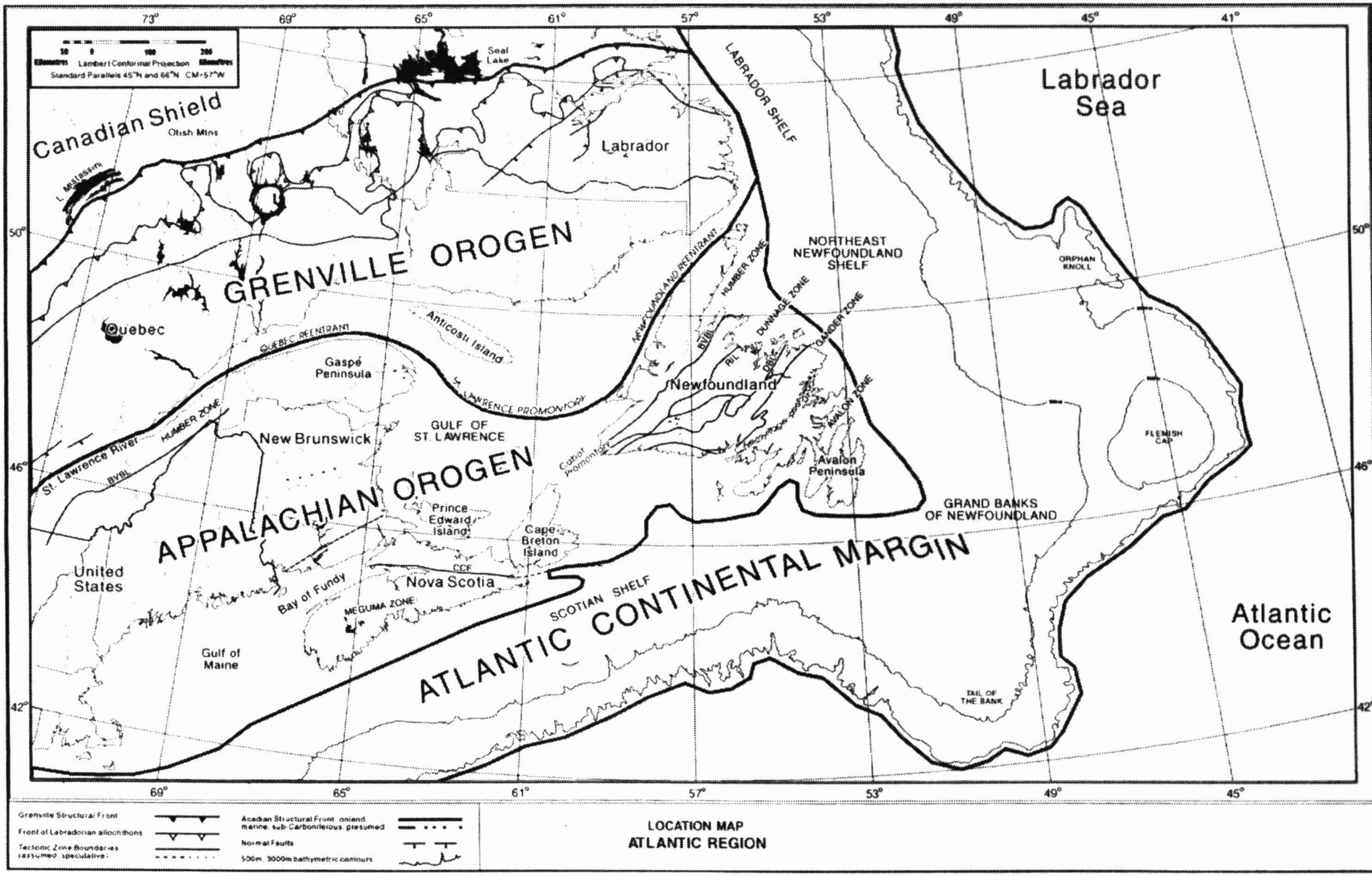


**Figure 1** Major tectonic elements of Atlantic Canada. Abbreviations are: BVBL - Baie Verte-Brompton Line; CCF-Cobequid-Chedabucto Fault; DBL-Dog Bay Line; DF-Dover Fault; RIL-Red Indian Line.

closing of Iapetus, then opening of the Atlantic, is called the Accordion Effect, or in Newfoundland, the Harry Hibbs Effect (Williams and Stevens, 1974) after Newfoundland's well-known accordionist.

Following the latest paleogeographic reconstructions, the closing of Uranus and Grenvillian Orogeny led to the assembly of Rodinia, a Neoproterozoic supercontinent (McMenamin and McMenamin ,1990). The closing of Iapetus and Appalachian orogenies led to the assembly of Pangea, a late Paleozoic supercontinent. Thus the Appalachian and Grenville orogens are collisional. Appalachian deformed rocks are recognized around the Atlantic Borderlands, dispersed by opening of the North Atlantic Ocean. Rocks of the Grenville Orogen are recognized worldwide, dispersed first by the opening and closing of Iapetus, then the opening of the Atlantic.

This paper summarizes the major structural and stratigraphic features of the modern Atlantic margin, the Appalachian Orogen, and the Grenville Orogen, and describes their geophysical expressions according to the latest magnetic and gravity data sets, and structural contours. We then compare constructional features of the North Atlantic Ocean with those of its Iapetus forerunner, and destructional features of Iapetus with tectonic features of the Grenville Orogen; thus developing insights into the demise of Uranus.

Analyses of the Atlantic margin and Appalachian miogeocline, or early Paleozoic Iapetus margin, are complementary. Whereas the Atlantic margin is analysed by remote tools of bathymetry, magnetics, gravity, seismics, and a few drill holes in deeply buried rocks, the uplifted and deformed Appalachian miogeocline has tremendous three-dimensional exposures of continuous stratigraphic sections. Since the Grenville Orogen lacks contemporary stratigraphic sections, its treatment emphasizes structural, metamorphic, and plutonic features. Comparisons with the Appalachian Orogen give some insight into the constructional phases of the Grenville Orogen and rationalizes its newly recognized major orogen-parallel belts.

## ATLANTIC CONTINENTAL MARGIN

### Definition and Extent

The Canadian Atlantic continental margin, related to the Atlantic cycle of the Accordion Effect, is a passive margin typical of those all around the Atlantic Ocean (Figs. 1, 2). The following account is taken from Keen and Williams, 1990 supported by some of our own data.

When the North Atlantic ocean began to open, eastern Canada lay in the middle of the supercontinent Pangea. Local rifting began in the Triassic (245 Ma) with the earliest ocean spreading beginning off Nova Scotia in the Jurassic (200 Ma) and progressing northward to the Grand Banks in the early Cretaceous (120 Ma), to northeast Newfoundland in the late Cretaceous (80 Ma), and to Labrador Sea in the early Eocene (53 Ma). The time of continental breakup can be defined stratigraphically at the continental margin by comparing the irregular synrift strata with the more uniform and continuous postrift strata. Postrift passive subsidence was controlled by cooling and thermal contraction of the lithosphere.

The Atlantic continental margin formed as a rifted margin, except for the segment bounded by the Southeast Newfoundland Transform (Fig. 2). Rifted margins are characterized by attenuated continental crust, stretched by normal faulting and shear deformation to about half of its usual thickness. Sedimentary rocks shed into the ocean basins underlie the continental shelf and slope and form a seaward-thickening wedge, out to a hinge line beyond which thicknesses increase markedly. The major Atlantic shelves include, from south to north, Scotian Shelf, the Grand Banks of Newfoundland, Northeast Newfoundland Shelf, and Labrador Shelf (Figs. 1, 2, 3). On the inner parts of the shelves, the pre-Mesozoic bedrock lies directly beneath relatively thin Quaternary sediments. Sediments at the continental rise merge with those overlying oceanic crust. At the Southeast Newfoundland Transform margin there is no broad zone of crustal thinning and it lacks a thick post-rift sedimentary sequence. These features are typical of margins formed by shearing and transform motion, and contrast with the thinned continental crust and thick sedimentary deposits formed at rifted margins by extensional forces.

The margin off northeast Newfoundland has the abnormally wide Orphan Basin and outer margin highs with thin cover at Orphan Knoll, Flemish Cap and Grand Bank. These highs are blocks of thicker crust seaward of the sedimentary hinge line, perhaps stranded by seaward stepping of the initial ocean spreading axes. This greatest stretching of continental crust at Orphan Basin developed within the Avalon Zone of the Appalachian Orogen. Where the ocean-continent transition is narrow in the region between the Charlie-Gibbs Fracture Zone and the Cartwright Arch to the north (Fig. 2), the basement is formed from other Appalachian zones or Grenville basement. An extensive zone of rifted continental crust, the presence of continental fragments, and the variable nature of post-rift subsidence are all anomalous features of the Orphan Basin.

The Mesozoic sedimentary basins of eastern Canada are part of a system of basins extending all along the eastern seaboard of North America. The present Canadian continental shelves are deeper in the north than in the south, and south of Cape Cod the sedimentary wedge of the rifted margin is exposed as the Atlantic Coastal Plain. Triassic-Jurassic rift basins are exposed within the Appalachian Orogen from the southeast United States to eastern Canada. The Fundy Graben is a local example. Many more are covered by Cretaceous and younger rocks and formed the locus for subsequent thicker deposition. Mesozoic sediments of the Jeanne d'Arc and Scotian basins are more than 20 km thick. The deeper basins of the Canadian margin are separated by arches or platformal areas of much thinner sedimentary cover. This alternation of basins and platforms is a distinctive feature, perhaps controlled by faulting.

### Tectonic and Stratigraphic Analysis

Late Triassic rifting that initiated the Canadian Atlantic margin extended from the northern Grand Banks to the Gulf of Maine, a distance of about 2000 km. The oldest sediments of narrow elongate rift basins are Upper Triassic nonmarine clastics, overlain by extensive Upper Triassic-Lower Jurassic salt deposits up to 2 km thick. In most regions the salt is overlain unconformably by carbonates followed by clastics. The change from salt to carbonate and the onset of clastics is interpreted to mark the onset of seafloor spreading in the Early to Middle Jurassic.

Lower Jurassic mafic volcanics and dykes occur in southern Nova Scotia and in northeastern Newfoundland. In

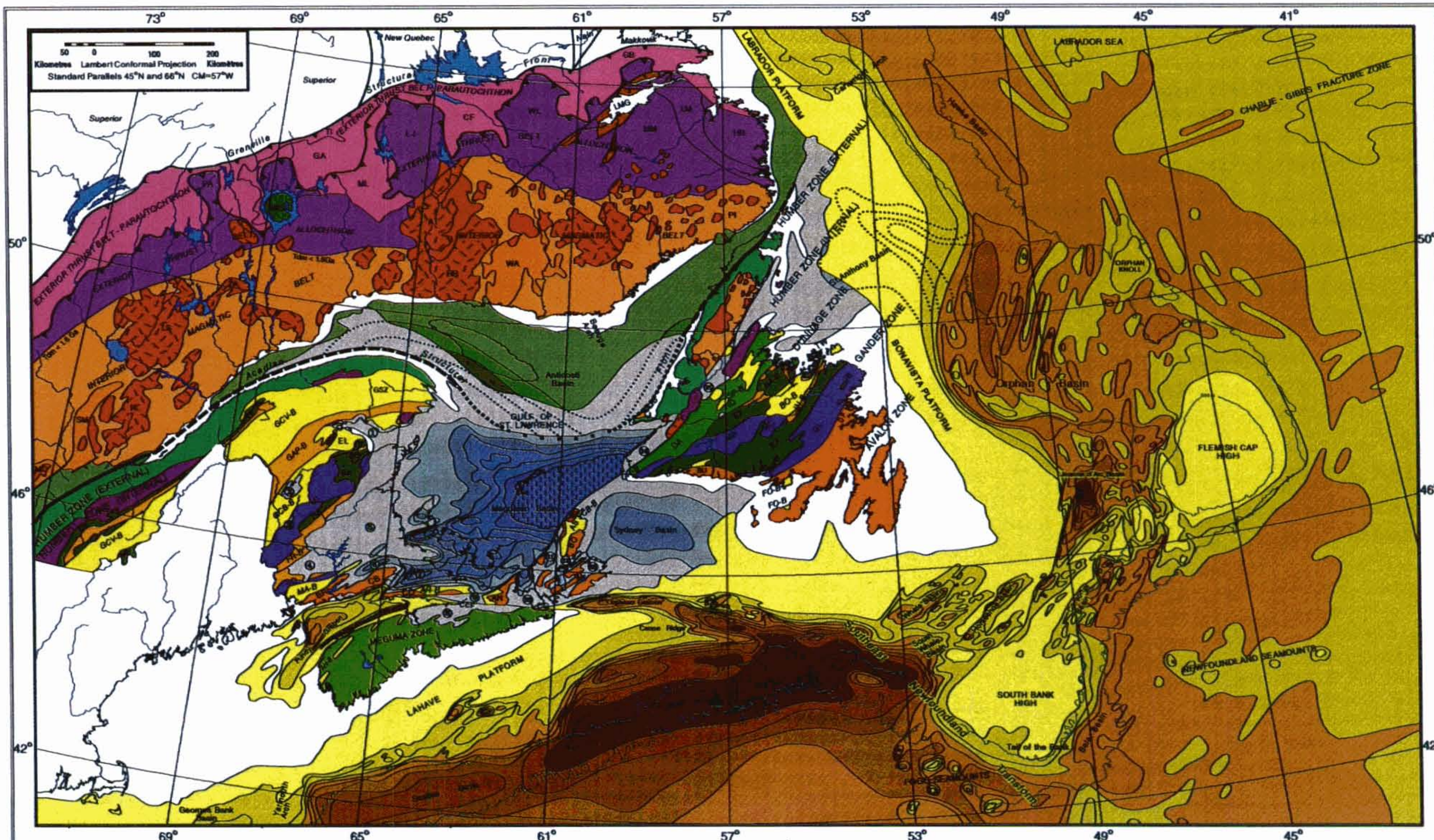


**Figure 2** Tectonic assemblages map, Atlantic Canada (from Williams and Grant, 1998).

## APPALACHIAN FORELAND

- Undeformed, mainly lower Paleozoic carbonates
- Upper Neoproterozoic redbeds of Lake Melville Graben

## APPALACHIAN OROGEN

### POST COLLISIONAL SUCCESSOR BASINS AND GRABENS

- Triassic and Jurassic volcanic rocks
- Triassic and minor Jurassic terrestrial sedimentary and volcanic rocks with associated mafic dykes and sills
- Carboniferous, mainly terrestrial sedimentary rocks

### COLLISIONAL SUCCESSOR BELTS

- Silurian and Devonian mainly terrestrial volcanic rocks, redbeds and terrigenous sedimentary rocks
- Upper Ordovician and Lower Silurian greywackes, conglomerates and marine turbidites

### APPALACHIAN MIOGEOCLINE

#### HUMBER ZONE (EXTERNAL)

- Cambrian-Ordovician carbonate sequence, includes Upper Neoproterozoic to Lower Cambrian rift facies volcanic rocks and clastic sedimentary rocks at base, foreland basin flysch at top, and Taconic allochthons
- Granitoid intrusions 1.2 - 1.0 Ma of Grenville inliers
- Anorthosite, gabbro 1.2 - 1.0 Ma of Grenville inliers
- Metamorphic rocks of Pinware Grenville inlier

#### HUMBER ZONE (INTERNAL)

- Upper Neoproterozoic to Lower Cambrian mainly psammites, pelites, metavolcanic rocks and small mafic-ultramafic bodies

### TERRANES OF IAPETUS TRACT AND ITS EASTERN MARGIN

#### DUNNAGE ZONE

- Cambrian and Lower Ordovician, mainly mafic volcanic rocks of Notre Dame and Twillingate subzones; granitoids, metasedimentary rocks, and mafic plutons of Dashwoods Subzone
- Cambrian and Lower to Middle Ordovician mixed volcanic rocks, shales, greywackes, cherts, limestones and melanges of Exploits Subzone and equivalents

#### GANDER ZONE

- Cambrian and Lower Ordovician quartzose greywackes, slates, and metasedimentary rocks

#### AVALON ZONE

- Middle to Upper Neoproterozoic volcanic and sedimentary rocks and associated intrusions, minor quartzite and marble, Cambrian and Lower Ordovician shales with Atlantic faunas

#### MEGUMA ZONE

- Cambrian and Lower Ordovician greywackes and shales

## GRENVILLE OROGEN

### EXTERIOR THRUST BELT - PARAUTOCHTHON

- Mainly Archean and Paleoproterozoic rocks bounded by Grenville Structural Front (northwest) and leading edge of ETB-allochthon (southeast). Rocks can be correlated with those of adjacent structural provinces outside the Grenville Orogen. Rocks affected by Grenvillian deformation and metamorphism but few (if any) contemporary plutons.

### EXTERIOR THRUST BELT - ALLOCHTHON

- Triassic volcanic rocks
- Upper Paleoproterozoic metamorphic and plutonic rocks bounded by front of Labradorian allochthons (northwest) and Tdm line of 1.6 Ga crust (southwest) or limit of numerous Grenvillian intrusions and Pinware boundary (northeast). Rocks emplaced during the Grenvillian Orogeny but already deformed and metamorphosed by the Labradorian Orogeny (1.6 - 1.7 Ga). Little or no correlation with rocks of the Exterior Thrust Belt - Parautochthon. Contains some Grenvillian plutons and many more pre-Grenvillian plutons, some of which occur in the ETB - Parautochthon or outside the Grenville Orogen, e.g. Trans Labrador Batholith.

### INTERIOR MAGMATIC BELT

- Granitoid intrusions 1.2 - 1.0 Ma
- Anorthosite, gabbro 1.2 - 1.0 Ma
- Middle Mesoproterozoic volcanic and sedimentary rocks of Wakeham Supergroup and equivalents
- Mesoproterozoic metamorphic rocks and associated plutons

**ATLANTIC CONTINENTAL MARGIN**
depth to pre-Mesozoic basement — 0 km, 4, 8, 12, 16, 20

**CARBONIFEROUS SUCCESSOR BASINS**
depth to pre-Carboniferous basement — 0 km, 4, 8, 12; evaporites

**APPALACHIAN FORELAND**
depth to pre-Paleozoic basement — 0 km, 4, 8

buried depth contours

### KEY TO STRUCTURAL LINES

- Grenville Structural Front
- Front of Labradorian allochthons
- Acadian Structural Front : onland, submarine, sub-Carboniferous, presumed
- Normal Faults
- 500m, 3000m bathymetric contours

**GRENVILLE TERRANES**

| | |
|---|---|
| AT | Atikonak |
| CF | Churchill Falls |
| GA | Gagnon |
| GB | Groswater Bay |
| HR | Hawke River |
| LA | Labrieville |
| LJ | Lac Joseph |
| LS | Lac St. Jean |
| LM | Lake Melville |
| MM | Mealy Mountains |
| ML | Molson Lake |
| MO | Morin |
| PA | Pambrun |
| PL | Parc des Laurentides |
| PI | Pinware |
| RR | Romaine River |
| SM | St. Maurice |
| TI | Timiskaming |
| WA | Wakeham |
| WL | Wilson Lake |

**OTHER FEATURES:**

| | |
|---|---|
| LMG | Lake Melville Graben |
| MIS | Manicouagan Impact Structure |

**APPALACHIAN SUBZONES**

| | |
|---|---|
| AN | Antigonish |
| AB | Armstrong Brook |
| AS | Aspy |
| BA | Bathurst |
| BE | Belledune |
| BL | Blair River |
| BO | Bras d'Or |
| BR | Brookville |
| BU | Burgeo |
| CB | Coldbrook |
| DA | Dashwoods |
| EL | Elmtree |
| EB | Estrie-Beaucé |
| EX | Exploits |
| GL | Gander Lake |
| GP | Gaspésie |
| HA | Hayesville |
| IB | Indian Bay |
| MP | Meelpaeg |
| ME | Mégantic |
| MR | Mira |
| MI | Miramichi |
| MC | Mount Cormack |
| ND | Notre Dame |
| PO | Popelogan |
| SC | St. Croix |
| TE | Témiscouata |
| TW | Twillingate |

**PALEOZOIC BELTS**

| | |
|---|---|
| AN-B | Annapolis |
| AR-B | Arisaig |
| BA-B | Badger |
| BO-B | Botwood |
| CB-B | Cape Breton |
| CR-B | Cape Ray |
| CL-B | Clam Bank |
| FO-B | Fortune |
| FR-B | Fredericton |
| GA-B | Gaspé |
| IN-B | Indian Islands |
| LA-B | La Poile |
| MA-B | Mascarene |
| SP-B | Springdale |

**PALEOZOIC BASINS (onshore)**

| | |
|---|---|
| 10 | Antigonish |
| 14 | Bay St. George |
| 3 | Carlisle |
| 5 | Central |
| 12 | Central Cape Breton |
| 7 | Cumberland |
| 15 | Deer Lake |
| 4 | Marysville |
| 8 | Minas |
| 6 | Moncton |
| 2 | Plaster Rock |
| 1 | Restigouche |
| 9 | Stellarton |
| 13 | Sydney |
| 11 | W. Cape Breton |

| OTHER | |
|---|---|
| CG | Chedabucto Graben |
| CCF | Cobequid-Chedabucto Fault |
| DF | Dover Fault |

List of abbreviations used on the tectonic assemblages map shown in Figure 2.

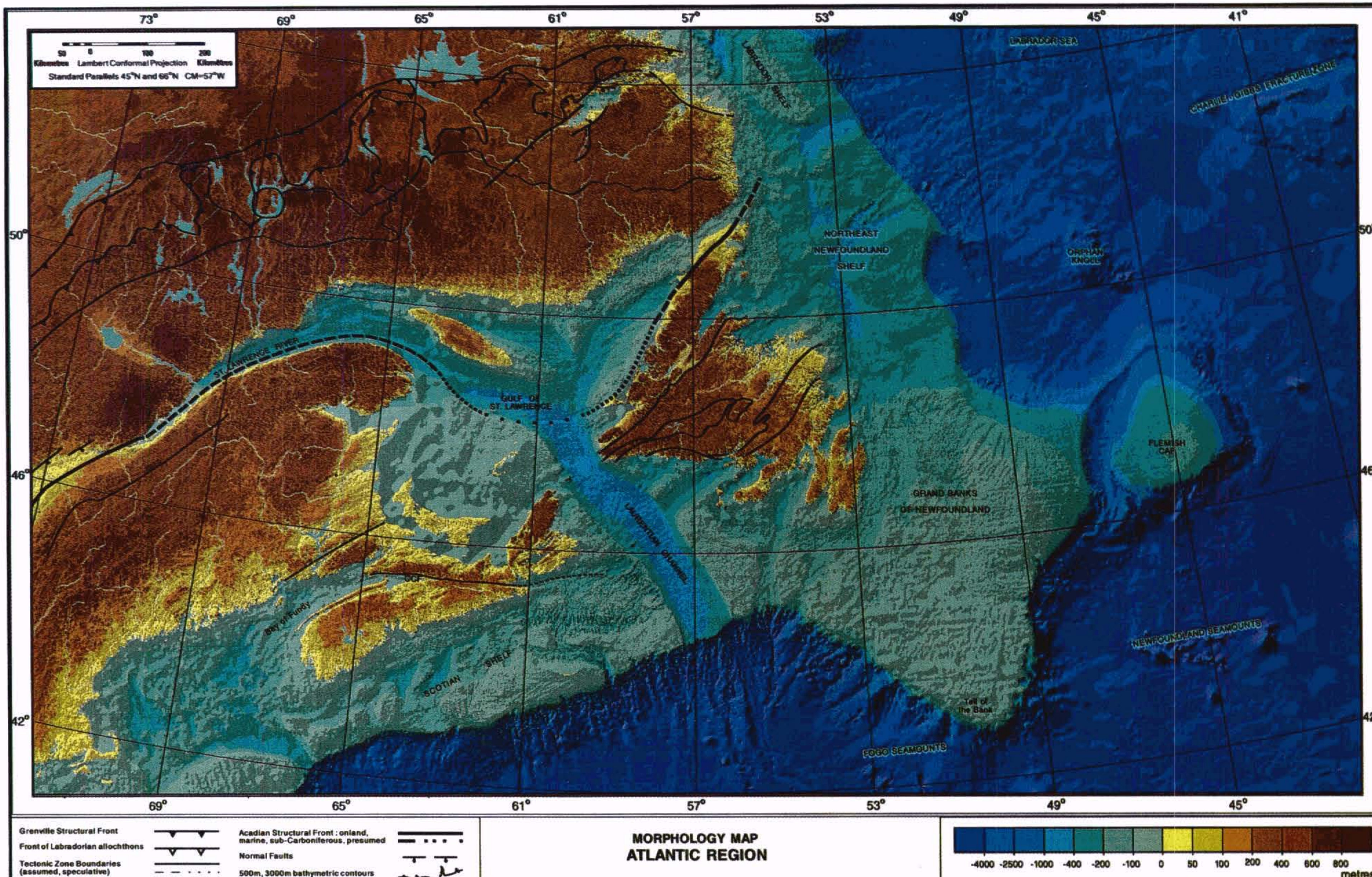


Figure 3 Morphology map, Atlantic Canada. Overlay shows some major zone and terrane boundaries from Figure 2 (from Macnab and Oakey, 1999).

Nova Scotia, the North Mountain Basalt of the Fundy Graben rests conformably on Upper Triassic redbeds. Early Jurassic dykes (Shelburne, Avalon) trend subparallel to the present margin. The stratigraphic record indicates continental rifting followed by slow subsidence and marine incursion.

On the Grand Banks, the development of rift basins persisted until the Cretaceous. The Southeast Newfoundland Transform was active until the mid Cretaceous with seafloor spreading between Africa and North America. Lower Cretaceous volcanic rocks occur in subsurface near the Tail of the Bank, along the eastward projection of the Paleozoic Avalon-Meguma zone boundary (Fig. 2). Oceanic volcanic rocks of comparable age occur nearby in the Fogo and Newfoundland seamounts.

The Grand Banks mark the transition from Triassic rifting toward the south to Early Cretaceous rifting toward the north. Whereas Triassic rifting involved North America and Africa, the Early Cretaceous rifting involved North America and Europe. In Orphan Basin, basement faulting, subsidence and sedimentation appear to have started in the Early Cretaceous. A pronounced breakup unconformity, Avalon unconformity, separates Lower Cretaceous sediments and overlying Cenozoic sediments. Jurassic rifting is suggested by the occurrence of Jurassic lamprophyre dykes and mafic intrusions in northeast Newfoundland. Farther north on the Labrador Shelf, most of the Lower Cretaceous sediments are nonmarine and are preserved in regions between basement highs.

After seafloor spreading began, the sedimentary basins subsided with almost continuous sedimentation. Subsidence curves exhibit the familiar exponential shape, indicative of cooling and thermal contraction of the lithosphere. A time constant of about 60 m.y. for lithospheric cooling is compatible with that of the oceanic lithosphere and with many other continental regions.

Deposition in the Scotian Basin follows that predicted for Atlantic type continental margins. Mesozoic-Cenozoic deposition in the basins of the Grand Banks is more complicated with two episodes of rifting and subsidence. The principal source rocks for the major oil and gas discoveries in offshore eastern Canada are the Upper Jurassic shales of the Verrill Canyon Formation in the Scotian Basin and the Egret Member of the Rankin Formation in the Jeanne d'Arc Basin. Reservoir rocks are generally Late Jurassic to Early Cretaceous. They include the Mic Mac, Mississauga and Logan Canyon formations in the Scotian Basin, the Jeanne d'Arc, Hibernia, Catalina, Eastern Shoals, Avalon and Ben Nevis formations in the Jeanne d'Arc Basin, and the Bjarni Formation in the Hopedale Basin of the northern Labrador Shelf.

## APPALACHIAN OROGEN

### Definition and Extent

The Appalachian Orogen, the result of the lapetus cycle of the Accordian Effect, is a deformed belt of Paleozoic and older rocks with concommitant Paleozoic metamorphism and intrusion. Structural trends are generally northeast, parallel to the Grenville Orogen and its subdivisions (Fig. 2). The Canadian segment from northeast Newfoundland to the United States border is about 1000 km long and its maximum width is 600 km. From Canada, the Appalachians extend southwestward through the eastern United States to the Pacific margin in Mexico. On the eastern side of the Atlantic, Appalachian continuations are found in Ireland and the British Isles, East Greenland, Scandinavia, Northwest Africa, the Iberian Peninsula, and France. The following account is taken from Williams, 1995 supported by some of our own more recent data.

### General Statement and Divisions

West of the Appalachian Orogen, Paleozoic rocks are undeformed and they overlie a crystalline basement of the Grenville Orogen. In the Gulf of St. Lawrence, the Anticosti Basin is outlined by structural contours depicting depth to Precambrian Grenville basement (Fig. 2). Its northern flank is a gently southdipping, southward thickening homocline of Cambrian to Silurian strata. Its southeast margin is the Devonian, Acadian (Appalachian) Structural Front. Where exposed in western Newfoundland, the Acadian front is a triangle zone with middle Ordovician and Silurian rocks thrust eastward above middle Ordovician sandstones and Ordovician allochthons of the orogen. Lower Paleozoic rocks east of the structural front also overlie a Grenville gneissic basement along the foreland margin. This part of the orogen is known as the Appalachian miogeocline or Humber Zone (Fig. 2). East of the Humber Zone, lower Paleozoic rocks exhibit sharp and rapid facies contrasts across faulted boundaries that allow the definition of a number of distinct early Paleozoic geologic zones. The zonation of commonest usage is that of Humber, and successively outboard Dunnage, Gander, Avalon and Meguma. Most of the lithic units that define these zones are traceable southwestward along the full length of the Appalachian Orogen (Williams, 1978). They are also extrapolated northeastward across the British Caledonides.

The Humber Zone is viewed as the Paleozoic passive margin of Laurentia, a forerunner of the North American continent that broke out of Rodinia. Outboard zones are suspect terranes, or composite suspect terranes, accreted to Laurentia during the closing of the Paleozoic lapetus ocean. According to this model, the Dunnage Zone represents vestiges of lapetus, the Gander Zone represents the eastern margin of lapetus, and the Avalon and Meguma zones are outboard Gondwanan terranes.

Middle Paleozoic rocks are assigned to belts (Fig. 2). These represent a number of tectonic settings, although lithic and stratigraphic differences between their rocks are nowhere as pronounced as those between rocks of zones. Some belts trend acutely across the Humber miogeocline and already accreted terranes as cover sequences, *e.g.*, Gaspé Belt of Quebec and Springdale Belt of Newfoundland. Others are sited along zone boundaries, either above earlier structural junctions or possibly separating early Paleozoic zones, *e.g.*, Fredericton Belt of New Brunswick. Still others have rocks that are in stratigraphic continuity with rocks of zones, in cases where the older rocks are unaffected by early Paleozoic orogeny, *e.g.*, Annapolis Belt of Nova Scotia.

Upper Paleozoic rocks define basins that represent a mainly terrestrial cover across the whole orogen with local anomalously thick sections controlled by rifts and uplifted blocks. Mesozoic rocks define graben related to Atlantic rifting. Nomenclature of belts, basins, and graben follow the latest Decade of North American Geology synthesis (Williams, 1995).

Seismic reflection studies indicate that a Grenville lower crustal block extends in subsurface well beyond the exposed edge of the miogeocline or Humber Zone. It meets a Central lower crustal block beneath the Dunnage Zone. A steep boundary between the Gander and Avalon zones extends to the mantle and separates Central and Avalon lower crustal blocks. The Humber Zone is the surface expression of the Grenville lower crustal block. The Dunnage Zone is allochthonous above the Grenville and Central lower crustal blocks. The Gander Zone may be the surface expression of the Central lower crustal block or it too may be allochthonous. The Avalon Zone and corresponding lower crustal block is a microplate rooted in the mantle. The Meguma Zone has its own Sable lower crustal block.

### Humber Zone or Appalachian Miogeocline

The eastern boundary of the Humber Zone is a steep structural zone marked by discontinuous ophiolite occurrences, the Baie Verte-Brompton Line (Fig. 1). External and internal divisions of the Humber Zone (Fig. 2) are defined on structural and metamorphic contrasts. The External Humber Zone has mildly deformed rocks allowing stratigraphic analysis. The Internal Humber Zone has polydeformed and regionally metamorphosed rocks that are unsuitable for such analyses.

The stratigraphic and structural elements of the external Humber Zone fit the model of an evolving continental margin and spreading Iapetus Ocean. It began with 1) deposition of Upper Precambrian to Lower Cambrian clastic sedimentary and volcanic rocks with coeval dyke swarms and carbonatite intrusions, the rift stage dated at about 600-550 Ma, 2) deposition of a Cambrian-Ordovician mainly carbonate sequence, the passive margin or drift stage at about 550-460 Ma, 3) deposition of Middle Ordovician polymictic clastic rocks of easterly derivation that transgress the carbonate sequence and are the first intimation of offshore disturbance, the foreland basin or compressive stage at about 460-450 Ma, and 4) emplacement in the Middle Ordovician of allochthons that are a sampling of rocks from the continental slope and rise and adjacent oceanic crust, the destructive stage at about 450 Ma.

Rocks of the Internal Humber Zone are mainly metaclastics from the ancient slope and rise. Timing of structural and metamorphic events recognized in the Internal Humber Zone are in general agreement with the stratigraphic and sedimentologic analyses of the External Humber Zone.

After the emplacement of Middle Ordovician allochthons, rocks of the Internal Humber Zone and Grenville basement were further imbricated and emplaced above the External Humber Zone by out-of-sequence thrusts.

The sinuous course of the Humber Zone, expressed in the Quebec Reentrant, St. Lawrence Promontory, and Newfoundland Reentrant (Fig. 1), is interpreted as the result of an initially orthogonal continental margin along which offset linear rifts were linked by perpendicular transform faults.

### Accreted Zones

The **Dunnage Zone** is recognized by its abundant volcanic assemblages, ophiolite suites, and melanges. Sedimentary rocks include slates, greywackes, epiclastic volcanic rocks, cherts, and minor limestones, all of marine deposition. Stratigraphic sequences are variable and formations are commonly discontinuous. Most rocks are of Late Cambrian to Middle Ordovician age.

The Dunnage Zone is widest and best preserved in northeast Newfoundland at the matching Newfoundland and Hermitage reentrants (Fig. 1). There it is divided into two large subzones, the Notre Dame Subzone in the west and the Exploits Subzone in the east, separated by the Red Indian Line (Figs. 1, 2). This is a major tectonic boundary traceable across Newfoundland and separating subzones contrasted by structures, stratigraphies and faunas. Two small areas of volcanic and sedimentary rocks are assigned to the Twillingate and Indian Bay subzones in northeast Newfoundland. A larger area of metamorphic rocks, tonalites and mafic-ultramafic complexes defines the Dashwoods Subzone of southwest Newfoundland.

The Dunnage Zone is narrow or absent in southwest Newfoundland and Cape Breton Island at the matching St. Lawrence and Cabot promontories (Fig. 1). It reappears in northern New Brunswick where six subzones are recognized. The Belledune, Elmtree, and Popelogan subzones occur in two discrete inliers in the north. The Armstrong Brook, Bathurst, and Hayesville subzones occur farther south. Tectonic emplacement of northern subzones above southern subzones occurred in the Late Ordovician-Early Silurian and produced the largest known blueschist belt in the Appalachian Orogen. The Dunnage Zone of Quebec is divided into the Estrie-Beaucé, Mégantic, Témiscouata, and Gaspésie subzones from southwest to northeast. Rocks of the Estrie-Beaucé, Témiscouata, and Gaspésie subzones are laterally equivalent. The Mégantic Subzone has different rocks and stratigraphy.

An ophiolitic basement to its early Paleozoic volcanic-sedimentary sequences was part of the original Dunnage Zone definition. However, some Early and Middle Ordovician Dunnage rocks are unconformable upon disturbed and eroded ophiolite suites and ophiolitic melanges along the Dunnage-Gander zone boundary in northeast Newfoundland. Also, in the Indian Bay and Bathurst subzones, Lower and Middle Ordovician volcanic-dominated sequences overlie Gander Zone clastic sedimentary rocks. Dunnage zone rocks that link an early Paleozoic oceanic basement in one place with a Gander continental clastic sequence in another are overstep sequences.

The type area of the **Gander Zone** is northeast Newfoundland where a thick monotonous sequence of polydeformed quartz greywacke, quartzite, siltstone and shale grades eastward into psammitic schist, gneiss and migmatite. The youngest possible age of the Gander Zone sedimentary rocks in Newfoundland is constrained by the Arenig to Llandeilo age of its oldest cover rocks. Tremadoc to middle/late Arenig graptolites occur in the clastic sequence of the Gander Zone in New Brunswick.

The Newfoundland Gander Zone comprises three discrete subzones (Fig. 2). The type area and its southward continuation is the Gander Lake Subzone. The inland areas are the Mount Cormack and Meelpaeg subzones. These inland subzones are structural windows or core complexes, and relationships indicate a two-layer crust with Dunnage Zone rocks above Gander Zone rocks. In New Brunswick, the Gander Zone includes the clastic sequences of the Miramichi and St. Croix subzones.

Almost one-half the area of the Gander Zone consists of granitic intrusions, and one-half of the remainder comprises metamorphic rocks ranging from greenschist to upper amphibolite facies. Foliated biotite granite, foliated to massive garnetiferous muscovite-biotite leucogranite, and potassic megacrystic biotite granite are characteristic. Since granites of this type and size are atypical of oceans or ophiolitic basement, it is concluded that the Gander Zone lies above continental crust.

The **Avalon Zone** is defined by its well-preserved upper Precambrian sedimentary and volcanic rocks and overlying Cambrian-Ordovician shales and sandstones. In Newfoundland it extends offshore to the Flemish Cap, making it the broadest zone of the Canadian Appalachians, more than twice the combined width of all other zones. It is much narrower in Nova Scotia and southeast New Brunswick.

In Newfoundland, the zone is extended from its type area of the Avalon Peninsula to include the Burgeo Subzone. In Cape Breton Island, the Mira Subzone is similar to the Newfoundland type area, the Bras d'Or Subzone has Cambrian strata like that of the type area, and the Aspy Subzone, while atypical, has Ordovician depositional links with the Bras d'Or Subzone. In New Brunswick, the Coldbrook and Broad River subzones have upper Precambrian volcanic rocks of typical Avalon aspect. The Brookville Subzone has mainly metamorphic and plutonic rocks, akin to the Aspy Subzone of Cape Breton Island.

Boundaries of the Avalon Zone are major faults. These faults disrupt the continuity of lithic belts within the Avalon Zone and account for its extreme variability in width from Newfoundland to New Brunswick.

Late Precambrian orogenies recognized in the Avalon Zone are unrelated to the Iapetus cycle. Middle Paleozoic orogeny was more intense, especially where the zone is narrow in Nova Scotia and New Brunswick.

The Avalon Zone differs from other zones of the Appalachian Orogen in the following ways: its late Precambrian rocks evolved during the Grenville-Appalachian time gap, although they are in part coeval with the early stages of the Appalachian cycle; its full complement of Cambrian strata, mainly shales, contain Acado-Baltic trilobite faunas distinctive from those of the Humber miogeocline; the widest expanse of the Avalon Zone across the Grand Banks of Newfoundland is virtually unaffected by Paleozoic deformation; and the zone has distinctive mineral deposits.

The mild effects of Paleozoic and late Precambrian deformation on the wide Newfoundland Avalon Zone and offshore extensions suggest that the present configuration of alternating late Precambrian volcanic and sedimentary rocks represents undisturbed late Precambrian elements. The pattern indicates volcanic ridges flanked and separated by marine sedimentary basins. A modern analogue may be the Marianas region of the Pacific Ocean.

The **Meguma Zone** is defined by a thick siliciclastic sequence, the Meguma Supergroup, that ranges in age from Late Cambrian or earlier to Early Ordovician and is up to 13 km thick.

Before the advent of plate tectonics, an eastern provenance for Meguma clastics was difficult to explain in their present coastal setting. Since the Meguma Zone was the last to accrete, its derivation should be the easiest to solve by trans-Atlantic correlation.

Stratigraphic sections, provenance, sequence stratigraphy, paleontology, igneous petrology, and geophysics all indicate that the Meguma Zone was linked to Morocco and was a part of the continental margin of Gondwana. It was stranded against North America following Iapetus closure and Atlantic opening.

**Middle Paleozoic Belts**

Most Middle Paleozoic rocks occur in successor basins or belts with terrestrial rocks common. The belts are most extensive in Quebec, New Brunswick and Nova Scotia (Fig. 2). From west to east, these are the Gaspé, Fredericton, Mascarene, Arisaig, Cape Breton, and Annapolis belts. The middle Paleozoic record in Newfoundland is fragmentary and there is no correspondence between Newfoundland and mainland belts. From west to east the Newfoundland belts are Clam Bank, Springdale, Cape Ray, Badger, Botwood, La Poile, and Fortune. The broad offshore area of the Newfoundland Grand Banks has undeformed, marine, middle Paleozoic sedimentary rocks unlike those of the onland orogen.

Stratigraphic sections of most middle Paleozoic belts show an upward change from marine to terrestrial rocks; with all rocks deformed together and cut by plutons. This change from marine to terrestrial conditions preceded middle Paleozoic orogenesis. Contrasting Silurian groups in northeast Newfoundland record the marine-terrestrial change in the Botwood and Indian Islands belts on opposite sides of their faulted boundary, the Dog Bay Line (Figs. 1, 2). Accordingly, the Dog Bay Line is regarded as a local terminal Iapetus suture.

The onset of middle Paleozoic deformation is defined as early to middle Silurian in some places and rocks as young as late Devonian are locally involved. The shoaling-upward trend occurred everywhere in advance of deformation and its age variations imply diachronous onset of Acadian Orogeny.

Middle Paleozoic volcanism, deformation, plutonism and metamorphism are all more important in interior parts of the Canadian Appalachians and decrease westward across the Humber Zone and eastward across the Avalon Zone. Thus Acadian Orogeny of Newfoundland is confined to a relatively narrow zone between the much wider Grenville and Avalon lower crustal blocks. This does not apply to New Brunswick and nearby Nova Scotia where the Avalon block is narrow, and to Nova Scotia where the outboard Meguma Zone and Annapolis Belt are affected by intense Acadian plutonism and local high grade metamorphism.

**Late Paleozoic Basins**

Upper Paleozoic rocks extend across the exposed Canadian Appalachians as an unconformable cover on rocks of early Paleozoic zones and middle Paleozoic belts. They also extend offshore and underlie much of the Gulf of St. Lawrence, the southern Grand Banks, and the shelf off northeast Newfoundland. They extend across the Acadian Structural Front south of Anticosti Island and along the estuary of the St. Lawrence River (Fig. 2).

The rocks are everywhere the same, mainly continental red and grey sedimentary rocks that include fluvial and fluvio-lacustrine strata, coal measures, marine limestone, and evaporites. Volcanic rocks of bimodal aspect occur locally, toward the bases of stratigraphic sections. The rocks are mainly Carboniferous but they locally include Upper Devonian and Permian strata.

They occur in discrete depocentres or basins. These generally trend northeast, parallel to older structures, and they are in places bounded by faults that partly controlled their initiation and subsequent evolution. Some basins with contrasting earlier histories are linked by similar strata, indicating the same later development. The thickest and most extensive strata are in the Magdalen Basin, outlined by structural contour lines marking the underlying Acadian deformed zone in Figure 2.

The basins are best developed and best preserved from Gaspé Peninsula to Cape Breton Island. From northwest to southeast these are the Restigouche, Plaster Rock, Carlisle, Central, Marysville, Moncton, Cumberland, Minas, Stellarton, Antigonish, Western Cape Breton, Central Cape Breton, and Sydney basins (Fig. 2). Two depocentres in Newfoundland are the Bay St. George and Deer Lake basins; with small redbed outliers elsewhere. Rocks of the Magdalen Basin are continuous with those of adjacent mainland basins and the Bay St. George Basin in Newfoundland. The name Maritimes Basin is a general term for all upper Paleozoic rocks in Atlantic Canada.

Late Paleozoic deformation is mild or nonexistant throughout most of Atlantic Canada, except along the northwest shoreline of the Bay of Fundy in southern New Brunswick. There, the Carboniferous rocks are involved in thrusts with polyphase deformation and subhorizontal penetrative cleavage. Granitic intrusions of Early Carboniferous age occur locally in southern New Brunswick, in northwestern Nova Scotia, in the Meguma Zone, and the western Avalon Zone of Newfoundland.

Tectonic controls for Carboniferous deposition were either extensional, punctuated by periods of transverse compression, or dextral wrench movements. Possibly, some basins began as extensional rifts and evolved as wrench-tectonic basins. There is no evidence for oceanic crust of plate boundaries in the late Paleozoic stratigraphic record of Atlantic Canada.

### Mesozoic Graben

Mesozoic rocks of Atlantic Canada are mainly Triassic and Early Jurassic continental redbeds, tholeiitic basalts, and related mafic dykes and small intrusions. The rocks are up to 3500 m thick and confined onland to the Fundy Graben with a few small outcrops in the Chedabucto Graben to the east. Mafic dykes and small intrusions that are Triassic to Early Cretaceous occur beyond the limits of the Fundy and Chedabucto graben. Small isolated outcrops of Cretaceous clays and sands also occur outside the Fundy and Chedabucto graben in central Nova Scotia and southwestern Cape Breton Island.

The Mesozoic rocks are related to the early stages of rifting that led to opening of the Atlantic Ocean.

### Significance and Interpretation

Rocks of the temporal zones, belts, basins, and graben record the full history of the Iapetus cycle and the beginning of the Atlantic cycle. Zones defined by lower Paleozoic rocks are the fundamental divisions. Apart from stratigraphy and structure, zones are expressed by geophysics, paleontology, metallogeny, plutonism, metamorphism, isotopic signatures and other features.

Middle Paleozoic rocks show less contrast because most are post-accretionary. The same applies to upper Paleozoic rocks of basins that are entirely a post-accretionary cover.

Stratigraphic and sedimentologic analyses of the Canadian Appalachians indicate that its elements were assembled during two major accretionary events. Emplacement of allochthons across the Humber Zone and interaction of the Dunnage Zone and Humber Zone in the Early and Middle Ordovician was the first event. It is attributed to northwestward obduction of oceanic crust and mantle and head-on collision between a continental margin and an island arc. Its effects are recognized in the Humber and adjacent Dunnage zones and they are attributed to Taconic Orogeny. The Gander Zone and Dunnage Zone in Newfoundland also interacted at this time with southeastward ophiolite obduction. Oceanic tracts probably existed in the central Dunnage Zone until the Silurian. Accretion of the Avalon Zone to the Gander Zone was later, in the Silurian-Devonian, and accretion of the Meguma Zone to the Avalon Zone occurred in the Devonian. Structural, plutonic, and metamorphic effects of these later events are attributed to Acadian Orogeny in its broadest sense. Its surface effects were probably controlled by compression and collision between deep crustal blocks. Carboniferous (Alleghanian) deformation is recorded by major transcurrent faults and attendant thrust zones. These effects were superposed on the already assembled orogen.

Accretion of the Appalachian Orogen therefore progressed outward from the Humber miogeocline with the boundaries of earliest interaction marked by melanges and ophiolite complexes, implying head-on collisions. Later boundaries between eastern zones are steep mylonites and brittle faults, implying oblique movements.

The Iapetus cycle from rifting to drifting to subduction and eventual collisional events is expressed also in a full range of related mineral deposits (Swinden and Dunsworth, 1995).

## GRENVILLE OROGEN

### Definition and Extent

The Grenville Orogen, although the youngest province of the Precambrian Canadian Shield, represents the first cycle of the Accordion Effect. Its rocks were involved in Neoproterozoic deformation, metamorphism, and plutonism active between 1300 and 950 Ma. The Grenville Orogen is exposed from coastal Labrador almost 2000 km to Lake Huron and southern Ontario. Its maximum exposed width is about 600 km and subsurface extensions into the Appalachian Orogen indicate widths of 800 km or more (Figs. 2, 4). From the Canadian Shield it extends in subsurface beneath cover rocks of the North American Interior Platform to the Llano Uplift of Texas and the Oaxacan inliers of southwest Mexico (Davidson, 1998). Grenville inliers also occur along the full length of the Appalachian Paleozoic foreland thrust belt, and some, *e.g.*, Goochland and Oaxacan, may lie on the Gondwanan side of the Appalachian (Iapetan) suture. On the European side of the North Atlantic, Grenville correlatives occur in the Caledonian foreland in northern Ireland and Scotland, and Grenville rocks reappear on the opposite side of the Caledonides as the Sveconorwegian Province in Scandinavia (Gower *et al.*, 1990).

### General Statement and Divisions

The following account of the northeast portion of the Grenville Orogen in Canada is taken mainly from Rivers *et al.* (1989), Hoffman (1989), Gower *et al.* (1990), Gower and Hall (1993), Davidson (1995; 1998), and personal communications with friends and colleagues

The northeast portion of the Grenville Orogen in Canada has mainly high-grade metamorphic and plutonic rocks. Apart from a few younger groups and plutons in the southeast, almost all of the province is composed of rocks that were metamorphosed and deformed prior to Grenvillian Orogeny.

Deep seismic reflection results confirm surface observations that the orogen is asymmetric, one-sided and consists of southeast dipping crustal-scale imbricates bounded by northwest directed, broad ductile thrust zones. These are underlain by a basal crust-penetrating thrust expressed at the surface as the Grenville Structural Front. Grenvillian intrusions are confined mainly to an interior belt along its southeast margin.

The latest analyses distinguish an Exterior Thrust Belt and an Interior Magmatic Belt (Fig. 2). The Exterior Thrust Belt is further divided into a parautochthon in the northwest and an allochthon in the southeast. All these divisions extend northeast-southwest for the full length of the exposed orogen. The Exterior Thrust Belt-Parautochthon contains rocks that can be correlated across the Grenville Structural Front with those of adjacent provinces of the Canadian Shield. The Exterior Thrust Belt-Allochthon comprises regional metamorphic and plutonic rocks of unknown or doubtful affinity, many of which are dated at 1.7-1.5 Ga (Labradorian Orogen). These were transported northwestward during Grenvillian Orogeny along major ductile shears, with only mild Grenvillian metamorphic overprint. The Interior Magmatic Belt is defined by voluminous granites and large anorthosite-mangerite-charnockite-granite plutons dated between 1300-950 Ma. Numerous small late to post-Grenvillian plutons in the northeast are dated at 966-956 Ma. The northwest limit of the Interior Magmatic Belt also coincides, or almost coincides, with a pre-Grenvillian crustal boundary inferred from Nd model ages in southern Ontario. The Interior Magmatic Belt also contains the youngest recognizable stratigraphic rock groups (1.3-1.2 Ga) within the orogen. These were undeformed before Grenvillian Orogeny.

**Exterior Thrust Belt-Parautochthon**

The Exterior Thrust Belt-Parautochthon contains the oldest rocks of the Grenville Orogen that are correlated across the Grenville Structural Front with rocks of the Superior, New Quebec, Torngat (Rae), and Makkovik provinces (Fig. 2). A sharp change in metamorphic grade across the Grenville Structural Front indicates marked uplift in the southern hanging wall. Significant hanging wall uplift and deep erosion is also indicated where other distinctive foreland rocks, such as cover sequences of Labrador (Seal Lake Group), Quebec (Otish and Mistassini groups, Fig. 1) and Ontario (Huron Supergroup), cannot be traced across the front. Plutonic rocks of Grenvillian age are sparse or absent.

In coastal Labrador, the Grenville Structural Front crosses plutonic rocks of the Trans Labrador Batholith (1.65 Ga) that extends north of the front into the Makkovik Province. The front is a 3-km structural transition bounded by mylonite zones. An increase in metamorphic grade, coupled with kinematic indicators, imply a zone of reverse displacement with Grenville rocks uplifted relative to those in the Makkovik Province. Most of the Trans Labrador Batholith affected by Grenvillian Orogeny occurs in the Groswater Bay Terrane (Fig. 2). A southward increase in metamorphic grade across the Groswater Bay Terrane is interpreted as an imbricate zone that exhumes progressively deeper crust.

Farther west, reworked Archean rocks of the Torngat Orogen or Rae Province comprise the parautochthonous Churchill Falls Terrane (Fig. 2). The more informative Paleoproterozoic miogeoclinal sequence of the New Quebec Orogen (Kaniapiskau Supergroup) is known as the Gagnon Terrane. Its distinctive stratigraphy and presence of iron formation are still easily recognized in higher metamorphic grades for more than 100 km south of the Grenville Structural Front. Archean basement to the New Quebec miogeoclinal sequence is assigned to the Timiskaming Terrane. Its low grade Archean greenstones and metasedimentary rocks are prograded to amphibolite facies, and Archean granulites of the Ashuanipi Complex are retrograded to greenschist-amphibolite facies.

Metamorphosed and deformed equivalents of Proterozoic mafic intrusions in the Grenville foreland are also recognized in the Exterior Thrust Belt-Parautochthon of Labrador. These include the 1.46 Ga Shabogamo Gabbro and the 1.43 Ga Michael Gabbro.

The extent of the Exterior Thrust Belt-Parautochthon from the Grenville Structural Front to the leading edge of the Exterior Thrust Belt-Allochthon is a minimum for how much of the Grenville Orogen was derived from the pre-Grenvillian North American craton.

**Exterior Thrust Belt-Allochthon**

The Exterior Thrust Belt-Allochthon is made up of high-grade metamorphic rocks and plutonic rocks that define several separate terranes bounded by ductile shear zones. In eastern Labrador, the Exterior Thrust Belt-Allochthon contains the Hawke River, Lake Melville, and Mealy Mountains terranes (Fig. 2). Farther west it contains the Wilson Lake, Lac Joseph, parts of Molson Lake, and Pambrun terranes. These are defined mainly on the kinds and quantities of metamorphic *versus* plutonic rocks, and only rarely are protoliths recognized, *e.g.*, mafic volcanic rocks in the Hawke River Terrane. The allochthonous rocks have no direct correlatives in the parautochthon. However in Labrador, metamorphism and deformation in the allochthon at 1.7-1.6 Ga (Labradorian) is coeval with the Trans Labrador Batholith of the parautochthon, suggesting that parautochthon and allochthon were once parts of the same Labradorian Orogen before Grenvillian telescoping and overprinting. Shabogamo gabbro cuts both the parautochthonous Gagnon Terrane and nearby parts of the Molson Lake Terrane, implying juxtapositioning before 1.46 Ga.

The northwestern leading edge of the allochthon has a sinuous trace marked by an abrupt change in metamorphic grade from medium to upper amphibolite facies in the footwall to high grade granulites in the hanging wall. The boundary is marked by ductile shears with northwest polarity, agreeing with the metamorphic inversion across the boundary. Eclogites toward the base of the Molson Lake Terrane indicate profound Grenvillian uplift. Granulites of the Wilson Lake Terrane and the northern lobe of the Pambrun Terrane are almost separated from their southeastern sources, and the Lac Joseph Terrane has a central window that exposes rocks of the underlying Molson Lake Terrane.

In Labrador, a large massif of anorthosite, gabbro and related granitoid rocks in the Mealy Mountains Terrane, and similar rocks of the White Bear Arm suite in the Hawke River Terrane and large gabbro masses (Ossokmanuan suite) in the Lac Joseph Terrane, all have late Labradorian ages, 1645-1625 Ma. Ages and tectonic signatures of some of these allochthonous plutons match those in the Grenville foreland, supporting other evidence that the Grenville Orogen is principally composed of reworked older crust. Some well-preserved pre-Grenvillian igneous suites are indistinguishable from Grenvillian igneous suites.

**Interior Magmatic Belt**
The Interior Magmatic Belt lacks the extensive tracts of high-grade pelitic gneisses and calc alkaline plutonic rocks of the Exterior Thrust Belt. Instead, it includes abundant alkali-rich granitoid rocks, most of which are post-Labradorian, and abundant-mangerite-charnockite-granite suites.

In Labrador, the Interior Magmatic Belt is represented by the Pinware Terrane (Fig. 2). It has supracrustal units, foliated to gneissic granitoid rocks (1.5-1.4 Ga), layered mafic intrusions and mafic dykes, syn to late Grenvillian granitoid rocks, and late to post-Grenvillian granitoid rocks. The syn to late Grenvillian granitoids are foliated but appear to lack mafic dykes, hence are assumed to be younger. These are generally circular, homogeneous and undeformed, with ages of 966-956 Ma.

Ages of 1.45-1.39 Ga like those of the Pinware Terrane characterize the St. Maurice Terrane of southern Quebec. It comprises deformed volcanic-plutonic rocks with locally recognizable pillow lavas and volcanic suites, interpreted as an island arc.

The Wakeham Supergroup (Wakeham Terrane, Fig. 2) in southeastern Quebec displays primary sedimentary and volcanic rocks, allowing stratigraphic analysis. An older group with rhyolite dated at 1.27 Ga and associated granites at 1.24 Ga shed detritus into unconformably overlying basal conglomerates, in turn overlain by cross-bedded arkose and hematitic siltstones. High-grade migmatitic gneisses, including orthogneisses of Labradorian age, underlie the Wakeham Supergroup along its northern margin. The Wakeham Supergroup is cut by several small plutons of undeformed granite and it is regionally metamorphosed to greenschist facies.

The large volumes of plutonic rocks of the Interior Magmatic Belt have no counterparts outside the Grenville Orogen. The Wakeham Supergroup of the interior orogen is of similar age as the Seal Lake Group in its foreland of Labrador, and similar lithologies of mafic volcanic rocks and associated redbeds imply widespread terrestrial conditions across the orogen. Other groups of this age in southern Ontario have been interpreted as a continental margin and juvenile island arc.

**Significance and Interpretation**
The Grenville Structural Front in Atlantic Canada transgresses older provinces of the Canadian Shield, but the Labradorian event recognized in the Exterior Thrust Belt-Allochthon may have localized internal Grenvillian events. Whatever the controls of Labradorian plutonism, be they Labradorian accretionary events or anorogenic extensional events, they affected a broad area that included the Exterior Thrust Belt and the foreland area outside the Grenville Orogen.

The voluminous Grenvillian plutons of the Interior Magmatic Belt and their timing and linear arrangement are compatible with formation at or near a plate margin.

The decrease in age of rocks across the Grenville Orogen from northwest to southeast, the Labradorian age of plutonism in the Exterior Thrust Belt compared to the Grenvillian age of plutonism in the Interior Magmatic Belt, the likelihood of an ancient crustal boundary within the southwestern allochthon indicated by Nd model ages, all support a model of an accretionary margin that migrated southeastward during successive accretionary events, culminating with Grenvillian collisional orogeny. Grenvillian plutonism at 1300-950 Ma overlapped ductile deformation and regional metamorphism in the External Thrust Belt, thus the entire Grenville Orogen was assembled at this time. The age and lithologies of the Wakeham Supergroup in the Interior Magmatic Belt and its possible correlation with the Seal Lake Group in the Grenville foreland, also indicates accretion by about 1.27 Ga.

Paleogeographic restoration of Rodinia is essential to any regional analysis of the Grenville Orogen that includes paired sides with opposite polarity of external thrust belts and an axial zone or oceanic tract. Before Rodinia break-up, imminent Laurentia must have lain entirely within the Rodinia Supercontinent as the late Precambrian-early Cambrian Laurentian continental margins were everywhere initiated at the same time around its total periphery. Since there is no preserved opposing side to the Grenville Orogen in Canada, the Canadian part of the Laurentian margin may have been initiated along a Grenvillian suture within Rodinia. Most Grenville Inliers in the Appalachian Orogen have high-grade metamorphic and plutonic rocks, with Grenvillian plutons like those of the Interior *Magmatic Belt*. A stratigraphic record of Grenvillian events is reported in west Texas with a possible internal suture in the Llano Uplift (Mosher, 1998).

Mineral deposits of the Grenville Orogen are either related to rocks and events older than the Uranus cycle or to magmatic late stages of the Grenvillian Orogeny.

**MORPHOLOGY**
Offshore, the continental shelves display eroded expanses of basement bedrock, separated by isolated banks and basins, grading to flat sediment-covered banks near the shelf edges (Fig. 3). The well-defined Laurentian Channel directs the outflow from the *St. Lawrence River* and other tributaries across the Gulf of St. Lawrence to the continental shelf edge south of Newfoundland. It separates the Scotian Shelf from the Grand Banks. Transverse troughs, marginal channels and shallow banks of the continental shelves mainly result from glacial erosion, which overdeepened and straightened former river channels and accentuated cuestas.

The continental shelves typically extend seaward for 200 km, except east of Newfoundland where the shelf widens to 400-700 km to encompass the Tail of the Bank, Flemish Cap, and Orphan Knoll. The broad basin separating Orphan Knoll from the inner shelf, and a narrower pass isolating Flemish Cap, define areas of considerable crustal thinning and tectonic subsidence. Well-defined canyons incise the continental slope and rise, especially off Nova Scotia, artifacts of temporal variations in relative sea-level and sediment supply. Volcanic edifices marking the Fogo and Newfoundland seamount chains stand above the abyssal plain at the foot of the slope. The Charlie-Gibbs Fracture Zone is expressed as a set of linear ridges in the deeper basin northeast of Orphan Knoll.

Despite considerable overprinting and reworking of surface topography by glacial processes, several tectonic and structural features still have a distinct morphologic expression. In the Appalachian Orogen of Newfoundland and New Brunswick, prominent ridges are aligned in a northeast-southwest orientation consistent with bedrock struc-

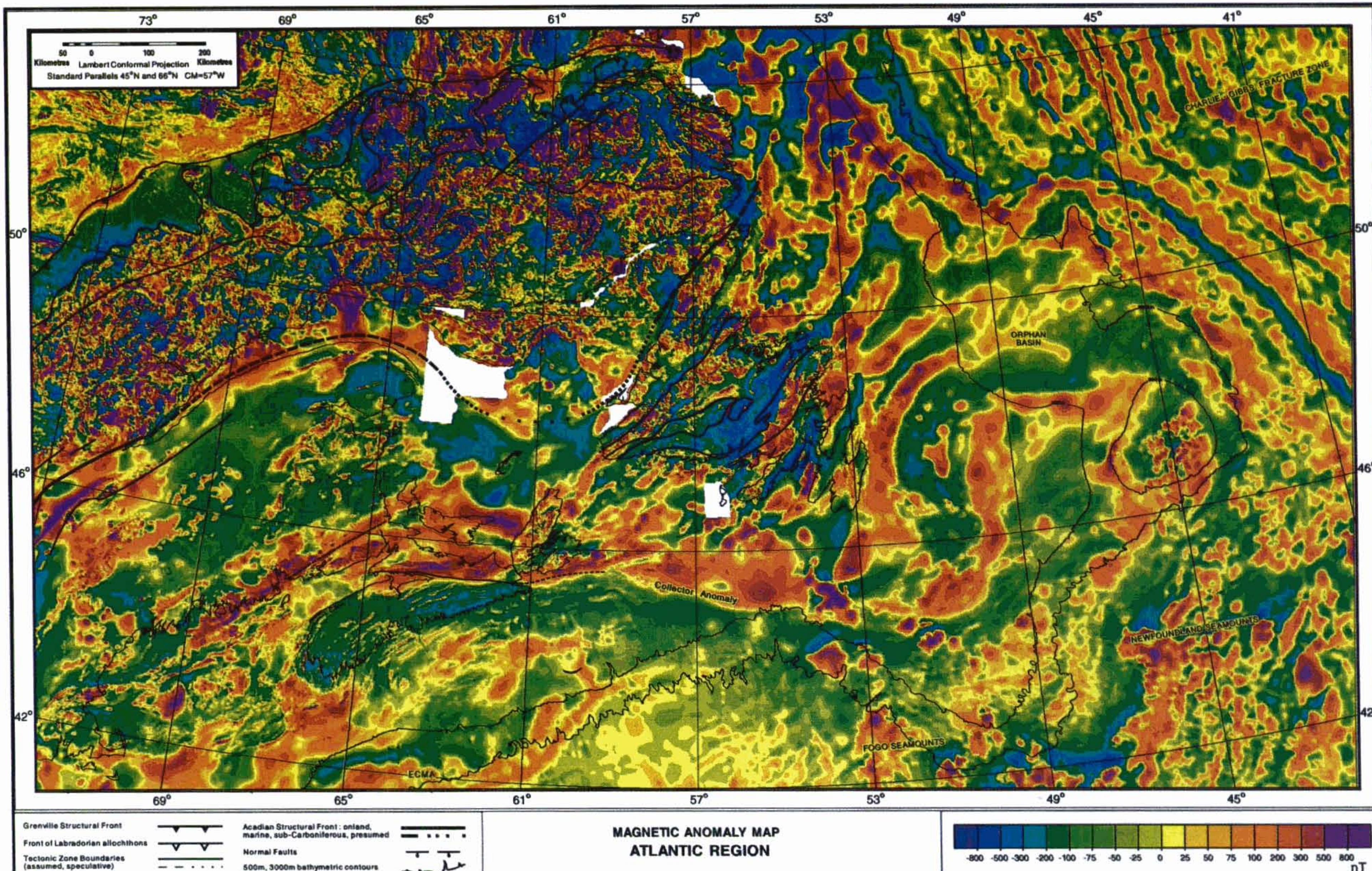


**Figure 4** Magnetic anomaly map, Atlantic Canada. Terminus of East Coast Magnetic Anomaly (ECMA) is marked off southern Nova Scotia (from Oakey and Dehler, 1998).

tures. Several tectonic boundaries have an associated physiographic expression. Most notable is the Cobequid-Chedabucto fault zone, separating the Avalon and Meguma zones in Nova Scotia. Also visible along the Bay of Fundy shore of Nova Scotia is a prominent ridge formed by Triassic-Jurassic basalts, flanked by a low-standing onshore component of the sedimentary rift.

The highest topography in the region is over the Grenville Orogen, and elevations are greatest just south of the Grenville Structural Front. There is no discernible trend or pattern to this landscape to match bedrock structure, or gravity and magnetic anomalies.

## GEOPHYSICAL EXPRESSION

The magnetic and gravity anomaly patterns of Atlantic Canada reflect the variety of ages, compositions, metamorphic grades, and deformational histories of the suites of rocks that comprise the region. Structural provinces are recognized by similarities in anomaly character and trends, while tectonic boundaries tend to truncate patterns. High magnetic and gravity anomaly values tend to be associated with gabbroic intrusive bodies and rocks of high metamorphic grade, whereas low values commonly coincide with thick sedimentary sequences and granitic rocks. The regional characteristics of the magnetic and gravity anomaly patterns over Atlantic Canada have been described already in several overviews (*e.g.*, Woodside and Verhoef, 1989; Keen *et al.*, 1990; Williams *et al.*, 1994; Miller, 1995). Here we relate some of the observed anomalies to the major tectonic and stratigraphic features discussed above.

### Magnetic Anomalies

The magnetic anomaly pattern varies from the characteristic striping of oceanic crust beyond the continental slope and rise to the subdued and broadly sweeping anomalies over the modern continental margin and Appalachian Orogen to the chaotic, short-wavelength anomalies of highly variable amplitude over the Precambrian Grenville Orogen (Fig. 4). Many of the magnetic anomalies on the continental shelf are offshore extensions of the anomalies observed over land. The anomaly pattern is more subdued with fewer short-wavelength features, as anomaly sources are buried at greater depths beneath sediment cover. This effect is particularly noticeable in Orphan Basin. The conceptual continent-ocean boundary lies landward of the oldest seafloor magnetic lineations and seaward of trends arising from prerift geological features of the continental shelf. This boundary is not everywhere apparent in the magnetic anomaly field. This may be the result of a broad zone of mafic dyke injection, like that associated with the rifted Iapetan margin in northwest Newfoundland. A linear positive feature, the East Coast Magnetic Anomaly, marks the approximate continent-ocean boundary along much of the Atlantic United States margin. This anomaly is visible near the 3000-m bathymetric contour south of Nova Scotia but is absent farther north (Fig. 4). The characteristic magnetic striping pattern associated with oceanic crust spreads eastward from the foot of the slope northeast of Newfoundland. A major offset in the regular pattern marks the Charlie-Gibbs Fracture Zone. Elsewhere, other features such as the Fogo and Newfoundland seamount chains, with associated positive magnetic anomalies, imply the presence of oceanic crust.

The magnetic anomalies associated with the Appalachian Orogen are generally of much lower amplitude and longer wavelength than those to the north of the Acadian Structural Front. Many of the zone boundaries are fault-controlled and have distinct magnetic anomalies or gradients associated with them. These characteristic signatures allow the zone boundaries to be extrapolated into offshore areas with relative success, particularly on the continental shelf northeast of Newfoundland.

Moderate-amplitude, short-wavelength anomalies characterize much of the external Humber Zone, with pronounced high-amplitude anomalies over the Grenville inliers of western Newfoundland. Negative anomalies are associated with thick carbonate sequences and with metasedimentary rocks of the Internal Humber Zone.

High-amplitude magnetic anomalies mark the northern half of the Newfoundland Dunnage Zone. Much of this high-amplitude is attributed to the predominance of lower Paleozoic volcanic and mafic plutonic rocks. Longer wavelength, negative anomalies over the southeast portion of the Newfoundland Dunnage Zone reflect its mainly sedimentary rocks. A thick cover of middle and upper Paleozoic sedimentary rocks subdues much of the magnetic signature associated with the Dunnage Zone in New Brunswick.

The negative anomaly associated with the southernmost Exploits Subzone continues without notable interruption to the Newfoundland Gander Zone. A band of positive values marks the eastern part of the zone and extends southward across the Gander-Avalon boundary. The negative values appear to correspond to regions of sedimentary and volcanic rocks, while the positive values outline regions dominated by granitic intrusions. It is difficult to distinguish a magnetic signature for the Gander Zone in New Brunswick because of its middle and upper Paleozoic sedimentary cover, with corresponding long-wavelength, negative anomalies.

The Avalon Zone has a distinctive magnetic signature consisting of alternating bands of positive and negative anomalies that sweep across the Avalon Peninsula of Newfoundland and curve across the continental shelf to the northeast. Positive values are attributed to ridges of late Precambrian volcanic rocks, with negative contrast provided by flanking sedimentary basins. Anomalies associated with the Avalon Zone in northern Nova Scotia and southeastern New Brunswick are predominantly positive.

The Meguma Zone has a broad negative anomaly, punctuated by thin bands of more positive values that reflect the structural trend of the steep sedimentary strata. The negative anomaly, and the sharp contrast between positive and negative values that marks the Avalon-Meguma boundary, can be followed eastward from Nova Scotia through the Orpheus Graben to the Grand Banks southeast of Newfoundland (Collector Anomaly).

The Grenville Orogen is characterized by a complex patchwork of discontinuous high-amplitude, short-wavelength magnetic anomalies. This irregular magnetic expression in part reflects variations in regional metamorphism and tectonic level resulting from thrusting, vertical uplift, differential erosion, and extensional tectonics. Similar magnetic patterns mark other regional metamorphic terranes of Precambrian shields.

The highest magnetic amplitudes occur over the northeast portion of the province, which has mainly high-grade metamorphic and plutonic rocks. Elsewhere, prominent positive anomalies are associated typically with large gabbroic complexes, and negative anomalies tend to overlie anorthosite and related rocks. The Grenville Structural Front is arguably the most prominent and continuous magnetic feature of the North American continent. It provides clear demarcation between the predominantly east-west and north-south directed patterns of the northern Canadian Shield and a band of low-amplitude negative anomalies over the Exterior Thrust Belt-Parautochthon. The arcuate trend of the Grenville Structural Front extended offshore passes south of a major positive magnetic anomaly, and it may continue offshore close to the southern margin of a magnetic high that characterizes the Makkovik Province. The sinuous northwest leading edge of the Exterior Thrust Belt-Allochthon against the parautochthon is marked by an abrupt change in aeromagnetic signature, relatively flat over the parautochthon to short wavelength high relief of the allochthon. This reflects high-grade granulites in the hanging wall of the allochthon boundary thrust compared to middle to upper amphibolite grade in the parautochthon footwall. This boundary is less well-defined in eastern Labrador where negative anomalies are also associated with the Lake Melville Graben and with the Lac Joseph, Wilson Lake, and Lake Melville terranes. Iron formations of the Kaniapiscau Supergroup in the Gagnon Terrane have a marked magnetic expression that allows tracing across the Grenville Structural Front for more than 100 km into the Exterior Thrust Belt-Parautochthon. The Interior Magmatic Belt is characterized by short-wavelength, variable amplitude anomalies with no discernible trend. Localized positive anomalies tend to correspond with small circular granitoids, particularly in the eastern regions. Broad areas of negative values are associated with sedimentary rocks (*e.g.*, Wakeham Supergroup) and with large volumes of anorthosites and related rocks. The anomaly pattern extends with similar character over the northern Gulf of St. Lawrence, gradually becoming subdued as the source rocks lie at greater depths beneath Paleozoic sedimentary rocks of the Anticosti Basin.

**Gravity Anomalies**

The complex history of crustal thinning, faulting, and subsidence associated with the formation of the modern Atlantic continental margin is reflected in the highly variable gravity signature (Fig. 5). Rift basins that formed as graben or half-graben during the opening of the Atlantic, such as the Whale and Jeanne d'Arc basins, generally have negative gravity anomalies. Broad positive anomalies are associated with the relatively thick crust and shallow basement of the Flemish Cap and South Bank highs. One of the most notable features is the large positive free-air anomaly that follows the 500-m bathymetric contour at the edge of the continental shelf and around Flemish Cap. Seaward of this anomaly the crust was thinned during rifting, and the shape of the anomaly is related to the style and intensity of crustal thinning. Large anomalies tend to be associated with regions of significant lithospheric flexure or rift flank uplift, such as the inner edge of Orphan Basin. A striking free-air positive anomaly landward of the shelf break in Orphan Basin is one of the more problematic features of the margin. A negative anomaly near the foot of the slope that parallels the shelf-edge positive anomaly relates to the transition from continental to oceanic crust and is also influenced by sedimentary deposits, especially at the Nova Scotia margin. The gravity anomalies assume a more uniform character over oceanic crust, and it is easy to pick out small features such as the positive anomalies marking the Newfoundland and Fogo seamount. A linear negative gravity anomaly highlights the age discontinuity in oceanic crust at the Charlie-Gibbs Fracture Zone.

In the Appalachian Orogen, gravity anomalies associated with the Humber Zone are generally positive, particularly over the Grenville inliers of western Newfoundland. Strong positive values also mark parts of the Internal Humber Zone where mafic metavolcanic and intrusive rocks are present in significant quantities. Negative anomalies indicate areas with a substantial cover of Paleozoic sedimentary rocks.

Strong positive anomalies mark the northern half of the Dunnage Zone with its abundant mafic volcanic and ophiolitic rocks. The shape of the gravity anomaly matches the region of high-amplitude magnetic anomalies. Highest values overlie the Notre Dame Subzone and extend with increasing width and amplitude over the continental shelf to the northeast. Strong values also overlie the much narrower Dashwoods Subzone of southwestern Newfoundland. Weaker, and in places negative, anomalies overlie the Exploits Subzone where sedimentary rocks predominate. The gravity signature of the Dunnage Zone in New Brunswick is also generally negative.

Negative anomalies are associated with the metasedimentary rocks of the Gander Zone in Newfoundland and its inferred continuation across the continental shelf to the northeast. A prominent negative anomaly overlies the Meelpaeg Subzone and appears to correlate with a major granitic body. Gravity anomalies over the Gander Zone in New Brunswick are also generally negative and pronounced lows follow the trend of the Miramichi Subzone.

Positive gravity anomalies are associated with the volcanic, intrusive, and metamorphic rocks of the Avalon Zone in southeast Newfoundland and the adjacent continental shelf. These anomalies, in combination with the negative anomalies over associated sedimentary rocks, produce an arcuate pattern of alternating polarity similar to the magnetic anomaly signature. Positive anomalies are affiliated with rocks of the Avalon Zone in northern Nova Scotia and southernmost New Brunswick.

The faulted contact between the Avalon Zone and the Meguma Zone on mainland Nova Scotia is identified by a moderate southerly decrease from positive to negative anomaly values. The gradient is pronounced where the fault extends offshore to the east to form the northern flank of Orpheus Graben. Significant granitic intrusions within the Meguma Zone are easily identified by pronounced negative anomalies.

A broad negative Bouguer gravity anomaly is associated with the Grenville Orogen. The most pronounced negative anomaly follows the Grenville Structural Front and forms part of a paired anomaly indicative of a southeastward-dipping, crustal-scale feature. Low gravity values extend over the parautochthonous Exterior Thrust Belt to the south, then increase moderately over the rest of the Grenville Orogen. Within the Exterior Thrust Belt-Allochthon, anorthosite massifs typically are marked by negative anomalies, although positive anomalies in some instances suggest more mafic rocks lie at depth. Metagab-

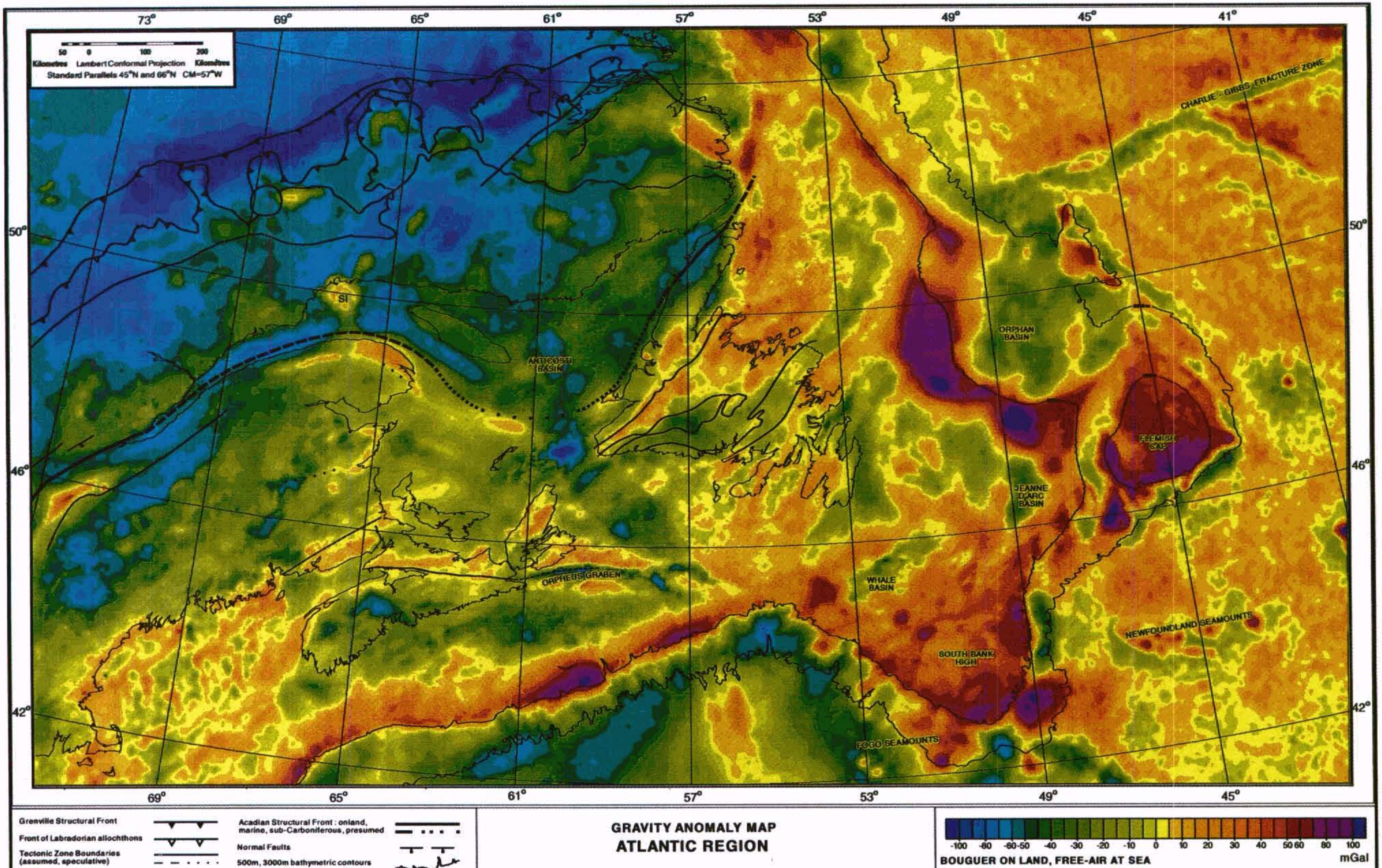


**Figure 5** Gravity anomaly map, Atlantic Canada. SI is Sept Iles gabbro-anorthosite intrusion (from Dehler and Roest, 1998).

bros and upthrust high-grade metamorphic rocks, as in the Lac Joseph and Mealy Mountains terranes, yield positive anomalies. A notably strong positive anomaly straddles the Hawke River Terrane near coastal Labrador. Within the Interior Magmatic Belt, positive anomalies are associated with the gneissic granitoid and mafic rocks of the Pinware Terrane, and with the volcanic rocks of the St. Maurice Terrane. The Sept Iles gabbro-anorthosite at 565 Ma is about 60 km in diameter judging by the extent of its aeromagnetic and gravity anomalies in the St. Lawrence estuary 100 km west of Anticosti Island. Elsewhere, local positive anomalies correlate with anorthosites and related rocks.

The negative anomalies of the Grenville Orogen continue southward into the Gulf of St. Lawrence. Thick deposits of Paleozoic sediments overlie Grenville basement in Anticosti Basin and the gravity anomaly mimics the structural depth contours. A moderate gradient, flanking more positive gravity values to the south, follows the trend of the Acadian Structural Front across the gulf region.

## TECTONIC INHERITANCE AND OROGEN COMPARISONS

On the scale of the North Atlantic region, there is an obvious spatial relationship between the location of present continental margins, the distribution of rocks affected by Paleozoic orogenies, and those affected by Neoproterozoic orogenies. Thus modern tectonic patterns in the North Atlantic may have been determined by events that began before 1000 Ma.

Some Paleozoic zone boundaries and Precambrian structural features coincide with offsets in the present Atlantic margin and present oceanic fracture zones. Most obvious is the prolongation of the Charlie-Gibbs Fracture Zone into the Dover Fault, indicating that modern Atlantic ocean crust offset is colinear with the Paleozoic continental lower crustal block boundary. Similarly the offset at the Cartwright Arch and its seaward prolongation into the Cartwright Fracture Zone is colinear with the Grenville Structural Front. In general, oceanic fracture zones can be traced into boundaries between basins and platforms, even though the boundaries do not correspond to any well-defined older lineaments.

The Tail of the Bank is a modern promontory defined by the orthogonal intersection of the Southeast Newfoundland Transform and the rifted margin. It mimics the Paleozoic St. Lawrence Promontory at the Iapetan margin of Laurentia. The Paleozoic transform linking the St. Lawrence Promontory to the Quebec Reentrant projects northwestward and is colinear with the Paleoproterozoic Labrador Trough miogeocline that takes an orthogonal bend at the Grenville Structural Front into the Gagnon Terrane and reappears in the Mistassini and Otish groups farther west. Although inheritance and ancestral controls are implied among these features, there are no observable structural breaks from one to another.

Although pre-existing boundaries were convenient, they were not essential for the development of Mesozoic rift structures. The polarity of extensional forces during Atlantic rifting seems to be the overruling factor; where perpendicular to the Humber Zone and Paleozoic orogen south of the Grand Banks, the Appalachians are split longitudinally, whereas to the north, the bifurcation of the mid-Atlantic ridge in the Labrador sea cuts across the Appalachian Orogen, the Grenville Orogen, and older structural provinces of the Canadian Shield, oblivious to earlier structures. The Southeast Newfoundland Transform does not appear to have developed along a pre-existing lineament, and normal faults within the Orphan Basin appear to be perpendicular to the northeasterly trend of Avalon structures. Furthermore, the fundamental Avalon-Meguma zone boundary is not expressed in a rift or transform margin, although it localized the Carboniferous Minas Basin, the Mesozoic Fundy, Chedabucto and Orpheus graben, and the mid-Cretaceous volcanism at the Tail of the Bank.

Finally, some features have maintained tectonic activity over long periods but have never developed into continental margins. Thus, the St. Lawrence River Valley has evidence of incipient Iapetan and Atlantic rifting, and it continues to be a zone of high earthquake activity.

The North Atlantic Ocean and its Atlantic margin provide an actualistic model for the Paleozoic Iapetus Ocean that led to the zonation of the Appalachian Orogen. Just as Atlantic rifting involved a broad area of several hundred kilometres, so too did Iapetan rifting extend well inland toward the Grenville Structural Front, as witnessed by the Lake Melville Graben. The breakup unconformity marking the rift-drift transition at the Atlantic margin, defined by seismic reflection, downhole stratigraphy, and the age of adjacent ocean crust, has an Iapetan counterpart in the Appalachian Humber Zone of northwest Newfoundland. The widths of the North Atlantic continental shelf/slope/rise and the thicknesses of sediments are comparable to palinspastically restored widths of the Humber Zone and thicknesses of its sedimentary rocks. Extended and thinned Paleozoic basement beneath Mesozoic rocks of the Atlantic margin has similar thickness and structural style of normal faults as Grenville basement seen in seismic reflection profiles of the Humber Zone. The form of the North Atlantic margin at the Tail of the Bank mimics and provides an explanation for the sinuosity of the deformed Laurentian margin as expressed in the Quebec Reentrant, St. Lawrence Promontory and Newfoundland Reentrant. The crust and mantle beneath the North Atlantic is analagous to Paleozoic volcanic rocks and ophiolite suites of the Appalachian Dunnage Zone, and Atlantic microcontinents (*e.g.*, Rockall Plateau) and oceanic volcanic islands and seamounts (*e.g.*, Iceland, the Faeroes, Newfoundland seamounts) are typical of Appalachian suspect terranes. Expectedly, other Appalachian terranes were generated during subduction.

Variations in tectonic and depositional styles at modern margins may help to understand variations in foreland thrust belts such as that of the Humber Zone. Platformal segments of margins with thin cover might be expected to respond differently to thrusting than heavily sedimented regions such as the Scotian Basin. Promontories with thin cover, such as the Tail of the Bank, should behave differently than reentrants with thick cover. This might explain why Appalachian reentrants are wide zones of thrusting in cover rocks whereas ancient promontories have exposed basement and narrow thrust zones.

In the scenario of real estate exchanges that resulted from opening of the North Atlantic, the opening and closing of Iapetus, and the opening and closing of Uranus, segments of the Paleozoic North American miogeocline are now found on the eastern side of the

Atlantic as parts of the European plate, *e.g.,* Hebredian foreland of the British Caledonides. Other segments of the miogeocline, although not now part of the North American continent, remain within the American plate, *e.g.,* East Greenland Caledonides. South of the Grand Banks, the North Atlantic opened well outboard of the Iapetus (Appalachian) suture, leaving a variety of Paleozoic terranes stranded at the margin of the North American craton.

Since the Grenville Orogen is largely one-sided, with a singular northwest polarity of structures, and without a Uranus collisional suture preserved in Canada, locally Iapetus must have opened inboard of the Uranus (Grenville) suture. Whereas the history of Iapetus is preserved in contemporary stratigraphic sections, Uranus has no comparable late Neoproterozoic stratigraphic record. The Grenville Orogen lacks a foreland miogeocline, except perhaps for West Texas (Mosher, 1998) and it is made up almost entirely of older, reworked rocks. Only its 1300-950 Ma intrusions of the Interior Magmatic Belt are typical of collisional orogens. These are in some respects similar to the distribution of Paleozoic plutons in the interior part of the Appalachian Orogen.

The width of deformed and metamorphosed rocks across the Grenville Orogen is much greater than the width of comparable rocks in the Appalachian Orogen. This implies that the closing of Uranus was a much more intense telescoping and collisional event compared to that of the closing of Iapetus.

Compared to the Atlantic continental margin and the Appalachian Structural Front, the Grenville Structural Front is straight, implying a local straight shoreline to Uranus before assembly of Rodinia. In the southeastern United States, the Grenville Front, local Llano Front, has a major orthogonal bend, implying an Uranus continental margin with a promontory and transform much like features of Iapetus and the Atlantic.

Many more similarities and contrasts can be gleaned by even a cursory inspection of the available thematic maps of Atlantic Canada.

## ACKNOWLEDGEMENTS

We thank Ron Macnab for his initiation and input into the planning for the thematic maps that form the basis for this paper. We thank Toby Rivers, Charles Gower, David Corrigan, Aphrodite Indares, and John Ketchum for discussion and supplying literature on the Grenville Orogen. We also thank Tony Davidson for reprints and an advanced copy of his Grenville compilation map. Thanks also to James Butrica, Memorial University Classics scholar, for helping with Greek mythology, to Ward Neale and Scott Swinden for their helpful external reviews, and to Ruth Jackson and Bob Courtney for their thorough internal reviews.

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Accepted as revised 15 March 1999