GEOLOGY OF THE APPALACHIAN-CALEDONIAN OROGEN IN CANADA AND GREENLAND

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GEOLOGY OF THE APPALACHIAN-CALEDONIAN OROGEN IN CANADA AND GREENLAND

edited by

Harold Williams

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Gently dipping late Precambrian redbeds of the Signal Hill Group, Cape Spear, Newfoundland looking north to Cape Spear. Cape Spear is the most easterly point of North America. Photo by Harold Williams GSC 1994-800.

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Chapter 1 – Introduction (by Harold Williams)

PREAMBLE AND DEFINITION

The Canadian Appalachian region includes the provinces of insular Newfoundland, Nova Scotia, New Brunswick, Prince Edward Island, and the southern part of Quebec along the south side of the St. Lawrence River (Fig. 1.1). It has an area of approximately 500000 km2 and it is widest (600 km) at the Canada-United States International Boundary in New Brunswick and Nova Scotia. A larger unexposed area of Appalachian rocks and structures extends across the Gulf of St. Lawrence and seaward to the Atlantic continental edge. Because of its coastal setting and insular makeup, the region offers tremendous shoreline exposures along marine passages.

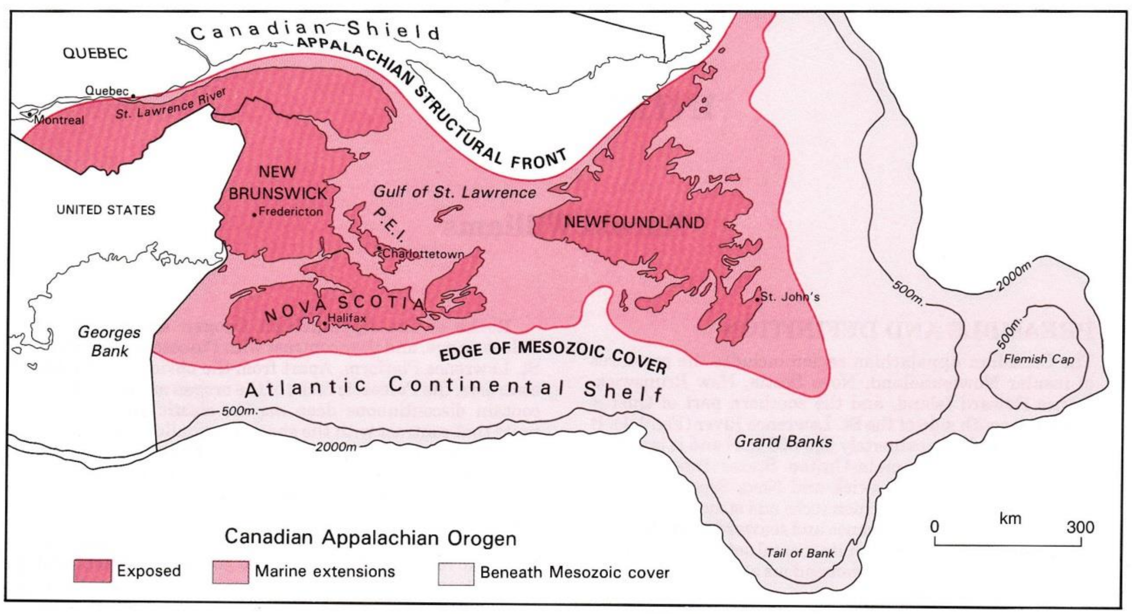
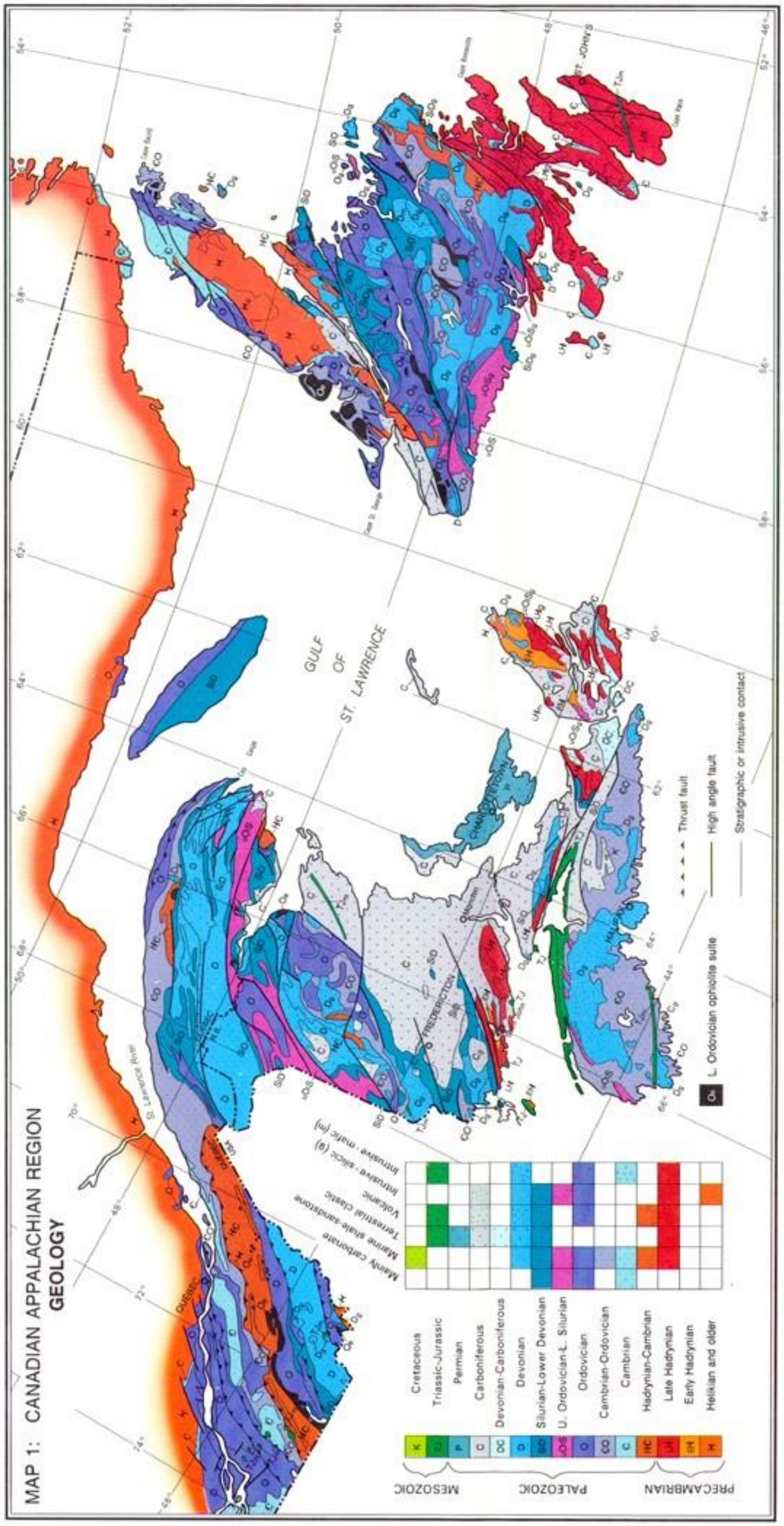


Figure 1.1. Canadian Appalachian region.

The Appalachian region is a Paleozoic geological mountain belt or orogen. This means that its rocks have been affected by orogeny, the combined effects of folding, faulting, metamorphism, and plutonism. Paleozoic folds and faults of several generations trend northeastward. Regional metamorphic rocks occupy continuous belts in interior parts of the orogen, and granitic batholiths are common throughout its length (Maps 1 and 2).


MAP 1: CANADIAN APPALACHIAN REGION
GEOLOGY
GULF OF ST. LAWRENCE
QUEBEC
FREDERICTON
CHARLOTTETOWN
HALIFAX
ST. JOHN'S
St. Lawrence River
MESOZOIC
PALEOZOIC
PRECAMBRIAN
Cretaceous
Triassic-Jurassic
Permian
Carboniferous
Devonian-Carboniferous
Devonian
Silurian-Lower Devonian
U. Ordovician-L. Silurian
Ordovician
Cambrian-Ordovician
Cambrian
Hadrynian-Cambrian
Late Hadrynian
Early Hadrynian
Helikian and older
Mainly carbonate
Marine shale-sandstone
Terrestrial clastic
Volcanic
Intrusive - silicic (g)
Intrusive - mafic (m)
L. Ordovician ophiolite suite
Thrust fault
High angle fault
Stratigraphic or intrusive contact

The word "Appalachian" was first used in a geographic context for the morphological mountains in the southeast United States. It has displaced the word "Acadian" formerly applied to this region of eastern Canada. In the present context, the word "Appalachian" is used for the geological mountain belt without regard for its morphological expression.

Like the Cordilleran and Innuitian orogens, the Appalachian Orogen occupies a position peripheral to the stable interior craton of North America (Fig. 1.2). Undeformed Paleozoic rocks of the craton overlie a crystalline Precambrian basement. The exposed basement forms the Canadian Shield. The cover rocks define the Interior Platform. The Canadian Appalachian region is bordered to the west by that part of the Canadian Shield known as the Grenville Structural Province, and by that part of the Interior Platform known as the St. Lawrence Platform.

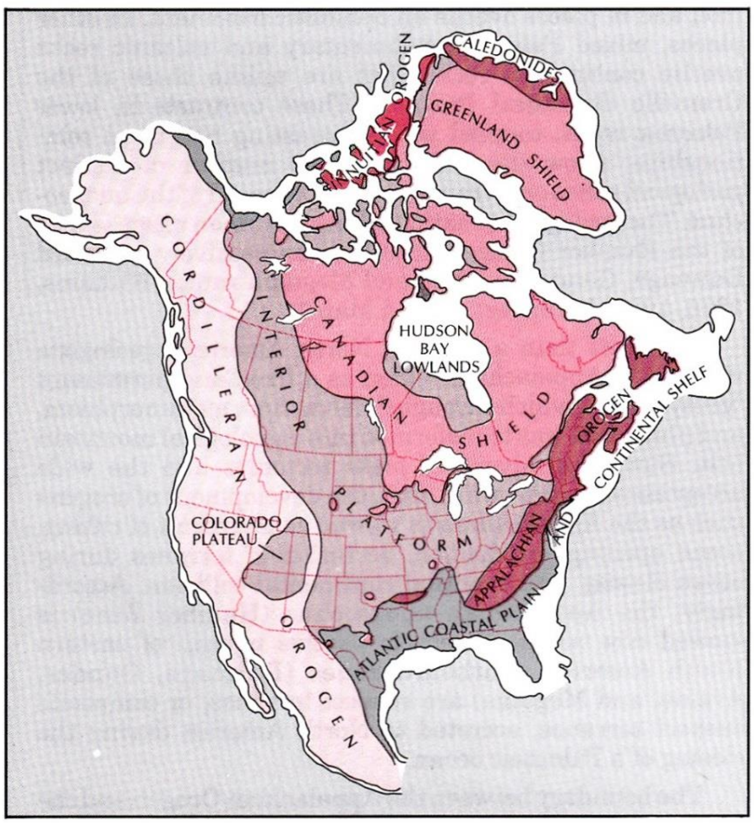


Figure 1.2. Phanerozoic orogens of North America.

Rocks of the Appalachian Orogen are mainly of Paleozoic age, and they contrast with Paleozoic rocks of the St. Lawrence Platform. Apart from the obvious structural contrasts, the Paleozoic rocks of the orogen are thicker and contain discontinuous deep marine clastic and volcanic units that contrast with the sheet-like shallow water limestones and mature quartz sandstones of the platform. As well, there are major differences in contained Paleozoic faunas, metallogenic characteristics, and geophysical expression.

Along the west flank of the Appalachian Orogen, the Paleozoic rocks overlie a Grenville gneissic basement and are continuous and correlative with cover rocks of the St. Lawrence Platform, although they have slightly older units at the base of the section. This part of the orogen is known as the Appalachian miogeocline. East of the miogeocline, fault-bounded Zones of lower Paleozoic rocks exhibit sharp and rapid facies contrasts. Volcanic rocks are common and in places overlie an ophiolitic basement. In other places, mixed Paleozoic sedimentary and volcanic rocks overlie continental rocks that are unlike those of the Grenville Structural Province. These contrasts in lower Paleozoic rocks, coupled with contrasting basement relationships, allow the definition of a number of distinct geological zones or terranes that lie outboard of the miogeocline. The geological zonation in most common usage is that of the Humber (miogeocline), and successively outboard Dunnage, Gander, Avalon, and Meguma zones (Williams, 1976, 1978, 1979; Fig. 1.3 and Map 2).

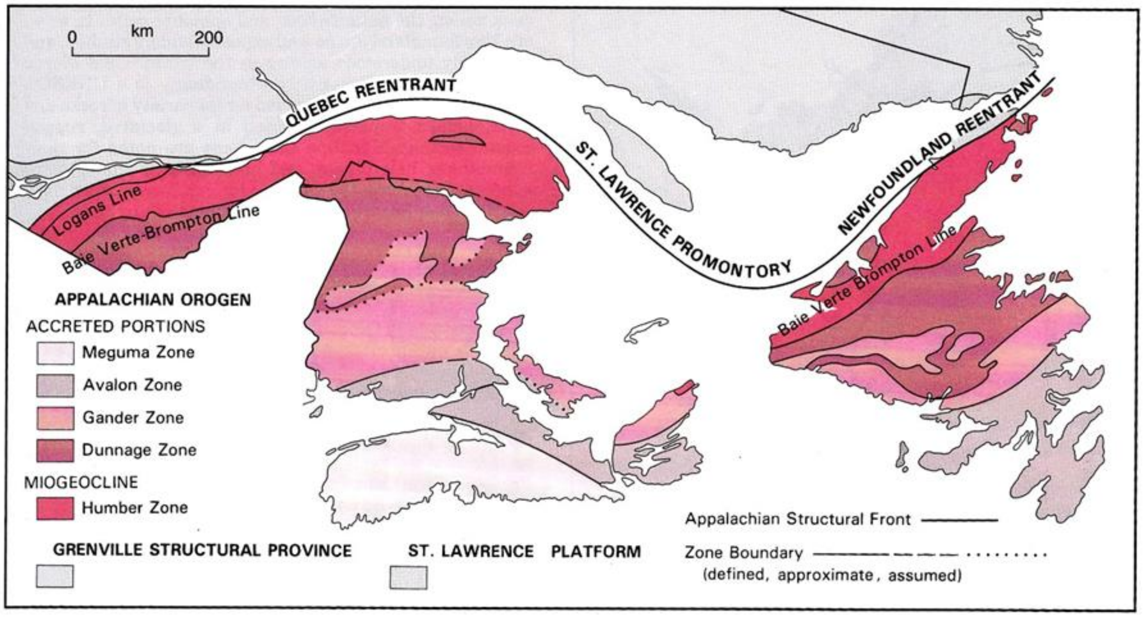
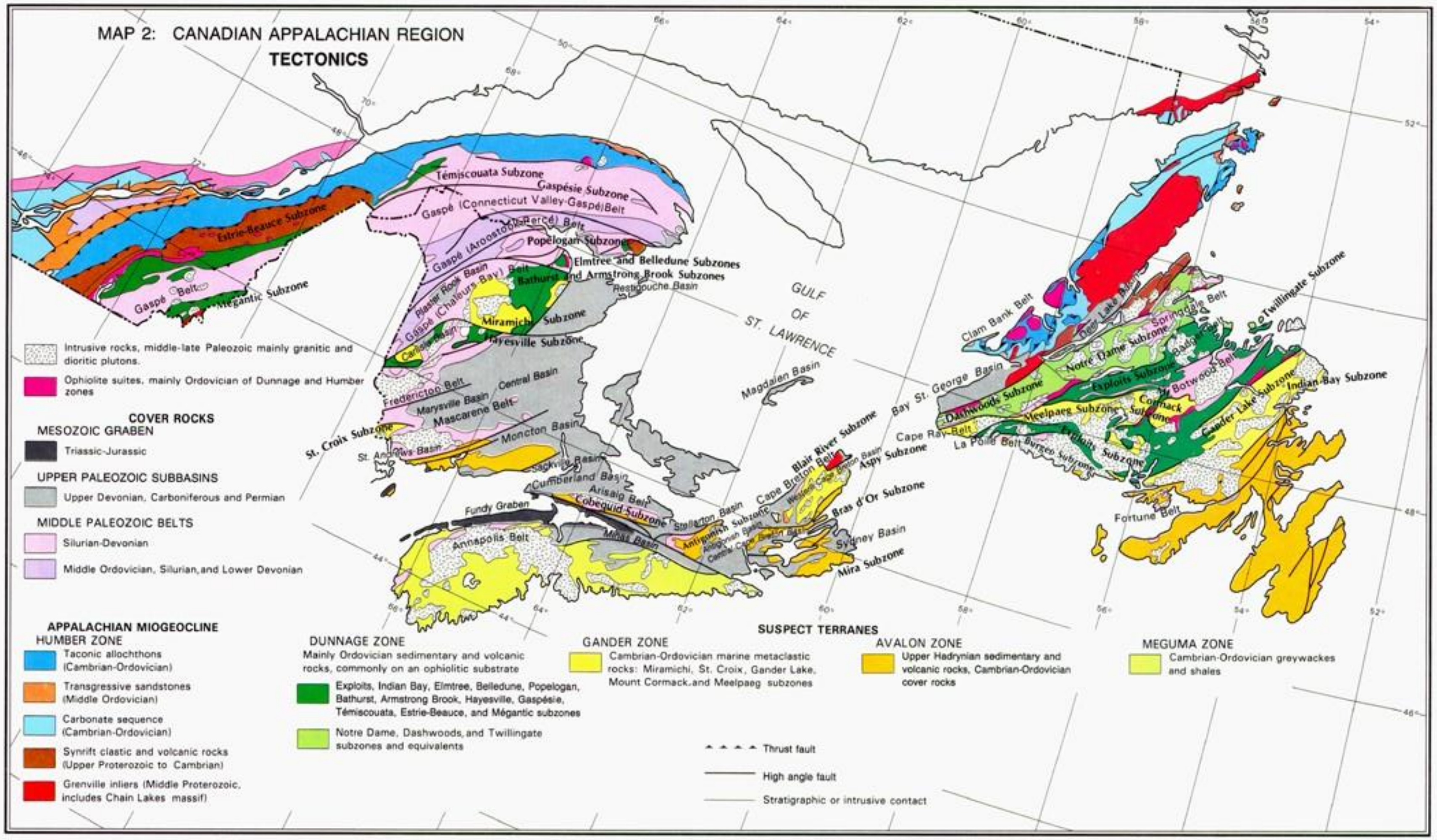


Figure 1.3. Simple zonation of the Canadian Appalachian region.

For more than a century, North American geologists viewed the Appalachian region as a fixed and permanent "geosyncline", which through deformation, metamorphism, and plutonism was transformed into a geological mountain belt. Since the advent of plate tectonics and the wide acceptance of continental drift, the development of orogens such as the Appalachians is viewed as the result of rifting, ocean opening, subduction, accretion of terranes during ocean closing, and eventual continental collision. Accordingly, the Appalachian miogeocline (Humber Zone) is viewed now as the Paleozoic passive margin of eastern North America. Outboard zones (Dunnage, Gander, Avalon, and Meguma) are suspect terranes, or composite suspect terranes, accreted to North America during the closing of a Paleozoic ocean.


MAP 2: CANADIAN APPALACHIAN REGION
TECTONICS
Intrusive rocks, middle-late Paleozoic mainly granitic and dioritic plutons.
Ophiolite suites, mainly Ordovician of Dunnage and Humber zones
COVER ROCKS
MESOZOIC GRABEN
Triassic-Jurassic
UPPER PALEOZOIC SUBBASINS
Upper Devonian, Carboniferous and Permian
MIDDLE PALEOZOIC BELTS
Silurian-Devonian
Middle Ordovician, Silurian, and Lower Devonian
APPALACHIAN MIOGEOCLINE
HUMBER ZONE
Taconic allochthons (Cambrian-Ordovician)
Transgressive sandstones (Middle Ordovician)
Carbonate sequence (Cambrian-Ordovician)
Synrift clastic and volcanic rocks (Upper Proterozoic to Cambrian)
Grenville inliers (Middle Proterozoic, includes Chain Lakes massif)
DUNNAGE ZONE
Mainly Ordovician sedimentary and volcanic rocks, commonly on an ophiolitic substrate
Exploits, Indian Bay, Elmtree, Belledune, Popelogan, Bathurst, Armstrong Brook, Hayesville, Gaspésie, Témiscouata, Estrie-Beauce, and Mégantic subzones
Notre Dame, Dashwoods, and Twillingate subzones and equivalents
SUSPECT TERRANES
GANDER ZONE
Cambrian-Ordovician marine metaclastic rocks: Miramichi, St. Croix, Gander Lake, Mount Cormack, and Meelpaeg subzones
AVALON ZONE
Upper Hadrynian sedimentary and volcanic rocks, Cambrian-Ordovician cover rocks
MEGUMA ZONE
Cambrian-Ordovician greywackes and shales
Thrust fault
High angle fault
Stratigraphic or intrusive contact
Témiscouata Subzone
Gaspésie Subzone
Gaspé (Connecticut Valley-Gaspé) Belt
Estrie-Beauce Subzone
Popelogan Subzone
Elmtree and Belledune Subzones
Bathurst and Armstrong Brook Subzones
Restigouche Basin
Mégantic Subzone
Gaspé Belt
Miramichi Subzone
Hayesville Subzone
Fredericton Belt
Central Basin
Marysville Basin
Mascarene Belt
Moncton Basin
St. Croix Subzone
St. Andrews Basin
Sackville Basin
Cumberland Basin
Arisaig Belt
Cobequid Subzone
Fundy Graben
Annapolis Belt
Minas Basin
Stellarton Basin
Antigonish Subzone
Cape Breton Belt
Blair River Subzone
Aspy Subzone
Bras d'Or Subzone
Sydney Basin
Mira Subzone
GULF OF ST. LAWRENCE
Magdalen Basin
Bay St. George Basin
Cape Ray Belt
La Poile Belt
Burgeo Subzone
Clam Bank Belt
Deer Lake Basin
Notre Dame Subzone
Springdale Belt
Twillingate Subzone
Dashwoods Subzone
Exploits Subzone
Botwood Belt
Meelpaeg Subzone
Cormack Subzone
Gander Lake Subzone
Indian Bay Subzone
Fortune Belt

The boundary between the Appalachian Orogen and the St. Lawrence Platform is drawn at the structural front between the deformed rocks of the orogen and the undeformed rocks of the platform (Fig. 1.3). This boundary is coincident, or nearly so, with Logan's Line, a major structural junction between transported rocks from well within the orogen and structurally underlying rocks of the miogeocline. The exposed edge of the miogeocline occurs much farther east where it is marked by a narrow steep belt of ophiolite occurrences, the Baie Verte-Brompton Line (Williams and St-Julien, 1982).

Stratigraphic and sedimentological analyses of the Canadian and United States Appalachians indicate that terranes east of the miogeocline were accreted during three main events (Williams and Hatcher, 1983). The accretionary events are approximately coeval with three major orogenic episodes that occurred during the Early-Middle Ordovician (Taconic), Silurian-Devonian (Acadian), and Carboniferous-Permian (Alleghanian). Opening of the present North Atlantic Ocean was initiated well east of the accreted Appalachian terranes. Thus, a variety of Appalachian terranes were stranded at the margin of the North American craton. The sinuous form of the miogeocline in Canada, expressed in the Quebec Reentrant, St. Lawrence Promontory, and Newfoundland Reentrant (Fig. 1.3), probably reflects an orthogonal ancient continental margin bounded by rifts and transform faults analogous to the modern Grand Banks (Thomas, 1977; Williams and Doolan, 1979).

The closing of the Paleozoic Iapetus Ocean (Harland and Gayer, 1972) and opening ofthe North Atlantic explain why 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 (Fig. 1.4). Other segments of the miogeocline, although not now part of the North American continent, remain within the American plate. The Greenland Caledonides represents such a segment and for that reason the geology of East Greenland is discussed in this volume (Chapter 12).

PHYSIOGRAPHY AND GLACIATION

The Canadian Appalachian region has a glaciated surface of highlands, uplands, lowlands, valleys, and fiords (Fig. 1.5). Its broken hummocky nature contrasts with the St. Lawrence Lowlands to the northwest and the smooth flat surface of the Atlantic Continental Shelf to the southeast. Highest elevations occur to the west and northwest where the rocks of the miogeocline form local highlands. From there, an undulating upland slopes gently southeastward to the coast, although it is dissected by valleys and interrupted by lowlands.

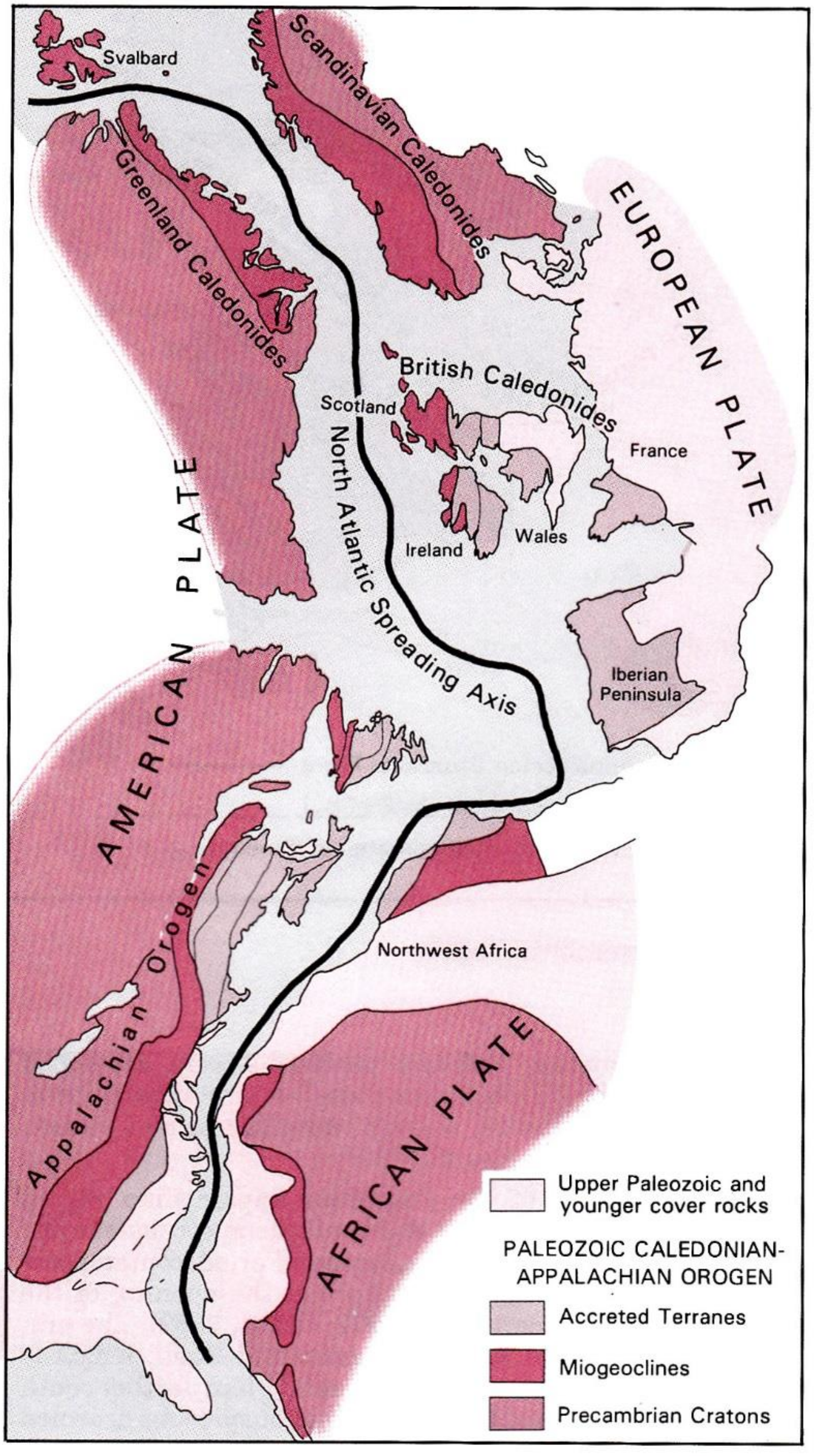


Figure 1.4. Tectonic elements of the restored North Atlantic region (after Williams, 1984).

Lowlands of the Canadian Appalachian region occur in the vicinity of the Gulf of St. Lawrence and these are underlain by mainly subhorizontal Carboniferous rocks. Within the Gulf of St. Lawrence, there is no morphological distinction between the St. Lawrence and Appalachian lowland provinces. The absence of an elevated miogeocline makes this region unique for the length of the Appalachian mountain chain.

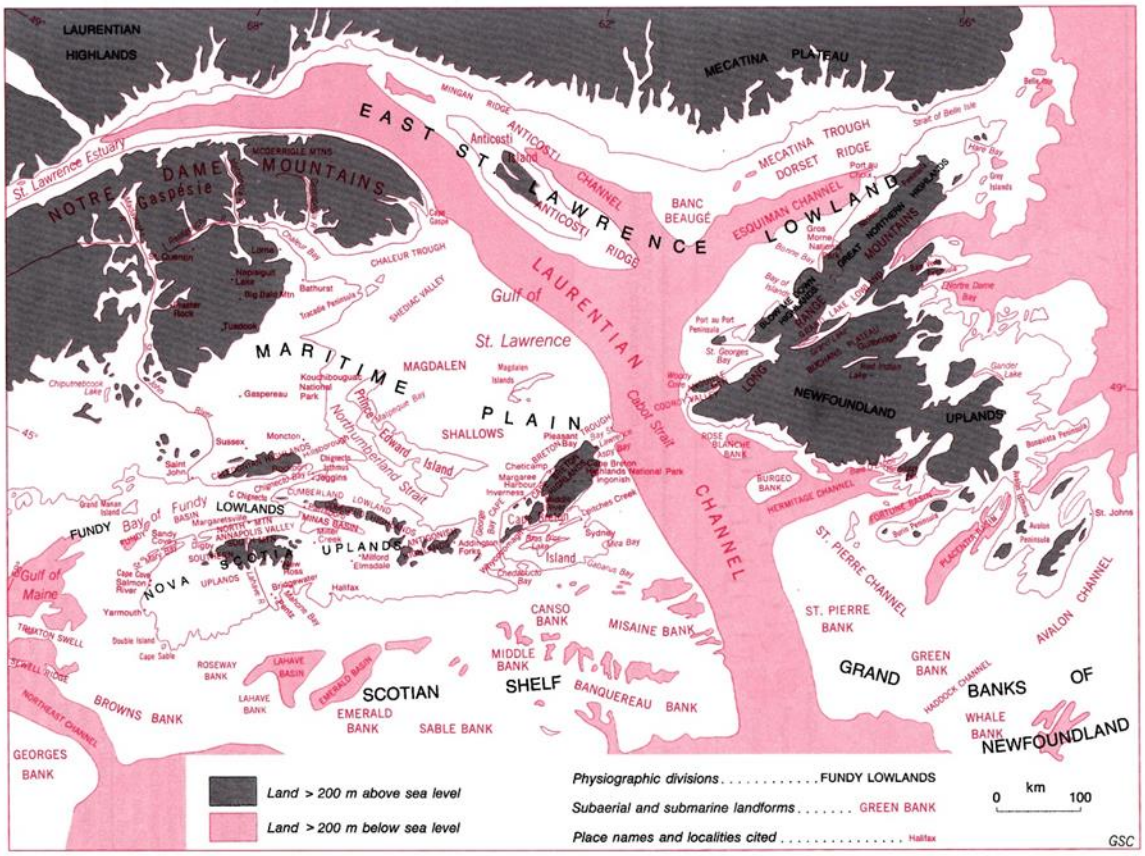


Figure 1.5. Physiography of the Canadian Appalachian region (after Grant, 1989).

The Atlantic Continental Shelf is underlain by Mesozoic and Cenozoic strata (Fig. 1.1). These thicken profoundly toward the shelf edge and they form Canada's newest petroleum frontier. Offshore landforms were developed during periods of Late Cretaceous-Tertiary subareal erosion, producing mesas, cuestas, interfluves, and stream valleys (King, 1972; Grant, 1989).

Physiography of the Canadian Appalachian region probably relates to a long and continuous erosional cycle that had its beginning in the Jurassic Period, contemporaneous with continental breakup and the opening of the North Atlantic Ocean (King, 1972; Grant, 1989). The present setting of the Atlantic Continental Shelf, which is partly emerged as the Atlantic Coastal Plain farther south in the eastern United States, and the conspicuous drowned coastline of the Atlantic Provinces may reflect pre-Pleistocene tilting and tectonic subsidence (King, 1972; Grant, 1989).

Glacial erosion and deposition contributed to the landscape by surficial modification of former features. Pleistocene ice sheets advanced south and southeastward across the region, and the island of Newfoundland supported its own ice cap that flowed radially to the sea (Fig. 1.6). Fiord development is extensive around the Newfoundland coast but overdeepening is less evident elsewhere. Glacial retreat began about 20 000 years ago, and glacial rebound brought the surface of the Atlantic region to its present position (Grant, 1989; Occhietti, 1989).

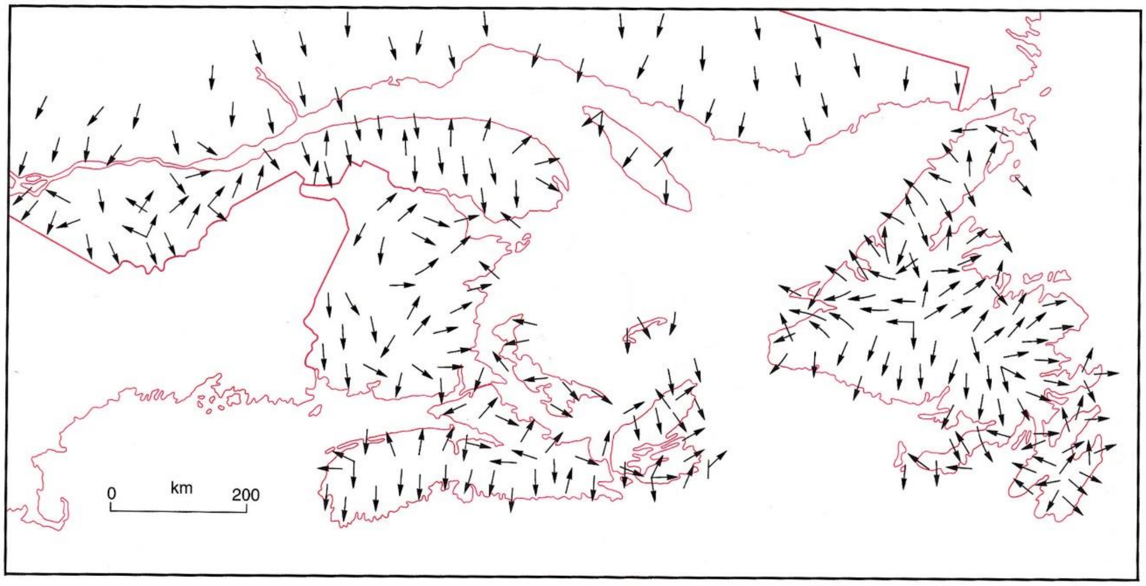


Figure 1.6. Glacial features of the Canadian Appalachian region (modified from Grant, 1989 and Occhietti, 1989). Arrows indicate direction of glacial ice movement.

ACCESS AND CULTURE

The Appalachian region is the oldest settled part of Canada. It is covered by a network of paved roads and secondary gravel roads in populated areas. Because forest industries are important, there are numerous logging roads and trails. Navigable rivers and large lakes provide access to other parts of the region. Float planes or helicopters are available for charter near most major centres. Some shoreline sections can be walked, but a boat is usually necessary to negotiate headlands and cliffed shoreline. Boats are easily hired in the numerous fishing villages scattered along the coast.

Exposures across northeast Newfoundland provide an unsurpassed cross-section of the orogen, and many of the latest Appalachian concepts emanated from this area. Allochthonous terranes such as those along the St. Lawrence River in Quebec and western Newfoundland rank among the nation's best, and ophiolite suites in western Newfoundland are as well exposed, widely studied, and intimately understood as any in the world. Gros Morne National Park in western Newfoundland is a UNESCO World

Heritage Site, recognized for its variety of rocks and relationships, superbly exposed in a glaciated, rugged coastal setting. Maritime Canadians are noted for their friendliness, helpfulness, and hospitality so that anyone may visit, traverse the countryside, and inspect the outcrops at their leisure, free of harassment of any kind.

GEOPHYSICAL EXPRESSION AND OFFSHORE EXTENSIONS

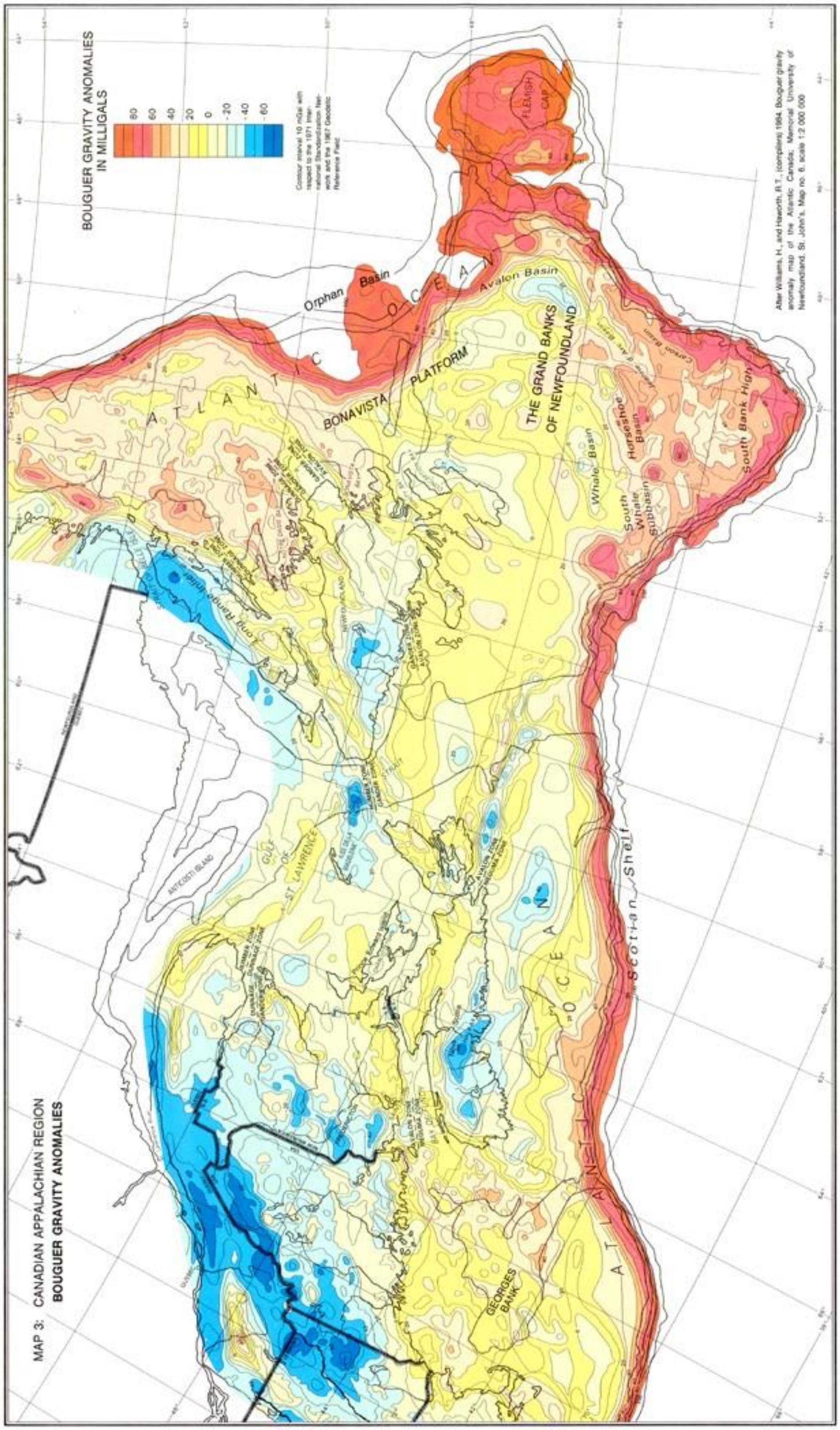
The Appalachian Orogen has a geophysical expression that allows extension of its onland rocks and structures sea ward to the submerged and covered edge of continental crust at the Atlantic margin.

The Bouguer anomaly field over the onIand orogen, and the free-air anomaly field over marine areas, have a general level tens of milligals higher than that over the Grenville Province of the Canadian Shield (Map 3). Major anomalies and gradients trend northeast, parallel to structural trends and lithofacies belts, and are traceable to the continental edge. A positive gradient from west to east lies at or near the exposed edge of the Appalachian miogeocline. Ophiolite complexes and mafic volcanic belts in central parts of the orogen have a strong positive expression (Haworth and Jacobi, 1983; Williams and Haworth, 1984a; Shih et aI., 1993a).

Similarly, aeromagnetic and sea magnetic anomalies follow major structures and are especially useful in extending ophiolitic and volcanic belts offshore (Map 4, Williams and Haworth, 1984b; Shih et aI., 1993b). Where the Appalachian magnetic basement is deeply covered by younger sediments at the continental edge, the magnetic anomalies are expectedly broad and less distinct. A prominent positive anomaly, the East Coast Magnetic Anomaly, occurs at the morphological shelf edge east of Nova Scotia and southward, but it is absent along the torturous rifted margin of the Grand Banks in Newfoundland. One suggestion is that the East Coast Magnetic Anomaly is a Paleozoic collisional zone that was the locus for opening of the North Atlantic (Nelson et aI., 1985). Part of this collisional zone occurs inland in the southeastern United States (Brunswick Magnetic Anomaly) and it may be truncated off Nova Scotia by the axis of Atlantic spreading, and therefore displaced to the African continental margin.

The Avalon-Meguma zone boundary is marked by the Collector Magnetic Anomaly extending offshore to the continental edge where it is collinear with the Newfoundland Seamounts (Williams and Haworth, 1984b; Shih et aI., 1993b). Other features of the modern margin also reflect ancestral controls, e.g. the Charlie Gibbs Fracture Zone coincides with the extension of the Gander-Avalon zone boundary off northeast Newfoundland, and the Tail of the Bank mimics the St. Lawrence Promontory.

Seismic reflection studies indicate that a Grenville lower crustal block extends in subsurface well beyond the exposed edge of the miogeocline (Fig. 1.7). It meets a


MAP 3: CANADIAN APPALACHIAN REGION
BOUGUER GRAVITY ANOMALIES
BOUGUER GRAVITY ANOMALIES IN MILLIGALS
80
60
40
20
0
-20
-40
-60
Contour interval 10 mGal with respect to the 1971 International Standardization Network and the 1967 Geodetic Reference Field
After Williams, H., and Haworth, R.T. (compilers) 1984. Bouguer gravity anomaly map of the Atlantic Canada; Memorial University of Newfoundland, St. John's, Map no. 6, scale 1:2 000 000
ATLANTIC OCEAN
Orphan Basin
FLEMISH CAP
Avalon Basin
BONAVISTA PLATFORM
THE GRAND BANKS OF NEWFOUNDLAND
Whale Basin
Horseshoe Basin
South Whale Subbasin
South Bank High
Long Range Inlier
GULF OF ST. LAWRENCE
ANTICOSTI ISLAND
Scotian Shelf
GEORGES BANK

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 tooted in the mantle (Keen et al., 1986; Marillier et al., 1989).

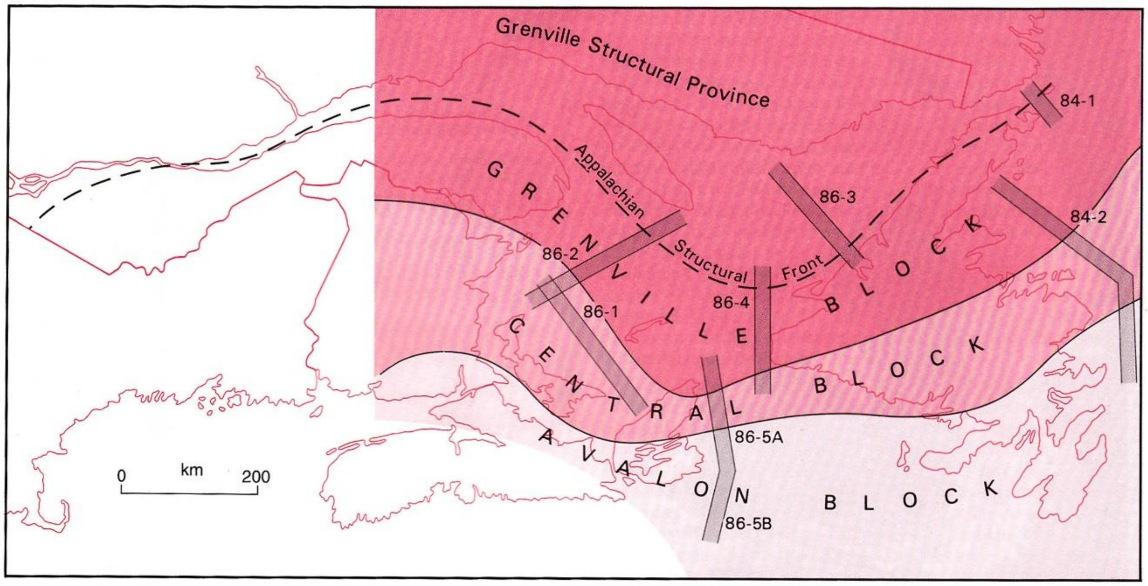


Figure 1.7. Lower crustal blocks of the Canadian Appalachian region (after Marillier et al., 1989), as determined along deep reflection lines, e.g. 86-1, etc.

EXTENSIONS AND SETTING IN THE NORTH ATLANTIC

The Canadian Appalachians extend southwestward through the eastern United States to Alabama. There, Paleozoic rocks and structures are overlapped unconformably by Mesozoic and younger strata of the Atlantic Coastal Plain (Fig. 1.8). West of the Mississippi Embayment, deformed Paleozoic rocks reappear in the Ouachitas of Arkansas and Oklahoma and they occur still farther west in the Llano and Marathon uplifts of Texas. Paleozoic rocks and structures are known in Mexico where they are overprinted by younger structures of the Cordilleran Orogen (Ruiz et al., 1988). The Appalachian Orogen is therefore continuous to the Pacific margin of the continent.

The Appalachian miogeocline, everywhere developed upon Grenville basement, is the most continuous feature of the orogen. Basement inliers and their cover rocks form the Blue Ridge Province of the U.S. Appalachians and imbricated cover rocks farther west form the Valley and Ridge Province. Fossiliferous and little metamorphosed Paleozoic rocks that make up the accreted parts of the Canadian Appalachians continue into New

England but equivalents are largely absent in the southern U.S. Appalachians where the centrally located Inner Piedmont Hud Charlotte belts are composed entirely of crystalline rocks. Farther east however, the U.S. Carolina Slate Belt, which extends to the coastal plain onlap, is a natural continuation of the Canadian Avalon Zone. Detailed treatment of the U.S. Appalachians with maps and illustrations is contained in Hatcher et al. (1989). The Tectonic Lithofacies Map of the Appalachian Orogen (Williams, 1978a) in its largest format at 1:1 000 000 scale is also a useful illustration for Canadian-United States comparisons.

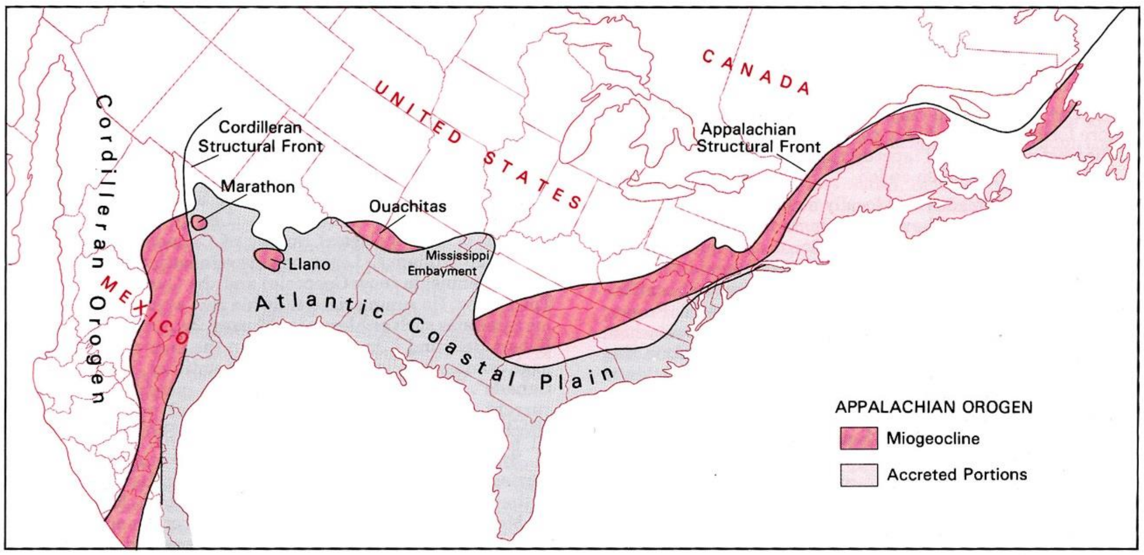


Figure 1.8. Appalachian Orogen, Newfoundland to Mexico. Approximate area of Paleozoic rocks in Mexico contained in Sierra Madre and Acatlan terranes (Ruiz et al., 1988).

Restoration of the North Atlantic (Fig. 1.4) juxtaposes the Atlantic continental shelf with the marine shelves of Ireland, the Iberian Peninsula, and northwest Africa. A miogeocline, equivalent to that of the Appalachians, occurs in the northwest British Caledonides. In the British Isles, most of the miogeoclinal rocks are metamorphosed but locally in Scotland the Durness succession has an early Paleozoic stratigraphy and faunas identical to those of the Appalachian miogeocline. Reworked Grenville basement is recognized locally in the miogeocline of Ireland and Scotland but the undeformed foreland to the miogeocline has much older Precambrian rocks of the Laxfordian (1800 Ma) and Scourian (2500 Ma) provinces. Beyond the British Isles, rocks like those of the Appalachian miogeocline reappear in the Caledonides of East Greenland. Equivalents of the 1000 Ma Grenville Structural Province locally form the basement to the miogeoclinal cover rocks there but the Greenland miogeocline, like that of Scotland, is developed mainly upon much older Precambrian rocks. Beyond Greenland, miogeoclinal rocks of the Hecla Hoek Group occur III Northern Svalbard (Williams, 1984).

The Appalachian miogeocline and its extensions therefore formed a remarkably continuous continental margin, the western margin of Iapetus that can be traced for almost 10,000 km and is open ended.

Accreted terranes that locally include volcanic rocks on ophiolitic basement have equivalents in the British Isles and ophiolitic complexes are common on the opposing margin of Iapetus in the Scandinavian Caledonides. Other easternmost Appalachian terranes have natural continuations in northwest Africa, the Iberian Peninsula France and Wales. Some of these are huge and rival the Appalachian miogeocline in width and continuity, e.g. Avalon Zone. The Tectonic Map of Pre-Mesozoic Terranes in Circum-Atlantic Phanerozoic Orogens (Keppie and Dallmeyer, 1989) is a useful illustration for North Atlantic connections. Collections of papers are found in Kerr and Fergusson (1981) and Dallmeyer (1989).

Parallelism of the Grenville Structural Province and the Appalachian miogeocline in eastern North America implies Precambrian ancestral control for the development of the Paleozoic margin. Similarly, parallelism of the Appalachian Orogen and the North Atlantic margin implies further mimicry and Paleozoic ancestral control of the modern continental margin (Fig. 1.9).

The North Atlantic Ocean and its continental margins provide an actualistic model for the Paleozoic Iapetus Ocean that led to the development of the Appalachian Orogen. The widths of the North Atlantic continental shelves and the thicknesses of sediments at the North Atlantic margins are comparable to palinspastically restored widths of Paleozoic margins and thicknesses of their miogeoclinal sections. The form of the North Atlantic margin mimics and provides an explanation for the sinuosity of the deformed Appalachian miogeocline. The crust and mantle beneath the North Atlantic is analogous to Paleozoic volcanic rocks and ophiolite suites, and marine microcontinents (e.g. Rockall Plateau) and oceanic volcanic islands and seamounts (e.g. Iceland, the Faeroes, Newfoundland seamounts) are potential suspect terranes (Fig. 1.10).

HISTORY OF INVESTIGATION

Geological investigations in the Appalachian region began even before the creation of the Geological Survey of Canada in 1842. These include studies in Nova Scotia by Abraham Gesner and in Newfoundland by J.B. Jukes. With the creation of the Geological Survey of Canada, the newly appointed William E. Logan began systematic fieldwork in Gaspe Peninsula (now Gaspésie) and the Quebec Eastern Townships. He summarized fully his own work and that of his associates such as Alexander Murray, James Richardson, Robert Bell, and Elkanah Billings in the momentous 983-page volume published in 1863 and entitled "Geology of Canada". Logan's stratigraphy and his insight into such current concerns as ancient continental margins and allochthonous terranes are still respected (Stevens, 1974).

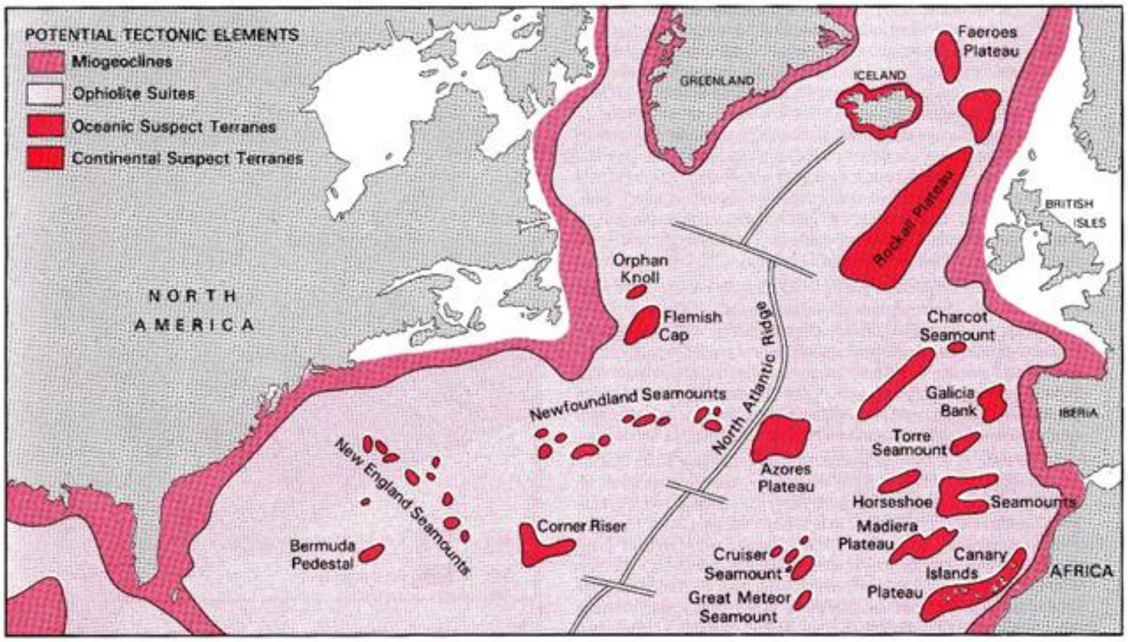


Figure 1.10. North Atlantic region – prospective orogen (after Williams, 1984).

Systematic studies and reconnaissance mapping were carried out in the Appalachian region during the latter half of the 19th century. L.W. Bailey, G.F. Matthew, R.W. Ells, W. McInnes, and C. Robb together studied and mapped the geology of New Brunswick, outlining the major lithic units and general distribution of mineral deposits. Hugh Fletcher and E.R. Faribault produced a series of 1:63 360 geological maps covering the important coal producing and gold mining districts of Nova Scotia, the combined result of more than 86 years of fieldwork. Alexander Murray was appointed in 1864 to the newly created Geological Survey of Newfoundland. Murray's appointment coincided with the beginning of a 40-year boom in copper mining, and he and J .P. Howley published numerous reports and a generalized geological map of the island (Murray and Howley, 1881, 1918; Howley, 1925).

More detailed studies of regional geology and of mineral districts and mines were advancing in the early 1900s. Most of this work was carried out by the Geological Survey of Canada supplemented by that of provincial mines departments.

Geological mapping of the Quebec Appalachians, initiated by the Geological Survey of Canada, was expanded and eventually succeeded by work of the Quebec Department of Mines in the 1950s and 1960s. Classic stratigraphic and paleontological studies were made in Gaspésie and along the St. Lawrence River by J .M. Clarke and Charles Schuchert.

Geological mapping continued in New Brunswick, in large part under the guidance of W.J. Wright, up to 1953 and the staking rush that signalled the beginning of the Bathurst mining boom. The New Brunswick Research and Productivity Council was established in 1962, and in 1965 the Provincial Department of Mines embarked upon a program of expanded geological fieldwork with increased permanent staff.

In Nova Scotia, a program of modern-day 1:63 360 mapping coupled with biostratigraphic studies was begun by the Geological Survey of Canada with W.A. Bell and others. The program continued through the 1940s and 1950s to its completion. Onland geological investigations are continuing under the direction of the Provincial Mines Branch, and offshore studies are being conducted by the Atlantic Geoscience Centre and the Nova Scotia Research Council.

Few geological studies were made in Newfoundland during the early 1900s, except for those of the Princeton University expeditions. The Geological Survey of Newfoundland was reactivated in 1933 under A.K Snelgrove and later under C.K. Howse. In 1949, the year of confederation with Canada, responsibilities for regional geology were assumed by the Geological Survey of Canada and the Geological Survey of Newfoundland was disbanded. The Geological Survey of Newfoundland was reactivated in 1952 under the direction of D.M. Baird. Since 1949, the Geological Survey of Canada completed a program of 1:253 440 reconnaissance mapping. Most recent studies are carried out by a much expanded Geological Survey of Newfoundland that is mainly concentrating on 1:50 000 mapping and a study of mineral deposits.

As a result of previous and present geological activity, all of the Canadian Appalachian region is covered by 1:253440 or 1:250000 reconnaissance mapping and more than half is covered by modern 1:63 360 or 1:50 000 mapping. Mineral districts are covered in more detail. Contributions by university research teams have added much to our understanding of the orogen over the past 20 years, especially by Memorial University in Newfoundland, Dalhousie University in Nova Scotia, the University of New Brunswick in New Brunswick, and Université Laval and Université de Montréal in Quebec. Recent, or relatively recent geological map compilations are available for all provinces at various scales (Keppie, 1979; Potter et al., 1979; van de Poll, 1983, 1989; Avramtchev, 1985; Colman-Sadd et al., 1990).

Aeromagnetic maps at 1:63 360 or 1:50 000 scale are available for the Canadian Appalachian region through the Geological Survey of Canada, and gravity data are also available, although in less detail. Seismic refraction and reflection work has focused mainly on offshore regions, but several seismic reflection lines were completed across the miogeocline in Quebec (St-Julien et aI., 1983). Deep reflection lines were done off northeast Newfoundland (Keen et al., 1986) and in the Gulf of St. Lawrence (Marillier et aI., 1989) as part of the Frontier Geoscience Project. Deep reflection transects across insular Newfoundland were completed as part of the Canadian Lithoprobe Project in

1989 (Williams et aI., 1989; Piasecki et al., 1990). Isotopic ages are available for most large plutons and ophiolite complexes, with precision ranging from that of early K-Ar ages to more reliable Rb-Sr, U-Pb, and Sm-Nd ages.

A number of syntheses, reviews and collections of papers on Canadian Appalachian geology, with rather complete reference lists, have been published over the last 25 years. These include Neale and Williams, 1967; Kay, 1969; Poole et al., 1970; Rodgers, 1970; Geological Association of Canada, 1971; Williams et al., 1972; Tozer and Schenk, 1978; Williams, 1979; Wones, 1980; St-Julien and Beland, 1982; and Hatcher et aI., 1983.

The International Geological Correlation Program, Project 27, the Caledonian-Appalachian Orogen, has led to an inventory of Appalachian geology (Schenk, 1978). It terminated in 1984 and several 1:1 000 000 and/or 1:2000 000 Appalachian compilation maps are published: tectonic lithofacies (Williams, 1978a,b), magnetic anomaly (Zietz et aI., 1980a, b), Bouguer gravity anomaly (Haworth et aI., 1980a, b), and a structural map (Keppie, 1982). Project 27 is replaced by the International Geological Correlation Program, Project 233, Terranes in Circum Atlantic Paleozoic Orogens.

The discovery of major offshore oil and gas deposits brought new interest to the geology of the North Atlantic continental margin and a much accelerated level of activity. Collections of papers are found in Yorath et aI., 1975; Vogt and Tucholke, 1986; Sheridan and Grow, 1988; Tankard and Balkwill, 1989; and Keen and Williams, 1990. Transects of the Atlantic margin, including the onland Appalachian Orogen, are part of the Decade of North American Geology (DNAG) Project on North American continental margin transects, and this work is leading to worthwhile comparisons between the Appalachian miogeocline and the modern Atlantic margin (Haworth et aI., 1985, in press). Perhaps the most exciting recent work is the deep reflection experiments that led to the definition of lower crustal blocks. Relating surface geology to deep structure is a new and exciting challenge in the study of the Canadian Appalachian region.

HISTORY OF IDEAS

Since the acceptance of plate tectonics and the realization that the earth's crust is a mosaic of moving plates, great strides have been made in understanding where geological mountain belts are sited and how they evolved. In view of our present streamlined theories it is interesting to reflect on what went before, and to look at earlier attempts to rationalize the development of the Appalachian mountain system from the viewpoint of fixed continents and permanent oceans. "No thorough grasp of a subject can be gained unless the history of its development is clearly appreciated" (Geikie, 1905). Since many previous ideas emanated from the Appalachian region of eastern North America, it is appropriate to review some of them here.

Before the advent of plate tectonics about 25 years ago, the protolith of the Appalachian Orogen was viewed as a geosyncline. The nature of geosynclines, their developmental patterns, and their position with respect to continents and ocean basins were controversial and enigmatic topics. Few agreed on such fundamental concepts as controls of initiation and siting, basement relationships, and causes of subsidence and ensuing mountain building.

The idea of a geosyncline is summarized by King (1959) and partly reproduced here. It began with James Hall in 1857 (published in 1883), a stratigrapher and paleontologist for the State of New York where rocks of the Interior Platform pass eastward into the Appalachian Orogen. Hall observed that undeformed sedimentary rocks of western New York are thin, whereas deformed rocks of the Appalachian region in eastern New York are thick; although both formed during the same Paleozoic time span and were deposited in shallow water. He reasoned that there must be some relationship between the greater thickness of shallow water sedimentary rocks in the Appalachians and their deformed nature. The Appalachian region must have subsided more than the platformal region and Hall suggested that the greater subsidence resulted from gradual yielding of the crust beneath the weight of the sediments themselves. Along the axis of the subsiding area, the sedimentary rocks were folded and in places ruptured to localize igneous intrusions. This was followed by uplift and erosion to produce the geological mountain belt. Hall viewed mountain building as largely a matter of thick sedimentary accumulation, subsidence of the crust under the weight of the sediments, and subsequent uplift. In this model, deformation was incidental to the sediment accumulation and a consequence of the subsidence. Geological mountains were thus related to the slow surficial processes of erosion and sedimentation, and drainage patterns determined their siting.

James Dwight Dana, a well-known contemporary of Hall, while agreeing with the facts was critical of the explanation for mountain building (Dana, 1873). Dana appraised Hall's explanation as "a theory of the origin of mountains with the origin of mountains left out". Dana envisaged fundamental differences between continents and ocean basins, and he believed in a cooling earth with a contracting interior that led to crustal compression. Greatest yielding to such compression was between the continents and oceans along belts warped down to form the "geosynclinals" (later geosynclines) and warped up to form the "geanticlinals" (later geanticlines). The crust was therefore bent down by outside forces to form a sediment receptacle. Eventually the geosynclinals were destroyed by the compression to which they owed their beginnings through "a catastrophe of plications and solidifications" (Dana, 1873).

Dana was the first to use the term geosyncline and because the theories of both Hall and Dana were based on Appalachian examples, the Appalachian system is the type geosyncline. Dana envisaged a geanticline to the east of the geosyncline which assured a continual supply of detrital material. He also envisaged compression toward the continent, related to an oceanic crust that contracted more quickly than continental crust. This further suggested a position for geosynclines peripheral to continents.

Charles Schuchert, a ruling figure among North American stratigraphers, was a champion of Dana's views and for many years perpetuated the idea of troughs (geosynclines) and borderlands (geanticlines). He outlined the borderland and geosynclinal elements of the North American continent (Schuchert, 1923; Fig. 1.11), and further subdivided the Canadian Appalachians into two geosynclinals and two geanticlinal elements (Schuchert and Dunbar, 1934; Fig. 1.12). This model influenced thinking on the nature of the Canadian Appalachians for many years and was still in use, in modified form, up to the time of the fifth edition of the Geology and Economic Minerals of Canada (Douglas, 1970).

The standard work on North American geosynclines is that of Marshall Kay (1951). He named and classified geosynclines (partly after the German geologist Hans Stille) according to their position with respect to platforms and continental margins, and according to their shape and relative age. He further subdivided his real geosynclines or orthogeosynclines into two main parts, dependent upon rock types; the miogeosyncline with mainly shallow water sedimentary rocks that bordered the platform, and the eugeosyncline with deep marine sedimentary and volcanic rocks that lay farther offshore at the continental margin. Kay drew attention to the presence of volcanic rocks in North American Phanerozoic orogenic belts. He interpreted the volcanic rocks as products of island arcs that ringed the North American continent during its Paleozoic evolution (Fig. 1.13). Sedimentary studies (Krynine, 1948) supported Kay's model and suggested that volcanic islands and contemporary tectonic lands were a more likely provenance for mixed detritus of the geosynclines than the crystalline basement rocks of the borderlands of Dana and Schuchert. Furthermore, the borderland concept found little support in emerging geochronological and geophysical studies.

The notion that geosynclines were peripheral to continents was always favoured by North American geologists since the time of Dana, because of the symmetry of the North American continent and the annular arrangement of its Paleozoic mountain belts (Fig. 1.2). Almost any cross-section of the continent from the interior outward contains the same progression of morphological and tectonic elements; uplands of the ancient Canadian Shield, Phanerozoic lowlands of the Interior Platform, Phanerozoic mountains, modern continental margin, and ocean basin (Fig. 1.14). Kay's work and the substitution of contemporary volcanic arcs for ancient crystalline borderlands firmly established the hypothesis that the North American continent grew, much like a tree, by the addition of younger and outward geosynclinal belts. This was the fixist idea of continental accretion that persisted as a popular model in North America up to the time of plate tectonics, e.g. Wilson (1954), Engel (1963). Probably the most widely cited cross-section to confirm the validity of the concept is that from the Archean Superior Province of the Canadian Shield eastward across the Proterozoic Grenville Province, the Paleozoic Appalachian Orogen, and modem Atlantic margin (Fig. 1.15).

Even before the wide acceptance of continental drift and plate tectonics in North America, models for the evolution of the Appalachian geosyncline emphasized analogies with modern continental margins. Thus, Drake et al. (1959) noted the similarity between the paired inner trough and continental rise prism of the present North Atlantic margin and the Paleozoic miogeosynclinal and eugeosynclinal couple of Kay. Dietz (1963) and Dietz and Holden (1966) argued that Kay's miogeosynclinal zone represented an eastward thickening sedimentary wedge, "the miogeocline", that changed eastward at a bank edge into a continental rise clastic-volcanic facies, "the eugeocline". Rodgers (1968) strengthened the analogue between the Appalachian miogeocline and modern continental shelf by delineating a Paleozoic carbonate bank along the eastern margin of North America that was marked by a bank-edge limestone breccia facies. He furthermore compared the Appalachian Paleozoic bank and the modern Bahama Bank, and suggested that the Paleozoic bank was bounded eastward by a drop-off in bathymetry or sharp declivity, which possibly coincided with the edge of North American Grenville basement.

Because most of these actualistic North American models failed to invoke some form of continental drift, or failed to explain orogens that occur in central parts of continents, they were not generally accepted. Even at home in the Canadian Appalachians, the fixist accretionary models did not adequately accommodate the tectonic relations across the well exposed and remapped northeast Newfoundland section (Williams, 1964). There, the Paleozoic miogeocline-eugeocline pair is bounded to the east, not by a contemporary oceanic domain, but by Precambrian rocks overlain by a Cambrian shelf sequence. The outboard position of the eastern Newfoundland Precambrian terrane (Avalon Zone), and the two-sided nature of the system, refuted the fixist idea of Paleozoic accretion (Fig. 1.16).

These enigmas led Wilson (1966) to propose that the western and eastern parts of the Appalachian Orogen were separated in the early Paleozoic by a proto-Atlantic ocean (Fig. 1.17), which closed in the late Paleozoic to juxtapose the North American and African-European continents. Mesozoic opening of the modern North Atlantic occurred along a slightly more eastern axis so that the African-European Avalon terrane remained in North America. Wilson's model was viewed with scepticism and extreme caution for the next few years but was endorsed enthusiastically after the emergence of plate tectonic theory (McKenzie and Parker, 1967). Today, the model of producing an orogen through a cycle of ocean opening and closing is known as the "Wilson cycle" in honour of its originator.

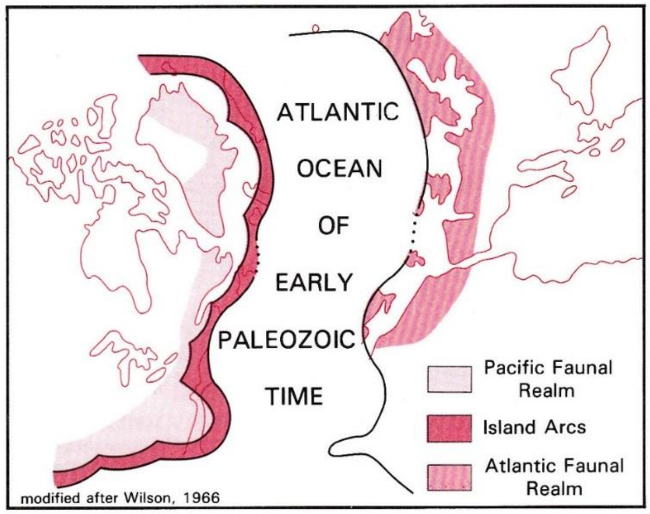


Figure 1.17. Proto-Atlantic ocean of early Paleozoic time (after Wilson, 1966).

The first plate tectonic model for the Appalachian Orogen that incorporated rocks and structures into the scheme of a Wilson cycle is that of Dewey (1969) and Bird and Dewey (1970). It defined the margins of Iapetus and its oceanic tract, and traced the evolution of the Appalachian miogeocline from a rifted margin, through its passive development, to its collisional destruction (Fig. 1.18). The implications of onland ophiolite suites were worked out by Stevens (1970), Church and Stevens (1971), Dewey and Bird (1971), and Williams (1971). As in previous decades, many of these latest Appalachian concepts drew heavily upon relationships in Newfoundland.

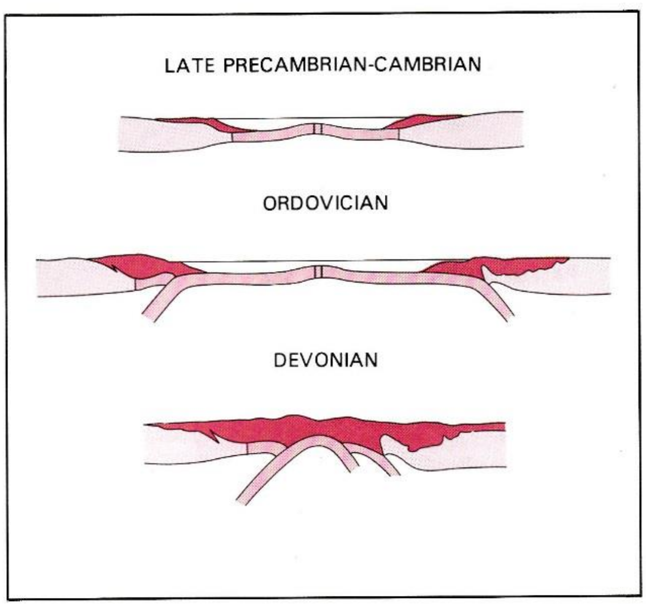


Figure 1.18. Schematic cross-sections illustrating the plate tectonic evolution of the Appalachian-Caledonian Orogen (modified from Dewey, 1969).

Since then there has been a plethora of conceptual plate models for the Appalachians. Their multitude and frequency make it increasingly difficult to retain a youthful enthusiasm for new attempts to incorporate the latest refinements as the database expands.

Now, with an appreciation of the array of complexities inherent in any Wilson cycle model, the emphasis has shifted to recognizing the major tectonostratigraphic divisions in the orogen, establishing structural and stratigraphic relationships, and interpreting the accretion history. More objective accounts based on geographic tectonstratigrahic zones (Williams et aI., 1972; Williams, 1979) are forerunners of present suspect terrane analyses (Williams and Hatcher, 1982, 1983; Zen, 1983; Keppie, 1985, 1989). Their precept is that once the miogeocline is identified all outboard elements are viewed as paleogeographically suspect until proven otherwise (Coney et aI., 1980). This is an objective approach to the analysis of any orogen. Still more cautiously, there is a move afoot to revert to Appalachian zonal analyses (Williams et aI., 1988), with the descriptive term "zone" recommended over "terrane" in cases were the nature of boundaries is doubtful.

APPRAISAL OF EARLIER IDEAS

The problems of geosynclines were always inextricably interwoven with problems of orogenic belts - their siting and processes of mountain building. The idea of a geosyncline therefore brought attention to some of these important problems in tectonics. Problems of the controls of "geosynclinal" subsidence are still addressed today, although expressed differently in models of rifting and thermal subsidence of passive continental margins (Keen, 1979). Following the establishment of the geosynclinal concept by Hall and Dana, it was a natural progression for the next generation of geologists to classify and subdivide geosynclines (Schuchert, 1923; Kay, 1951). The resulting fixist idea of continental accretion found support in North America because of the Paleozoic symmetry of the continent and hints of Precambrian symmetry within the Canadian Shield (Wilson, 1949). Of course the asymmetry of most other continents and the location of some Phanerozoic orogenic belts within continents, e.g. Urals, clearly spoke against the North American fixist accretionary model. Obviously there could be no reconciliation of these concepts without accepting some form of continental drift.

Plate models based upon the Wilson cycle of opening and closing oceans are by far the most viable and actualistic. They not only explain the siting of miogeosynclinal parts of orogens as continental margins and eugeosynclinal parts as accreted terranes but provide a mechanism for mountain building through subduction and collisional events. However, the wave of subjective, poorly-constrained plate models that flourished for more than two decades has waned in the wake of an awareness of the array of complexities and paleogeographic uncertainties in palinspastic restorations of orogenic belts. This is displayed in the current popularity of the suspect terrane outlook and reversions to zonal subdivisions for meaningful "as is" analyses with emphasis on timing and mechanisms of accretion. A shift toward objective analyses, rather than hypothetical scenarios is refreshing, especially as expressed by students who were educated during and after the advent of plate tectonics - a time when it was more fashionable to produce a conceptual model then to dwell on rocks and relationships. And where would we be today without plate tectonics? Probably writing the very best papers on geosynclines or tectonostratigraphic zones, while still wrestling with the problems of fixed continents and permanent oceans.

STANDARDS, SYMBOLS, AND NAMES

The geological time scale used in this volume is that adapted for the Decade of North American Geology (DNAG) Project (Palmer, 1983). Structural symbols are those in common usage by the Geological Survey of Canada. Most text figures use a Lambert projection; maps 1 to 6 use the DNAG base, a modified transverse Mercator projection.

ACKNOWLEDGMENTS

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Chapter 2 - TEMPORAL AND SPATIAL DIVISIONS (by Harold Williams)

PREAMBLE AND PREVIOUS ANALYSES

A wealth of detailed data exists for the Canadian Appalachian region. Presentation of data for an orogen as complex as the Appalachian can be problematical. In this chapter the presentation of these data is based on temporal and spatial divisions of rock units. Previous analyses of the Canadian Appalachian region reflected theories in vogue at the time of their undertaking. Thus prior to the wide acceptance of plate tectonics and continental drift, analyses reflected geosynclinal theory. These varied in detail, from the early work of Schuchert (1923) to the sophisticated compound geosynclines that served

[1] Pages 3- 17, GEOLOGY OF THE APPALACHIAN-CALEDONIAN OROGEN IN CANADA AND GREENLAND Geological Survey of Canada, Geology of Canada, No. 6, Edited by Harold Williams, 1995

as a theme for the fifth edition of the Geology and Economic Minerals of Canada (Poole et al., 1970). Subsequent to plate tectonics, conceptual plate models have abounded. Many were contrived on local relations and abandoned as new information on the geology was uncovered.

Analyses based on "as is" tectonostratigraphic spatial divisions are those that have met with most success. Thus divisions in the U.S. Appalachians (King, 1950, 1959) such as Appalachian Foreland, Valley and Ridge, Blue Ridge and Piedmont provinces, are still in wide usage. Similarly, the tripartite division of Newfoundland (Williams, 1964, see Fig. 1.16), Western Platform, Central Volcanic Belt and Avalon Platform (Kay and Colbert, 1965) remains little changed, though introduced well before the plate tectonic revolution. These are meaningful geographic divisions used in objective syntheses that describe rocks and structures, while attempting to separate what is known, from what is interpreted.

In any objective "as is" account, decisions must be made at the outset on the relative importance of temporal versus geographic divisions. Time-slice analyses work best for simple orogens with few tectonostratigraphic divisions, or where there are established linkages between rocks of one area and those of another. Geographic divisions are necessary for orogens that are complex and made up of terranes or zones that maintain a distinctiveness over long periods. A combination of temporal and spatial divisions is required in the case of the Canadian Appalachians where early Paleozoic geographic entities eventually lose their distinctiveness and share a later Paleozoic history.

TEMPORAL AND SPATIAL DIVISIONS

Rocks of the Canadian Appalachian region are divided into four broad temporal categories; early Paleozoic and older, middle Paleozoic, late Paleozoic, and Mesozoic. There are lithological distinctions and in most places unconformities between rocks of each temporal category (Table 2.1). Names of divisions within the temporal categories are taken from geographical localities.

The zonal division for lower Paleozoic and older rocks (Humber, Dunnage, Gander, Avalon, and Meguma), introduced more than 15 years ago (Williams, 1976), remains functional and still serves as a useful framework for new models and future studies. It is therefore retained as the first order division of the Canadian Appalachian region, with important breakdowns into sub zones in some places (Fig. 2.1 and Map 2). Rocks of these zones display the sharpest contrasts in lithology, stratigraphy and thickness across the orogen. The zones also exhibit structural, faunal, geophysical, plutonic and metallogenic contrasts, thus enhancing their distinctiveness. As well, the surface rocks of some zones coincide with lower crustal blocks. Because zones are based on the oldest rocks of the orogen, they are fundamental to understanding its protoliths and controls of subsequent development. Obviously, the zone boundaries are defined best where rocks of appropriate age are exposed over broad areas. This is the case in Newfoundland, but each zone can be traced by limited exposure across the entire Canadian Appalachian region (Fig. 2.1 and Map 2).

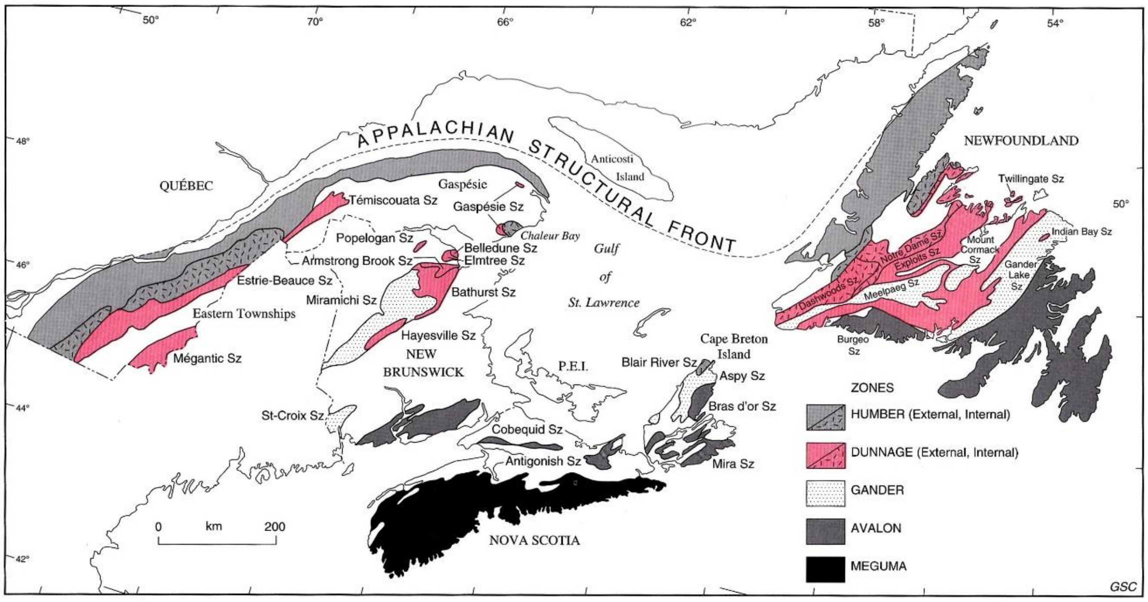


Figure 2.1. Outcrop areas of lower Paleozoic and older rocks that define zones and subzones of the Canadian Appalachian region.

Middle Paleozoic rocks also exhibit lithological, stratigraphic and thickness variations across the orogen, and as in the case of early Paleozoic zones, they define middle Paleozoic belts (Fig. 2.2). Some of these divisions are new and few are as well-known as zones. The belts are clearest among the extensive middle Paleozoic rocks exposed in Quebec, New Brunswick and Nova Scotia. These are Gaspe, Fredericton, Mascarene, Arisaig, Cape Breton, and Annapolis. The middle Paleozoic record in Newfoundland is fragmentary and there is no belt-for-belt equivalence with the mainland. Different names are used, which are Clam Bank, Springdale, Cape Ray, Badger, Botwood, La Poile, and Fortune. The broad offshore area of the Newfoundland Grand Banks has middle Paleozoic rocks unlike those of the onland orogen. These are discussed in Chapter 11 with offshore extensions of the Appalachian Orogen.

The contrasts among rocks of middle Paleozoic belts are less distinctive, compared to those of early Paleozoic zones. Lithological and stratigraphic contrasts are most important, but eastern mainland belts also have faunal, plutonic, and metallogenic distinctiveness. In areas affected by Ordovician deformation, middle Paleozoic belts cross early Paleozoic zones. Thus in the Gaspésie-New Brunswick area, the Gaspé Belt crosses the Humber, Dunnage, and Gander zones, indicating that these early Paleozoic zones were already in proximity during the middle Paleozoic. Similarly in Newfoundland, the Springdale Belt straddles the Humber-Dunnage zone boundary. In areas unaffected by Ordovician deformation, lower and middle Paleozoic rocks are conformable and middle Paleozoic belts are coincident with early Paleozoic zones. Thus the Annapolis Belt and Meguma Zone of Nova Scotia define the same area, and the Badger Belt of Newfoundland lies within the Dunnage Zone.

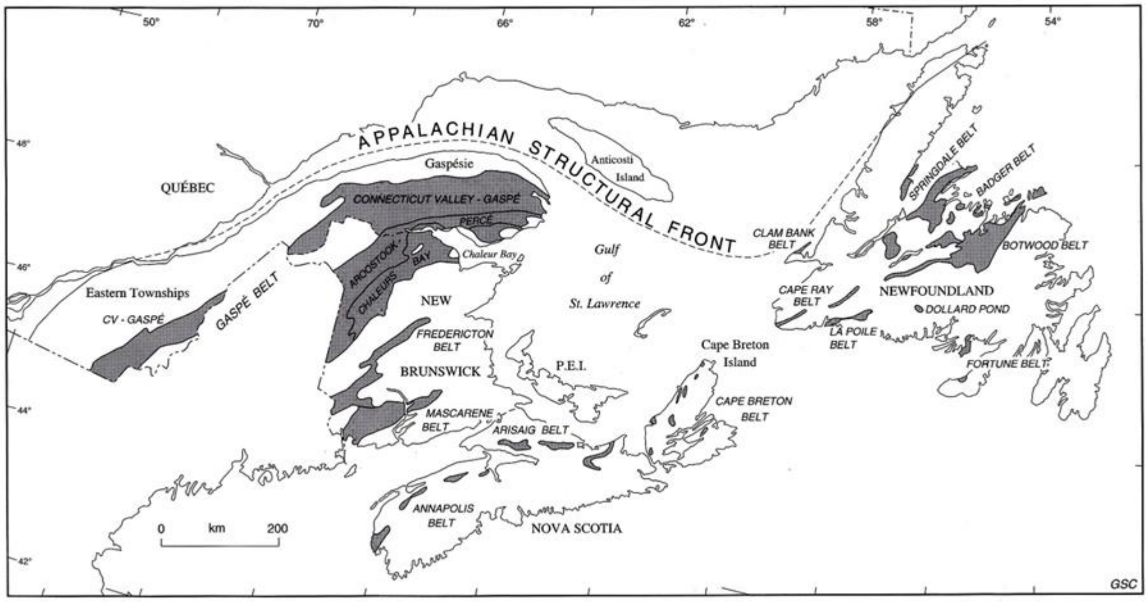


Figure 2.2. Outcrop areas of Middle Paleozoic rocks that define belts of the Canadian Appalachian region.

Upper Paleozoic rocks of the Canadian Appalachian region are mainly terrestrial cover sequences that unconformably overlie deformed middle Paleozoic and older rocks. The rocks are everywhere essentially the same, dominantly redbeds with local volcanic units toward the bases of the sections. Their thicknesses define a number of basins, chiefly located in New Brunswick and Nova Scotia (Fig. 2.3). Their distribution is unrelated to the geometry of belts or zones, but some coincide with ancestral structural boundaries.

Mesozoic rocks, mainly Triassic and Jurassic, are redbeds and basalts that unconformably overlie deformed upper Paleozoic and older rocks. These are restricted onland to the Fundy Graben in the Bay of Fundy area and the Chedabucto Graben to the east (Fig. 2.3). Coeval dykes are more widespread.

The temporal rock divisions are in most places separated by structural events, although these are not everywhere coeval and controls may be different from one area to another. Taconic Orogeny (Early and Middle Ordovician) affected the Humber Zone and western parts of the Dunnage Zone (Map 5). Ordovician deformation also affected parts of the Gander Zone and the eastern Dunnage Zone, at least in Newfoundland. It is absent in the Avalon and Meguma zones and parts of the northern Newfoundland Dunnage Zone. Middle Paleozoic orogeny affected the entire orogen, except for parts of the Newfoundland Avalon Zone (Map 6). It has been generally considered Acadian and of Devonian age but there is growing evidence for Silurian orogenesis in Newfoundland

and in Cape Breton Island (Dunning et al., 1988, 1990; Addendum, note 1). Alleghanian Orogeny of Carboniferous-Permian age affected a narrow area of thick deposition (Map 6). It is partly coincident with the Avalon-Meguma zone boundary in Nova Scotia and the Humber-Dunnage zone boundary in Newfoundland.

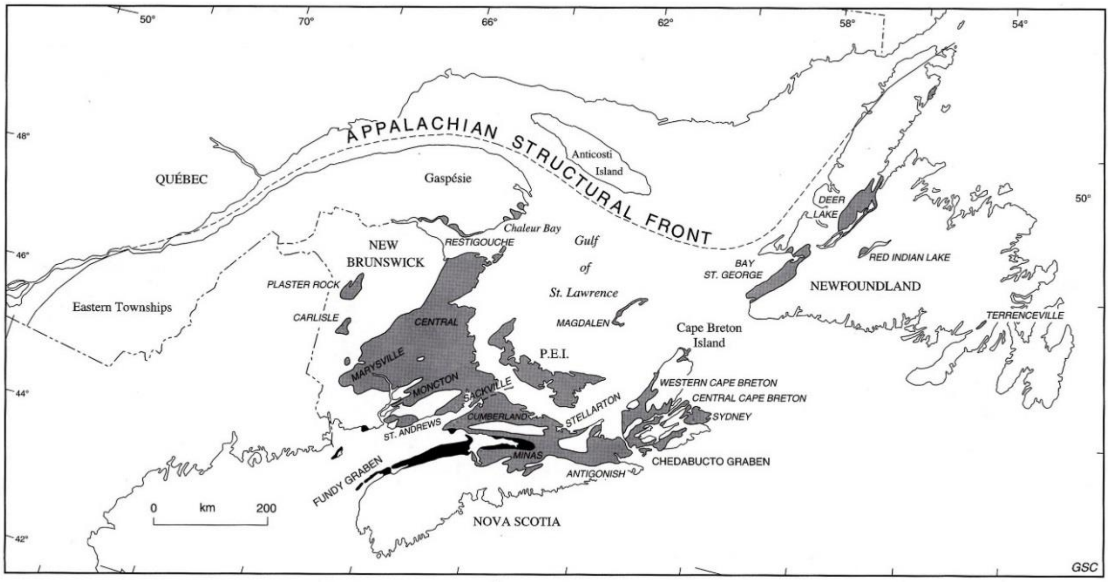
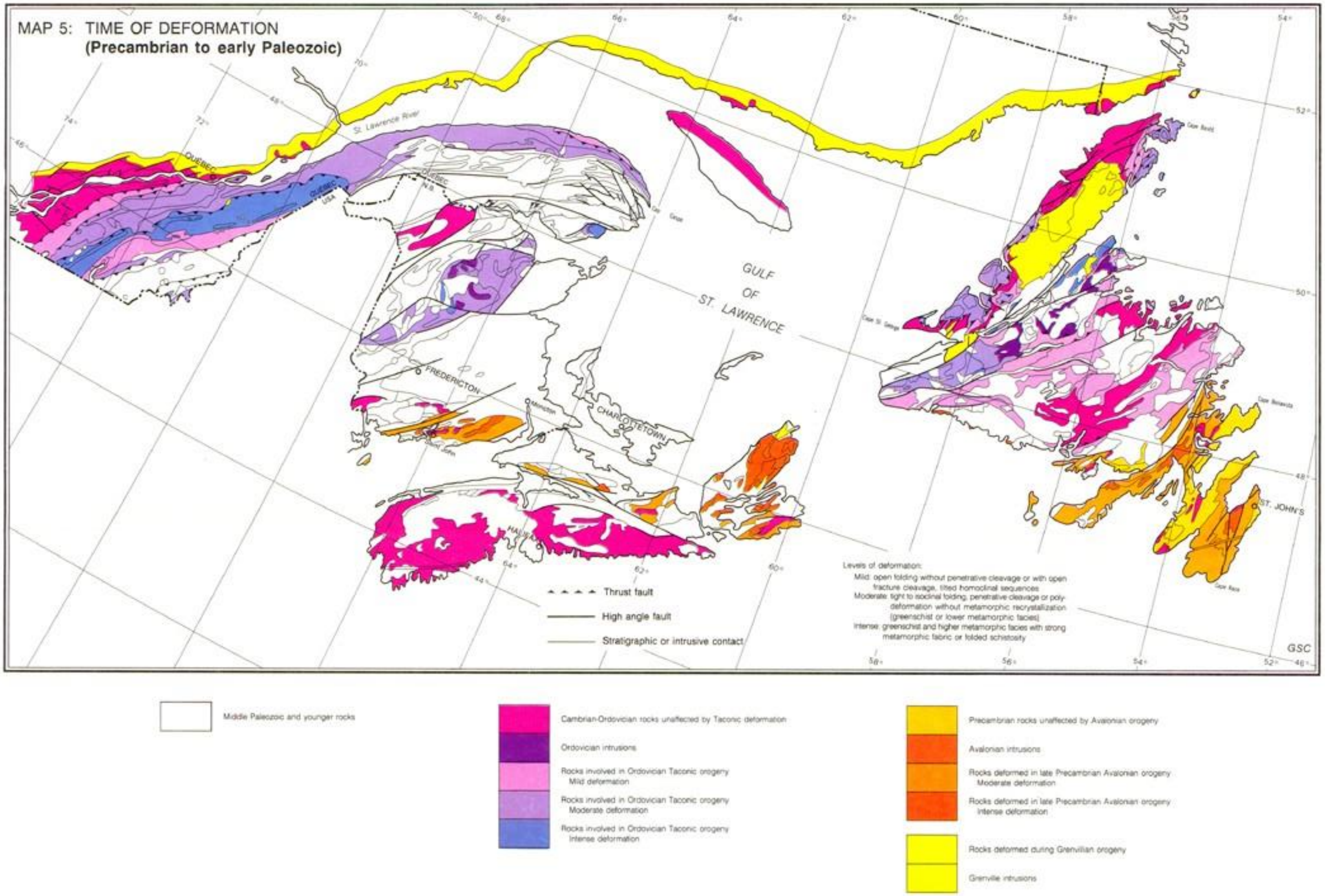


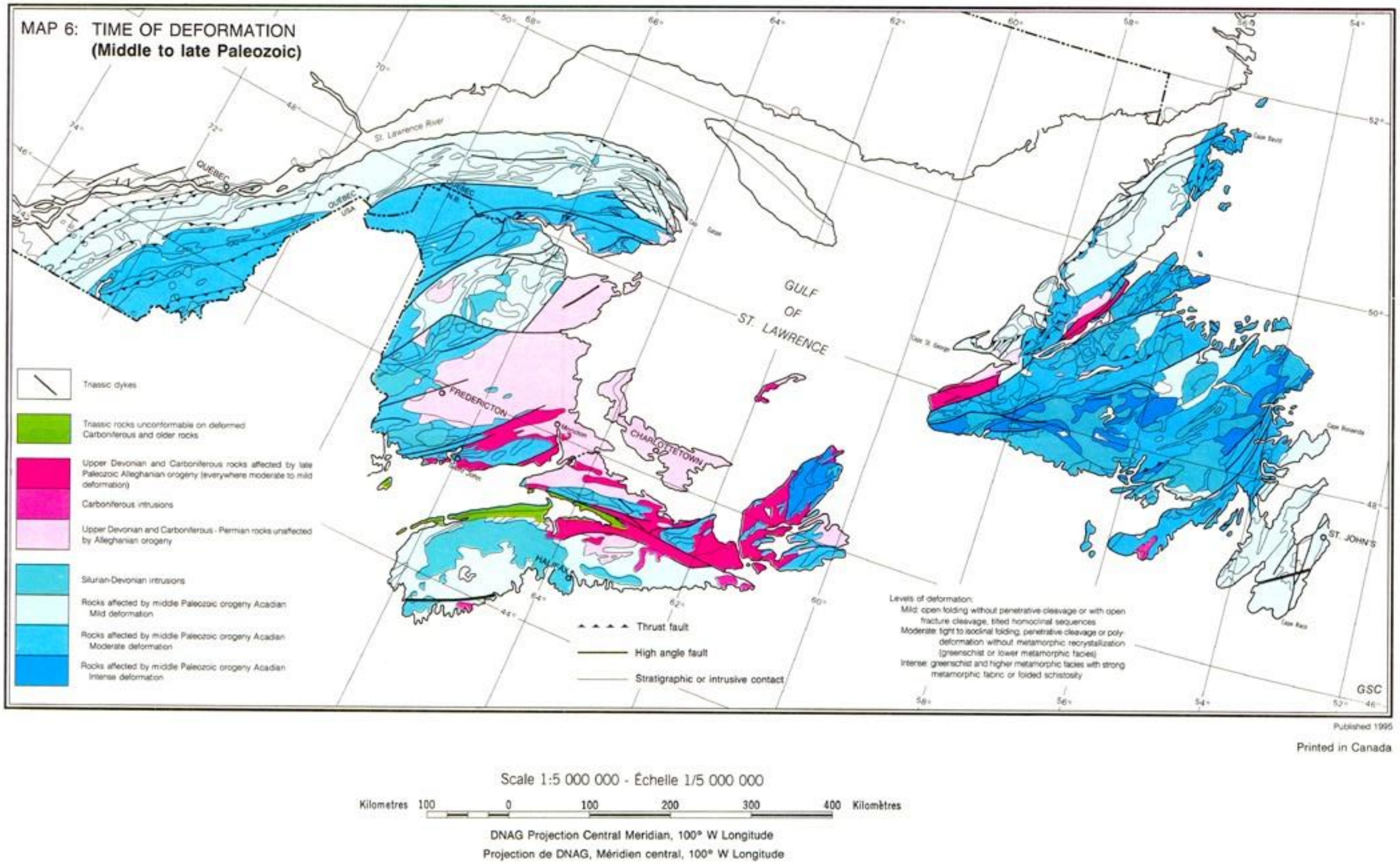
Figure 2.3. Outcrop areas of upper Paleozoic and Mesozoic rocks that define basins and graben, respectively, of the Canadian Appalachian region.

In a general way, variations in structural style, plutonism, metamorphism, and other features correspond to lithic and stratigraphic contrasts exhibited among rocks of the four temporal divisions, thus adding to their importance. This is expected, as each temporal division represents a change in depositional environments and tectonic settings: entirely marine rocks of early Paleozoic zones, mixed marine and terrestrial rocks of middle Paleozoic belts, mainly terrestrial rocks of late Paleozoic basins, and entirely terrestrial rocks of Mesozoic graben.

Table 2.1 provides a list of subdivisions and the necessary systematics to describe stratigraphic and structural relationships. Zones are discrete entities. The Humber Zone represents that part of the orogen that is linked stratigraphically to the North American craton, or the Appalachian miogeocline. Others represent accreted parts of the orogen or suspect terranes. Belts may represent a number of tectonic elements. Some trend acutely across the miogeocline and already accreted terranes as cover sequences. Others are sited along zone boundaries, either above earlier structural junctions or possibly separating early Paleozoic zones/terranes. Still others form internal parts of zones/terranes, in cases where the older rocks are unaffected by early Paleozoic orogeny. Late Paleozoic basins represent a mainly terrestrial cover across the whole orogen with local anomalously thick sections controlled by subsidence and uplifted blocks. The Mesozoic Fundy and Chedabucto graben occur as a single rift coincident with a thick Carboniferous basin and the earlier Avalon-Meguma zone boundary.



MAP 5: TIME OF DEFORMATION
(Precambrian to early Paleozoic)
St. Lawrence River
QUEBEC
FREDERICTON
CHARLOTTETOWN
GULF
OF
ST. LAWRENCE
ST. JOHN'S
Thrust fault
High angle fault
Stratigraphic or intrusive contact
Levels of deformation:
Mild: open folding without penetrative cleavage or with open fracture cleavage, tilted homoclinal sequences
Moderate: tight to isoclinal folding, penetrative cleavage or poly-deformation without metamorphic recrystallization (greenschist or lower metamorphic facies)
Intense: greenschist and higher metamorphic facies with strong metamorphic fabric or folded schistosity
GSC
Middle Paleozoic and younger rocks
Cambrian-Ordovician rocks unaffected by Taconic deformation
Ordovician intrusions
Rocks involved in Ordovician Taconic orogeny Mild deformation
Rocks involved in Ordovician Taconic orogeny Moderate deformation
Rocks involved in Ordovician Taconic orogeny Intense deformation
Precambrian rocks unaffected by Avalonian orogeny
Avalonian intrusions
Rocks deformed in late Precambrian Avalonian orogeny Moderate deformation
Rocks deformed in late Precambrian Avalonian orogeny Intense deformation
Rocks deformed during Grenvillian orogeny
Grenville intrusions



MAP 6: TIME OF DEFORMATION
(Middle to late Paleozoic)
St. Lawrence River
QUEBEC
QUEBEC USA
QUEBEC N.B.
GULF OF ST. LAWRENCE
FREDERICTON
CHARLOTTETOWN
HALIFAX
ST. JOHN'S
Triassic dykes
Triassic rocks unconformable on deformed Carboniferous and older rocks
Upper Devonian and Carboniferous rocks affected by late Paleozoic Alleghanian orogeny (everywhere moderate to mild deformation)
Carboniferous intrusions
Upper Devonian and Carboniferous - Permian rocks unaffected by Alleghanian orogeny
Silurian-Devonian intrusions
Rocks affected by middle Paleozoic orogeny Acadian Mild deformation
Rocks affected by middle Paleozoic orogeny Acadian Moderate deformation
Rocks affected by middle Paleozoic orogeny Acadian Intense deformation
Thrust fault
High angle fault
Stratigraphic or intrusive contact
Levels of deformation:
Mild: open folding without penetrative cleavage or with open fracture cleavage, tilted homoclinal sequences
Moderate: tight to isoclinal folding, penetrative cleavage or poly-deformation without metamorphic recrystallization (greenschist or lower metamorphic facies)
Intense: greenschist and higher metamorphic facies with strong metamorphic fabric or folded schistosity
GSC
Published 1995
Printed in Canada
Scale 1:5 000 000 - Échelle 1/5 000 000
Kilometres 100 0 100 200 300 400 Kilomètres
DNAG Projection Central Meridian, 100° W Longitude
Projection de DNAG, Méridien central, 100° W Longitude

NATURE OF BOUNDARIES

Rocks that define zones were in most cases widely separated at deposition. Since they are telescoped into a mountain belt now, their boundaries are tectonic. This applies to all except some Dunnage-Gander zone boundaries where mixed sedimentary and volcanic rocks assigned to the Dunnage Zone are stratigraphically above rocks of the Gander Zone (van Staal, 1987; O'Neill and Knight, 1988). The Humber and Dunnage zones were first juxtaposed in the Ordovician (Williams and St-Julien, 1982). Dunnage-Gander zone boundaries are also interpreted as Ordovician tectonic junctions in most places but they are commonly overprinted by middle Paleozoic ductile deformation (Piasecki, 1988; Currie and Piasecki, 1989). Most Ordovician boundaries are marked by ophiolite complexes and melanges, and the boundaries are concordant with respect to adjacent lithic units or structures. Gander-Avalon and Avalon-Meguma zone boundaries are later, of Silurian-Devonian age. They are marked by steep mylonite zones or brittle faults that are discordant with respect to adjacent lithic units and structures (Blackwood and Kennedy, 1975; Dallmeyer et al., 1981; Keppie, 1982).

The early Paleozoic zonation applies to the total area of the orogen. Expressed in another way, there is no evidence in the Canadian Appalachians of structural blocks or terranes that are made up entirely of middle Paleozoic or younger rocks.

Middle Paleozoic belts are in most places separated by exposed older rocks of underlying zones. Their present outlines and extent are largely the result of erosion.

Late Paleozoic basins developed upon deformed rocks of belts and zones. They are continuous across all zones and belts from northern Gaspésie to eastern Nova Scotia. Present exposures are erosional remnants of a once more continuous cover.

The Mesozoic Fundy Graben contains redbeds and mafic volcanic rocks that overlie deformed Carboniferous and older rocks. The graben coincides with the Avalon-Meguma zone boundary, the locus of deep Carboniferous basins, and projects offshore through the Chedabucto Graben toward the Orpheus Graben. Mesozoic dykes cross early Paleozoic zones, middle Paleozoic belts, and late Paleozoic basins indiscriminately.

EARLY PALEOZOIC AND OLDER ZONES

The zonal division of Humber, Dunnage, Gander, Avalon, and Meguma is used here because of its familiarity, wide usage, and practicality (Table 2.1, Fig. 2.1, and Map 2). Recent work has led to subdivision of the Dunnage and Gander zones in Newfoundland (Williams et al., 1988, 1989; Piasecki et al., 1990; Williams, Chapter 3; Williams et al., Chapter 3), New Brunswick (van Staal, 1987; van Staal and Fyffe, Chapter 3), Quebec (Tremblay et al., Chapter 3), and to refinements of divisions and boundaries in Cape Breton Island of Nova Scotia (Barr and Raeside, 1989).

Although the zones are defined, first and foremost, on rocks and stratigraphy, they fit well with present conceptual models of the orogen. Thus according to a Wilson cycle model, the Humber Zone records the development and destruction of an Atlantic-type passive margin, the ancient continental margin of eastern North America; parts of the Dunnage Zone represent vestiges of Iapetus with volcanic sequences and melanges built upon oceanic crust; and the Gander, Avalon, and Meguma zones are a sampling of tectonic elements that lay outboard or on the opposing side of Iapetus.

The zonal division also fits suspect terrane analyses of the Appalachian Orogen (Williams and Hatcher, 1982, 1983; Zen, 1983; Keppie, 1985, 1989). These analyses emphasize the important distinction between the miogeocline, which was linked to the North American craton, and outboard terranes of unknown paleogeography that were accreted during the evolution of the orogen. Thus the Humber Zone represents the Appalachian miogeocline and the Dunnage, Gander, Avalon, and Meguma zones are all accreted terranes.

Further to the suspect terrane viewpoint, it should be emphasized that some zones are composite. The Humber

Zone includes structural elements transported across it, such as volcanic groups and ophiolite complexes that are really Dunnage outliers. Similarly, the Dunnage and

Avalon zones are composite or superterranes. Terrane division into impractical and unmappable sizes is avoided.

The following definitions and descriptions of the early Paleozoic zones, middle Paleozoic belts, late Paleozoic basins, and Mesozoic graben are mainly summarized from Chapters 3 to 6. More complete references are given there. Correlations across the Atlantic are taken from Williams (1978b, 1984) and Keppie and Dallmeyer (1989).

Humber Zone

The Humber Zone (Fig. 2.1 and Map 2) is recognized in western Newfoundland and Quebec. A small area of Grenville gneisses (Blair River Complex) in northern Cape Breton Island is either part of the Humber Zone (Barr et al., 1987; Barr and Raeside, 1989) or basement to the Avalon Zone (Keppie et al., 1990, Chapter 3).

The Humber Zone is separated into external and internal parts based on structural and metamorphic styles. In the external Humber Zone a crystalline basement is correlated with Precambrian rocks of the nearby Grenville Province of the Canadian Shield. The basement rocks are cut by mafic dykes, and toward the west the basement is overlain unconformably by an arkosic clastic unit with local mafic flows. The basal clastic/volcanic unit is overlain by Cambrian shales and quartzites and a thick Cambrian to Middle Ordovician carbonate sequence. This is capped by a Middle Ordovician shale.-sandstone unit, in turn overlain by chaotic melanges and transported sedimentary and igneous rocks of Taconic allochthons.

Deformation increases from west to east so that stratigraphic and structural relationships are less clear in the internal Humber Zone. There, rocks are mainly psammitic and pelitic schists with some marble units and chloritic schists. Basement rocks are recognized in some places but they are highly deformed and commonly indistinguishable from schistose cover. The structural style of the external Humber Zone is that of a foreland fold and thrust belt. In Quebec, and western Newfoundland, deformed and metamorphosed rocks of the internal Humber Zone are thrust above less deformed and less metamorphosed rocks of the external Humber Zone.

The western margin of the Humber Zone is defined by the limit of Appalachian deformation (Fig. 2.1, Maps 5 and 6). Its eastern margin is a steep structural belt (Williams and St-Julien, 1982), marked by ophiolite occurrences that separate polydeformed schists of the internal Humber Zone to the west from less deformed volcanic sequences of the Dunnage Zone to the east (Fig. 2.1). The Humber-Dunnage boundary is well defined in northeast Newfoundland and in the Quebec Eastern Townships, where ophiolitic rocks at the boundary form the world's richest asbestos belt. The boundary is offset and hidden by younger cover rocks throughout much of Gaspésie and it is enigmatic and difficult to delineate among the heavily intruded and metamorphosed crystalline rocks and ophiolite complexes of southwest Newfoundland.

Taconic Orogeny is recognized as the first major event to affect the Humber Zone, wherever stratigraphic relationships or isotopic data allow its definition. Acadian Orogeny (Silurian-Devonian) also affected most of the zone, and locally in Newfoundland its eastern parts are affected by Alleghanian deformation (Maps 5 and 6).

The Humber Zone has a uniform width of approximately 100 km and its facies belts and tectonic elements follow the curvilinear course of the zone from western Newfoundland to Quebec. The Taconic structural front (Logan's Line) and the Acadian structural front are almost coincident along its western margin. The course of the Alleghanian structural front is erratic, cutting across older structures (Maps 5 and 6).

Taconic allochthons of the external Humber Zone are made up of a number of structural slices, many of which contain distinctive rock assemblages. These assemblages and structural slices are arranged in a consistent order of structural stacking. Lowest slices contain sedimentary rocks, mainly sandstones, shales, limestones, and limestone breccias. These rocks range in age from late Precambrian to Early and Middle Ordovician. In some places it can be shown that the lowest structural slices contain the stratigraphically youngest sedimentary rocks. Higher structural slices contain volcanic rocks and ophiolite complexes typical of the Dunnage Zone. These are dated isotopically as Late Cambrian to Early Ordovician (Dunning and Krogh, 1985).

Different structural slices exhibit different deformational styles, and most structures were imprinted prior to or during the assembly and transport of the allochthons. These vary from intense foliations, tectonic banding, and folded schistosities in ophiolitic rocks, to scaly cleavages, rootless folds, and overturned beds in sedimentary rocks. Lower slices have internally complex geometries of rock units and the slices are rarely morphologically distinct. Higher structural slices are of simpler internal makeup and some have marked morphological expression. Stratigraphic relationships, palinspastic restorations, and structural considerations all indicate that the allochthons were assembled from east to west and that the structurally highest slices travelled the farthest (Williams, 1975).

Rocks typical of the Canadian Humber Zone extend the full length of the Appalachian Orogen (see Fig. 1.8). Grenville inliers like those of western Newfoundland reappear in the U.S. Appalachians of Vermont and extend along the Blue Ridge Province to Georgia (Williams, 1978a). The cover is everywhere the same; clastic and volcanic rocks at the base overlain by a thick Cambrian-Ordovician carbonate sequence. A clastic unit everywhere overlies the carbonate rocks. Taconic allochthons like those of western Newfoundland and Quebec continue through the type area of New York to the Hamburg Klippe of Pennsylvania. Restoration of the North Atlantic indicates that the Cambrian-Ordovician carbonate rocks of Scotland and east Greenland are continuations of the North American Humber Zone (see Fig. 1.4).

Dunnage Zone

The Dunnage Zone (Fig. 1.3, 2.1 and Maps 1 and 2) is distinguished by its lower Paleozoic dominantly mafic volcanic rocks, ophiolite suites, melanges and associated greywackes, slates, cherts, and minor limestones. Some of these marine rocks rest on an ophiolitic substrate. Others have stratigraphic relationships with rocks of the Gander Zone (van Staal, 1987). Many more are of unknown basement relationship. A few rocks within the Dunnage Zone of Newfoundland and Quebec seem to be out of structural, metamorphic, and temporal context with respect to nearby volcanic rocks and ophiolite suites.

Recent work in central Newfoundland has led to a major two-fold division of the Dunnage Zone into a northwestern Notre Dame Subzone (containing the Twillingate Subzone) and a southeastern Exploits Subzone (Williams et al., 1988; Fig. 2.1). The Indian Bay Subzone is a small area of Exploits-type rocks within the northeast Gander Zone (Wonderly and Neuman, 1984). Another division, Dashwoods Subzone or Central Gneiss Terrane of van Berkel and Currie (1988) in southwestern Newfoundland, has rocks and structures characteristic of both the Dunnage and Humber zones and appears to be a tectonic mixture. …

Deformation across the Newfoundland Dunnage Zone is less intense than that in adjacent parts of the Humber and Gander zones. Sub-Silurian unconformities are everywhere present across the Notre Dame Subzone but rare in the Exploits Subzone, where Ordovician-Silurian sections are in places continuous. …

Ophiolitic complexes along the western margin of the Newfoundland Dunnage Zone are imbricated, and although steeply dipping to overturned, the sequences of units face eastward. At the Humber-Dunnage boundary, the ophiolite complexes are overlain by olistostromes and coarse conglomerates, in turn overlain by volcanic sequences. Immediately eastward, the ophiolites are succeeded by volcanic rocks without intervening olistostromes. Intensity of deformation increases westward toward the Humber-Dunnage boundary and, at the boundary, Dunnage ophiolite complexes are structurally and metamorphically gradational with ophiolitic melanges and metaclastic rocks that are part of the eastern Humber Zone.

The Dunnage Zone is widest (150 km) and best defined in northeast Newfoundland. It is narrow and ill-defined in the southwest portion of insular Newfoundland, and it is Ophiolitic complexes and Paleozoic oceanic rocks can be traced southward into the New England Appalachians, and a large mafic-ultramafic complex at Baltimore, Maryland lies along a natural continuation of the Humber-Dunnage boundary (Williams, 1978a). Ophiolitic rocks occur farther south, but these occurrences are small and the oceanic rocks are commingled with high-grade metaclastic rocks. On the eastern side of the Atlantic, ophiolitic complexes and volcanic sequences like those of the Canadian Dunnage Zone occur in the Midland Valley of Scotland and there are numerous examples throughout the Scandinavian Caledonides (see Fig. 1.4).absent in Cape Breton Island. Apart from exposures in New Brunswick and Quebec, most of its mainland course is hidden by younger cover rocks.

Gander Zone

The Gander Zone (Fig. 2.1 and Map 2) is characterized by a thick sequence of pre-Middle Ordovician arenaceous rocks that are in most places polydeformed and metamorphosed. Relationships with adjacent migmatites and granitic gneisses of the zone have been interpreted as both unconformable and gradational. Most evidence points to a continental crystalline basement beneath the zone.

In Newfoundland, the Gander Zone is divided into the Gander Lake, Mount Cormack, and Meelpaeg subzones (Fig. 2.1). The nature and timing of Dunnage-Gander boundaries are controversial. The Exploits (Dunnage) Gander Lake (Gander) boundary is tectonic where ophiolitic rocks of the Gander River Complex (O'Neill and Blackwood, 1989) abut sandstones of the Gander Lake Subzone, but the contact has been interpreted as stratigraphic where mafic-ultramafic rocks are absent (Currie et al., 1979, 1980; Pajari et al., 1979; Blackwood, 1982; Blackwood and Green, 1982). On the south coast of Newfoundland, the boundary has been interpreted as a thrust (Colman-Sadd, 1976), a conformable contact (Blackwood, 1985), and a major sinistral ductile shear zone (Piasecki, 1988). Exploits-Mount Cormack and Exploits-Meelpaeg boundaries are interpreted almost everywhere as tectonic (Colman-Sadd and Swinden, 1984; Williams et al., 1988, 1989).

The analysis of the Mount Cormack Subzone as a structural window in central Newfoundland (Colman-Sadd and Swinden, 1984) indicates that the Exploits Subzone is allochthonous, at least in part, above the Gander Zone. Quartzites and psammitic schists of the Mount Cormack Subzone are surrounded by upward- and/or outward-facing ophiolite suites. The ophiolitic rocks and their cover belong to the Exploits Subzone. Quartzites and psammites resemble those at Gander Lake, type area of the Gander Zone.

The Meelpaeg Subzone is also interpreted as a structural window, although ophiolite complexes are absent at most Meelpaeg-Exploits boundaries. Colman-Sadd and Swinden (1984) estimated a minimum displacement of 60 km on the Exploits-Mount Cormack boundary, and subsequent recognition of Gander equivalents at the northwestern Meelpaeg boundary, (Colman-Sadd, 1987, 1988), requires that this be increased to over 100 km. In most places, Meelpaeg-Exploits boundaries are major ductile shear zones that also coincide with sharp increases in metamorphic intensity toward the Meelpaeg Subzone (Colman-Sadd, 1984, 1985, 1987, 1988; Williams et al., 1988, 1989). A model that incorporates Dunnage-Gander zone relationships in Newfoundland has been proposed recently (Williams and Piasecki, 1990; Addendum, note 2). …

At its type area in northeast Newfoundland, rocks of the Gander Zone have a flat schistosity related to recumbent structures. Lineations indicate mainly orogen-parallel transcurrent movements. The latest studies support the interpretations of Kennedy and McGonigal (1972) and Kennedy (1975) for pre-Middle Ordovician deformation overprinted by middle Paleozoic events (Williams et al., 1991).

Local stratigraphic contacts between Lower to Middle Ordovician Dunnage and Gander zone rocks are not incompatible with the structural relationships (Williams and Piasecki, 1990). However at deeper levels, the ultimate Gander-Dunnage distinction presumably contrasts a granitic continental basement and arenaceous cover (Gander) with an ophiolitic oceanic basement and volcanic cover (Dunnage).

The Gander Zone is about 50 km wide in northeast Newfoundland but may be much wider in subsurface. Psammites and amphibolites of the Meelpaeg Subzone are possibly continuous with the Port aux Basques Gneiss at the southwest corner of Newfoundland (Williams et al., 1989; Colman-Sadd et al., 1990; Fig. 2.1 and Map 2). …

Avalon Zone

Rocks of the Avalon Zone (Fig. 2.1 and Map 2) are mainly upper Precambrian sedimentary and volcanic rocks overlain by Cambrian to Lower Ordovician shales and sandstones. All of these rocks are relatively undeformed and unmetamorphosed compared to nearby parts of the Gander Zone. The oldest rocks of the Avalon Zone are marbles, quartzites, and gneisses in New Brunswick and Nova Scotia. These are interpreted to underlie the upper Precambrian sedimentary and volcanic rocks with structural unconformity, but contacts are mainly faults.

In some places the upper Precambrian sedimentary and volcanic rocks pass upward with structural conformity into Cambrian shales. In other places, unconformities and late Precambrian intrusions interrupt stratigraphic sections. These late Precambrian structural and intrusive events define the Avalonian Orogeny, which is unique to this zone (Map 5).

The Avalon Zone encompasses a variety of diverse geological elements among its upper Precambrian rocks, implying a composite makeup. If composite, the elements of the zone were assembled in the late Precambrian, as its Cambrian rocks have similar stratigraphy and distinctive Atlantic realm trilobite faunas throughout its length. In fact, the continuity of its Cambrian rocks and faunas gave rise to the notion of an "Avalon Platform" along the eastern margin of the orogen.

In Newfoundland, the boundary between the Avalon and Gander zones is marked by major faults (Fig. 2.1). The boundary in New Brunswick is also faulted. Silurian rocks are a cover sequence to a late Precambrian-Cambrian basement of the Burgeo Subzone (Dunning and O'Brien, 1989; O'Brien, 1989). The Bras d'Or Subzone of Cape Breton Island (Fig. 2.1 and Map 2) has plutonic and metamorphic affinities like those of the Burgeo subzone (Dunning et al., 1990), implying links between Cape Breton Island and southwest Newfoundland (see also Keppie and Dallmeyer, 1989). The Mira, Antigonish and Cobequid sub zones of Nova Scotia contain elements similar to the Avalon Zone in its type area in Newfoundland.

The width of the Avalon Zone varies considerably from eastern Newfoundland to southeast New Brunswick. In Newfoundland, Avalonian rocks extend offshore across the Grand Banks to Flemish Cap (Fig. 1.1), making the Avalon Zone twice as wide as the rest of the orogen to the west. In New Brunswick, the zone is narrower, less than half the width of the rest of the orogen.

Rocks and structures like those of the Avalon Zone extend the full length of the Appalachian Orogen through the New England area to the Slate Belt of the southern U.S. Appalachians (Williams, 1978a). Similar rocks occur in a number of places on the opposite side of the Atlantic (see Fig. 1.4).

Meguma Zone

The Meguma Zone (Fig. 2.1 and Map 2) is restricted to mainland Nova Scotia but its geophysical expression suggests that it underlies a large part of the nearby Atlantic continental shelf (Map 4). Its boundary with the Avalon Zone is a major fault (Keppie, 1982), which is traceable offshore by linear geophysical anomalies (Maps 3 and 4). …

The Meguma Zone was first deformed by Acadian Orogeny, and Alleghanian deformation is important along its boundary with the Avalon Zone.

Lower Paleozoic rocks of the Meguma Zone are unknown elsewhere in North America but equivalents occur in Morocco, northwest Africa (Fig. 1.4, Schenk, Chapter 3).

Other Contrasting Features of Canadian Appalachian Zones

The early Paleozoic zonation of the orogen based on rocks and stratigraphy is also expressed in a variety of other contrasts including geophysics, structural style, metamorphism, plutonism, metallogeny, and faunas. …

Most features that enhance zonal distinctiveness are those related to late Precambrian-early Paleozoic development. However, some younger plutonic, structural, and metallogenic features are also typical of certain zones, implying inheritance and a prolonged influence of older rocks and deep structure on later orogenic development.

Geophysics

The form of the Canadian Appalachians and the shapes of its early Paleozoic zones are expressed in the Bouguer and magnetic anomaly fields of the region (Maps 3 and 4; Addendum, note 4). Geophysical expression also defines the extent and geometry of the orogen across offshore regions. Anomalies that reflect structural trends follow the sinuous course of the Humber Zone from western Newfoundland through the Gulf of St. Lawrence to southeast Quebec. The Humber-Dunnage boundary has a clear magnetic expression and it is coincident, or nearly so, with a gradient in the Bouguer anomaly field from negative values in the west to positive values in the east. The Dunnage Zone of northern Newfoundland has a strong positive Bouguer anomaly. Gravity values decrease eastward across the Gander Zone and they increase in places along the Avalon Zone. Offshore, the Avalon Zone has large "S"-shaped positive magnetic anomalies that are thought to express the form of late Precambrian volcanic belts (Haworth and Jacobi, 1983; Miller, Chapter 7). …

Structure

The earliest Appalachian structures of the Humber Zone are directed westward and are associated with the Ordovician emplacement of Taconic allochthons (Map 5). Intense polyphase deformation occurs along its eastern margin, and its rocks there are among the most deformed within the orogen. In contrast, the Dunnage Zone has mainly upright structures and some of its rocks are less deformed than nearby parts of the Humber Zone. Intensity of deformation increases eastward across the Gander Lake Subzone in Newfoundland and structures are commonly recumbent. Structural windows of Gander Zone rocks in the southeastern Dunnage Zone of Newfoundland (Fig. 2.1) are also more metamorphosed and deformed than surrounding Dunnage Zone rocks. In central New Brunswick, Dunnage and Gander zone rocks are polydeformed. Structures of the Avalon and Meguma zones are upright and deformation is less intense.

The Humber, Dunnage, and Gander zones exhibit Ordovician deformation effects that are absent in the Avalon and Meguma zones (Map 5). All zones were affected by middle Paleozoic deformation, except for parts of the Newfoundland Avalon Zone (Map 6).

Metamorphism

Intensity of regional metamorphism coincides with intensity of Ordovician (Taconic) and middle Paleozoic (Acadian) deformation. Metamorphism related to Taconic deformation increases in intensity from west to east across the Humber Zone, from subgreenschist to upper greenschist and amphibolite facies. Dunnage Zone rocks are of greenschist or lower grade, except locally near its boundaries with the Humber and Gander zones. Intensity of regional metamorphism, mainly of Silurian age (Dunning et aI., 1988, 1990), increases eastward across the Newfoundland Gander Lake Subzone, and rocks of the Mount Cormack and Meelpaeg sub zones are higher grade than surrounding rocks of the Dunnage Zone. Metamorphism is low-grade throughout most of the Avalon Zone, and there is a sharp metamorphic contrast in most places across the Gander-Avalon zone boundary, especially in northeast Newfoundland. Most of the Meguma Zone has low-grade metamorphism, but metamorphism reaches amphibolite facies where plutons are abundant in some eastern areas. …

Plutonism

There is a spatial relationship between the distribution of plutonic rocks and early Paleozoic zones in Newfoundland (Williams et aI., 1989), although there are exceptions (Currie, Chapter 8). Precambrian plutons unrelated to Appalachian orogenesis are restricted to the Humber and Avalon zones. These are mainly 1000 Ma granites in Grenville inliers of the Humber Zone and 600 Ma calcalkalic plutonic suites of the Avalon Zone. Late Precambrian alkali and peralkali plutons occur at the eastern margin of the Humber Zone and western margin of the Avalon Zone. Deformed early Paleozoic tonalites, trondjhemites, and quartz diorites occur throughout the Notre Dame Subzone of the Dunnage Zone and small bodies are allochthonous across the Humber Zone. …

Faunas

Some zones have distinct faunal characteristics. Early Paleozoic shelly faunas of North American affinity occur in the H umber Zone and Notre Dame Subzone of the Dunnage Zone. Ordovician brachiopod faunas of the Celtic realm occur in the Exploits Subzone of the Dunnage and Gander Zone. Ediacara-type late Precambrian faunas and Atlantic realm Cambrian trilobite faunas occur in the Avalon Zone (Nowlan and Neuman, Chapter 10).[2]

Chapter 3 - LOWER PALEOZOIC AND OLDER ROCKS

The five-fold zonation of Humber, Dunnage, Gander, Avalon and Meguma is the first order geographic division of this temporal category. Within each zone the oldest rocks are treated first. Where continuity or correlation is established among distinctive rock packages throughout a zone, each rock package is treated separately, from north to south and province by province. In other cases, all of the lower Paleozoic and older rocks of a zone are treated by provinces, from north to south.

HUMBER ZONE

Introduction (by Harold Williams)

The Humber Zone, or Appalachian miogeocline, takes its name from Humber Arm of western Newfoundland. It has two divisions of contrasting structural style and metamorphic grade: a western or external division where deformation is moderate, regional metamorphism is low grade, and where stratigraphic sections are preserved or

[2] Ibid., p. 23 -34

easily restored; and an eastern or internal division where deformation is intense, regional metamorphism is medium to high grade, and where stratigraphic and structural relationships are commonly in doubt (Fig. 3.1). Contacts between external and internal divisions of the Humber Zone are important structural junctions where not hidden by younger cover rocks.

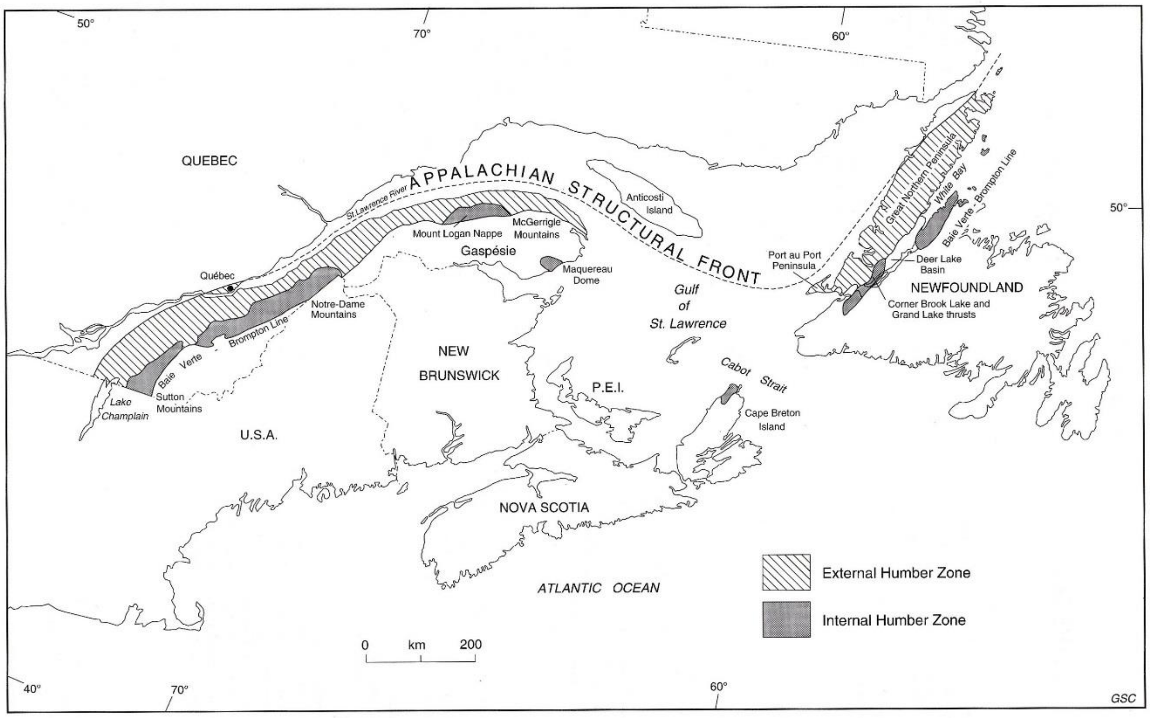


Figure 3.1. External and internal divisions of the Humber Zone in Canada.

Rocks of the external Humber Zone are subdivided into distinct stratigraphic and structural packages as follows: Grenville basement rocks, upper Precambrian to Lower Cambrian clastic sedimentary and volcanic rocks, Cambrian-Ordovician carbonate sequence, Middle Ordovician clastic rocks stratigraphically above the carbonate sequence and/or integral parts of Taconic allochthons, and allochthonous rocks structurally overlying the Middle Ordovician clastic rocks.

These stratigraphic and structural packages also occur in internal parts of the Humber Zone. Where correlations are reasonably clear, descriptions of the deformed and metamorphosed (internal) examples follow treatment of the less deformed (external) examples, from north to south and province by province. Where correlations are uncertain or unknown, the deformed rocks are treated under the general heading "Humber Zone internal".

Allochthonous rocks of the Humber Zone are of late Precambrian to Middle Ordovician age. These are mainly sedimentary rocks in lower structural slices that are coeval with the carbonate sequence and underlying sedimentary and volcanic rocks. They are viewed as eastern or offshore facies equivalents. Higher structural slices are a sampling of Dunnage Zone marine volcanic sequences and ophiolite suites. They are described here as they are integral parts of Ordovician allochthons emplaced upon the autochthonous sequence.

The oldest cover rocks above Humber Zone allochthons are Middle Ordovician (Caradoc) limestones, sandstones and shales of the Long Point Group in western Newfoundland. These are treated with the Clam Bank Belt of middle Paleozoic rocks as they are part of an unconformable overlap sequence. In Quebec, rocks of Caradoc age are integral parts of Ordovician allochthons and are therefore included in the Humber Zone. This situation arises because of the diachronous nature of events between Newfoundland and Quebec. Silurian and younger rocks, where present, are unconformable on rocks of the Humber Zone.

The external part of the Humber Zone forms the Great Northern Peninsula of western Newfoundland and its rocks and structures extend southward to Port au Port Peninsula. All tectonostratigraphic elements that define the zone are represented. On the opposite side of the Gulf of St. Lawrence, the external Humber Zone is defined almost entirely on its allochthonous rocks that overlie the Middle Ordovician clastic unit at the top of the underlying autochthon. These extend from Gaspésie along the south shore of the St. Lawrence River to the United States border.

Rocks of the internal Humber Zone are traceable in Newfoundland from White Bay to the southern end of Grand Lake. Relationships are debatable farther southwest in Newfoundland where the Dashwoods Subzone apparently includes both Humber and Dunnage zone rocks (Map 2). In this area, metamorphism, plutonism and structural styles make a Humber-Dunnage distinction impractical. Reworked Grenville gneisses form a small area at the northwest tip of Cape Breton Island, Nova Scotia, and metaclastic rocks of the internal Humber Zone reappear in the Maquereau Dome of Gaspésie, Quebec. Farther west, rocks of the internal Humber Zone are present in the Mount Logan Nappe of the Chic-Chocs Mountains (Hibbard et aI, this chapter) and they form a wide continuous belt along the Notre-Dame Mountains and Sutton Mountains of Quebec.

The western limit of the Humber Zone is the Appalachian structural front, which separates deformed rocks of the orogen from undeformed rocks of the St. Lawrence Platform. It lies beneath the Gulf of St. Lawrence and St. Lawrence River for most of its length, except in parts of western Newfoundland and between Quebec City and the United States border. In western Newfoundland the structural front is defined by thrusts or steep reverse faults and it is marked by thrusts in southwestern Quebec.

The boundary between external and internal divisions of the Humber Zone in Newfoundland is the Corner Brook Lake and Grand Lake thrusts. To the north it is hidden by Carboniferous rocks of the Deer Lake Basin and to the south by the Gulf of St. Lawrence. In Quebec, it is defined by major thrust faults along the northern flanks of the Notre-Dame Mountains and Sutton Mountains. Farther east, it is hidden by middle Paleozoic rocks in Gaspésie.

The eastern boundary of the internal Humber Zone is the Baie Verte-Brompton Line, a steep structural zone of discontinuous ophiolite occurrences that defines the Humber-Dunnage zone boundary (Williams and St-Julien 1982). It is well defined in northeast Newfoundland and in southwestern Quebec, but it is covered by younger rocks throughout Gaspésie.

The Humber Zone corresponds with the St. Lawrence Geosyncline of Schuchert (1923) and Schuchert and Dunbar (1934), who interpreted the geosyncline as an inland seaway between the North American Craton and the New Brunswick Geanticline. Long before that, it was viewed, much as it is today, as a North American marine "continental plateau" open to a "Palaeo-Atlantic" ocean (Logan, 1863; after Stevens, 1974). In Newfoundland, and still before the wide acceptance of plate tectonics, the Humber Zone was the western Newfoundland Shelf (Williams, 1964a) or the Western Platform (Kay and Colbert, 1965). Since then, all studies support the paradigm of an ancient continental margin that originated through rifting, evolved as a passive Atlantic-type margin, and was destroyed by ophiolite obduction and accretion of outboard terranes (Rodgers, 1968: Dewey, 1969; Bird and Dewey, 1970; Stevens 1970' Williams, 1971a; Williams and Stevens, 1974; St-Julie~ and Hubert, 1975; and many others). In fact, stratigraphic and tectonic analyses of the late Precambrian and early Paleozoic development of the Humber Zone rival those of any ancient continental margin.

Rodgers (1968) suggested that the eastern limit of Grenville inliers in the Appalachian Orogen is roughly coincident with the edge of the early Paleozoic continental shelf, so that the declivity at the shelf edge lay above the basement edge. Palinspastic restoration implies continental crust well east of the shelf edge (Williams and Stevens, 1974). Seismic reflection studies off northeast Newfoundland (Keen et aI., 1986) and in the Gulf of St. Lawrence (Marillier et al., 1989) indicate that Grenville basement extends in subsurface to central parts of the Newfoundland Dunnage Zone. Similarly in Quebec, onland seismic reflection profiles indicate a relatively undeformed basement and autochthonous cover that extends in subsurface to the Baie Verte-Brompton Line and beyond (St-Julien et aI., 1983; Stewart et aI, 1986).

The Humber Zone has negative Bouguer gravity anomalies compared to positive anomalies of the adjacent Dunnage Zone (Map 3). A gravity gradient expressed along the full length of the Appalachian miogeocline, from negative values on the continent side to positive values eastward, is one of the major geophysical features of the Appalachian Orogen (Haworth et aI., 1980a, b). Whether the gradient represents the edge of a Paleozoic passive continental margin, a Paleozoic collisional zone or Mesozoic extensional effects related to the modern Atlantic (Nelson et al., 1986), is unclear. The regional negative gravity field extends well south of the Humber Zone in Quebec and a marked gradient in Newfoundland crosses acutely the exposed Long Range Grenville inlier (Map 3). There is no clear relationship between the gravity gradient and the Baie Verte-Brompton Line or between the gradient and the edge of the Grenville lower crustal block as defined by deep seismic reflection experiments.

Faunas of the Humber Zone are typically North American. Some show local provincialism controlled by shallow marine conditions at the ancient continental shelf or deeper marine environments at the slope and rise. Shallow marine shelly faunas of the Ordovician Toquima-Table Head Faunal Realm occur in the carbonate sequence of the Humber Zone and are found all along the ancient periphery of North America (Ross and Ingham, 1970). Diverse shelly, graptolIte, and conodont faunas occur in deeper water carbonate breccias and shales. Examples in the Cow Head Group of Newfoundland provide ample opportunity for Cambrian-Ordovician biostratigraphic zonation and correlation with strata of the continental interior (e.g. Williams and Stevens, 1988). This is one of several reasons that make the Cow Head Group a leading contender for the Cambrian-Ordovician boundary stratotype (Barnes, 1988).

The Humber Zone was affected by Taconic (Middle Ordovician) and Acadian (Silurian-Devonian) deformation. Taconic deformation is indicated by stratigraphic and structural analyses, and confirmed by sub-Silurian unconformities in western Newfoundland and Quebec. Acadian deformation is demonstrated by unconformities between deformed Silurian-Devonian rocks and less deformed Carboniferous cover. It is also indicated by Devonian intrusions that cut deformed Silurian-Devonian rocks. Alleghanian (Permian-Carboniferous) deformation so important in the southern U.S. Appalachians, is mild or absent in the Humber Zone of Canada. Intensities of both Taconic and Acadian deformations increase eastward across the Humber Zone.

There are few Paleozoic plutons in the exposed Humber Zone, except for its internal parts in Newfoundland. One exception is the Devonian McGerrigle Mountains pluton of Quebec (DeRomer, 1977), which cuts transported rocks near the Appalachian structural front.

Mineral deposits of the Humber Zone are those unique to Grenville basement (titanium, iron) or the carbonate cover (lead-zinc deposits of Mississippi Valley type). Others are integral parts of transported ophiolite suites (asbestos, chromite, nickel, copper-pyrite), or related to Devonian plutons (skarn deposits at the periphery of the McGerrigle Mountains pluton).

Humber Zone External

Grenville Basement Rocks (by P. Erdmer and Harold Williams)

Introduction

Crystalline basement rocks occur in both the external and internal divisions of the Humber Zone (Fig. 3.2). These are gneisses, schists, granitoids and metabasic rocks that are correlated with rocks of the Grenville Structural Province of the nearby Canadian Shield. Those of the external Humber Zone are for the most part unaffected by penetrative Paleozoic deformation, although they are faulted and in places retrograded. Those of the internal Humber Zone are deformed with their cover rocks and display Paleozoic fabrics. External occurrences form the cores of northeast-trending anticlines or they are brought to the surface by high angle faults or west-directed thrusts. Internal occurrences are thrust slices or structural culminations in high-grade metamorphic areas where their distinction from cover rocks is in places difficult. Most metamorphic and plutonic isotopic ages are about 1200 to 1000 Ma, except where the rocks are affected by intense Paleozoic deformation. Basement gneisses in the Long Range Inlier of Newfoundland crystallized at or before 1550 Ma (H. Baadsgaard, pers. comm., 1990).

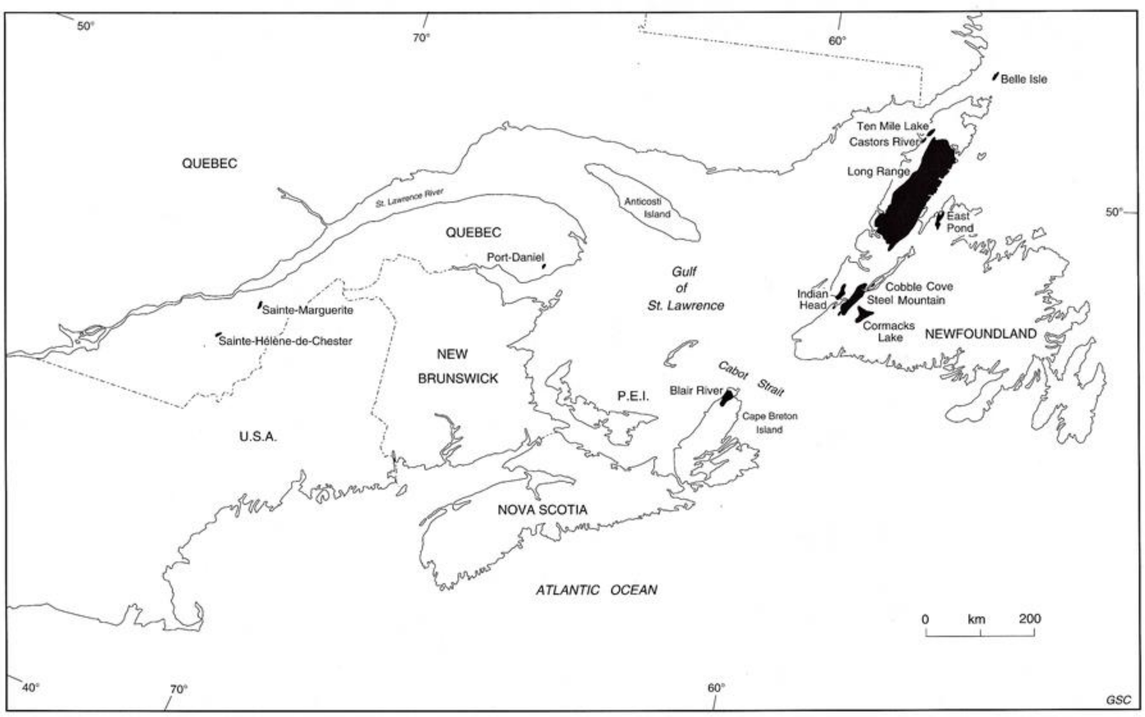


Figure 3.2. Distribution of Precambrian basement inliers in the Humber Zone.

Occurrences of basement rocks in the external Humber Zone are restricted to western Newfoundland. The Long Range Inlier is by far the largest with smaller inliers to its north and south at Belle Isle and Indian Head, respectively. Other small faulted examples occur nearby at Ten Mile Lake and Castors River.

Internal Humber Zone occurrences in Newfoundland are the East Pond Metamorphic Suite at Baie Verte Peninsula, the Cobble Cove Gneiss at Glover Island of Grand Lake, the Steel Mountain Inlier south of Grand Lake, and possibly the Cormacks Lake Complex of the Dashwoods Subzone. …

Humber Zone external, Newfoundland

Belle Isle Inlier

The Belle Isle Inlier and its cover rocks form a small island of 70 km2 in the Strait of Belle Isle (Fig. 3.3). Crystalline Precambrian rocks form the core of the island with an overlying discontinuous veneer of cover rocks dipping seaward along its periphery (Williams and Stevens, 1969; Bostock, 1983). Mafic columnar flows (Lighthouse Cove Formation) directly overlie pink gneisses on the west side of the island and an eastward-thickening unit of boulder conglomerate, coarse sandstone, and quartzite (Bateau Formation) occurs between basement and volcanic rocks on its eastern side. Arkosic sandstones (Bradore Formation) and fossiliferous Lower Cambrian shales (Forte au Formation) occur stratigraphically above the volcanic rocks.

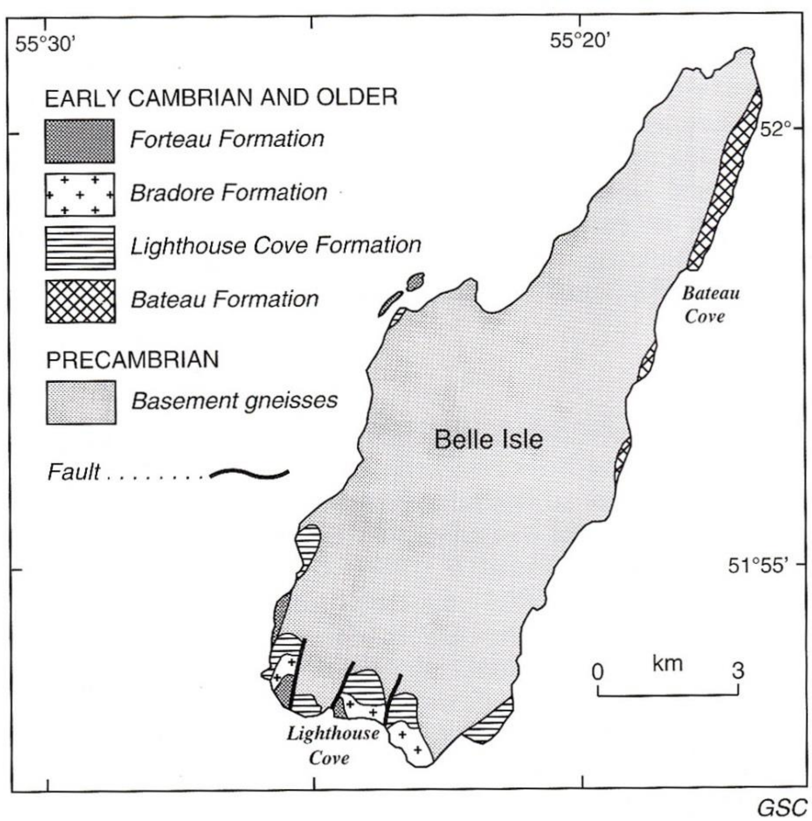


Figure 3.3. Geology of the Belle Isle Inlier.

Biotite-quartz-feldspar gneiss is the dominant rock type. Gneissic foliation is contorted and cut by granite pegmatites. Steep northeast-trending mafic dykes of the Long Range Swarm (Bostock, 1983) cut the gneisses and pegmatites. The melanocratic dykes form a conspicuous ramifying network among leucocratic gneisses in coastal exposures, and locally the dykes are as abundant as host gneisses. Relationships are especially clear at the southwest corner of the island where mafic dykes cut pink gneisses and blend upward into gently-dipping flows that overlie the gneisses. The dykes and volcanic rocks are coeval and this is confirmed by an absence of dykes in Lower Cambrian strata above the volcanic rocks. The dykes are affected by retrograde greenschist metamorphism (Bostock, 1983).

Faults of at least two generations cut the Precambrian basement rocks at Belle Isle. A younger set of northeast-trending faults cuts the gneisses and cover rocks, including fossiliferous Lower Cambrian strata. An older set on the east side of the island separates structural wedges of steeply-dipping beds of the Bateau Formation from the gneisses. These have no obvious effect on mafic dykes, indicating that the faults are older (Bostock, 1983).

Long Range Inlier

The Long Range Inlier forms the highlands of the Great Northern Peninsula of western Newfoundland with an area of 8500 km2. It is the largest external basement massif of the Appalachian Orogen. Its rocks are known as the Long Range Complex (Baird, 1960; Williams, 1985a) or Basement Gneiss Complex (Bostock, 1983) and they extend across most of the width of the external Humber Zone. Upper Precambrian to Lower Cambrian unconformable cover rocks dip gently away from the basement rocks at the north and south ends of the inlier and an equivalent unconformity that dips eastward is preserved locally along its eastern side at White Bay (Fig. 3.4). Its western boundary is largely marked by thrusts or steep reverse faults (Williams et al., 1985a, b; Cawood and Williams, 1986, 1988; Grenier and Cawood, 1988). These juxtapose crystalline basement with the Cambrian-Ordovician sedimentary cover, although basement-cover stratigraphic relationships are preserved locally within hanging-wall segments of the faulted boundary. At Western Brook Pond, St. Pauls Inlet, and south of Portland Creek Pond, the crystalline rocks are thrust above both the carbonate cover sequence and rocks of the Humber Arm Allochthon. At the southeast edge of the inlier, Cambrian-Ordovician cover rocks are detached from the crystalline basement (Owen, 1986) and Carboniferous rocks are unconformable on the lower Paleozoic and Precambrian basement rocks.

Parts of the Long Range Inlier were investigated by Foley (1937) and Fritts (1953) and mapped in reconnaissance fashion by Baird (1960), Neale and Nash (1963) and the

British Newfoundland Exploration Company. Results of this work are summarized by Clifford and Baird (1962). The inlier is covered by systematic mapping at 1:100 000 and 1:125 000 scales (Bostock, 1983; Erdmer, 1986a, b) and locally at 1:50 000 scale (Owen, 1986).

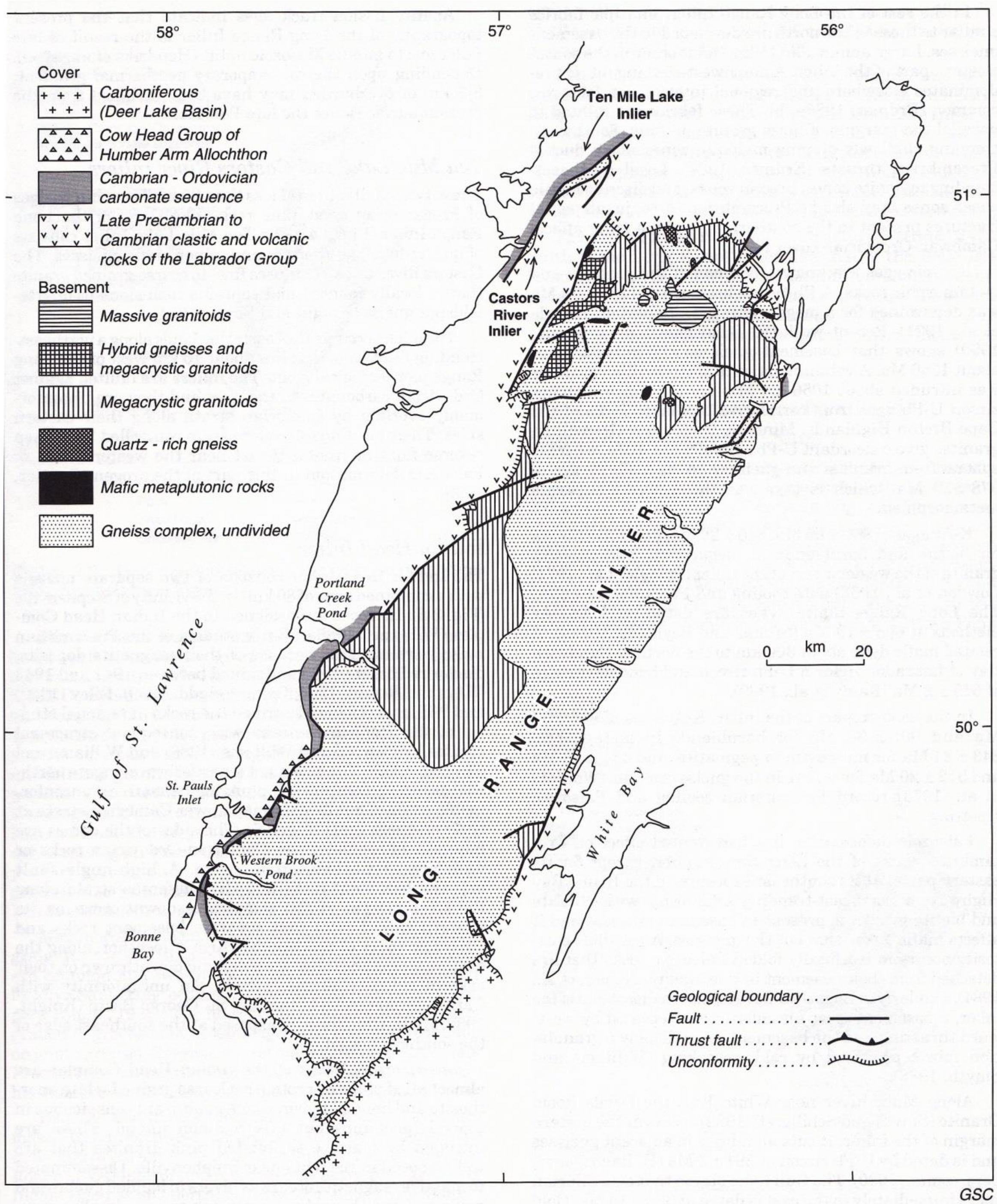


Figure 3.4. Geology of inliers of the Great Northern Peninsula: Long Range, Ten Mile Lake, and Castors River.

Lithologies are nearly uniformly high-grade quartz-feldspar gneisses and granites. At the inlier's northern portion the rocks are biotite-quartz-feldspar gneiss and hornblende-biotite-quartz-feldspar gneiss with lesser amounts of quartz-rich gneiss, pelitic schist, amphibolite and calc-silicate gneiss (Bostock, 1983). Most of these are thought to be of sedimentary protolith. Small mafic plutons, now amphibolite, hypersthene amphibolite, meta peridotite and metadiorite cut the leucocratic gneisses. The mafic plutons are in turn cut by distinctive megacrystic foliated to massive granites of at least two suites. Pegmatites that occur in most outcrops probably relate to the granites. Northeast-trending diabase dykes of the Long Range Swarm (Bostock, 1983) cut all other rocks of the inlier. These are up to 50 m wide and they are coeval with basalt flows that locally overlie the gneisses at the north end of the inlier (Clifford, 1965; Williams and Stevens, 1969). Mafic dykes are thinner and they decrease in frequency toward the west.

In southern parts of the inlier, rocks and relationships are similar to those in the north. The commonest foliated rocks are pink to grey quartz-feldspar gneiss, quartz-rich gneiss, pelitic to psammitic schist, amphibolite and minor marble and calc-silicate rock. The bulk of the gneisses appear to have plutonic protoliths (Owen and Erdmer, 1986). A gabbro-anorthosite pluton, up to 15 km in diameter, occurs near the south end of the inlier. All these rocks are cut by large plutons of massive to foliated megacrystic granite to charnockite. Diabase dykes occur locally but they are less common than in the north.

Plutonism both accompanied and followed Precambrian regional metamorphism of the basement gneiss complex. The emplacement of mafic plutons in the northern part of the inlier accompanied regional metamorphism of amphibolite to granulite facies. Pelitic rocks contain microcline-sillimanite-cordierite (or garnet) assemblages, and remnants of hypersthene are preserved in several localities (Bostock, 1983). Some megacrystic granites cut the high grade metamorphic rocks and locally imprint lower amphibolite facies aureoles on the country rocks. Andalusite overprints sillimanite in pelitic aureole rocks and cummingtonite and anthophyllite occur sparingly. Other massive, mostly equigranular granites lack metamorphic aureoles.

Retrograde greenschist facies metamorphism affected eastern parts of the inlier with development of epidote and chlorite, recrystallization of biotite, replacement of sillimanite by muscovite, and sericitization of feldspars. It occurred in at least two phases. The first preceded the emplacement of the Long Range mafic dykes, indicating a Precambrian age, the second postdated the dykes and related volcanic rocks indicating a Paleozoic age (Bostock, 1983; Owen and Erdmer, 1986).

In central and southern portions of the Long Range Inlier, amphibolite and locally granulite facies mineral assemblages (two-pyroxene gneisses) occur in many places, with metamorphic grade increasing from amphibolite in the northeast to granulite in the southwest. The metamorphism predates most of the large granite plutons and possibly the gabbro-anorthosite suite. Metamorphic temperatures increase from 600-

650°C to nearly 800°C southwestward across the amphibolite-granulite transition; metamorphic pressures vary between 5 and 8 kilobars throughout the inlier (Owen and Erdmer, 1990). Retrograde effects are greatest at the southeast tongue of the inlier and along its southeast margin. This retrogression is Paleozoic 'as it involves nearby Cambrian-Ordovician cover rocks.

Precambrian structures within the inlier are complex. In its northern part, the basement gneisses display three episodes of folding (Bostock, 1983). Large areas of shallowly-dipping foliation are separated by steep structural zones or by granitic plutons and faults. Most folds trend northeast with gently-plunging axes. These range from early isoclines to late open structures. A few folds of different orientation may be controlled by late granitic plutons. Gneissic banding, schistosity and mineral lineations are present in nearly every rock type, except in the granitic plutons.

In the rest of the Long Range Inlier, multiple fabrics similar to those in the north are developed in the basement gneisses. Large amplitude (15 km) folds occur in the southwestern part of the inlier. A northwest-striking fabric predominates elsewhere and regional interference folds are common (Erdmer, 1986a, b). These fabrics are rotated to parallel the margins of large granite plutons. Southwest-trending shallowly-dipping mylonite zones mark ductile Precambrian thrusts (Erdmer, 1984). Local northeast-trending mylonite zones, breccia zones, and discrete brittle shear zones may also be Precambrian. A conjugate set of fractures present in the southern part of the inlier affects Cambrian-Ordovician cover rocks.

Isotopic ages are known for some of the granites and metamorphic rocks. A Rb-Sr isochron age of 1130 ± 90 Ma was determined for a megacrystic granite pluton (Pringle et aI., 1971). Recent work (H. Baadsgaard, pers. comm., 1990) shows that basement gneisses crystallized at or about 1550 Ma. A voluminous suite of Grenvillian granites was intruded about 1056 ± 4 Ma; an age which matches zircon U-Pb ages from correlative basement rocks of the Cape Breton Highlands. Minerals from a few Grenvillian granites give concordant U-Pb ages of970 ± 4 Ma, whereas sphene from granites and gneisses yields a Pb-Pb age of 978 ± 10 Ma, which is taken as the age of a separate metamorphism.

K-Ar ages of960 ± 65 Ma, 840 ± 20 Ma, and 945 ± 65 Ma for biotite and hornblende in megacrystic and massive granite of the western part of the inlier (Pringle et al., 1971; Lowdon et aI., 1963) date cooling and Precambrian uplift. The Long Range mafic dykes are dated by 40Ar_39Ar methods at 605 ± 10 Ma (Stukas and Reynolds, 1974a). A related mafic dyke about 300 km to the north at Sandwich Bay of Labrador yields a U-Pb zircon and baddeleyite age of 615 ± 2 Ma (Kamo et aI., 1989).

In the eastern part of the inlier, K-Ar ages of 903 ± 37 Ma and 903 ± 38 Ma for hornblende in metagabbro, 843 ± 24 Ma for muscovite in pegmatite, and 434 ± 18 Ma and 512 ± 20 Ma for biotite in the gneiss complex (Wanless et al., 1973) record Precambrian cooling and Paleozoic resetting.

Paleozoic deformation has had limited effect on Precambrian rocks of the Long Range Inlier, except for its eastern parts. At its southeast exposure on the Bonne Bay Highway, a northeast-trending schistosity with chlorite and biotite growth is present in basement gneisses and it affects mafic dykes that cut the gneisses. A parallel schistosity occurs in isoclinally folded Paleozoic rocks that are detached from their basement in this locality (Nyman et al., 1984). Similarly at Sugarloaf Cove at the northeast end of the inlier, a basement-cover unconformity is repeated by westward thrusting and the basement rocks display a granulation fabric produced by cold reworking (Williams and Smyth,1983).

Along Main River near White Bay, the Devils Room Granite (Smyth and Schillereff, 1982) occurs at the eastern margin of the inlier. It cuts all fabrics in adjacent gneisses and is dated by U-Pb zircon at 391 ± 3 Ma (H. Baadsgaard, pers. comm., 1990). The Gull Lake pluton that cuts Silurian rocks immediately to the east is dated at 372 ± 10 Ma. Gold mineralization in both the Precambrian basement rocks and nearby Silurian rocks may relate to this phase of middle Paleozoic plutonism.

Apatite fission track ages indicate that the present topography of the Long Range Inlier is the result of late Paleozoic to middle Mesozoic uplift (Hendriks et al., 1990). Depending upon the contemporary geothermal gradient, 3-5 km of overburden may have been stripped from the present surface since the late Paleozoic.[3]

Summary and discussion

All basement inliers and structural slices of Precambrian rocks in the Humber Zone, with the single exception of an exotic crystalline block in melange at Port-Daniel, are similar to rocks of the Grenville Structural Province of the nearby Canadian Shield. The rocks are mainly of igneous protolith with minor occurrences of marble, quartzite and metaclastic sedimentary rocks. The age of the oldest rocks is unknown, other than that they were crystallized at or before 1550 Ma and metamorphosed as early as 1230 Ma. The emplacement of mafic intrusions accompanied or followed the earliest recognized phase of regional metamorphism and the deformed rocks are cut by granites dated at about 1000 Ma. Regional metamorphism is mainly of amphibolite facies and locally reaches granulite facies. This implies deep erosion of Precambrian rocks before deposition of late Precambrian-early Paleozoic cover sequences.

[3] Ibid., p. 47-54

Mafic dykes cut the basement rocks in almost all inliers and they feed basalts that unconformably overlie the basement rocks in Newfoundland. This igneous activity is dated isotopically as latest Precambrian and stratigraphic relationships provide an upper age limit of Early Cambrian. Where best developed in the northeastern part of the Long Range Inlier, the dykes decrease in width and frequency from southeast to northwest. Relationships in the Belle Isle Inlier indicate that late Precambrian faulting affected coarse clastic cover rocks before the emplacement of the mafic dyke swarm. This implies rift-related deformation. Late Precambrian retrogression may relate to this extensional tectonism.

The present positions of the inliers are controlled by Paleozoic structures so that their dimensional orientations are parallel to Appalachian structural trends and facies belts. Internal fabrics and fold axes trend northwest in some examples, perpendicular to Appalachian structures. As northwesterly trends are common in the Grenville Structural Province of the Canadian Shield, this suggests minimal or no rotation during Paleozoic deformations.

Grenville inliers of the external Humber Zone are unaffected by Paleozoic deformation except for faulting and gentle folding. Retrograde metamorphism increases from west to east across the width of the Long Range Inlier, and cover rocks are intensely deformed and detached from their basement in the east. Some thrusts affect only the cover rocks. Others are deep shears that bring the basement to the surface. Major detachment zones must therefore lie deep within the basement.[4]

Interpretation and significance

Features of the upper Precambrian-Lower Cambrian sedimentary rocks, volcanic rocks, mafic dyke swarms and associated plutons are all consistent with a model of continental rifting and the initiation of the Appalachian cycle (Williams and Stevens, 1969, 1974; Strong and Williams, 1972; Pintson et al., 1985; Kumarapeli, 1985; Williams et al., 1985a; and many others). The rifting affected a broad area that extended inland several hundred kilometres from the present Appalachian Structural Front.

The timing and duration of rifting is defined by isotopic ages of igneous rocks and stratigraphic analysis of overlying fossiliferous strata. Rifting began at least 600 Ma ago and persisted to about 550 Ma ago.

In the Humber Zone, sedimentation was mainly terrestrial or mixed marine and terrestrial. Rapid lateral changes in facies and thickness of sedimentary rocks and rift affinities of coeval flows fed by dykes, imply deposition in rift basins. Faults,

[4] Ibid., p. 60

contemporaneous with sedimentation and locally predating mafic dyke intrusion, may have been listric normal faults like those so common beneath breakup unconformities at modern continental margins. Marine shales and limestones of the Forteau Formation rest on Bradore redbeds in western Newfoundland and southeast Labrador. An abrupt termination of coarse clastic deposition and absence of coarse detritus in the succeeding Forteau Formation signals a broad submergence and permanent change in the tectonic regime. This is interpreted to mark the transition from continental rifting to ocean spreading (Williams and Hiscott, 1987; Fig. 3.14). The marine transgression and onset of carbonate deposition is regarded as the result of cooling and thermal subsidence, rather than a eustatic rise of sealevel, as it is synchronous with the cessation of rifting.[5]

Taconic Allochthons

Harold Williams

Introduction

Transported rocks of Taconic allochthons, above the Middle

Ordovician clastic unit of the autochthonous section, are a spectacular structural feature of the Humber Zone. Contorted marine shales, sandstones, and melanges of the allochthons contrast sharply with the underlying mildly deformed carbonate sequence. Volcanic rocks and ophiolite suites seem particularly out-of-context with respect to Grenville basement and its cover rocks. Taconic allochthons make up a large proportion of the exposed parts of the external Humber Zone, especially in Quebec (Fig. 3.38).

Two well-known discrete allochthons occur in western Newfoundland: the Hare Bay Allochthon at the tip of the Great Northern Peninsula and the Humber Arm Allochthon between St. George's Bay and Portland Creek (Williams, 1975a). The Old Man’s Pond Allochthon (Williams et al., 1982) is regarded as an eastern outlier of the Humber Arm Allochthon. The Southern White Bay Allochthon (Smyth and Schillereff, 1982) is another example on the east side of the Great Northern Peninsula (Fig. 3.38). …

The western edge of the transported rocks is Logan's Line, first defined at Quebec City (Logan, 1863; Stevens, 1974) and traceable southward to Vermont (Williams,

1978a). Its northern course is covered by the St. Lawrence River, but it is exposed near the tip of Gaspésie. In Newfoundland, Logan's Line is discontinuous and defined by the leading edges of the Humber Arm and Hare Bay allochthons (Fig. 3.38).

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[5] Ibid., p. 67

Taconic allochthons of the external Humber Zone are described for Newfoundland and serve as an example of structural styles found all along the west flank of the Appalachian Orogen in Canada. Allochthons are absent or poorly defined in internal parts of the Humber Zone, except for occurrences of small disrupted ophiolitic rocks and melanges. These are treated under the general heading "Humber Zone internal" (Hibbard et al., Chapter 3).

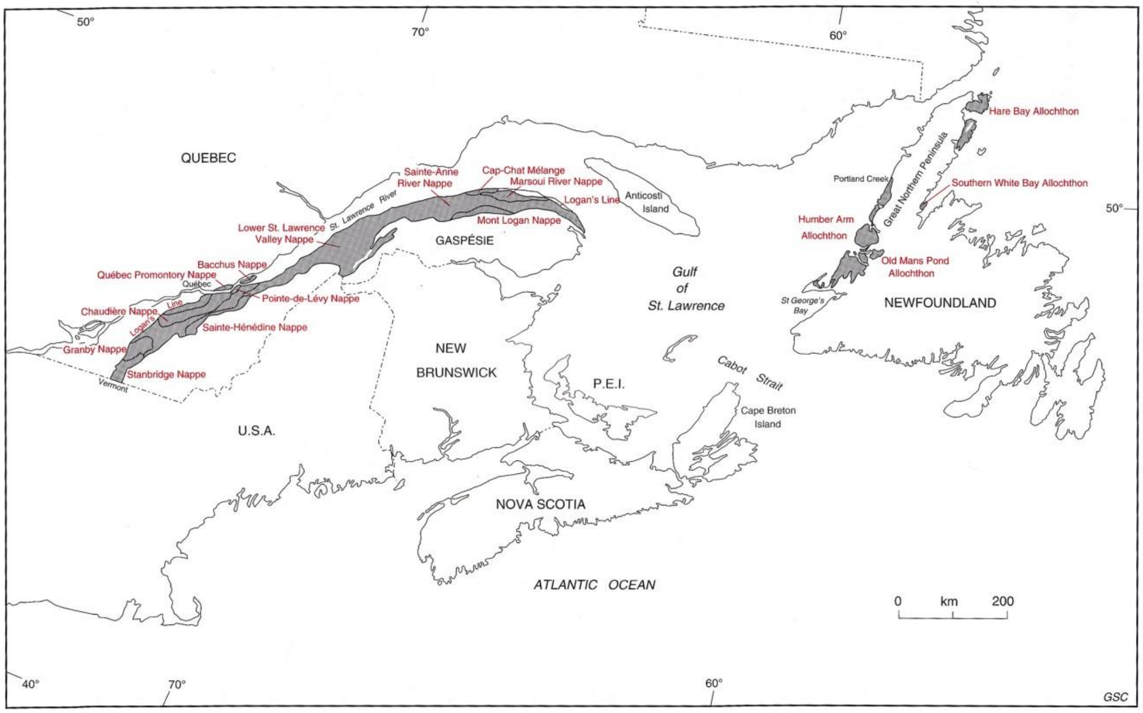

Figure 3.38. Distribution of Taconic allochthons in the Canadian Appalachian region.

Newfoundland

Harold Williams

Taconic allochthons of western Newfoundland exhibit a variety of igneous and metamorphic rocks in upper structural slices that are rare or absent in most Appalachian examples. Especially well-known are the ophiolite suites and metamorphic soles of the Bay of Islands Complex in the Humber Arm Allochthon and the St. Anthony Complex of the Hare Bay Allochthon (Williams and Smyth, 1973; Williams, 1975a). A complete stratigraphy from late Precambrian to Early Ordovician has been deciphered among sedimentary rocks of the Humber Arm Allochthon and some facies, such as the Cambrian-Ordovician Cow Head breccias, are renowned for their sedimentological and paleontological characteristics (James and Stevens, 1986; Barnes, 1988). Gros Morne National Park, situated in the Humber Zone of western Newfoundland, was declared a World Heritage Site in 1987 based mainly on its rocks and geological relationships.

The Humber Arm and Hare Bay allochthons occupy structural depressions. The Humber Arm Allochthon is surrounded to the east by the Cambrian-Ordovician carbonate sequence and separated from the Hare Bay Allochthon by a major structural culmination that exposes Grenville basement of the Long Range Inlier. The Old Man's Pond Allochthon is separated from the Humber Arm Allochthon by a narrow culmination that exposes the carbonate sequence. The Southern White Bay Allochthon occurs on the east side of the broad anticlinal Long Range Inlier. Because these structural depressions and culminations are later than the emplacement of the allochthons, the present exposures are erosional remnants of once-more-continuous sequences that covered larger areas of western Newfoundland.

History of Ideas

When Schuchert and Dunbar (1934) summarized the geology of western Newfoundland, they attempted to set up a single stratigraphic column that included transported rocks of the Humber Arm and Hare Bay allochthons at the top of the Cambrian-Ordovician carbonate sequence. There were difficulties, however, as some of their upper stratigraphic units contained fossils older than those of underlying units. At that time, plutonic rocks of the allochthons were viewed as intrusions (Ingerson, 1935; Buddington and Hess, 1937; Smith, 1958). Suggestions of significant lateral transport to explain the position and contrasts between the Cambrian-Ordovician carbonate sequence and coeval sedimentary and volcanic rocks of the overlying sequences are credited to Johnson (1941) and Kay (1945). However, the implications of this idea and first meaningful analysis is that of Rodgers and Neale (1963), based mainly on parallel relationships in New York and the demonstration of allochthonous rocks there. They reasoned that the deep-water clastic rocks were deposited far to the east of the shallow water carbonate sequence and subsequently transported westward to overlie the carbonate sequence. They further interpreted the plutonic rocks, such as those of the Bay of Islands Complex, as integral parts of the transported sequences; both because of their spatial affinity with the transported rocks, and like the sedimentary and volcanic rocks, they appear out-of-place within the fame work of the carbonate sequence of western Newfoundland. According to the view of Rodgers and Neale (1963), the plutonic rocks of the ophiolite suites were intrusions, emplaced into the sedimentary and volcanic rocks at their place of deposition and all transported together.

Lilly (1963) and Stevens (1965) worked out the stratigraphy of the Humber Arm Supergroup and Stevens (1970) implied that the ophiolite suites represented oceanic crust in separate structural slices (see also Cooper, 1936; 1937; Tuke, 1968). Steven's analysis of the Humber Arm Allochthon as a sampling of rocks from a continental margin and adjacent ocean has been substantiated by all subsequent work. For more insight into this topic the reader is referred to Rodgers and Neale (1963), Stevens (1970), Williams (1971a), and Williams and Stevens (1974).

Previous Work

The first comprehensive mapping and studies of parts of the Humber Arm and Hare Bay allochthons were by Cooper (1936, 1937); Betz (1939); Troelsen (1947); Walthier (1949); Smith (1958); Lilly (1963); Stevens (1965, 1968); Gillis (1966); Tuke (1968); and Smyth (1971). The southern portion of the Humber Arm Allochthon is included in the reconnaissance map of the Stephenville area (Riley, 1962) and its northern part in the reconnaissance map of the Sandy Lake area (Baird, 1960). Since the advent of plate tectonics, a multitude of studies focus on transported rocks of the Humber Arm and Hare Bay allochthons. These are listed in the bibliographies of Williams (1975a, 1985a) and Williams and Smyth (1983). All of the Humber Arm and Hare Bay allochthons have been remapped at 1: 100 000 and 1:50 000 scales (Williams, 1973, 1985a, b; Williams et al., 1983, 1984, 1985b; Williams and Smyth, 1983; Williams and Cawood, 1986; Cawood and Williams, 1986; Cawood et al., 1987). A map of the entire Hare Bay Allochthon is available at 1:125 000 scale (Williams and Smyth, 1983) and a compilation map of the Humber Arm Allochthon at 1:250 000 scale (Williams and Cawood, 1989).

The Southern White Bay Allochthon was defined during reconnaissance studies in northwest Newfoundland (Williams, 1977a) and it was named and studied in more detail by Smyth (1981) and Smyth and Schillereff (1982). The Old Man's Pond Allochthon was defined by studies in the Pasadena area (Williams et al., 1982; 1983; Gillespie, 1983; Waldron and Milne, 1991).

Williams (1975a) summarized relationships within the Humber Arm and Hare Bay allochthons as they were known at that time. The present account.is based largely on that summary, augmented by more current information. The Humber Arm Allochthon is treated first as many of our present concepts and stratigraphic relationships were developed from this example.

Humber Arm Allochthon

The Humber Arm Allochthon is 200 km long and about 50 km across at its widest part (Fig. 3.39). Its structural thickness is in the order of a few kilometres. Because the intensity of post-emplacement deformation increases eastward across the allochthon, relationships are clearest in the west. At its western leading edge, sedimentary rocks of the allochthon are separated by melange from gently-dipping sandstones and shales at the top of the autochthonous sequence. Toward the east, its boundaries are steep and locally faulted with stratigraphic omission at the top of the autochthonous sequence.

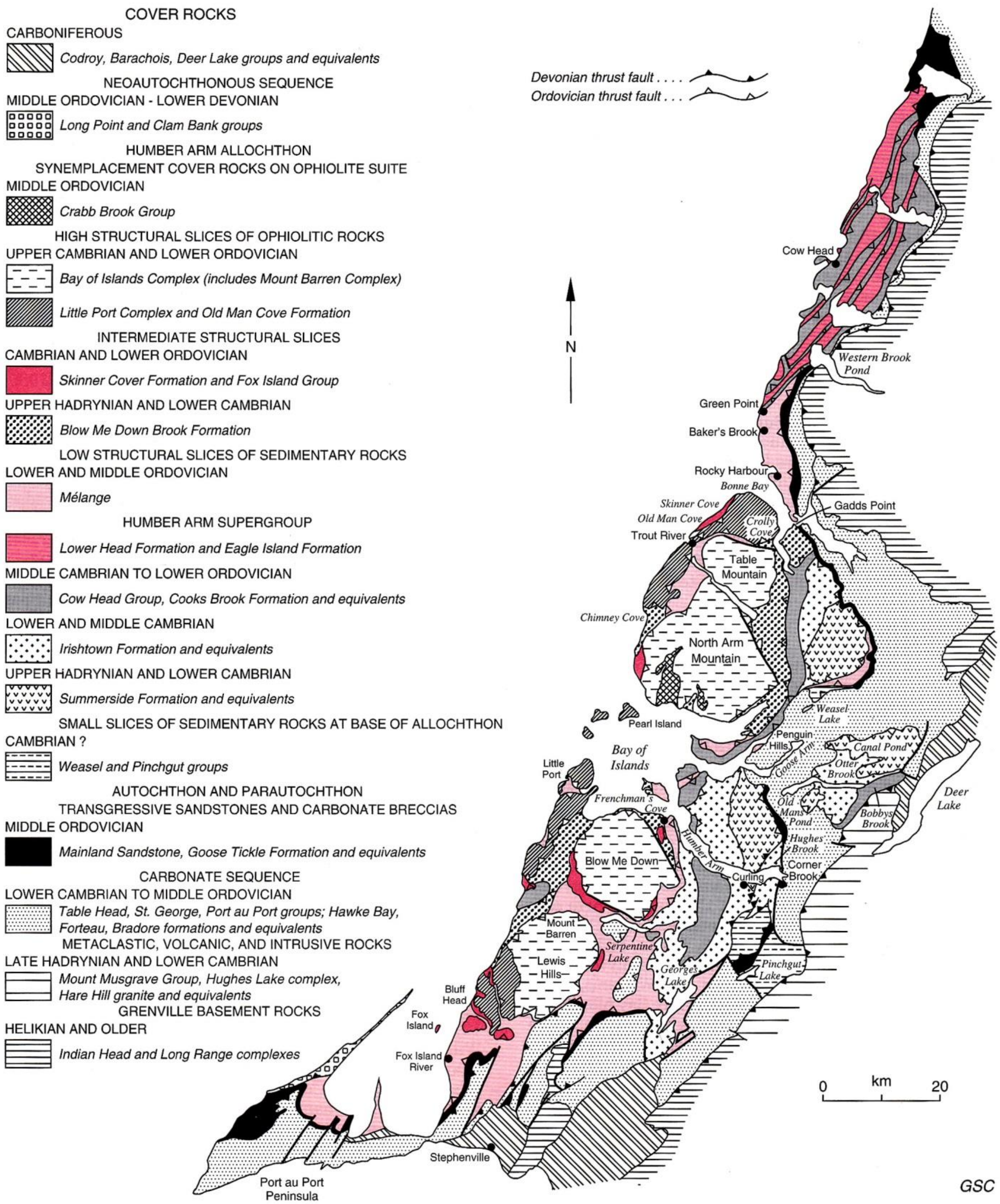

Figure 3.39. General geology of the Humber Arm Allochthon, modified after Williams and Cawood (1989). For more detail the reader is referred to GSC Map 1678A – Geology of the Humber Arm Allochthon.

Relationships are confused by post-emplacement folds and thrusts of eastward polarity between Georges Lake and Corner Brook (Bosworth, 1985; Waldron, 1985; Williams and Cawood, 1986), and by westerly thrusts that bring cover rocks and basement above the allochthon north of Bonne Bay (Williams et al., 1985b; Williams, 1985b; Williams et al., 1986; Cawood and Williams, 1988; Grenier and Cawood, 1988; Grenier, 1990). At Port au Port Peninsula, the Middle Ordovician (Caradoc) Long Point Group overlies sedimentary rocks of the Humber Arm Allochthon. The contact has been interpreted as an unconformity, following the lead of Rodgers (1965). Offshore seismic data suggest a fault, with the Long Point Group thrust eastward above the allochthon as the upper portion of a triangle zone (Stockmal and Waldron, 1990).

Sedimentary rocks of lower structural slices of the Humber Arm Allochthon are assigned to the Humber Arm Supergroup (Stevens, 1970). It is subdivided into the Curling Group (Stevens, 1970) in the vicinity of Humber Arm and southward, the informal Bonne Bay group (Quinn and Williams, 1983; Williams et al., 1984; Quinn, 1985) between Bay of Islands and Bonne Bay, and the Cow Head Group and Lower Head Formation (Kindle and Whittington, 1958; Williams et al., 1985b; James and Stevens, 1986) to the north of Bonne Bay. Other units are the informal Weasel and Pinchgut groups in separate slices at the base of the allochthon along its eastern margin (Williams et al., 1984; Williams and Cawood, 1986).

Four volcanic and plutonic units occur in higher slices of the allochthon. From structurally lowest to structurally highest, these are: (1) Skinner Cove Formation, Fox Island Group and related volcanic rocks (Troelsen, 1947; Williams, 1973; 1985a; Williams et al., 1984; Williams and Cawood, 1989), (2) Old Man Cove Formation (Williams, 1973), (3) Little Port Complex (Williams and Malpas, 1972; Williams, 1973) and the related Mount Barren Complex (Karson, 1977, 1979; Williams, 1985a), and (4) Bay of Islands Complex (Cooper, 1936; Smith, 1958; Williams, 1973; 1985a; Williams and Cawood, 1989). A complete section of stacked units is nowhere exposed and probably nowhere exists. In most places the higher slices directly overlie sedimentary rocks but locally they overlap and overlie one another. The stacking order is built up from local relationships.

Two conspicuous carbonate slivers occur beneath the Bay of Islands Complex and above melange of lower structural levels. These are the Serpentine Lake and Fox Island River slices (Godfrey, 1982; Williams and Godfrey, 1980a, b). They are gently dipping, upright sections of thick bedded, white and grey limestones and dolomites of the St. George and Table Head groups. A smaller example occurs at Penguin Hills (Lilly, 1967; Williams et al., 1983). These are interpreted either as integral parts of the allochthon, entrained during Middle Ordovician assembly and transport, or features of later gravity collapse and late stage transport of ophiolites and parts of the carbonate sequence across the already-assembled allochthon (Cawood, 1989).

Humber Arm Supergroup

The Curling, Bonne Bay, and Cow Head groups are all partly correlative and their successions of stratigraphic units are for the most part relatively clear. The rocks occur in a number of lower structural slices, especially evident in the case of the Cow Head Group (Fig. 3.40).

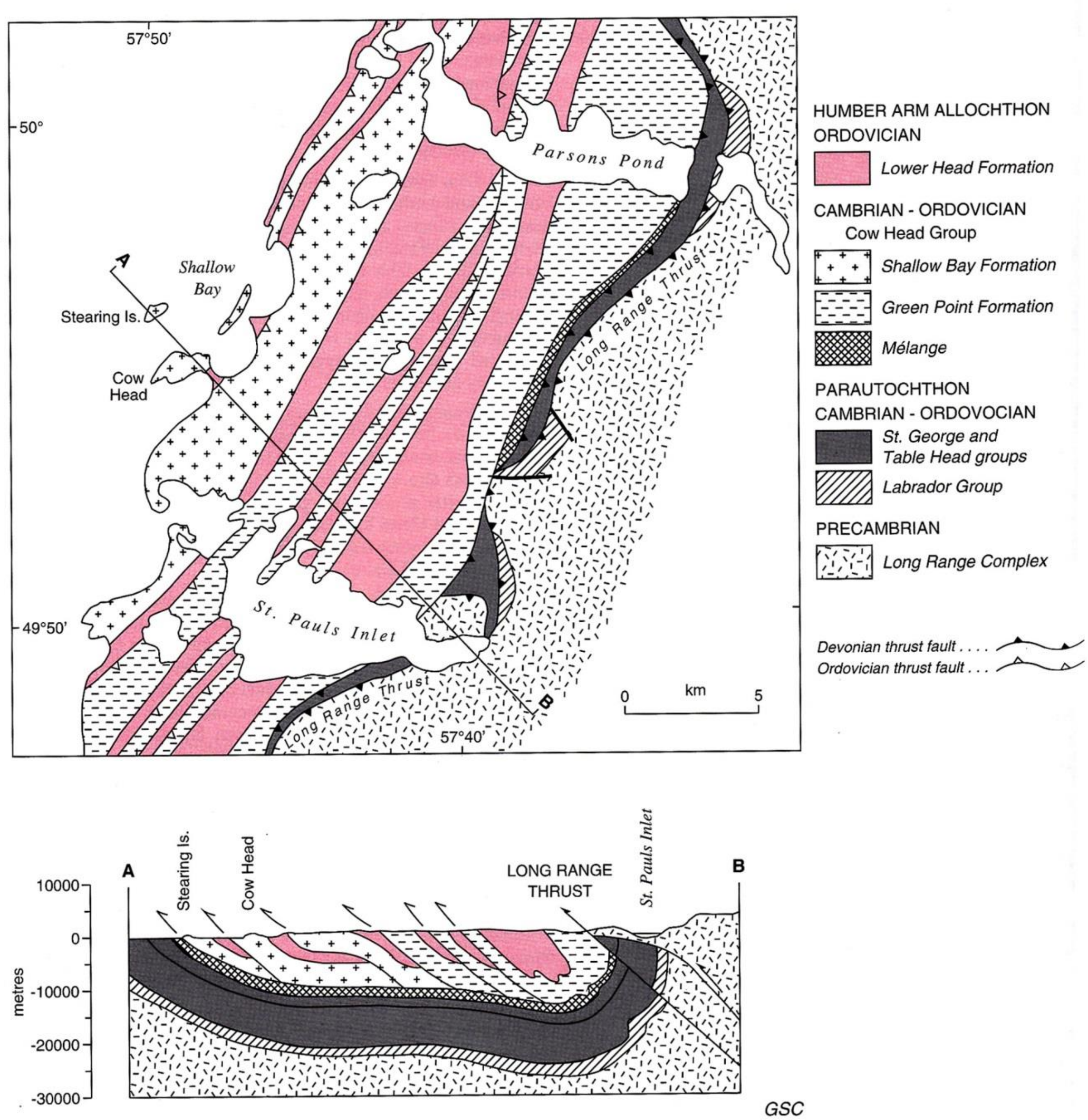

Figure 3.40. Distribution of thrust slices and facies belts of the Cow Head Group.

The Curling Group (former Humber Arm Series, Schuchert and Dunbar, 1934; Humber Arm Group, Smith, 1958) comprises the Summerside, Irishtown, Cooks Brook, Middle Arm Point, and Eagle Island formations, from bottom to top. There is no single complete section and the overall succession is built up from partial sections exposed at or near Humber Arm. The Summerside Formation consists of monotonous quartz greywackes with purple slate interbeds. Its thickness is estimated at a kilometre or more with base unexposed. The Irishtown Formation consists of dark grey shale with prominent thick white quartzite units and local polymictic conglomerates containing plutonic clasts of Grenville basement and a variety of sedimentary rocks including fossiliferous Lower Cambrian limestones. In contrast, the middle formations of the Curling Group represent a condensed sequence of thin bedded shales and platy limestones with prominent limestone breccia units (Cooks Brook Formation) overlain by black and green shales and buff siltstones (Middle Arm Point Formation). Thicker polymictic clastic rocks reappear at the top of the group (Eagle Island formation) containing chromite and other ophiolite detritus (Stevens, 1970; Botsford, 1987).

The Summerside Formation is considered Early Cambrian or late Precambrian, by correlation with similar units along the west flank of the Humber Zone (Williams and Stevens, 1974) and similar rocks (Blow Me Down Brook Formation) in an overlying structural slice contain Oldhamia (Lindholm and Casey, 1989). Early Cambrian limestone boulders in Irishtown conglomerates indicate the formation is no older than Early Cambrian. Limestone at the base of the Cooks Brook Formation is Middle Cambrian and the Eagle Island and Middle Arm Point formations contain Early Ordovician graptolites (Stevens, 1970; Erdtmann and Botsford, 1986).

The Bonne Bay group was defined because of uncertain correlations between its formations and those of the Curling Group. The Mitchells and Barters formations correlate with the Summerside and Irishtown formations of the Curling Group. The McKenzies formation is a combined Cooks Brook-Middle Arm Point correlative that lacks limestone breccias so prominent at Humber Arm.

The Cow Head Group (Kindle and Whittington, 1958; Williams et al., 1985b; James and Stevens, 1986) is a thin (300 m) sequence of coarse limestone breccias, platy limestones, and dolomitic shales of Middle Cambrian to late Early Ordovician age. It is overlain by polymictic sandstones and conglomerates of the Lower Head Formation. The limestone breccias and sandstones occur in east-dipping, east-facing stratigraphic sections that are repeated in northeast-trending belts. The coarsest limestone breccias occur in western belts with finer, thinner and fewer breccias in eastern belts (Fig. 3.40). The Cow Head Group correlates with the Cooks Brook and Middle Arm Point formations of the Curling Group and the McKenzies formation of the Bonne Bay group. Lower Head sandstones are correlatives of the Eagle Island formation at the top of the Curling Group.

The Cow Head Group is famous for its coarse limestone breccias and contained faunas. In a general way, fossiliferous limestone blocks are of the same age as enclosing shales (Kindle and Whittington, 1958; James and Stevens, 1986; Pohler, 1987). The stratigraphic sections contain shelly faunas, graptolites, and conodonts that allow comparisons among biostratigraphic subdivisions using different fossil assemblages. For this reason, the Cow Head Group is a potential world stratotype for the Cambrian-Ordovician boundary (Barnes, 1988).

The Weasel and Pinchgut groups that occur in separate slices at the base of the allochthon near Humber Arm are possible correlatives of the autochthonous carbonate succession and the allochthonous Cow Head Group. Grey to buff dolomitic shales and platy grey limestones resemble the Reluctant Head Formation of the autochthon. Carbonate breccias, some with a sandy lime matrix, resemble breccias of the Cow Head Group.

The Blow Me Down Brook Formation and correlative Sellars formation form an extensive and continuous structural slice of clastic sedimentary rocks above the Curling and Bonne Bay groups, respectively. The rocks are coarse quartz-feldspar sandstones derived from a crystalline source. Red pillow lavas and breccias occur at the stratigraphic base of the Blow Me Down Brook Formation at Woods Island. The sandstones at Blow Me Down Brook were first interpreted as part of the highest stratigraphic unit of the Curling Group (Stevens, 1970). The name Sellars formation was introduced because the rocks at Bonne Bay were interpreted as late Precambrian or Early Cambrian and, while lithologically similar and almost physically continuous with the Blow Me Down Brook Formation, they were corrrelated with the Summerside and Mitchells formations (Quinn, 1985). Recent discovery of Oldhamia in the Blow Me Down Brook Formation indicates an Early Cambrian age (Lindholm and Casey, 1989).

Melanges are extensively developed among sedimentary rocks of the Humber Arm Allochthon (Fig. 3.39). Between Bonne Bay and Stephenville, western portions of the sedimentary allochthon are mainly melange whereas eastern portions comprise intact stratigrahic sections. The largest area of melange occurs between Fox Island River and Port aux Port Peninsula. Another large area extends from Green Point to Bonne Bay and continues as a narrow zone at the base of the allochthon from Bonne Bay to Bay of Islands. Some of the melanges were given local names: Companion Melange at Frenchman’s Cove (Williams, 1973), Gadds Point melange (Williams et al., 1984), Rocky Harbour melange (Williams, 1985b), and Crolly Cove melange (Williams, 1985b; Williams and Cawood, 1989).

Melanges consist mainly of greywacke, quartzite, dolomitic shale, chert, and limestone blocks in a black, green, and red scaly shale matrix. Volcanic blocks occur in some structurally lower melanges and they are common in structurally higher melanges. A melange along the east side of Lewis Hills contains a sampling of ophiolitic blocks including amphibolite and greenschist of the Bay of Islands metamorphic sole (Williams, 1985a). Melange with serpentinite and gabbro blocks in a greasy green serpentinite matrix is exposed in a roadcut at the base of the Blow Me Down ophiolite slice at Humber Arm (Cawood et al., 1988). Serpentinite melange also occurs below the Little Port Complex farther west. North of Bonne Bay, the Rocky Harbour melange contains huge blocks of limestone breccia, and at Bakers Brook it contains large areas of shale, quartzite, and conglomerate with Lower Cambrian fossiliferous limestone clasts.

The Rocky Harbour melange forms a continuous zone at the base of the allochthon from Western Brook Pond to Humber Arm. It is concordant and gradational with the underlying clastic unit at the top of the autochthon. Steep stratigraphic contacts between formations of the overlying Bonne Bay group and a steep structural contact between the McKenzies and Sellars formations all terminate abruptly and at high angles against the Rocky Harbour melange.

On the scale of an outcrop, blocks in melange range from a centimetre or less to a metre or more in diameter. Most are round or equidimensional. At Fox Island River, volcanic blocks range in diameter from a few metres to a few kilometres. Blocks beyond a kilometre across are oblate to discoidal in form and the largest are the flat ophiolite massifs of the Bay of Islands Complex. There is every gradation between the smallest equidimensional blocks and the largest structural slices.

Skinner Cove Formation, Fox Island group and related rocks.

The Skinner Cove Formation (Williams, 1973), formerly the Skinner Cove Volcanics (Troelsen, 1947), is a remarkably unaltered and relatively undeformed sequence of layered volcanic rocks with minor sedimentary interbeds. Correlatives occur as far south as Bluff Head (Fig. 3.39). They overlie sedimentary rocks and melanges of the Humber Arm Supergroup and they are overlain by higher igneous slices. In the type area at Skinner Cove, the formation constitutes a uniform southeast-dipping succession beneath the Old Man Cove Formation and Little Port Complex (Fig. 3.41). At localities farther south, the Little Port Complex and Bay of Islands Complex overlie the volcanic rocks. Local exposures of volcanic rocks along the west side of Table Mountain are interpreted as large blocks torn from the main Skinner Cove slice and embedded in melange.

The rocks include black pillow basalts with white or pink limestones between pillow interstices, red volcanic breccias, latitic flows, distinctive agglomerates with black basalt fragments in a white limestone matrix, pink to grey shales and minor limestones. The Skinner Cove volcanic rocks have pronounced alkali chemical characteristics. Detailed descriptions and chemical data are given by Baker (1978) and descriptions of possible correlatives by Schillereff (1980), Godfrey (1982), and Quinn (1985). Shelly fossils and graptolites reported previously as dating the Skinner Cove Formation (Williams, 1975a) are from melange that is not in stratigraphic continuity with other rocks of the formation.

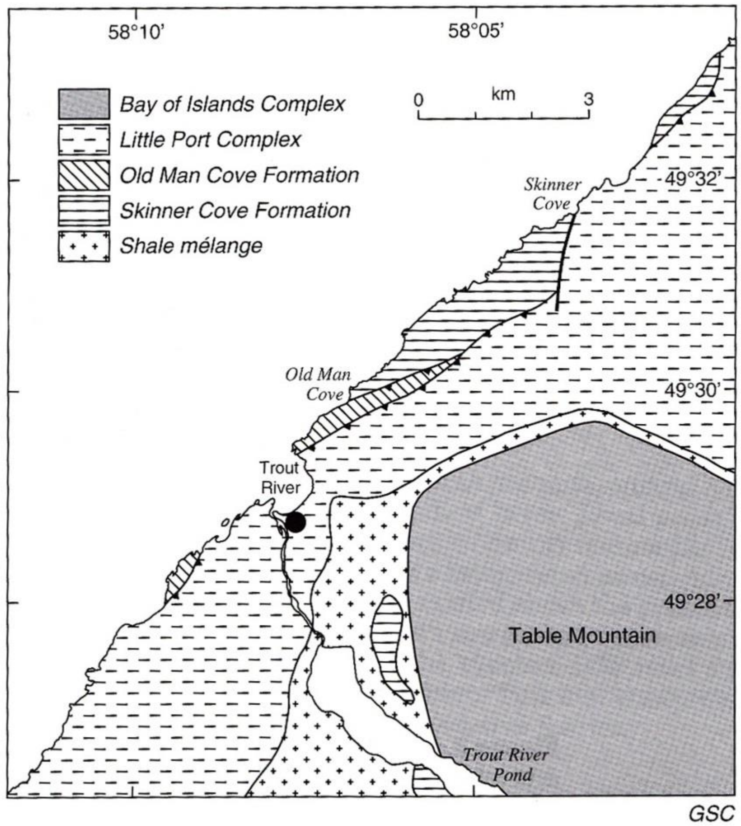

Figure 3.41. General setting of the Skinner Cove and Old Man Cove formations with respect to nearby groups and structural slices.

Large discrete volcanic blocks, some a few kilometres across, occur along the east side of the Bay of Islands massifs from Bonne Bay to Fox Island River (Fig. 3.42).

These are mainly green and red pillow lavas and pillow breccias with minor pink limestone and shale. Some resemble the Skinner Cove Formation and others resemble pillow lava of ophiolite suites. Occurrences at Bonne Bay are named the Crouchers formation (Williams et al., 1984) and those farther south, the Fox Island group (Williams and Cawood, 1989). A spatial association with Sellars sandstones between Bonne Bay and Bay of Islands suggests that some of the volcanic blocks may be dislodged from a stratigraphic section such as the Blow-Me-Down Brook Formation at Woods Island of Humber Arm.

Old Man Cove Formation

The Old Man Cove Formation (Williams, 1973), previously included in the Skinner Cove Volcanics (Troelsen, 1947), constitutes a single small slice that occurs between the Skinner Cove Formation and overlying Little Port Complex (Fig. 3.41). Its rocks are polydeformed greenschists with minor marble beds, interpreted as original tuffs and limestones. Undeformed mafic dykes are an integral part of the structural slice and they cut the deformed and metamorphosed rocks. The dykes are of Skinner Cove affinity, and therefore suggest a link between the Skinner Cove volcanic rocks and predeformed rocks of the Old Man Cove slice (W.S.F. Kidd, pers. comm., 1988). The age of the Old Man Cove Formation is unknown. It resembles lithologies in the metamorphic soles of the Bay of Islands and St. Anthony complexes (Williams and Smyth, 1973), and also greenschists of the Birchy Complex (Williams et al., 1977; Hibbard, 1983) at the Baie Verte Peninsula. Its structural position beneath the Little Port Complex suggests it may represent a partially preserved metamorphic sole related to the transport of the Little Port Complex.

Little Port Complex

The Little Port Complex (Williams and Malpas, 1972; Williams, 1973) forms narrow northeast-trending coastal slices between Lewis Hills and Bonne Bay (Fig. 3.39). Its plutonic rocks were first regarded as part of the Bay of Islands Igneous Complex (Smith, 1958). Its rocks have also been called the Coastal complex (Karson and Dewey, 1978), an informal field term, now dropped. The Little Port Complex overlies the Humber Arm Supergroup in most places. Between Trout River and Bonne Bay it overlies the Skinner Cove and Old Man Cove formations (Fig. 3.41). The Bay of Islands Complex is separated from the Little Port Complex by a wide valley, except at Lewis Hills. There, deformed gabbros, pendotites and tonalite gneisses of the Mount Barren Complex (Karson, 1979; Williams, 1985a) occur between the Little Port Complex to the west and the Bay of lslands Complex to the east; all part of the Lewis Hills massif.

The oldest rocks of the Little Port Complex are foliated layered gabbros, amphibolites and minor peridotites. Quartz diorites or tonalites cut deformed amphibolites and produce intrusion breccia on Big Island of the Bay of Islands. The granitic rocks vary from massive to well-foliated and occur as northeast-trending bodies that parallel the form of the Little Port structural slices. On the south side of the Bay of Islands, the succession of Little Port slices trends northwest and the long dimension of granitic bodies and main foliations in gabbroic rocks all trend in the same northwest direction (Comeau, 1972).

Massive mafic dykes cut foliated gabbros, amphibolites and granitic rocks and the dykes are inseparable from mafic volcanic rocks that are also part of the complex. The dykes trend northeast in most places and form thin sheeted sets that separate deformed plutonic rocks from nearby, relatively un deformed volcanic rocks. The dykes are almost everywhere brecciated (Williams and Malpas, 1972).

Volcanic rocks of the Little Port Complex are mainly green and red mafic pillow lavas and pillow breccias. Porphyritic dacite and grey silicic flows occur within the northern slice between Chimney Cove and Bonne Bay. Volcanic boulder conglomerate and sandstone are included in the complex at Little Port. Locally, the volcanic rocks contain prehnite, pumpellyite and analcime (Zen, 1974).

The Little Port Complex has the components of an ophiolite suite. However, the proportions of its rock types, especially an abundance of tonalite, and intricate internal structures, contrast with the orderly succession and proportions of pristine units in the nearby Bay of Islands Complex.

Tonalites of the Little Port Complex at Trout River yield a U-Pb zircon ages of 508 ± 5 Ma (Mattinson, 1975; Williams, 1975b) and 505 +3/-2 Ma (Jenner et al., 1991).

Bay of Islands Complex

The Bay of Islands Complex occurs in four separate massifs (Fig. 3.42). The two northernmost massifs, Table Mountain and North Arm Mountain, are separated by a left lateral tear fault at Trout River Pond. A similar structural style and internal makeup of the Blow-Me-Down massif suggests it was once part of the same northern slice. The Lewis Hills massif has an internal structure that contrasts with northern massifs. The Bay of Islands Complex overlies the Humber Arm Supergroup and locally overlies Skinner Cove correlatives. It is interpreted to form the highest structural slice at Trout River (Fig. 3.42) although its contact with the Little Port Complex is not exposed.

The Bay of Islands Complex (Cooper, 1936; Williams, 1973; Malpas, 1976), also termed the Bay of Islands Igneous Complex (Cooper, 1936; Smith, 1958), has a complete ophiolite suite of rock units from ultramafic rocks, through gabbros and sheeted dykes to mafic pillow lavas. As well it includes a metamorphic sole of polydeformed amphibolites and greenschists welded to the stratigraphic base of its ultramafic unit (Williams and Smyth, 1973; Malpas, 1979, Jamieson, 1986). Complete sections are present at Blow-Me-Down and North Arm Mountain where the ophiolite suites are disposed in synclines with northeast-trending subhorizontal axes (Fig. 3.42). At North Arm Mountain the ophiolite suite is unconformably overlain by Llandeilo breccias of the Crabb Brook Group, which is an integral part of the North Arm Mountain massif (Casey and Kidd, 1981).

The tectonic bases of the Bay of Islands massifs are subhorizontal, so that the ophiolite units are truncated structurally at depth in much the same manner as they are truncated erosionally at the surface (Fig. 3.42). Thus the approximately 10 km

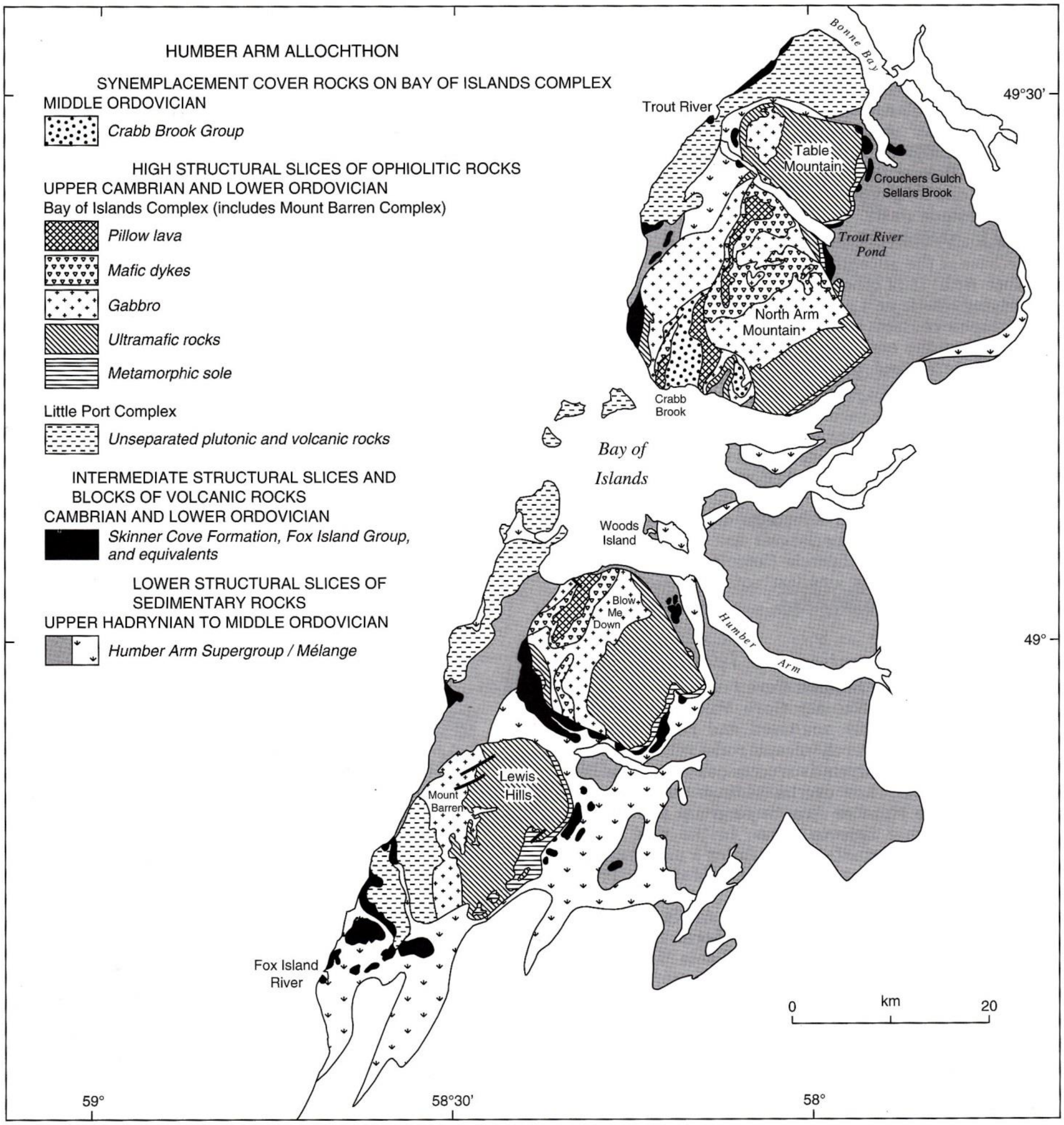

Figure 3.42. Distribution of discrete volcanic blocks and slices within the Humber Arm Allochthon and internal lithic units of the Bay of Islands Complex.

stratigraphic sections of the ophiolite suite occur in structural slices that are less than a kilometre thick (Williams, 1975a, 1985a). The morphological expressions of the massifs refute the idea of steeply dipping basal contacts at North Arm Mountain (Casey and Kidd, 1981) and steeply dipping contacts beneath the Little Port Complex at Trout River (Idleman, 1986).

Trondjemite of the Bay of Islands Complex is dated at 504 ± 10 Ma (Mattinson, 1976) and 505 Ma (Jacobsen and Wasserburg, 1979), which are identical within the limits of analytical error to a date of 508 ± 5 Ma for the Little Port Complex (Mattinson, 1975; Williams, 1975b). More precise U-Pb zircon ages for the Bay of lslands Complex are 485.7 +1.9/-1.2 Ma (Dunning and Krough, 1985) and 484 ± 5 Ma (Jenner et aI., 1991). 40Ar_39Ar ages on hornblendes from the metamorphic sole of the complex are 469 ± 5 Ma (Dallmeyer and Williams, 1975) and 464 ± 9 Ma (Archibald and Farrar, 1976; recalculations after Dunning and Krough, 1985).

The Bay of lslands Complex has prehnite-pumpellyite metamorphism in its basaltic pillow lavas. Local areas of volcanic rocks with zeolite minerals (mainly laumontite) at the top of the pillow lava unit are interpreted as remnants of a zeolite facies zone that once existed above the prehrute-pumpellyite zone. Metamorphism increases to greenschist and low amphibolite facies at the sheeted dyke level and upper parts of the underlying gabbro. This metamorphism is a static hydration without penetrative fabrics.

Old Man's Pond Allochthon

The Old Man's Pond Allochthon lies to the east of the Humber Arm Allochthon and occupies a circular area of about 300 km2 between Bay of Islands and Deer Lake (Fig. 3.39). The two allochthons are less than 10 km apart where they are separated by exposures of the carbonate sequence from Hughes Brook to Goose Arm. The Old Man's Pond Allochthon can be viewed therefore as an erosional outlier of the Humber Arm Allochthon.

The Old Man's Pond Allochthon is surrounded by rocks of the carbonate sequence, except along its southeastern margin where it is faulted against the Hughes Lake Complex. Structures are complex and a post emplacement penetrative cleavage that affects all rocks in the area dips moderately northwest. Contacts between the Old Man's Pond Allochthon and the surrounding carbonate sequence are poorly exposed. Nowhere are the allochthonous rocks above the stratigraphic top of the carbonate sequence; rather different units within the allochthon are juxtaposed with carbonate rocks from different levels of the autochthonous section. Most contacts are marked by valleys, suggesting steep faults. Two isolated occurrences of altered gabbro and serpentinized ultramafic rocks, obviously tectonic blocks, occur at the northern periphery of the allochthon (Williams et al., 1983).

Rocks of the Old Man's Pond Allochthon are assigned to the informal Old Man's Pond group (Williams et aI., 1982, 1983) which is divisible into three formations, namely Canal Pond Otter Brook and Bobbys Brook formations. The Canal Pond formation occupies the northern portion of the allochthon and occurs in a small outlier at its northern periphery. It is an arenaceous unit consisting of grey to green and pink greywackes, grey to white quartzites, quartz pebble conglomerates, and green to purple slates. The Otter Brook formation is the most extensive and underlies the broad central portion of the allochthon. It consists primarily of dark grey slates and siltstones with prominent units of white thick bedded quartzites and quartz pebble conglomerates. The Bobbys Brook formation, along the southeast margin of the allochthon, consists of thin-bedded grey marbles and grey phyllites with local occurrences of oolitic limestone and limestone breccia, some of which contain button algae in their matrices.

The order of stratigraphic units of the Old Man's Pond group has not been worked out within the allochthon the ages of the units are unknown. However, lithic similarities between rocks of the Old Man's Pond group and the Curling Group imply correlation. The Canal Pond formation resembles the Summerside Formation at the base of the Curling Group, the Otter Brook formation is virtually identical to the succeeding Irishtown Formation, and the Bobbys Brook resembles the overlying Cooks Brook Formation. These correlations imply an ascending stratigraphy in the Old Man's Pond group from northwest to southeast. Button algae and local oolitic beds in the Bobbys Brook formation further imply correlation with the Cambrian Penguin Cove and Reluctant Head formations of the carbonate sequence (Williams et aI., 1982, 1983).[6]

Chapter 9 - *Chromite*

The lower stratigraphic levels of the Bay of Islands Complex in the H umber Arm Allochthon, western Newfoundland, contain lenses, layers and dense disseminations of chromite associated with dunite. The principal occurrences include the Springers Hill and Bluff Head deposits in the Lewis Hills massif (Fig. 9.12) and the Stowbridge deposit in the North Arm Mountain massif. Springers Hill deposit, the largest of these, contains an estimated 9100 tonnes of massive and heavily disseminated refractory and chemical grade chromite occurring as discontinuous, massive to disseminated layers-schlieren enveloped by dunite bands and hosted by harzburgite. The main zone is truncated at depth by low angle mylonitic shear zones (Dunsworth et aI., 1986) and the chromitiferous bands have been folded and transposed during ductile deformation within the oceanic domain. The main chromite occurrence at Bluff Head consists ofthin layers of disseminated to massive metallurgical grade chromite hosted by massive dunite (Dahl and Watkinson, 1986; Dunsworth et aI., 1986) whereas the Stowbridge showing consists of a 4 to 10 m wide zone of discontinuous chromite layers in a penetratively deformed dunite-clinopyroxene-dunite and wehrlite. Page and Talkington (1984) reported traces of PGEs in chromitite from the main Springers Hill and Stowbridge deposits.[7]

[6] Ibid., p. 99-108
[7] Ibid., p. 695

Bay of Islands Complex, Humber Arm Allochthon, western Newfoundland

The Bay of Islands Complex is one of the best exposed and most extensively studied ophiolite complexes in Newfoundland. Although widely interpreted as MORB-like, recent geochemical data indicate that pillow lavas in the Bay of Islands Complex include Island arc tholelites, and ultramafic rocks show evidence of derivation from magmas of boninitic affinity. Recent workers have suggested that this ophiolite complex represents a transitional back-arc setting, with the subducting slab influencing magma generation (Elthon, 1991; Jenner et al., 1991). TrondhJeffilte from the Bay of Islands Complex has been dated as 486 +2/-1 Ma (Dunning and Krogh, 1985), suggesting that it is approximately coeval with the Betts Cove Complex.

The Bay of Islands Complex is host to several volcanogenic sulphide occurrences (Fig. 9.19). The largest of these, the York Harbour deposit, consists of numerous small (up to approximately 60 000 tonnes) lenses of brecciated massive chalcopyrite, pyrite, and sphalerite underlain by chalcopyrite- rich stringer stockwork zones (Graham, 1969; Duke and Hutchinson, 1974; MacDougall et al., 1991), which occur along a 350 to 400 m strike length at the contact between two basalt units. The deposits produced approximately 91 000 tonnes of ore prior to 1913 and are estimated to contain reserves of approximately 200 000 tonnes grading 2.68% Cu, 8.25% Zn, 35 to 70 g/t Ag and less than 1.0 g/t Au (MacDougall et al., 1991).[8]

Chapter 10

PALEONTOLOGICAL CONTRIBUTIONS TO PALEOZOIC PALEOGEOGRAPHIC AND TECTONIC RECONSTRUCTIONS (G.S. Nowlan and R.B. Neuman)

INTRODUCTION

Fossils provide essential information for the determination of prior locations of the components of ancient orogenic belts such as the Appalachians. In this chapter we review the record of fossils from the Canadian Appalachians that, together with those from the Appalachians in the United States (Neuman et al., 1989), assist in determining the paleogeographic and tectonic evolution of this orogenic system. The rocks of the Canadian Appalachians are more fossiliferous than their counterparts in the United States because they are generally less deformed and metamorphosed, and because there are important differences in the geology of the orogenic belt in the two countries.

Paleontological studies in Canada have long contributed to the development of ideas on the history of the orogen. The Cambrian faunas of the Avalon Zone in Newfoundland and southern New Brunswick, and correlatives in northwestern Europe were assigned

[8] Ibid., p. 703-705

by Walcott (1891) to an "Atlantic Coast Province", considered by him to be different from those of the "Appalachian Province" elsewhere in the Canadian and U.S. Appalachians. Following the introduction of the idea of continental drift (Wegener, 1928), Grabau (1936) explained the similarity of the stratigraphy and faunas of eastern North America and northwestern Europe by deposition in contiguous synclines that were parts of his hypothetical "Pangea." After the general acceptance of continental drift, Wilson (1966) proposed that a Paleozoic "proto-Atlantic Ocean" preceded the present Atlantic. In his view the Atlantic Cambrian faunas populated the eastern margin of the "proto-Atlantic Ocean", contemporaneous Pacific faunas populated its western margin, and the complex area of the northern Appalachians between them resulted from the post-Cambrian convergence of the opposite margins of that old ocean basin. With the appreciation that the orogen consists of a collage of suspect terranes (discrete crustal blocks whose paleogeography cannot be definitely ascertained; Williams and Hatcher, 1983), paleontological information becomes increasingly important in the identification of such terranes as has been demonstrated in the Cordillera of western North America (Jones et al., 1977).

Paleontology can be used for such purposes because fossils have the potential to yield information concerning ancient habitats as well as ages. Of the several kinds of discriminations that can be made, those that indicate paleoclimates and former geographic isolation are particularly important for determination of paleogeography. Tropical biotas and their physical environments can be distinguished from boreal biotas of high latitudes (realms); within these realms are areas that contain variously distinctive biotic associations, the products of isolation by barriers to biotic exchanges; the term "provinces" is commonly applied to the more important of these.

Comparison of modern and ancient realms and provinces requires the comparison of environmentally similar biotas; in aquatic settings, for example, variable factors include water depth, sediment supply, and salinity. Different organisms reflect different aspects of their environments; those that live out their adult stages in shallow waters attached on or near the seafloor (such as brachiopods and corals) are more likely to reflect the temperatures of that water and its neighbouring landmasses than are mobile or free-swimming organisms such as many molluscs and trilobites, pelagic (floating) organisms such as many graptolites, and eurybathic organisms such as conodonts.

The literature of paleobiogeography consists largely of works concerned with the distribution of constituent taxa of specific groups of organisms; many of these papers are accompanied by small-scale maps. This contribution is based on that literature, on the current knowledge of the authors, and discussions with their colleagues. The main outlines of the occurrence and distribution of Phanerozoic fossils on the larger continental blocks is reasonably well known, but those of the Precambrian are poorly known, as are those of crustal fragments, or the suspect terranes that constitute the

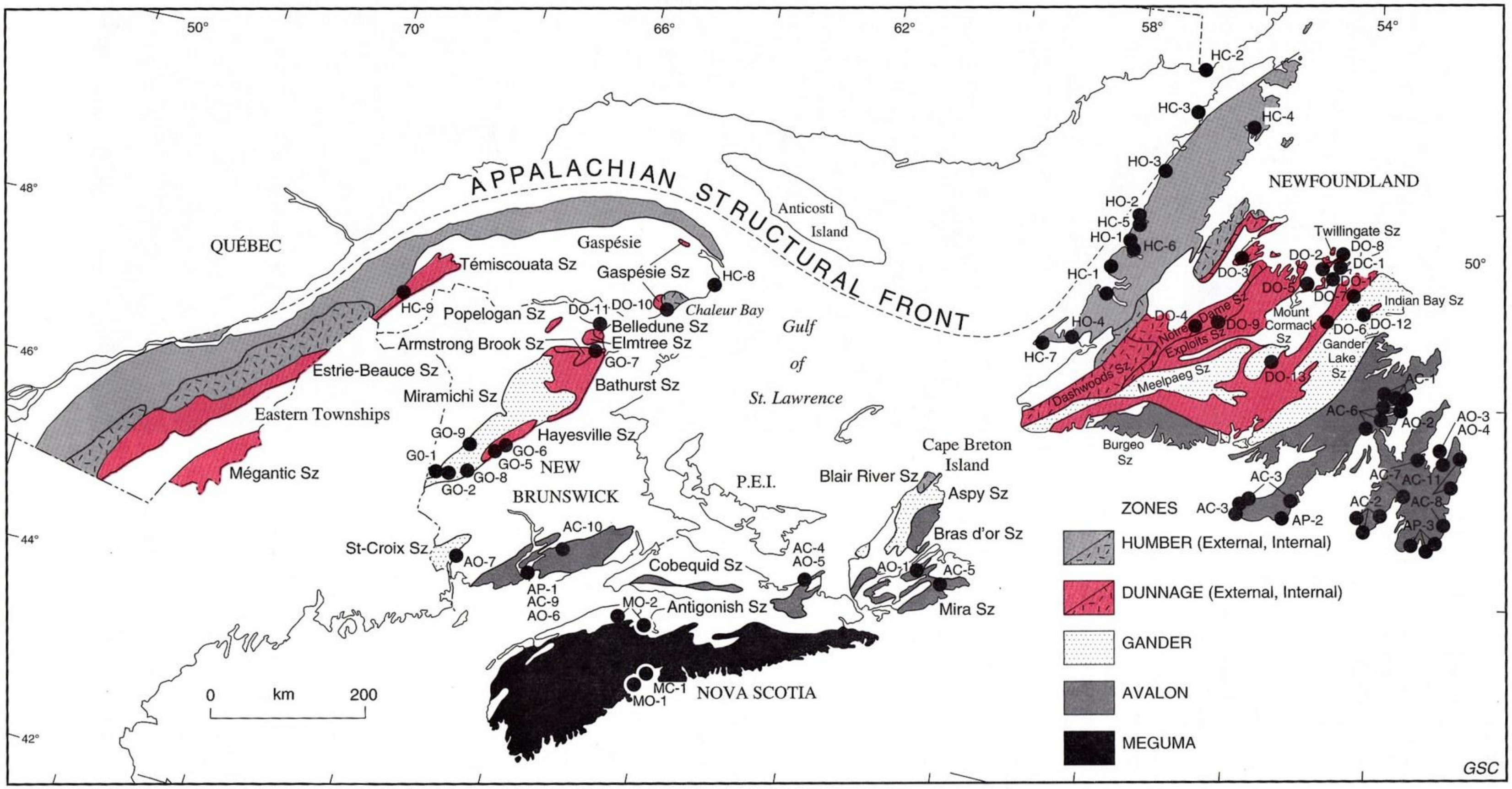

Figure 10.1. Late Precambrian-early Paleozoic (Cambrian-Middle Ordovician) outcrop areas and zonal and subzonal subdivision of the Canadian Appalachian region with locations of fossil localities discussed in text. Localities coded as to zone as follows: A – Avalon Zone; D – Dunnage Zone; G – Gander Zone; H – Humber Zone; M – Meguma Zone; and as to age as follows P – Precambrian, C – Cambrian, O – Ordovician. A combination of two letter codes followed by a number is an unique identifier of zone, age, and location.

Appalachians. Relevant data are presented here chronologically in the context of the lithotectonic zones, belts, and basins adopted for this volume. Interpretations that follow are largely consistent with commonly accepted reconstructions, as the reconstructions incorporate many of these interpretations.

Fossils that occur throughout the Appalachian Orogen have useful application in the reconstruction of its development. Stromatolites in carbonate rocks provide information on the geographic setting of some of the oldest (middle Proterozoic Helikian, >800 Ma) rocks of the Avalon Zone. Late Proterozoic Hadrynian (900-570 Ma) imprints of soft-bodied organisms, trace fossils, and enigmatic shelly fossils, also in the Avalon Zone, suggest the outlines of a later ancient geography. The "Atlantic realm" Cambrian fauna is now known to characterize the Avalon Zone, distinctive from the "Pacific realm" ofthe Humber miogeocline, but the few Cambrian fossils from the intervening terranes have yielded little information. Increased organic diversity and abundance beginning with the Ordovician, together with changing geological patterns and diverse marine habitats provide abundant materials for paleogeographic assessments throughout the orogen. Marine deposition was considerably reduced after the Acadian Orogeny, and the Middle Devonian and Carboniferous record is based largely on nonmarine faunas and floras in isolated successor basins. …

The oldest fossils in the Appalachians are stromatolites in rocks of the Avalon Zone in New Brunswick and Newfoundland. … The stromatolites and other evidence of shallow-water deposition suggest correlation of the Green Head with the shallow-water sequence of the Grenville Group of southern Ontario and Quebec that contains similar stromatolitic limestone (Currie, 1987), a correlation that leads to the inference that the basement of the Avalon Zone is a rifted fragment of Grenville crust. …

Ediacaran fossils have not been found in upper Proterozoic rocks (Hadrynian equivalents) in the Humber Zone. …

The trace fossil Oldhamia occurs throughout the world in rocks of Cambrian and possibly late Proterozoic (Hadrynian) age that were probably deposited in deep water (Hofmann and Cecile, 1981). It has long been known to occur at several places in the northern Appalachians of the United States, but there were no confirmed occurrences in the Canadian Appalachians until its discovery in abundance at several places in the Blow Me Down Brook Formation of western Newfoundland. Its presence here led to interpretation of those rocks as having been derived from the rifted margin of North America (HC-l; Lindholm and Casey, 1989,1990).

Trilobites, the most common, abundant and widespread macrofossil in Cambrian rocks, were major factors in Wilson's (1966) prescient identification of exotic terranes in the Appalachians. Continuing investigations amply confirm Walcott's (1891) distinction of "Atlantic" and "Pacific" faunal realms, and the occurrences of assemblages of Cambrian trilobites and other fossils diagnostic of these faunal realms can now be described in terms of the currently accepted lithotectonic zones of the Appalachians. …

A major breakthrough in the understanding of the Humber Zone came with the interpretation of deep-water Cambro-Ordovician rocks in western Newfoundland as Taconic klippen that overlie shallow-water carbonates of the same age (Rodgers and Neale, 1963). Studies of the Newfoundland Humber Zone fossils of Arenig-Llanvirn age, together with sedimentology of the rocks that contain them, defined final stages of the continental shelf (St. George Group; Ulrich and Cooper, 1938; Whittington and Kindle, 1969; Barnes and Tuke, 1970; Flower, 1978; Stouge, 1982; Boyce et al., 1988), its margin, and its pene-contemporaneous erosion/deposition products (HO-2; Cow Head Group; James and Stevens, 1986; Pohler et al., 1987; Ross and James, 1987). The foundering and fragmentation of the shelf is recorded in the rocks of the Table Head Group (Klapp a et al., 1980) that contain a more diversified assemblage of benthic fossils (HO-3; Whittington and Kindle, 1963; Whittington, 1965; Ross and Ingham, 1970; Ross and James, 1987) that together with their conodonts of both North American and North Atlantic provinces (Stouge, 1984) record deposition in progressively deepening water prior to emplacement of the Humber Arm Allochthon and other manifestations of Taconic Orogeny. Trilobites of Avalon Zone affinity have been reported from continental slope deposits where they occur with brachiopods of eastern North American affinity (Dean, 1985).[9]

DISCUSSION AND CONCLUSIONS

Paleontologists have been important contributors to the present knowledge of the geology of the Appalachian Orogen and to evolution of ideas concerning its development because fossils provide information that can be used in assessing the paleogeography and tectonics of an orogenic belt. Fossil assemblages provide information on the age of the enclosing sediments, past climates, water depths, and paleoenvironments. Global patterns of fossil distribution playa leading role in the recognition of paleocontinental masses and their boundaries, as well as the proximity of continents through time. Thus paleontology is one of several disciplines drawn upon for the construction of paleogeographic maps (Ziegler et aI., 1979). At a more local scale the juxtaposition of different biofacies may permit the estimation of horizontal displacement. Some fossils, particularly microfossils such as conodonts and palynomorphs, may be treated as inanimate objects that respond to physical parameters such as temperature and thus provide information on depth of burial, proximity of plutons, and other important aspects related to tectonic development.

[9] Ibid., p. 817-823

Data derived from fossils and their distribution has several advantages that are important for their use in interpretation of paleogeographic, structural or tectonostratigraphic problems. Foremost among these is the fact that fossil data are independent of tectonic models (Fortey and Cocks, 1986). They can therefore provide impartial tests for tectonic hypotheses, and may themselves lead to the formulation of tectonic hypotheses. Secondly, the amount of detail available in paleontological information is considerable because of the complexity of the organisms that provide the material. Identification of a trilobite or conodont is less likely to be in error than an analytical test performed on the enclosing rock, because the amount of information available from their complex morphology provides many constraints on their interpretation. Furthermore, errors made are more likely to be recognized because the fossils are illustrated and additional material can be collected. Thirdly, the fossil record provides a history of biological evolution, the nature of which is considerably different from the physical parameters employed in other aspects of tectonic analysis, mainly because evolution has proceeded in certain identifiable directions. The importance of each fossil specimen can therefore be related to the evolution of successive assemblages, the development of which is related to biological and environmental, rather than physical factors. It is therefore not surprising that paleontology has served as a catalyst to new interpretations of the Appalachian Orogen and also as a corroborator of well-established hypotheses.

It is the value of fossils as time indicators that allows for the fundamental observation that the Appalachian Orogen developed through Paleozoic accretion to the continental nucleus of North America. Knowledge of the relative age of strata in the component parts of the orogen has been important for initial recognition and characterization of those parts and has elucidated the timing of events responsible for their assembly. For example, recognition that the Cow Head Group contains Middle Cambrian to Middle Ordovician fossils and that it overlies a sequence of strata of similar age permitted the revolutionary recognition of Taconic klippen in western Newfoundland (Rodgers and Neale, 1963), an idea that had a profound effect on the development of subsequent tectonic models. The value of biostratigraphy for determining temporal relationships has been critical to understanding of the timing of Appalachian events. For example, the end of the Taconic Orogeny in Newfoundland is known from the Caradoc age of the Long Point Group which directly overlies allochthonous strata. Similarly post-Acadian units have been dated as Late Devonian.

Perhaps the earliest application of paleontology to understanding of the Appalachian Orogen is the use of provincialism in Cambrian trilobites to demonstrate the distinctiveness of the Humber and Avalon zones. Faunal evidence played a role in Schuchert's (1923) recognition of geanticlines separating the St. Lawrence (Humber) and Acadian (Avalon) geosynclines, a model that was influential for many years in discussions of the Appalachian Orogen. The development of models of geosynclinal development (e.g. Kay, 1951) relied heavily on the paleobiogeographic and paleoenvironmental implications of fossils. For many years, paleontologists pointed out the similarity of Avalon Zone faunas to those of Europe (e.g. Grabau, 1936; Hutchinson, 1962). Faunal differentiation across the orogen also contributed to Williams' (1964) idea of the two-sided symmetry of the Appalachian Orogen, which in turn, led to the definition of the proto-Atlantic Ocean by Wilson (1966). In Wilson's model the Cambrian sequences of the Atlantic province were remnants of the land that lay on the eastern margin of the proto-Atlantic Ocean (Avalon Zone) and the complex area between Atlantic province faunas (Dunnage and Gander zones) and those of the eastern part of North America (Humber Zone) resulted from a post-Cambrian convergence of the two sides of an ancient ocean. In fact, Wilson's (1966, p. 676) opening paragraph draws attention to the importance of faunal realms by quoting a passage from Hutchinson (1962) in which he noted the difficulty of correlation of strata in the Avalon Peninsula of Newfoundland with those in the rest of North America based on trilobites.

It is now clearly established that Cambrian fossils show strong biogeographic control in the Appalachian Orogen with trilobites of one faunal realm (Atlantic) characterizing the Avalon Zone on the eastern margin of Iapetus and another (Pacific) characterizing the Humber Zone on the western margin of Iapetus. Species characteristic of the Avalon Zone were also capable of trans-Iapetus migration from time to time. Faunas from the Dunnage Zone are sparse but provide useful information on the extent of the Laurentian (North American) margin in the Cambrian and in some cases exhibit endemism that may be the result of development on offshore shoals or oceanic islands developed in the same climatic belt.

The faunal differentiation between the two sides of the Iapetus Ocean diminishes from the Cambrian to the Ordovician, although provincially distinct faunas continue because the ocean remained a formidable barrier to migration for many groups. Early to Middle Ordovician benthic trilobite and brachiopod faunas occurring around the margins of North America (Humber Zone) are quite distinctive from those in the Iapetus Ocean. …

Comparison of Ordovician rocks and fossils of the Appalachian lithotectonic zones with those of the British-Irish Caledonides strongly supports the existence, and helps define the extent, of the Iapetus Ocean (Williams, 1978; Harper and Parkes, 1989). This is apparent from comparison of the distribution of rocks and fossils in the North American Appalachian and British-Irish Caledonian orogens. In the Appalachians the east-to-west progression from the Laurentian continental margin (Humber Zone/Toquima-Table Head Province) through those of mid-oceanic settings (Dunnage Zone/Celtic Province) to peri-Gondwanan sites (Gander Zone/Celtic Province) compares well with the Caledonian west-to-east progression from the Gondwanan continental margin (Anglesey Zone-Rosslare terrane/Celtic Province), across a continental margin volcanic arc (Bellewstown and Grangegeeth terranes/Celtic Province) (Murphy, 1987; Harper et a1., 1990), to a fragment of the Laurentian continental margin (northern Scotland) and a marginal volcanic arc (County Mayo, Ireland) (Hebrides and Northwestern terranes/Toquima-Table Head Province). Although these and other comparisons are consistent in their support of the existence of the Iapetus Ocean, the outline of its shores and the position of islands within it can be only vaguely estimated, and its bathymetry remains largely unknown. …

A suspect terrane is an internally homogeneous belt of strata characterized by similar stratigraphy, structure, tectonic history, mineral deposits, paleomagnetic signatures and, above all, faunas. The faunas not only serve to distinguish the terrane but they are the keys in assessing its origin from the points of view of age, environment of deposition, and possible paleogeography. …

The value of paleontological contributions to paleogeographic and tectonic reconstructions of the Appalachian orogen is immense. Many exciting new discoveries remain to be made.[10]

Chapter 11 - SUMMARY AND OVERVIEW (by Harold Williams)

PREAMBLE

This chapter summarizes, and repeats without referencing, information presented in preceding chapters. …

The summary follows the systematics introduced earlier, treating all rocks according to the four broad temporal divisions; lower Paleozoic and older rocks, middle Paleozoic rocks, upper Paleozoic rocks, and Mesozoic rocks. The rocks of each temporal division are subdivided into spatial divisions. Thus, the lower Paleozoic and older rocks are separated into the Humber, Dunnage, Gander, Avalon, and Meguma zones and sub zones as depicted in Figure 11.1. The middle Paleozoic rocks are separated into belts: Gaspe, Fredericton, Mascarene, Arisaig, Cape Breton, and Annapolis for the mainland; and Clam Bank, Springdale, Cape Ray, Badger, La Poile, Botwood, and Fortune for Newfoundland (Fig. 11.2). The upper Paleozoic rocks define a number of basins, and Mesozoic rocks define graben (Fig. 11.3). A compilation and classification of volcanic rocks for the Canadian Appalachian region is provided for comparisons with other divisions (Fig. 11.4).

The Canadian Appalachians provide an excellent example of an orogen that built up through accretion and eventual continental collision. In this model of a typical Wilson cycle, the Humber Zone is the Appalachian miogeocline or continental margin of

[10] Ibid., p. 832-835

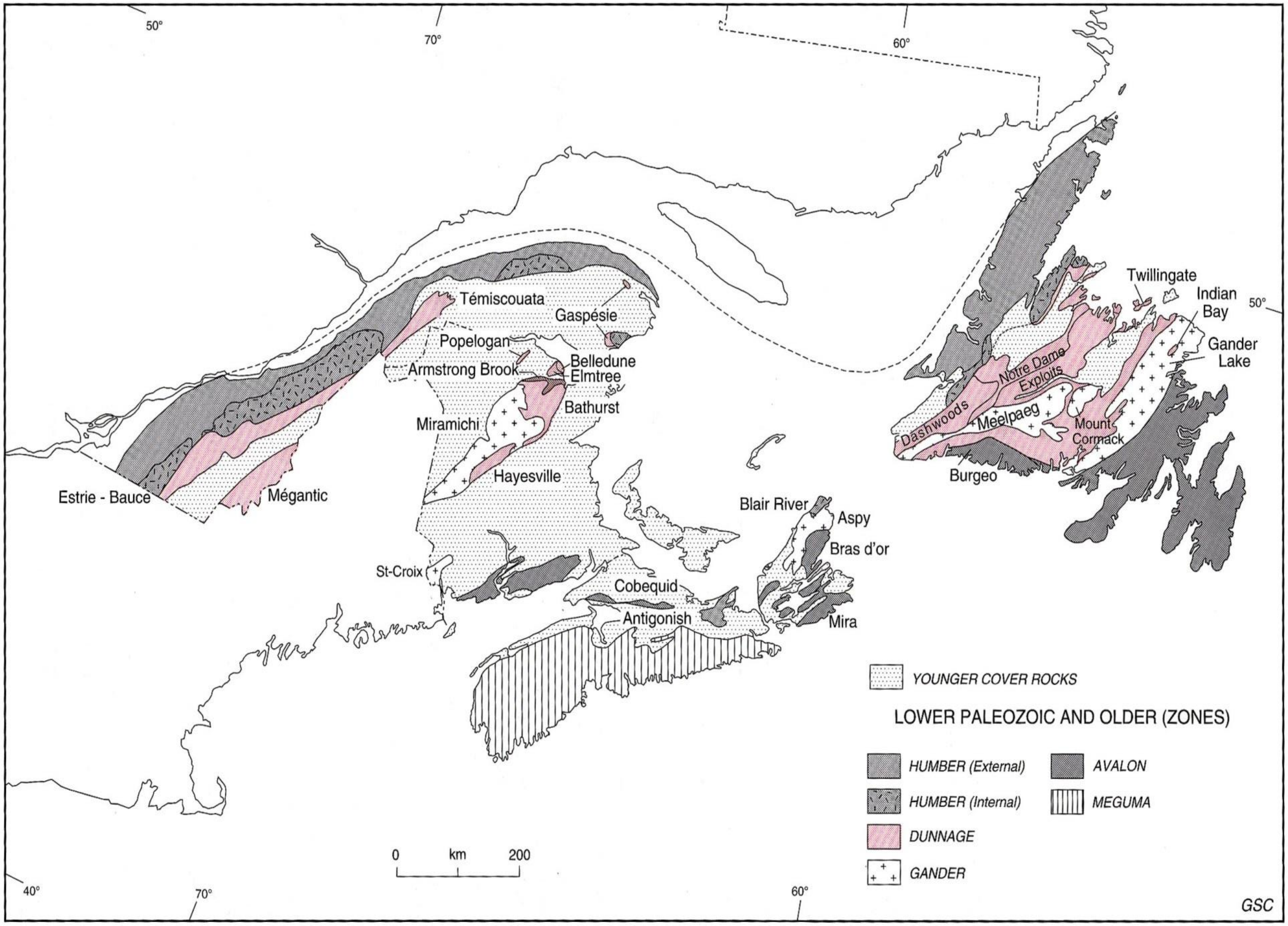

Figure 11.1. Zones and subzones of the Canadian Appalachian region.

LEGEND

ATLANTIC CYCLE
Passive margin rift

12	*Upper Triassic to Lower Jurassic LREE-enriched tholeiitic basalts*

APPALACHIAN CYCLE
Post-continental collision rift

11	*Upper Devonian to Carboniferous LREE-enriched tholeiitic basalts, alkalic basalts, and rhyolites; minor trachyandesites, trachytes, and peralkaline rhyolites*
10	*Silurian to Lower Devonian LREE-enriched tholeiitic to transitional alkalic basalts, calc-alkaline andesites, dacites, rhyolites, and minor peralkaline rhyolites*

Oceanic island

9	*Lower Ordovician alkalic to transitional tholeiitic basalts*

Continental margin back arc

8	*Lower to Middle Ordovician rhyolites and dacites; minor tholeiitic and alkali basalts*

Intra-oceanic and continental margin volcanic arc/rifted arc

7	*Upper Cambrian to Lower Ordovician LREE-enriched, HFSE-depleted tholeiitic basalts overlain by LREE-enriched tholeiitic and alkalic basalts; abundant andesites, dacites, and rhyolites in mature arcs*

Sub-arc ophiolite/island arc

6	*Lower Ordovician ultramatic cumulates, gabbros, sheeted dykes, and LREE-HFSE-depleted tholeiitic basalts and boninites overlain by LREE-enriched tholeiitic basalts; minor andesites and dacites*

Back-arc ophiolite

5	*Lower Ordovician ultramafic cumulates, gabbros, sheeted dykes, and LREE-depleted tholeiitic basalts*

Passive margin rift

4	*Upper Hadrynian to Lower Cambrian tholeiitic and alkalic basalts, minor peralkaline rhyolites*

AVALONIAN CYCLE
Post-arc rift

3	*Upper Hadrynian-Early Cambrian LREE-enriched tholeiitic basalts, alkalic basalts, and rhyolites; minor peralkaline rhyolites (565-540 Ma)*

Ensialic volcanic arc/back arc

2	*Upper Hadrynian LREE-HFSE-depleted tholeiitic basalts, slightly LREE-enriched tholeiitic basalts, calc-alkaline basalts, andesites, dacites, and rhyolites (680-565 Ma)*

Oceanic crust

1	*Lower Hadrynian alkali basalts overlain by LREE-depleted tholeiitic basalts (760 Ma)*

Figure 11.4.

Laurentia, and outboard zones are accreted parts of the orogen or suspect terranes. These zones are the fundamental divisions upon which all younger rocks and events are superposed. Rocks and relationships are described first for the Humber Zone, then successively outboard zones. The earliest interaction among zones occurred in the Ordovician with accretion of western parts of the Dunnage Zone to the Humber Zone and amalgamation of eastern parts of the Dunnage Zone to the Gander Zone. Middle Paleozoic Belts comprise mainly cover sequences, but some belts are confined to zones (Annapolis Belt above Meguma Zone) or parts of zones (Badger Belt above eastern Dunnage Zone), and others occur at zone boundaries. There is no evidence that the Avalon and Meguma zones were incorporated into the orogen before the Silurian-Devonian, and open marine tracts probably existed in the Newfoundland Dunnage Zone after Ordovician deformation of bordering areas. The arrival of the Avalon and Meguma zones apparently coincided with important middle Paleozoic tectonism. Upper Paleozoic basins developed upon the accreted orogen. Most of their rocks are terrestrial and undeformed, but deformation is important locally and a few granite batholiths are dated isotopically as late Paleozoic. Graben are treated last as their rocks are unconformable upon deformed upper Paleozoic rocks. The graben are related to rifting that initiated the Atlantic Ocean.

These accounts are followed by geophysical characteristics of the orogen and its offshore extensions, paleontology, metallogeny, and a summary of zonal linkages and accretionary history, in an attempt to explain orogenic development.

ANCESTRAL NORTH AMERICAN MARGIN: HUMBER ZONE

The lower Paleozoic rocks of the Humber Zone are coextensive with the cover rocks of the St. Lawrence Platform. Its western limit is the Appalachian structural front which separates the deformed rocks of the orogen from equivalent undeformed rocks of the St. Lawrence Platform. Its eastern boundary with the Dunnage Zone is the Baie Verte-Brompton Line, a steep structural zone marked by discontinuous ophiolite occurrences. An external division and internal division of the Humber Zone are defined on structural and metamorphic contrasts (see Fig. 3.1).

External Humber Zone

The stratigraphic and structural elements of the external Humber Zone fit the model of an evolving continental margin. It began with: (a) rifting of a Grenville crystalline basement and deposition of upper Precambrian to Lower Cambrian clastic sedimentary and volcanic rocks with coeval dyke swarms and carbonatite intrusions, the rift stage, (b) deposition of a Cambrian-Ordovician mainly carbonate sequence, the passive margin stage, (c) deposition of Middle Ordovician clastic rocks of outboard derivation that transgress the carbonate sequence and are the first intimation of offshore disturbance, the foreland basin stage, and (d) emplacement of allochthons in the Middle Ordovician that are a sampling of rocks from the continental slope and rise and adjacent oceanic crust, the destructive stage. Any of these rocks can be used to define the Humber Zone. Naturally, the more elements recognized, the sharper the definition. Rocks of the internal Humber Zone are polydeformed and metamorphosed so that their stratigraphic and sedimentological records are less informative. The available data suggest deposition on the continental slope and rise, mainly upon a continental Grenville basement, but possibly linked to an oceanic basement in Newfoundland. The internal Humber Zone is important for its structural and metamorphic records of the destruction of the continental margin. These are in general agreement with the stratigraphic and sedimentological records of the external Humber Zone.

Rift stage

Basement rocks of the Humber Zone are mainly gneisses, schists, granitoids, and metabasic rocks that are part of the Grenville Structural Province of the adjacent Canadian Shield (Fig. 3.2). Most metamorphic and plutonic ages are between 1200-1000 Ma with some about 1500 Ma. The basement rocks occur in both external and internal divisions of the Humber Zone. Occurrences in the external Humber Zone are restricted to western Newfoundland. These are the Long Range Inlier, the largest of the entire Appalachian Orogen, and the Belle Isle and Indian Head inliers to its north and south, respectively. Other small faulted examples occur nearby at Ten Mile Lake and Castors River. Internal Humber Zone occurrences in Newfoundland are the East Pond Metamorphic Suite at Baie Verte Peninsula, the Cobble Cove Gneiss at Glover Island of Grand Lake, the Steel Mountain Inlier south of Grand Lake, and possible basement rocks of the Cormacks Lake Complex of the Dashwoods Subzone in southwestern Newfoundland. …

Occurrences in the external Humber Zone, such as the Belle Isle and Indian Head inliers, form the cores of northeast-trending anticlines. The Long Range Inlier and the smaller Ten Mile Lake and Castors River inliers were brought to the surface by steep reverse faults or west directed thrusts. The basement rocks are overlain by upper Precambrian or Lower Cambrian cover rocks with preserved unconformable relationships in most places. Occurrences in the internal Humber Zone of Newfoundland are thrust slices or structural culminations in high-grade metamorphic areas. …

Rocks of basement inliers are mainly of igneous protolith with minor marble, quartzite, and metaclastic rocks. The extensive Long Range Inlier has mainly quartzfeldspar gneisses and granites. In the north, the rocks are biotite-quartz-feldspar gneiss and hornblende-biotitequartz-feldspar gneiss with lesser quartz-rich gneiss, politic schist, amphibolite, and calc-silicate gneiss. In the south, they are pink to grey quartz-feldspar gneiss, quartzrich gneiss, pelitic to psammitic schist, amphibolite, and minor marble and calc-silicate rock. Small mafic plutons, now amphibolite, hypersthene amphibolite, metaperidotite, and metadiorite cut the leucocratic gneisses. The mafic plutons are cut by distinctive megacrystic foliated to massive granites of at least two suites. Pegmatites that occur in most outcrops probably relate to the granites. Northeast-trending diabase dykes of the Long Range Swarm cut all other rocks. …

Precambrian regional metamorphism is uniformly high grade. Amphibolite to granulite facies in the northern part of the Long Range Inlier was accompanied by the emplacement of mafic plutons. …

In the external Humber Zone, retrograde metamorphism affected the Long Range, Belle Isle, and Indian Head inliers. It occurred in at least two phases in the Long Range Inlier. The first preceded the emplacement of the Long Range mafic dykes. The second postdated the dykes and related volcanic rocks and increases in intensity from west to east. Relationships in the Belle Isle Inlier indicate that late Precambrian faulting affected coarse clastic cover rocks before the emplacement of the Long Range dyke swarm. This implies rift-related deformation and Precambrian retrogression related to extensional tectonism. The second metamorphic event is Paleozoic.

Upper Precambrian-Lower Cambrian clastic sedimentary and volcanic rocks record the rifting stage of the Laurentian margin and initiation of the Appalachian cycle (Fig. 3.11). They are mainly terrestrial red arkosic sandstones and conglomerates, bimodal volcanic rocks, marine quartzites, and greywackes. Abrupt changes in thickness and stratigraphic order are characteristic and these features contrast with uniform stratigraphy, constant thickness and broad lateral continuity of overlying Lower Cambrian marine formations (Fig. 3.14). Extensive swarms of mafic dykes are in places coeval with mafic flows. Isotopic ages of volcanic rocks, mafic dykes, and related small anorogenic plutons range between 620 and 550 Ma. Rocks and relations are well-preserved in the external Humber Zone of Newfoundland and locally in the internal Humber Zone of Newfoundland and Quebec. Correlatives are represented in the basal parts of stratigraphic sections that make up the sedimentary slices of Taconic allochthons. Metamorphosed clastic rocks and mafic volcanic rocks and dykes, now amphibolites, that occur in basal parts of stratigraphic sections in the internal Humber Zone are also correlatives.

Examples in southeast Labrador, just outside the Appalachian deformed zone, are virtually continuous with mildly deformed rocks of the nearby orogen in Newfoundland...

Three formations are recognized among the upper Precambrian-Lower Cambrian clastic sedimentary and volcanic rocks in the external Humber Zone of western Newfoundland. A basal clastic unit (Bateau Formation) is overlain by mafic volcanic rocks (Lighthouse Cove Formation), in turn overlain by red arkosic sandstones (Bradore Formation). The formations are transgressive northwestward with all units locally resting on Grenville basement….

In southeast Labrador, the trends of the late Precambrian-Early Cambrian Iapetus margin and Mesozoic Atlantic margin are almost perpendicular. The distribution of Iapetan clastic dykes and outliers of horizontal cover rocks indicate that the present exposed surface of the Canadian Shield was the surface at the time of Iapetan rifting. …

Passive margin stage

A Cambrian-Ordovician carbonate sequence occurs above the rift related rocks of the Humber Zone or it directly overlies Grenville basement. These rocks also extend across the St. Lawrence Platform. They are mainly limestones and dolomites with lesser siliciclastic rocks that range in age from Early Cambrian to Middle Ordovician. They record the development of a passive continental margin, and the beginning of Taconic Orogeny at the margin. The Cambrian-Ordovician carbonate sequence is the most distinctive and characteristic element of the Humber Zone. The stratigraphic analysis of the platformal rocks and equivalent continental slope/rise facies in Newfoundland is as sophisticated as that of any continental margin analysis, regardless of age.

The rocks are preserved best in western Newfoundland throughout the external Humber Zone and nearby (Fig. 3.15). They are mainly hidden by Taconic allochthons along the Quebec segment of the Humber Zone. Small examples occur at Gaspesie and more deformed examples occur in the Sutton Mountains and Lake Champlain area to the west. The rocks occur in the St. Lawrence Lowlands west of Quebec City, and they occur at Mingan Islands on the north shore of the St. Lawrence River.

In Newfoundland, the carbonate sequence is divided into the Labrador, Port au Port, St. George, and Table Head groups. …

Present exposures of the carbonate sequence were part of a continental margin platform, the landward portion of which is preserved only in Quebec. …

Carbonate sedimentation occurred in two tectonic settings: (1) trailing passive margin sedimentation from the late Early Cambrian to the late Early Ordovician, and (2) Middle Ordovician carbonate sedimentation along the cratonic edge of the Taconic foreland basin. The Early Cambrian passive margin history in western Newfoundland is preserved in the upper part of the Labrador Group (Forteau and Hawke Bay formations) and comprises mixed siliciclastic and carbonate marine strata laid down above nonmarine to nearshore sandstones (Bradore Formation, early rift facies). …

Foreland basin stage

Clastic rocks above the carbonate sequence represent a major reversal in the direction of sediment supply to the Humber Zone, from the North American continent to outboard elements of the Dunnage Zone. Autochthonous and allochthonous examples occur in the Humber Zone, and the rocks extend beyond the western limit of Appalachian deformation to the St. Lawrence Platform (Fig. 3.27). The clastics contain recycled quartz grains, fresh and weathered feldspars, a variety of sedimentary rock fragments, mafic to felsic volcanic rock fragments, local serpentinite grains, and a heavy mineral suite containing green and green-brown hornblende, hypersthene, and chromite.

The autochthonous flysch lies stratigraphically above the Cambrian-Ordovician carbonate sequence, except where original relationships have been obscured by thrusting. Thicknesses range from about 250-4000 m, and ages range from Llanvirn in Newfoundland to Caradoc and Ashgill in Quebec.

Allochthonous flysch lies stratigraphically above Lower Ordovician shales and limestone breccias, interpreted as continental slope and rise deposits. These occurrences range in thickness from about 200-2500 m, and in age from Arenig to Caradoc.

In western Newfoundland, autochthonous flysch overlies the Table Head Group, a predominantly shallow-water limestone unit. …

In western Newfoundland, allochthonous flysch is found in lower structural slices of the Humber Arm Allochthon in the Port-au-Port area, in the Bay of Islands area, and north of Bonne Bay where it overlies limestone conglomerates at the top of the Cow Head Group. The age of the flysch is Arenig to Llanvirn. Sole markings indicate derivation from the north to northeast. …

The transition from carbonate platform to deep foreland basin in the autochthon of western Newfoundland includes a complicated record of platform collapse, fault movements, and derivation of limestone boulder conglomerates from the crests of fault blocks. …

Destructive stage

Taconic allochthons, above the Middle Ordovician clastic unit of the autochthonous section, are a spectacular structural feature of the external Humber Zone. Contorted marine shales, sandstones, and melanges in lower structural slices contrast sharply with the underlying mildly deformed carbonate sequence. Volcanic rocks and ophiolite suites in higher slices are particularly out-of-context with respect to Grenville basement and its cover rocks. Allochthons are absent or poorly defined in internal parts of the Humber Zone, except for occurrences of small disrupted ophiolitic rocks and melanges.

The best known examples in western Newfoundland are the Humber Arm and Hare Bay allochthons. The Old Man's Pond Allochthon is an eastern outlier of the Humber Arm Allochthon. The Southern White Bay Allochthon is a small occurrence on the east side of the Great Northern Peninsula. …

The western edge of the transported rocks is Logan's Line, first defined at Quebec City and traceable southward to Vermont. Its northern course is covered by the St. Lawrence River, but it is exposed near the tip of Gaspésie. In Newfoundland, Logan's Line is discontinuous and defined by the leading edges of the Humber Arm and Hare Bay allochthons (Fig. 3.38).

The Humber Arm and Hare Bay allochthons of western Newfoundland are described as they exhibit a variety of igneous and metamorphic rocks in upper structural slices that are rare or absent in most Appalachian examples. Especially well-known are the ophiolite suites and metamorphic soles of the Bay of lslands Complex in the Humber Arm Allochthon and the St. Anthony Complex of the Hare Bay Allochthon. A complete stratigraphy from late Precambrian to Early Ordovician has been deciphered among sedimentary rocks of the Humber Arm Allochthon and some facies, such as the Cambrian-Ordovician Cow Head breccias, are renowned for their sedimentologic and paleontologic characteristics. Gros Morne National Park, situated in the Humber Zone of western Newfoundland, was declared a World Heritage Site in 1987, mainly because of its rocks and geological relationships.

The Humber Arm (Fig. 3.39) and Hare Bay (Fig. 3.43) allochthons occupy structural depressions. The Humber Arm Allochthon is surrounded to the east by the Cambrian-Ordovician carbonate sequence and separated from the Hare Bay Allochthon by a major structural culmination that exposes Grenville basement of the Long Range Inlier. These structural depressions and culminations are later than the emplacement of the allochthons. However, conodont colouration indices in underlying and surrounding rocks indicate that the allochthons were never much larger than their present areas. Conspicuous carbonate slivers occur beneath the Bay of Islands Complex and above melange of lower structural levels. They are gently dipping, upright sections of thick bedded, white and grey limestones and dolomites of the St. George and Table Head groups. These are interpreted either as integral parts of the allochthon, entrained during Middle Ordovician assembly and transport, or features of later gravity collapse and transport of ophiolites and underlying carbonates across lower levels of the already assembled allochthon.

Melanges are extensively developed among sedimentary rocks of the Humber Arm Allochthon (Fig. 3.39). They consist mainly of greywacke, quartzite, dolomitic shale, chert, and limestone blocks in a black, green, and red scaly shale matrix. Volcanic blocks are most common in structurally higher melanges and some contain a sampling of ophiolitic blocks in a greasy green serpentinite matrix. Volcanic blocks range in diameter from a few metres to a few kilometres. Blocks beyond a kilometre across are oblate to discoidal and the largest are the flat ophiolite massifs of the Bay of Islands Complex. There is every gradation between the smallest equidimensional blocks and the largest structural slices of the allochthon.

Rocks of lower sedimentary slices of the Humber Arm Allochthon are mainly eastern deeper water correlatives of the passive margin carbonate sequence, but relationships at deposition are nowhere preserved. The oldest allochthonous clastic rocks are correlated with autochthonous rift-related clastics. They were derived from a crystalline Grenville source before and during continental breakup and before the development of the carbonate sequence. Volcanic rocks, such as those at the base of the Blow-Me-Down Brook Formation in the Humber Arm Allochthon and within the Maiden Point Formation of the Hare Bay Allochthon, are possible Lighthouse Cove correlatives. Overlying shales, quartzites, and polymictic conglomerates with Lower to Middle Cambrian carbonate clasts are coeval with breakup and the initiation of the carbonate sequence. …

Volcanic rocks and ophiolite suites of higher structural slices are of unknown paleogeography with respect to other rocks of the Humber Zone. The Skinner Cove volcanic rocks of the Humber Arm Allochthon have been interpreted as oceanic islands, possibly seamounts. Alternatively, they could represent rift-facies volcanic rocks like those at the base of the Blow-Me-Down Brook Formation. The Bay of Islands Complex is interpreted as oceanic crust and mantle. Metamorphism in volcanic rocks and dykes is interpreted as a depth controlled static seafloor hydration. A lack of metamorphism in deeper gabbros possibly reflects an absence of surficial fluids necessary to accomplish the hydration.

The metamorphic soles of the ophiolite suites, now subhorizontal or steeply dipping surfaces frozen into the ophiolite sequences, are interpreted as high temperature shear zones resulting from transport of hot mantle and oceanic crust. The best example occurs beneath the White Hills Peridotite of the Hare Bay Allochthon where the Ireland Point Volcanics, Goose Cove Schist, and Green Ridge Amphibolite were accreted to the base of the peridotite. Contacts between rock units within the accreted metamorphic sole that were first interpreted as gradational are now interpreted as ductile shears. Thus the Green Ridge Amphibolite is retrograded toward its base; the Goose Cove Schist is prograded toward its top, and the overall inverted metamorphic gradient is fortuitous. The juxtaposition of oceanic and continental margin rocks along this shear zone suggests that it represents the interface between down-going and overriding plates in a subduction zone. The lithologies and pressure/temperature paths suggest assembly at a depth of 10 km where the geothermal gradient was abnormally high because the overriding plate was hot. Rocks of the upper plate were metamorphosed somewhere else and they were cooling when juxtaposed with the continental plate.

An integrated geochronological, isotopic, and geochemical study of the Little Port and Bay of Islands complexes of the Humber Arm Allochthon shows: (1) a significant age difference between a U-Pb zircon age of 505 +3/-2 Ma for the Little Port Complex and a U-Pb zircon and baddaleyite age of 484 ± 5 Ma for the Bay of Islands Complex, (2) Little Port trondhjemites are characterized by initial ENd values of -1 to +1 whereas those in the Bay of Islands Complex are +6.5, and (3) geochemical signatures in mafic and felsic volcanic rocks of the complexes are diverse and show a complete gradation between volcanic arc and non-volcanic arc patterns. These data contradict an earlier interpretation that the complexes were coeval parts of the same ophiolite suite connected by a mid-ocean ridge transform fault. An alternative interpretation relates the Little Port Complex to a volcanic arc and the Bay of Islands Complex to a supra-subduction zone setting.

Structural stacking within the allochthons indicates that the highest volcanic and ophiolitic slices are the farthest travelled. The occurrence of ophiolitic detritus in allochthonous Lower Ordovician sandstones and the local presence of volcanic and ophiolitic blocks in basal melanges, indicate assembly from east to west and emplacement as already assembled allochthons.

The extensive melanges developed among the lower slices of the allochthons are interpreted as the result of surficial mass wastage with later structural overriding. The broad flat Maiden Point slice of the Hare Bay Allochthon has internal recumbent folds throughout that pre-date the formation of underlying melange, and blocks of ampibolites and greenschists of the Bay of Island metamorphic sole occur in underlying low grade melange. Thus many of the structural styles exhibited within the allochthons predated assembly and melange formation. The leading edges of the higher structural slices in both the Humber Arm and Hare Bay allochthons have a tendency to disrupt, repeat, and disintegrate.

Complex internal structures of the lower sedimentary slices were developed during transport and emplacement. As a generality, the lowest sedimentary slices contain the stratigraphically youngest rocks. The slices have little morphological expression and their outlines and external geometries are in places poorly known. Higher igneous slices have clearer morphological expression and sharper boundaries. Some of their internal structures predate transport. Others relate to transport and emplacement. The earliest indication of assembly of the allochthons is the reversal in sedimentary provenance as recorded in the stratigraphy of lower structural slices. This and other features indicate diachroneity of assembly and emplacement along the length of the Canadian

Appalachians with earlier events in Newfoundland compared to Quebec. An unconformable Llandeilo cover on the Bay of Islands Complex is interpreted as coeval with transport, and the Caradoc Long Point Group was deposited after emplacement of the Humber Arm Allochthon.

Ordovician structures are confused in places where middle Paleozoic thrusts bring Grenville basement rocks and the Cambrian-Ordovician carbonate sequence above the Taconic allochthons. Final emplacement of uppermost slices of ophiolitic and/or volcanic rocks and carbonate slivers may relate to gravity collapse of an overthickened allochthon.

Preservation of allochthons such as those in western Newfoundland suggests burial soon after emplacement. A lack of ophiolitic and other detritus in Silurian, Devonian, and Carboniferous rocks suggests prolonged burial. Present exposure is the result of Mesozoic and Tertiary uplift.

Internal Humber Zone

The internal Humber Zone consists of intensely deformed and regionally metamorphosed rocks of greenschist to amphibolite facies that contrast with less deformed and relatively unmetamorphosed rocks of the external Humber Zone and adjacent Dunnage Zone (Fig. 3.45). It consists of an infrastructure of gneisses and subordinate schists, and a cover sequence of metaclastic rocks with minor metavolcanic rocks and marble, and tectonic slivers of mafic-ultramafic rocks. The infrastructure is mainly equivalent to Grenville basement, now remoulded with the cover sequence. The cover rocks are equivalent to allochthonous and authochthonous sequences of the external Humber Zone. The infrastructure is most extensive and varied in Newfoundland, with only small structural enclaves recognized in Quebec. In both areas, the contact with the cover sequence is generally tectonic, although locally it has been interpreted as an unconformity. …

Westward-directed thrusts bring metaclastic rocks of the internal Humber Zone against the external Humber Zone or the two are separated by steep faults. The continuity of the internal Humber Zone in Newfoundland is disrupted by Carboniferous cover rocks and in Quebec, Silurian-Devonian rocks locally overlie the older deformed rocks.

The infrastructure records the deepest tectonism in the Humber Zone, as it occupied the lowest stratigraphic levels. The presence of Grenville basement this far east in the Humber Zone indicates that protoliths of the internal Humber Zone were deposited near the less deformed miogeoclinal rocks to the west. In Newfoundland, the cover sequence is interpreted to overlap both continental and oceanic substrates.

The lower portions of the cover sequence are remarkably similar; in general they are characterized by metabasalts and coarse metasedimentary rocks that are locally of shallow water origin, and in some places they include felsic metavolcanic rocks.

ACCRETED TERRANES

Dunnage Zone

The Dunnage Zone is recognized by its abundant volcanic assemblages, ophiolite suites, and melanges (Fig. 3.61). 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.

An ophiolitic basement to its volcanic-sedimentary sequences was part of the original Dunnage Zone definition. Accordingly, in plate tectonic models the zone was described as vestiges of the Iapetus Ocean, preserved between the continental Humber and Gander zones. It is now clear that whereas some volcanic-sedimentary sequences of the Dunnage Zone are conformable above the ophiolite suite, others of Early and Middle Ordovician age are unconformable upon disturbed and eroded ophiolite suites and ophiolitic melanges….

The Humber-Dunnage boundary, the Baie Verte-Brompton Line, is everywhere a tectonic junction, and there are no Middle Ordovician cover rocks that link the Humber and Dunnage zones. The Gander-Dunnage boundary has always been problematic. In northeast Newfoundland, it is a tectonic boundary marked by mafic-ultramafic rocks of the Gander River Complex. In central and southern Newfoundland the boundaries are structural with allochthonous Dunnage Zone rocks above Gander Zone rocks. The Dunnage-Gander boundary beneath the Indian Bay Subzone of northeast Newfoundland is interpreted as stratigraphic.

Newfoundland

The Newfoundland Dunnage Zone is separated into two large subzones and a few smaller ones. The two large divisions are the Notre Dame Subzone in the west and the Exploits Subzone in the east, separated by the Red Indian Line, a major tectonic boundary traceable across Newfoundland (Fig. 3.62).

Summary and conclusions

In Newfoundland, most features of the Ordovician volcanic rocks of the Notre Dame Subzone suggest an ancient island arc built upon an ophiolitic substrate. Other geochemical studies suggest marine volcanism other than that of island arcs (Fig. 11.4). Eastward subduction is favoured, as there is no evidence for a proximal island arc in the stratigraphic record of the Humber Zone. …

Even before the wide acceptance of plate tectonics, the Gander Zone clastic rocks were viewed as a prism of sediment built up parallel to an Avalon shoreline on the eastern side of a Paleozoic ocean. The idea persisted chiefly because the Gander clastic rocks are of continental affinity and Gander Zone gneisses and migmatites resemble continental basement. Accordingly, the Gander Zone is commonly termed the eastern margin of Iapetus. However, there are no confirmed basement relationships or stratigraphic analyses comparable to those for the Humber miogeocline. Thus, the Gander Zone has also been viewed as a suspect terrane.[11]

GEOPHYSICAL CHARACTERISTICS

Seismic reflection

Recent information on the crustal configuration of the Canadian Appalachian region has come from deep seismic reflection experiments. These data from Newfoundland and offshore have dramatically changed our interpretation of the subsurface of the orogen.

The initial survey northeast of Newfoundland completed in 1984 demonstrated three lower crustal blocks. A Grenville lower crustal block was interpreted as the ancient North American continent, extending in subsurface beneath an allochthonous Dunnage Zone. It abuts a Central lower crustal block at mid-crustal to mantle depths. The central block is overlain by rocks of the eastern Dunnage Zone and Gander Zone. …

PALEONTOLOGY

The paleontology of the Canadian Appalachian region contributes to its zonal division. Losses of provincialism coincide with times of accretion.

Precambrian-Cambrian

The oldest fossils are stromatolites, *Archaeozoon acadiense*, in the Middle Proterozoic Green Head Group of the New Brunswick Avalon Zone. The fossils and other evidence of shallow-water deposition suggest correlation with the Grenville Group of southern

[11] Ibid., 845-860

Ontario and Quebec that contains similar stromatolitic limestone. This implies that Grenville rocks occur in the Avalon Zone.

Soft-bodied organisms of Ediacaran type are known from upper Precambrian rocks in the Newfoundland Avalon Zone, and small calcareous and phosphatic fossils of latest Precambrian to Middle Cambrian age precede the first appearance of trilobites.

The best known assemblages of late Precambrian palynomorphs are acritarchs and nonseptate organic filaments from the Newfoundland Avalon Zone. They resemble those in the lower Dalradian succession of Scotland and the Brioverian of the Armorican Massif of France.

Late Precambrian and Early Cambrian ichnofossil assemblages are similarly rich and diversified in siliciclastic rocks of the Avalon Zone. Comparable assemblages are not known elsewhere in the Appalachians, but their widespread distribution across Eurasia and in northwestern Canada suggests a lack of provincialism.

Continuing investigations of trilobites confirm the "Atlantic" and "Pacific" faunal realms known for about 100 years. Middle and Upper Cambrian rocks of the Humber Zone contain a sequence of polymerid trilobites and other fossils of essentially continent-wide distribution. Early and Middle Cambrian trilobites in the Taconic allochthons of the Humber Zone have elements of both Atlantic and Pacific realms. Trilobites resembling those of the North American shelf indicate shallow-water deposition, whereas agnostid trilobites, best known from the Acado-Baltic region, indicate contemporaneous deposition in cooler or deeper water. Genera and species of trilobites from rocks of the Avalon Zone, notably species of Paradoxides, are congeneric, and many are conspecific with those from contemporaneous rocks of similar kinds in the Atlantic borderlands from Norway to Morocco, but these taxa are unknown in the carbonate rocks of the St. Lawrence Platform or from the Humber Zone. …

Ordovician

Earliest Ordovician fossils of the Humber and Avalon zones reflect continuity with those of Cambrian age. …

Taconic Orogeny profoundly altered Appalachian depositional and paleontological patterns. The Long Point Group of western Newfoundland is richly fossiliferous and its middle Caradoc forms resemble those in the central and southern Appalachians and Scotland.

Discussion and conclusions

Perhaps the earliest application of paleontology to subdividing the Appalachian Orogen was the recognition of provincialism in Cambrian trilobites in what are now the Humber and Avalon zones. This differentiation also contributed to the idea of a two-sided symmetrical orogen, which in turn, led to the definition of the Iapetus Ocean.

The faunal differentiation between the two sides of the Iapetus Ocean diminishes from the Cambrian to the Ordovician, although provinciality continues because the ocean remained a formidable barrier to migration for many groups. Early to Middle Ordovician benthic trilobite and brachiopod faunas occurring around the margins of North America (Humber Zone) are quite distinctive from those in the Iapetus Ocean. For example, in the early Middle Ordovician, the Toquima-Table Head faunal realm occupied a belt peripheral to the platform. Coeval assemblages of largely different brachiopods and trilobites occur in rocks that were deposited on the fringes of islands within Iapetus and on the margins of the Armorican Platform (Celtic Province). Ocean-closing events associated with Ordovician orogeny are recorded in the Exploits Subzone of the Dunnage Zone where volcaniclastic rocks containing Arenig/Llanvirn fossils of the Celtic Province are overlain by Llandeilo carbonate rocks containing fossils of North American affinities. This corresponds with the time of ophiolite obduction in western Newfoundland and it followed juxtapositioning of the Exploits Subzone and the Gander Zone.

Conodonts of the North Atlantic province and graptolites provide important links across Iapetus because both groups occurred in open ocean waters. Distinct conodont assemblages occurred within North America in the warmer, presumably more saline waters (North American Midcontinent province).

The breakdown of strong provinciality in the Caradoc can be interpreted as evidence of the increasing proximity of the margins of the Iapetus Ocean during the Middle Ordovician. Provincialism was reduced further in the Late Ordovician with the progressive narrowing of Iapetus, and many Silurian forms are considered to be cosmopolitan.

In the context of a continually contracting Iapetus Ocean, it must be explained why early Silurian faunas seem to be cosmopolitan whereas later Silurian and Early Devonian faunas are provincial at a time when the ocean was presumably narrower. Perhaps the massive terminal Ordovician extinction event reduced diversity to the extent that recognition of provincialism in the Early Silurian is precluded by the lack of diversity in many fossil groups. The provincialism demonstrated by ostracodes, brachiopods and vertebrates during the Late Silurian supports the idea that the Fredericton Belt was the site of a Silurian seaway. However, it is probable that environmental factors and not geographic distance played an important role in provincialism at this time. Whatever the controls, provincialism in late Silurian and Devonian organisms change progressively until European or Old World forms invaded North America by the Middle Devonian. After that time, Carboniferous faunas and floras of the Canadian Appalachian region are similar to those of Western Europe, confirming that accretion was complete.[i]

METALLOGENY

Mineral deposits are related in time and space to the Appalachian orogenic cycle. Just as the rocks of any orogen contrast with coeval rocks of adjacent platforms, so too are mineral deposits as characteristic of orogens as the rocks and processes themselves. There is a regular and somewhat predictable relationship between kinds and ages of mineral deposits and orogenic development. Improved plate tectonic models for the Canadian Appalachians and improved accretionary analyses allow a more complete understanding of mineral deposits and their relationships to constructional and destructional stages of orogenic development than was heretofore possible. The Canadian Appalachian region is therefore an excellent laboratory for metallogenic studies in a complex accretionary and collisional orogen.

The mineral deposits are grouped according to three main stages of orogenic development: (1) pre-orogenic - includes mineral deposits from previous orogenic cycles and deposits formed at continental margins and in the intervening ocean during rift and drift phases of development; the deposits are confined to tectonostratigraphic zones; (2) syn-orogenic - includes mineral deposits controlled by faulting and granitoid plutonism that occurred during accretion of outboard terranes; these deposits occur in both zones and belts; and (3) post-orogenic - includes mineral deposits related to late- or post-orogenic faulting, granitoid intrusion, and development of successor basins; these deposits occur across the entire orogen.

The pre-orogenic late Precambrian to Middle Ordovician-Lower Silurian elements of the orogen define four metallogenic entities, now represented by the Humber, Dunnage-Gander, Avalon and Meguma zones. Preaccretion metallogeny proceeded independently in these entities and their contrasting deposits reflect their diverse geological histories.

Syn-orogenic mineral deposits formed during and immediately following initial accretion (Taconic Orogeny) at the Humber-Dunnage zone boundary with hydrothermal activity related to major faults and granitoid intrusions. At this time, a pre-accretion metallogeny was still proceeding independently in outboard zones (eastern Dunnage, Gander, Avalon, Megwna). Deformation-related and granitoid-related mineralization increased in intensity and abundance as accretion and crustal thickening proceeded through the Silurian and Devonian. Syn-orogenic mineralization, which eventually encompassed all of the accreted outboard terranes, consists of two principal types: (1) structurally controlled and (2) granitoid-related.

The post-orogenic stage of mineralization is related to the development of late Paleozoic overlap assemblages in Devonian to Permian successor basins.

Pre-orogenic deposits

Humber Zone

The development of the Humber Zone began with late Precambrian-Early Cambrian rifting of Grenville basement and concomitant dyke intrusion, volcanism, and clastic sedimentation. This was followed by a passive margin stage with a Cambrian-Ordovican carbonate sequence, and destruction of the margin by ophiolite obduction in the Middle Ordovician.

The metallogeny of the Humber Zone includes at least six broad classes of deposits (Fig. 9.1): (1) iron-titanium oxide deposits in Grenville anorthosite inliers of western Newfoundland; (2) sulphides hosted by Precambrian carbonates of Cape Breton Island; (3) paleoplacer heavy mineral occurrences in Cambrian incipient rift sequences of southeastern Quebec; (4) cupriferous sulphide occurrences in Cambrian incipient rift sequences of southeastern Quebec; (5) zinc and lead occurrences, locally accompanied by Ba, U, and other metals, in the lower Paleozoic carbonate sequence of southeastern Quebec and western Newfoundland; and (6) epigenetic Ba-Pb-Zn deposits in Cambrian clastic rocks in the Lower St. Lawrence Lowlands. All of these deposit types are related to rocks that define the Humber Zone.

Dunnage and Gander zones

Cambrian and Ordovician volcanic rocks of the Dunnage Zone are particularly rich in mineral deposits (Fig. 9.11). Ensimatic island arc volcanic activity continued sporadically from the Cambrian to the Middle Ordovican. Lower Ordovician ophiolitic rocks are preserved throughout the Newfoundland Dunnage Zone as well as in Taconic allochthons of western Newfoundland, the Elmtree Subzone of New Brunswick, and the ophiolite belt of southeastern Quebec. All are interpreted to record rifting i~ arc .or back-arc environments. At least some of the volcanic activity was approximately coeval with clastic sedimentation of the Gander Zone. Subsequent ensialic back-arc rifting environments are recorded in northern New Brunswick and probable equivalents in the Hermitage Flexure region of southern Newfoundland.

Mineral deposits unique to the Dunnage-Gander zones comprise two broad types: (1) mineralization in the ultramafic and mafic plutonic parts of ophiolite complexes (i.e. magmatic chromite and sulphides, epigenetic Ni arsenides and sulphides, and metasomatic products of the ultramafic rocks such as asbestos, talc, and magnesite) in central and western Newfoundland, Gaspesie, and southeastern Quebec; (2) volcanic-and sediment-hosted massive sulphide deposits including various types of volcanogenic sulphide deposits in central and western Newfoundland, northern New Brunswick, and southeastern Quebec.

Significant occurrences of chromite are found in Newfoundland in the Bay of Islands, Pipestone Pond, Coy Pond, and Great Bend complexes, and in ophiolite suites of southeastern Quebec (Fig. 9.11). Minor occurrences of nickeliferous, locally platinum group elements (PGE)-rich sulphides have been reported from the Bay of Islands Complex and there are numerous Ni occurrences associated with dismembered ophiolitic rocks in Gaspesie. Nickeliferous deposits in southeastern Quebec, possibly of Outokumpu type, are apparently related to hydrothermal activity in the early stages of Taconic Orogeny. Metasomatism of ophiolitic ultramafic rocks during accretion to the Laurentian margin resulted in the formation of talc and asbestos.

Despite the similarities of geological and tectonic settings of the Appalachian ophiolite-hosted volcanogenic massive sulphide (VMS) deposits, recent geochronological work confirms that not all are of the same age. Mineralized ophiolites in western Newfoundland formed in the early Arenig (ca. 488 Ma), those in southeastern Quebec in the late Arenig (ca. 479 Ma) and those in northern New Brunswick in the Llanvirn (ca. 461 Ma) suggesting repetition of back-arc environments favourable for VMS formation.

Submarine volcanic and epiclastic sedimentary sequences in the Dunnage Zone record volcanism, sedimentation and mineralization in a long-lived and complex series' of Cambrian to Middle Ordovician island arcs and back-arc basins around the margins of Iapetus. These sequences are rich in volcanic-hosted massive sulphides, both as massive exhalative and stockwork deposits. The deposits range in size from small to supergiant (Brunswick No. 12) and from relatively lean to extremely rich (Buchans).

Recent tectonic models for various parts of the northern Appalachians emphasize the complexity of the tectonic development of the remnants of Iapetus. All ophiolite suites that contain significant volcanogenic sulphide mineralization exhibit geochemical and/or isotopic evidence of development in supra-subduction settings. It is. now recognized that VMS mineralization occurred in a variety of geological and tectonic settings and at several different times during the Cambrian-Ordovician history of Iapetus. …

Granitoid-related mineralization

Granitoid intrusion occurred at many times and in response to various tectonic events during the accretionary and post-accretionary history of the Appalachian Orogen. Intrusive rocks range in composition from gabbro to high-silica granite, and include sub alkaline, alkaline, and peralkaline types. Granitic rocks occur in all zones and a variety of tectonic settings.

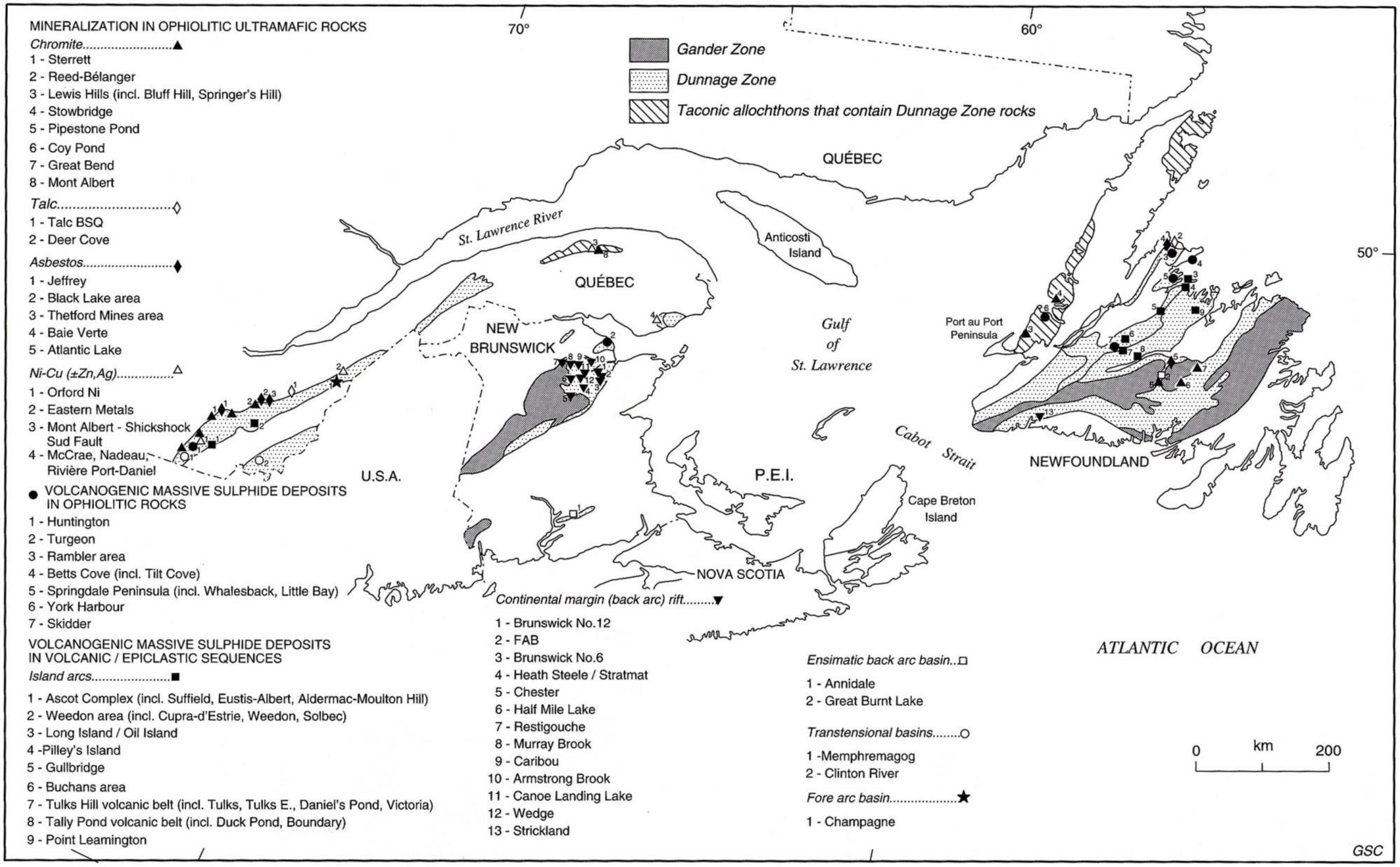

Figure 9.11. Principal mineral occurrences in the Dunnage and Gander zones of the Canadian Appalachians. Symbols may represent either single deposits or groups of deposits.

Summary and conclusions

The present plate tectonic model for mineral deposits used here is similar to models advanced many years ago, based on geosynclinal development and the orogenic cycle. The principal difference is that the plate tectonic framework provides actualistic and readily observable analogues for ancient processes. The empirical observations that led to former models are as valid today as they were half a century ago. As the geological database expands there will be added refinements to tectonic and metallogenic models leading to an integrated understanding of the orogen.

The oldest mineral deposits are the products of earlier orogenic cycles, preserved in continental crust that was incorporated in the Appalachian cycle. Thus, magmatic iron-titanium deposits in the Humber Zone are geologically part of the Grenville orogenic belt, whereas late Proterozoic volcanogenic massive sulphides, carbonate-hosted, and granite-related deposits in the Avalon Zone are geologically part of the Pan-African orogenic belt. Some of these occurrences provided metals which were remobilized and/or upgraded by Appalachian orogenic processes. …

The beginning of accretion at the Laurentian margin in the Early Ordovician led to transport of ophiolite suites and their mineral deposits and led to the generation of new types of deposits. Because accretion apparently spanned a considerable period, the drift and accretionary stages of the orogen overlap. …

The processes of accretion included reactivation of pre-existing trans-crustal faults, formation of new faults, and crustal thickening that produced granitoid magmas. Heat was locally provided by the magmas that utilized coeval structures for ascent. As crustal thickening proceeded, deeper partial melting and granitic magma generation provided further opportunities for the transfer of metals from the lower to upper crust.[ii]

ZONAL LINKAGES AND ACCRETIONARY HISTORY

Stratigraphic and sedimentological 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 structural effects and stratigraphic expression are recognized in the Humber and adjacent Dunnage zones and they are attributed to Taconic Orogeny (Map 5). The Gander Zone and Dunnage Zone in Newfoundland also interacted at this time with southeastward ophiolite obduction, but gaps 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 (Map 6). 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.

Ordovician effects of the first event are absent in the Avalon and Meguma zones (Map 5). All zones were affected by middle Paleozoic deformation, except for eastern parts of the Newfoundland Avalon Zone (Map 6).

Precambrian orogenic effects unrelated to the Appalachian cycle are restricted to the Humber and Avalon zones. In the Humber Zone, the present positions of Grenville inliers are controlled by Paleozoic structures so that their dimensional orientations are parallel to Appalachian structural trends and facies belts. Internal fabrics and fold axes trend northwest in some examples, perpendicular to Appalachian structures. As northwesterly trends are common in the Grenville Structural Province of the Canadian Shield, this suggests minimal or no rotation during Paleozoic deformations. The Avalon Zone encompasses a variety of diverse Precambrian elements, implying a composite makeup. These elements were assembled in the late Precambrian as Cambrian rocks have similar stratigraphies and distinctive Atlantic realm faunas.

Humber-Dunnage interaction (Taconic Orogeny)

Stratigraphic expression and sedimentological linkages

The earliest indication of assembly of Taconic allochthons is the reversal in sedimentary provenance recorded in the stratigraphy of their lower structural slices. In Newfoundland, the easterly derived clastic rocks are as old as Arenig. The youngest rocks of the underlying autochthon are Llanvirn. The North Arm Mountain massif of the Bay of Islands Complex has an unconformable cover of Llandeilo age, interpreted as coeval with transport. The first post-orogenic phase of sedimentation is represented by the Caradoc Long Point Group. These and other features bracket the timing of Taconic Orogeny and indicate that Taconic events in Newfoundland are older than those in Quebec. …

Structural expression

In the external Humber Zone, different structural slices of Taconic allochthons exhibit different deformational styles, and most structures were imprinted prior to or during the assembly and transport of the allochthons. These vary from intense foliations, tectonic banding, and folded schistosities in ophiolitic rocks and their metamorphic soles, to scaly cleavages, rootless folds, and overturned beds in sedimentary rocks.

Lower slices have internally complex geometries of rock units and the slices are rarely morphologically distinct. Higher structural slices are of simpler internal makeup and some have marked morphological expression. Stratigraphic relationships, palinspastic restorations, and structural considerations all indicate that the allochthons were assembled from east to west and that the structurally highest slices travelled the farthest. Assembly began in the Early Ordovician and final emplacement was Middle to Late Ordovician.

Limestone breccias of the Cow Head Group and overlying easterly derived clastic rocks in western Newfoundland occur in repeated east-dipping, east-facing stratigraphic sections. The coarsest limestone breccias are in western sections with finer, thinner, and fewer breccias in eastern sections. The overlying clastic rocks are everywhere in thrust contact with an allochthonous slice, indicating entrainment in a west-directed thrust complex soon after deposition.

Early recumbent folds with penetrative cleavage in some higher sedimentary slices have subhorizontal axes and face westward, in the general direction of tectonic transport. These structures are coeval with assembly and transport.

The metamorphic soles of allochthonous ophiolite suites are interpreted as high temperature shear zones resulting from transport of hot mantle and oceanic crust. The juxtaposition of oceanic and continental rocks within the dynamothermal soles indicate an interface between underlying and overriding plates. Hornblende cooling ages are Early and Middle Ordovician.

Rocks of the internal Humber Zone are characterized by multiphase deformation and metamorphism that began with the interaction of the continental Humber Zone and the oceanic Dunnage Zone. Relationships in Newfoundland suggest that the multideformed cover sequence overlaps the ancient continent-ocean transition. Associated melanges display all structures evident in surrounding rocks. Hence their formation preceded metamorphism and penetrative deformation.

The earliest deformation is characterized by ductile shear zones and thrusts, that in places contain ultramafic rocks. The ultramafic rocks were incorporated before the earliest fabrics developed, and some shear zones may represent extensions of ophiolitic melange zones. This suggests that the earliest deformation involved tectonic transport from the oceanic Dunnage Zone onto the Humber miogeocline.

Peak metamorphic conditions of the internal Humber Zone are greenschist to lower amphibolite facies in most places. Of particular note are blueschist facies in the Tibbit Hill mafic volcanic rocks of Quebec and eclogite facies in the infrastructure of Newfoundland. The Dunamagon Granite in Newfoundland, dated isotopically at 460 ± 12 Ma, cuts the metamorphic rocks. Thus an Early Ordovician age is inferred for the tectonothermal events. Cooling ages from Newfoundland indicate that regional metamorphism had subsided by the Middle Silurian. Cooling ages in Quebec are Late Ordovician in most areas.[iii]

[i] Ibid, p. 877 -880
[ii] Ibid., p. 880-883
[iii] Ibid., p. 883-884