Chapter 11

SUMMARY AND OVERVIEW

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Harold Williams

PREAMBLE

This chapter summarizes, and repeats without referencing, information presented in preceding chapters. Some of these chapters were written more than 5 years ago and there have been important subsequent changes. A few new references are therefore cited. This chapter was written also with an eye toward suitability for a Canadian overview volume.

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 subzones as depicted in Figure 11.1. The middle Paleozoic rocks are separated into belts: Gaspé, 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 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.

Williams, H.
1995: Summary and overview; Chapter 11 in Geology of the Appalachian-Caledonian Orogen in Canada and Greenland, (ed.) H. Williams; Geological Survey of Canada, Geology of Canada, no. 6, p. 843-890 (also Geological Society of America, The Geology of North America, v. F-1).

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

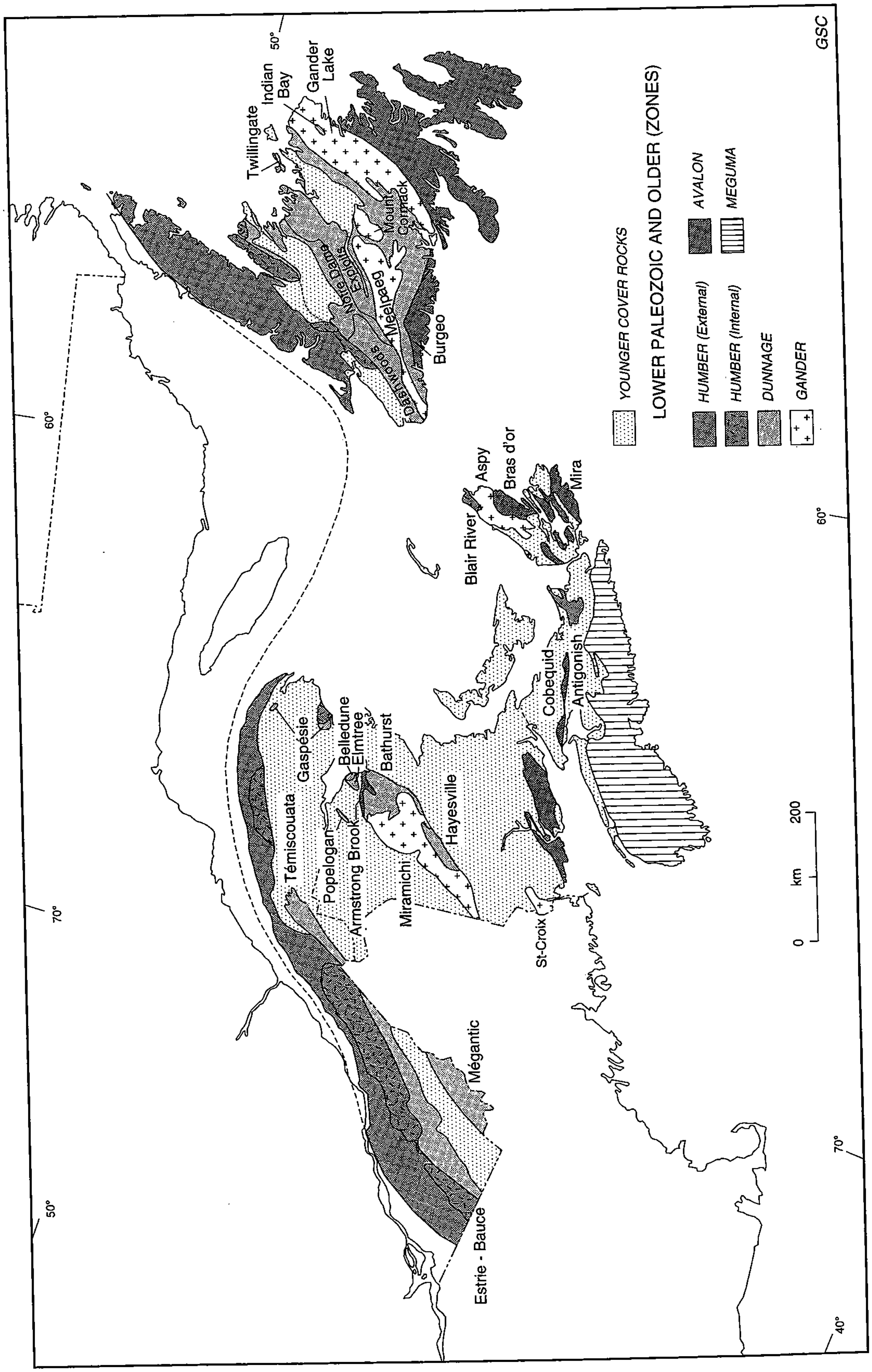

Figure 11.1. Zones and subzones of the Canadian Appalachian region.

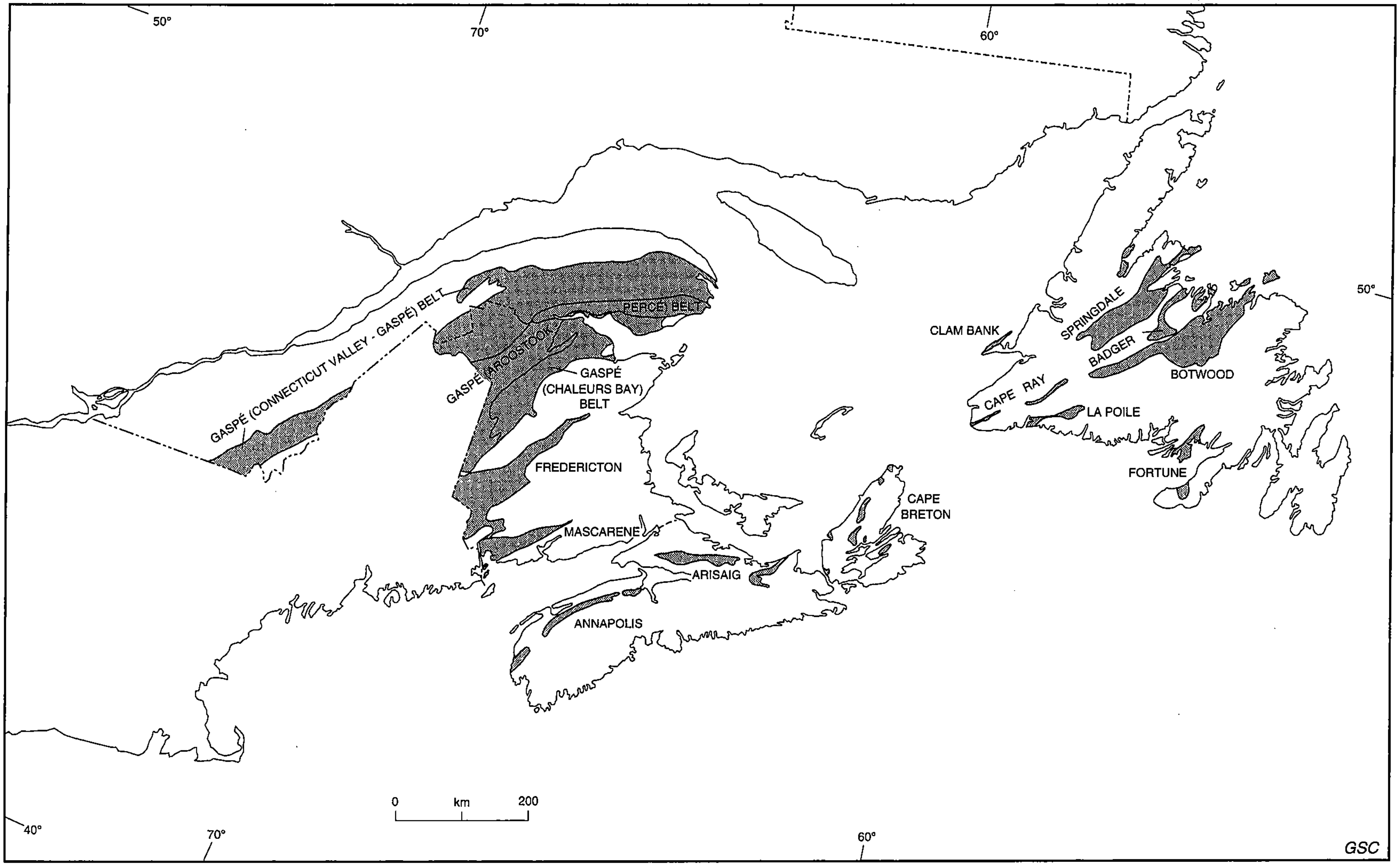

Figure 11.2. Belts of the Canadian Appalachian region.

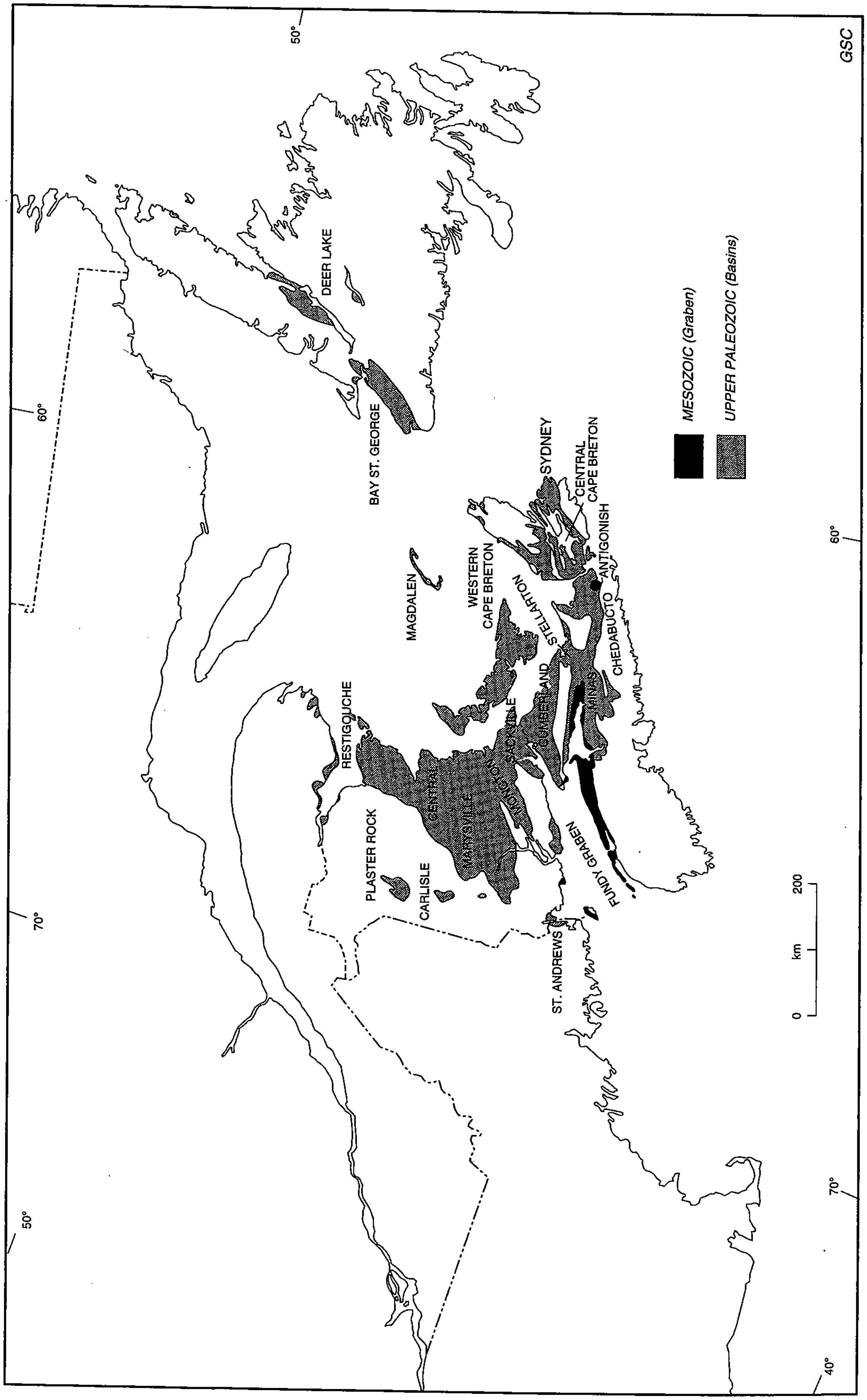

Figure 11.3. Basins and graben of the Canadian Appalachian region.

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.

Metamorphic and plutonic rocks of the Blair River Complex that occur at the northwest corner of Cape Breton Island, Nova Scotia, are also Grenville basement. Other Precambrian crystalline rocks occur in three widely separated areas of the Quebec internal Humber Zone. These are the Port Daniel Inlier, the Sainte-Marguerite Fault Slice, and the Sainte-Helène-de-Chester Fault Slice, from east to west.

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. These basement rocks were deformed with their cover and a basement-cover distinction is not everywhere clear. Thus, the boundaries of the East Pond Metamorphic Suite and Cormacks Lake Complex are poorly defined.

The Blair River Complex of Cape Breton Island is separated from metamorphic rocks of the Aspy Subzone to the east by a wide zone of mylonite developed along the Wilkie Brook Fault. The Port Daniel Inlier occurs in a major fault zone bordering the Maquereau Dome of Gaspésie. The Sainte-Marquerite Complex forms three faulted slivers up to 3 km long within the Richardson Fault Zone, which forms the boundary between the internal and external divisions of the Humber Zone in Quebec. The Sainte-Helène-de-Chester occurrence is a fault slice within the Bennett schists, a few kilometres northwest of the Baie Verte-Brompton Line.

Rocks of basement inliers are mainly of igneous protolith with minor marble, quartzite, and metaclastic rocks. The extensive Long Range Inlier has mainly quartz-feldspar gneisses and granites. In the north, the rocks are biotite-quartz-feldspar gneiss and hornblende-biotite-quartz-feldspar gneiss with lesser quartz-rich gneiss, pelitic schist, amphibolite, and calc-silicate gneiss. In the south, they are pink to grey quartz-feldspar gneiss, quartz-rich 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.

Coarse grained white anorthosite and banded hypersthene gabbro of the Indian Head Inlier are conspicuous in coastal headlands and these are intruded by massive to foliated pink granites and coarse grained pegmatites.

The Steel Mountain Inlier consists of coarse grained grey to pale purple anorthosite, gabbroic anorthosite, norite, and minor pyroxenite in the south and granitic, granodioritic, and amphibolitic gneisses with crosscutting bodies of granite and syenite in the north. Some small occurrences of marble and quartzite near Grand Lake are part of the basement complex, others may be Paleozoic structural enclaves.

The dominant lithology of the Blair River Complex is quartzo-feldspathic gneiss with associated amphibolite, granitic gneiss, and minor calcareous rocks. Small bodies of gabbroic to granitic rocks, syenite, and anorthosite are intimately mixed with the gneisses. In other places, anorthosite cuts the gneisses and is in turn cut by syenite.

Foliation patterns in the Precambrian inliers are extremely variable. In the northern part of the Long Range Inlier broad areas of shallowly dipping foliation are separated by steep structural zones or by granitic plutons and faults.

Banding and gneissic foliation in rocks of the southern massif of the Indian Head Inlier trend northwest, perpendicular to the length of the inlier and to Paleozoic structures. Similarly, anorthosites of the Steel Mountain Inlier have a mild northwest-trending foliation in the west that is overprinted by a Paleozoic northeast fabric toward the east.

The dominant trend of fold axes in the Cormacks Lake Complex is northwest, and northwest trends also occur in the East Pond Metamorphic Suite. These are like Grenville structural trends in the Steel Mountain and Indian Head inliers, and suggest Precambrian ages for these complexes.

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. Pelitic rocks contain microcline-sillimanite- cordierite (or garnet) assemblages, and remnants of hyper- sthene are preserved in some localities.

In central and southern portions of the Long Range Inlier, amphibolite and locally granulite facies mineral assemblages (two-pyroxene gneisses) are recorded, with metamorphic facies 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.

Metamorphism in mafic gneisses of the Indian Head Inlier reaches amphibolite and granulite facies. Biotite-hornblende-plagioclase gneisses are common and two-pyroxene plagioclase gneisses occur locally. Sapherine occurs at one locality.

Granitic gneisses and schists of the Steel Mountain Inlier contain amphibolite- to granulite-facies mineral assemblages. This high-grade metamorphism may be older than nearby anorthosites.

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. Other discrete occurrences at Lake Melville and Sandwich Bay of Labrador are 300 km farther north and lie at the northwest limit of the Grenville Structural Province. In Quebec, the Grenville dyke swarm dated at 575 Ma extends 700 km inland beyond the Appalachian structural front along the Ottawa Valley. Coeval anorogenic intrusions occur along the Saguenay, St. Lawrence, and Ottawa valleys.

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. The Bradore Formation is overlain by fossiliferous shale, siltstone, and limestone of the Lower Cambrian Forteau Formation, the basal formation of the succeeding carbonate sequence.

Mafic dykes of the Long Range swarm are coeval with the Lighthouse Cove Formation and they cut the Bateau Formation. Chemical and petrographic data show that they are typical tholeiites and there is no detectable difference between the Long Range dykes and Lighthouse Cove volcanic rocks of southeast Labrador, Belle Isle, and northeast Newfoundland.

Some northeast-trending faults in the basement coincide with thickness changes in the Bradore Formation. Other contemporary faults at Belle Isle affected the Bateau Formation but not nearby mafic dykes. The surface on which the Bateau, Lighthouse Cove, and Bradore formations accumulated was therefore irregular with sharp local relief that led to significant thickness variations.

At Hughes Lake in the internal Humber Zone of western Newfoundland, a deformed and metamorphosed bimodal volcanic suite and associated granite are overlain by psammitic and pelitic schists. The granite is dated at 602 ± 10 Ma and interpreted as a high-level anorogenic pluton. Silicic volcanic rocks have trace-element characteristics typical of rhyolitic end members of alkali igneous suites. Mafic flows and dykes are tholeiites, similar to the Lighthouse Cove Formation and dykes of the Long Range Swarm. Basal metaclastic rocks are correlated with the Bradore Formation although they are much thicker.

The age of the granite, its hypersolvus textural features, its association with a bimodal volcanic suite, the alkaline affinities of associated silicic volcanic rocks, and the presence of mafic dykes and flows all suggest a consanguineous igneous suite that formed in a rift setting.

The Tibbit Hill volcanics in the internal Humber Zone of Quebec are equated with occurrences in Newfoundland and nearby examples in Vermont. They are predominantly altered basalts that are polydeformed and metamorphosed. Abundances of immobile elements and enrichment patterns indicate transitional or alkalic basalts of "Within Plate" affinity, contaminated by continental crust. Comenditic metafelsites that form a minor unit in the volcanic sequence are dated at 554 +4/-2 Ma.

Outside the Appalachian deformed zone, the Double Mer Formation is a sequence of red arkosic sandstones, conglomerates, siltstones, and shales that occurs in graben at Lake Melville and Double Mer. Bedding attitudes suggest broad open folding with thicknesses of sediment possibly reaching 5 km. Conglomerates at the northern margin of the Double Mer graben are interpreted as fanglomerates.

Coupled with northerly paleocurrents elsewhere in the graben, the pattern suggests a half graben with a faulted northern margin and a north-sloping floor. Relationships to the south suggest that the Mealy Mountains formed a contemporary upland at the southern edge of the Lake Melville Graben.

The Double Mer Formation is traditionally correlated with the Bradore Formation of southeast Labrador. Its depositional graben are parallel to the northeast direction of late Precambrian-Cambrian mafic dykes. A northeast-trending dyke, which crosses a small graben at Sandwich Bay, yields a U-Pb zircon and baddeleyite age of 615 ± 2 Ma.

The Grenville dyke swarm and Ottawa Graben are probably linked with the Tibbit Hill volcanic rocks, although the Tibbit Hill volcanic rocks are alkalic to transitional, whereas the dyke rocks are tholeiitic. The mafic dyke-volcanic episode is roughly coeval with the emplacement of alkali complexes, including several carbonatite complexes dated at 565 Ma.

Faults, 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. Overlying marine shales and limestones mark an abrupt termination of coarse clastic deposition and a broad submergence and permanent change in the tectonic regime. This is interpreted to mark the transition from continental rifting to ocean spreading. 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.

Widths of the Ottawa Graben and Lake Melville-Double Mer graben are in the order of 50 to 100 km, typical of modern rift valleys.

The Ottawa Graben has the geometry of an aulacogen or failed arm of a triple rift system. Its setting at the Sutton Mountains structural salient is interpreted as an original deep embayment in the rifted margin. The Long Range Swarm, and Lake Melville and Double Mer graben are parallel to the ancient Iapetus continental margin, much as Triassic-Jurassic dyke swarms and graben of the Appalachian Orogen are parallel to the modern Atlantic margin.

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. This provides the possibility of studying listric normal faults and transfer faults related to Iapetan rifting, and also similar features related to the opening of the Atlantic Ocean that should be superimposed on Iapetan effects at high angles. The Cartwright Fracture Zone at the modern Atlantic margin off Labrador may reflect the Lake Melville rift system. Other examples of ancestral controls and micmicry abound.

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 Gaspésie 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 Québec 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. In the St. Lawrence Lowlands of Quebec, the succession includes the Potsdam, Beekmantown, Chazy, Black River and Trenton groups; and the Romaine and Mingan formations on the north shore of the St. Lawrence River.

Where the rocks occur in thrust slices of the Sutton Mountains and Lake Champlain areas they include the Oakhill Group, Milton Dolomite, Rock River Formation, and Phillipsburg Group. Cambrian carbonates in Gaspésie are the Murphy Creek and Corner-of-the-Beach formations.

Present exposures of the carbonate sequence were part of a continental margin platform, the landward portion of which is preserved only in Quebec. There, a rolling and faulted paleotopography is onlapped by progressively younger rock units northwards across the St. Lawrence Lowlands. At Montmorency Falls near Québec City, the Middle Ordovician Trenton Group lies directly on Grenville basement. At Mingan Islands and in the subsurface of Anticosti Island, upper Lower Ordovician carbonates overlie Precambrian basement. The landward edge of Cambrian carbonates was between Gaspésie and Anticosti Island and southeast of the St Lawrence Lowlands. This implies that a relatively narrow Cambrian shelf was overstepped by Ordovician rocks. The shelf edge is nowhere preserved. Coeval rocks of the continental slope are preserved in Taconic allochthons.

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). Equivalent strata of the Oakhill Group and Milton Dolomite occur only in thrust slices in Quebec. Carbonate deposition was established throughout western Newfoundland during the Middle Cambrian and continued to the Early Ordovician. During this period of about 70 Ma, strata belonging to the Port au Port and St. George groups formed the major part of the 1500 m sequence. In Quebec, carbonate sedimentation was not widespread until the Early Ordovician when the Beekmantown and Phillipsburg groups were deposited above sandstones of the Potsdam Group. Cambrian carbonate sedimentation is recorded near Percé of Gaspésie by Middle and Upper Cambrian carbonates, and shallow water, Cambrian carbonate clasts in allochthonous Ordovician deepwater sediments.

The St. George Unconformity is a major break between the St. George and Table Head groups in Newfoundland. Dramatic variations in thickness reflect a combination of faulting, uplift, and erosion. On Mingan Islands, the Romaine Formation was tilted before erosion so that the unconformity is a planar karst surface which bevels several units.

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 Quebec, parautochthonous flysch that occurs along the south side of the St. Lawrence River was deposited along the axis of a foreland basin, with paleocurrents predominantly to the west in the lower to middle part of the sequence, and to the east at its top. In the intervening Gulf of St. Lawrence, shaly flysch occurs in the subsurface beneath Anticosti Island.

Autochthonous flysch also extends about 100 km east of Quebec City to the Canada-United States border, and across strike to the northwest for about 50 km onto the St. Lawrence Platform. In the core of the Chambly-Fortierville Syncline, the flysch is overlain conformably by redbeds of the Rivière Bécancour Formation. This is the only place in the Canadian Appalachians where terrestrial molasse sediments are preserved directly above Ordovician flysch. A deep seismic reflection profile across the eastern end of the Chambly-Fortierville Syncline shows that the flysch is in part buried by thrust sheets, and is itself somewhat telescoped by folding and thrusting.

Thrust slices that overlie the autochthon locally contain units of sandy flysch at the top of their stratigraphic sections. These allochthonous units are older than those of the adjacent autochthon. They overlie Lower Ordovician shales, limestone breccias, and older rocks that are interpreted as continental slope and rise deposits.

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.

In Quebec, the oldest allochthonous flysch units are of relatively proximal character and late Arenig to early Llanvirn age.

The St. George Unconformity in Newfoundland developed near the carbonate platform edge. An equivalent unconformity is only weakly developed or absent landward in the St. Lawrence Lowlands. This Middle Ordovician unconformity is interpreted to represent erosion along the crest of a migrating peripheral bulge associated with loading and landward migration of Taconic thrust sheets. Flysch was deposited in an evolving foreland basin developed upon the shallow marine carbonate platform, with rapid subsidence in the order of kilometres.

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. In particular, the Cape Cormorant boulder conglomerates contain a mixture of Cambrian and Ordovician carbonate clasts shed into the developing black shale and flysch environment from the tops of uplifted blocks. Elsewhere in western Newfoundland and also in the Quebec City area, deepening and tilting of the foundering platform edge generated wet-sediment slides in argillaceous facies.

Black shale deposits probably represent local sites of low siliciclastic sediment supply during the early phases of basin filling. There is no obvious relationship between times of early black shale deposition and times of Ordovician eustatic sea-level rise, as has been suggested for black shales of the British Isles. Nevertheless, unusually fine grained units within thick flysch formations may have been deposited during times of high sea level.

Some autochthonous flysch units in the Québec City area and Gaspésie have been interpreted as small submarine fans. Other flysch units between Montréal and Québec City appear to have been deposited on a basin floor controlled by differential subsidence, and characterized by active intrabasinal horsts. Because of strong fault control, morphological submarine fans were apparently not formed.

Intense deformation and production of mélange below the allochthonous flysch units may partly pre-date the end of flysch deposition. Abrupt basal contacts are incompatible with fan progradation, and suggest deposition in small basins, probably on slopes formed by stacking of Taconic thrust sheets.

Paleoflow data and stratigraphic analyses support a model for earliest flysch deposition near promontories of the ancestral North American margin and latest deposition in reentrants. The earliest deposition in southwestern Newfoundland and eastern Gaspésie occurred close to the St. Lawrence Promontory. The latest deposition of Quebec occurred in the Quebec Reentrant, an area that was removed from early collisional effects. The ages of other allochthonous and autochthonous flysch units can be explained by progressive collision of an island arc or arcs with an irregular continental margin.

The difference in age between allochthonous and autochthonous flysch in the same part of the orogen is interpreted as a function of the distance that the allochthons were transported toward the continental margin.

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 mélanges 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 mélanges.

The best known examples in western Newfoundland are the Humber Arm and Hare Bay allochthons. The Old Mans 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 (Fig. 3.38).

Transported rocks in Quebec form a series of structural slices, the Lower St. Lawrence River nappes, that make up most of the exposed external Humber Zone. The largest nappes from north to south are the Sainte Anne River, Marsoui River, Shickshock, Lower St. Lawrence Valley, Chaudière, St. Henedine, Bacchus, Point-de-Levy, Quebec Promontory, Grandby, and Stanbridge (Fig. 3.38).

The western edge of the transported rocks is Logan's Line, first defined at Québec 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 Islands 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 then their present areas.

Conspicuous carbonate slivers occur beneath the Bay of Islands Complex and above mélange 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.

Mélanges 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 mélanges 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. The condensed limestone breccia, thin platy limestone, shale units of the Cow Head Group are the continental slope/rise equivalents of the carbonate platform sequence. At Cow Head, repeated belts are interpreted as thrust slices developed during transport and emplacement. The pattern of abundant coarse limestone breccias in western slices and finer, thinner and fewer breccias in eastern slices implies a proximal (west) to distal (east) facies arrangement that is still discernible across the thrust slices (Fig. 3.40). Overlying sandstones with chromite and other ophiolite detritus are part of the foreland basin flysch units that appear first in the allochthonous sequences.

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 E_{Nd} 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 mélanges, indicate assembly from east to west and emplacement as already assembled allochthons.

The extensive mélanges 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 Allochton has internal recumbent folds throughout that pre-date the formation of underlying mélange, and blocks of ampibolites and greenschists of the Bay of Island metamorphic sole occur in underlying low grade mélange. Thus many of the structural styles exhibited within the allochthons predated assembly and mélange 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.

The Dashwoods Subzone of Newfoundland contains large tracts of paragneiss that may be equivalent to similar rocks in the internal Humber Zone.

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. In Newfoundland, these units include lithic correlatives of the lower Labrador Group of the external Humber Zone. In Quebec, they include the Tibbit Hill, the Montagne Saint-Anselme, and Shickshock metavolcanics, as well as lower parts of the Shickshock and Maquereau groups. All of the metabasalts in these units have tholeiitic rift-related petrochemical signatures. Thus, regional correlation and petrochemical analyses indicate that the cover sequence was deposited in a late Precambrian rift setting. Younger strata of the cover sequence most reasonably represent deposits of a contin-ental slope and rise.

ACCRETED TERRANES

Dunnage Zone

The Dunnage Zone is recognized by its abundant volcanic assemblages, ophiolite suites, and mélanges (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 mélanges, and in eastern Newfoundland and northern New Brunswick Lower and Middle Ordovician volcanic-dominated sequences are stratigraphically above Gander Zone clastic sedimentary rocks. Rocks that link a Dunnage oceanic basement in one place with a Gander continental clastic sequence in another are overstep sequences. Regardless of basement relationships, the Middle Ordovician or older volcanic-sedimentary sequences between the Humber and Gander zones are included as part of the Dunnage Zone. Locally in central Newfoundland and Quebec, Middle Ordovician clastic rocks on a mélange substrate are conformable below Lower Silurian rocks. The Silurian rocks are assigned to the Badger Belt in central Newfoundland, but in Quebec they are viewed either as part of the Dunnage Zone or part of the Gaspé Belt.

The Dunnage Zone is widest in northeast Newfoundland, although it is narrow and disappears southwestward at Cape Ray. It is absent on the opposite side of Cabot Strait in Cape Breton Island. Ophiolitic rocks, mélanges, and volcanic sequences reappear in northern New Brunswick. The Dunnage Zone is hidden by the Gaspé Belt in much of eastern Quebec. In eastern Gaspésie, the Humber-Dunnage boundary is offset by dextral transcurrent faults and it follows the Shickshock-Sud Fault farther southwest. Dunnage Zone rocks reappear in the Témiscouata inlier and they form a continuous belt of ophiolitic rocks, mélanges, and marine sedimentary and volcanic rocks throughout the eastern townships of Quebec.

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.

In New Brunswick, Dunnage Zone volcanic rocks overlie an ophiolitic substrate on both sides of the Rocky Brook-Millstream Fault. Farther south in the Bathurst area, the volcanic rocks overlie quartzites of the Gander Zone with a conglomerate unit marking the stratigraphic base. Tectonic emplacement of northern belts above southern belts occurred in the Late Ordovician-Early Silurian and produced the largest known blueschist belt in the Appalachian Orogen.

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). Two small areas of volcanic and sedimentary rocks are assigned to the Twillingate and Indian Bay subzones in northeast Newfoundland. A larger area of metamorphic rocks, tonalites and mafic-ultramafic complexes, the Dashwoods Subzone, extends from Grand Lake to Port aux Basques of southwest Newfoundland.

The Notre Dame and Exploits subzones have numerous contrasts as follow: (a) Early to early Middle Ordovician faunas of the Notre Dame Subzone have North American affinities whereas those of the Exploits Subzone have Celtic affinities, (b) the Notre Dame Subzone was affected by Taconic Orogeny whereas nearby parts of the Exploits Subzone are unaffected, (c) the subzones have different plutonic histories, (d) the Exploits Subzone contains more sedimentary rocks and mélanges, (e) lead isotopic signatures in volcanogenic sulphide deposits are different in each zone, and (f) structural inliers of the Gander Zone (Mount Cormack and Meelpaeg subzones) are confined to the Exploits Subzone.

The Notre Dame Subzone has one of the widest ophiolite recurrences in the Appalachian Orogen (the Birchy-Advocate-Point Rousse-Betts Cove corridor). The stratigraphic order of ophiolitic units is toward the east or southeast. The overall structural arrangement indicates westward verging imbricate slices with eastward-facing stratigraphy. Intensity of deformation and metamorphism decreases progressively from west to east, or upward through this structural pile.

Recent U-Pb zircon geochronological studies indicate that the Notre Dame Subzone ophiolites are Early Ordovician and about the same age as the Bay of Islands Complex. Ophiolitic components of the Birchy Complex at the Baie Verte-Brompton Line are structurally commingled with metaclastic rocks of the internal Humber Zone, and some may have been oceanic basement to the eastern depositional edge of the metaclastic rocks.

The Exploits Subzone is a composite and structurally complex collection of rocks of varying ages, geochemical groupings and tectonic environments. U-Pb zircon dating of the volcanic sequences within the Victoria Lake Group has identified three age groupings; 513 ± 2 Ma for the Tally Pond volcanics, 498 +6/-4 Ma for the Tulks Hill volcanics, and 462 +4/-2 Ma for the Victoria Mine sequence. The Roebucks quartz monzonite, intrusive into the Tulks Hill volcanic rocks, is dated at 495 ± 4 Ma and is probably coeval with the volcanism. Two large plutons, the Valentine Lake and Cripple Back Lake quartz monzonites, dated as 563 ± 2 Ma and 565 +4/-2 Ma, are late Precambrian, and interpreted to be structurally emplaced within the Victoria Lake Group.

Mélanges occur all across the northeast Exploits Subzone. These include the Dunnage, Dog Bay Point, and Carmanville mélanges from west to east. The mélanges have been interpreted mainly as major slumps. However, some features are difficult to explain by simple surficial slumping; such as structural and metamorphic variations in the Carmanville Mélange that imply tectonic recycling, injection of resistive volcanic blocks by dykes of pebbly shale, and the Dunnage Mélange is the locus for contemporary intrusions.

The Twillingate Subzone contains a large tonalite batholith dated at 510 Ma. It cuts mafic volcanic rocks and it is older than ophiolite suites of the Notre Dame and Exploits subzones. Amphibolite facies metamorphism, intense deformation, and mylonitization along the southern margin of the Twillingate Subzone are out of context with adjacent, younger, less metamorphosed and less deformed rocks of the Notre Dame Subzone.

The Indian Bay Subzone has volcanic rocks and fossiliferous sedimentary rocks typical of the Dunnage Zone, but they occur within the northeast Gander Zone.

The Dashwoods Subzone has metaclastic rocks that are possible Humber Zone correlatives. These may represent Humber inliers in the western Dunnage Zone. Where Humber metaclastic rocks and Dunnage ophiolitic rocks are structurally commingled, metamorphosed, and intruded together, a Humber-Dunnage distinction is impractical.

New Brunswick

Six subzones are recognized in the New Brunswick Dunnage Zone. North of the Rocky Brook-Millstream Fault, the Belledune, Elmtree, and Popelogan subzones occur in two discrete Ordovician inliers that are surrounded by middle Paleozoic rocks of the Chaleurs Uplands. South of the Rocky Brook-Millstream Fault, the Armstrong Brook, Bathurst, and Hayesville subzones occur in the Miramichi Highlands (Fig. 3.80).

The Belledune Subzone contains the Devereaux and Point Verte formations. The Devereaux Formation has ophiolitic components of mainly gabbros, dykes, and basalts. Its isotopic age of 463 ± 1 Ma is significantly younger than the ophiolite suites of the Newfoundland Dunnage Zone. The Point Verte Formation consists of basalt, greywacke, shale, limestone, and chert. Most of its basalts are alkalic, atypical of ophiolitic suites.

Sedimentary and volcanic rocks of the Elmtree Subzone (Elmtree Formation) are compositionally similar to rocks in the Tetagouche Group of the Bathurst Subzone. Their age is probably Llanvirn-early Caradoc, like other Ordovician volcanic rocks in northern New Brunswick. A 1-2 km thick mélange, characterized by chaotically deformed sedimentary rocks, separates the Elmtree Formation and overlying Pointe Verte Formation. The mélange is interpreted as a major thrust zone that superposes older rocks above younger rocks.

Volcanic rocks of the Popelogan Subzone (Balmoral Group) have a chemistry unlike those of the Belledune Subzone and subzones south of the Rocky Brook-Millstream Fault.

The Armstrong Brook Subzone has basalts that are primitive tholeiites with Mid-Ocean Ridge Basalt (MORB) characteristics, including flat rare earth element (REE) patterns. These basalts have a thin, discontinuous layer of mylonitic gabbro at their base along the contact with underlying, very highly strained blueschists. The blueschists are part of an alkalic basalt suite, which is chemically similar to the Llandeilo high-Cr alkalic basalts of the Pointe Verte Formation in the Belledune Subzone.

The Tetagouche Group of the Bathurst Subzone is dominated by a large complex of felsic metavolcanic rocks that have compositions mainly ranging from dacite to rhyolite. The lowest parts of the Tetagouche Group include shallow-water deposits that disconformably overlie relatively deep-water turbidites of the Miramichi Group (Gander Zone). Quartzite and phyllite pebbles derived from the Miramichi Group are locally abundant in felsic agglomerates of the Bathurst Subzone, suggesting that the felsic volcanic magma came up through crust underlain by the Miramichi Group. This supports other indications that both the Miramichi and Tetagouche groups are underlain by a common continental crust.

A conglomerate similar to the basal Tetagouche Group marks the Penobscot unconformity in Maine. This phase of development in nearby New Brunswick was apparently unrelated to pentrative deformation and immediately preceded extrusion of volcanic rocks.

Although some of the felsic volcanic rocks in the Bathurst Subzone are autochthonous or parautochthonous with respect to the underlying clastic sedimentary rocks of the Miramichi Group, most volcanic rocks are allochthonous.

Ordovician stratigraphy of the Hayesville Subzone is similar to that in the Bathurst Subzone to the north.

There are important differences between the Armstrong Brook and Bathurst subzones: (1) north of their tectonic boundary, basalts are compositionally like those found at mid-ocean ridges or are intermediate between mid-ocean ridge and island-arc tholeiites whereas to the south the volcanic rocks are typical of a continental margin rift sequence; (2) no silicic volcanic rocks are interlayered with basalts of the Armstrong Brook Subzone; (3) the sedimentary rocks overlying basalts in the Armstrong Brook Subzone contain numerous limestone lenses and coarse, thick-bedded quartz- and feldspar-rich lithic wackes as in the Pointe Verte Formation, which are rare or absent in the Bathurst Subzone; and (4) red phyllite, chert, jasper, and Zn-Pb-Cu-Ag type massive sulphides, typical of metalliferous sediments found in the Bathurst Subzone, are absent in the Armstrong Brook Subzone, which contains only one Cyprus type Cu-pyrite sulphide prospect, *i.e.*, Middle River Copper.

Lower to Middle Ordovician rocks in the Bathurst and Hayesville subzones are similar to rocks of the Exploits and Indian Bay subzones in Newfoundland, and all contain the same faunas. The correlation with the Exploits Subzone is further strengthened by isotopic dates of volcanic units and similarities between lead isotopes from massive sulphides of the Bathurst and Exploits subzones.

Quebec

The Dunnage Zone of Quebec is divided into the Estrie-Beauce, Mégantic, Témiscouata, and Gaspésie subzones from southwest to northeast. Marine volcanic and sedimentary rocks range in age from Early Ordovician to Early Silurian. Rocks of the Estrie-Beauce, Témiscouata, and Gaspésie subzones are interpreted as laterally equivalent. The Mégantic Subzone has different rocks and stratigraphy.

The Estrie-Beauce Subzone comprises three tectonostratigraphic units: (1) the Saint-Daniel Mélange, which includes the ophiolite complexes at Thetford-Mines, Asbestos, and Mount Orford, (2) the Ascot Complex, and (3) the Magog Group. High-grade metamorphic rock slices in the Saint-Daniel Mélange are correlated with the Chain Lakes Massif and the mélange contains olistoliths of Caldwell sandstones of the internal Humber Zone. The Ascot Complex has three distinctive lithotectonic domains that are dominated by felsic volcanic rocks. These are separated by chaotic phyllites correlated with the Saint-Daniel Mélange. The Magog Group is a 10 km-thick flysch-dominated sequence of Late Llandeilo to Early Caradoc age that unconformably overlies the Saint-Daniel Mélange.

The Témiscouata Subzone contains mainly mélange-type rocks that are separated from the allochthonous Québec Supergroup of the external Humber Zone by the Lac-des-Aigles Fault. Southeast of the fault, the chaotic Trinité Group is unconformably overlain by the Middle Ordovician to Lower Silurian Cabano Formation. The Cabano Formation is conformably overlain by the Llandovery Pointe-aux-Trembles and Lac Raymond formations which are in turn conformably overlain by the Silurian-Devonian cover sequence of the Gaspé Belt. Chaotic rocks of Trinité Group are correlated with the Saint-Daniel Mélange of the Estrie-Beauce Subzone and the Cabano Formation is correlated with the Magog Group. The Pointe-aux-Trembles and Lac Raymond formations are interpreted as arc-related volcanic and sedimentary suites, much like the Ascot Complex and Magog Group, but somewhat younger. Based on this interpretation, the Cabano/Pointe-aux-Trembles/Lac Raymond formations are included in the Témiscouata Subzone of the Dunnage Zone.

The Gaspésie Subzone is defined mainly on ophiolitic mélanges along the Shickshock-Sud Fault and at the periphyry of the Maquereau Inlier. Clastic sequences of Llanvirn to Caradoc age unconformably overlie mélanges as follow: (1) the Llanvirn Neckwick Formation of the basal Mictaw Group is unconformable upon the Rivière Port-Daniel Mélange, (2) the Llandeilo Dubuc Formation of the upper Mictaw Group overlies the Rivière du Milieu mélange, and (3) the Llanvirn Arsenault Formation rests unconformably on the McCrea mélange. The Silurian Chaleurs Group unconformably overlies the Mictaw Group.

A complete sequence from the basal Arsenault Formation to Silurian rocks of the Gaspé Belt may exist in the western part of the Aroostook-Percé Anticlinorium. This introduces difficulties in defining a Dunnage Zone-Gaspé Belt boundary. If the sequence is complete and gradational, the boundary is arbitrary as it is in the Témiscouata Subzone. If there is a hiatus between the Arsenault Formation and overling rocks (Garin Formation), the boundary is most reasonably placed at the hiatus. Nevertheless, a structural unconformity that is present in many other places is missing at this locality. A parallel situation exists in the Exploits Subzone of northeast Newfoundland where the Dunnage Mélange is overlain by Caradoc shales that are gradational with a greywacke unit that is Llandovery at its top.

The Mégantic Subzone includes volcanic and sedimentary rocks of the Clinton Formation and the ophiolitic Chesham Mélange, which is correlated with the Hurricane Mountain Mélange of Maine. The Frontenac Formation is removed from the Mégantic Subzone as its age is Silurian-Devonian (Tremblay et al., addenda in Chapter 3).

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.

Similar chemical trends suggesting island arc as well as other volcanic regimes are established for rocks of the Exploits Subzone.

Lower Ordovician (Arenig-Llanvirn) black shale and limestone occurrences throughout both the Notre Dame and Exploits subzones are sporadic, localized, widely separated, and all of somewhat different ages. The situation suggests evolving, multiple Early Ordovician tectonic

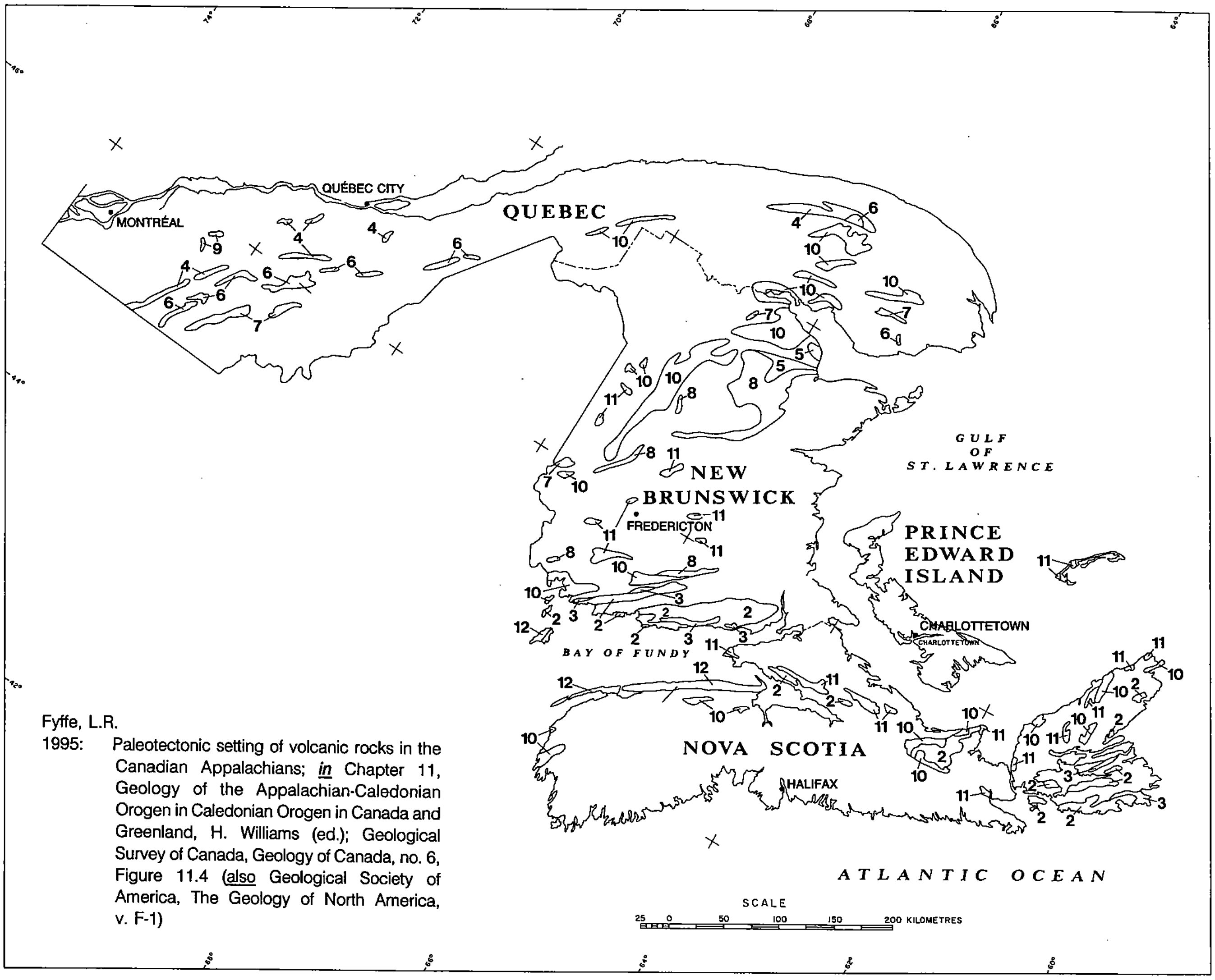

Figure 11.4. Paleotectonic setting of volcanic rocks in the Canadian Appalachians (compiled by L.R. Fyffe, 1991).

elements without significant continuity, even within a particular subzone. The idea of a Dunnage collage in Newfoundland is also supported by: (a) the transitional chemical affinities of most Dunnage ophiolite suites, implying that none represents the crust of a major ocean, (b) some volcanic rocks overlie an ophiolitic substrate but others contain zircons with inheritance from older crust, (c) volcanic rocks and tonalites of the Twillingate Subzone are older than surrounding ophiolite suites, and (d) late Precambrian ages for quartz monzonites (Valentine Lake and Cripple Back Lake) of the Exploits Subzone.

In New Brunswick, volcanic rocks of the Tetagouche Group are interpreted as a continental margin, rift sequence, produced in late Arenig/Llanvirn times. They formed during the opening of an ensialic back-arc basin, which subsequently developed into a marginal sea floored by upper Landeilo-lower Caradoc ophiolitic rocks of the Belledune and Armstrong Brook subzones. Other volcanic rocks of the Popelogan Subzone are interpreted as part of a Middle Ordovician volcanic arc.

In Quebec, the Ascot Complex of the Estrie-Beauce Subzone and correlatives may represent a dismembered volcanic arc complex. The Saint-Daniel, Trinité, and Gaspésie mélanges are probably all remnants of a single accretionary prism, and the Magog, Cabano-Pointe aux Trembles-Lac Raymond, and Mictaw-Arsenault units are overlying deposits of a forearc basin. Relationships suggest diachronous arc volcanism and forearc sedimentation; older in the southwest (Estrie-Beauce Subzone), and younger in the northeast (Gaspésie Subzone).

The Dunnage Zone is therefore a complex composite entity. Its definition is clearest where its volcanic sequences and mélanges are developed upon an ophiolitic substrate. However, other volcanic assemablages overlie continental rocks of the Gander Zone.

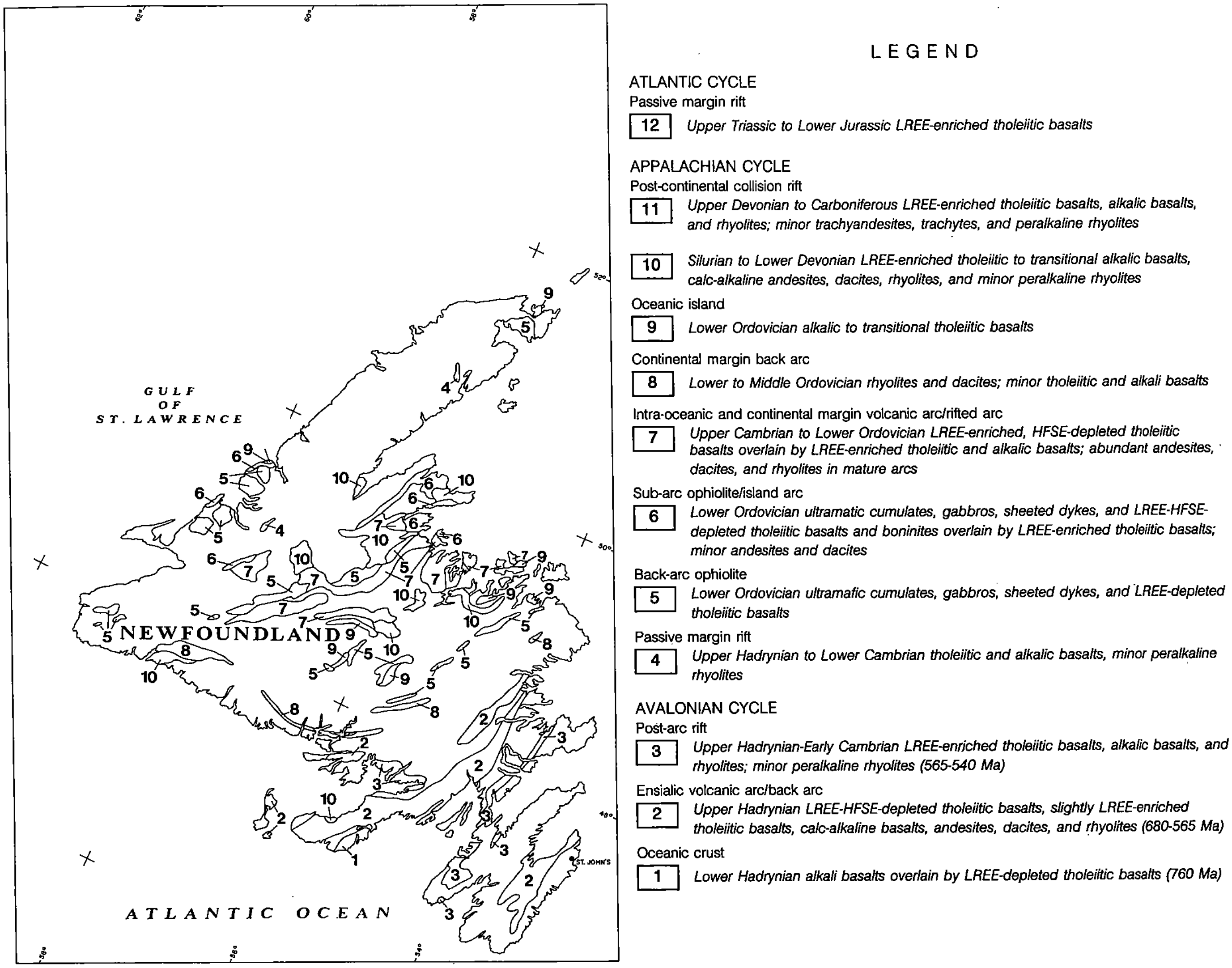

Figure 11.4. (cont.)

There is little evidence for Ordovician penetrative deformation in most of the Dunnage Zone, more than that its Ordovician mélanges indicate mobility, and that the makeup of clastic sedimentary sequences imply uplift and erosion. In many other places, even where Ordovican deformation is demonstrated by unconformable relationships, the deformation is mild compared to middle Paleozoic deformation.

Gander Zone

The type area of the Gander Zone is northeast Newfoundland where a thick monotonous sequence of polydeformed quartz greywacke, quartzite, siltstone and shale grade eastward into psammitic schist, gneiss and migmatite. These sedimentary rocks contrast with the mixed volcanic-sedimentary assemblages of mainly lower grade rocks of the bordering Dunnage and Avalon zones (Fig. 3.111a). The age of the Gander Zone sedimentary rocks in Newfoundland is constrained mainly by the age of its oldest cover rocks. These are Arenig to Llandeilo, and if the fossiliferous rocks are in stratigraphic contact with the monotonous clastic sequence, the Gander Zone clastics are mainly Early Ordovician and earlier. Tremadoc to middle-late Arenig graptolites occur in the clastic sequence of the Gander Zone in New Brunswick. An occurrence of *Oldhamia* in Gander Zone correlatives in Maine indicates a Cambrian age.

Clastic rocks of the type area in Newfoundland extend southward to Bay d'Espoir and crystalline rocks extend around the Hermitage Flexure to southwestern Newfoundland. However, the nature, or even the existence, of the Gander Zone in southwestern Newfoundland is debatable and most rocks there are now assigned to the Burgeo Subzone, a possible equivalent of the Bras d'Or Subzone of Cape Breton Island. The Aspy Subzone of Cape Breton Island is included with the Gander Zone because of plutonic and metamorphic styles, but most of its dated rocks are younger and atypical. In New Brunswick, the Gander Zone includes the clastic sequence of the Miramichi Group in the Miramichi Subzone, and clastic rocks of the Cookson Group in the St. Croix Subzone.

The Gander-Avalon boundary is a sharp tectonic junction in Newfoundland: the Dover and Hermitage Bay faults. An unconformity between a basal conglomerate on the Cheticamp Lake Gneiss of the Aspy Subzone and deformed diorite of the Bras d'Or Subzone in Nova Scotia indicates a depositional contact (Lin, 1993). If the Aspy Subzone is a Gander Zone equivalent, and the Bras d'Or Subzone an Avalon Zone equivalent, Gander and Avalon zones in Nova Scotia locally have the same late Precambrian plutons and Ordovician-Silurian cover rocks. In New Brunswick, the Gander-Avalon boundary is hidden by Silurian rocks.

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.

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

Rocks of the Gander Zone exhibit folded cleavages or schistosities and are almost everywhere more deformed than rocks in the adjacent Dunnage and Avalon zones. Coupled with evidence of Early to Middle Ordovician juxtapositioning with ophiolitic rocks of the Dunnage Zone, relationships hint at pre-Middle Ordovician deformation. The latest isotopic data suggest that major deformation and regional metamorphism are Silurian.

Newfoundland

The Newfoundland Gander Zone comprises three discrete subzones (Fig. 3.111a). The type area and its southward continuation is the Gander Lake Subzone. The inland areas are the Mount Cormack and Meelpaeg subzones. These inland subzones are structural windows or core complexes and relationships indicate a two-layer crust, with Dunnage Zone rocks above Gander Zone rocks. The Gander Zone was extended previously to include rocks between La Poile Bay and Grey River, Burgeo Subzone, chiefly because of metamorphic and plutonic styles, and because these rocks occur along strike with Gander Zone metamorphic and foliated plutonic rocks in the Hermitage Flexure. The Burgeo Subzone is now assigned to the Avalon Zone and correlated with rocks of the Bras d'Or and Aspy subzones of Cape Breton Island.

Three lithic units are recognized in the Gander Lake Subzone in the vicinity of Gander Lake and eastward (Fig. 3.11b). From west to east, these are the low grade clastic rocks of the Gander Group, low- to medium-grade metamorphic rocks of the Gander Group (Square Pond Gneiss), and medium- to high-grade metamorphic rocks of the Hare Bay Gneiss.

The Gander Group consists of interbedded psammite and pelite with quartz-granule sandstone and quartzite. Its depositional setting is uncertain. Sharp interbeds of quartz sandstone within pelite suggest distinct pulses of sand transport into a mud-dominated shallow marine or shelf environment. Thick, graded sandstone beds suggest turbidity currents and a deeper basinal setting. A major lithic change between the monotonous clastic sedimentary rocks and overlying mixed lithologies of the Indian Bay Subzone coincides with the unconformity between the Davidsville Group and Gander River Complex of the nearby Dunnage Zone.

The Square Pond Gneiss consists of psammitic and semipelitic metasedimentary rocks with zones of schist and migmatite. Psammite with a "pinstripe" or "herring bone" banding is characteristic. The Hare Bay Gneiss consists of migmatitic and tonalitic gneiss containing xenoliths and rafts of paragneiss and amphibolite. All contacts are now regarded as gradational.

Metamorphic rocks extend along the eastern margin of the Gander Lake Subzone to Bay d'Espoir on the south coast. There, the Little Passage Gneiss is correlated with the Square Pond and Hare Bay gneisses to the north. The boundary between the Little Passage Gneiss and rocks of the Dunnage Zone is a major ductile shear with left lateral sense of displacement. Isotopic ages indicate Silurian tectonism.

The Mount Cormack Subzone is an oval area of clastic rocks and metamorphic equivalents correlated with the Gander Group. It is surrounded, or almost so, by ophiolite complexes whose sequences of stratigraphic units everywhere face outwards from the Mount Cormack Subzone. Accordingly, the Mount Cormack Subzone is interpreted as a window of Gander Zone rocks exposed through an allochthonous cover of ophiolitic and volcanic-sedimentary rocks of the Dunnage Zone.

The Meelpaeg Subzone consists of psammitic rocks and metamorphic or migmatitic equivalents. These rocks are correlated with clastic rocks of the Mount Cormack Subzone and the Gander Group. Boundaries of the Meelpaeg Subzone are tectonic, where not truncated by intrusions.

In all parts of the Gander Lake Subzone there is a metamorphic progression southeastward that culminates in migmatitic gneisses intruded by syntectonic granitoid plutons. The juxtaposition of migmatites of the Gander Lake Subzone and greenschist or lower grade Precambrian rocks of the Avalon Zone is one of the sharpest metamorphic breaks at any zone boundary.

The Mount Cormack Subzone has a systematic progression of concentric metamorphic isograds that are roughly conformable with its oval outline (Fig. 3.114). From the periphery inward, they indicate a rapid increase in grade from greenschist to migmatitic upper amphibolite facies. The Through Hill Granite in the centre of the subzone has a variety of features that suggest an origin through anatexis of supracrustal rocks.

Structural styles, metamorphism, and plutonism are all consistent with the model of a major Dunnage allochthon above the Gander Zone. A two layer crust explains the presence of widespread granitic plutons throughout the ophiolitic Dunnage Zone and more intense metamorphism, migmatization and plutonism in the Gander Zone. Broad zones of ductile shearing were later. Where shearing affected rocks of both the Dunnage and Gander zones, structural, metamorphic and plutonic styles have no regard for the zone boundary.

Cape Breton Island, Nova Scotia

The Aspy Subzone is characterized by a variety of low- to high-grade metamorphic rocks intruded by Silurian-Devonian granitic rocks. It is included with the Gander Zone mainly because: (1) the Aspy Subzone lies between rocks of Humber affinity to the northwest and Avalon affinity to the southeast, (2) structural, metamorphic and plutonic styles of the Aspy Subzone are more akin to those of the Gander Zone than to any other zone, and (3) rocks of the Aspy Subzone were correlated with those of the Burgeo Subzone and the La Poile Belt of southwest Newfoundland. However, no monotonous psammitic sequence like that of the Newfoundland and New Brunswick Gander zones is present and there are no indigenous layered rocks of definite Ordovician or older age. Correlation with the Burgeo Subzone also suggests Avalon Zone affinity.

The Eastern Highlands shear zone and associated faults overprint the Aspy-Bras d'Or subzone boundary, that was originally stratigraphic (Lin, 1993). Seismic data suggest that the boundary dips to the south, and that the Bras d'Or Subzone is thrust against the Aspy Subzone. This is consistent with the presence of southerly dipping thrusts within the Eastern Highlands shear zone. The Chéticamp Pluton and associated diorites and gneisses in the western part of the Aspy Subzone suggest Bras d'Or Subzone affinities.

The stratified rocks of the Aspy Subzone are greenschist to amphibolite facies phyllites and schists, and upper amphibolite facies gneisses of volcanic and sedimentary protoliths. A diverse suite of mainly Silurian and Devonian plutons, which range from strongly foliated to massive, is a distinctive feature.

Complex deformation and metamorphism, combined with poor exposure, make it difficult to determine whether tectonic or stratigraphic breaks exist within the metavolcanic-metasedimentary sequences, and the relations among phyllites, schists, and gneisses are controversial. U-Pb zircon ages of felsic volcanic rocks indicate that they are early Silurian. Mafic volcanic units have petrological characteristics like those of volcanic-arc tholeiites, and are interpreted to have formed in a subduction zone. Metamorphism and protracted deformation occurred during Silurian to Devonian. The latest model has the Aspy Subzone as an island arc separated from the Bras d'Or Subzone by a small back-arc basin (Lin, 1993).

New Brunswick

The New Brunswick Gander Zone is characterized by a thick, complexly deformed sequence of Cambrian-Ordovician quartz sandstones and pelite that constitute the Miramichi and Cookson groups in the Miramichi and St. Croix subzones, respectively. Inclusion of the St. Croix Subzone extends the Gander Zone of New Brunswick southward to the Avalon Zone boundary, corresponding with its limits in Newfoundland. This boundary in New Brunswick is mainly hidden by Silurian to Lower Devonian volcanic and sedimentary rocks of the Mascarene Belt. The St. Croix Subzone is separated from the Miramichi Subzone by Silurian turbidites of the Fredericton Belt (Fig. 3.80). A wedge of complexly deformed pelite and psammite of Gander aspect has recently been recognized along the Fredericton Fault, which transects the central portion of the Fredericton Belt.

The Miramichi Group in the northern part of the Miramichi Highlands consists of dark grey to black, locally graphitic shales, rhythmically interbedded with medium- to thick-bedded, light grey to olive-green, graded quartz sandstones. Greenschist-facies quartz sandstones and shales in the central Miramichi Highlands pass westward through a steep metamorphic gradient into amphibolite-facies rocks. These are thin banded, fine grained amphibolites which contain dark green hornblende-rich bands alternating with light grey plagioclase-rich bands. The amphibolites are interlayered with cordierite-andalusite-bearing pelites and psammites, and with granitic gneiss containing microcline augen. The granitic gneisses were originally interpreted as Precambrian basement to the Miramichi Group. U-Pb ages are Ordovician.

The St. Croix Subzone contains black carbonaceous slate and minor thin-bedded wacke overlain by a pillowed basalt member and a thick sandstone-rich sequence at the top. Graptolites from the base of the sequence are Early Ordovician (Tremadoc), and Caradoc near its top. Northeast of the Saint John River, a thick steeply dipping volcanic succession is included in the subzone.

The tectonometamorphic history of the Gander and Dunnage zones of New Brunswick are remarkably similar. There is no correspondence between structural styles and stratigraphic divisions. At least five generations of structures have been recognized by overprinting relationships. These are interpreted as part of one continous orogenic event that is constrained between the Late Ordovician and Middle Devonian. The earliest structures are interpreted to have formed by progressive thrusting in an accretionary wedge (Fig. 3.97). Exhumation of parts of the accretionary wedge started at least in the Early Silurian.

Avalon Zone

The Avalon Zone is defined in most places by its well preserved upper Precambrian sedimentary and volcanic rocks and overlying Cambrian-Ordovician shales and sandstones. In a few places it is defined by isotopic ages and intrusive relationships. The Avalon Terrane or Avalon Composite Terrane are other names for the Avalon Zone.

The Avalon Zone (Maps 1 and 2, and Fig. 3.126) is the broadest of Canadian Appalachian zones and is more than twice the combined width of zones to the west in its type area of Newfoundland. It is much narrower in Nova Scotia and southeast New Brunswick.

Boundaries of the Avalon Zone are major faults. In Newfoundland, its western boundary is the Dover-Hermitage Bay Fault. In New Brunswick, its western boundary is the Belleisle Fault or the Taylor Brook Fault farther west. The

Burgeo Subzone is a recent extension of the Avalon Zone in Newfoundland. Ambiguity exists regarding the full extent of the Avalon Zone in Cape Breton Island, Nova Scotia. One interpretation places the northwestern Avalon boundary between the Bras d'Or and Mira subzones; another suggests that all of Cape Breton Island, including Grenvillian basement at its northwest extremity, belongs to the Avalon Zone. The southern boundary of the Avalon Zone with the Meguma Zone is the Cobequid Fault of Nova Scotia. These faults disrupt the continuity of lithic belts within the Avalon Zone and account for its extreme variability in width from Newfoundland to New Brunswick.

The upper Precambrian sedimentary and volcanic rocks were affected by late Precambrian Avalonian Orogeny, expressed by granite plutonism and generally mild deformation. More intense Precambrian deformation occurs locally. Middle Paleozoic orogeny was intense, especially where the zone is narrow in Nova Scotia.

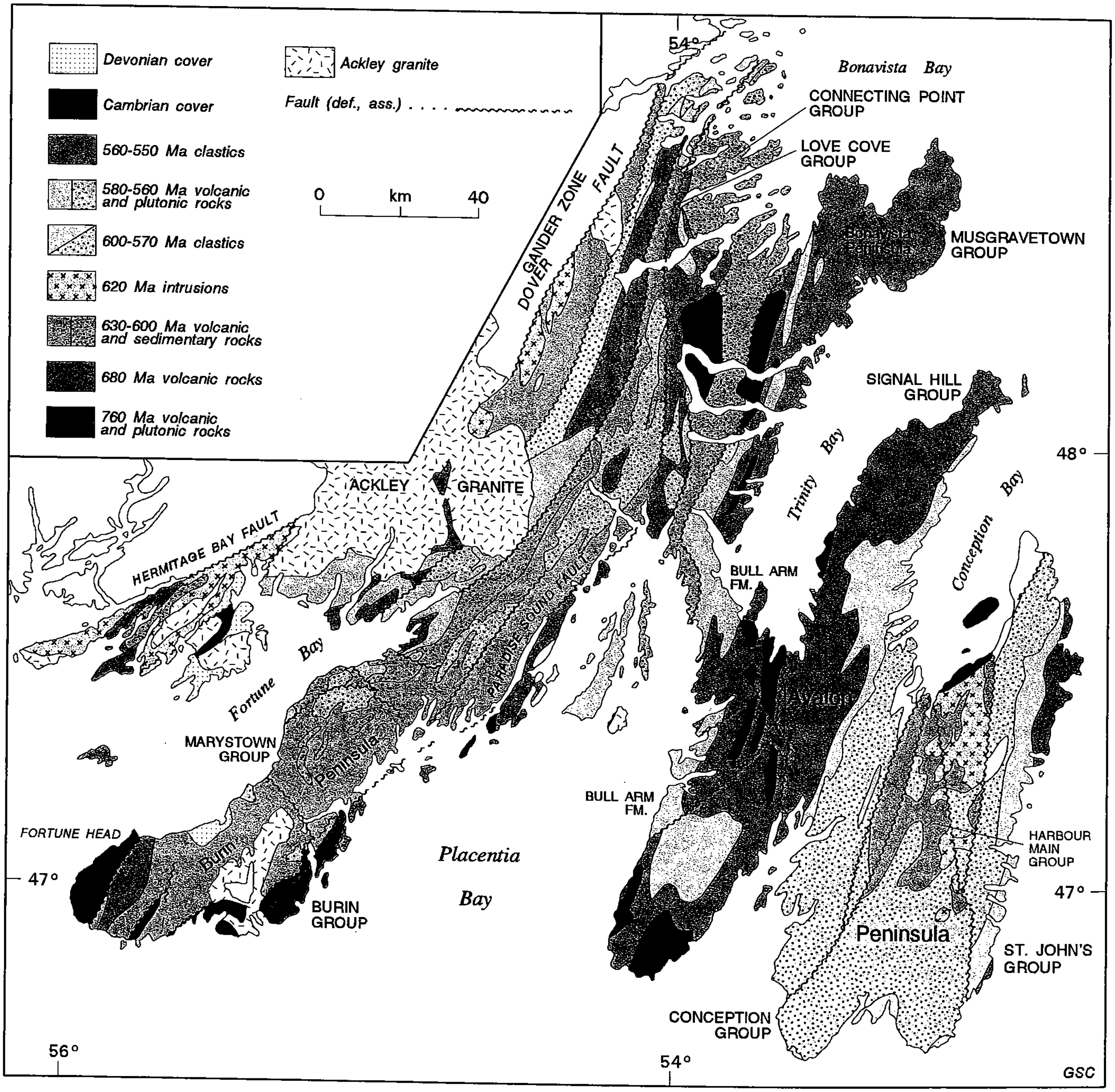

Figure 11.5. Divisions of the Newfoundland Avalon Zone by age (after O'Brien et al., 1990).

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

Newfoundland

The oldest rocks of the Newfoundland Avalon Zone are those of the Precambrian Burin Group, a mixed assemblage of sedimentary and volcanic rocks with a stromatolite-bearing carbonate olistostrome near its base. A comagmatic gabbro sill is dated at 763 +2.2/-1.8 Ma. The rocks occur in a fault-bounded area.

Later Precambrian rocks underlie most of the type area of the Avalon Peninsula and similar rocks occur west of the Avalon Peninsula (Fig. 3.128). They are separable into three lithological units that have at least local stratigraphic significance: a basal volcanic unit dominated by ignimbrites and volcanic breccias; a middle marine sedimentary unit of grey-green sandstones, siltstones, and siliceous argillites overlain by shales and sandstones; and an upper unit of terrestrial sedimentary and volcanic rocks dominated by red and grey sandstones and conglomerates.

The basal volcanic unit has several kilometres of felsic to mafic, subaerial to submarine volcanic rocks. Original textures of ignimbrites, welded tuffs, and flow-banded rhyolites are remarkably well-preserved.

The middle marine unit is dominated by green to grey siliceous fine grained sedimentary rocks. It also includes conglomerate, mixtite of glacial origin, tuff, agglomerate, minor pillow lava, and mafic dykes. Its thickness in the southern Avalon Peninsula is about 4.5 km. Some clasts in Precambrian glacial deposits, such as quartzite, foliated granite, and detrital garnets are exotic to the Newfoundland Avalon Zone. Casts and impressions of soft-bodied metazoans of *Ediacaran* type are known from the top of the unit.

The upper unit of terrestrial sedimentary and volcanic rocks has a thickness in excess of 5 km. Volcanic rocks occur locally at or near the base of the section. In other places, grey sandstones at the base represent a transition from shallow marine to subaerial environments. Thick bedded red arkosic sandstones and red conglomerates higher in the succession indicate a major shoaling- and coarsening-upward cycle.

Precambrian-Cambrian relationships are variable, though well known, throughout most of the Newfoundland Avalon Zone. Preserved sections of upper Precambrian rocks in places pass upwards into Cambrian strata without significant disconformity. This is exemplified by the section at Fortune Head that is the Precambrian-Cambrian boundary stratotype. In other places, unconformities are common both within the upper Precambrian successions and below the Cambrian cover.

Late Precambrian intrusive rocks are common. One suite, dated isotopically from 620 to 580 Ma, consists of hornblende and biotite granite, granodiorite, and diorite with calc-alkaline affinities. Its isotopic ages and field relations demonstrate a coeval relationship with the basal volcanic unit. Another suite of smaller plutons, confined to the western part of the Avalon Zone, consists of gabbro, alkali granite, riebeckite peralkaline granite, and related hybrid rocks. Preliminary Rb-Sr ages for this suite are from 560 to 540 Ma. These intrusions are peralkaline and probably related to volcanic rocks at the base of the upper terrestrial unit.

Evidence for late Precambrian Avalonian Orogeny is provided by granite intrusion, block faulting, gentle folding, and low grade regional metamorphism. High strain zones and penetrative fabrics indicate local intense Precambrian deformation. The effects of Paleozoic deformation, plutonism, and regional metamorphism decrease eastward and locally Cambrian-Ordovician rocks of the eastern Avalon Peninsula are subhorizontal.

In the western Avalon Zone of the Hermitage Bay Peninsula, at least four prominent orogenic events are recognized: ca. 760 Ma, ca. 680 Ma, ca. 630-600, and ca. 575-550 (O'Brien et al., 1990, 1992, 1994). Intrusive relations and ductile shears in Precambrian rocks that are unconformably overlain by other upper Precambrian rocks demonstrate distinctive tectonic events that occurred at least twice prior to the deposition of a Cambrian platformal cover. Coeval Precambrian tectonic events are recorded in similar Precambrian rocks in the Burgeo Subzone. There, the Precambian rocks have an unconformable Silurian cover and the northern boundary of the Burgeo Subzone was the locus of a widespread and complex Silurian tectonothermal event which reactivated funadamental Precambrian structures (O'Brien et al., 1992).

A recent subdivision of Precambrian rocks of the Newfoundland Avalon Zone based on isotopic ages is depicted in Figure 11.5. Differences between this subdivision and the broad lithic correlations (Fig. 3.128) imply major facies changes and/or separate terranes within the Newfoundland Avalon Zone.

Nova Scotia

Rocks of the Avalon Zone in Nova Scotia occur in Cape Breton Island, the Antigonish Highlands and Cobequid Highlands. The Mira Subzone of southeastern Cape Breton Island has upper Precambrian volcanic and sedimentary rocks overlain by Cambrian-Ordovician rocks typical of the Avalon Zone in its type area. The adjoining Bras d'Or Subzone to the north is regarded as Avalonian in some analyses because: (1) its Precambrian marbles and quartzites of the George River Group are correlated with the Green Head Group of the Avalon Zone in New Brunswick, and (2) it has Cambrian shales with a fauna typical of the Avalon Zone, although the Cambrian rocks may be allochthonous. Another view defines the Avalon Zone on its Cambrian-Ordovician overstep sequence that contains an Acado-Baltic fauna, and/or its Silurian-Lochkovian cover that contains a Rhenish-Bohemian fauna, and all of Cape Breton Island is assigned to the Avalon Zone. Whether or not Cape Breton Island represents a narrow cross-section of the entire Appalachian Orogen, or an oblique section of the Avalon Zone with progressively deeper levels from southeast to northwest, is debatable. Expressed in another way, does the Iapetus suture cross Cape Breton Island or does it lie offshore to the north?

The oldest rocks of Cape Breton Island are ortho- and paragneisses and amphibolites in the Blair River Complex, with metamorphic ages of about 1000 Ma. Strongly deformed metasedimentary rocks of the George River Group and correlatives consist of quartzite, carbonate, greywacke, slate and minor metavolcanic rocks. These may also be affected by events in the order of 1000 Ma. Contacts between gneisses and metasediments are tectonic.

Upper Precambrian rocks in the Mira Subzone (Fig. 3.126) are subaerial and shallow marine pyroclastic rocks, flows, and small intrusions. In the Antigonish Highlands they consist of a bimodal sequence of basalt, basaltic andesite, and rhyolite overlain by a thick succession of turbidites with volcanic clasts, and minor basalts. Overlying turbidites are tuffaceous, green and siliceous. In the northern and western Cobequid Highlands, the upper Precambrian rocks have a similar stratigraphy and volcanic geochemistry to those of the Antigonish Highlands.

In the Mira Subzone, the upper Precambrian rocks are overlain by Cambrian-Ordovician sediments with an Acado-Baltic fauna. In the Boisdale Hills of the Bras d'Or Subzone, a Middle Cambrian section contains a thick bimodal volcanic suite. In the Antigonish Highlands, Cambrian-Ordovician sediments rest unconformably upon deformed upper Precambrian rocks. Bimodal volcanic rocks are interbedded with the Lower Cambrian sedimentary rocks.

Plutonic rocks are common throughout the Avalon Zone of Nova Scotia and they fall into two age groups: about 635-600 Ma and about 565-490 Ma. The calc-alkaline geochemistry of the older group of plutons suggests that they are genetically related to coeval volcanic rocks. Unlike southern Cape Breton Island, the plutons in the Antigonish and Cobequid highlands cut polydeformed volcanic-sedimentary rocks. However, ages indicate that sedimentation, deformation, and intrusion were penecontemporaneous.

The younger group of plutons may be the subvolcanic equivalents of upper Precambrian-Cambrian volcanic rocks.

New Brunswick

The Avalon Zone of New Brunswick has mainly upper Precambrian to Lower Cambrian volcanic, sedimentary, and intrusive rocks. Most of the upper Precambrian volcanic rocks are assigned to the Coldbrook Group. It is inferred to overlie carbonates and clastic rocks of the Green Head Group, including the spatially associated Brookville Gneiss. It is overlain by redbeds of the Ratcliffe Brook Formation and shales of the Cambrian-Ordovician Saint John Group. Isotopic dates define two groups of intrusions at about 600-550 Ma and 547-510 Ma.

Metacarbonates and clastic sedimentary rocks of the Green Head Group and Brookville Gneiss are either basement to the Coldbrook Group or a separate unrelated terrane (Fig. 3.144). The Green Head Group consists of a lower mainly carbonate unit (Ashburn Formation) and an upper mainly clastic unit (Martinon Formation). Stromatolites in the Ashburn Formation suggest a mid Proterozoic age (1400-1000 Ma). The Brookville Gneiss consists of a diapiric core of orthogneiss surrounded by a mantle of paragneiss, largely formed from the Green Head Group. One isotopic age of about 605 Ma and another that defines a maximum age of 641 Ma suggest that the Brookville Gneiss is much younger than previously considered. Its contact with the Green Head Group is tectonic.

The Martinon Formation may be equivalent to the lower part of the Coldbrook Group as: (1) it unconformably overlies other rocks with the contact marked by a distinctive marble conglomerate, (2) it is of turbiditic origin and therefore sedimentologically different from Ashburn carbonates, and (3) it contains numerous basalt sills suggesting that it is akin to volcanic rocks of the Coldbrook Group.

The contact between the Green Head Group and Coldbrook Group was considered to be an unconformity because of the more deformed and metamorphosed nature of the Green Head Group. If the Martinon Formation is equivalent to the lower part of the Coldbrook Group, an unconformity is expected.

Three lithological divisions are recognized in the Coldbrook Group: (1) a subaqueous sequence, at least 5000 m thick, that is dominated by fine grained mafic and felsic tuffaceous rocks, massive and pillowed mafic flows, greenish grey and purple siltstone, and greenish grey sandstone; (2) a subaerial sequence, several kilometres thick, composed of felsic and lesser mafic volcanic rocks with minor sedimentary rocks; and (3) a turbiditic sequence of greenish, thin bedded, siliceous siltstones and sandstones (Fig. 3.145).

Volcanic rocks of the first division are the oldest and approximately coeval with granite and diorite dated at 600-550 Ma. Those of the second division are terrestrial with ages of about 547-510 Ma and in part co-magmatic with syenogranitic and gabbroic plutons. Volcanic rocks of both divisions are mainly bimodal. Other volcanics of the Coldbrook Group are calc-alkalic.

The Ratcliffe Brook Formation is predominantly a redbed sequence with minor limestone (Fig. 3.146). The lithology and stratigraphy of these rocks are distinct from Cambrian shales of the Saint John Group. They unconformably overlie pillow basalt of the Coldbrook Group and a 625 Ma granite east of Saint John. The redbeds postdate the main Coldbrook volcanism and they are overlain by trilobite- bearing Cambrian rocks.

The first episode of deformation is related to the emplacement of Brookville orthogneiss diapirs into the Green Head Group. U-Pb zircon ages indicate that this deformation is much younger than previously considered. The fact that amphibolite grade metamorphism only occurs in Green Head rocks that are spatially associated with Brookville gneisses, suggests that metamorphism and orthogneiss emplacement were coeval. This style of deformation does not affect the Coldbrook Group or younger rocks.

Correlations and interpretation

Marbles and quartzites of the George River and Green Head groups were interpreted as a cover sequence above crystalline basement, but contacts are tectonic and this interpretation is not supported by the latest isotopic ages. If stromatolitic blocks in the Newfoundland Burin Group are correlatives of the stromatolitic Green Head Group, the marbles and quartzites are older than the 763 Ma age of the Burin Group. Since the Burin Group has ophiolitic chemical affinities, implying the existence of oceanic crust, possibly its stromatolitic blocks were derived from a contemporary carbonate platform. Correspondence in age, composition, and regional setting of the Burin Group with Pan African ophiolitic rocks suggest African links.

Upper Precambrian volcanic and sedimentary rocks, dated at about 600 Ma, are the products of extensive subaerial and submarine eruptions and they occur in Newfoundland, Nova Scotia, and New Brunswick. In the type area of the Avalon Peninsula in Newfoundland, the volcanic rocks are high alumina, low titanium basalts of transitional to mildly alkaline chemical affinity. West of the Avalon Peninsula, they are calc-alkaline and tholeiitic. In Nova Scotia, correlative basalts are tholeiites of continental rift affinity, others are calc-alkalic basaltic andesites, and associated rhyolites have volcanic arc affinities. In New Brunswick, lower parts of the volcanic sequence are calc-alkaline. Almost everywhere, these volcanic rocks are coeval with voluminous calc-alkaline, diorite-granodiorite-granite intrusions without significant metamorphism or structural complications. The geochemistry of the volcanic rocks of southern Cape Breton Island and southern New Brunswick indicates that they were erupted in a volcanic arc environment. In both regions, the mafic rocks display a remarkably similar compositional zonation which resembles the across-arc variations observed in modern volcanic arcs. The progressive compositional changes that include a transition from island arc tholeiites along the southeastern coasts to calc-alkaline rocks inland to the northwest, suggest a northwest-dipping subduction zone with a trench located to the southeast.

This volcanic-plutonic activity was at least in part contemporaneous with sedimentation in deep marine basins. The extremely thick basin-fills in Newfoundland include complex successions of turbidites with tillites and olistostromes. Similar marine successions of mainly greenish siliceous rocks occur in Nova Scotia and New Brunswick. This phase of development may have lasted for about 50 Ma.

The discrete occurrences of upper Precambrian rocks in Cape Breton Island, Antigonish Highlands, and Cobequid Highlands of Nova Scotia are viewed as part of a single magmatic-volcanic complex. A model of a rifted ensialic magmatic arc floored by continental basement is favoured. Diachronous deformation associated with opening and closing of intra-arc rifts may have controlled Avalonian Orogeny.

The mild effects of Paleozoic and late Precambrian deformation on the wide Newfoundland Avalon Zone suggest that the present configuration of alternating upper Precambrian volcanic and sedimentary belts is a relict of late Precambrian evolution. The pattern indicates volcanic ridges flanked and separated by marine sedimentary basins. A modern analogue for the alternating volcanic and sedimentary belts in Newfoundland may be the Marianas region of the Pacific Ocean. This model is supported by a comparison of the upper Precambrian marine sedimentary rocks and recent counterparts in basins adjacent to existing island arcs.

Comparisons between the late Precambrian evolution of the Avalon Zone and Pan-African terranes suggest similar tectonic controls and support a late Precambrian accretionary model for the Canadian Avalon Zone.

Upper Precambrian to Cambrian terrestrial clastic rocks were deposited as shoaling-upward fan-deltas and alluvial fans within fault-bounded basins. Associated volcanic rocks are terrestrial bimodal suites. Comagmatic plutons are strongly alkaline or peralkaline and dated at about 550 Ma. These volcanic and sedimentary rocks are completely different compared to the older volcanic and sedimentary rocks. This phase of activity followed Avalonian Orogeny. It may be explained by a model of pull-apart basins or continental rift basins, like the Basin and Range Province of the western United States. If the isotopic ages of about 550 Ma are reliable, this phase of activity was penecontemporaneous with the rift-drift transition as defined in the stratigraphy of the Humber miogeocline, and a major episode of worldwide rifting. Other models relate this phase of activity to the final stages of an accretionary event. The choice here is between interpreting the upper Precambrian-Cambrian rocks as volcanics and molasse related to collisional tectonics, or the fill of rift basins formed in advance of imminent Cambrian subsidence and marine transgression.

The synchroneity of late Precambrian subduction beneath the Avalon Zone and rifting in the Humber Zone implies that the Avalon Zone was not located within the Iapetus Ocean. Paleomagnetic data suggest affinities with Gondwana and Armorica. Preservation of the mildly deformed Avalonian magmatic arc sequences contrasts with their structural styles and general absence in collisional orogens. This suggests that termination of late Precambrian subduction was not the result of continent-continent collision, but instead may reflect global plate reorganization associated with the breakup of a late Proterozoic supercontinent.

Meguma Zone

The Meguma Zone is defined by a thick siliciclastic sequence, the Meguma Supergroup, that ranges in age from Late Cambrian or older to Early Ordovician. It occupies all of the southern mainland of Nova Scotia and extends offshore (Fig. 3.149, Map 2). If its strata were unfolded, the restored width would exceed the present width of the Canadian Appalachians. The base of the Meguma Supergroup is not exposed. The boundary between the Meguma Zone and Avalon Zone is the Cobequid Fault (also called Glooscap Fault and Minas Geofracture).

The Meguma Supergroup is overlain by another thick siliciclastic succession, the Annapolis Supergroup of Silurian and Early Devonian age. The Annapolis Supergroup defines the Annapolis Belt. The separation of a Meguma Zone and Annapolis Belt is artificial as: (1) both zone and belt define the same geographic area; (2) some rocks of the Annapolis Supergroup are possibly Early Ordovician and therefore older than those normally found in middle Paleozoic belts; (3) Acadian Orogeny was the first major event to affect rocks of both the Meguma Zone and Annapolis Belt; and (4) the Meguma Supergroup and Annapolis Supergroup are viewed as integral parts of the same stratigraphic section and interpreted in the same model of an evolving continental margin. The Meguma Zone and Annapolis Belt are defined only to maintain the systematics of the time-slice subdivision used here. Both are integral parts of the Meguma terrane, since there are no established linkages until Carboniferous time.

Stratigraphy

The Meguma Supergroup is divided into the Goldenville and Halifax groups (Fig. 3.151). Contacts between all formations within these groups are gradational and conformable. The maximum measured thickness of the Goldenville Group is 6.7 km. The Halifax Group is 11.8 km. The overall minimal thickness of each group is about 7 km.

The contact with the overlying Annapolis Supergroup is a paraconformity, but locally it may be an angular unconformity, a disconformity, and a conformable contact. The contact has also been interpreted locally as a thrust. In general, uppermost strata of the Meguma Supergroup are marine whereas basal strata of the overlying Annapolis Supergroup are subaerial volcaniclastic rocks. Because fossils below the boundary are Tremadoc and those above are Caradoc or younger, a paraconformity is implied.

Provenance and depositional model

The dispersal pattern in the lower portion of the Meguma Supergroup is remarkably constant both regionally and stratigraphically. In general, the sedimentary transport direction is northward in the southwest exposure area, changing gradually through 90 degrees in the central area, to eastward in the far eastern extremity of the exposure area (Fig. 3.152). This dispersal pattern is very similar to recent depositional patterns at continental margins of the western North Atlantic.

Conservative palinspastic calculations indicate that the volume of the Meguma Supergroup in Nova Scotia is at least equal to a block with an area of Ontario and a height of 5 km.

Petrography of the Meguma Supergroup indicates that the source area was rich in quartz, biotite, and plagioclase but relatively poor in potash feldspar. The source area was vast, deeply eroded, cratonic, quartz-rich, granodioritic, and presumably of Precambrian age.

The uppermost part of the Meguma Supergroup along the northwest rim of the zone contains a diamictite that may be a glaciomarine tillite or drift-ice deposit. A relative drop in sea level, suggested by shoaling in the upper part of the Halifax Group, may reflect significant global glacioeustatic sea-level changes.

The model for deposition of the Meguma Supergroup is a continental margin. The Goldenville Group is interpreted as an ancient abyssal-plain fan. Thicker sandstone packages in the Goldenville Group are submarine-fan channel complexes flanked by raised levees; currents on the levees diverged from those in the channel axis. The Halifax Group is interpreted to be the mid- or upper-fan area of a muddy deep-sea fan, passing upwards into a prograding continental slope and shelf. The lower part of the group resembles modern deep-sea channel-levee complexes; the upper may have accumulated principally from turbidity currents on a rapidly prograding continental slope. The decrease in grain size from the Goldenville to Halifax groups probably results from submergence of the source-continent.

Summary and North Atlantic connections

Since the Meguma Zone was the last to accrete against eastern North America, its derivation should be the easiest to solve by trans-Atlantic correlation.

In terms of sequence stratigraphy, the Meguma Supergroup is a type 1 sequence, equivalent to a supercycle. The Goldenville and basal part of the Halifax groups comprise a low-stand systems tract of basin-floor fan overlain by a slope fan and prograding wedge. The upper part of the Halifax Group consists of transgressive systems and high-stand systems tracts. Although the Meguma Supergroup was deposited on a continental margin, its cycle corresponds in time with the Sauk cratonic sequence. Vectoral and scalar sedimentary structures indicate that the source-area lay to the present southeast.

Stratigraphic sections, provenance, sequence stratigraphy, paleontology, igneous petrology, and geophysics suggest that the Meguma Zone is a part of the continental margin of Gondwana, stranded against North America following Jurassic rifting. Other remnants are postulated in Mali, Mauritania, and southern Morocco. Rifting of the Gondwana margin created a plethora of microcontinents or microplates, including present parts of North Africa, the Middle East, central and southwestern Europe, eastern and western Avalonia, Florida, and the Meguma Zone.

There were several previous suggestions of correlation between the Meguma Supergroup of the Meguma Zone and the Gander Group of the Gander Zone, as both are thick siliciclastic sequences of about the same age. The correlation was always hampered because the two sequences are separated by the Avalon Zone. However, if the Avalon Zone was not part of the Iapetus Ocean, then both the Gander Group and Meguma Supergroup could have built up as a single unit at the eastern margin of Iapetus. The different accretionary histories of the Gander Group and Meguma Supergroup and the present arrangement of zones are circumstances of the complex closing history of Iapetus.

MIDDLE PALEOZOIC BELTS

Rocks of middle Paleozoic belts are less distinctive compared to those of early Paleozoic zones. There are no middle Paleozoic ophiolite suites, few mélanges, and other rocks that can be related to plate boundaries and plate interactions. Most of the rocks occur in successor basins with terrestrial rocks predominant. The belts are most extensive in Quebec, New Brunswick and Nova Scotia. From west to east, these are the Gaspé, Fredericton, Mascarene, Arisaig, Cape Breton, and Annapolis belts (Map 2 and Fig. 11.2). The middle Paleozoic record in Newfoundland is fragmentary and there is no correspondence between Newfoundland and mainland belts. From west to east the Newfoundland belts are Clam Bank, Springdale, Cape Ray, Badger, Botwood, La Poile, and Fortune. The broad offshore area of the Newfoundland Grand Banks has middle Paleozoic rocks unlike those of the onland orogen.

The belts are defined on lithological and stratigraphic contrasts, but some eastern mainland belts also have faunal, plutonic, and metallogenic distinctiveness. In areas affected by Ordovician deformation, the rocks of middle Paleozoic belts are unconformable on those of early Paleozoic zones. Thus 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 the oldest deposits of middle Paleozoic belts coincide 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 Exploits Subzone of the Dunnage Zone.

Where stratigrahic sections are conformable, Caradoc and older rocks are assigned to zones or subzones in most cases. Thus in central Newfoundland, Caradoc shales are assigned to the Exploits Subzone and conformable greywackes, above the shales, to the Badger Belt. However, Caradoc rocks are included in the Clam Bank Belt where they are part of the unconformable cover to rocks of the Humber Zone. Other problems arise in the Quebec Dunnage Zone where a mélange substrate has a Llanvirn or Llandeilo unconformable cover that is structurally conformable with Caradoc and Silurian rocks of the Gaspé Belt. One interpretation places a boundary at a hiatus between Llanvirn rocks and overlying conformable Caradoc rocks (Bourque et al., Chapter 4); another includes all of the Ordovician rocks and some Lower Silurian rocks in the Dunnage Zone (Tremblay et al., Chapter 3).

Stratigraphic sections of most middle Paleozoic belts show an upward change from marine to terrestrial rocks, with all rocks deformed together and cut by plutons. This change from marine to terrestrial conditions preceded middle Paleozoic orogenesis.

Quebec, New Brunswick, and Nova Scotia

Gaspé Belt

Middle Paleozoic rocks of the Gaspé Belt belong to three major structural divisions, from north to south, the Connecticut Valley-Gaspé Synclinorium, the Aroostook-Percé Anticlinorium and the Chaleurs Bay Synclinorium (Fig. 4.1 and 11.2).

The middle Paleozoic rocks are separable into four broad temporal and lithological packages (Fig. 4.2): (1) Middle Ordovician-lowermost Silurian (Llanvirn? to Llandovery) deep water fine grained siliciclastic and carbonate facies; (2) Silurian-lowermost Devonian (Llandovery to Lochkovian) shallow to deep shelf facies; (3) Lower Devonian (Pragian-Emsian) mixed siliciclastic and carbonate fine grained deep shelf facies; and (4) upper Lower to Upper Devonian (Emsian to Frasnian) nearshore to terrestrial coarse grained facies. Rocks of the Connecticut Valley-Gaspé and the Chaleurs Bay synclinoria are either in stratigraphic continuity with those of the Aroostook-Percé Anticlinorium, or contacts are faults. Along the northern margin of the Connecticut Valley-Gaspé Synclinorium, the middle Paleozoic sequence is unconformable above pre-Taconic rocks of the Humber Zone. In the Chaleurs Bay Synclinorium, the Silurian sequence is unconformable above the pre-Taconic Maquereau-Mictaw groups of the Humber Zone and rocks of the Elmtree Inlier in the Dunnage Zone. In southern Gaspésie and northern New Brunswick, the middle Paleozoic sequences are overlain unconformably by Carboniferous rocks.

Upper Ordovician-lowermost Silurian rocks occupied a relatively deep marine basin. Sedimentological studies of siliciclastic rocks suggest a source containing volcanic, metamorphic, sedimentary, plutonic and ultrabasic rocks, such as the Elmtree inlier to the south. A progressive change from deeper terrigenous deposition to shallower carbonate deposition reflects basin infilling with carbonate detritus derived from the contemporary Anticosti Platform to the northeast.

Palinspastic restoration of Gaspésie indicates that rocks of the northern part of the Gaspé Belt developed in an unstable shelf setting that followed the irregular course of the Humber Zone margin along the Gaspésie . Repetitions of facies belts in map pattern, implying repeated southward-facing shorelines, are explained by dextral offsets of a single shoreline on major transcurrent faults. Shallow marine shales on the south side of Chaleurs Bay are interpreted as part of the same shelf rather than an opposing shelf on the opposite side of the Gaspé depositional basin. Structural analysis supports a wrench tectonics model for Acadian deformation.

Three distinctive unconformities occur in the middle Paleozoic sequence of Quebec and adjacent New Brunswick (Fig. 4.3). The oldest unconformity corresponds to Taconic Orogeny. The second unconformity is dated as late Ludlow-early Pridoli and corresponds to the Salinic Disturbance recognized in Maine. It is either an angular unconformity or an erosional disconformity. The third unconformity is angular and separates Middle or Upper Devonian rocks from Carboniferous rocks. It corresponds to the Acadian Orogeny.

The Gaspé Belt is a successor basin located in the embayment at the junction between the Québec Reentrant and St. Lawrence Promontory of the Humber Zone. This Upper Ordovician to Middle Devonian basin was mostly sited above the Dunnage Zone between the already destroyed Taconic margin (Humber Zone, Fig. 4.14), and the Miramichi Subzone of the Gander Zone. Coeval volcanism was generated in an intraplate tectonic environment.

Fredericton Belt

The Fredericton Belt comprises a thick sequence of Silurian turbidites lying between the Miramichi and St. Croix subzones of New Brunswick. Basement relationships of the Fredericton Belt are unknown, but clastics of Gander Zone aspect are brought to the surface along the Fredericton Fault that transects the central portion of the belt (Fig. 3.80).

The Fredericton Belt has been interpreted as a remnant of a middle Paleozoic ocean that closed by subduction during Acadian orogenesis. This model is supported by the presence of Early Devonian Eastern Americas brachiopod assemblages in the Aroostook-Percé division of the Gaspé Belt to the northwest and Rhenish-Bohemian brachiopod assemblages in Silurian-Devonian rocks of the Mascarene Belt to the southeast. The absence of contemporary arc-volcanic rocks do not support the model and Nd-isotope studies on granites suggest that the crustal basement to the Fredericton Belt is similar to that of the St. Croix and Miramichi subzones. The Fredericton Belt has also been interpreted as a foredeep formed by tectonic loading in front of southward-advancing nappes. In this model, its Wenlock to Ludlow lithic wackes represent a clastic wedge that prograded over more mature Llandovery quartz wackes as the tectonic landmass of the Miramichi Subzone emerged to the northwest. Finer grained, calcareous beds to the southeast represent a distal facies.

Mascarene Belt

The Mascarene Belt of southern New Brunswick consists of a lithologically and structurally diverse sequence of Silurian to Lower Devonian volcanic and sedimentary rocks intruded by locally voluminous, Silurian-Devonian mafic intrusions, granitoid complexes, and felsic dykes. Five subbelts are recognized on facies and stratigraphy but faunas and depositional environments are everywhere the same. The Silurian-Devonian sequences reflect filling of a basin in which fairly deep-water deposition, in the Early Silurian, gave way to shallow water and eventually subaerial deposition in the Early Devonian. Most of its rocks were deposited above an Avalon Zone basement.

Arisaig Belt

Upper Ordovician to Lower Devonian rocks of the Arisaig Belt (Fig. 4.25) developed upon the Avalon Zone. A Silurian coastal section is complete and consists of shallow marine to brackish water fossiliferous shales and siltstones. In the Antigonish Highlands, underlying volcanic rocks are predominantly continental, bimodal, within-plate, rift varieties. In the Cobequid Highlands, volcanic rocks are scarce and the sequence is dominated by sedimentary rocks similar to those of the Antigonish Highlands.

Cape Breton Belt

Most middle Paleozoic rocks in Cape Breton Island are within the Aspy Subzone and they were described with the Gander Zone. However, other discrete occurrences of Silurian and Devonian units are present. These include a sedimentary unit near the Mabou Highlands, the Ingonish Island Rhyolite, the Fisset Brook Formation, and the McAdam Lake Formation (Fig. 4.30).

The chemical characteristics of the volcanic rocks in the Fisset Brook Formation are consistent with a within-plate setting. The unit is generally considered to have formed in a post-Acadian pull-apart basin. Post-tectonic middle to late Devonian plutons, with typical "A-type" features, are inferred to be plutonic equivalents of Fisset Brook rhyolites.

A model for the Late Ordovician to Early Devonian development of the Aspy Subzone depends on whether all of Cape Breton Island is part of the Avalon Zone or if its subzones are discrete entities. The geochemistry of the volcanic rocks implies subduction. One model suggests a Silurian arc with subduction beneath the Laurentian margin. Another model suggests local Silurian subduction within the Avalon Zone. Regardless of models, the volcanic and plutonic rocks of Cape Breton Island record a change from Silurian-Devonian compression to local Devonian-Carboniferous extension.

Annapolis Belt

The Annapolis Belt is defined by thick sequences of fine grained shallow marine siliciclastic sedimentary rocks and volcaniclastic rocks of the Annapolis Supergroup. It ranges in age from Early Ordovician to Early Devonian.

Separation of the Annapolis Belt and Meguma Zone is artificial as both are integral parts of the same terrane. This terrane has well-defined metallogenic, plutonic, and tectonic characteristics that contrasts with those of the adjacent Avalon Zone. Intense deformation in the vicinity of the Glooscap Fault supports major transport to juxtapose these very different terranes.

The model for deposition of the Annapolis Supergroup is one of relatively shallow-water sedimentation on a Gondwanan continental shelf. Ordovician volcanic rocks at the base of the Annapolis Supergroup signal the first volcanic event and subaerial exposure. Sedimentary rocks are part of a shelf margin system. Some are related to Saharan glaciation that was of late Caradoc and younger age. Silurian volcanic rocks indicate further subaerial exposure and overlying Ludlow black slates suggest post-glacial submergence. Lower Devonian rocks contain the first abundant shelly fossils. These belong to the Rhenish-Bohemian realm that includes middle and southern Europe and North Africa.

Arguments for a West African source for the Meguma Supergroup are applicable also to the Annapolis Supergroup. Both supergroups are viewed as integral parts of the same stratigraphic section and interpreted in the same model of an evolving continental margin.

Newfoundland

Rocks included in this temporal category in Newfoundland range in age from Middle Ordovician (Caradoc) to Middle Devonian, although the majority are Silurian. Stratigraphic sections include red sandstones and conglomerates toward their tops, and terrestrial volcanic rocks are abundant in central Newfoundland belts. Middle Ordovician to Lower Silurian rocks, where present, display sharp contrasts from one belt to another, e.g. limestones of the Clam Bank Belt compared to coarse turbidites of the Badger Belt. Net stratigraphic thicknesses in places exceed several kilometres.

Clam Bank Belt

The Clam Bank Belt is defined on a homoclinal sequence of Middle Ordovician to Devonian rocks along the western shore of the Port au Port Peninsula (Fig. 4.39, 4.40). The Long Point Group at the base is a carbonate sequence of Caradoc age. The conformably overlying Clam Bank Group is a redbed sequence that contains a Silurian-Devonian fauna. These rocks provide a record of deposition and deformation between the Middle Ordovician emplacement of the Humber Arm Allochthon and deposition of Carboniferous cover rocks, in an area where relationships are otherwise hidden by the Gulf of St. Lawrence.

Rocks of the Clam Bank Belt were viewed traditionally as unconformable upon the Humber Arm Allochthon, linking the allochthon with platformal rocks farther west. However, recent interpretations favour a faulted contact, with rocks of the Clam Bank Belt thrust eastward as the upper level of a structural triangle zone.

Springdale Belt

The Springdale Belt is defined on its extensive terrestrial volcanic rocks and associated terrestrial to shallow marine clastic sedimentary rocks (Fig. 4.41). Middle Silurian fossils occur at White Bay and volcanic rocks at Springdale are dated isotopically as Silurian. Unconformities between rocks of the Springdale Belt and underlying Ordovician or older rocks are recorded wherever basal relationships are preserved. Granites of Silurian and Devonian age cut rocks of the Springdale Belt and all are locally overlain by undeformed Carboniferous rocks.

The latest studies indicate that depositional patterns within the Springdale Belt were controlled by volcanic centres that terminated as cauldron subsidence features. The most extensive areas of volcanic rocks and the thickest volcanic sections occur side by side with consanguineous high level plutons. Four or more nested volcanic centres are suggested, all partly interlocking and aligned northeasterly (Fig. 4.45). In the east, unconformities with ophiolitic rocks of the Dunnage Zone are exposed locally and an ophiolitic substrate is indicated by serpentinite inclusions in volcanic and intrusive rocks. In the west at White Bay, volcanic and sedimentary rocks overlie the Humber Zone.

The numerous, long, linear, steep, northeast-trending faults that transect the Springdale Belt may follow middle Paleozoic structures that controlled volcanism, plutonism, and sedimentation at or near the Humber-Dunnage boundary. The lithologies and chemistry of the volcanic rocks seem to refute a subduction model and it is difficult to define a contemporary oceanic tract.

Cape Ray Belt

The Cape Ray Belt is defined by discontinuous occurrences of Silurian and Devonian terrestrial sedimentary and bimodal volcanic rocks that are traceable from Cape Ray 150 km northeastward (Fig. 4.46). Silurian redbeds are unconformable above the Ordovician Annieopsquotch ophiolite complex of the Notre Dame Subzone toward the northeast, and Devonian volcanic rocks and conglomerates are unconformable on Ordovician tonalites of the Dashwoods Subzone near Cape Ray.

The rocks occur along the Cape Ray fault zone that was viewed as a suture between continental rocks of the Humber Zone and Gander Zone. The latest studies suggest that the Dashwoods Subzone to the northwest includes rocks typical of both the Humber and Dunnage zones, all structurally commingled, intruded, and metamorphosed together. Southeast of the fault zone, the Port aux Basque Gneiss is correlated with rocks of the Meelpaeg Subzone, implying Gander affinities. The Springdale and Botwood belts appear to converge southwestward into the Cape Ray Belt, implying a paleogeography unrelated to Ordovician tectonic elements.

The narrow Cape Ray Belt coincides, at least in part, with an ancestral zone of intense deformation and mylonitization. An intracratonic ductile shear zone may have localized Devonian deposition. After deposition, the Devonian rocks were deformed and mylonitized (Dubé and Lauzière, 1994). Deformation is much more intense in the southern Cape Ray Belt than elsewhere in the Springdale and Botwood belts.

Badger Belt

The Badger Belt (Fig. 4.47) is distinguished by its preponderance of greywackes and overlying polymictic conglomerates of the Badger group that exceed 3 km in thickness. The rocks are dated by shelly faunas of Middle to Late Llandovery age. The thick marine clastic sequences are conformable above Middle Ordovician (Caradoc) black graptolitic shales of the Exploits Subzone. Silurian mélanges, locally with fossiliferous shale matrices and containing huge Ordovician volcanic, limestone, and black argillite blocks are a distinctive lithology in upper parts of stratigraphic sections. The rocks range from deep to shallow marine and they contrast with redbeds and terrestrial volcanic rocks of other Newfoundland belts.

All of the sections exhibit the same pattern of large-scale coarsening upward, which is interpreted as a shoaling and infilling of one or several marine basins. A variety of sedimentary features indicate a mainly northern provenance. This is supported by a local unconformity between Ordovician volcanic rocks and Silurian conglomerate at northern New World Island. Coupled with sub-Silurian unconformities throughout the adjacent Springdale Belt, an emergent landmass to the west and northwest is indicated.

Whereas the greywackes and conglomerates of the Badger Belt almost everywhere overlie Caradoc shales, the shales overlie various older assemblages such as the Victoria Lake Group, Wild Bight Group, Exploits Group, Summerford Group, Dunnage Mélange, and deformed mafic-ultramafic rocks of the Gander River Complex, from west to east.

Structural styles of the Badger Belt with southeast thrusting, or northwestward underplating of outboard elements from the southeast, coupled with mélange formation, resemble structural styles of accretionary prisms either in forearc or foreland basin settings. Some Silurian mélanges are olistostromes that mark the leading edges of contemporary thrust faults. The significance of some other mélanges is debatable.

The Silurian structural style was possibly controlled by an encroaching Gander terrane that underthrust rocks of the Exploits Subzone and led to southeast thrusting as the heretofore undeformed Paleozoic rocks of the Exploits Subzone were compressed against the stabilized Taconic deformed parts of the Notre Dame Subzone. Geochronological evidence of an important Silurian metamorphic and plutonic event along the eastern Gander Zone also fits this model.

Botwood Belt

Rocks of the Botwood Belt (Fig. 4.53) are mainly terrestrial volcanic rocks overlain by fluviatile red and grey cross-bedded sandstones. Polymictic conglomerates occur in places along its western margin and greywackes like those of the Badger Belt occur beneath its volcanic rocks in the northeast and along its eastern margin.

Correlation between greywackes and conglomerates of the Badger Belt with those of the Botwood Belt implies continuity of these rocks across the Exploits Subzone. Stratigraphic relationships between greywackes of Badger type and underlying Ordovician rocks, of the Davidsville Group to the east indicate that the Davidsville Group was part of the conformable substrate beneath the Silurian deposits of eastern Notre Dame Bay. An unconformity between the Davidsville Group and ophiolitic rocks of the Gander River Complex at the Dunnage Zone-Gander zone boundary, and an absence of Silurian rocks above the Gander Zone suggest an eastern limit to the depositional basin.

Recognition of the Dog Bay Line as a major structural junction that separates different Silurian rock groups requires subdivision of the Botwood Belt into western and eastern parts (Williams et al., 1993). A new belt, the Indian Islands Belt, is introduced for the narrow part of the former Botwood Belt southeast of the Dog Bay Line. Its rocks are Silurian calciferous shales, sandstones, conglomerates, and redbeds assigned to the Indian Islands Group. They are disconformable upon upon Ordovician shales and mélange exposed along the west side of Gander Bay.

The Dog Bay Line is marked by a wide zone of disrupted Ordovician rocks and it is an important Silurian tectonic boundary that may (see addendum to Chapter 4) mark the terminal Iapetus Suture.

La Poile Belt

The La Poile Belt forms an integral part of the Hermitage Flexure and its rocks occur above the Burgeo Subzone in southwestern Newfoundland (Fig. 4.56). Two separate outcrop areas consist of subaerial felsic volcanic and associated epiclastic rocks interdigitated with crossbedded quartz sandstones of nonmarine shallow-water origin. The rocks are assigned to the La Poile Group. Some of its felsic volcanic rocks are dated isotopically as Silurian and the group is 3.5 to 5 km thick.

Conglomerates at the base of the La Poile Group lie nonconformably on the Roti Granite dated at 563 ± 4 Ma in the northeast part of the belt. Rocks that are cut by the Roti Granite include amphibolite (Cinq Cerf gneiss) and less metamorphosed green siltstones, argillites, and volcanic rocks of the Burgeo Subzone.

The structural styles and basal relationships of the La Poile Group contrast with those in other Newfoundland belts. Northwest thrusting of Silurian rocks above the Ordovician Bay du Nord Group, northwest thrusting of southerly belts of mainly upper Precambrian rocks above the La Poile Group, and an unconformity between Silurian and upper Precambrian-Cambrian rocks are unique to southwestern Newfoundland.

The La Poile Belt separates rocks assigned to the Dunnage Zone to the north from upper Precambrian rocks of the Burgeo Subzone to the south. Gander Group correlatives are absent in this area, although syntectonic plutons and Paleozoic structures typical of the Gander Zone extend around the Hermitage Flexure and into the La Poile area.

Fortune Belt

Several middle Paleozoic units occur along the north shore of Fortune Bay and another occurs on its southeast side at Grand Beach. These overlie rocks of the Avalon Zone. The oldest rocks of northern Fortune Bay are mainly red arkosic sandstones and conglomerates with clasts of metamorphic and plutonic rocks derived from the adjacent Gander Zone. They are nonconformable upon the late Precambrian Simmons Brook Batholith. A younger and less deformed conglomerate unit nearby contains Late Devonian plants. All of these rocks are cut by Devonian granite.

Volcanic rocks at Grand Beach of the Burin Peninsula are dated isotopically as Devonian and they are interpreted as cover to upper Precambrian rocks.

Sedimentology and intrusive relationships among middle Paleozoic rocks of the Fortune Belt indicate fluviatile and alluvial deposition between periods of granite intrusion and contemporary deformation. This is supported by the synchronous ages of silicic volcanic rocks at Grand Beach and Acadian plutonism. Possibly, the synorogenic deposits of the Fortune Belt reflect transcurrent faulting and uplift associated with the accretion of the Avalon Zone against the Gander Zone.

Grand Banks

Seismic stratigraphy, drill cores, and palynological analyses indicate that 8000 m of Cambrian to Devonian rocks cover some 50 000 km^2 east of the Avalon Peninsula on the Grand Banks of Newfoundland. These rocks are mainly marine and they contrast with mainly terrestrial onshore sections. Formline structural mapping revealed 4000 m of Ordovician-Silurian strata that are gently folded about north-northwest axes. These are overlain unconformably by a synclinal outlier of Devonian strata 700 m thick.

Upper Ordovician and Silurian rocks are grey laminated fissile siltstones with burrows and fragments of brachiopods and bryozoa, light grey calcareous siltstones which are laminated and bioturbated with well-sorted beds of fossil fragments, and non-fossiliferous, bioturbated siltstones. The rock types and fauna indicate deposition in a variety of shallow marine environments. Devonian rocks are redbeds of continental affinity.

Mild deformation in the Paleozoic rocks offshore supports the onland observation of decreasing intensity of Paleozoic deformation from west to east across the Newfoundland Avalon Zone. Furthermore, there is no middle Paleozoic plutonism or regional metamorphism recorded in the offshore sections. The presence of an offshore Devonian basin of terrestrial rocks records a change to subaerial conditions as noted in the onland successions, although this change is later in the case of the offshore.

Overview of middle Paleozoic belts

Lithologies and stratigraphies of Middle Ordovician to lowermost Silurian rocks of middle Paleozoic belts are different, and they imply deposition in discrete basins, separated by emergent lands. The rocks of middle Paleozoic belts everywhere overlie rocks of older zones, indicating that all the important elements of the orogen were established by middle Paleozoic time. Nowhere are middle Paleozoic rocks conformable on a contemporary ophiolitic basement, indicating the existence of an important middle Paleozoic ocean.

The oldest rocks of the Gaspé Belt are Caradoc and these are conformable on Llanvirn strata. The latter may be part of the same sequence or an important hiatus may be present. Regardless, there is no structural discordance and the section spans the interval of Taconic orogeny that affected the Humber Zone to the north. Since the Gaspé sequence in question lies on an ophiolitic mélange substrate, the formation of the mélange may represent disruption and an early phase of Taconic Orogeny in this area. A similar situation exists in the Badger Belt of Newfoundland where Silurian marine clastics overlie Caradoc shales, in turn deposited on the Dunnage Mélange.

The geographic and tectonic setting of the Clam Bank Belt in Newfoundland suggests a connection with the northern portion of the Connecticut Valley-Gaspé division of the Gaspé Belt, and rocks of the Clam Bank Group may correlate with the Griffon Cove River Formation of northeastern Gaspésie. Southern parts of the Connecticut Valley-Gaspé division and the Aroostook-Percé division have no Newfoundland counterparts.

Silurian greywackes of the Fredericton Belt resemble those of the Badger Belt. However, the Llandovery shelly faunas of the Badger Belt are absent in the Fredericton Belt, and the Badger and Fredericton belts have very different positions compared to the early Paleozoic zonation of Newfoundland and New Brunswick.

Silurian and Devonian rocks are conformable in most places. Local stratigraphic sections record upward shoaling with marine sections capped by terrestrial redbeds. This change is rarely contemporaneous across the belts and in some cases may be diachronous along the course of a single belt. The change is recorded earliest in the Lower to Middle Silurian rocks of the Newfoundland Botwood Belt. It appears to be latest in the Gaspé and Annapolis belts where marine Lower Devonian rocks are present.

Middle Paleozoic deformation affected the rocks of all belts, although it is more intense in some areas than in others. Silurian plutonism and metamorphism accompanied deposition and/or deformation in some places, but there are few well-documented examples of Silurian or Devonian rocks that make up high grade regionally metamorphosed parts of the orogen. Granites cut middle Paleozoic rocks of all belts, with the exception of the Clam Bank Belt and eastern parts of the Avalon Peninsula and offshore. Most are post tectonic with respect to deformation in the middle Paleozoic rocks; but some are syntectonic and others are spatially and genetically related to midddle Paleozoic volcanic rocks. The onset of middle Paleozoic deformation is not everywhere sharply defined. Isotopic ages indicate Silurian onset and that rocks as young as Late Devonian are locally involved. The shoaling-upward trend occurred everywhere in advance of deformation and its age variations imply diachronous onset of Acadian Orogeny.

There is no obvious relationship between middle Paleozoic belts and the distribution of middle Paleozoic intrusive and metamorphic rocks, except in places such as the Springdale Belt where plutons are subvolcanic, and the Annapolis Belt where its plutonic history is distinctive.

Middle Paleozoic volcanism, deformation, plutonism and metamorphism are all more important in interior parts of the Newfoundland Appalachians and decrease westward across the Humber Zone and eastward across the Avalon Zone. This applies also to Cape Breton Island and Quebec-New Brunswick cross sections. It does not apply to the outboard Meguma Zone and Annapolis Belt where plutonism is intense with local high grade metamorphism.

Major strike-slip displacements, megashears and transpression zones are words of increasingly common usage in tectonic models for the middle Paleozoic development of the Canadian Appalachians. Transcurrent motions may have provided the controls for middle Paleozoic volcanism and deposition in tectonically active basins. Continued movements possibly led to deformation in the same areas.

The significance of Silurian-Gedinnian, Rhenish-Bohemian fauna restricted to mainland belts developed upon the Avalon and Meguma zones and subsequent appearance on the Laurentian margin during the Siegenian and Emsian is difficult to assess. The analysis seems the same as that for Cambrian and Early Ordovician faunas on opposite sides of the orogen that lost their distinctiveness in the Middle Ordovician. Most evidence suggests Avalonian accretion during the Silurian, although the Meguma terrane was accreted later. The Miramichi Highlands may have been an effective land barrier between the mainland belts, or possibly the Fredericton Belt was an effective marine barrier. No such middle Paleozoic faunal distinction is recognized in Newfoundland, or at least no equivalent analysis exists.

LATE PALEOZOIC BASINS

Upper Paleozoic rocks of the Canadian Appalachian region are mainly of Carboniferous age but they include Upper Devonian beds at the base of some sections and Permian strata at the top of some others. The rocks are mainly coarse-to fine-grained continental red and grey sedimentary rocks that include fluvial and fluvio-lacustrine strata, coal measures, marine limestone, and evaporites. Volcanic rocks of bimodal aspect occur locally, most commonly at the bases of mainland stratigraphic sections. The rocks extend across the exposed orogen as an unconformable cover on lower Paleozoic zones and middle Paleozoic belts and extend offshore and underlie much of the Gulf of St. Lawrence, the southern Grand Banks, and the northeast Newfoundland Shelf. They occur in discrete depocentres, some of which are connected by higher stratigraphic units. The depocentres are referred to as basins. They generally trend northeast, parallel to older structures, and they are in places bounded by faults that partly controlled their initiation and subsequent evolution. The basins are best developed and best preserved from Gaspésie to Cape Breton Island. From northwest to southeast these are the Restigouche, Plaster Rock, Carlisle, Central, Marysville, Moncton, Sackville, Cumberland, Minas, Stellarton, Antigonish, Western Cape Breton, Central Cape Breton, and Sydney basins (Fig. 11.3). Two depocentres in Newfoundland are the Bay St. George and Deer Lake basins; with small redbed outliers at Conche, Red Indian Lake, Terrenceville, and Spanish Room. The Magdalen Basin in the Gulf of St. Lawrence is the largest and deepest structure, and its rocks are continuous with adjacent mainland basins and the Bay St. George Basin in Newfoundland. The name Maritimes Basin is a general term for all upper Paleozoic rocks in Atlantic Canada.

A relatively narrow, northeast-trending, fault-bounded and fault-dominated central region from the Bay of Fundy to western Newfoundland has thicknesses of upper Paleozoic rocks in excess of 12 km. These rocks are extensively deformed and they contrast with thinner, undeformed rocks of bordering areas. The central region is referred to as the Maritimes Rift and it contains the Moncton, Sackville, Cumberland, Magdalen, and Bay St. George basins. The bordering area to the north is the New

Brunswick Platform, although the cover rocks are not conventional platformal deposits. It contains the Plaster Rock, Carlisle, Marysville, and Central basins. The Maritimes Rift has a "horst and graben" style of basement morphology. Local activity on normal, thrust, and strike-slip faults resulted in a complex temporal and spatial pattern of stratigraphic units. The upper Paleozoic rocks at Chaleur Bay in the north and Passamaquoddy Bay in the south are isolated occurrences, the Restigouche and St. Andrews basins, respectively.

The oldest rocks are coarse fanglomerates (Late Devonian) largely confined to the Maritimes Rift and associated with boundary faults. Deformation affected the thickest sections. Middle and Upper Carboniferous rocks are in places unconformable upon deformed rocks of the Maritimes Rift and locally they overlap boundary faults onto adjacent platformal areas. Other evidence of unconformable overlap and local episodic deformation is common within both lower and upper parts of Carboniferous sections. The youngest rocks are redbeds (Early Permian) of Prince Edward Island.

The former extent of upper Paleozoic rocks in Atlantic Canada is debatable. Some estimates imply that up to 3000 m of sedimentary cover has been eroded since the Early Permian. This suggests that most, if not all of the Atlantic region, was once covered by Upper Paleozoic strata.

A change from Lower Carboniferous thick redbed accumulations to Middle and Upper Carboniferous grey and red fluvioclastic deposits with coal measures is equated with a major paleoclimatic change from arid to humid tropical.

Late Paleozoic deformation is most intense along the northwest shoreline of the Bay of Fundy in southern New Brunswick. There the Carboniferous rocks are involved in thrusts with polyphase deformation and subhorizontal penetrative cleavage. Granitic intrusions of Early Carboniferous age occur locally at Mount Pleasant and the Saint John area of southern New Brunswick, in the Cobequid Highlands of northwestern Nova Scotia, and in the Meguma Zone of Nova Scotia.

Upper Palaeozoic strata have played a significant role in the economic development of the Atlantic region. Oil, natural gas, oil shale, coal, salt, gypsum, potash, lime, building stone and base metals have been producted intermittently for over a century and new discoveries are possible. Tin, tungsten, and molybdenum occur in Upper Devonian/Lower Carboniferous felsic volcanic and intrusive rocks at Mount Pleasant, southern New Brunswick.

Stratigraphy

The original stratigraphic subdivision of the Maritimes Basin Carboniferous sequence into six major units is to a large extent still in wide usage. The group names and their biostratigraphic ages based on European stages are listed below.

The Horton Group of Late Devonian-Early Carboniferous (Late Famennian-Tournaisian) age consists of red and grey-green polymictic conglomerates, arkosic sandstones, mudstones, oil shales, and minor non-marine evaporites. Horton Group strata overlie pre-Acadian basement with angular unconformity. The Horton equivalent in Newfoundland is the Anguille Group.

The Windsor Group of Early Carboniferous (Viséan-early Namurian) age consists of marine limestones, evaporites, and intercalated redbeds. It overlies the Horton Group and represents the only known marine incursion into the Maritimes Basin prior to the Late Carboniferous, at a time when the paleoclimate was arid. The most extensive and thickest Windsor sequence occurs in the Magdalen Basin. The Windsor equivalent in Newfoundland is the Codroy Group.

The Canso-Riversdale Group (Mabou Group in Nova Scotia) is of Early-Middle Carboniferous (mainly Namurian) age. It consists of red and grey terrestrial strata with a variety of facies that range from evaporitic to lacustrine. It is gradational and conformable above the Windsor Group.

The Cumberland Group of Westphalian age consists of approximately 2700 m of red and grey fluvial conglomerates, sandstones, and mineable coal measures. It includes the classical coal measures and plant-bearing beds in the coastal cliffs of the Joggins area, northwestern Nova Scotia. The sequence is gradational with the Canso-Riversdale Group below and locally oversteps older Carboniferous strata onto basement. Equivalent strata in the Sydney Basin of Nova Scotia are the Morien Group of Westphalian C to Stephanian age. Newfoundland equivalents are the Barachois Group.

The Northumberland Strait Supergroup includes the Pictou Group and overlying Prince Edward Island Group. The age of the supergroup extends from Middle Carboniferous to late Early Permian (early Westphalian C to Artinskian). The Pictou Group is conformable above the Cumberland Group. In Nova Scotia it has two major facies: a mainly grey, coal bearing facies and a predominantly redbed facies. Pictou strata of the New Brunswick Platform and the Moncton Basin consist of alternating grey and red facies. The Prince Edward Island Group is similar to the Pictou Group of New Brunswick except that its rocks are red, rather than grey and red, and they lack coal.

Tectonic history

Tournaisian to lower Viséan strata of the Horton Group and equivalents were deposited in a series of rift basins, probably half-graben, as indicated by basin-margin facies and patterns of stratal thickening and paleoflow. Marine seismic sections show fault-bounded structures filled with probable Horton strata beneath much of the Gulf of St. Lawrence. The Deer Lake Basin in Newfoundland has evidence for Tournaisian to Viséan movements on the Cabot Fault Zone. The widespread and apparently coeval occurrences of organic-rich lacustrine strata in the Horton Group imply some interconnection between the depocentres and suggest a period of accelerated regional subsidence. The earliest phase of Carboniferous deformation, involving folding, faulting, and uplift affected Horton strata in some basins prior to the deposition of the Windsor Group.

Strong topographic relief, partly inherited, persisted throughout deposition of the mid to upper Viséan Windsor Group, as indicated by facies relations and basin-margin facies. The unusually thick and extensive evaporites of Nova Scotia and offshore probably accumulated in an embayment or semi-enclosed basin, remote from a major Viséan seaway. The onset of Windsor sedimentation was sudden, with the Viséan sea inundating a broad, complex area. Depositional cycles identified in places in the Windsor Group may reflect glacioeustatic events.

The conformable change from the marine Windsor Group to evaporitic lacustrine Canso-Riversdale and Mabou groups indicates a return to non-marine conditions. This is roughly coeval with a major phase of Gondwanan glaciation and lowering of sea level.

An important tectonic phase, accompanied by widespread faulting, local uplift and concomitant basin development affected much of Nova Scotia and adjacent areas in the mid Carboniferous. The effects of this activity include: (1) a change from lacustrine and fine grained alluvial strata of the Mabou Group to the coarser clastic facies of the predominantly alluvial Cumberland (Riversdale) and Pictou groups; (2) basin inversion and faulting in southern New Brunswick; (3) faulting and mylonitization of the Early Carboniferous Cape Chignecto pluton at the western end of the Cobequid Highlands; (4) intensive deformation, including overturning of Lower Carboniferous strata in the Minas Basin and areas adjacent to the Cobequid Fault; (5) formation of the Stellarton Basin as an extensional structure in association with the Cobequid-Hollow fault system; (6) unconformities, commonly angular, between the Mabou and Cumberland-Pictou groups at numerous locations, with Namurian and Westphalian A-C strata missing; and (7) a widespread thermal event within the Meguma Zone dated at 320-300 Ma, approximately mid-Namurian to Stephanian.

Westphalian to Early Permian sedimentation was predominantly alluvial. Upper Carboniferous sediments encroached on most adjacent basement areas suggesting a progressive diminution of tectonic activity. In the Sydney Basin and elsewhere, faults that cut Lower Carboniferous strata cannot be traced into Upper Carboniferous strata, and paleoflow data suggest progressively reduced intrabasinal relief.

Upper Lower Permian redbeds of Prince Edward Island exhibit gentle folds indicating continued tectonic activity. The presence of coals of bituminous rank in many Westphalian sections implies substantial burial, possibly to a depth of several kilometres. This suggests that most upland areas were buried during the Permian, at which time the Atlantic area formed an extensive alluvial plain.

Subsidence in the Atlantic region probably terminated by the early Triassic. Fission-track analysis of apatites in a variety of rocks in Nova Scotia indicate Permian to early Mesozoic cooling ages below about 100°C, probably because of uplift. This uplift was coeval with the onset of Atlantic seafloor spreading and the breakup of Pangea.

Structural models and correlations

There are two main interpretations for the structural controls of the Maritimes Basin. One favours a stress regime that was largely extensional (continental rifting) punctuated by periods of transverse compression; the other favours a dextral wrench tectonic setting. Evidence cited in support of rifting and transverse compression includes: (1) texture, chemistry and stratigraphic relations of Mid Devonian to Lower Carboniferous volcanic rocks, including those of the Devonian Fisset Brook Formation and Fountain Lake Group of Nova Scotia and Viséan volcanics on the Îles de la Madeleine, that suggest eruption in a terrestrial setting related to intraplate continental rifting; (2) the apparent "basin and range", block-faulted topography of the basement floor; (3) the presence of thick alluvial fanglomerates adjacent to upland source areas; (4) the presence of northeast-trending normal and high angle reverse faults in southern New Brunswick and locally in Nova Scotia and Newfoundland; and (5) the lack of evidence for large-scale lateral offset of Windsor Group strata on opposite sides of the Belleisle Fault in New Brunswick.

A wrench tectonic model is based on dextral strike-slip motion documented on major faults that transect upper Paleozoic strata, and the following features and observations: (1) basins bordered by demonstrable steep dextral faults fit the pull-apart model; (2) the geometry of folds within the basins with axes oblique to boundary faults is a well known pattern in wrench tectonic zones; (3) exceptionally thick homoclinal sections with consistent dips in a direction parallel to the long dimension of the basins imply a shifting depocentre in unison with lateral fault movements; some of these thicknesses are much greater than depth to basement; (4) continuity and apparent steep dips of faults associated with basin development and their tendency to splay and enclose elongate blocks of basement rocks, similar to piercement structures along the Alpine Fault Zone of New Zealand; (5) reverse movements noted on some boundary faults are also consistent with transpression in a zone of wrench tectonics; and (6) a major zone of thrusting that involves basement rocks, coeval plutons, recumbent folds, and penetrative fabrics in southeast New Brunswick can be explained as the compressional zone resulting from dextral offset on the major Cobequid Fault and westward advancement of the Meguma Zone against the Avalon Zone.

The age of faulting is generally unknown, apart from a few cases where unconformable overstep is preserved or provenance relations are known. Most faults had important post-Carboniferous movement, and others followed ancestral basement structures, which complicates structural analyses. Possibly, the Maritimes Basin began as a rift system, then evolved partially or entirely as a wrench-tectonic system.

Upper Paleozoic rocks of Atlantic Canada are very different in structural style and tectonic setting compared to correlatives in the southern Appalachians of the United States. In Atlantic Canada the rocks occur in broad undeformed areas of little relief that are mainly beneath sealevel. This contrasts with the deformed, elevated upper Paleozoic rocks in the Valley and Ridge province of the U.S. Appalachians, and with the Piedmont Province in the south that contains large Carboniferous plutons in a contemporary regional metamorphic terrane that lacks identifiable upper Paleozoic layered rocks. Even the contrasts with nearby New England are marked in that the upper Paleozoic rocks of New England are polydeformed, intruded, and affected by regional metamorphism in amphibolite facies. Atlantic Canada has no equivalent to the Alleghanian or Hercynian structural fronts as deformation in Canada is confined to narrow fault-bounded areas bordered by broad areas of little or no deformation. The control of Alleghanian Orogeny in the U.S. Appalachians was the head-on collision of Laurentia with northwest Africa as the indentor. Possibly the Alleghanian thrusting in the central and southern Appalachians was accommodated by wrench tectonics in Atlantic Canada on the northern side of the African indentor.

MESOZOIC GRABEN

Mesozoic rocks of Atlantic Canada are mainly Triassic and Lower Jurassic continental redbeds, tholeiitic basalts, and related mafic dykes and small intrusions. The sedimentary and volcanic rocks up to 3500 m thick occur in the Fundy Graben of the Bay of Fundy area with a few small outcrops in the Chedabucto Graben to the east (Fig. 11.3, 6.1). Geophysical surveys indicate that Mesozoic strata underlie much of the Bay of Fundy and extend offshore from Chedabucto Bay to the Orpheus Graben. Mafic dykes and small intrusions that are Triassic to Early Cretaceous occur beyond the limits of the Fundy and Chedabucto graben (Fig. 6.2). Small isolated outcrops of Cretaceous clays and sands also occur outside the Fundy and Chedabucto graben in central Nova Scotia and southwestern Cape Breton Island.

The Mesozoic rocks are related to the early stages of rifting and drifting that led to opening of the Atlantic Ocean. The Fundy Graben is typical of Mesozoic graben present along the length of the Appalachian Orogen and Atlantic continental shelf. It is bounded by faults and sited, in part, above the Carboniferous Minas Basin and the Avalon-Meguma zone boundary.

Stratigraphy, age, and depositional environment

The Triassic-Lower Jurassic rocks of the Fundy Graben are assigned to the Fundy Group. The rocks are best exposed in Nova Scotia where they consist of the Wolfville Formation, Blomidon Formation, North Mountain Basalt, and Scots Bay Formation, from bottom to top. Table 6.1 summarizes correlations of Mesozoic formations in Atlantic Canada.

The Wolfville Formation lies unconformably upon Carboniferous rocks of the Minas Basin and pre-Carboniferous metamorphic rocks and Devonian granites. Exposed thicknesses range from 60 m to 750 m and the formation is apparently thicker in the centre of the Bay of Fundy (Fig. 6.3d). The rocks comprise a red sequence of coarse breccias, conglomerates, sandstones, and mudstones. The Wolfville Formation grades laterally and vertically into the Blomidon Formation which has exposed thicknesses from 7 m to 370 m (Fig. 6.3c). The Blomidon Formation has planar, crossbedded and cross-laminated sandstones together with horizontal and cross-laminated siltstones, mudstones, and claystones.

The Lower Jurassic North Mountain Basalt, locally up to 400 m thick, overlies the Blomidon Formation and extends throughout most of the Bay of Fundy.

The basalts have undergone zeolite to greenschist facies metamorphism and a middle unit at North Mountain contains a variety of zeolite minerals.

The Lower Jurassic Scots Bay Formation (Fig. 6.1b, a) consists of calcareous sandstones, calcareous siltstones, limestones, and silicified nodules of limestone and tree trunks. It is 2 m to 7 m thick and overlies the North Mountain Basalt.

Coarse breccias of the Chedabucto Formation at Chedabucto Bay (Fig. 6.1b, f) exceed 61 m in thickness and the rocks resemble those of the Wolfville Formation. In New Brunswick, Mesozoic sedimentary rocks occur on Grand Manan Island (Fig. 6.1b, d) and close to the northwest faulted margin of the Fundy Graben.

Lower Cretaceous deposits of central Nova Scotia are unconsolidated, red, grey and white kaolinitic clays and white, unconsolidated, almost pure silica sands (Fig. 6.1a, g). The clay deposits are economically important sources of pottery clay and the silica sands have various industrial uses. Similar silica sands occur in southern New Brunswick. The sedimentary rocks occur in depressions and sinkholes that have escaped erosion. Compaction studies on coals indicate that over 700 m of Cretaceous sedimentary rocks may have covered Nova Scotia.

Mesozoic ages for rocks of the Fundy Graben are based on pelecypods, amphibian, and reptilian remains and footprints as well as fish scales and bone fragments. A variety of late Carnian to early Norian trace fossils occur in the upper Wolfville Formation and its dinosaur footprints may be the oldest in Canada. The oldest rocks in the Fundy Graben are Anisian, or early Middle Triassic.

The McCoy Brook Formation along the northern shores of Minas Basin is well-dated by an Early Jurassic (Hettangian) tetrapod fauna. Its much-publicized fossil discoveries may help explain world-wide faunal extinctions at the Triassic-Jurassic boundary. One theory equates faunal extinction with meteorite impact at Manicouagan, Quebec.

Clastic rocks of the Wolfville Formation have been interpreted as deposits of a proximal alluvial fan together with braided river and eolian sand dune settings. Paleoflow directions (summarized in Fig. 6.3e) show that alluvial fan detritus was derived from highlands bordering the Fundy Graben and generally moved south on the north side of the graben and north on its south side.

Facies relationships and sedimentary structures indicate that cross-laminated and crossbedded clastic rocks of the Blomidon Formation represent the distal sheet-flood deposits of alluvial fans as well as sand flats, playa mudflats, and lakes. Periodic movement on the Cobequid Fault produced numerous depositional cycles of sand-flat sandstones followed by playa mudstones and/or lacustrine claystones. Flow directions appear similar to those for the Wolfville Formation.

Calcareous clastic rocks, limestones and silicified organic material of the Scots Bay Formation represent carbonate sedimentation in a near-shore lacustrine environment.

The Mesozoic paleoclimate during deposition in the Fundy and Chedabucto graben varied from semiarid, as indicated by the paucity of weathered grains, scarcity of carbon, and the oxidized state of iron in the sediments, to hot and humid with high precipitation and an annual dry season. Eolian sandstones, caliche paleosols, alluvial fan conglomerates and playa gypsiferous mudstones confirm arid to semiarid conditions with seasonal precipitation. Lycopsid megaspores in the Blomidon Formation support a desert-like climate. Southwest to northwest paleowind directions inferred from eolian sands of the Fundy Graben reflect the direction and effect of prevailing subtropical trade winds that led to an arid environment.

Primary sedimentary structures show that Cretaceous deposits are deltaic. The purity of the clay and silica sand may be the result of intense weathering during the Early Tertiary in a humid subtropical climate with high rainfall.

Igneous rocks (Fig. 6.2) fall into three age categories: Late Permian-Early Triassic, Late Triassic-Early Jurassic, and Middle Jurassic-Early Cretaceous. Upper Permian-Lower Triassic rocks are represented by the Malpeque Bay Sill in Prince Edward Island. Upper Triassic-Lower Jurassic rocks include the North Mountain Basalt and Shelburne Dyke of Nova Scotia, the Minister Island and Caraquet dykes in New Brunswick, two dykes on Anticosti Island, and the Avalon Dyke in Newfoundland. Middle Jurassic-Lower Cretaceous rocks include the alkaline Budgells Harbour pluton and associated lamprophyre dykes of the Notre Dame Swarm in Newfoundland.

Igneous activity reached a maximum during the Early Jurassic with extrusion of the voluminous North Mountain Basalt and emplacement of mafic dykes.

High-Ti phlogopite in the Malpeque Bay Sill indicates an affinity with alkaline igneous rocks such as lamprophyres. The sill is chemically similar to nephelinites. The North Mountain basalts are high-Ti quartz normative tholeiites. The Avalon, Shelburne, Caraquet, and Anticosti Island dykes are high-Ti quartz normative tholeiites, but the Caraquet Dyke is transitional between high-Ti and low-Ti types (Table 6.3). Lamprophyric rocks from the Notre Dame Swarm have evolved compositions and their alkaline nature may reflect extreme source-region metasomatism.

Structure and interpretation

The Fundy Graben is a major asymmetrical syncline with a steeper north limb and gentle plunge to the southwest (Fig. 6.1). The graben is bounded to the north by east-west faults of the extensive Cobequid system (Fig. 6.2) and it is cut by north-south faults that offset Lower Jurassic strata and all other faults. Total vertical movement on the east-west faults was at least 3500 m as given by the thickness of Mesozoic strata in the Bay of Fundy. Greater movement may have occurred at the southern end of the graben where seismic studies indicate 9000 m of Mesozoic strata. The detailed stratigraphy of alluvial fan deposits adjacent to the boundary faults reflects, at least in part, the timing and nature of fault movement. It began in the Triassic. A seismic reflection study of the offshore extension of the Cobequid Fault along the Orpheus Graben indicates that movement continued into the Early Cretaceous. Seismic evidence indicates that the Cobequid Fault dips eastward below the Bay of Fundy, apparently representing a major detachment surface formed through reactivation of a Paleozoic basement thrust. This suggests a detachment model for graben formation.

The northeast-southwest orientation of the Caraquet, Minister Island, Shelburne, and Avalon dykes (Fig. 6.4a) indicates a northwest-southeast direction of maximum extension during the Early Jurassic. The orientation of Early Cretaceous lamprophyre dykes in Notre Dame Bay is north-northwest-south-southeast (Fig. 6.4b) indicating a local east-northeast-west-southwest maximum extension direction.

North-south to northwest-southeast wrench or transverse faults displaced the vertical Caraquet, Minister Island and Shelburne dykes. Brittle transcurrent faults of similar orientation influenced topography and controlled drainage on the eastern shore of Nova Scotia. They overprint all earlier structures and follow older, Devonian joint systems. These are also parallel to oceanic fracture zones and may represent transfer faults.

The North Mountain Basalt and coeval dykes of Atlantic Canada are the most northerly occurrence of igneous rocks of the Eastern North American dolerite province. This province extends all along the eastern seaboard and is the most extensive magmatic province related to opening of the Atlantic Ocean. Ages for the Eastern North American dolerites range from 205-165 Ma with a peak at 190 Ma. The province's western boundary (Fig. 6.7) is almost coincident with the eastern boundary of the Appalachian miogeocline. Dykes tend to decrease in number to the north so that only five major dykes are identified in Atlantic Canada. Early Jurassic igneous activity and onland basin subsidence ceased abruptly by the Middle Jurassic when North Africa separated from Eastern North America, with the rifted margin parallel to structural trends of the Appalachian Orogen.

Middle Jurassic to Cretaceous intrusions define the New England-Quebec magmatic province (130-90 Ma). Igneous activity was largely restricted to more northerly areas around the Atlantic Ocean and produced small, localized eruptions of predominantly alkaline to strongly alkaline rocks. This province includes the lamprophyres at Notre Dame Bay, Newfoundland and alkaline intrusions of the Monteregian Hills in Quebec. It affected a narrower band of continental crust, and resulted in a rift axis that crossed Paleozoic structural trends when the Grand Banks of Newfoundland separated from the Iberian Peninsula with subsequent opening of the Labrador Sea.

GEOPHYSICAL CHARACTERISTICS

Gravity, magnetic, and seismic studies are the most important that allow comparisons between surface geology and geophysical expression. Magnetic anomalies are the best indicators of near surface boundaries. The gravity data provide information on the deeper structure. Magnetic and gravity maps also allow extension of geological features where exposure is poor and beneath marine areas. Deep seismic reflection data allow comparisons between lower crustal blocks and surface geological features.

Gravity signatures

The gravity field of the Appalachian Orogen is significantly higher than the adjoining Grenville Province where typical Bouguer anomalies are between -60 mGal and 0 mGal (Map 3). A strong eastward gravity gradient from predominantly negative to predominantly positive values is located in the eastern part of the Humber Zone, especially in Newfoundland and offshore. The gradient is typical of the paired anomaly signature attributed to the transition from an older to a younger crust with the positive values over the younger region. 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. 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 basement as defined by deep seismic reflection experiments. 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, is unclear.

The trend of the Long Range dyke swarm is parallel to the prominent gravity gradient that crosses the Long Range Inlier and the dykes are most abundant at the change from negative to positive values. A more northerly trend of the gravity gradient at the Strait of Belle Isle follows a change in the direction of the dykes. Possibly the locus of dyke injection and the gravity gradient have the same late Precambrian control in the deeper crust.

Gravity and magnetic anomalies associated with the exposed Tibbit Hill volcanic rocks in Quebec suggest a much more voluminous volcanic mass in subsurface, up to 250 km long, 45 km wide, and 8 km thick. It is convex toward the northwest and marks a triple rift junction involving the Ottawa Graben and Quebec Reentrant in the Appalachian Orogen.

Strong positive Bouguer anomalies east of the gravity gradient coincide with the Dunnage Zone in Newfoundland. A positive Bouguer anomaly of 50 mGal in northeast Newfoundland is the broadest positive Bouguer anomaly in the interior part of the Appalachian Orogen. However, the anomaly is less than that predicted if mafic volcanic and ophiolitic rocks extended to mantle depths. The region of highest values is coincident with the Notre Dame Subzone. A linear belt of anomalies in excess of +30 mGal extends from the northeast coast southwest to Cape Ray. The eastern edge of this belt generally follows the 0 mGal contour. At the northeast coast of Newfoundand it approximately coincides with the Dunnage-Gander zone boundary. Where the Dunnage Zone is narrow in southwest Newfoundland, the positive Bouguer anomaly field is also narrow.

The presence of the Dunnage Zone beneath the Gulf of St.Lawrence is difficult to document using gravity data (Map 3), as the lower Paleozoic rocks are overlain by upwards of 9 km of Carboniferous cover rocks. Similarly in New Brunswick, large amplitude, long wavelength Bouguer gravity anomalies are basement anomalies suppressed by the thick middle Paleozoic cover.

The Gander Zone in Newfoundland is typified by negative, long wavelength, Bouguer gravity anomalies. Local positive anomalies may be indicative of ophiolite complexes or mafic intrusions. The eastern boundary of the Gander Zone with the Avalon Zone is delineated in Newfoundland and offshore to the north and south by a transition from the predominantly negative gravity anomalies of the Gander Zone to the alternating positive and negative anomalies of the Avalon Zone. Tracing the boundary between southern Newfoundland and Cape Breton Island and between the Gander and Avalon zones in New Brunswick and in the Gulf of St. Lawrence is difficult.

In New Brunswick, the Gander Zone gravity anomalies are mainly negative. The anomalies are negative relative to the Avalon Zone to the south and east but are more positive than those in the Humber Zone in the vicinity of the Gaspé Belt.

The Avalon Zone has arcuate belts of alternating positive and negative gravity and magnetic anomalies.

The Meguma Zone has mainly negative anomalies centred on large granite intrusions.

Magnetic signatures

The magnetic signatures are more complicated and variable than the gravity field (Map 4). This arises from the nature of the magnetic anomalies, the greater density of observations, and their greater dependence on depth to source. The magnetic signatures are helpful in tracing zone boundaries and establishing the structural fabric within particular zones.

In the Humber Zone, magnetic anomalies tend to be broad and of low amplitude indicating deep magnetic sources beneath the Cambrian-Ordovician carbonate sequence. Pronounced high amplitude, short wavelength magnetic anomalies occur throughout the Long Range Inlier of Newfoundland (Map 4) and over the Blair River Complex of Cape Breton Island. Moderate amplitude magnetic anomalies occur over major obducted ophiolitic bodies in Quebec and Newfoundland. The boundary between the Humber and Dunnage zones in Quebec and New Brunswick is expressed by the arcuate pattern of high magnetic anomalies which can be traced from the Brompton area of Quebec to Chaleur Bay (Map 4). The boundary is difficult to follow beneath sediments of the Anticosti Basin because of the depth to source.

Dunnage Zone magnetic data exhibit several horizontal wavelengths and variable intensities. Anomalies have short wavelengths, and high amplitudes that reflect its local volcanic belts. In general the magnetic anomalies are positive. The highest amplitude magnetic anomalies, in excess of 6000nT coincide with Jurassic plutons in central Newfoundland. Anomalies expressing mafic and ultramafic plutons along both sides of the Dunnage Zone are less intense, typically having amplitudes of a few hundred nanoTeslas and wavelengths of a few kilometres to tens of kilometres. These patterns can be used to constrain the geometry of various features and to trace them offshore northeast of Newfoundland. The fundamental differences in the magnetic character between the western and eastern parts of the Dunnage Zone in Newfoundland supports its subdivision into Notre Dame and Exploits subzones.

Several major plutons, such as the Mount Peyton in the Newfoundland Dunnage Zone, are recognized by their elliptical signatures of a perpheral high surrounding a magnetic low over the pluton itself. This contrasts with more typical magnetic highs over the plutons in New Brunswick, e.g. the St. George Batholith.

The Dunnage Zone in New Brunswick is typified by positive anomalies which begin at Chaleur Bay and continue inland to the Maine border. Extrapolation of boundaries depicted in Figure 7.6 are a compromise between gravity, magnetic, and geological information.

The Gander Zone has moderate amplitude, long wavelength, negative magnetic anomalies which can be traced throughout Newfoundland and offshore. The overall negative anomalies are interrupted by the narrow belt of positive anomalies associated with the Gander River Complex along the eastern margin of the Dunnage Zone. Subsequent detailed studies in northeast Newfoundland reveal two subtle positive anomaly belts east of the Dunnage zone boundary. These have been ascribed to the presence of mafic and ultramafic material in local thrusts or intrusions.

In New Brunswick, the Gander Zone is also typified by negative magnetic anomalies with minor positive areas in its northeastern part.

The arcuate belts of alternating positive and negative magnetic anomalies of the Avalon Zone are 20-100 km wide with amplitudes of 200-400 nT. Onshore in Newfoundland the positive anomalies correlate with belts of Precambrian volcanic rocks. This signature may be traced northeast of Newfoundland to the continental shelf in the vicinity of the Charlie-Gibbs Fracture Zone. South of Newfoundland the arcuate anomaly patterns are terminated by the Collector Anomaly which expresses the Avalon-Meguma zone boundary (Map 4). Recent deep reflection data, refraction data, and additional magnetic data have corroborated the placement of this boundary offshore in the Tail of the Banks area. More recent studies south of Newfoundland have led to the recognition of distinctive Avalon magnetic signatures which can be traced southward into a major northwest-striking fault. Several other northwest-trending features are interpreted as Carboniferous or younger faults. Similar features have been recognized in both the gravity and magnetic data in the southern Avalon Zone of Newfoundland and across the Avalon-Gander zone boundary in Bonavista Bay.

A magnetic signature adjacent to the Fredericton-Norembega Fault that crosses the Fredericton Belt and Carboniferous basins may mark the Gander-Avalon zone boundary in New Brunswick. This implies that the St. Croix Subzone lies on the Avalon side of this boundary. An extension of the Collector Anomaly passes through Chedabucto Bay and Minas Basin along the trace of the Cobequid Fault. These broad positive anomalies mark the southeastern extent of the Avalon Zone on land and are interpreted as the southern boundary of the zone offshore.

The Meguma Zone has distinctive northeast-trending linear magnetic anomalies of moderate amplitude. These correlate with the general structural trends of the folded Meguma Supergroup and they are truncated by Devonian plutons. The characteristic linear patterns can be used to extend the Meguma Zone offshore, especially near the Nova Scotian coast. The zone is not found in Newfoundland but is interpreted to underlie the southeastern parts of the Grand Banks (Fig. 7.6).

In addition to magnetic expressions of structural trends in the major Appalachian zones, there are other features which appear on large scale magnetic maps and on individual track records offshore. Linear, short wavelength, low amplitude anomalies northeast of Newfoundland may reflect Mesozoic dykes, based on the presence of similar dykes and anomalies on land. A magnetic signature of the Avalon Dyke extends offshore, but drilling attempts failed to prove its presence. A similar offshore feature in the Avalon Zone south of Newfoundland may express another dyke. There are similar magnetic signatures over dykes in Nova Scotia and New Brunswick. All of these features along with the strongly magnetic Mesozoic plutons of central Newfoundland provide evidence of Mesozoic tectonic activity.

Also evident on magnetic maps, especially magnetic shadowgrams, and to a lesser extent on gravity maps, are regional northwest-trending lineations which appear to truncate major gravity and magnetic anomaly patterns (Maps 3 and 4). High resolution aeromagnetic data from the Gulf of St. Lawrence support the notion of northwest-trending right-lateral faults that offset zones and their boundaries.

Northwest-trending magnetic patterns are also recognized in Newfoundland and throughout the Grand Banks and extreme offshore areas. In Newfoundland, the trends are interpreted as two sets of linears that overprint the Dover Fault and the Ackley Granite suite that stitches the Gander and Avalon zones. Using gravity, magnetic, topographic, and geological maps it is possible to identify a series of such features which occur almost regularly across Newfoundland (Fig. 7.6). Similar features can be recognized in Nova Scotia, New Brunswick, and in the adjacent offshore regions (Fig. 7.6). At present there is no structural analysis of fracture patterns or their timing. The association of the magnetic anomalies with bathymetric and topographic features imply late structural features unrelated to Appalachian trends, and they are parallel to the Newfoundland Fracture Zone on the southern nose of the Grand Banks. The features are also perpendicular to the general trends of known Mesozoic dykes. On the Grand Banks, transfer faults related to Cretaceous and younger basin formation have similar orientation, suggesting that the magnetic anomalies reflect transfer faults related to the Mesozoic opening of the Atlantic Ocean.

A prominent positive magnetic 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 Mesozoic opening of the North Atlantic. Part of the 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.

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 (Fig. 7.1) 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. The boundary between the Gander and Avalon zones, the Dover Fault, is seen to be a major, steep feature having distinctly different seismic character on either side. It is interpreted as the boundary between the Central and Avalon lower crustal blocks. Subsequent surveys in 1986 in the Gulf of St. Lawrence confirmed this general interpretation of lower crustal blocks. The reflection data also indicate that the Grand Banks are underlain by rocks typical of the Avalon Zone. Both refraction and deep reflection data on the southern Grand Banks indicate that the Avalon-Meguma zone boundary is vertical and cuts the deep crust. Other reflection data from the Bay of Fundy and Gulf of Maine further imply that the Meguma Zone has a distintive basement that defines the Sable lower crustal block (Keen et al., 1990).

The Grenville lower crustal block is wedge-shaped and its subsurface edge follows the form of the Appalachian structural front. It corresponds with the Humber tectonostratigraphic zone. The Dunnage Zone is allochthonous above the opposing Grenville and Central lower crustal blocks. Their boundary is interpreted as a deep collisional zone, the Iapetus Suture. The Gander Zone may be the surface expression of the Central lower crustal block, or it too may be allochthonous. The Avalon Zone corresponds to the Avalon lower crustal block. The Meguma Zone corresponds to the Sable lower crustal block. Results of the 1989 onland Lithoprobe line in Newfoundland failed to show a significant distinction between the Central and Avalon lower crustal blocks, so that the situation beneath the Dunnage Zone is simpler with a Grenville block or Laurentian margin juxtaposed with a combined Central-Avalon block or Gondwana margin (Quinlan et al., 1992). The spatial coherence, if not seismic continuity, between lower crustal blocks and surface zones implies genetic links and common controls during the early Paleozoic development of the Canadian Appalachians.

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 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.

Trilobites, including *Paradoxides* and other Middle Cambrian Acado-Baltic genera, were recently reported from the Meguma Zone in the uppermost part of the Goldenville Group. Their paleogeographic and biostratigraphic significance confirm that these rocks were deposited on the eastern side of Iapetus over a long period encompassing much of the Cambrian and Early Ordovician.

Ordovician

Earliest Ordovician fossils of the Humber and Avalon zones reflect continuity with those of Cambrian age. Tentative identification of *Adelograptus tenellus* (Linnarsson) in the earliest Tremadoc part of the Cookson Group in the St. Croix Subzone in southwestern New Brunswick links that part of the sequence with the Baltic area and other parts of Europe.

Most fossil groups exhibit increased provincialism during Arenig and early Llanvirn time. Provincialism was considerably reduced in late Llanvirn-early Llandeilo time.

Division of the Dunnage Zone of Newfoundland into the Notre Dame and Exploits subzones was prompted by several factors including contrasting fossils of Arenig age. Those in the Notre Dame Subzone are conodonts, trilobites, and brachiopods of North American affinity. Arenig-Llandeilo fossils in the Exploits Subzone are dominantly brachiopods associated with smaller numbers of trilobites. These assemblages, and similar ones in the Gander Zone, characterize the Celtic biogeographic province that probably represents peri-insular settings and water temperatures intermediate between the warm waters of the North American continental margin and the cold waters of the Armorican and Baltic platform margins.

Fossils of late Llanvirn-early Llandeilo age, largely conodonts of North Atlantic provincial affinities, occur in limestone at many localities in the Exploits Subzone, recording a transition into warmer water environments. Associated trilobites and brachiopods of the Scoto- Appalachian biogeographic province, confirm this warming trend.

The Dunnage Zone in Quebec and New Brunswick is narrower, less well defined, and has fewer fossils. Late Arenig brachiopods of Celtic province affinities occur in tuffaceous siltstones that overlie slate and quartzite of the Miramichi Subzone.

Fossils of Arenig age in the Avalon Zone are sparse but distinctive. Inarticulate brachiopods from Bell Island, Newfoundland are similar to those from the Armorican Quartzite, France. The Wabana sedimentary iron ores contain distinctive European trilobites and abundant specimens of the arthropod trace fossil *Cruziana*. The linkage between the Avalon Zone and parts of Europe is supported by the graptolite *Didymograptus* (sensu lato) *simulans*, from near the base of the Wabana Group that is conspecific with the type specimens from the Skiddaw Group in the English Lake District. Oolitic hematite containing inarticulate brachiopods also occurs in the northern Antigonish Highlands of Nova Scotia. This sedimentary facies and associated fossils probably represent a circum-Gondwana nearshore environment.

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. Ashgill faunas occur in shallow-water carbonate rocks on Anticosti Island, and in a wide variety of rocks in the Gaspé Belt (Aroostook-Percé division). The Anticosti examples include brachiopods that link it to the North American brachiopod biogeographic province, and rugose and tabulate corals that, with some exceptions, have similar affinities. Most of the carbonate rocks of the Gaspé Belt (Aroostook-Percé division) were deposited in deeper water than that of the Anticosti Basin. Recent work has led to the assignment of specific generic suites to depth-controlled benthic assemblage communities. Conodonts of the Anticosti and Percé sequences are similar in that both are dominated by representatives of the North American Midcontinent Province.

The Hirnantian assemblages of brachiopods in the uppermost Ordovician beds at Anticosti Island and Percé are of special interest. This assemblage is characterized by a significant reduction in the number of brachiopod genera, presumably in response to rapid cooling of the world's oceans coincident with the latest Ordovician Saharan glaciation. Late Ordovician trilobites have southern Appalachian affinities, and associated conodonts are of North Atlantic province affinity.

Ashgill fossils, largely brachiopods, occur in clastic rocks of the Badger Belt at New World Island. Assemblages of brachiopods differ from place to place, but their generic composition was apparently governed by local environments. The most common and diversified assemblages consist of genera (e.g. *Christiania, Dolerorthis, Plectatrypa, Sampo*) that characterize the North-European brachiopod biogeographic province.

Silurian-Early Devonian

Silurian and Early Devonian biogeographic patterns were essentially continuations from the Late Ordovician, although there are different names for similar biogeographic subdivisions. For example, the Late Ordovician faunas of the Appalachians were classed from their brachiopods as North American and North European provinces of a cosmopolitan realm. By contrast, Silurian and Early Devonian brachiopod-based biogeographic units place most of the Appalachians in the North Atlantic region of the North Silurian biogeographic realm, with outboard belts (Mascarene, Arisaig, and Annapolis) assigned to the Old World realm. The Early Devonian name for the larger part of the Appalachians is the Appalachian Brachiopod Province. The term for the same area in the Early Devonian, based on rugose corals, is the Eastern Americas Realm. Local depositional environments may be partly responsible for differences in Early Silurian, Late Silurian, and Early Devonian faunas in the Gaspé Belt.

The Fredericton Belt was a marine trough separating the North Silurian faunas of the Chaleurs Bay division of the Gaspé Belt from the Old World faunas of the Mascarene Belt. Evidence of oceanic crust is lacking but the Fredericton Belt separates markedly different shelly and ostracode faunas. Possibly the Miramichi Highlands was a Silurian land barrier.

All but the latest Silurian fossils of the Mascarene Belt belong to cosmopolitan taxa, but some ostracodes of Late Silurian (Pridoli) age are north-European (Old World) realm. The same ostracodes occur in uppermost Silurian strata of the Arisaig Belt.

A report of thelodonts of Late Silurian age from the White Rock Formation in the Annapolis Belt suggests that the Avalon and Meguma zones were in proximity in the Late Silurian. The Old World affinities of the Annapolis Valley sequence are also confirmed by the Rhenish assemblage of Early Devonian brachiopods in the Torbrook Formation.

Middle Devonian-Carboniferous

In the northwestern Connecticut Valley-Gaspé division of the Gaspé Belt several limestone units contain brachiopods of mixed provincial affinity, indicating that Old World forms had almost reached the main part of the North American continent by the Middle Devonian.

The Lower Carboniferous (Viséan) Windsor and Codroy groups contain marine fauna related to those of Western Europe. These faunas differ markedly from the endemic early Carboniferous (Mississippian) assemblages of the eastern interior and Mississippi Valley regions of North America. Ostracodes and conodonts confirm the affinity of these faunas with the widespread Viséan faunas of western Europe. Early Carboniferous spore assemblages from the Canadian Appalachians also resemble those from western Europe. Pennsylvanian faunas (mostly arthropods and bivalves) and flora are similar to Namurian and Westphalian fossils of western Europe.

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.

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. Pre-accretion 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, Meguma). 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 in 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, Gaspésie, 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 Gaspésie. 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.

Avalon Zone

The Avalon Zone contains several types of mineral deposits formed mainly during late Precambrian magmatism and early Paleozoic sedimentation (Fig. 9.35). Submergent facies of pre-600 Ma Andean-type arc volcanic sequences contain volcanic-hosted massive sulphide deposits in Newfoundland, Cape Breton Island, and southern New Brunswick. An epithermal style of alteration and mineralization possibly related to two younger episodes of Precambrian magmatism is developed throughout the Newfoundland Avalon Zone and there is at least one possible late Precambrian carbonate-hosted base metal sulphide deposit in central Cape Breton Island. Calc-alkalic plutons related to a late magmatic episode contain minor occurrences of granophile elements in Newfoundland and porphyry-style mineralization in Cape Breton Island. Peralkaline plutons of the same age in Newfoundland contain concentrations of rare metals. Early Paleozoic stable shelf sedimentation in the Newfoundland Avalon Zone resulted in the formation of extensive sedimentary manganese and iron deposits.

Styles and ages of mineralization in the Bras d'Or and Burgeo subzones support other evidence for assignment to the Avalon Zone.

Meguma Zone

Two classes of mineral deposits formed during the pre-accretion history of the Meguma Zone/Annapolis Belt: (1) Concordant base metal occurrences related to the Goldenville-Halifax group transition zone; and (2) Clinton-type iron occurrences within the Devonian Torbrook Group of the Annapolis Belt. In addition, there is a suite of structurally controlled hydrothermal deposits that are unique to the Meguma Zone, including concordant gold-bearing quartz veins hosted by the Goldenville Group and other small stratabound and crosscutting veins (Fig. 9.47).

Three general mechanisms have been proposed for the origin of the Meguma gold veins: 1) syngenetic, hydrothermal deposition on the seafloor, 2) early syntectonic deposition from hydrothermal fluids of diverse origins, and 3) late syntectonic deposition from magmatic or deep crustal hydrothermal fluids.

Syn-orogenic deposits

Structurally controlled mesothermal/ epithermal mineralization

Structurally controlled precious and base metal deposits with mesothermal and epithermal characteristics formed throughout the accretionary and post-accretionary history of the Canadian Appalachians. During the gold exploration boom of the 1980s, a significant number of new deposits were discovered and renewed interest spurred research into the nature and origin of this class of deposit.

Mesothermal and lesser epithermal mineralization accompanied orogenic events at the accreting Laurentian margin and throughout the maturing post-accretion orogen. There are a few characteristics that are common to most deposits. Mineralization is typically related to major structures but it is commonly sited in second or third order subsidiary structures. Alteration is typically propylitic and of relatively local extent. Carbonate alteration is ubiquitous and there is commonly a strong association with rocks of contrasting competency (producing dilation during tectonism) and iron-rich lithologies (a chemical trap for gold). There is usually a marked association between gold and pyrite. However, comparison of characteristics of mineralization and alteration in different parts of the orogen show considerable complexities. In some areas, gold occurs in intensely altered country rocks whereas in others, it is in quartz veins associated with minimal alteration. Likewise, metal associations are not homogeneous. In some areas, gold is associated with antimony and arsenic whereas in others, it is associated with base metals. Clearly, local geological features have exercised considerable influence on the form and character of this class of deposits.

Although the timing of mineralization is not well constrained, such constraints as do exist indicate that structurally controlled mineralization was a protracted event that lasted from the Silurian to the Carboniferous. Ages of cross-cutting plutons and geological evidence show that at least some gold mineralization in central Newfoundland was probably associated with Silurian orogenic events. Mineralization occurs in Carboniferous rocks in southern New Brunswick. Major, possibly transcrustal, structures which were subject to reactivation were clearly a controlling factor in focussing hydrothermal fluids and mineralization.

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 subalkaline, alkaline, and peralkaline types. Granitic rocks occur in all zones and a variety of tectonic settings. Granites with I-type, S-type and A-type characteristics can be recognized, as well as large batholiths with mixed affinities.

The wide variety of granites and magmatic episodes has produced a broad spectrum of mineral deposits (Fig. 9.65). These include important concentrations of granophile elements (e.g. East Kemptville, Nova Scotia; Mount Pleasant, New Brunswick), base and precious metals (e.g. Gaspé Copper and Madeleine Mines, Quebec; Nigadoo River and Lake George, New Brunswick), Ni and platinum group elements (e.g. St. Stephen, New Brunswick), and industrial minerals (e.g. St. Lawrence fluorspar, Newfoundland). Although most of the economically significant granite-related mineralization in the Canadian Appalachians occurred during the Devonian, significant mineralization is also associated with older peraluminous plutons (e.g. central Newfoundland, New Brunswick) and with younger Carboniferous plutons (notably the peralkaline granites of southern Newfoundland), and Mesozoic plutons (alkaline granites, syenites, and carbonitites of southeastern Quebec and adjoining New England).

Post-orogenic deposits

Several mineralizing episodes can be recognized in late Paleozoic overlap assemblages: (1) Late Devonian to early Viséan: (a) minor occurrences of U are related to late Devonian rift-related felsic volcanics; (b) base mineral occurrences are found near the contact with the overlying marine evaporitic rocks of the Viséan Windsor Group; (c) rare paleoplacer deposits occur at the unconformity between the Meguma Supergroup slates and Horton Group conglomerates; (2) Viséan: (a) abundant evaporitic deposits (e.g.. anhydrite, salt, secondary gypsum hydrated from anhydrite, potash) formed at several stratigraphic levels in the Windsor/Codroy groups; (b) syngenetic low grade enrichments in Cu, Pb, Zn sulphides, pedogenic-diagenetic Fe and Mn and local barite and celestite replacements formed, especially near disconformity redox boundaries between marine carbonates and underlying redbeds; (3) Late Pennsylvanian: climate- controlled lead deposits formed in lower Westphalian sandstones (e.g., Yava Deposit, Cape Breton Island); (4) Late Westphalian to Stephanian: numerous epigenetic mineral deposits formed, apparently from metalliferous brines developed deep in the basins and driven toward the basin margins where they interacted with reactive host rocks both along escape paths (faults and fractures) and reservoir-stratigraphic traps. The basal Windsor Group carbonate rocks were a primary host; (5) Late Permian: reddening of upper Carboniferous strata, especially in the Cumberland Basin, where low water tables generated numerous solution-roll front type Cu, Ag 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.

During the rift stage, the principal mineral deposits were beach placers in southeastern Quebec. Because incipient rifting in the Canadian Appalachians was apparently not accompanied by extensive hydrothermal activity, there does not seem to have been extensive remobilization of metals within the crust, or transfer of metals between crustal levels.

During the drift stage, conditions were favourable on the continental margins adjacent to Iapetus for the formation of certain mineral deposit types such as Pb-Zn in shelf carbonate sequences. Basinward on the passive margin, uraniferous phosphorites were also formed. At about the same time, shallow seas spread across the stable Avalon Zone with sedimentary manganese and iron deposits. This stage of development provided the main opportunities for mass transfer from the mantle to the crust and mineral deposits such as chromite and base metals in ophiolitic suites formed from juvenile metal sources. Local subduction near continental margins resulted in hydrothermal circulation and ore formation on or near continental crust (e.g. Bathurst) and may have involved crustally derived metals as well. This ore-forming episode apparently operated mainly during extensional tectonic regimes, probably enhanced by the high heat flow and the focussing of hydrothermal fluids by extensional fracture systems. Most of the deposits of this type formed in back arc basins as no remnants of true oceanic crust and no metal deposits of a major spreading ridge are recognized.

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. Between the Middle Ordovician to Early Silurian, syn-accretion metallogeny began in the accreted inboard terranes while the outboard terranes were still experiencing drift-phase metallogeny. Thus evidence for Silurian subduction in the Aspy Subzone is supported by occurrences of volcanogenic sulphide deposits.

The processes of accretion included reactivation of preexisting 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.

Accretionary processes were accompanied by dewatering of nearby sedimentary basins liberating fluids that produced base metal and barite veins. Similar processes may have been partially responsible for the formation of epigenetic carbonate-hosted Zn and Pb deposits, although the timing and source of metals is not well constrained.

Post-accretion mineralizing processes were accompanied by a dramatic decrease in the intensity of tectonism, with the result that mass transfer of minerals occurred principally within the upper crustal levels. Most sediment hosted mineralization is believed to be related to movement on large faults within and around successor basins, with local fluid circulation in the immediate basement. Relief on boundary faults provided opportunities for placer deposits derived from the immediately adjacent highlands. Evaporitic basins produced thick deposits of sulphates which contributed soluble salts to basinal fluids, enhancing their metal-carrying capacity. Metals were probably derived from the sediments in the basins and from the immediately adjacent basement. Depositional environments were provided by porous units: sandstones, carbonates, or dilatent zones in competent units.

Mesozoic rocks, structures, and intrusions are related to the Atlantic spreading episode and another cycle of metallogeny.

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 first indication of major instability in the external Humber Zone is the sub-Middle Ordovician St. George Unconformity. It is interpreted to represent erosion along a migrating peripheral bulge associated with assembly and transport of Taconic allochthons.

The transition from carbonate platform to deep foreland basin includes a complicated record of platform collapse, fault movements, and deposition of limestone boulder conglomerates. Subaerial erosion of rocks that lay mainly east of the Humber Zone produced polymictic flysch units of chiefly Middle Ordovician age that are found now in both autochthonous and allochthonous successions, and they extend westward beyond the limit of Appalachian deformation. The deposition of deep marine clastics above shallow marine carbonates indicates rapid subsidence under the load of Taconic thrust sheets.

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.

Discontinuous ophiolite complexes along the Baie Verte-Brompton Line are associated with mélanges, either occurring as huge blocks within mélange (Quebec) or as basement to a mélange cover (Quebec and Newfoundland). Clastic sequences, such as the Magog Group and correlatives, occur above mélanges of the Estrie-Beauce, Témiscouata, and Gaspésie subzones. The clastic sequences are as old as Llanvirn and some have sedimentary links with Taconic allochthons of the Humber Zone. The mélanges in Quebec also contain deformed clasts from the adjacent internal Humber Zone. Similarly in Newfoundland, the Flat Water Pond Group of probable early Middle Ordovician age contains metamorphic clasts from the internal Humber Zone. These relationships suggest that mélange formation on the Baie Verte-Brompton Line was coeval with early assembly of Taconic allochthons and that the allochthons were in a sediment shedding position when clastic aprons like the Magog Group were deposited. The sedimentary evidence also indicates that parts of the internal Humber Zone were deformed and metamorphosed by early Middle Ordovician time.

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 mélanges 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 mélange 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.

In Gaspésie, early deformation of the Maquereau Group of the internal Humber Zone predated tectonic accretion to adjacent ophiolitic mélange, that in turn predated deposition of the Llanvirn Mictaw Group.

Ordovician deformation in the Dunnage Zone is mild compared to that in adjacent parts of the Humber Zone. Sub-Silurian unconformities are everywhere present across the Notre Dame Subzone, and locally present in the Estrie-Beauce, Témiscouata, and Gaspésie subzones. In New Brunswick, Ordovician rocks north of the Rocky Brook-Millstream Fault are mildly deformed and overlain unconformbly by Silurian strata.

The Notre Dame Subzone has one of the widest ophiolite belts in the Appalachian Orogen exposed along its coastal section. The overall structural arrangement indicates westward verging imbricate slices with eastward-facing stratigraphy. Intensity of deformation and metamorphism decreases progressively from west to east, or upward through the structural pile. An unconformable Silurian cover indicates that the imbrication is Ordovician.

Deformation and metamorphism in the Dashwoods Subzone are interpreted as Ordovician, based on isotopic dates and crosscutting relationships. Along the southeast margin of the Dashwoods Subzone, Devonian rocks of the Windsor Point Group are nonconformable on foliated tonalites and granites.

Older rocks in the Dunnage Zone

The Twillingate Subzone of Newfoundland is a small area of mafic volcanic rocks cut by tonalite dated at 510 ± 16 Ma (Fig. 3.76). Amphibolite facies metamorphism, intense deformation, and mylonitization along its southern margin are out of context with low grade rocks of the Notre Dame Subzone. Mafic dykes of the Notre Dame Subzone cut mylonitic tonalite and have cooling ages up to 470 Ma. The Twillingate tonalite is significantly older than ophiolite complexes of the Dunnage Zone.

Crystalline rocks occur in the Saint-Daniel Mélange and in ophiolitic mélange northwest of the Maquereau Dome of Gaspésie. Some of these are correlated with the Precambrian Chain Lakes massif of Maine. Relationships in the Mégantic Subzone also imply early to middle Ordovician interaction with the Chain Lakes massif. Two large plutons in the Exploits Subzone, the Valentine Lake and Cripple Back Lake quartz monzonites, dated at 563 ± 2 Ma and 565 +4/-2 Ma, are structurally emplaced and of uncertain significance.

Dunnage-Gander amalgamation

Ordovician sedimentary links between the Exploits Subzone and Gander Lake Subzone in Newfoundland are provided by Upper Arenig-Lower Llanvirn and Upper Llanvirn-Lower Llandeilo conglomerates that contain a sampling of ophiolitic clasts (Dunnage rocks) and quartzose sedimentary clasts (Gander rocks). Some of the ophiolitic clasts have fabrics that predate incorporation in the conglomerates, but whether or not the same is true for Gander clasts is debatable. An occurrence of ophiolitic olistostromal mélange at the Mount Cormack-Exploits subzone boundary contains ultramafic and quartzite blocks in a black shaly matrix, implying an Ordovician age. There is no evidence of fabrics in quartzite blocks before incorporation in the mélange.

The structural evidence for the Exploits Subzone (Dunnage) above the Mount Cormack Subzone (Gander) in Newfoundland is especially clear. The age of the Pipestone Pond Complex at 494 Ma sets a lower limit to the time of Dunnage transport. Metamorphic isograds in the Mount Cormack Subzone have a concentric pattern and the synmetamorphic Through Hill Granite, associated with the highest grade metamorphic rocks, is dated at 464 Ma (Colman-Sadd et al., 1992). These features suggest that the Mount Cormack Subzone is not a simple structural window, but rather a core complex with attendant metamorphism and plutonism. The Partridge Berry Hills Granite dated at 474 Ma stitches the Mount Cormack-Exploits boundary (Colman-Sadd et al., 1992). This and sedimentological evidence all support an Early Ordovician age for Dunnage-Gander interaction.

Rocks of the Gander Zone almost everywhere exhibit folded cleavages or schistosities and appear to be more deformed than rocks in the adjacent Dunnage and Avalon zones. Coupled with the presence of unconformities between Lower and/or lower Middle Ordovician conglomerates and mafic-ultramafic rocks of the Gander River Complex, relationships hint at pre-Middle Ordovician deformation in the Gander Zone. Relations in the Mount Cormack Subzone confirm Ordovician deformation, metamorphism and intrusion. However, the major deformation and regional metamorphism along the eastern margin of the Newfoundland Gander Zone is Silurian. This roughly coincides with imbrication and development of Silurian mélanges throughout the northeast Exploits Subzone.

The Baie Verte-Brompton Line and the northern Exploits-Gander Lake subzone boundary on opposite sides of the Newfoundland Dunnage Zone have several important similarities: (a) both are marked by discontinuous mafic-ultramafic complexes; (b) there is a sub-Middle Ordovician unconformity developed above mafic-ultramafic rocks along the Exploits-Gander boundary and an inferred sub-Middle Ordovician unconformity above mafic-ultramafic rocks of the Baie Verte-Brompton Line; (c) Ordovician conglomerates above the unconformities are of local derivation, unsorted, immature, and typical of rapidly evolving sources; (d) the conglomerates contain sedimentary clasts, deformed in some examples, that indicate linkages with the deformed Humber Zone to the west and the Gander Zone to the east; (e) mélanges occur locally at both boundaries; (f) in a general way, regional metamorphism increases in adjacent rocks outward and away from the Dunnage zone, although the times of metamorphism may be different (recent chronological studies of the internal Humber Zone in Newfoundland indicate important Silurian plutonism and high grade regional metamorphism (Cawood et al., 1994); (g) the present steep to overturned structures change outwards from the Dunnage Zone into flatter structures in metaclastic rocks; and (h) polarity of first structural transport is away from the Dunnage Zone with later transcurrent movements.

In contrast to the mainly tectonic Dunnage-Gander contacts in Newfoundland, most of the Tetagouche Group in the New Brunswick Dunnage Zone represents a conformable to disconformable stratigraphic cover to the Miramichi Group of the Gander Zone. Although contacts are commonly tectonized, field relationships do not support the idea that Middle Ordovician volcanic and sedimentary rocks represent the remnants of an enormous klippe of Dunnage Zone rocks above Gander Zone rocks. A disconformity between the basal Tetagouche Group and the Miramichi Group is marked by a thin layer of conglomerate. A similar conglomerate in Maine at the contact between the Grand Pitch and Shin Brook formations marks the sub-Middle Ordovician Penobscot unconformity. However in New Brunswick, the Miramichi and Tetagouche groups are deformed together and there is no correspondence between structural styles and stratigraphic divisions.

Faunal and other distinctions between the Notre Dame and Exploits subzones in Newfoundland suggest separation during their Early and early Middle Ordovician development. A sub-Silurian unconformity and absence of Caradoc shales and younger Ordovician rocks throughout the Notre Dame Subzone contrast with continuous deposition in north-central parts of the Exploits Subzone. The earliest subzone linkage is provided by volcanic clasts from the Notre Dame Subzone found in Upper Ordovician-Lower Silurian conglomerates and olistostrome of the Exploits Subzone. Structural evidence for a late Ordovician-early Silurian collisional event is scarce, except for eastward thrusting in the Exploits Subzone and local development of lower Silurian mélanges. Paleontological evidence suggests links between Laurentia and the Exploits Subzone by Llandeilo time.

The St. Croix Subzone-Avalon Zone boundary in New Brunswick is mainly hidden by Silurian to Lower Devonian volcanic and sedimentary rocks of the Mascarene Belt. The Silurian rocks are unconformable upon Ordovician rocks at Cookson Island.

Although Dunnage-Gander relations resemble Dunnage-Humber relations on the opposite side of the orogen, some important differences in the east are: (1) no stratigraphic analysis exists for a Gander Zone continental margin comparable to that for the Humber Zone; (2) metaclastic rocks that define the Gander Zone have no defined basement and their maximum age is unknown; (3) there is no stratigraphic or sedimentological expression of ophiolite emplacement in rocks of the Gander Zone; (4) ophiolite complexes of the Exploits Subzone lack dynamothermal soles of Bay of Islands type; (5) extensive mélanges and allochthons of Taconic style are absent in the east; (6) in both northeast Newfoundland and New Brunswick lower and middle Ordovician rocks are overstep sequences either stratigraphically above the Gander Zone or conformable and unconformable above rocks of the Dunnage Zone; (7) penetrative deformation related to Early Ordovician Dunnage-Gander interaction is poorly defined or absent, and rocks of the Miramichi and Bathurst subzones in New Brunswick have the same stuctural history; and (8) rocks of the Gander and Dunnage zones are cut by large middle Paleozoic plutons that confuse Ordovician relationships.

Gander-Avalon-Meguma accretion (Acadian Orogeny)

Accretion of the Avalon Zone to the Gander Zone is considered to be Silurian as there are no confirmed earlier linkages. The Meguma Zone and Annapolis Belt maintained a distinctiveness into the Devonian. The earliest linkage with the Avalon Zone is Carboniferous, so that the time of Avalon-Meguma accretion is considered Devonian.

The expressions of Silurian-Devonian accretion and the styles of Acadian Orogeny contrast sharply with expressions of Ordovician accretion and styles of Taconic Orogeny. The boundaries of Ordovician accreted zones are marked by ophiolite complexes and mélanges. In contrast, the Gander-Avalon boundary and the Avalon-Meguma boundary are steep faults with local wide zones of ductile shearing. Furthermore, whereas the evidence of an oceanic tract between the Humber and Gander zones is virtually unassailable, oceanic vestiges are absent at the boundaries of more outboard Zones. The mechanism of earliest accretion was by obduction of the Dunnage Zone across the opposing Humber and Gander zones. Later accretion of the Avalon and Meguma zones was controlled by transcurrent movements.

The structural effects of Acadian Orogeny are more widespread than those of earlier events. Whereas Taconic Orogeny is confined to the eastern Humber Zone and adjacent Dunnage Zone, with coevel effects at the Dunnage-Gander zone boundary (Map 5), Acadian Orogeny affected the entire exposed orogen, except for parts of the eastern Avalon Zone in Newfoundland (Map 6). This phase of orogenesis also coincides with the plutonic and metamorphic peaks in the development of the orogen.

Taconic Orogeny affected Cambrian-Ordovician marine rocks and was followed by marine deposition. Acadian Orogeny affected Silurian-Devonian rocks that were terrestrial in upper parts of stratigraphic sections, and the orogenic event was followed by terrestrial deposition. Acadian Orogeny marked a complete and permanent change in the development of the orogen.

Where middle Paleozoic stratigraphic sections are complete, such as in the Gaspé Belt, the Acadian event is dated as middle to late Devonian. In the absence of Devonian rocks, the stratigraphic definition of Acadian Orogeny is less certain. Lower and Middle Devonian rocks of the Canadian Appalachians are everywhere deformed, albeit mildly in some places. Large Devonian plutons cut most zones and belts of the orogen. Recent isotopic ages indicate a major Silurian orogenic event in central Newfoundland and there is evidence for a similar event in the Aspy Subzone and elsewhere. It affected Ordovician and Silurian rocks and it predated the emplacement of granites dated at about 400 Ma.

Sedimentary and stratigraphic linkages

The earliest linkage between the Gander and Avalon zones in Newfoundland is Silurian or Devonian, dependent on the age of the Cinq Isles and Pools Cove formations of the Fortune Belt that contain Gander Zone plutonic and metamorphic detritus and that lie unconformably on rocks of the Avalon Zone. The middle Paleozoic rocks of the Gaspé Belt overlap the Humber, Dunnage, and Gander zones, indicating that these zones were accreted before the end of the Ordovician. In New Brunswick, Lower Silurian rocks of the Fredericton Belt link the Miramichi and St. Croix subzones and Silurian rocks of the Mascarene Belt link the St. Croix Subzone and Avalon Zone.

The Meguma Zone has a dintinct Devonian stratigraphy and plutonic expression. Its first link with the Avalon Zone is established by the age of Carboniferous cover rocks.

The spread of the Late Silurian-Lochkovian Rhenish-Bohemian fauna onto Laurentia during the Pragian and Emsian agrees with other evidence for middle Paleozoic Avalon and Meguma accretion.

Structural expression

The effects of Acadian deformation extend all the way across the Canadian Appalachians from the Humber Zone in the west to the Meguma Zone in the east. At the surface, the Acadian foreland structural front of the Humber Zone coincides roughly with Logan's Line or the foreland limit of Taconic allochthons.

In Quebec, rocks of the northwestern portion of the Connecticut Valley-Gaspé division of the Gaspé Belt have a structural style like that of the Valley and Ridge Province of the U.S. Appalachians. Folds have wavelengths and amplitudes measured in kilometres and thrust faults occur on the north flanks of some anticlines. Across a zone of steep faults, rocks of the southeastern Connecticut Valley-Gaspé division are tightly folded with slaty cleavage. Tight to isoclinal, nearly upright folds on all scales are also a characteristic feature of the Aroostook-Percé division of the Gaspé Belt. Rocks of the Chaleurs Bay division are less deformed compared to the Aroostook-Percé division.

Major dextral faults in the Gaspé Belt are one of the most important features of Acadian Orogeny. Repetitions of the Matapédia Group in map pattern, implying several southward-facing shorelines, are explained by dextral offsets of a single shoreline on major transcurrent faults. Shallow marine shales on the south side of Chaleur Bay are interpreted as part of the same shelf rather than an opposing shelf on the opposite side of the Gaspé Belt.

In New Brunswick, Silurian rocks of the Fredericton Belt have polyphase deformation in the south, whereas only one phase of folding is recognized in most of its northern part.

The Arisaig Belt of Nova Scotia has shallow southeast-plunging upright folds. The Middle Devonian McAras Brook Formation postdates these structures suggesting a mid-Devonian age of deformation. The counter-clockwise orientation of the folds suggests that they were produced by dextral motions on the Hollow Fault. In the northern Cobequid Highlands, folding of Silurian-lower Devonian sedimentary rocks also pre-dates deposition of Upper Devonian redbeds and volcanic rocks. In the southern Antigonish Highlands, deformation is heterogenous and is restricted to shear zones, with local evidence of thrusting and development of positive flower structures. At least some of this deformation affected Upper Devonian rocks and is therefore younger than that in the northern Antigonish Highlands.

The Annapolis Belt has broad, shallowly plunging, upright folds with sub-vertical cleavage. Acadian Orogeny is the first major event to affect the Meguma Zone/Annapolis Belt.

In Newfoundland, the morphological Acadian front is a west directed thrust or steep reverse fault. Offshore seismic reflection profiles suggest a triangle zone similar to those developed at the foreland edges of other thrust belts. Devonian deformation is defined at Port au Port where the Silurian-Devonian Clam Bank Group is deformed and nearby Carboniferous rocks are undeformed. At Baie Verte Peninsula, structural styles of Silurian rocks vary from mild open folding to intense polyphase deformation, and the latest structures are east directed. Much of the plutonism and regional metamorphism in the internal Newfoundland Humber Zone is locally Silurian (Cawood et al., 1994).

Silurian rocks of the Springdale Belt are mildly deformed in most places where they lie unconformably upon deformed Ordovician or older rocks. Deformation is more intense throughout the Badger and Botwood belts. There, Ordovician and Silurian rocks are in places conformable and deformed together. In the Botwood Belt, a Silurian isotopic age for volcanic rocks that are unconformable above steeply dipping folded rocks of the Silurian Botwood Group is further evidence for Silurian deformation. Also, a 408 ± 2 Ma age for the Loon Bay intrusive suite places a Late Silurian upper limit on the timing of thrust faulting and folding in the Badger Belt.

Intensity of deformation increases southwestward along the Exploits Subzone and Botwood Belt toward the narrow Cape Ray Belt. Devonian rocks of the Windsor Point Group are polydeformed at Cape Ray. East over west oblique thrusting produced mylonites in the Windsor Point Group and this polarity of structure corresponds to northwest thrusting in the Silurian La Poile Belt.

Isotopic dates suggest a Silurian age for the intense deformation that increases eastward and southeastward across the Gander Lake Subzone and extends westward around the Hermitage Flexure.

The Gander-Avalon zone boundary along the Dover Fault is a wide zone of mylonitization that affects granite and metamorphic rocks on the Gander side and less deformed upper Precambrian sedimentary and volcanic rocks on the Avalon side. Deformation within the Avalon Zone is mild compared to that of the adjacent Gander Zone. Tight upright folds affect parts of the western Avalon Zone, whereas eastern parts have open folds. Some Cambrian-Ordovician rocks in the eastern Avalon Zone, such as those at Conception Bay, are subhorizontal. Offshore, Paleozoic deformation is uniformly mild or absent across the Grand Banks. A mild erosional unconformity separates marine Silurian and terrestrial Devonian rocks.

Metamorphic expression

Where tectonostratigraphic zones are wide, such as in northeast Newfoundland and Quebec-New Brunswick, middle Paleozoic metamorphism occurs in relatively narrow belts. Where zones are narrow, as in southwest Newfoundland and Cape Breton Island, regional metamorphism affects most rocks and zones. Intensity of regional metamorphism, mainly of Silurian age, increases eastward across the Newfoundland Gander Lake Subzone. 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 across the Dover Fault in northeast Newfoundland. Silurian metamorphism is high grade in the Aspy Subzone. The metamorphic facies of the Meguma Zone is greenschist, with an increase to amphibolite facies in the west. Hornblende-hornfels facies is developed close to granitic batholiths.

Plutonic expression

Middle Paleozoic plutons extend across the orogen from eastern parts of the Humber Zone to western parts of the Avalon Zone in Newfoundland and across the Avalon and Meguma zones in Nova Scotia. There are few middle Paleozoic plutons in the exposed Humber Zone, except for its internal parts in Newfoundland. One exception is the Devonian Mount McGerrigle pluton of Quebec, which cuts transported rocks near the Appalachian structural front. Another is the Devonian Devils Room granite of White Bay, Newfoundland that cuts all fabrics in adjacent gneisses of the Long Range Inlier.

Some post-tectonic middle Paleozoic plutons have a zonal preference, others cut zone boundaries or follow coeval volcanic belts that transgress zone boundaries. Alkali plutons that span the eastern Humber Zone and Notre Dame Subzone are coeval with Silurian volcanism and a series of nested calderas that cross the Humber-Dunnage boundary. Acadian composite plutons with early peripheral mafic phases and later granitic phases are common in the Exploits Subzone, but also cut the Red Indian Line. Foliated to massive middle Paleozoic biotite granites and garnetiferous muscovite leucogranites are typical of the Gander Zone and occur in all subzones. Most of these are of Silurian-Devonian age but some are Ordovician. Lineations and foliations in deformed examples are everywhere

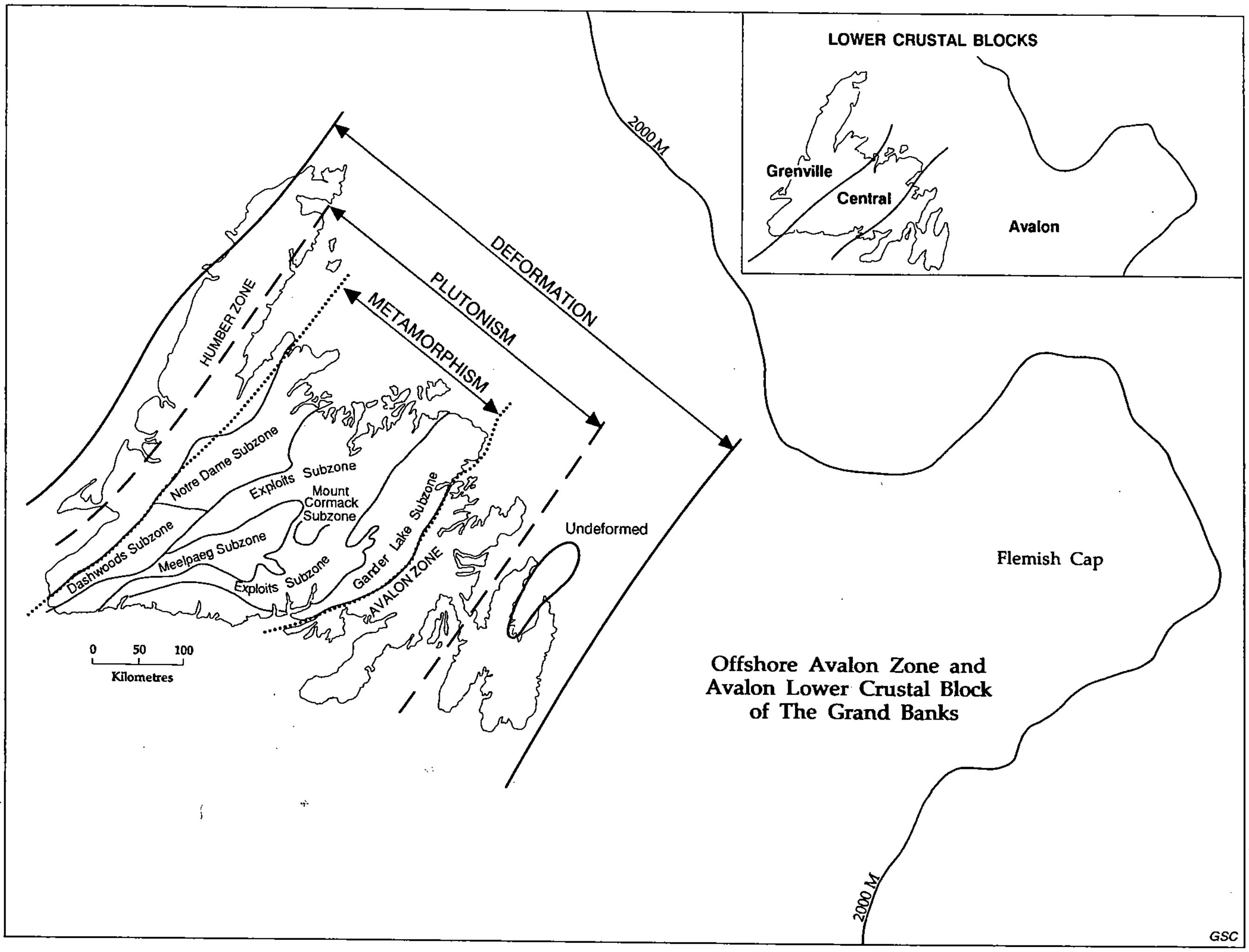

Figure 11.6. Comparison of limits of Acadian deformation, plutonism and upper greenschist to amphibolite facies regional metamorphism across the Newfoundland Appalachians and Atlantic continental margin.

parallel to those of host or nearby migmatites and mylonites, suggesting emplacement during shearing. Undeformed examples indicate that intrusive activity outlasted ductile shearing. A variety of features of the leucogranites suggest an origin through anatexis of supracrustal rocks, such as numerous xenoliths of partially assimilated country rock, a peraluminous chemistry, and high strontium isotope initial ratios. This underscores their localization in high grade areas of the Gander Zone and nearby anomalously high grade areas of the Exploits Subzone.

Sm-Nd isotopic characeristics of the Gander Group sedimentary rocks and the Hare Bay Gneiss are consistent with derivation from the same protolith sedimentary sequence. These rocks and Silurian-Devonian intrusions contrast with those of the Dunnage, Humber, and Avalon zones confirming fundamental differences in the lower crust (D'Lemos et al., 1994).

Coarse grained porphyritic biotite granites cut all other plutons and zone boundaries. Petrological and age differences among intrusions of the Ackley suite on opposite sides of the Gander-Avalon boundary may reflect underlying crustal contrasts, in accord with the seismic data for a vertical boundary between the Central and Avalon lower crustal blocks. Rocks as young as Late Devonian are cut by the Belleoram Granite in the western Avalon Zone of Fortune Bay.

In New Brunswick, an Acadian magmatic suite of bimodal plutonic and extrusive rocks crosses all boundaries between the Dunnage, Gander and Avalon zones, including a late Ordovician-early Silurian blueschist suture that links the Dunnage and Gander zones.

The Meguma Zone has a distinct Devonian plutonic history and its middle Paleozoic intrusions do not cross the Meguma-Avalon zone boundary.

Discussion

The lack of complete Silurian and Devonian sections in the Humber Zone and St. Lawrence Platform precludes a stratigraphic analysis of the sedimentological effects of Acadian Orogeny. Possibly, easterly derived Silurian-Devonian redbeds of the Clam Bank Belt are a molasse related to uplift in interior parts of the orogen. Likewise, Silurian-Devonian redbeds and conglomerates of the Fortune Belt and the Devonian redbeds that overlie Silurian rocks with mild unconformity on the Grand Banks may represent molasse deposits on the opposing side of the orogen.

The shape of the ancient continental margin of eastern North America had an important control on the local extent and intensity of Acadian deformation. At the St. Lawrence Promontory, deformation in the Devonian Windsor Point Group is more intense than that in Silurian-Devonian rocks elsewhere. Furthermore, Paleozoic rocks of the Newfoundland Reentrant at the Strait of Belle Isle are locally outside the Appalachian deformed zone, although the rocks are part of the Appalachian system by any other definition.

Juxtaposed lower crustal blocks beneath the Dunnage Zone explain the presence and abundance of large granitic plutons that cut its oceanic rocks. The localization of deformed middle Paleozoic plutons to the Gander Zone may reflect diapiric emplacement during doming of a lighter Gander crust through a heavier Dunnage cover. Ductile shearing may also localize plutonism here.

In Newfoundland, the area affected by Acadian Orogeny is symmetrically disposed between the edges of the wide opposing Grenville and Avalon lower crustal blocks (Fig. 11.6). Deformation at the surface spans the eastern portion of the Grenville lower crustal block, all of the Central lower crustal block, and western parts of the Avalon lower crustal block. The limits of plutonism also span these regions but within narrower limits. High grade regional metamorphism is more restrictive, mainly above the Central lower crustal block.

In Nova Scotia, Acadian Orogeny affected the Mira Subzone (Avalon Zone and Avalon lower crustal block) but intensity of deformation, regional metamorphism and middle Paleozoic plutonism are less important than in the Bras d'Or and Aspy Subzones to the northwest (Central lower crustal block). This resembles the situation in Newfoundland. Similarly in New Brunswick, middle Paleozoic plutons are less abundant in the Avalon Zone compared to the adjacent Gander Zone. However, the Meguma Zone of Nova Scotia, outboard of the Avalon, exhibits the full effects of Acadian deformation, metamorphism, and plutonism. This supports other data for a Sable lower crustal block that had its own unique controls on surface orogenic effects in the Meguma Zone.

These spatial relations imply that Acadian Orogeny resulted from the middle Paleozoic collisional interaction between lower crustal blocks. The main zone of Acadian deformation, regional metamorphism and plutonism expectedly coincides with the narrow, intervening Central lower crustal block and the edges of the Grenville and Avalon lower crustal blocks. Where the Avalon Zone and corresponding lower crustal block are especially wide in Newfoundland, the basement behaved rigidly and cover rocks are undeformed across its eastern parts.

Alleghanian Orogeny

Late Paleozoic deformation in the Canadian Appalachians is mild or non existent (Map 6). Late Paleozoic deformation affected the thickest sections of the Maritimes Rift from New Brunswick to western Newfoundland, and it is most intense along the northwest shoreline of the Bay of Fundy and along the Avalon-Meguma zone boundary. Middle and Upper Caboniferous rocks of the Maritimes Rift are in places unconformable on deformed Lower Carboniferous rocks and locally they overlap boundary faults onto adjacent stable areas. Along the northwest shore of the Bay of Fundy, Carboniferous rocks are involved in thrusts with polyphase deformation and subhorizontal penetrative cleavage. A few small plutons, dated isotopically as Carboniferous, occur outside the late Paleozoic basins in older rocks of the Avalon and Meguma zones.

The localization of late Paleozoic deformation along narrow faulted belts and along the Avalon-Meguma boundary favours a model of wrench tectonics. Dextral movement on the Cobequid Fault explains local deformation in the fault zone, and westward movement of the Meguma Zone (Sable lower crustal block) against the Avalon Zone (Avalon lower crustal block) is a simple and elegant explanation for the siting and polarity of thrusting along the northwest shore of the Bay of Fundy. A wrench tectonic regime in Atlantic Canada complements a compressional regime in the U.S. Appalachians.

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