T2.1 INTRODUCTION TO THE GEOLOGICAL HISTORY OF NOVA SCOTIA

The geological history of Nova Scotia spans more than 1.2 billion years. The major events in this history are summarized in Figure T2.1.1. A fundamental assumption in geology is that the natural laws operating today also operated in the past. This implies that the physical laws governing rates of evaporation of water from the sea, for example, are the same now as in the past; it does not say that the rates of evaporation over the Atlantic Ocean are the same now as in the past. Understanding how the laws act today to produce modern climate, however, allows one to interpret the record in the rocks to make deductions about the climates of the past. Application of this principle to the rocks, and to the features preserved in them, shows that the materials of the earth's crust have been reworked continuously in the cycle of erosion, deposition, burial, alteration, uplift, exposure and erosion again.

The geological record also shows that movement within and between large bodies of rock has been an integral part of their evolution. This has included movement upwards as mountains rose, downwards as the sea covered the land and laterally as sediments were compressed into folded rocks.

To explain the causes and pattern of this movement, the theory of crustal movement called "plate tectonics" has evolved. The main arguments for this theory are outlined below.

PLATE TECTONICS

A century ago, geologists realized there was a problem in the past distribution of plants and animals. For example, coal occurs in Spitsbergen and in Antarctica, where one would hardly expect it; the Permian reptile *Mesosaurus* is restricted to South America and South Africa, and marsupials are restricted to Australia; the Permo-Carboniferous flora of Europe is found also in the United States, in Iran and in Turkistan; the *Glossopteris* flora of Brazil is found in Antarctica, Africa, India, Australia and northern Russia; Permian glacial deposits occur in Brazil and Argentina, central and southern Africa, northern India and Australia, but not in the present northern hemisphere.

Wegener suggested in 1915 that the existing continents had once formed a single large continent that had broken up.[1] He reassembled the continents into a single large mass to which he gave the name Pangea

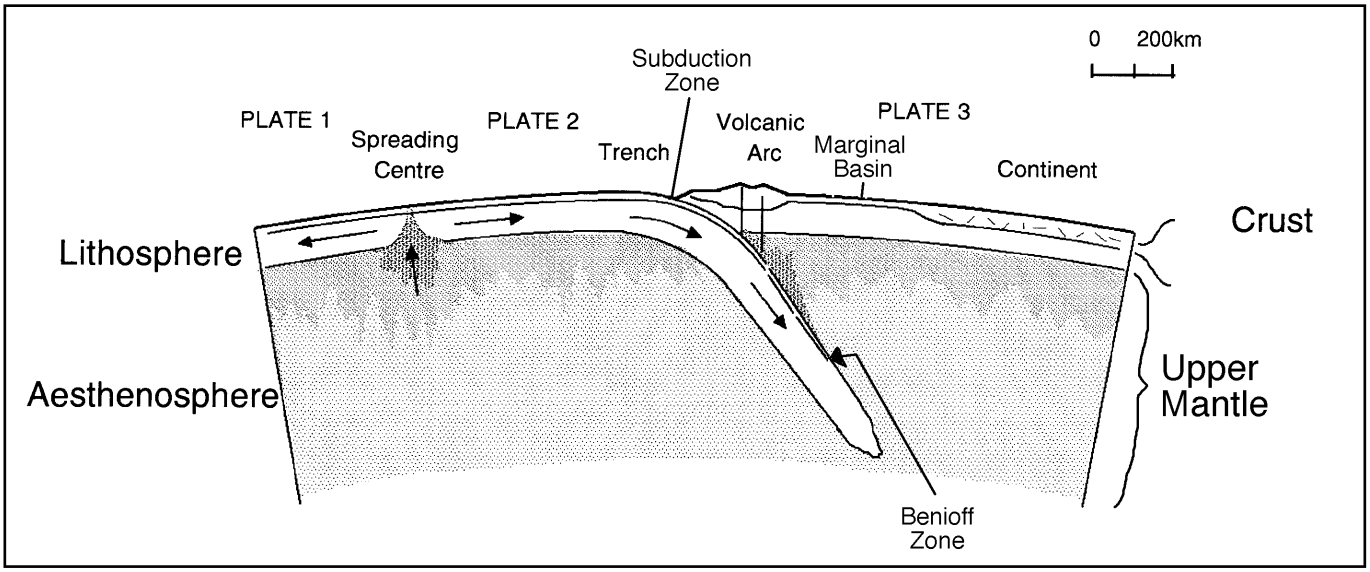

Figure T2.1.2: The upper mantle and crustal plates seen in a diagrammatic cross section. The continent is embedded in a plate of the lithosphere which is generated at the spreading centre (a mid-ocean ridge) and destroyed at the subduction zone, usually seen as a deep ocean trench. The Benioff zone is a zone associated with deep earthquake activity. It descends below the asthenosphere, a zone of partial melting of the crust. The marginal basin is a deep crustal area accumulating products of erosion from the continental margin. Other terms are explained in the text.

(Gk: the whole Earth). In that reassembly, for example, coalfields fell into place in equatorial regions, salt and gypsum (formed by the evaporation of seawater) and desert sandstones fell in the tropics, and the continental glaciers in the polar regions. He explained many things, such as the present distribution of coal, of salt and gypsum and of glacial deposits, as due to the break-up of Pangea to form the present continents, which had then drifted apart—hence "continental drift." Similar floras and faunas on opposite sides of modern oceans are then the result of the opening of the oceans. So, too, are such similarities of shape as that of the east coast of South America and the west coast of Africa.

Wegener also used this drift of the continents through the floor of the ocean to explain orogeny as the formation of mountain systems on the leading edge of the drifting continents—the western cordillera of the Americas, for example—and thus to solve another problem, the genesis of the enormous and long-continued forces necessary to produce fold mountains. This was an impossible mechanism for orogeny, and Wegener had difficulty in finding forces adequate to cause the drift. He marshalled a considerable array of geodetic, geological, geophysical, paleobiological and paleoclimatic arguments. Although the idea generated major symposia, and his book on the subject went through four editions in German and translation into English, French, Spanish and Russian, he was not able to convince most of his contemporaries.

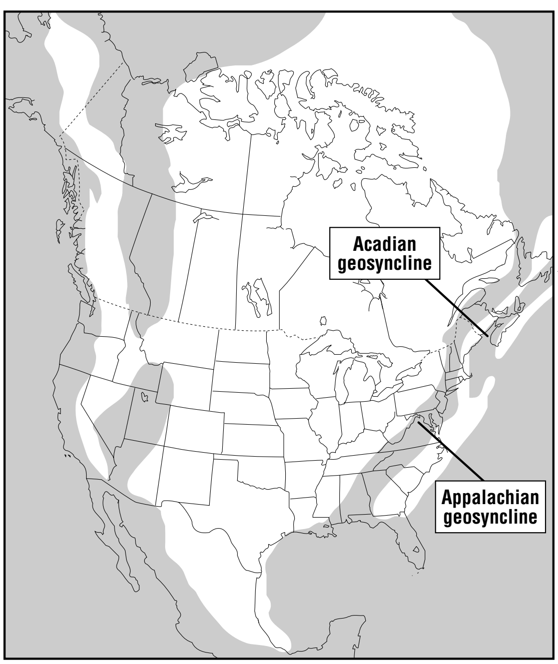

Figure T2.1.3: Cambrian Paleography. Maximum extent of the Early Cambrian seas. Hills remain where the late Precambrian ranges stood on the Canadian Shield; marginal highlands existed along both east and west margins of the continent.[2] (Reprinted by permission of John Wiley & Sons).

Archaeologists have long known that tiles, pottery and other items that have been strongly heated have acquired a weak magnetism as they cooled in the earth's magnetic field. About forty years ago, geologists discovered that cooling lavas do the same thing and that sedimentary rocks also acquire a "depositional magnetism" induced by the field of the earth at the time of deposition, and therefore parallel to it. Here was a locked-in record of paleomagnetic directions, and a method of locating the magnetic poles at the time the rocks were formed. Comparison of the paleomagnetism of rocks of the same age from North America indicated that, in Permian time, for example, the North Pole was in southern Mongolia, while the paleomagnetism of Permian rocks from Europe insisted it was in the Pacific Ocean, southwest of the Aleutian Islands. If the earth's magnetic field has always had two poles, one north and one south, then the continents must have moved relative to one another. Paleomagnetism is the prime direct and objective evidence for the reality of continental drift.

At about the same time, oceanographers discovered that the intensity of the magnetic field over the oceans shows a pattern of crude "stripes" that are symmetrical about the mid-ocean ridges. Those ridges are volcanic, and the cooling lavas, of course, become magnetized. If the volcanoes are fed by magma injected from below, and so spreading the ridge apart, the sea floor must be spreading outward on both sides of the ridge and would form a symmetrical magnetic record of changes in the earth's field. This concept of sea-floor spreading requires that the sea floor be consumed elsewhere, if the earth is not enlarging. Circulation of the oceanic floor back into the earth (subduction) at the oceanic trenches is a reasonable explanation. The descending cold slab of oceanic rock would explain the deep-focus earthquakes (to depths of 400 km) of the Benioff zone associated with the trenches (see Figure T2.1.2). Each mid-ocean ridge, of course, must have a corresponding subduction zone. Analysis of the distribution of ridges, troughs and earthquakes generated by the movement of the crust indicates that, at present, the earth's crust consists of about a dozen major parts (oceanic plates) moving at rates of a few centimetres per year. The driving mechanism is the earth's mantle. The crustal plates are carried upon the horizontally moving upper part of a convective circulation in the mantle material. Continents are embedded in the plates and carried along as passengers therein, so continental drift is implicit in plate tectonics, but not drift through the crustal plate, as Wegener would have had it. Applied to the present plate distributions, the theory proposes that Wegener's single continent was broken up during Jurassic and Cretaceous time, with the Atlantic Ocean opening to separate the Americas from Europe and Africa, that Australia and New Zealand were carried eastward and that India drifted into collision with southern Asia.

Orogeny is the result when continents collide, or when a continent at the edge of a plate overrides a subduction zone. The sediments previously accumulated on the continental margins, shelves and slopes will, of course, be involved in such an event and reappear as fold mountains.

APPLICATION TO ATLANTIC CANADA

General acceptance of the idea of plate tectonics naturally led to efforts to reconstruct the past distributions of continents and oceans.The primary evidence used for such reconstruction is

1. the paleomagnetic data from rocks of the appropriate ages (which gives paleolatitudes and the geographical orientation, but not longitude)
2. the character of the preserved fossils (which gives information about the environment in which they lived, about biological similarities and differences and, indirectly, about climate)
3. the character of the rocks themselves (which contain information about sources of sediments, the conditions of their deposition and the distribution of volcanic and other magmatic activity).

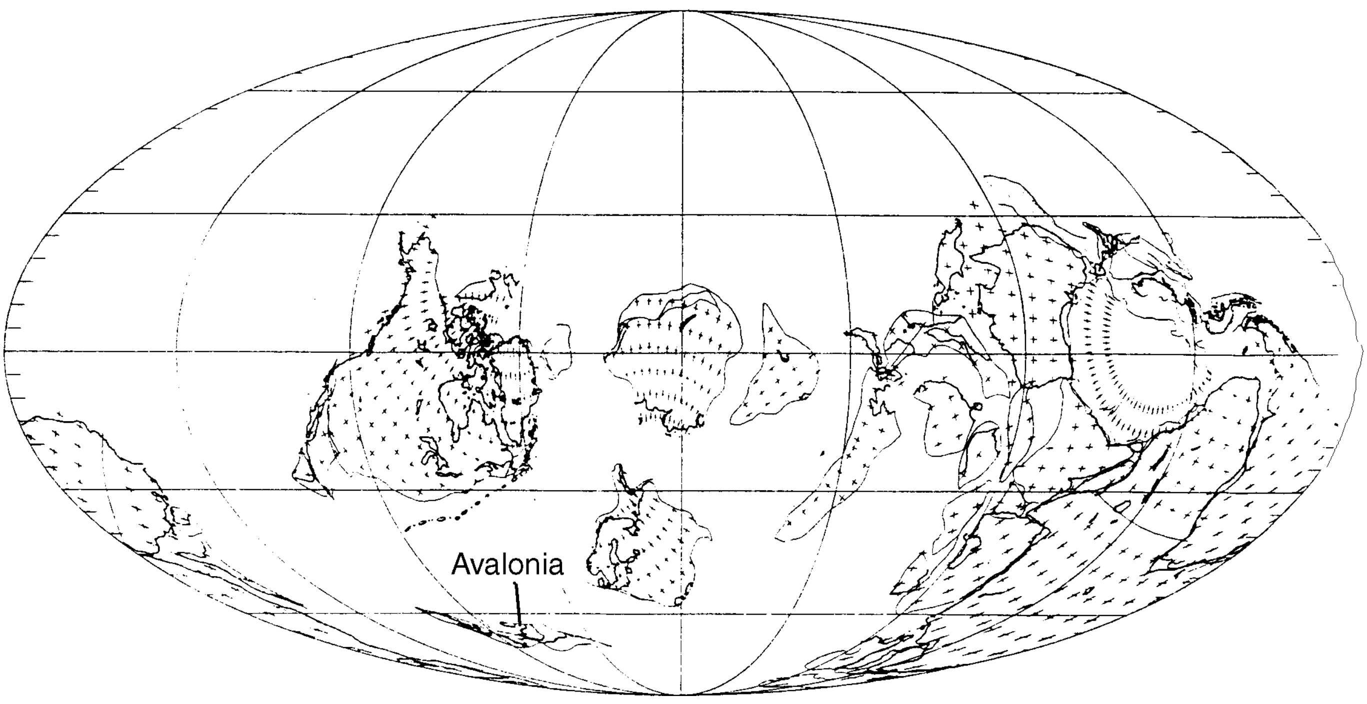

Figure T2.1.4: Position of Avalonia during the Early Ordovician. (Reprinted from McKerrow and Scotese,[3] with permission from Geological Society Publishing House).

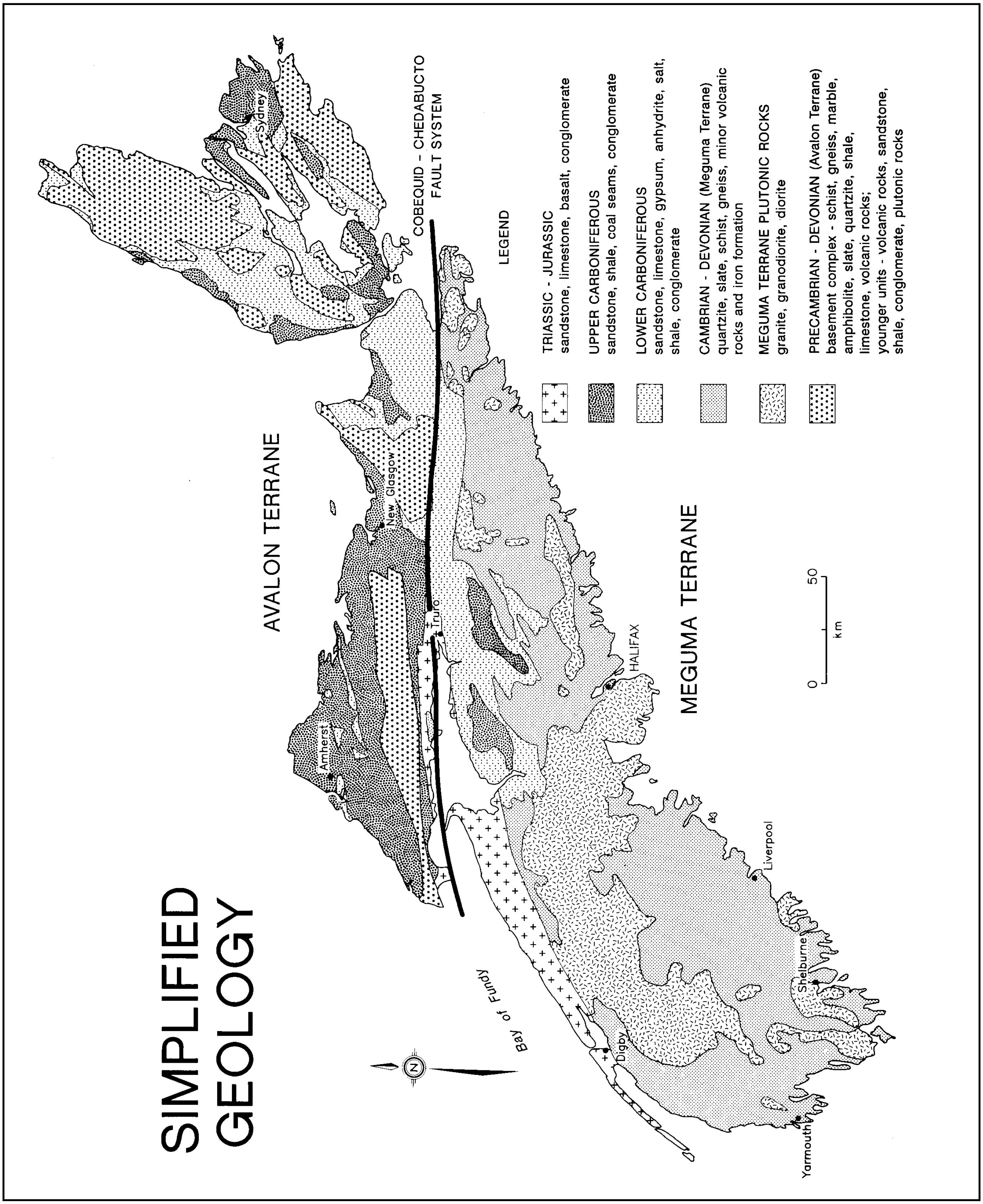

Figure T2.1.5: A simplified map of the geology of Nova Scotia; compiled by the Department of Natural Resources (Mines and Minerals Branch).

One such was prepared by the Geological Society of London, which held a symposium at Oxford in 1988 to discuss such reconstruction on a worldwide scale. The contributions of the participants were published in 1990, and the editors summarized the results in a series of maps which attempt to reconcile the data and the differences of opinion of the participants. Several of the maps are used in this document to illustrate the general distribution of the continents at various times. There is general agreement that North America (Laurentia), northern Europe (Baltica and Avalonia) and Siberia gradually aggregated into a single mass (Laurasia), while South America, Africa, Australia, India and Antarctica formed another huge mass (Gondwana). The two combined during Devonian time to form Pangea, which broke up again in Jurassic and Cretaceous time, as Wegener had argued.

We may use one of the maps to illustrate the changes wrought by plate tectonics. The Cambrian fossils of Nova Scotia are distinctly different from those farther northwest. To explain this, in a paleogeographic map published in 1960 (before the "rebirth" of the continental-drift theory about 1965), Dunbar inserted a land barrier to separate the Cambrian sea of Nova Scotia from that of New Brunswick (Figure T2.1.3).[2] Of the five tectonostratigraphic zones into which Williams divided the Appalachians in 1978, the Avalon Zone corresponds approximately with the Acadian geosyncline of Dunbar's map, and that zone is shown in Figure T2.1.4 as Avalonia. The differences in the faunas are now explained, because they were originally separated by more than 30 degrees of latitude.

The simplified geological map (Figure T2.1.5) shows the distribution of various rock types throughout the province and can be compared with a surficial map (Figure T3.4.3) to explain some surficial features. For example, the highland regions in Cape Breton and northern Nova Scotia are underlain by very old, highly resistant rocks. As a result, topographic highlands form and are often exposed or covered by a thin veneer of till. In contrast, softer rocks in the Annapolis Valley region were extensively eroded, formed catchment basins and were subsequently partially filled with thick sequences of glaciofluvial and alluvial deposits.

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Associated Topics

T2.2 – T2.7 Geology, T3.1 – T3.5 Landscape Development, T4.1 Post-glacial Climatic Change

References

1 Wegener, A. (1966) *The Origin of Continents and Oceans*, translated from the fourth (revised) German edition of 1929, by J. Biram. Methuen, London (New York: reprinted by Dover Publications).

2 Dunbar, C.O. (1960) *Historical Geology,* 2nd ed. Wiley, New York.

3 McKerrow, W.S., and C.R. Scotese, eds. (1990) Palaeozoic Palaeogeography and Biogeography. *Geological Society (London), Memoir* 12.

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Additional Readings

- Dewey, J.F. (1972) *Plate Tectonics*. Scientific American, Inc.
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T2.2 THE AVALON AND MEGUMA ZONES

**T2.2
The Avalon and
Meguma Zones**

A fault across Nova Scotia, from Cobequid Bay to Chedabucto Bay, neatly divides the province into two geological zones which are fundamentally different from one another. In 1978, Williams divided the Appalachians into five tectonostratigraphic zones, named for their distribution in Newfoundland.[1] From north to south across Newfoundland and Nova Scotia, they are Humber, Dunnage, Gander, Avalon and Meguma. He placed the northern boundary of the Avalon Zone through Fortune Bay, Newfoundland, and north of the Caledonian Highlands in southern New Brunswick. The south boundary is the Cobequid-Chedabucto Fault, so the whole of Cape Breton and northern Nova Scotia fell within the Avalon Zone. It appears as part of "Avalonia," (see Figures T2.1.4 and T2.2.2a) which also included southern Britain and northern France.[2] Prior to the Devonian Period, the Avalon and Meguma zones developed in different areas and later came into contact along the Cobequid-Chedabucto Fault. (The fault system also has other names: Glooscap Fault; Minas Geofracture.)

In the last fifteen years, Barr, Jamieson, Raeside and others have accumulated evidence to show that, in Cape Breton, the Avalon Zone is limited to the southern part of the island (see Figure T2.2.1). In the interim, also, the term "terrane" has come into use to describe the zones. A terrane is a distinct region or

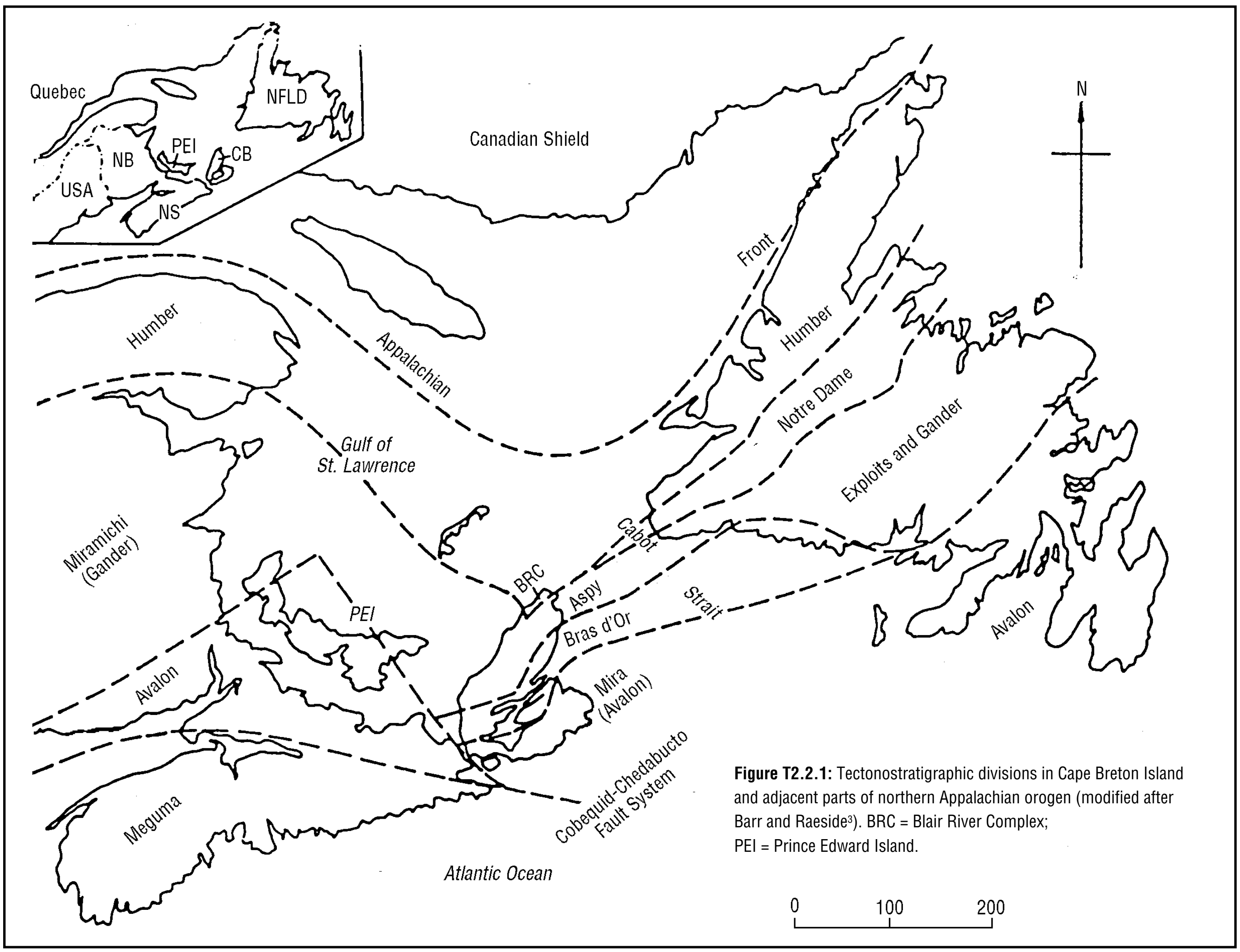


Figure T2.2.1: Tectonostratigraphic divisions in Cape Breton Island and adjacent parts of northern Appalachian orogen (modified after Barr and Raeside[3]). BRC = Blair River Complex; PEI = Prince Edward Island.

group of rocks with common stratigraphic units and origin. The northwestern areas of Cape Breton Island are composed of two other terranes — the Aspy and Bras d'Or—and a small fragment of the Precambrian Shield (the Blair River Complex).

AVALON ZONE

Distribution of Strata

Rocks of the Avalon Zone outcrop north of the Cobequid-Chedabucto Fault. They range in age from Precambrian to Devonian and are found in three areas: the Cobequid Highlands, the Pictou-Antigonish Highlands (Districts 310, 320) and in Cape Breton (Regions 100, 200 and Districts 310, 330). They occur in fault-bounded blocks which stand out in the landscape as prominent ridges because the rocks are resistant to weathering and because they have been pushed up relative to their surroundings.

Earliest Record

Precambrian rocks are found in all three areas and, with the exception of volcanic deposits in southern Cape Breton, are severely altered. Granites were intruded late in the Precambrian and again in Devonian time. Some of the rocks have been metamorphosed to high grade.

Northern Cape Breton consists of three parts, which have different metamorphic histories and ages. They are the Blair River Complex (at the northern tip of Cape Breton), the Bras d'Or terrane (Ingonish to East Bay) and the Aspy terrane (between the two).

The Blair River Complex consists of quartzo-feldspathic and amphibolite gneisses and minor amounts of calcareous rocks; these have been intruded by anorthosite, syenite and granite. The Pb/U (zircon) radiometric age of the syenite is about 1,000 million years. The Complex has a late-Grenvillian metamorphic age and resembles Grenville rocks of the Canadian Shield.

The Aspy terrane consists of volcanic and sedimentary rocks now metamorphosed to greenschist and amphibolite facies (i.e., low- to high-grade phyllites and schists). The Pb/U age is 430–440 million years, i.e., Ordovician-Silurian. It is separated from the Bras d'Or terrane by a shear zone up to 800 m wide.

The Bras d'Or terrane consists of sedimentary and volcanic rocks, generally metamorphosed only to relatively low grade, that were intruded by diorite and granite. The granites have Pb/U (zircon) ages of 555–565 million years, and so are Early Cambrian.

On the basis of age, of composition, and of magnetic and seismic continuity across Cabot Strait, the Blair River Complex is correlated with the Humber Zone in Newfoundland. This means the edge of the Precambrian part of the continent (Laurentia) extends as far south as northern Cape Breton. The Aspy and Bras d'Or terranes are correlated with the rocks of central Newfoundland; the Dunnage Zone does not appear in Cape Breton. These correlations remove northern Cape Breton from the Avalon Zone and redefine that zone to include only the Mira terrane, which is the part of Cape Breton south of the Boisdale Hills and Bras d'Or Lake (Figure T2.2.1). The northern mainland remains in the Avalon.

The Avalon Zone in southern Cape Breton contains late Precambrian volcanic rocks that were intruded by diorite and granite. Following an interval when those rocks were being eroded, red sandstones and conglomerates were deposited upon them, and followed by grey shales and siltstones of Early Cambrian age. During the remainder of Cambrian time, shales and siltstones were deposited in a marine basin that gradually deepened and then shoaled again, as is indicated by a disconformity (indicating a period of non-deposition) beneath the Late Cambrian shales and limestones. The fossils include brachiopods, crinoids, trilobites and graptolites. Comparison of this assemblage with those found elsewhere indicates that the Avalon Zone was associated with Europe and Africa (i.e., Gondwana) during the Cambrian period.

In the Pictou–Antigonish area, Cambrian rocks were deposited as lavas and volcanic ash interbedded with sands and muds. They include beds of oolitic hematite. Late Ordovician volcanism is indicated by the Bear Brook Formation, and ash beds show that the activity continued into Silurian time. The oldest sediments of the classic exposures near Arisaig are Silurian. The Arisaig Group has abundant fossils of great variety and is composed mainly of shales and fine-grained sandstones, deposited in a sea that gradually became shallower. In the upper part of the group there are Middle Silurian red beds (Moydart Formation) that indicate fluvial or estuarine deposition. Similar conditions returned in Early Devonian time (Knoydart Formation), and both formations contain abundant fossil fish spines and plates. The similarity of the fossil faunas to those of northern Europe is one of the reasons for believing that Avalonia and Baltica were close together in Silurian time (see Figure T2.2.2. a & b).

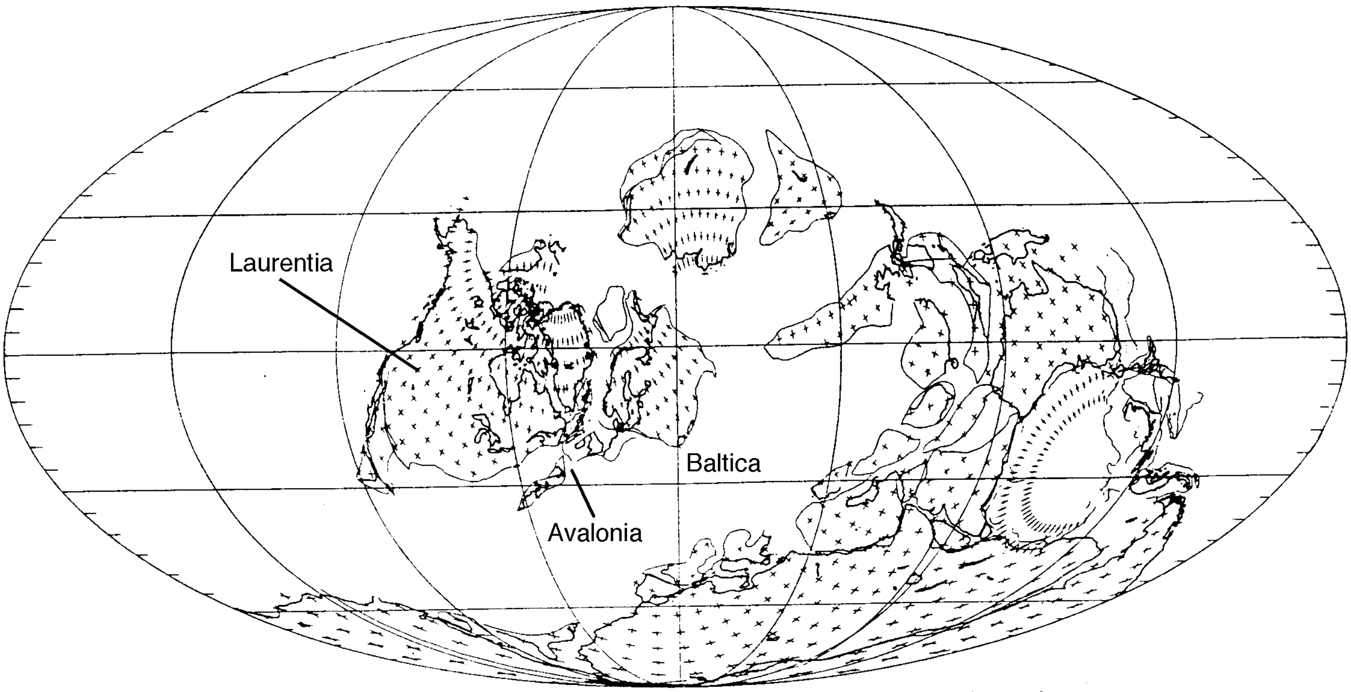


Figure T2.2.2a: Location of continents during the Middle Silurian. Nova Scotia was part of the subcontinent Avalonia attached with parts of Europe (Baltica) to the continent Laurentia. (Reprinted from McKerrow and Scotese[2], with permission of the Geology Society Publishing House.)

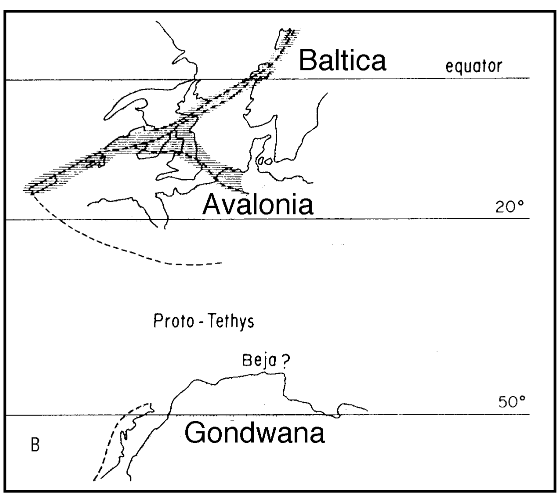


Figure T2.2.2b: Relative position of Avalonia and Baltica to the continent of Gondwana (South American and Africa) during the Middle Silurian. (Modified after J.P. Lefort[4])

In the Cobequids, the Silurian rocks are dominantly volcanic, and the interbedded sedimentary rocks are similar to those of the upper part of the Arisaig Group. The Devonian rocks are also similar to those of the Antigonish area.

The overlying Carboniferous rocks are discussed in T2.4. The Avalonian rocks were metamorphosed at different times, as shown in Figure T2.2.3.

MEGUMA ZONE

Regional Geologic Setting

The Meguma Zone occupies the southern mainland of Nova Scotia and extends seaward beneath younger sedimentary rocks. To the south and southeast it underlies the Scotian Shelf (Districts 910, 920, 930) and the continental shelf southeast of Cape Breton; to the east it underlies the tail of the Grand Banks of Newfoundland; and to the northwest it underlies the Bay of Fundy (Unit 912). Its total area is approximately 200 000 km^2. The base of the succession is unknown because of intrusive granites; the top is an erosional and angular unconformity representing the Acadian Orogeny. Geochemical and geophysical data suggest that the Meguma Zone *in toto* has been thrust over a southward extension of the Avalon Zone. Composite thickness of the stratigraphic succession exceeds 23 km; however, nowhere do all of the units occur at one locality, nor are their thicknesses constant.

Stratigraphy

The sedimentary rocks of the Meguma Zone consist almost entirely of fine-grained sandstones and shales. Minor amounts of volcaniclastic, conglomeratic and carbonate rocks are significant locally. The Meguma stratigraphic succession consists of three major groups of sandstone that alternate vertically with two thick groups of shale. Together they form two supergroups.[5] The basal Meguma Supergroup underlies most of southern Nova Scotia. An erosional remnant of the overlying Annapolis Supergroup occurs only along the northwestern margin of the Zone. The stratigraphic succession is also divisible by unconformities. These are indicated by local erosional and angular discordances but mainly by subaerial volcaniclastic rocks. The intervening four stratigraphic sequences each begins with basal sandstone, followed by black shale and capped by siltstone and/or sandstone. Igneous activity ends each sequence, usually as subaerial volcaniclastics but also as extrusive or intrusive sheets.

Sandstones of the Meguma Supergroup are different from those of the overlying Annapolis Supergroup. Both are metamorphic quartzites, but the Meguma sandstones were originally mixed feldspathic, quartz-rich sands and mud, perhaps with some volcanic debris. They occur as thick strata showing limited graded bedding, sole marks and, in places, horizontally directed burrows. Regional analysis of sandstone composition, texture and sedimentary structures shows that paleocurrents flowed from the present south-southeast. On the other hand, sandstones of the Annapolis Supergroup are dominantly quartzose, with small mud content. Sedimentary structures include abundant cross-stratification and vertically directed burrows. Paleocurrent patterns are almost random. The sandstones of the two supergroups record different environments. Those of the Meguma are the products of turbidity flows in deep water, channel complexes of submarine-fan systems.[6] The source area was to the present south-southeast and continental in size. Sandstones of the Annapolis Supergroup are the result of traction currents on a shallow-water continental shelf. Random paleocurrent patterns and the nature of bed forms in the sandstones suggest that cyclonic storms generated currents.[7]

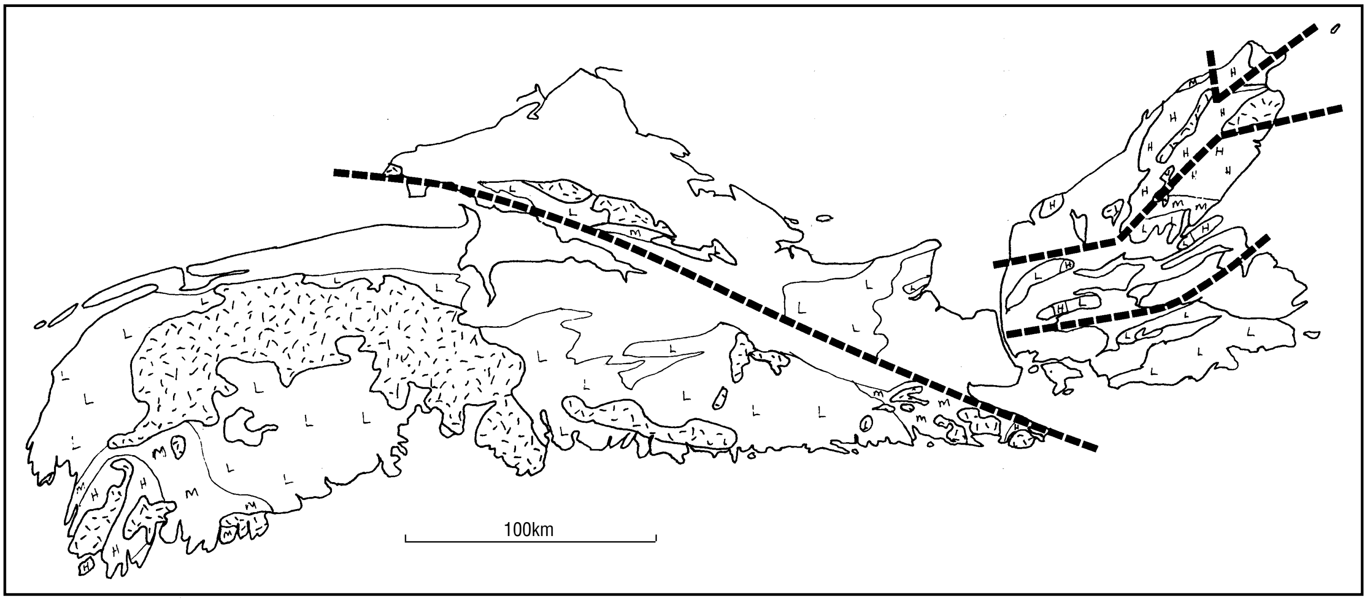
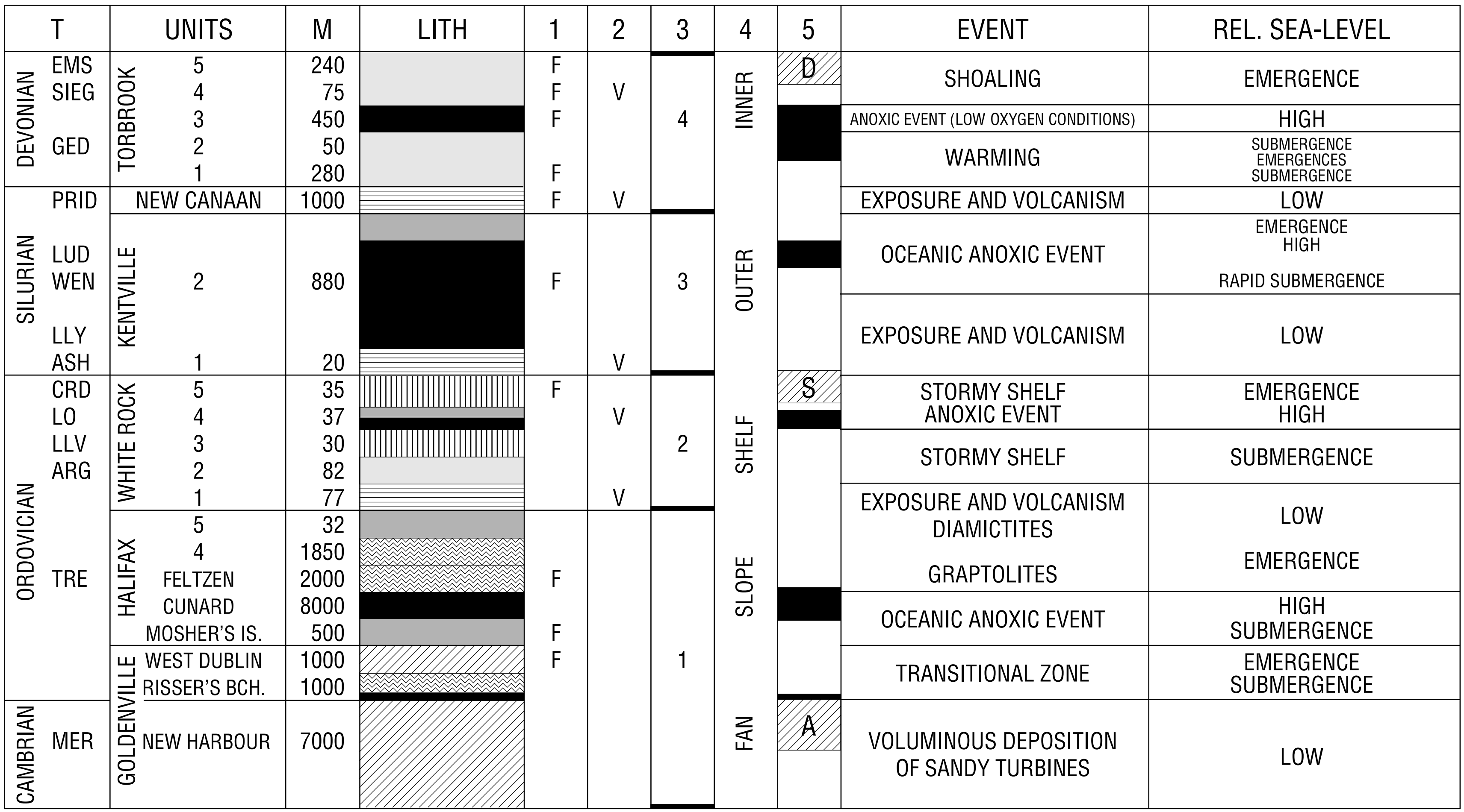


Figure T2.2.3: Metamorphism and Devonian plutonism in Nova Scotia. L—low-grade metamorphism; M—medium-grade metamorphism; H—high-grade metamorphism; stippled—Devonian granite. The age of metamorphism in the Meguma and Aspy terranes is Devonian; in the Bras d'Or terrane it is Cambrian; in the Avalon terrane it is late Precambrian; and in the Blair River Complex it is mid-Proterozoic.

The two major slates of the supergroups are black, carbon-rich and graptolitic. The base of the lower slate has a regionally extensive, thin, laminated, silty slate (the Mosher's Island Formation — see Figure T2.2.4). Significantly, it has a high metal content, including manganese, lead, copper, zinc and barium.[8] The thick remainder of the lower zone has sandstone layers that decrease in abundance and thickness upwards in the stratigraphic succession. Sedimentary structures also change from graded to cross-stratification. The upper slate is almost silt-free in its lower portion, but silt laminae increase in abundance and thickness upwards. The uppermost part is dominantly silt, so that colour changes to grey or green. Black slates of the Meguma Supergroup record a prograding wedge complex that shoaled upwards from the toe of a continental slope to an outer shelf.[7] In contrast, the main black slate of the



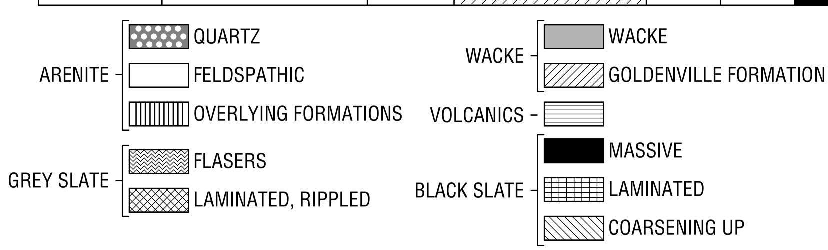


Figure T2.2.4: Summary and relationships of event stratigraphy and relative sea-level changes in the Meguma Zone. T refers to geologic time, and M to maximum measured thicknesses in metres. Major events are listed in the lithology column and columns 1 through 5: the lithology column gives predominant lithologies represented by patterns (to the left); column 1 indicates fossil-bearing intervals; column 2 shows episodes of volcanism; column 3 identifies unconformities by horizontal heavy lines (Meguma sequences are numbered); column 4 summarizes general, depositional environments; and column 5 displays (1) times of global anoxic events (black) and (2) major Paleozoic glacial episodes (A is for Andean; S, for Saharan; and D, for Devonian). Major events and relative sea-level changes in the Meguma Zone are listed in the next two columns.[7]

Annapolis Supergroup represents a deepening of water on a shelf. Both major slates and minor ones in the Annapolis Supergroup record global oceanic low-oxygen conditions (see Figure T2.2.4).

Volcaniclastic and conglomeratic sediments are minor but significant components in the Meguma Supergroup. The volcanic rocks can be locally thick, as along the boundary of the two supergroups. There, 10–30 m of basaltic pillow lavas overlie 10–50 m of acidic tuffs formed from airborne volcanic ash. Laterally, continuous layers of tuff are common. A significant volcanic event occurred in the western part of the Meguma Zone to form the base of sequence four (see Figure T2.2.4). Quartzose sandstones, marbles and slates containing boulders occur with the volcanic rocks. Most of the volcaniclastics are water-laid, but their thickness and lateral extent, and the presence of large boulders, suggest at least nearby exposure to the air. These rocks coincide with angular and erosional unconformities.

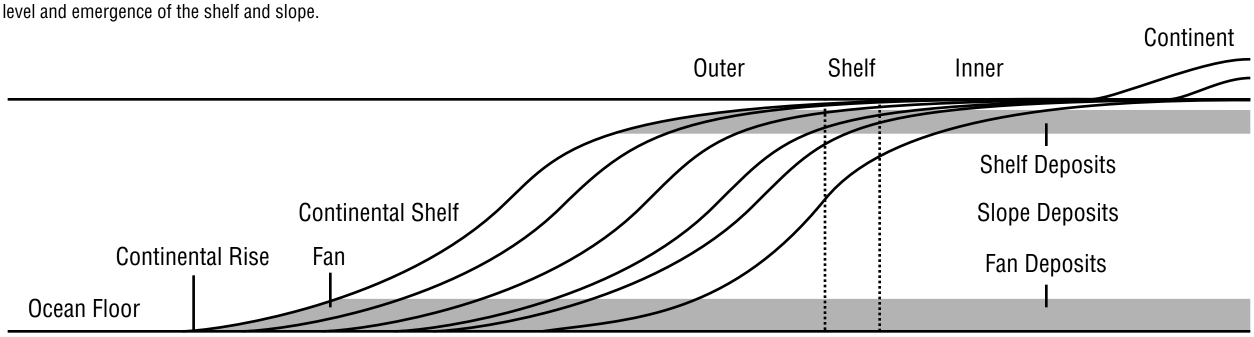
Skeletal fossils become abundant only in the upper groups of the Meguma Zone, although trace fossils are common throughout. The oldest fauna occurs at one locality near the Goldenville-Halifax contact. There, transported, broken trilobite fossils are Early Middle Cambrian in age.[9] Elsewhere in this Zone and in the thick overlying slate, fossil graptolites and acritarchs date sequence one (the Meguma Supergroup) as earliest Ordovician. In the Annapolis Supergroup, sequence two (White Rock Group) contains shells of possible Late Ordovician age. Sequence three is Late Silurian, as shown by graptolitic and shelly fauna. Shelly fossils are abundant in sequence four (Torbrook Group) and give an Early Devonian age. Thus, strata of the Meguma Zone range in age from possibly Late Middle Cambrian through Early Devonian. Three unconformities interrupt this record in the Early Ordovician, Late Ordovician and Late Silurian.

Derivation

The Meguma Zone is a good example of a terrane, at least until Carboniferous time. A terrane is a fault-bounded rock body of regional extent, characterized by a geologic history different from that of adjoining terranes. It is an exotic fragment of continental material added to ancestral North America by continental collision. The Meguma terrane is unlike the adjacent Avalon terrane in terms of sediments, metamorphism and formation of metallic minerals. The great problem with terranes is their source. The volume of Meguma sediments equals a block with the combined area of Portugal and Spain and a height of 5 km. This sediment is the product or erosion of a large southeastern continent, clearly not the Avalon terrane or even North America. The Meguma terrane is a fragment of that continent's margin, from rise to slope to shelf (see Figure T2.2.5). The source of the sediments must have been Gondwana. Two specific areas of Gondwana are likely. These are northwest Africa (North Gondwana) and northwest South America (West Gondwana).

The following is a summary of the North Gondwana hypothesis. From Cambrian through Early Devonian time, a vast, northward-directed dispersal system carried sediment across the North Gondwana margin. This drainage system was the size of the present Mississippi River complex. Headwaters in the south tapped fine-grained sandstones produced by Late Proterozoic glaciation and moun-

Figure T2.2.5: As a broad generalization, the rocks of the Meguma Zone accumulated on an advancing continental shelf, as old deposits of submarine fans on the continental rise were buried under sediments deposited on the continental shelf. In detail the process was complicated by periods of low sea level and emergence of the shelf and slope.



T2.2
The Avalon and Meguma Zones

tain building. Erosional remnants of this source rock exist now as buttes and mesas over much of southern Mali. Marine submergences from the north twice interrupted the northward transport of sands. The resulting stratigraphic record across the West African Craton and North Gondwana consists of three thick sandstones with intervening thick, marine shales. They are identical in time and lithology to those of the Meguma Zone. Rifting along the North Gondwanan margin created a plethora of microcontinents or microplates. Several have the same stratigraphic record, e.g., Saudi Arabia and the Welsh Basin. In particular, first the Avalon terrane collided with ancestral Atlantic Canada. Next, part of the continental margin of northwest Africa thrust over the Avalon during Middle Devonian collision between Africa and southeastern Atlantic Canada.

The following is a summary of the West Gondwana hypothesis. The Meguma terrane was deposited in an intramontane basin (intradeep) within or marginal to northwestern South/Central America. The Meguma fossil faunal and detrital zircon data indicate Gondwana affinities but are not more specific. Analysis of the distribution of distinctive Avalonian Cambrian–Ordovician strata, containing a unique Avalonian fauna and source regions for detrital zircons that occur in the Georgeville Group, suggests a western South American provenance. If the Meguma terrane was carried passively with the Avalon terrane, a South American source is also indicated. The intradeep interpretation implies that the basal thick sandstone of the Meguma Supergroup is associated with a Cambrian orogen. Orogens of this age are rare but are present in the Pampean Orogen (southwest Argentina). Transfer of the Meguma terrane from Gondwana to Laurasia about 400 million years ago is compatible with Laurasia–South America collision in the Silurian–Devonian rather than the Laurasia–Africa collision in the Early Carboniferous.

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Associated Topics

T2.1 Introduction to the Geological History of Nova Scotia, T2.3 Granite in Nova Scotia

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T2.3 GRANITE IN NOVA SCOTIA

Granite is a hard, impermeable crystalline rock and is resistant to erosion. In consequence, in Nova Scotia it tends to form knolls and upland areas characterized by a hummocky, boulder-strewn surface; thin, acid soils; and large areas of exposed bedrock. Water can penetrate the body of granite only along the joints (fractures), which may be several metres apart. Most precipitation is therefore held on the irregular surface in numerous interconnected bogs, shallow lakes and streams.

Granite is found throughout mainland Nova Scotia and Cape Breton in plutons of various sizes and represents about 20–25 per cent of the bedrock across the province. The largest pluton is the South Mountain Batholith, which is the dominant feature in the landscape of southwestern Nova Scotia. It extends in an arc from Yarmouth to Halifax and outcrops over an area of 10 000 km^2 (see Figure T2.3.1).[1]

AGE AND GENESIS

Over the years, there has been much discussion about the formation of granitic rocks. The theories generally are variants on two themes: (1) separation from a basaltic melt, and (2) extreme recrystallization, or even melting, of pre-existing rocks. Combinations of these two are also possible. There is general agreement that most of the Nova Scotia granites were once molten (magma).

Age studies show that, since the Precambrian, granites have formed in Nova Scotia during at least two periods of intense crustal disturbance when

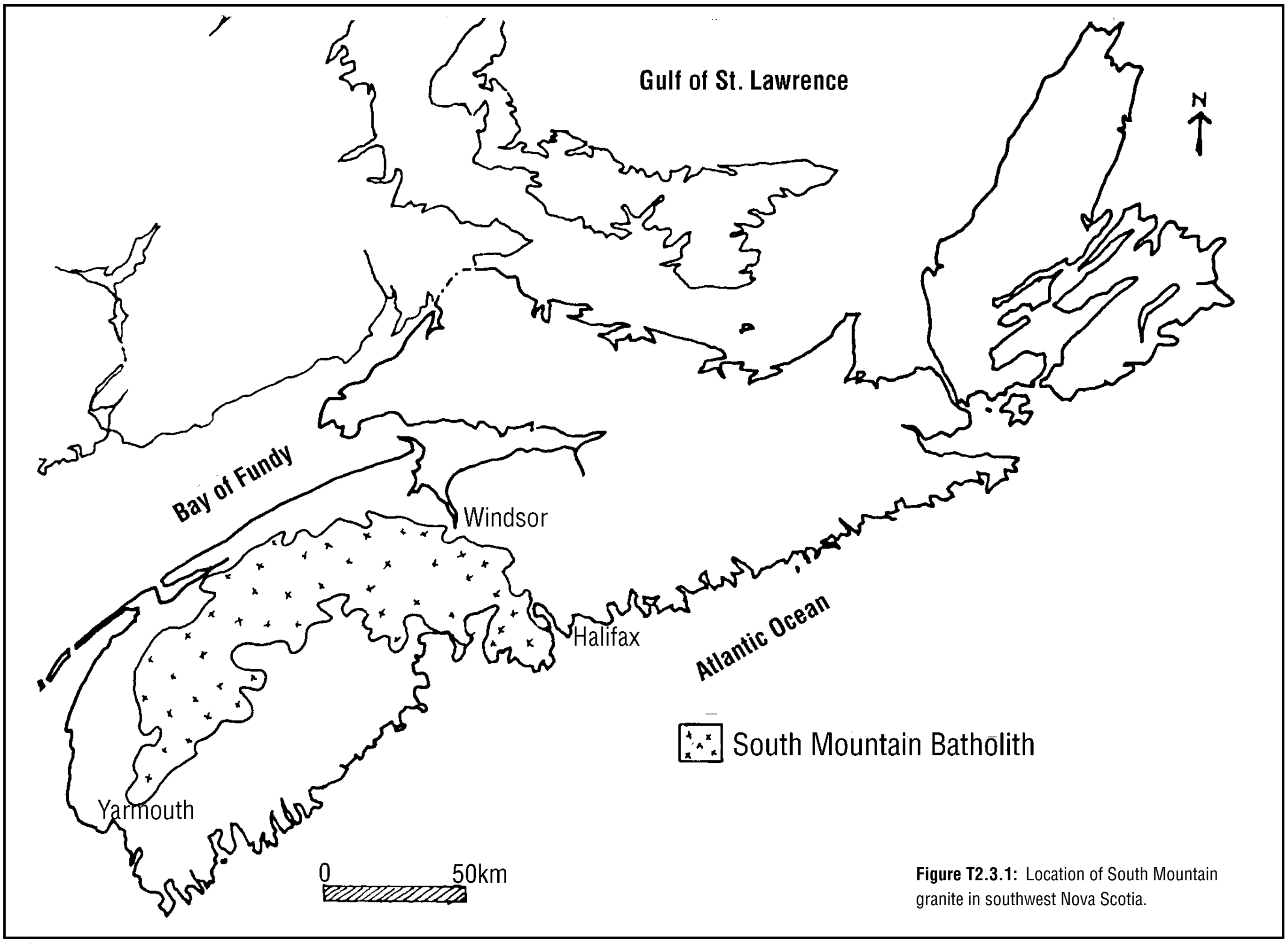

Figure T2.3.1: Location of South Mountain granite in southwest Nova Scotia.

sediments may have been thrust deep into the earth's crust and melted. These two major occasions were during the Cambrian and the Devonian periods.

The older group of granite plutons, around 550 to 500 million years old, is composed of relatively small bodies which are found exclusively north of the Cobequid-Chedabucto Fault in northern mainland Nova Scotia and Cape Breton. The younger group, roughly 370 million years old, is found throughout the province, but predominantly south of the Cobequid-Chedabucto Fault, within the sedimentary rocks of the Meguma Zone. These were generated during the Acadian Orogeny, when the thick Meguma sedimentary pile would have been squeezed against, and possibly over, the Avalon Zone. The South Mountain Batholith (Districts 440, 450), a very large body of granite which underlies about half of western Nova Scotia, falls within this younger group. It has been studied extensively during the past twenty years or so and is the best known of the granite bodies in the province. The description which follows is basically that of the South Mountain Batholith, although most other Devonian/Carboniferous plutons are likely to share similar characteristics.

The South Mountain Batholith is Late Devonian in age (ca. 370 million years) and is the largest body of granitoid rocks in the entire Appalachian system. The margin tends to be a granodiorite phase, but towards the centre of the batholith there are several other phases, including monzogranite and granite.

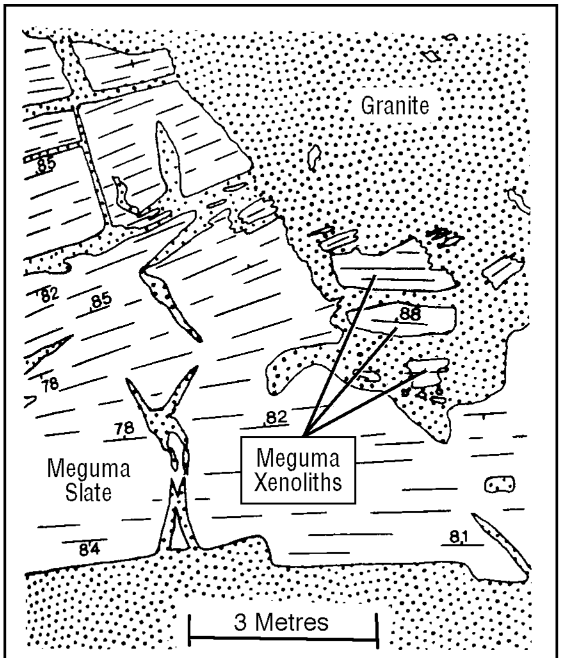

Figure T2.3.2[2]**:** Magmatic stoping. Arrested stoping at the margin of a large block of Meguma slates. Portuguese Cove (Unit 551).

Some of these rocks contain magmatic cordierite, andalusite or garnet. The Batholith as a whole is broadly concordant with the regional trends in the surrounding Meguma rocks, although locally, of course, it must cut across structures within them. Near its margin, it can contain screens of metamorphosed sedimentary rocks, or myriads of xenoliths (small fragments of the country rocks). Any foliation in the granite is due to movement in the viscous magma itself and was not imposed upon the rock by later tectonic stresses.

MODE OF EMPLACEMENT

Ascent of the Molten Rock

A hot magma which forms at a depth of 20–40 km in the earth's crust may rise either by forcing a path along lines of weakness or by breaking off and incorporating overlying rocks. There are no signs of strain within the sedimentary rocks surrounding the South Mountain Batholith, which might indicate forced passage, but several signs indicative of ascent by incorporation of blocks from the overlying strata (called country rock).

The contact with the surrounding Meguma country rock is generally steep, and in several places, blocks of sediment, some with obvious sedimentary banding, are incorporated into the granite mass. These blocks, or xenoliths, were gradually assimilated by the hot magma and can be found in various degrees of alteration in several localities near the margins of the granite; for example, at Portuguese Cove. The process of ascent by invasion and incorporation of country rock is called "stoping" (see Figure T2.3.2).

COOLING OF THE MAGMA

Foliation

As the magma cools, it develops crystals, which move in response to currents within it. Some remain in suspension, whereas others settle out into dense patches. Where there was relatively rapid movement of the viscous magma, rock fragments, blocky minerals (such as feldspars) and platy minerals (such as micas) reveal the flow pattern by alignment to produce a foliation in the granite.

Heating of the Surrounding Sediments

The heat that is given off by the liquid as it cools heats the surrounding sedimentary rocks for several kilometres. This is the thermal aureole of the granite. The physical change that takes place in the surrounding rocks is called thermal metamorphism. In general, this takes the form of hardening and recrystallization to form new minerals; the minerals so formed depend upon the temperature reached and upon the original composition of the country rocks. If the rock was a shale, then the most distant alteration will produce chlorite as a characteristic mineral. Closer to the batholith, biotite, garnet, staurolite and sillimanite appear in that order, with the sillimanite in a zone near the contact with the granite. This zoning is used to measure the intensity of the metamorphism (the metamorphic grade). For rocks of other compositions, the changes are recognized by comparing groups of minerals present in each rock type (metamorphic facies).

Mineral Deposits

In granitic rocks, crystals of quartz and feldspar form 80 per cent, or more, of the rock, and the balance is mainly micas and amphiboles. As the magma cools and the crystals form in it, any water present must collect in the still-fluid phase, because quartz and feldspars are anhydrous and the micas and amphiboles, which do contain some OH^- ions, are present only in small amounts. Because heat escapes only to the country rocks, the granite will generally freeze first at its margins and thence from the outside inward, with the still-fluid portion becoming increasingly enriched in water and in any elements that cannot be incorporated into the mineral crystals as they form. When the batholith is finally solid, the last remaining water-rich residue (the hydrothermal fluid) must be expelled. Fractures that developed in the solid shell due to contraction on cooling, to earlier movement of still-fluid portions, or to regional stresses provide channels through which the hydrothermal fluid can escape.

That fluid contains silica and many other elements in solution in small amounts. As it moves to regions of lower pressure on its journey through the fractures in the granite and the country rocks, the fluid will deposit its dissolved constituents in sequence as it cools and becomes saturated with one mineral compound after another. Within the solid, but still hot, part of the batholith, the deposits are quartz, feldspar and some rare minerals, as pegmatites, aplites and quartz veins. At lower temperatures, minerals containing tin, tungsten and molybdenum form, and at still lower temperatures, minerals containing copper, lead and zinc—and so on. In some cases, the concentration of the minerals may be sufficient to form ore. Commonly, the deposition of the low-temperature minerals is in the country rocks, many kilometres from the batholith. This will include the rocks of its roof, which now have been eroded away, along with any ore bodies they might have contained.

In Nova Scotia, the tin ore at East Kemptville formed in this way, and the gold ores were also formerly considered to have the same origin. Several deposits in Cape Breton, such as molybdenum at Eagle Head and zinc at Meat Cove, have a similar origin. As a different example, the copper-lead-zinc-silver-gold ore at Stirling is considered to have formed when the hydrothermal fluid flowed out onto the Precambrian sea floor.

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Associated Topics

T2.2 The Avalon and Meguma Zones, T12.3 Geology and Resources

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T2.4 THE CARBONIFEROUS BASIN

THE LOWER CARBONIFEROUS: INTERIOR MOUNTAIN VALLEY AND SEA

During late Paleozoic and early Mesozoic times, Atlantic Canada occupied an interior position in the near-equatorial region of Pangea. The attachment of North America to this supercontinent began in the Early Devonian Period and is represented in Atlantic Canada by the Acadian Orogeny, the result of the collision of the northeastern part of the North American continent and the continent of Africa. The collision created a large mountain belt with topography perhaps like the present-day Rocky Mountains of western Canada. The eroded roots of these Appalachian Mountains extend from the southeastern United States to Newfoundland, and they occur as the highland areas of Atlantic Canada.

Paleogeography

The waning phase of the Acadian Orogeny was followed by the development of a complex of interconnected sedimentary basins during the Late Devonian Period. The area was still tectonically active, and volcanic rocks, including basalts and rhyolites, were extruded locally, especially in the earliest stages of basin formation (e.g., Fountain Lake Group and the McAras Brook and Fisset Brook formations). From the surrounding mountains, gravels, sands and mud were transported in streams flowing to the northeast and deposited as the conglomerates, sandstones and mudstones that form the lower part of the filling of the basins (the Horton Group). There were repeated marine invasions into the basins in Middle Carboniferous time, when limestones and evaporites were deposited, but continental deposits again overlie them and coal was deposited in extensive swamps during the Late Carboniferous.

Erosion gradually reduced the topography of the mountains created by the Acadian Orogeny and transported the debris into the Carboniferous basins, which continued to deepen by progressive subsidence related in part to fault movement. The deposits gradually extended onto the gentle slopes of the eroded highland areas, which became buried beneath the sediments. The basins locally accumulated sediments up to eight kilometres deep (e.g., Cumberland County).

The present-day highlands were not highlands throughout the entire Carboniferous Period. For example, the Cobequid Hills (Unit 311), in northern mainland Nova Scotia, was not a highland until Late Carboniferous time, when it was tilted and uplifted by movement on the adjacent Cobequid-Chedabucto Fault system and became a source of coarse sediment.

The Late Devonian, Carboniferous to Early Permian basin-fill material in the Maritimes Basin probably extended over a much larger area than those rocks do today. Just as the older rocks were uplifted and eroded to become the Carboniferous basin-fill, the Carboniferous basins were uplifted and eroded to become the source of even younger basin-fill during the Mesozoic Era. The original sedimentary basins have been modified, deformed and broken apart by subsequent tectonic processes, producing a locally highly fragmented record of their original form. Erosion of the Carboniferous rocks not only reduced their areal extent, but their low resistance to erosion, compared to surrounding basement rocks (e.g., water-soluble strata of the Windsor Group), led to the development of lowlands and valleys (Region 500). In short, erosion of the hard, resistant rocks of the Avalon terrane produced our highlands, the somewhat less resistant Meguma and granitic rocks produced our upland areas, and the Carboniferous and Triassic rocks produced our lowlands. Today, the lowlands underlain by the soft Carboniferous and Triassic rocks are our agricultural areas, and their development is inherited from sedimentary basins formed between 280 and 380 million years ago. The coincidence of development and settlement in these areas and their underlying mineral and energy resources produces a growing challenge for land-use planning and future resource development.

Plate T2.4.1: The East Milford Quarry, Halifax County (Unit 511), showing the extensive evaporite deposits of the Windsor Basin. Photo: R. Merrick

Distribution

Strata of Early Carboniferous age are widely distributed in Nova Scotia. They were deposited in valleys formed by the down-faulting of blocks of older rocks and were then preserved in those valleys after later regional erosion. They underlie the lowland-valley areas in parts of Antigonish, Colchester, Cumberland, Guysborough, Hants and Halifax counties of mainland Nova Scotia (north of latitude 45 degrees). They also occur extensively in the lowlands of Cape Breton Island (Units 512, 522 and District 560), where they underlie an area equal to that of the highlands. Note that the Lower Carboniferous rocks do not come to the surface everywhere, but in some areas, such as in Cumberland County, are buried beneath extensive Upper Carboniferous strata.[1]

The thickness of Lower Carboniferous sediment differs from place to place. Typically it is greater than 2000 m and may be as much as 4000 m where the sediments are preserved in their entirety.

The Interior Valleys

In the beginning of Early Carboniferous time, the sedimentation pattern was dominated by the erosion of the local highlands and transportation by a complex drainage system to the lowlands. The steepest highland slopes were marked by coarse alluvial fans comprising poorly sorted boulder to gravelly sand debris. Initially the valley bottoms between the highlands were steep enough to have braided streams, which permit little vegetation, and there were a few lakes. The deposits are sandstones and mudstones, with minor conglomerate. Note that ground-stabilizing vegetation was rare, although the environment was suitable. These initial intermontane flood-plain, river and lake sediments are preserved today as the Horton Group and are 1000 to 2000 m thick. The climate in the later part of Horton time was evolving to hot, desert-like conditions (perhaps like the present-day Dead Sea). Strata typical of the Horton Group are exposed along the Avon River near Hantsport and Cheverie (Unit 511a).[2]

The Interior Seas and Lakes

This valley complex, which extended throughout Atlantic Canada, was then flooded by the rapid invasion of seawater. This invasion is inferred to have occurred along a low trough area extending from the interior of Pangea to the major world ocean called Tethys. Excess evaporation and restricted influx of seawater from the ocean caused this basin to become an evaporitic marine environment. Limestone, gypsum, salt and potash salts were deposited in a progressive sequence as the water reached saturation in each of these salts. The least soluble salts were deposited first and the most soluble ones last. Later, repeated flooding produced cyclic interbedded sequences of fossiliferous marine limestone, evaporites (mineral salts of seawater) including gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$), as well as thick sections of red mudrocks; collectively they form the Windsor Group. It is interesting to note that the repeated flooding and drying that produced the cyclic deposits in the Windsor Group may have been caused by variations in worldwide sea level controlled by glacial events in the southern part of Pangea. Strata typical of the Windsor Group are exposed along the Avon River near Avondale (Unit 511a), and near Antigonish and Port Hawkesbury.[2]

From their present distribution, the inland sea that deposited the Windsor rocks must have been about 800 km by 300 km at least (i.e., a bit smaller than the present Baltic Sea). Complete evaporation of seawater cannot produce gypsum or halite (NaCl) without also producing sylvite (KCl) and more complex salts. Individual deposits have 50 to 100 m of pure gypsum and anhydrite, so the more concentrated brines that would have produced sylvite and complex salts must have escaped. That is, the connection of the Windsor Basin to the ocean must have permitted both inflow of seawater, and simultaneous outflow of more saline water, from which the gypsum or halite had been precipitated.

The Windsor Group is approximately 1000 m thick and is a major source of industrial minerals and base metals mined today in the province. It is the primary source of limestone used in the manufacture of cement for concrete, of gypsum for wallboard and of salt for the fishery and road de-icing. Nova Scotia is one of the leading gypsum-producing areas in the world, providing 75 per cent of Canada's total production (see Plate T2.4.1). The mineral wealth of the Windsor Group is the legacy of salts deposited from an ocean invading a desert-valley region 340 million years ago.

The Windsor Group is overlain by up to 2000 m of red and grey mudrocks, sandstones and minor thin limestones of the Mabou Group (previously known as the Canso Group). The Mabou Group was deposited in a river-mudflat-and-lake complex which succeeded the evaporitic marine deposition in the underlying Windsor Group. The lower part of the Mabou Group contains interbeds of gypsum, anhydrite and salt, like the Windsor Group. This indicates the early lakes were very saline, perhaps like the Great Salt Lake in the western interior of the United States. The abundant red strata of the Mabou Group indicate that the prevailing climate was dry with highly seasonal precipitation. The co-existing grey mudrocks were deposited in extensive lakes that were probably sustained by river systems originating in distal regions. Strata typical of the Mabou Group are exposed along the Strait of Canso near Port Hastings (Unit 571).

The later part of the Early Carboniferous (between 310 and 315 million years ago) heralded a fundamental change in the depositional character of the basins in Nova Scotia and in much of Atlantic Canada. The climate evolved to become very wet and the region was flooded by extensive deposition of grey sandstones and mudrocks with coal deposits. The coal age was born in a burst of prolific, lush vegetation and wetlands in vast floodbasins.

THE COAL AGE

Paleogeography

In the Late Carboniferous, Nova Scotia had a subdued topography of low hills separated by broad river valleys and freshwater lakes. Vegetation flourished in the warm climate, particularly large trees (some 30 m high) and swamp plants. Some of the swamp plants had large tops and laterally spreading roots which were ideally suited to the topography, with its wide, flat, poorly drained surfaces. These plants grew densely in bogs and swamps along the floodplains, estuaries and shorelines of lakes, and possibly in coastal areas. As the plants died and decayed, they became buried and compressed by new organic material growing above. Some of these environments were stable for millions of years, experiencing only gentle subsidence or rhythmic oscillations in elevation. In these locations tremendous thicknesses of organic material accumulated, were compressed and eventually turned into coal.

In the Maritimes, coal was deposited in two types of basins: (a) limnetic basins—lakes and adjacent plains which were regularly flooded; and (b) paralic basins—in coastal lowlands subject to periodic, sustained influxes of seawater and marine sediments. On the mainland, all the coalfields, except possibly Joggins, are of the first type, and the Pictou field is typical. The coal was deposited in a narrow intermontane-lake basin that was subsiding between boundary faults, i.e., a graben. The rate of subsidence approximated the rate of accumulation for a very long time, and thick coal seams resulted (up to 13 m for the Foord seam). In the centre of the basin, clean, low-ash coal was formed. Mud accumulated on the margin of the basin, so the seams grade outward from the centre through shaly coal (high ash) to coaly shale to shale. By contrast, most of the coalfields of Cape Breton are of the second type, and Sydney is an example. Deposition occurred on the floodplain portion of the alluvial part of a large paralic basin. Some of the sediments were deposited by braided streams, and brackish-water foraminifera indicate that the sea encroached at other times. (The swamps of the Mississippi Delta are a modern example of such a basin.) At Sydney the seams are relatively thin (up to 3 m) but have great lateral continuity. They are broken up by rock partings—the sediment introduced by streams—and the seams terminate by such splitting and gradual pinching out of individual coal layers, not by lateral transition of coal into shale, as at Pictou.

Occurrence

The coal age began in Nova Scotia with the deposition of sandstones, black shales and thin coal seams in the Riversdale Group. Exposures of these strata are limited, and few contain economically important coal seams; the most extensive are those in the Port Hood area of Cape Breton. (The St. George's coal seam, in Newfoundland, is also of this group.) More-productive coal measures are found in the succeeding Cumberland and Pictou Groups (Districts 520, 580). The strata are predominantly sandstone and contain few fossils; however, a striking exception to this is the 1700 m of Cumberland sandstones which are exposed along the Chignecto Bay shoreline near Joggins and contain fossil trees, amphibians, the earliest reptiles, and two of the earliest land snails. In the Joggins section, there are also 65 coal seams, 39 of which are also found at Springhill. Other seams have also been worked at Debert. The Pictou coalfield, formed in the sandstones of the Pictou Group, occupies an area of 3 by 15 km. It has numerous thick coal seams of relatively limited area, and some deposits of oil shales. Some oil has been collected dripping from the roof of the Thorburn colliery.

At Mabou and Inverness in Cape Breton, the coalfields barely touch the land and lie mainly under the waters of the Gulf of St. Lawrence. Similarly, only 3 per cent of the huge Sydney coalfield is found onshore. The seams run for 30 km along the coast but dip northeastwards under the Cabot Strait. The practical mining limit is probably five or six kilometres offshore, but the seams have been identified in bore holes 40 km from the land. These deposits are part of the Late Carboniferous Morien Group. The Sydney Basin extends almost to Newfoundland.

THE "MARITIME DISTURBANCE"

At the end of the Carboniferous Period, there was a crustal disturbance in Nova Scotia which produced folds and faults in a narrow band between the Cobequids and the Southern Uplands. This was the shadow of a much larger disturbance felt in Europe and the rest of the Appalachians, and marked the final readjustment in the grouping of continents in Pangea. The coalfields within this band, particularly the Pictou field, were distorted and the seams were disrupted, thereby reducing their economic value. The coalfields of Cape Breton, however, were almost undisturbed.

Associated Topics

T2.2 The Avalon and Meguma Zones, T12.3 Geology and Resources

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T2.5 THE NOVA SCOTIAN DESERT

By the close of the Carboniferous Period, 280 million years ago, the shoreline of the inland sea had withdrawn to the east, and almost the entire surface area of Nova Scotia was above sea level. Only a small portion of Cape Breton remained under marine influence. This marine regression marked the beginning of the last continental phase of the province's geological history. Since that time, portions of Nova Scotia and the other Maritime provinces have been exposed to continuing subaerial erosion, with the products of this erosion being deposited into several large depressions.

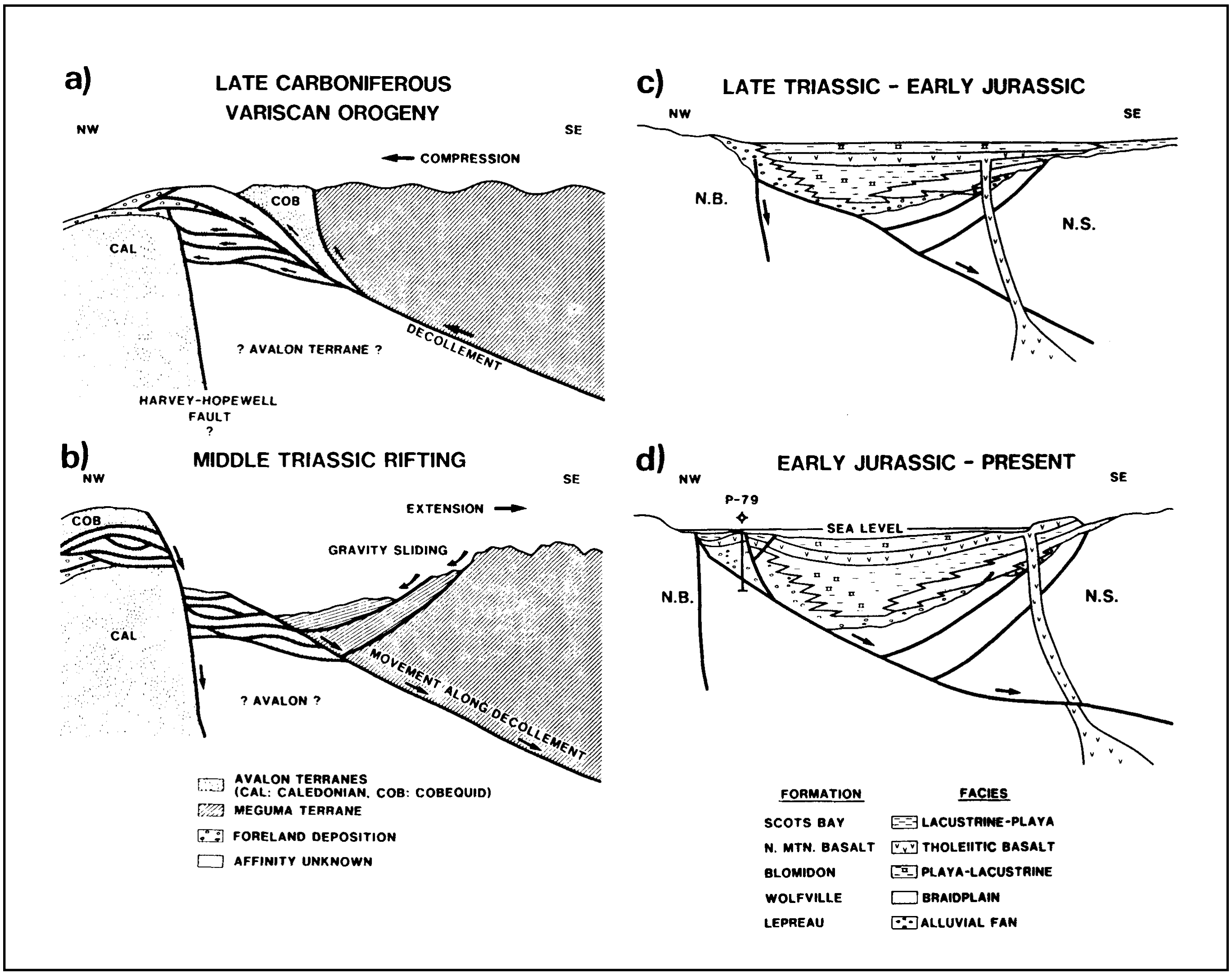

Figure T2.5.1: A cross-sectional profile across the Bay of Fundy, illustrating the interpreted structural and stratigraphic evolution of the Fundy Rift Basin. (a) Compressive collision of the Meguma terrane with Avalon terranes in southern New Brunswick, with the former being thrust over the latter along the inclined portion of the Minas Geofracture (décollement). (b) Reversal of motion on the décollement caused by extension, as the Meguma terrane moves down the fault plane in response to continental rifting further to the east, thus forming a deep depression. (c) The Triassic-Jurassic sedimentary section at about the end of the Early Jurassic. The position of the feeder dyke for the North Mountain Formation basalts is speculative. (d) The present-day profile of the Fundy Basin, with the strata having been deformed by faulting, probably during the Late Jurassic. The Cape Spencer P-79 exploration well was drilled on a large geologic structure in 1983, but did not encounter any hydrocarbons.[2] Figure T2.6.1 indicates the location of the profile line shown here.

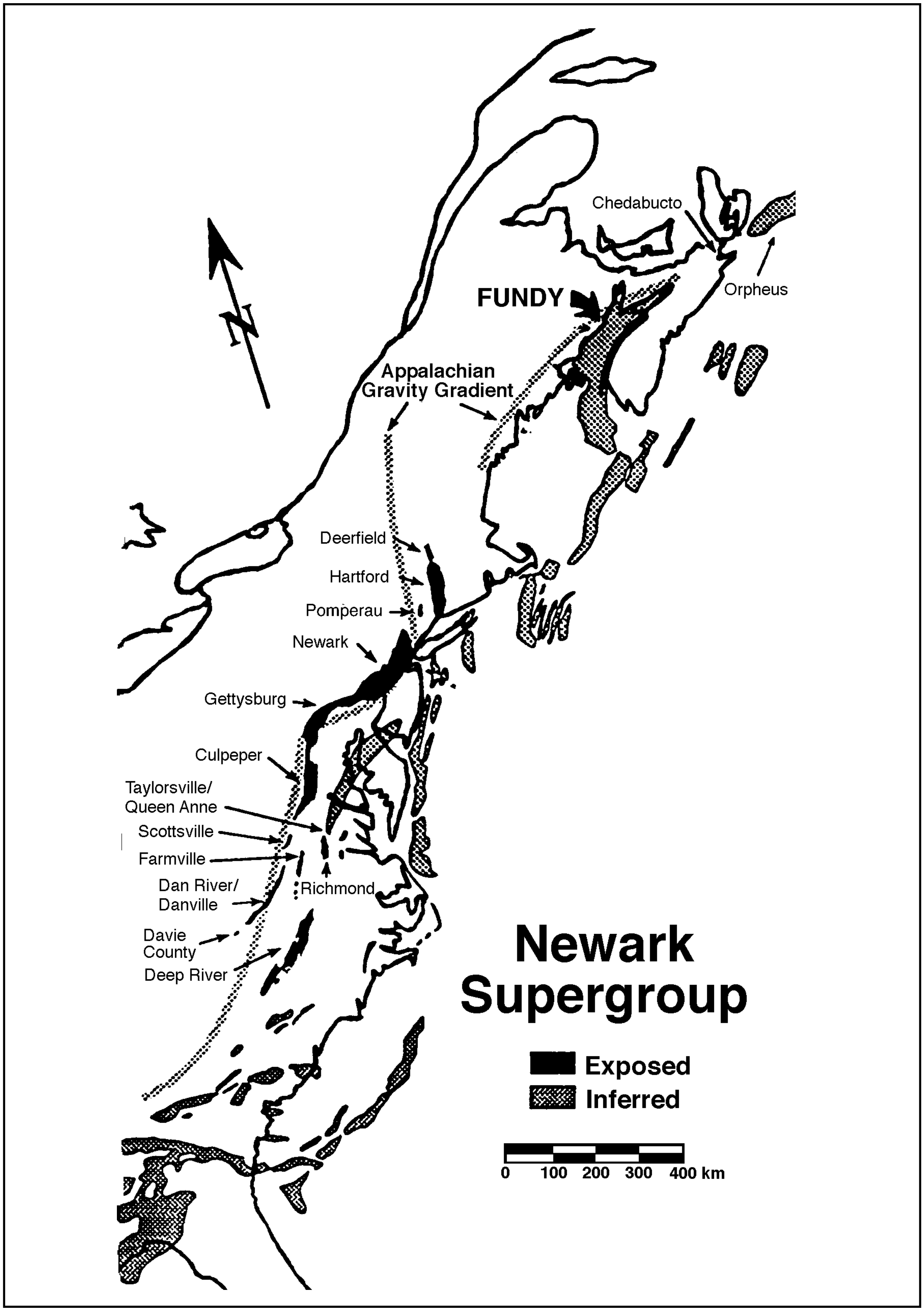

Figure T2.5.2: Distribution of Newark Supergroup basins, eastern North America (slightly modified after Olsen, et al.[3]). The Fundy Rift is the largest of all Newark-type basins and covers an area of about 14 000 km².

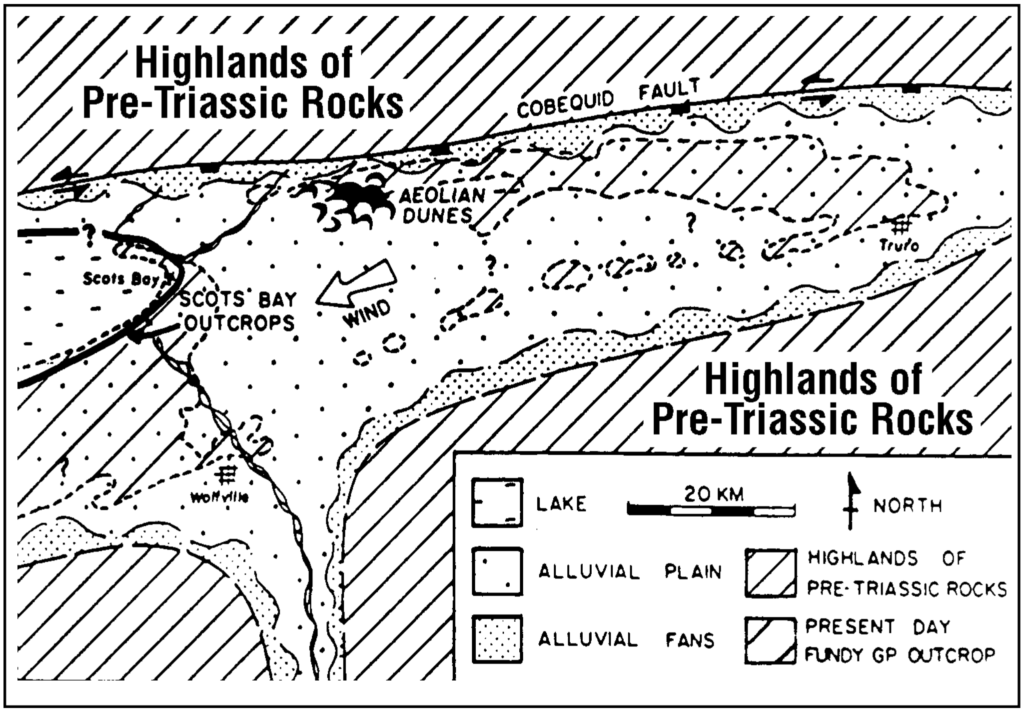

Figure T2.5.3: Paleogeographic map showing depositional facies of the Early Jurassic Scots Bay/McCoy Brook formations in the Minas Basin area. The present-day distribution of Fundy Group strata is within the areas outlined by the dashed lines. The dotted pattern is the interpreted maximum extent of Jurassic sediments (slightly modified after Birney-de Wet and Hubert[7]).

PERMIAN (280–230 MILLION YEARS AGO)

At the opening of the Permian Period, Nova Scotia occupied a central position on the Pangean supercontinent, at about 15 degrees north paleolatitude. The climatic conditions at this location were dominated by persistent easterly trade winds, which blew across the supercontinent, so that the climate was hot and dry, though having seasonal monsoonal rainfalls. The exposed rocks on the land surface became oxidized, were eroded to form red sands and muds and were deposited in a low, basinal area covering the Northumberland Strait, Prince Edward Island and the Gulf of St. Lawrence. Sediments derived from older strata in Nova Scotia and New Brunswick were redeposited within this basin and today form the foundation for the rolling landscape of Prince Edward Island.

During this time, Nova Scotia, including the continental shelf, was land undergoing erosion; the resulting sediments being deposited in the basinal area to the north. Any Permian-age sediments that were deposited were subsequently eroded away and thus are largely absent from the stratigraphic record of Nova Scotia.

TRIASSIC TO JURASSIC (230–140 MILLION YEARS AGO)

During the Middle Triassic, the Pangean supercontinent was subjected to extensional forces before the start of continental break-up. This process of continental rifting extended from the Gulf of Mexico to Newfoundland and beyond, and resulted in volcanism and development of subparallel fissures and faults along the thinned, weakened crust, as the crustal blocks of Pangea began to move apart[1] (see Figure T.2.5.1).

In the central portion of the rift, blocks of crustal material between parallel faults dropped down to form steep-sided, flat-bottomed valley- type structures called grabens. Further landward, away from the rift, the mechanics of fracturing were somewhat different and, in Middle Triassic time, when the Meguma terrane was pulled away from southern New Brunswick by sliding on the underlying Avalon terrane, the result was a series of half-grabens.

These half-grabens are known as the Fundy Rift System and can be traced through mainland Nova Scotia to Chedabucto Bay (District 570), into Chignecto Bay (Unit 913b), and out on to the Scotian Shelf (Region 900).[1] Similar rift basins are found extending down to the Gulf of Mexico.

The sediments which were deposited in the basins during rifting and the volcanic rocks within these basins are genetically similar to those in the Fundy Rift System, and thus are grouped together and collectively known as the Newark Supergroup (see Figure T2.5.2).[3]

In the Fundy region, three half-grabens are known to be filled with Triassic–Jurassic sediments: Fundy Basin, Chignecto Sub-basin and Minas Sub-basin. These sediments floor the similarly named bays.[2] Geological and seismic data indicate that up to 12 000 m of sediments fill the main Fundy Basin, about 6000 m fill the Chignecto Sub-basin and perhaps 3000 m fill the Minas Sub-basin. The strata in these basins are generally undisturbed, except along the faulted margins and where the Cobequid-Chedabucto Fault crosses the Fundy Basin.

The history of these basins records a long period of sedimentation interrupted by volcanism and ongoing tectonism along their faulted margins. The sedimentary fill in the basins records an overall filling-upwards sequence, from conglomerates to sands to shales and mudstones as the sources of the sediments were eroded away. These sediments and the associated basalts are collectively known as the Fundy Group; they range in age from the Early Middle Triassic to possibly the Early Middle Jurassic in the area of maximum deposition (depocentre) of the thick Fundy Basin. The whole sequence in the Fundy Basin was gently folded, possibly in the Middle Jurassic, and now has the shape of a tilted saucer which plunges southwestwards towards the mouth of the Bay of Fundy. These rocks are well exposed along the south shore of the Bay in the North Mountain–Annapolis Valley region and also all along the Minas Basin shoreline.

Rivers and braided streams flowing from the Meguma uplands formed alluvial fans along the fault-bounded margins of the basins and deposited thick sequences of poorly sorted conglomerates and lesser amounts of sandstones (the Wolfville Formation). Winds reworked some of these latter sandstones, which resulted in significant wind-blown dune deposits; these are spectacularly exposed at Red Head near Economy (District 710).[4,5]

The climate became drier and reduced the amount of water (and, hence, sediments) flowing into the basins. Evaporitic minerals such as gypsum were precipitated in temporary (ephemeral) lakes and mudflats which covered the basins (Blomidon Formation).[6] At the end of the Triassic Period, further rift-related stresses caused the formation of fissure-type volcanic eruptions, and the basins were covered with a virtually continuous sequence of lava flows of earliest Jurassic age (North Mountain Formation, District 720). The Triassic-Jurassic boundary occurs in the Blomidon sediments, a few metres from the base of the lava flows.

Following this event, slightly wetter climatic conditions began to develop. Fluvial sands and lacustrine muds and limestones of the McCoy Brook and Scots Bay formations were deposited on the surface of the basalt.[7,8]

Although these sediments are thick and extensive beneath the Bay of Fundy (at least 3000 m), they are limited to a few exposures in the Five Islands area (McCoy Brook Formation) in District 710 and several small, thin outcrops near Scots Bay (Scots Bay Formation) in District 720. Conditions were still dry enough at the beginning of the Jurassic that aeolian sand dunes were deposited into structural lows adjacent to the bounding faults in the Minas Sub-basin and are well exposed at Wasson's Bluff (see Figure 2.5.3).[3, 7]

The continental setting results in poor preservation of organic material, so fossils are rare in these deposits. Reptile and dinosaur remains occur in aeolian, alluvial fan and lacustrine sediments of the McCoy Brook Formation at Wasson's Bluff and in the lower Wolfville Formation fluvial sandstones at Carrs Brook in District 620. Rare reptile remains occur in Wolfville Formation sandstone along the south shore of Minas Basin.[9] Fish remains are present in Early Jurassic sediments of the McCoy Brook Formation on the west side of Five Islands Provincial Park, and in limestones of the Scots Bay Formation at Scots Bay.[9] Chertified logs are also very common at the latter site. Dinosaur footprints can be found in Wolfville Formation sandstones a few metres below its contact with the overlying Blomidon Formation in the cliffs at Pereau, near Kingsport.

No middle or late Jurassic deposits are to be found on land in Nova Scotia. The most recent, pre-glacial deposits in Nova Scotia are Cretaceous sands, clays and lignite in the Musquodoboit Valley near Middle Musquodoboit.[10] Evidence of climatic changes and geological events during the Jurassic Period must therefore be sought from the sedimentary record on the Scotian Shelf (see T3.5). The presence of red beds and salt in the offshore sequence indicates that the arid equatorial climate persisted into the Late Jurassic.[1]

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Associated Topics

T2.2 The Avalon and Meguma Zones, T2.4 The Carboniferous Basin, T3.5 Offshore Bottom Characteristics

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T2.6 THE TRIASSIC BASALTS AND CONTINENTAL RIFTING

In the long geological time period up to the end of the Carboniferous, almost all of Nova Scotia's geological units—the old crystalline rocks of the Avalon Zone and the folded slates and greywackes of the Meguma Zone, along with younger Devonian granites and Carboniferous limestones, salts, sandstones and coal—were assembled. All these were subjected to erosion under a hot, dry climate during the Permian and Early Triassic periods.

During the 150 million years prior to the Triassic Period, Nova Scotia occupied a central position in the interior of the supercontinent Pangea, which began to form in the Devonian Period and was completed by Late Carboniferous times. In Nova Scotia, the Permian Period was quiescent tectonically, with only erosion of pre-existing rocks occurring. During the Triassic, however, a new phase of crustal motion began. It eventually resulted in the break-up of Pangea into the present-day continents, and the formation of the Atlantic Ocean. But in many respects, the earliest manifestations of this tectonic event are the most significant for Nova Scotia, for at that time the last geological component was added: the Triassic–Jurassic

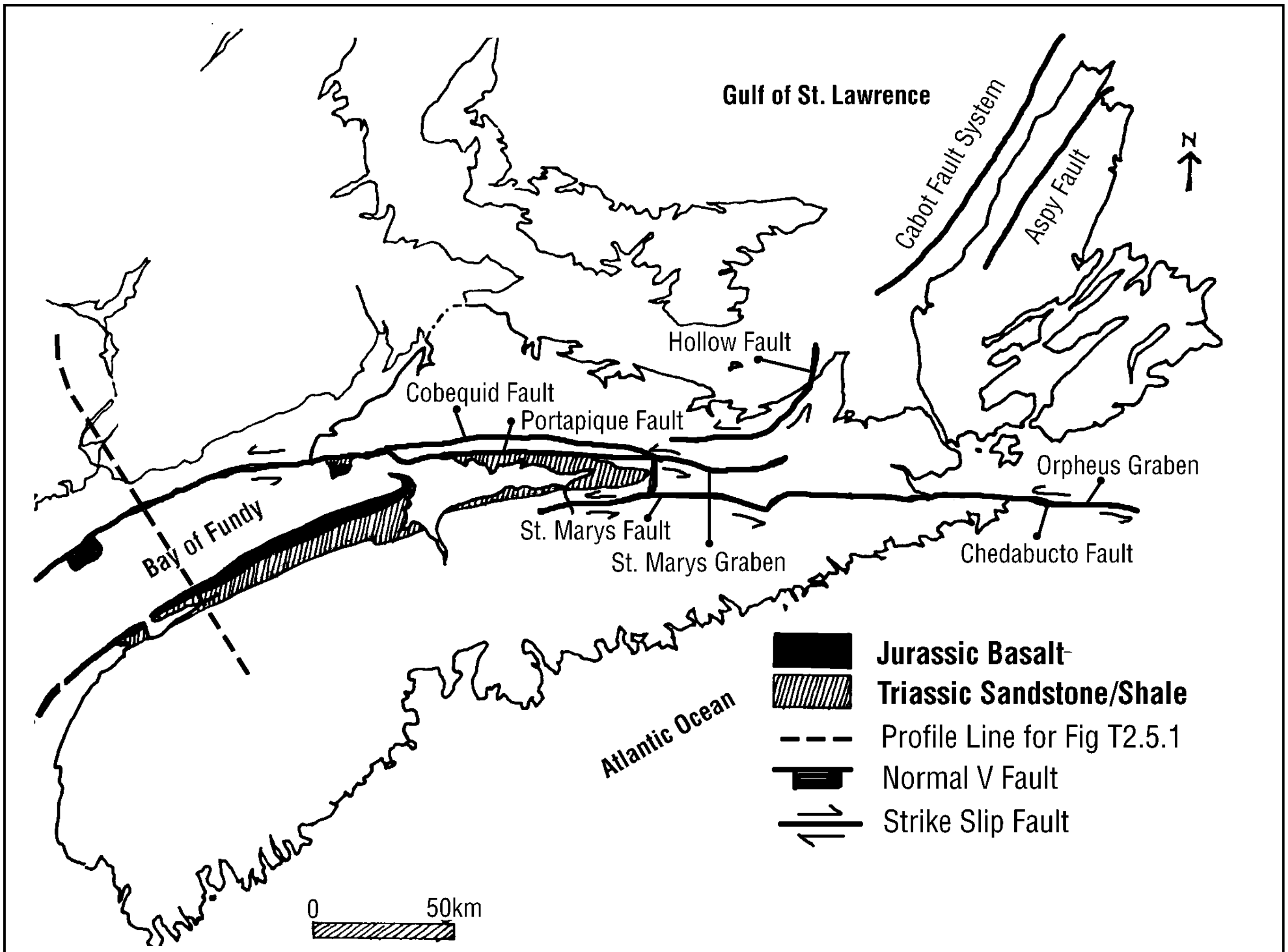

Figure T2.6.1: Major fault systems in Nova Scotia. The last major motion on any of these faults probably occurred during the Middle Jurassic, with the Meguma terrane (south of the faults) moving eastwards along the Cobequid-Chedabucto Fault system. Distribution of Middle Triassic–Early Jurassic rocks in Nova Scotia. The dashed line represents the approximate line of profile for Figure T2.5.1.

sediments and basalts. The basins into which these rocks were deposited became the precursors of the various important coastal features known today as the Bay of Fundy, Chignecto Bay, the Minas Basin and Chedabucto Bay.

CRUSTAL MOVEMENT BEGINS

Faults and Grabens

In the Triassic Period, Pangea began to break up again. The theory is that this occurred as follows. Heat loss from the mantle through the thin ocean floor is more rapid than through the thick continental crust, which acts as a blanket. Accumulation of heat expanded the continental crust, so that its surface was uplifted and the relatively brittle upper part was fractured. Upwelling currents in the mantle (mantle plumes) caused upraised blisters that broke into three rifts at 120 degrees to each other. (The Red Sea, the Gulf of Aden and the north end of the African Rift in Ethiopia would be a modern example.) Two of the rifts continued to widen, pulled apart by the movement of mantle material beneath the crust, and to extend to link with similar rifts above other mantle plumes, so building a lengthy rift system which eventually widened to become an ocean. The third rift permitted magma to reach the surface as volcanoes. The rift valley filled with volcanic rocks and with sediments eroded off its flanks, but it failed to open up. The Fundy–Chignecto Basin is considered to be such a "failed ocean."

In some cases the block of crust between two parallel faults dropped down, making a steep-sided valley-like depression called a graben. In Nova Scotia, half-grabens (downfaulted on only one side) were developed when Permian and older thrust faults and transverse faults were reactivated, such that the original compressive forces were released and extensional forces allowed the blocks to slide back down the fault plane[1] (see Figure T.2.5.1).

A series of such reactivated thrust and transverse (strike-slip) faults transected the province, and adjacent to these faults were formed several new sedimentary basins. These basins—the Fundy Basin, Minas Sub-basin and Orpheus Basin—presently underlie the Bay of Fundy, Minas Basin and Chedabucto Bay/eastern continental shelf, respectively (Region 900). Another branch of these faults may be represented by the Cabot Fault system (see Figure T2.6.1).[2,3]

These grabens gradually filled with thick sequences of continental-type sediments and volcanic rocks. The boundary faults remained as lines of weakness, however, and in the Cretaceous and Tertiary periods were exploited by erosion. They are now features of inland and coastal morphology.

VOLCANIC ROCKS—BASALTS

During this period of sustained tension, magma welled up some fractures adjacent to the sedimentary basins and either solidified as basaltic dykes and sills within the rock strata or was extruded at the surface as lava flows (see Figure T2.6.1). Several closely spaced fissure-type eruptive zones existed in the Bay of Fundy region, pouring lava out to cover eventually an area of at least 15 000 km^2. The basalts are Early Jurassic, with K–Ar ages of about 200 million years.[4,5] Onshore, the basalts of the North Mountain Formation have a maximum thickness of about 400 m, though they are estimated from seismic data to be up to 1000 m thick in the centre of the Fundy Basin.[1]

The volcanic rocks of the Fundy Rift system are continental-type basalts known as tholeiites. They now form, and are exposed along, the continuous ridge of the North Mountain (District 720), extending from Brier Island in the west to Cape Split in the east, in fault blocks along the north shore of the Minas Basin (District 710), on Isle Haute and on Grand Manan Island (New Brunswick).

The basalt at North Mountain is an erosional remnant. It is probable that the Great Dyke (from Pubnico to Sambro) also fed volcanoes, in which case basalt might have covered the entire mainland at one time.

Basalt Flows

At least seventeen flows have been identified in the Bay of Fundy area. They range in thickness from 1 to 60 m; most cover only a small area. All seventeen are exposed northeast of Digby Gut, but to the southwest along Digby Neck only two very thick ones are found. These two are separated by a layer of more easily eroded rock, which forms a valley down the centre of the Neck and out onto the islands.

When thick lava flows cool and contract, six-sided vertical joints form, which divide the flow into columns (columnar jointing). If these columns are undercut at their base by the sea, they tend to fall like chimneys. Cliffs formed by these flows, therefore, tend to be high, vertical and with a wave-cut platform at the base. Coastal features related to such columnar basalt are well displayed at many points along the southern Fundy shore from Cape Split to Brier Island, at Five Islands Provincial Park and at Partridge Island near Parrsboro (District 710).

Mineralization

As the lavas cooled after extrusion, escaping gases were trapped in the rock and formed cavities into which various minerals were precipitated; filled cavities are called amygdules. The minerals include agate, amethyst, jasper, calcite and many members of the zeolite family. At some locations, small deposits of native copper and magnetite are found in fracture zones within the basalts. Agate and jasper can be found as pebbles and cobbles along the beach at Scots Bay, and zeolites occur at various localities along the Fundy shore. (For an extensive listing of minerals found in the basalts and the location of their occurrences, see Sabina.[6])

Sills and Dykes

A sill is a layer of magma which was injected in between two layers of strata and therefore lies parallel to them. In Colchester County the basalt near Five Island Provincial Park is very fine grained and does not contain amygdules. It may, therefore, not have been extruded as lava, but injected between the Wolfville sandstone and the Blomidon shales as sills.

Dykes crosscut the sedimentary banding and structures, occupying the tensional fissures produced during the rifting process. In southern Nova Scotia, basalt is found in small dykes in the Yarmouth area and in the Great Dyke of Nova Scotia—a feature that runs from Pubnico 150 km eastwards to just off Sambro near Halifax Harbour.

MORPHOLOGY OF THE TRIASSIC–JURASSIC AREA

At some time during the Middle to Late Jurassic Period, sediments within the rift basins were tectonically disturbed through the reactivation of the basin-bounding faults and the formation of new ones. The principal strike-slip faults parallel the Colchester/Cumberland shore south of the Cobequid Highlands, but new splays from these faults developed and had a northeast orientation. The blocks of strata between these faults were thus shifted and tilted and now form the irregular hilly topography along the north shore of the Minas Basin from about Great Village to Five Islands. Further to the east, around the Minas Basin and into the Truro area, undisturbed and relatively flat-lying Middle Triassic deposits of the Wolfville Formation form coastal lowlands.

On the south side of the Bay of Fundy, the sandstones, shales and basalts gently sag down to form a spoon-shaped basin or syncline, with an axis that plunges towards the west. The trough of this gentle fold can be seen in the hook of Cape Split. The south side of North Mountain is truncated by a sharp scarp slope, behind which the soft Wolfville and Blomidon formations have been eroded to form the Annapolis–Cornwallis Valley.[7]

CONTINENTAL SEPARATION

When the continents finally separated in the Early Jurassic, the split did not occur along the lines of the early tensional features but further to the east, beyond the edge of the present continental shelf. Thus, the Meguma rocks which had originally been a margin of Gondwana were left behind on the west side of the Atlantic Ocean, and sutured to eastern North America.

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Associated Topics

T2.1 Introduction to the Geological History of Nova Scotia, T2.2 The Avalon and Meguma Zones, T2.5 The Nova Scotian Desert

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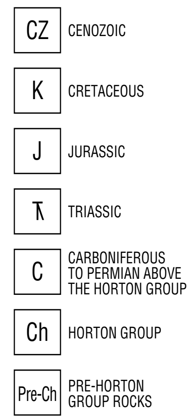
T2.7 OFFSHORE GEOLOGY

The Nova Scotia offshore covers approximately 40 million hectares and includes parts of Georges Bank, the eastern Gulf of Maine, Bay of Fundy, Gulf of St. Lawrence, Laurentian Channel and the Scotian Shelf and Scotian Slope, which together form part of the continental margin of eastern Canada. (See Region 900 on Theme Regions Map.) The margin evolved subsequent to the rifting of the supercontinent Pangea and the ensuing sediment accumulation in the basins has created conditions suitable for the generation and preservation of oil and natural gas.

The offshore areas of Nova Scotia are important links in the chronology of events that comprise the province's geological history. Accessibility, however, has limited the study of offshore stratigraphy and deposits. Until recently, information was derived from dredge materials from the fishing industry and scattered core samplings. During the last few decades, there has been increasing interest in offshore oil and natural-gas exploration, and more recently, marine mineral potential. The Geological Survey of Canada (GSC) and the Atlantic Geoscience Centre (AGC) support mapping programs for offshore geology, one of which produces an East Coast Basin Atlas Series. There is now a better understanding of the offshore geology and the relationships with marine processes. Topics T2.1–T2.6 discuss Nova Scotia's geologic story. This Topic summarizes the pieces which are in evidence offshore. More detailed information can be obtained from *Geology of the Continental Margin of Eastern Canada*.[1]



GEOLOGICAL SUBDIVISION OF THE OFFSHORE

The offshore is here taken to include all areas adjacent to the province which are covered by water (see Figure T2.7.1). Geologically, the offshore region can be divided into three parts:

1. the Gulf of St. Lawrence (Unit 914) and Laurentian Channel (Unit 932), where Carboniferous sedimentary sequences, similar to those occurring in the Cumberland and Sydney basins and overlying a complex basement of

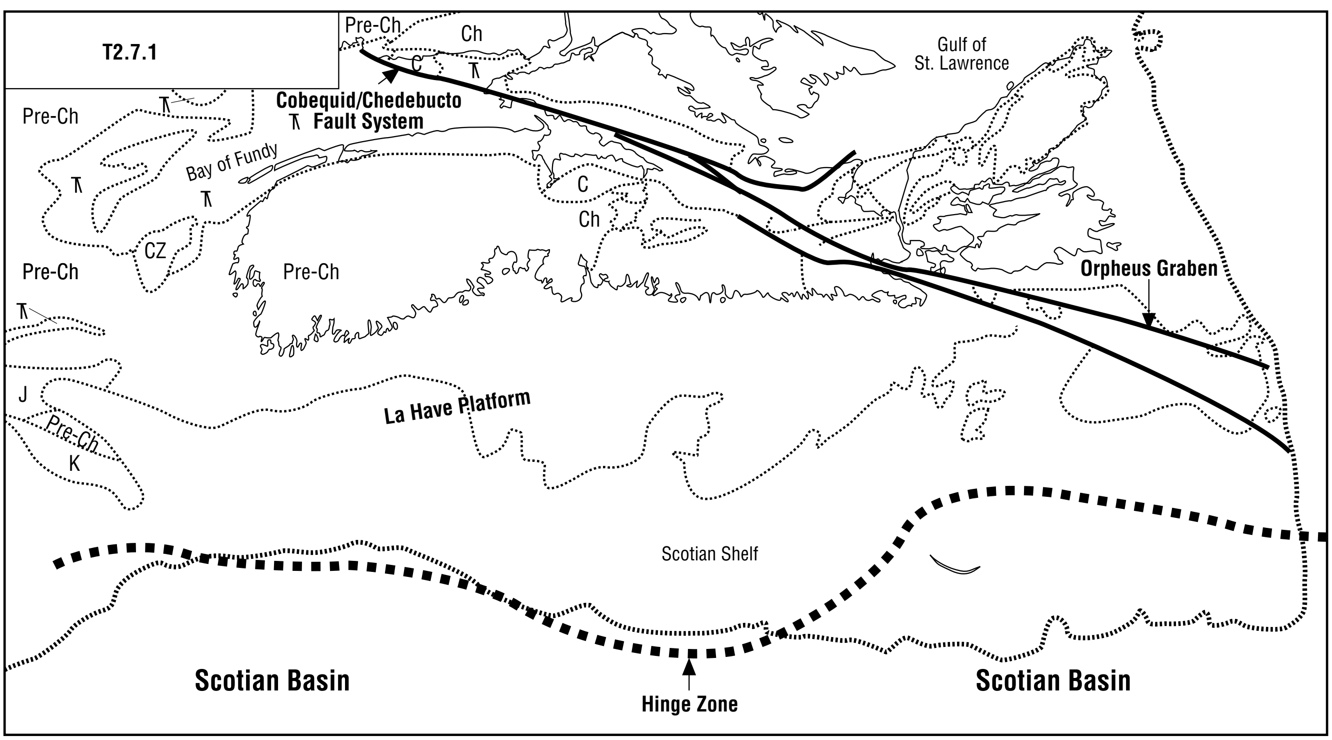


Figure T2.7.1: Structural geology of the Nova Scotia offshore.

T2.7 Offshore Geology

Avalon terrane metamorphic and igneous rocks, extend offshore into the larger Magdalen and Sydney basins

2. the Bay of Fundy, where the red Triassic and Jurassic sedimentary strata and basalts that occur in western Nova Scotia, overlying various Paleozoic formations, thicken northward toward the axis of the Fundy Basin (Unit 912)
3. the Scotian Shelf (Districts 920, 930) and Slope (District 940) where the Meguma Group rocks, which extend beneath the continental shelf, are onlapped by Jurassic, Cretaceous and Tertiary sedimentary beds of the Scotian Basin.[2]

The Scotian Basin can be further subdivided into:

(i) an inner area, where the Meguma basement is relatively shallow. This includes the LaHave Platform (District 930) and Canso Ridge (District 920). Its southern boundary is the "hinge zone": a zone of faulted basement blocks which marks a flexure in the crustal rocks between the platformal area and the adjacent basinal area

(ii) an outer area, consisting of a series of interconnected sub-basins containing very thick sedimentary rocks. This is the area of greatest potential for oil and gas discoveries (see Figure T2.7.2).

STRATIGRAPHY

The proto-Nova Scotian landscape has been more or less continuously exposed to erosive forces since the middle part of the Jurassic Period 180 million years ago. Its history from this point is essentially one of denudation rather than deposition, and consequently very little evidence of geological events has been preserved on land.

There are, however, two exceptions. First, at five locations in Nova Scotia, fluvial sediments have been

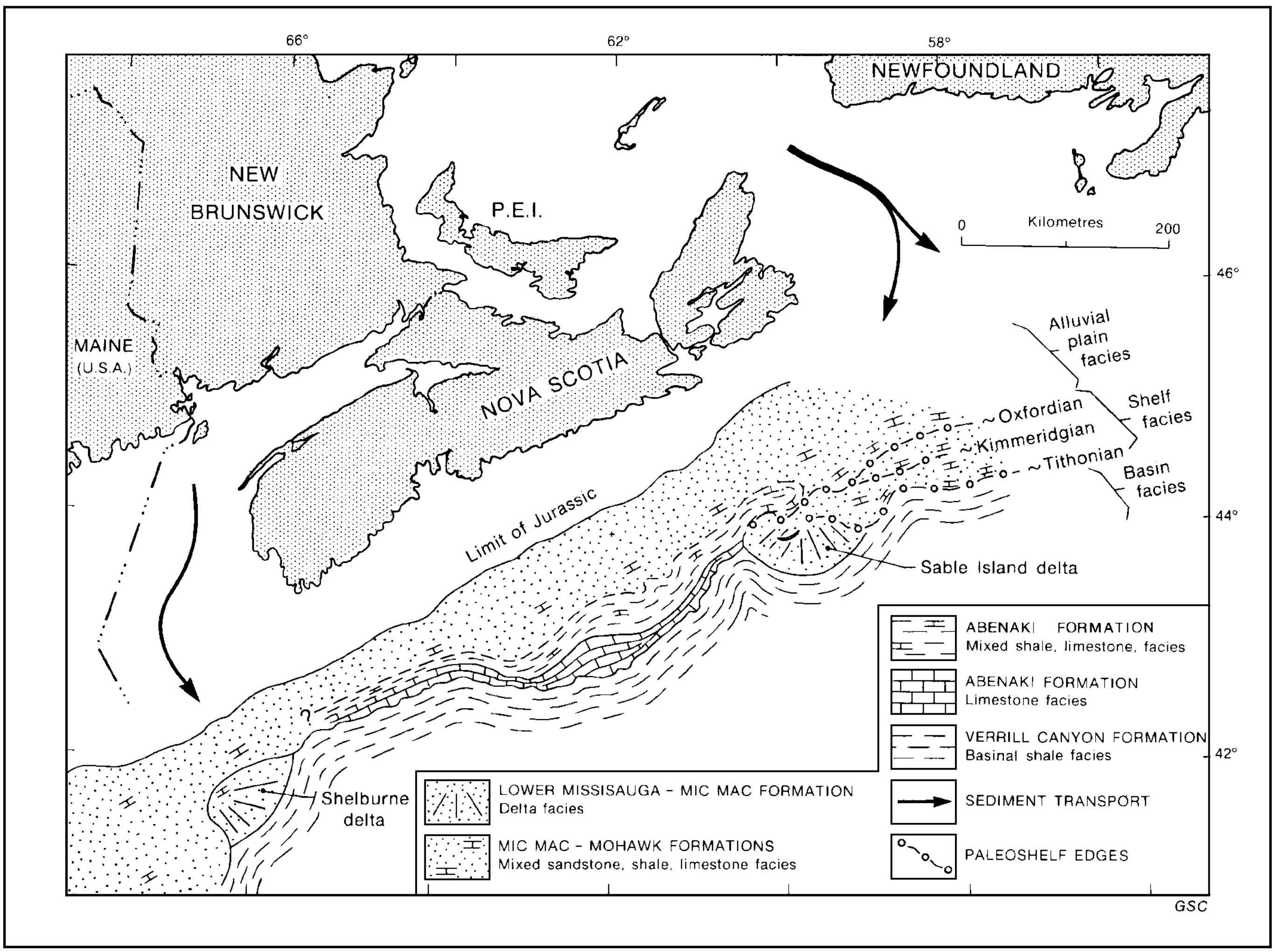


Figure T2.7.2: Generalized facies distribution reflecting depositional environments. Abenaki and equivalent formations, Scotian Shelf.[2]

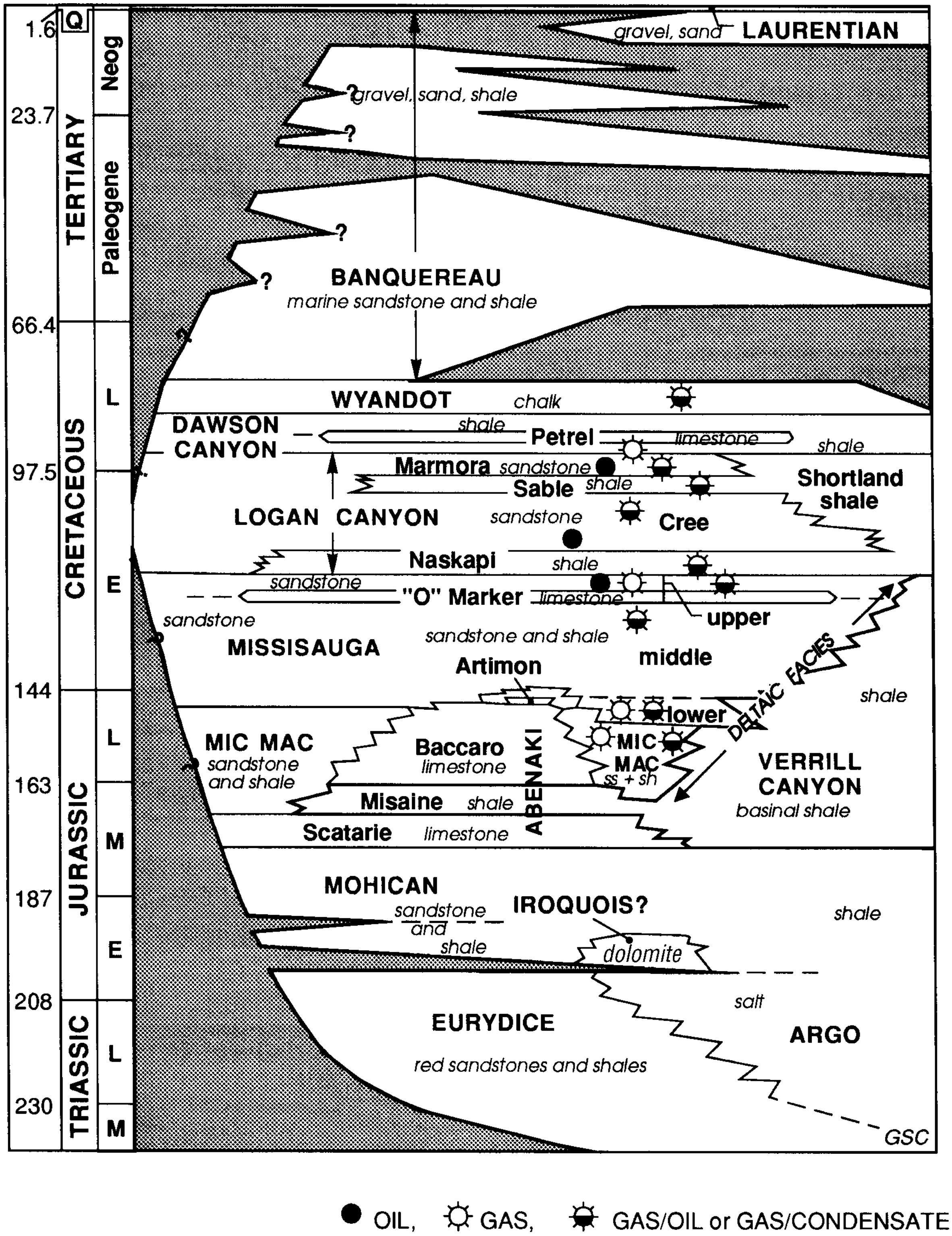


Figure T2.7.3: Hydrocarbon zones of the northeastern Nova Scotia continental shelf.[2]

discovered which contain assemblages of subtropical terrestrial flora (spores) and freshwater algal cysts (dinoflagellates) indicating an early Cretaceous age — ~110–120 million years ago. At another location, a 23-m-thick interval is dated as ~135 million years old. The second exception is the extensive blanket of glacial and glaciofluvial material deposited across all of Nova Scotia during the Pleistocene Epoch, which ended about 12,000 years ago.

This large gap in the geological record can be filled by data from the Scotian Shelf portion of the Scotian Basin. The Scotian Basin extends from Georges Bank in the southwest to the Grand Banks in the east and, in its thickest parts, may contain sedimentary strata totalling 20 km in thickness.[2, 3] There are a number of major structural elements within the Scotian Basin which, depending on their rate of subsidence and hence the amount of sediment accumulation, at present contain relatively thicker or thinner amounts of strata.

There are also several lithostratigraphic units in the Scotian Basin (see Figure T2.7.3). Most hydrocarbon discoveries have occurred in deltaic sediments of the MicMac, Mississauga and Logan Canyon formations.

The edge of the Scotian Basin subcrops Quaternary sediments approximately 30–50 km offshore from the southern coast of Nova Scotia.

This section summarizes the late Triassic, Jurassic and Cretaceous Periods, during which time the offshore area was the focus of significant sedimentation.

Triassic/Jurassic Red Beds and Salt

In the Late Triassic and the early part of the Jurassic Period, much of the Scotian Shelf was an emergent upland, containing a series of isolated to interconnected grabens and half-grabens into which were being deposited red sandstones and shales of the same age as the basal formations in the Fundy Basin. At this time, Nova Scotia was part of the supercontinent Pangea and was situated just north of the equator. Large amounts of salt were deposited into the deeper grabens as a result of the influx of seawater and a generally hot climate.[2]

Middle Jurassic Carbonate and Mud

Two significant changes occurred with the the continued northward movement of Pangea and the initial opening of the Atlantic Ocean in the Early Jurassic. First, the climate became more temperate and evaporite deposition ceased. Second, the broad area of the Scotian Shelf started to subside and land-derived sediments were deposited on top of the salt. These sediments were mainly sands near shore, containing organic matter from the continental land mass, while further offshore carbonates and muds, containing marine organic matter, were being deposited.

Late Jurassic Deltas

By the Late Jurassic (~160 million years ago) there were a variety of depositional environments south of Nova Scotia. South of southwestern Nova Scotia, a delta was developing at the mouth of a river system draining the Bay of Fundy–Gulf of Maine and adjacent regions. East of this feature, a narrow (10 to 20 km wide) carbonate shoal extended almost to where Sable Island is today, before being cut off by a second deltaic complex forming from a distributary of the ancestral St. Lawrence River (see Figure T2.7.2).

Woody material, which was washed in and buried within the deltaic sands and muds, is the principal source for the gas reserves around Sable Island. The water depth increased rapidly seaward of these features, and basinal shales, siltstones and fine-grained sandstones were deposited. These deltaic and basinal facies are important as potential source and reservoir rocks for crude oil and natural gas.[4,5,6]

Cretaceous Deltas

The southward retreat of the shoreline during a marine regression in the latest Jurassic and early part of the Cretaceous resulted in the development of fluvial and deltaic sediments on top of the Jurassic basinal sediments in the central part of the Scotian Basin, near Sable Island. A series of lesser marine transgressions and regressions occurred during the middle part of the Cretaceous, which resulted in the deposition of alternating source and reservoir beds. The whole sedimentary sequence was covered by fine muds during the Late Cretaceous, when seawater once more invaded the shelf and created deepwater conditions in the basin area.

Late Cretaceous/Early Tertiary
The later Cretaceous and early part of the Tertiary was a period of generally high sea level, with shoreline occasionally close to present day. By the late Tertiary, there was a general regression and the progradation of coarse clastics across the shelf.

Recent Deposits
During the latest phase of geological development on the Scotian Shelf, sediment banks have been built out along the edge of the continental shelf. The final veneer of glacial deposits, including moraines, was deposited as the Wisconsin ice sheet retreated.

CULTURAL FACTORS

Offshore areas of Nova Scotia are considered to be viable areas for hydrocarbon exploration and development (see T12.3).

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Associated Topics
T2.2 The Avalon and Meguma Zones, T2.6 The Triassic Basalts and Continental Rifting, T3.1 Development of the Ancient Landscape, T3.4 Terrestrial Glacial Deposits and Landscape Features, T3.5 Offshore Bottom Characteristics, T12.3 Geology and Resources

Associated Habitats
H1.1–H1.2 Offshore, H2.1–H2.6 Coastal

References

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Additional Reading

- Grant, A. C., K. D. McAlpine and J. A. Wade (1986) "The continental margin of eastern Canada: Geological framework and petroleum potential." In *Future Petroleum Provinces of the World*, edited by M.T. Halbouty. American Association of Petroleum Geologists (*Memoir* 40).

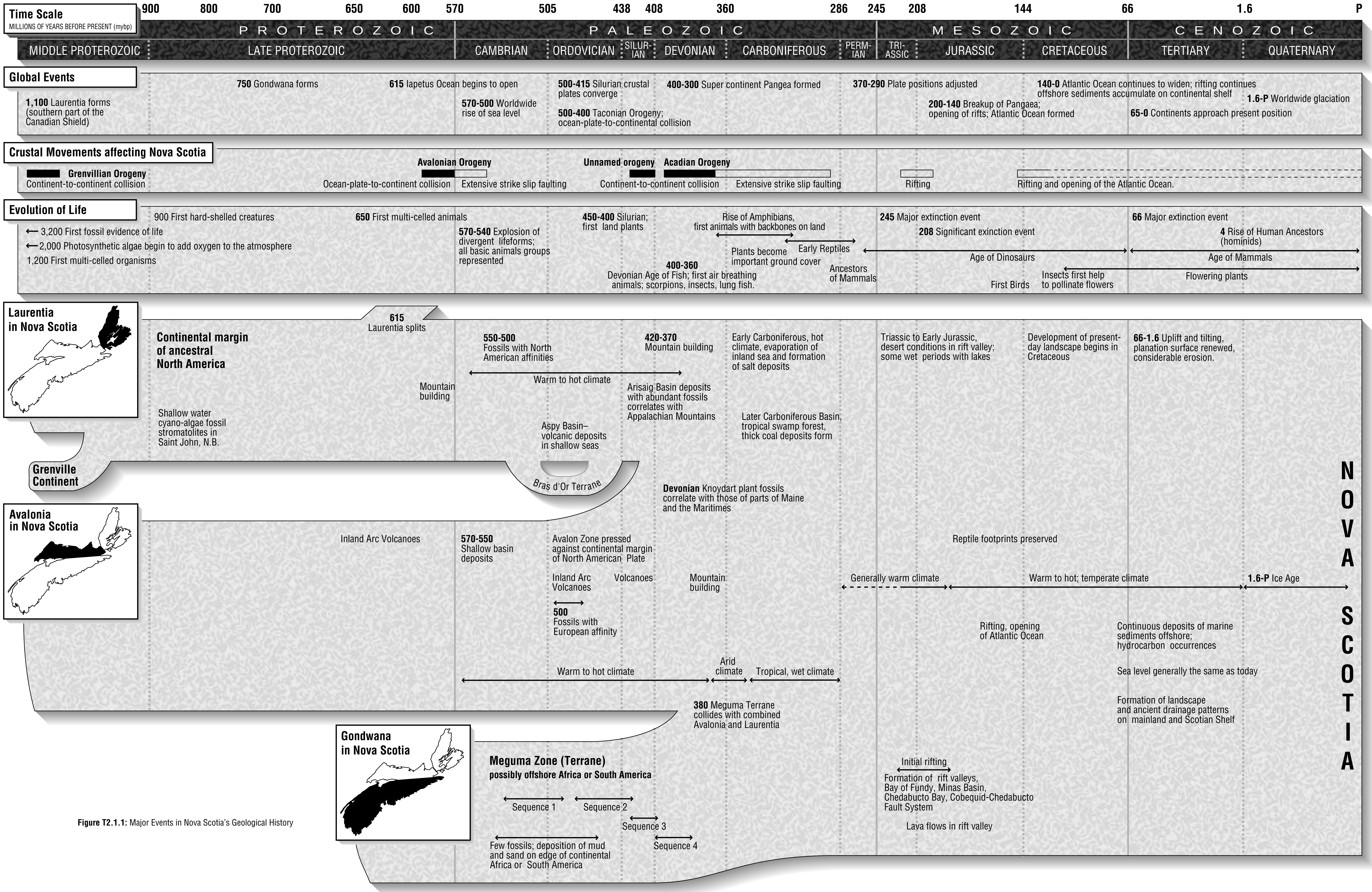

Figure T2.1.1: Major Events in Nova Scotia's Geological History