CHAPTER

20

Geological History of Canada

What are the main geological "building blocks" of North America?
How did the North American continent evolve?
How were the Atlantic provinces added to Canada?
Where did British Columbia come from?
Where can we find dinosaurs in Canada?
How did the Canadian Rockies form?
When did the ice sheets develop?
Why is it important to understand the geological history of Canada?

This chapter uses much of what has been discussed about geological processes earlier in the book to examine the geological history of our own country. Knowledge of Canada's geology is far from complete and is always being updated by new information—such as that produced by Lithoprobe, for example (see chapter 4). Canadians have prospered economically by finding and using natural resources such as copper, gold, oil, coal, iron, and nickel; the recent and highly publicized discovery of diamonds in the Northwest Territories continues this trend. Canada's economic well being is dependent on geological resources and the finding and use of new mineral and energy deposits, such as oil and gas, requires new generations of geoscientists armed with better knowledge of the varying geological conditions across Canada.

Poorly sorted Quaternary-age sediments exposed in the Hoodoos at Banff. These deposits were formed as debris flows were released onto the floor of the Bow Valley during glacier retreat. *Photo by Nick Eyles*

Access to and exploitation of these resources also requires knowledge of modern physical processes operating on the sea floors off Canada's coasts, in the permafrost terrains of the north, and in the earthquake- and landslide-prone mountain valleys of the west. At the same time, as urban populations grow so does society's dependence on the geosciences. The finding and protection of groundwater resources; the safe disposal of wastes; the design of foundations for buildings, roads, and other infrastructure; the location of sufficient quantities of construction materials such as sand and gravel; and the assessment of earthquake risk all require a detailed understanding of Canadian geology.

CANADA: A YOUNG NATION, BUT AN OLD COUNTRY

As a nation, Canada has been in existence since 1867. In that year, the Act of Confederation (also known as the British North America Act) brought together the provinces of Ontario, New Brunswick, Nova Scotia, and Quebec to create a larger and more powerful political entity. The country was welded together as an economic unit by a transcontinental railway, the completion of which was celebrated by the driving of the "last spike" in 1885 (figure 20.1). Later, other provinces saw the wisdom of joining this larger political and economic group; the last to join was Newfoundland in 1949.

In the very same fashion, but operating over a vastly longer time period, the North American continent was assembled by plate tectonics processes that brought together many smaller land masses. When fused and locked together, they have created the geological mosaic of the present-day continent. The process of continental building has not been a simple one and has taken more than 4 billion years to accomplish (figure 20.2).

FIGURE 20.1

Driving the last spike on the Canadian Pacific Railroad in November 1885 at Craigellachie in British Columbia. The building of the railway across the Canadian Shield resulted in exploration of the country's geology and the discovery of mineral resources such as the rich copper and nickel ores at Sudbury.

Public Archives of Canada

Construction of North America began at least 4,000 million years ago with the formation of the **Acasta Gneiss** of the Northwest Territories, which now forms part of the Slave Province of the Canadian Shield. The construction process has not been a simple one, as the continental mass we now call North America has itself been part of much larger land masses (called "supercontinents") that have since broken up. What remains today is a geological mosaic of fragments of the many former land masses that were fused together by plate tectonics processes. The building of North America was essentially complete by 65 million years ago, although the modern landscape is the result of geologically recent glaciations that have occurred in the last 2.5 million years. The last ice sheet left the southern portions of the country only 12,000 years ago, and finally melted in Labrador 6,000 years ago. Remnants of this vast ice sheet still survive on Baffin Island today as the Penny and Barnes Ice Caps (see chapter 16).

WHAT ARE THE MAIN GEOLOGICAL "BUILDING BLOCKS" OF NORTH AMERICA?

A Geologic Jigsaw

When one looks at a geological map of North America (such as the one inside the front cover of this book), the phrase "jigsaw puzzle" might come to mind. The northern part of the continent, in Canada, is underlain by the exposed part of the ancient core or **craton** of North America; this exposed part is called the *Canadian Shield* and consists predominantly of very old, Archean and Proterozoic rocks (figure 20.3*A*, *B*). These rocks range in age from 4 billion to approximately 1 billion years old and are largely devoid of fossils.

The craton is composed of a complex assemblage of several distinct geologic *provinces*. **Geologic provinces** are broad regions of similar rocks, usually covering many thousands of square kilometres, with characteristics that differ significantly from rock types present in adjacent areas. Individual geologic provinces have been subdivided into smaller units called *subprovinces*, which are fault-bounded units containing similar rock types, structures, and mineral deposits. Both geologic provinces and subprovinces were identified by geologists in the nineteenth century on the basis of broad-scale field mapping and form the basis of the earliest geologic maps of Canada.

Recent understanding of plate tectonics processes has clarified the origin of provinces and subprovinces. Provinces and subprovinces are now widely recognized to be **terranes.** Terranes are discrete fragments of oceanic or continental material that have been added to a craton at an active margin by accretion. (Note the different spelling and meaning from *terrain*, a physiographic term referring to topography.)

FIGURE 20.2A

Eon	Era	Period		Epoch	m.y.	
Phanerozoic	Cenozoic	Quaternary (Q)		Recent or Holocene		Present-day interglacial
					0.01	End of last glaciation
				Pleistocene		Erosion and sculpting of Great Lake basins, fiords and mountains by glaciers
					1.7	Beginning of continental glaciation in Canada
		Tertiary (T)	Neogene	Pliocene		
					5.3	First glaciers in Alaska
				Miocene		
					24	
			Paleogene	Oligocene		
					33.5	
				Eocene		First glaciers in Antarctica as globe cools but warm-loving forests still flourish in Canadian arctic
					54.8	
				Paleocene		Alberta's Tar Sands form Dinosaurs wiped out by giant meteorite strike
					65	Greenland breaks free of North America
	Mesozoic	Cretaceous (K)				Creation of Rocky Mountain fold belt
					145	British Columbia's copper deposits form
		Jurassic (JR)				Orogenies in Western Canada, **British Columbia built by accretion of terranes**
					200	
		Triassic (TR)				**Pangea** breaks up–early Atlantic Ocean forms and ancestral North America breaks free
					251	
	Paleozoic	Permian (P)				**Alleghanian Orogeny** completes the building of the Appalachian Mountain fold and thrust belt
					300	
		Carboniferous (C)	Pennsylvanian (P)			
					311	Formation of **Pangea**–coal deposits of Maritime provinces formed
			Mississippian (M)			
					355	Alberta's oil-bearing limestones form Saskatchewan's salt deposits accumulate
		Devonian (D)				
					418	**Acadian Orogeny** in eastern Canada marks arrival of Avalonia
		Silurian (S)				
					441	**Maritime Canada begins to be built by accretion of terranes during Taconic Orogeny**
		Ordovician (O)				
					490	Iapetus Ocean begins to close–several orogenies in eastern Canada
		Cambrian (Є)				Cambrian explosion of life begins at 540 Ma; Burgess Shale and Ediacaran fauna
					544	**Rodinia** breaks up–Iapetus Ocean forms at 620 Ma
Precambrian	Proterozoic Eon					Assembly of **Rodinia**–Grenville Orogeny at 1000 Ma completing the formation of the North American craton Sudbury Structure formed by giant meteorite strike at 1,850 Ma **Nena** forms
					2,500	Gowganda glaciation at c. 2,400 Ma
	Archean Eon					**Arctica** forms–first clear evidence of ancient bacterial life
					4,000	Acasta gneiss of Northwest Territories formed–oldest Canadian rocks
	Hadean Eon					
					4,600	FORMATION OF PLANET EARTH

A

B

FIGURE 20.2

(*A*) Time scale for the building of Canada's geology. Numbers are in millions of years. (*B*) Cambrian-Ordovician boundary (arrowed) exposed at Green Point, Gros Morne National Park, Newfoundland.

Photo by Nick Eyles

These likely originated as small continents and remnants of ocean-floor crust, each with its own complex geological history, and were welded together by plate tectonics processes to form the North American craton. Most of the North American craton was assembled between 1 and 4 billion years ago.

The full geographic extent of the craton is not immediately apparent from a map of the geology of North America as its outermost margins are buried by layers of younger "cover rocks" that reach thicknesses of more than 10 km (figure 20.3*A*). The North American craton is the largest in the world and extends from the Atlantic seaboard, west beneath the Rocky Mountains, and south as far as Texas. Greenland also consists of a detached mass of the same craton that broke off from North America during the opening of the northern North Atlantic Ocean some 80 million years ago.

The North American Craton versus the Canadian Shield

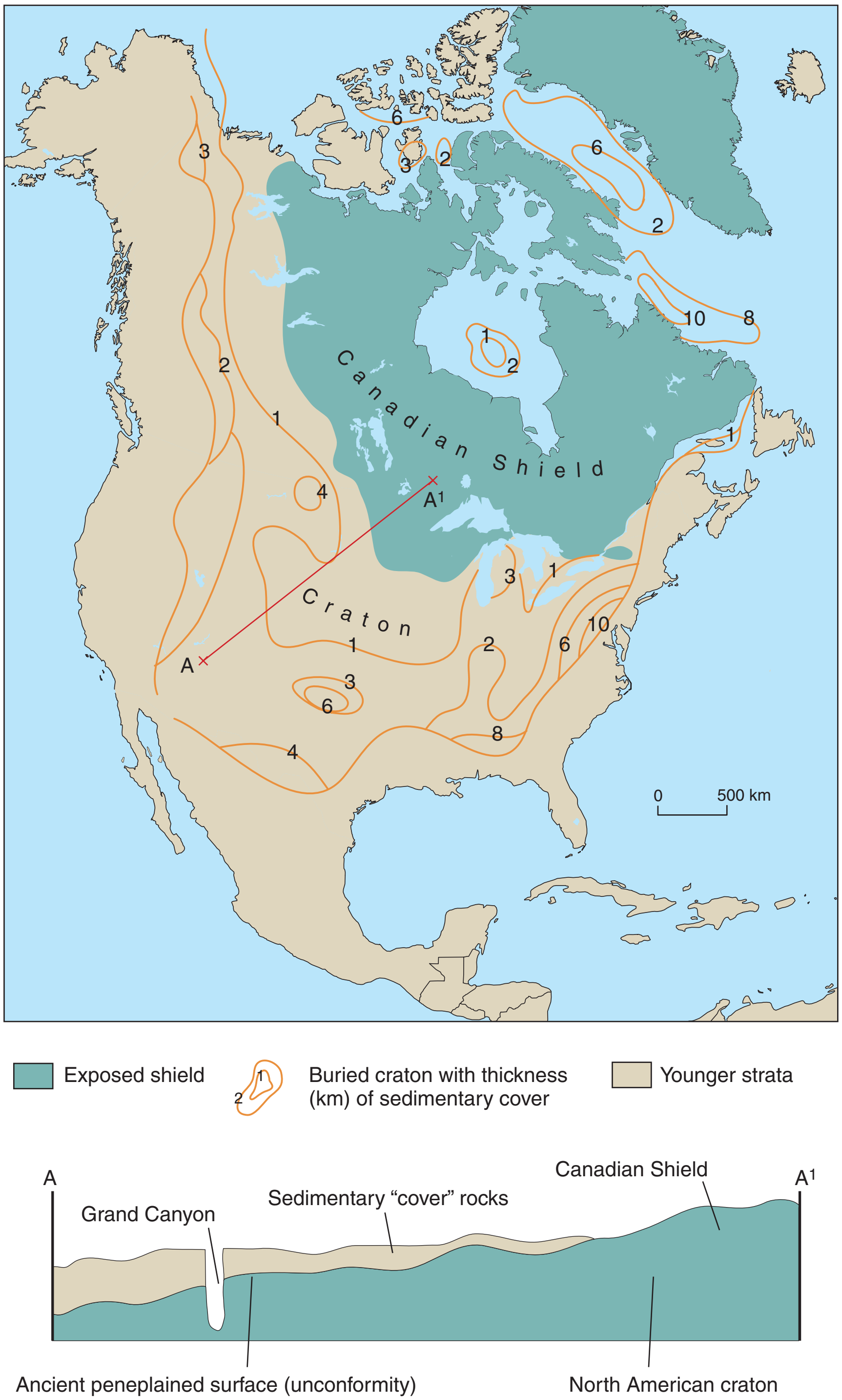
It is important to be aware of the difference between the **North American craton** and the **Canadian Shield.** The former refers to a large, continent-sized block of distinct geology making up the basement of much of North America (and Greenland). The Shield is the exposed part of the craton, and consists of a gently undulating surface that rises inconspicuously, almost like an arch, in its centre. The term "shield" was introduced by the Austrian geologist Eduard Suess around 1912. This was in reference to its dome-like form resembling a warrior's shield when placed flat on the ground.

The Canadian Shield is a large landform called a **peneplain** (derived from the Latin meaning *almost* a plain), which is a surface of low relief and great areal extent and age. Erosion and bevelling of the ancient rocks of the craton had created this peneplain by about 800 million years ago. The outer, gently sloping margins of the Shield are buried below younger sedimentary rocks, and the ancient peneplain surface now forms an unconformity between the craton below and younger rocks above. This unconformity can be seen in the sidewalls of the Grand Canyon in Arizona, where it separates metamorphic rocks of the craton from overlying Paleozoic cover rocks (see figures 19.16 and 19.17). This is the very same surface that is exposed many hundreds of kilometres to the north as the Canadian Shield (figure 20.3*A*).

The cover rocks that bury the outer margins of the North American craton are fossiliferous sedimentary strata of Paleozoic and Mesozoic age (figure 20.3*C*). These sedimentary rocks were deposited when the outer margins of the craton were depressed and flooded by shallow seas. This occurred primarily during mountain-building episodes (orogenies) that resulted from the collision of other land masses with the craton. During these events, the outer margins of the craton were depressed by the great weight of large mountain belts (including volcanoes) and their thick piles of sediment. Many other continents on Earth show the same basic anatomy of a central, ancient *craton* created by the fusion of many separate geological provinces (microcontinents), buried around its margins by younger sedimentary **cover strata.**

The Geologic Jigsaw of the North American Craton

This question has fascinated geologists since the middle of the nineteenth century—however, only since 1970, with the advent of plate tectonics, has an effective explanation been available. Early geologists recognized that, in general, rocks got younger as one travelled away from the geographic interior of North America to its coasts. Also, rocks that were uniform in character over enormous distances changed abruptly across very sharp boundaries. As early as 1870, several geologists were using the term "province" to describe the many distinct blocks of geology they discovered within the Canadian Shield. Famous Canadian geologist Sir William Logan was the first to write of "geological provinces" in the early 1860s; the term is still in use to describe areas of the Shield with distinctive geological characteristics (e.g., the Superior Province, shown in figure 20.4).



A

B

C

FIGURE 20.3

(*A*) A simplified version of the geological map of North America (such as that shown on the inside of the front cover of this book). The Canadian Shield is the exposed portion of the North American craton in the geographic centre of North America; the craton is covered by much younger sedimentary rocks ("cover rocks") on its margins. Schematic cross-section A-A' shows that the ancient peneplained surface of the craton, which forms an unconformity where buried by younger strata, also forms the exposed surface of the Canadian Shield. (*B*) The low-relief surface of the Canadian Shield. (C) Paleozoic "cover rocks" exposed along the Niagara Gorge, Ontario. The North American craton lies 600 m below.

Figure A by Nick Eyles; Photos B and C by Nick Eyles

FIGURE 20.4

The growth of North America showing the five principal building blocks of which the continent is composed and when each block was added. The boundary between areas 3 and 4 in eastern Canada is known today as Logan's Line, after its discovery by Canada's most famous geologist, Sir William Logan, along the St. Lawrence River near Quebec City in 1863.

1. The original North American continent, **Arctica**, which started to form about 2.5 billion years ago from smaller continents and was completed by about 1.9 billion years ago when old Archean cratons (e.g. Slave, Nain provinces) were welded together by the Trans-Hudson Orogen and others.
2. Added to the North American continent during the formation of **Nena** about 1.8 billion years ago after the Penokean Orogeny.
3. Added during the formation of **Rodinia** about 1.3 billion years ago during the Grenville Orogeny.
4. Added during the formation of **Pangea** about 600 million–300 million years ago.
5. Added after the breakup of **Pangea** about 250 million years ago.

Early settlers of Canada took a keen interest in geology and soon opened mines; some of the earliest gold mines were in Nova Scotia. Discoveries of coal soon followed, such as at Joggins, Nova Scotia, but these were essentially random finds by prospectors. Systematic study of the geology of Canada by professional geologists began with the newly formed Geological Survey of Canada (GSC) in the early 1840s, at a time when few topographic maps or roads existed. An impetus behind the formation of the GSC was the need to better understand the country's geological resources, mostly coal. Its first director was Sir William Logan, who sent Alexander Murray to work in Newfoundland and sponsored William Dawson to study the geology of Nova Scotia. Logan's magnificent map of the Geology of Canada (actually parts of Manitoba, southern Ontario, and Quebec) was published in 1869 and was a major achievement. The combination of a large, barely explored country and complex geology offered major challenges, both physical and mental. Canadian geologist A.C. Lawson declared in 1913 that "no one geologist, not for that matter two, can hope to become familiar with the details of more than a very small proportion of the entire field. The work to be done is appalling in its magnitude."

Even today, much of the Canadian Shield remains to be mapped in detail, but the basic geological survey started in the 1840s was essentially completed with the aid of broad-scale helicopter and other airborne surveys in the 1970s. At that time, emerging revelations about the workings of plate tectonics by geologists studying the sea floor provided the key to the origin of the Canadian Shield. The plate tectonics revolution identified that the Earth's outer surface was made of lithospheric plates that are always in the process of being newly built, destroyed, or welded together to form larger plates (see chapter 2). It is now realized that these processes have been operating on the Earth in some form over the past 4 billion years and are responsible for bringing together the various geological provinces of Canada. Processes operating in the modern world are thus being used to explain the evolution of the ancient North American craton, a working principle known as *uniformitarianism* (see chapter 19). In turn, the model of plate tectonics is also being tested against the ancient geological record preserved in the Canadian Shield.

HOW DID THE NORTH AMERICAN CONTINENT EVOLVE?

Stages in the Evolution of the North American Continent

Figure 20.4 shows the essential building blocks now recognized by geologists within the North American continent. Within the oldest part of the continent (Area 1 on figure 20.4), several geological provinces (such as Rae, Superior, and Wyoming) are rimmed by intensely deformed rocks that form ancient *orogens* (such as Torngat and Wopmay). As a broad generalization, geologic provinces can be regarded as the remains of individual continents that collided (see box 20.1). The **orogens** consist of crushed and deformed rocks that represent the remains of mountain belts or volcanic arcs formed during collision.

The earliest part of Canada's geological history is not well known and therefore is subject to much debate. Much remains to be discovered. Some geologists suggest that the growth of the North American continent can be broken down into five different stages. Each stage is characterized by a major plate tectonics event, when ancestral North America either collided with or ripped apart from other land masses. This process of repeated continental aggradation and breakup is known as the Wilson Cycle (see chapter 2), and has resulted in the development of **supercontinents** at certain times in Earth's history. Because of this cyclic process of continental aggradation and dispersal, each of the present-day continents (now widely separated on the globe) has a broadly similar geologic history. Hence, it is possible to work on the geology of Australia or South America, for example, and recognize the same tectonic events as those that affected parts of North America.

It is important to remember that our understanding of the early stages of Canada's geological history is preliminary at best. Some of the stages of development are speculative and their timing uncertain. However, one model of the five stages of continental growth and their timing is discussed below.

Stage 1—Arctica: North America in the Archean

The formation of the central part of the North American continent (Area 1 on figure 20.4) spans the entire Archean Era (4–2.5 billion years ago). Some of the oldest rocks so far dated on Earth are found in the Slave Province (Acasta Gneiss of the Northwest Territories, see chapter 10) and are thought to be between 3.96 and 4.05 billion years old. These rocks formed part of an ancient continent that some have named **Arctica** (figure 20.5). Speculative evidence suggests that Arctica had begun to form by 2.5 billion years ago, but its final assembly was not completed until after 2 billion years ago. The continent included much of present-day Siberia.

The Slave Province is today the focus of much mineral-exploration activity, especially for diamonds that occur in kimberlite pipes penetrating the ancient shield rocks (see box 4.4). Similarly, the Superior Province, which also formed part of Arctica, is of special importance to Canadians because of its great

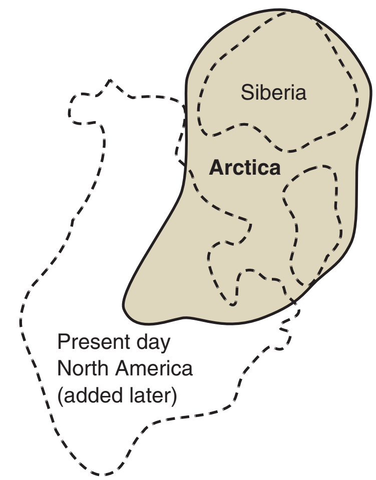


FIGURE 20.5
The continent Arctica about 2 billion years ago (Area 1 on figure 20.4).

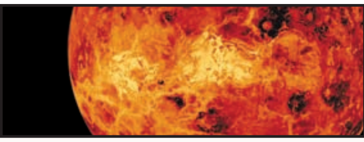
mineral wealth. Approximately 450 significant mineral deposits have been discovered to date within the Superior Province. More than 50 percent of Canada's entire annual gold production and 30 percent of its zinc, copper, and silver are mined from the Superior Province. Much undoubtedly remains to be discovered.

Detailed mapping of the ancient rocks of the Superior Province reveals smaller **subprovinces** composed of distinct rock types that record particular geologic events (figure 20.6). For example, *plutonic subprovinces* are composed of granites and record the intrusion of giant plutons into the Superior Province. *Greenstone subprovinces* consist of metamorphosed sea-floor volcanic rocks, such as **basalt**, originally formed on the floor of ancient Archean oceans (figure 20.7). These subprovinces contain thick banded iron deposits that form the major source of the world's iron and record the first large-scale production of oxygen by single-celled cyanobacteria on Earth. The *metasedimentary subprovinces* consist of deep-sea Archean ocean sediments. Together, the various subprovinces within the Superior Province record clear evidence of the operation of plate tectonics activity in the ancient past, much as we see it today.

The southern continental margin of Arctica was the site of a major glaciation (the **Gowganda glaciation**). This glaciation is one of the oldest recorded on Earth and is dated at around 2.4 billion years ago. The glacial deposits of the Gowganda Formation (figure 16.37*A*) form part of the Huronian Supergroup of Ontario, famous for the uranium deposits found near Elliot Lake.

Stage 2—Nena and Rodinia: North America in the Proterozoic

The next events in the development of the North American continent span the entire Proterozoic Era (from about 2.5 billion to 570 million years ago). The southern part of the Canadian Shield, including the Southern Province and the Yavapai and Mazatzal Orogenies (Area 2 on figure 20.4), had been added to Arctica by about 1.9 billion years ago or shortly thereafter, to form a larger land mass some geologists call **Nena.** The final

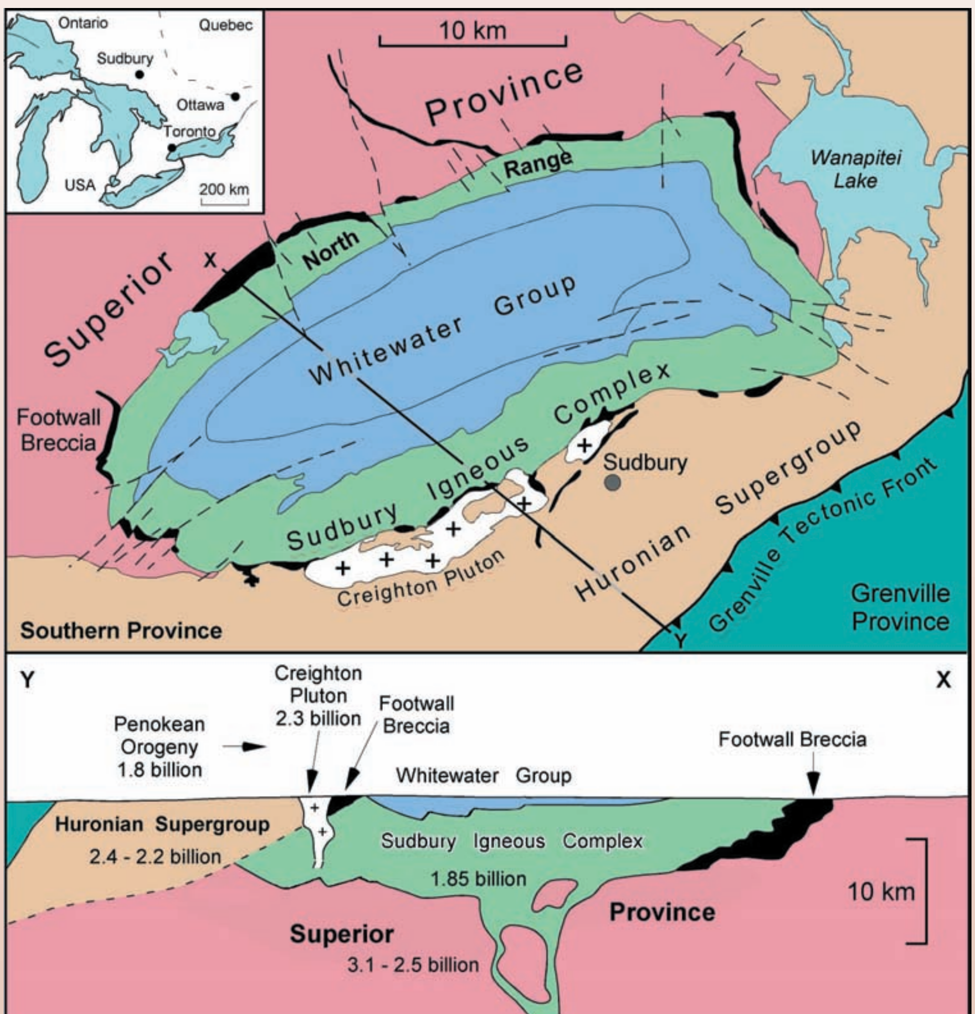


ASTROGEOLOGY 20.1

The Sudbury Impact Structure: Collision of an Ancient Meteorite

The huge 60-kilometre-long and 30-kilometre-wide crater preserved at Sudbury was originally circular and formed by a colossal meteorite impact around 1.8 billion years ago (box figure 1). Recent models suggest impact by a meteorite about 10 kilometres in diameter that broke through the Earth's crust melting vast volumes of melt rocks. This catastrophic event is also recorded in the Sudbury region by so-called **shatter cones** (box figure 2) and breccia and glass called *pseudotachylite* (or breccia; box figure 3), which are typical of meteorite impact structures worldwide. The impact crater was squeezed into its present oval shape during the *Penokean Orogeny*, shortly after it formed.

The Sudbury structure is famous for its rich nickel, copper, and platinum ores (box figure 4). These ores record the upwelling of mantle magmas as a result of the penetration of the meteorite through the crust to a depth of 35 km. The ore consists of massive sulphides, typically in the form of the minerals pentlandite, pyrrhotite, pyrite, and chalcopyrite, with about 2 percent nickel and platinum derived from the original meteorite and melted mantle rocks.



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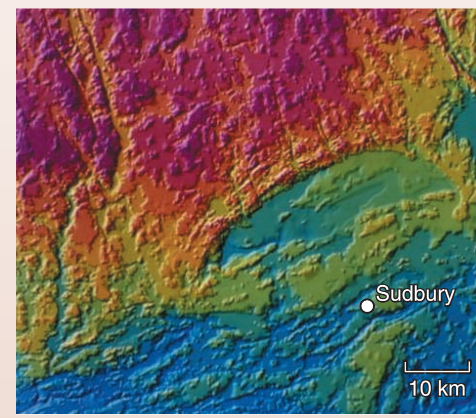


B

BOX 20.1 ■ FIGURE 1

Sudbury meteorite impact structure.

(*A*) Geological map and schematic cross-section.
(*B*) Digital elevation model showing the oval-shaped impact crater as an area of low topography (green and blue colours) to the north of Sudbury.

Photo B from www.unb.ca/passc/ImpactDatabase/images.html

BOX 20.1 ■ FIGURE 2

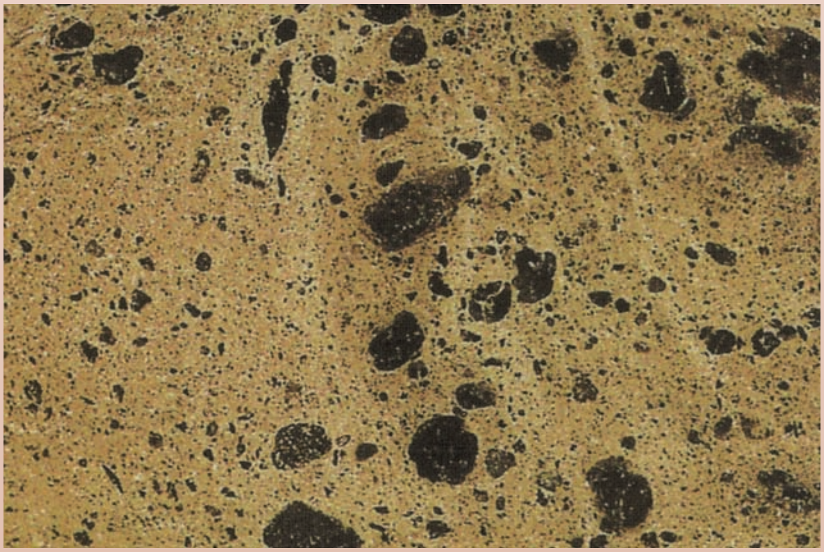
V-shaped shatter cones form when rocks are struck violently during a meteorite impact event. Shatter cones occur widely around the Sudbury area, especially along the access road to the Laurentian University campus.

Photo by Nick Eyles

BOX 20.1 ■ FIGURE 3

Breccia formed by the disintegration and mixing of rock when hit by a large meteorite and broken into angular fragments. This breccia is common in the Sudbury area.

Photo by Nick Eyles



BOX 20.1 ■ FIGURE 4

Close-up image of fine-grained copper sulphide ore with small fragments of dark-coloured country rock. Width of view is 10 cm.

Photo: GSC ESS photo library #1995-225C. Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2007 and Courtesy of Natural Resources Canada, and Geological Survey of Canada.

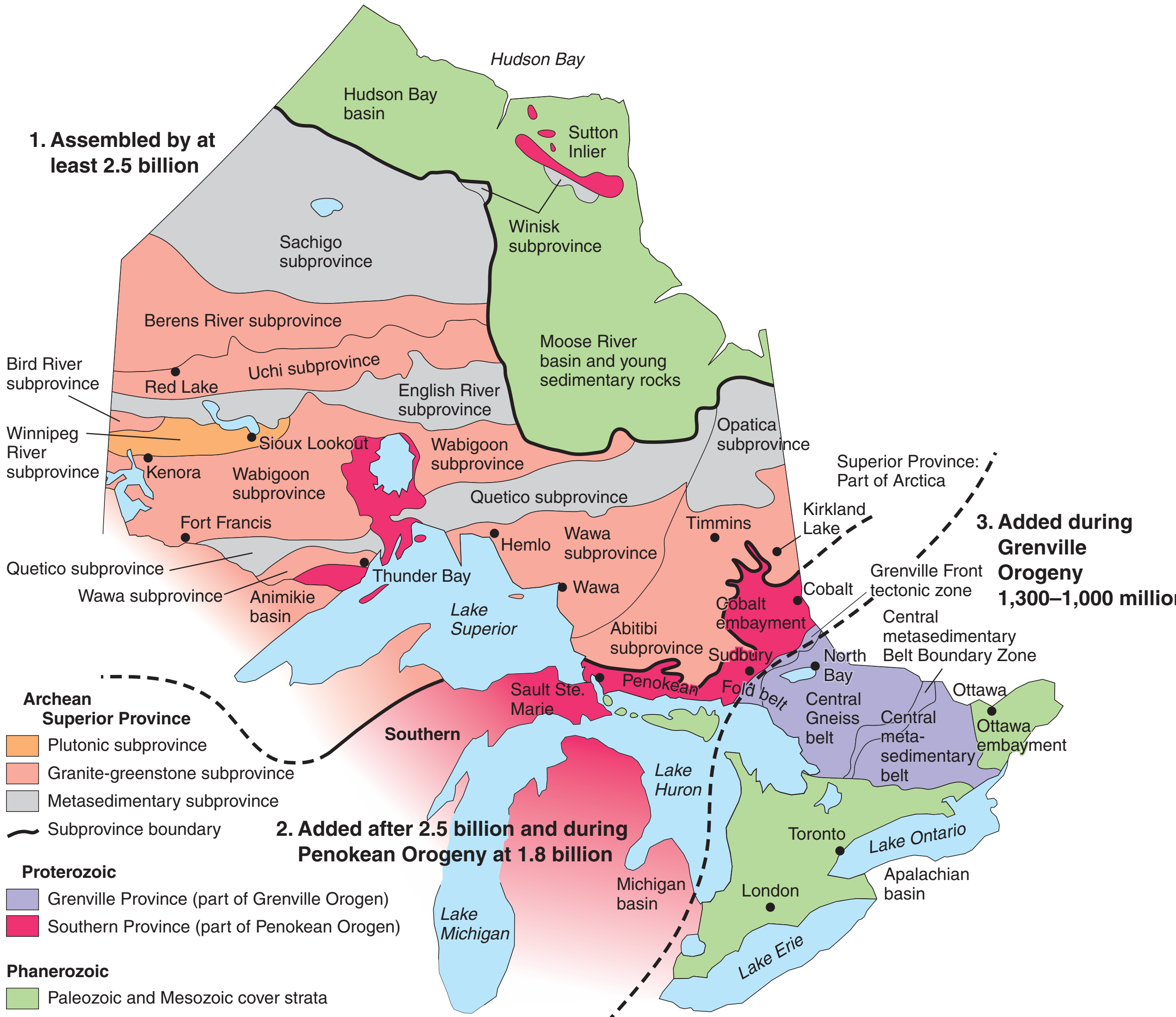


FIGURE 20.6

Geological map of Ontario showing structure within the Superior Province (1), younger Southern (2) and Grenville (3) provinces (areas 2 and 3 on Figure 20.4).
Fitzhenry and Whiteside Limited

assembly of Nena is recorded in Ontario by the *Penokean Orogeny*. This created a major Himalayan-type mountain range near what is now the northern end of Lake Huron (figure 20.6). The range was destroyed by erosion, but its deep roots remain as the Penokean Fold Belt along the northern border of Lake Huron in Ontario.

Stage 3—The Grenville Orogeny and Formation of Rodinia

The **Grenville Orogeny** was the result of the long-lived collision between ancestral South and North America between 1.3 and 1 billion years ago (figure 20.8*A*). Much of what is now eastern North America from southern Greenland to Northern Mexico was formed at this time by accretion of smaller land masses (Area 3 on figure 20.4). As a result of the collision, a huge supercontinent called **Rodinia** was created. Rocks accreted and deformed during the orogeny underlie much of southern Ontario and Quebec, extending through the Maritimes and into Newfoundland.

The Grenville orogenic belt (which can be called either the Grenville Province or the Grenville Orogen) is dominated by beautifully banded gneisses, highly metamorphosed sediments, and igneous rocks (figure 20.9). These once formed the deep roots of an ancient mountain range that some call the Grenville Mountains (figure 20.10). By 800 million years ago the forces of erosion had reduced the mountains to a peneplain. This surface has, in fact, changed little over the ensuing 800 million years and is represented

A

B

FIGURE 20.7

(*A*) Ancient pillow basalts formed when magma erupted and cooled underwater. Enormous thicknesses of pillow basalts make up the greenstone belts of the Slave and Superior provinces. Hot water circulating through the sea floor at the time of their formation scavenged and concentrated metals as "hydrothermal" deposits now mined for gold and other minerals. (*B*) The Giant Mine near Yellowknife in the Northwest Territories extracted gold from pillow basalts between 1947 and 1999. The process left arsenic-rich waste on the edge of Great Slave Lake, which is now being cleaned up.

Photos by Nick Eyles

today by the low-relief landscape of the exposed Canadian Shield. The Canadian Shield forms one of the most extensive and ancient landforms in the world and is remarkable because geologists have little detailed knowledge of how such a landscape formed.

Detailed mapping shows that the Grenville Province is, in fact, made up of many smaller terranes. These represent the highly deformed remnants of island arcs, microcontinents, and pieces of ocean floor that were not subducted and destroyed during the orogeny but were scraped off and accreted onto the eastern edge of Rodinia. The latest phase of the stage was the intrusion of many granite plutons and dikes that welded together the various terranes (refer to figure 20.15 later in this chapter).

Rodinia Breaks Apart

Supercontinents such as Rodinia are inherently unstable and with time inevitably self-destruct. This is because their large extent prevents heat from escaping from the Earth's interior and promotes the buildup of giant convecting "plumes" in the mantle. These plumes cause the land surface to rise in the form of a dome. Eventually, the convecting forces below are sufficiently great to tear, or rift, the supercontinent apart.

This process of continental breakup commences with the formation of a *triple junction*, which consists of interlinked *grabens* that eventually grow and widen into a new ocean basin. Initial breakup of Rodinia started around 750 million years ago and finished at about 570 million years ago, during the earliest Cambrian (figure 20.8*B*). The first break occurred along the western margin of North America when Antarctica and Australia broke away to form an ancestral Pacific Ocean (called the Panthalassic Ocean). Millions of years later, the last tear occurred along the eastern margin of North America and saw Europe and Africa drift off to form an ancestral Atlantic Ocean called the **Iapetus Ocean** (figure 20.8*B*). The process of continental rifting by the formation of interlinked grabens has left a legacy of failed grabens (called *aulacogens*) that are now preserved deep within North America, where they are infilled and buried by younger cover strata (see chapter 2).

The Iapetus Ocean closely resembled the modern Atlantic Ocean, and coastal sediments were deposited across extensive shallow continental shelves. These areas of warm water provided well-lit, nutrient-rich habitats for an enormous variety of marine organisms. These include corals, molluscs, brachiopods, trilobites, and echinoderms. Some paleontologists have speculated that the breakup of Rodinia and the opening up of a wealth of new habitats around the margins of the newly formed Iapetus Ocean was the major stimulus to the proliferation of organisms evident in the so-called **Cambrian Explosion** of early lifeforms such as those of the Burgess Shale and the Mistaken Point Formation (see boxes 1.11 and 20.2).

Stage 4—Pangea: North America in the Late Paleozoic and Some of the Mesozoic

The Iapetus Ocean was not long-lived and by about 480 million years ago was beginning to close. A land mass called Baltica (consisting of much of modern Europe) once more approached the eastern seaboard of North America (then called *Laurentia*, figure 20.8*C*) and eventually collided to form *Laurasia*. Collision of the two land masses caused a major orogenic event, the *Taconic Orogeny*. (The equivalent event in Europe is known as the Caledonian Orogeny and formed mountains in Wales, Scotland, and Scandinavia.) An arc of volcanic islands rose high above the active subduction zone off eastern North America and huge andesitic volcanoes, much like those found in today's Andes Mountains or in Japan and the Philippines, spewed volcanic ash into the continental interior (figure 20.11). Today, these ash beds provide important *marker horizons* within the thick sedimentary strata that

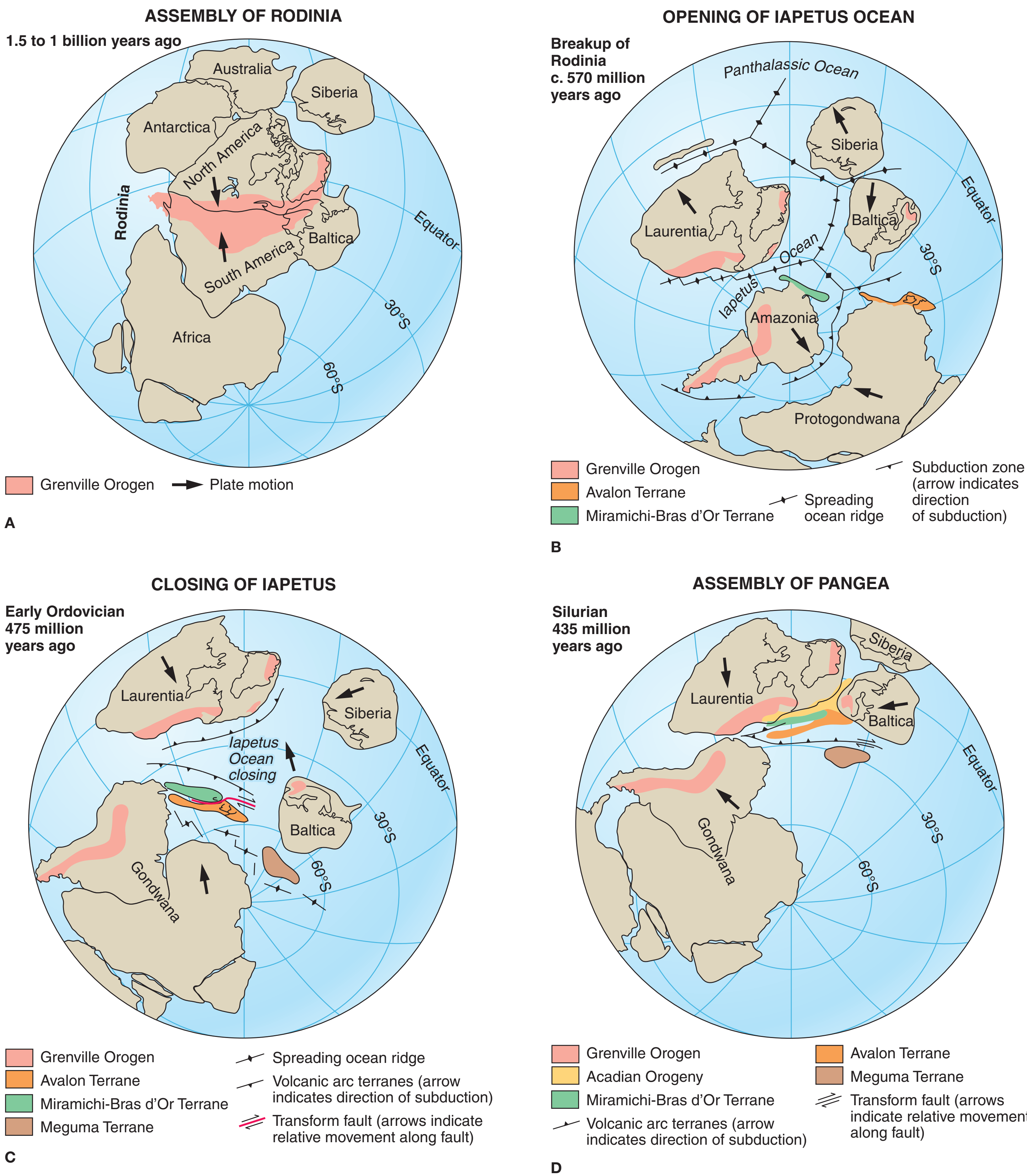


FIGURE 20.8

The building of eastern Canada. (*A*) Collision of North and South America caused the Grenville Orogeny and created the supercontinent Rodinia. (*B*) The breakup of Rodinia and development of the ancestral Atlantic Ocean, the Iapetus Ocean. (C/D) Closure of the Iapetus Ocean. Exotic far-travelled terranes were added (accreted) to eastern North America during the Ordovician (*C*) and Silurian (*D*). Parts of the floor of the Iapetus Ocean were shoved on land and are now preserved as ophiolites in western Newfoundland (see figure 20.13). The same process of terrane accretion built much of the province of British Columbia during the Mesozoic era (see figure 20.20).

FIGURE 20.9

Banded gneisses near Parry Sound, Ontario were produced at great depths below colliding land masses during the Grenville Orogeny between 1.3 and 1 billion years ago. These rocks are now exposed on the Canadian Shield as a result of slow uplift and erosion.

Photo by Nick Eyles

cover the outer margins of the North American craton. Each bed, now composed of weathered ash called *bentonite*, can be "fingerprinted" by reference to its unique chemical characteristics, providing geologists with an invaluable means of correlating strata across large areas of mid-continent.

Closure of the Iapetus Ocean resulted in the buckling of the outer margins of the North American craton and the formation of downwarped sedimentary basins, such as the Appalachian Basin, in the continent's interior (figure 20.11). These are called *intracratonic basins*, as they form on the craton and are underlain by continental crust rather than oceanic crust. Slow subsidence of the sea floor and the continual addition of new sediment allowed great thicknesses of sedimentary strata to accumulate in these basins over time. More than 10 km of Paleozoic sediments are preserved in parts of the Appalachian Basin (figure 20.3).

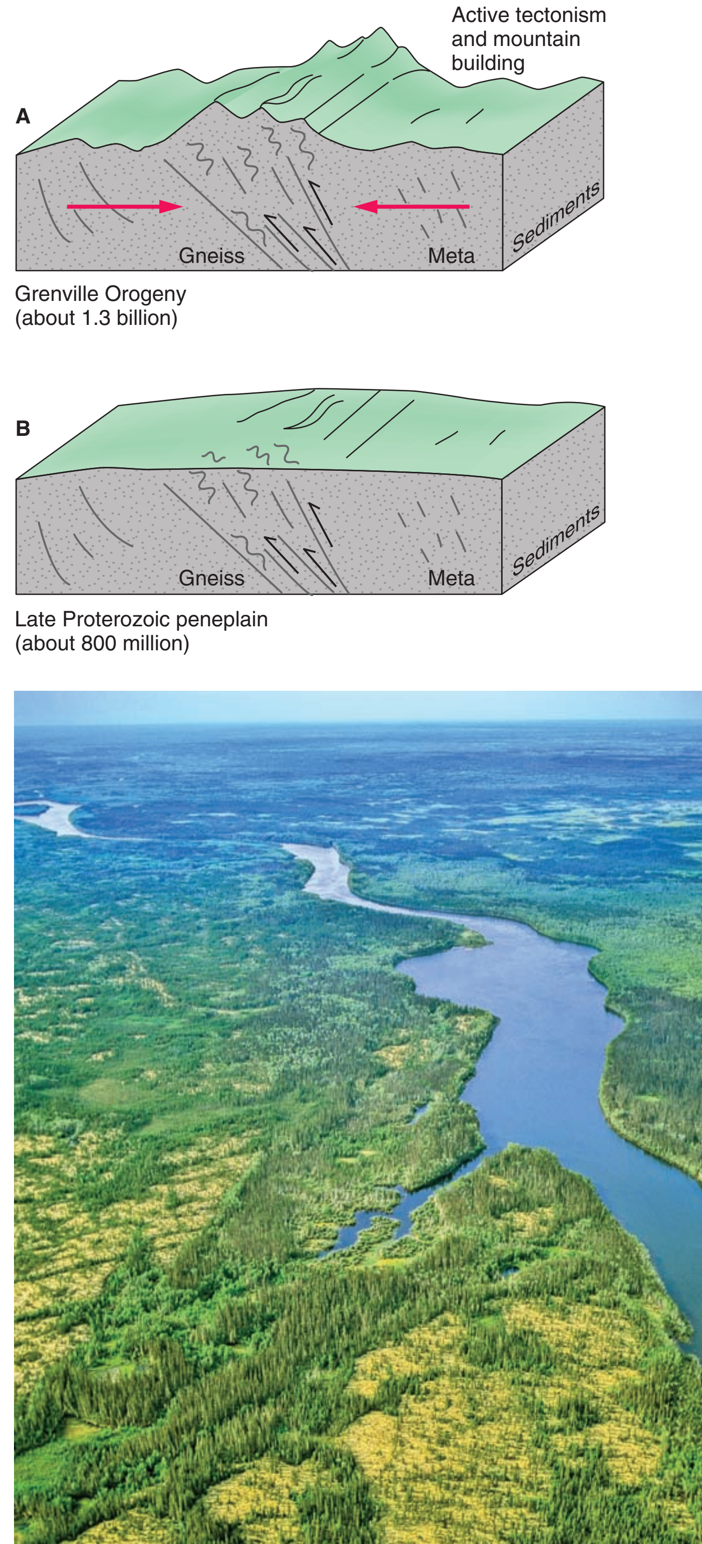


FIGURE 20.10

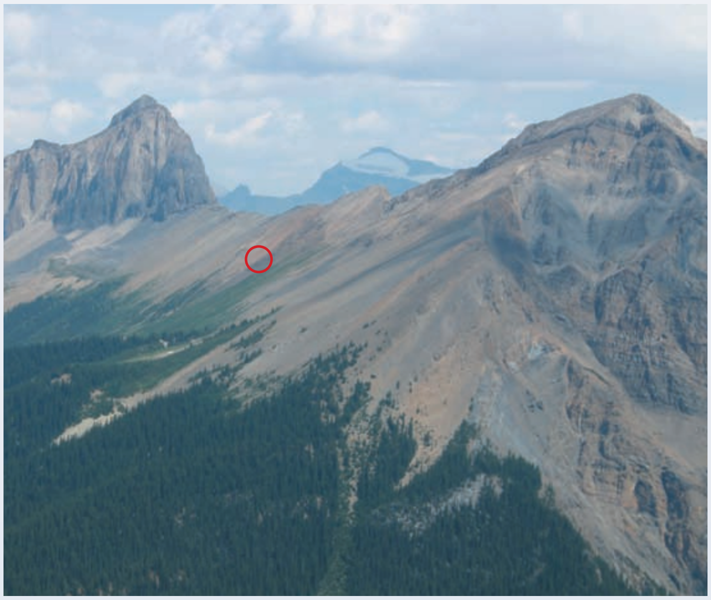
(A,B) Mountains formed during the Grenville Orogeny were eroded to form an almost flat peneplain by 800 million years ago. *(C)* The Canadian Shield forms an 800-million-year-old, low-relief landform that has barely been modified by geologically recent processes such as glaciation. Taltson River, Alberta.

Photo C © Jim Wark — Airphoto

IN GREATER DEPTH 20.2

The Oldest Animals in the World

The Cambrian explosion of new species, including those with backbones (chordates), is recorded by the enigmatic fossils of the Burgess Shale, found in Yoho National Park in British Columbia (see chapter 1). The world-famous Burgess Shale is exposed on the slopes of Mount Wapta (box figure 1). Mount Wapta forms a part of the Cathedral Escarpment, which formed the edge of an ancient carbonate reef. Some 505 million years ago, this reef overlooked deep water along the margin of western North America and the fine-grained muds that accumulated along its base formed the Burgess Shale. Strange-looking fossils were discovered in the Burgess Shale in 1909 by Charles Walcott—the site of the richest fossil finds is named Walcott's Quarry and is now a UNESCO World Heritage Site (see box 1.1). Slightly older but similar fossil groups have been found in China (the Chengjiang deposits), indicating that Burgess-type organisms were more widespread than previously thought. Fossils even older than those in the Burgess shales, some of the oldest definitive multicellular animals known to science—are also Canadian. These were formed by soft-bodied organisms and as a group are called the *Ediacara fauna*. Their ages range from about 565 to 543 million years; the oldest yet known anywhere in the world occur in Newfoundland in the Mistaken Point Formation (box figure 2). A very distinctive Ediacaran fossil is *Charnia masoni*, a large frond-like organism, almost 2 metres in length, resembling the shape of a modern-day lichen but that lived on the sea floor. Other Ediacaran organisms (called the "Twitya discs") are found in strata deposited at the same time as those of the Mistaken Point Formation but that outcrop in the Mackenzie Mountains of the Northwest Territories on the opposing paleo-Panthalassic coastline of North America.



BOX 20.2 — FIGURE 1

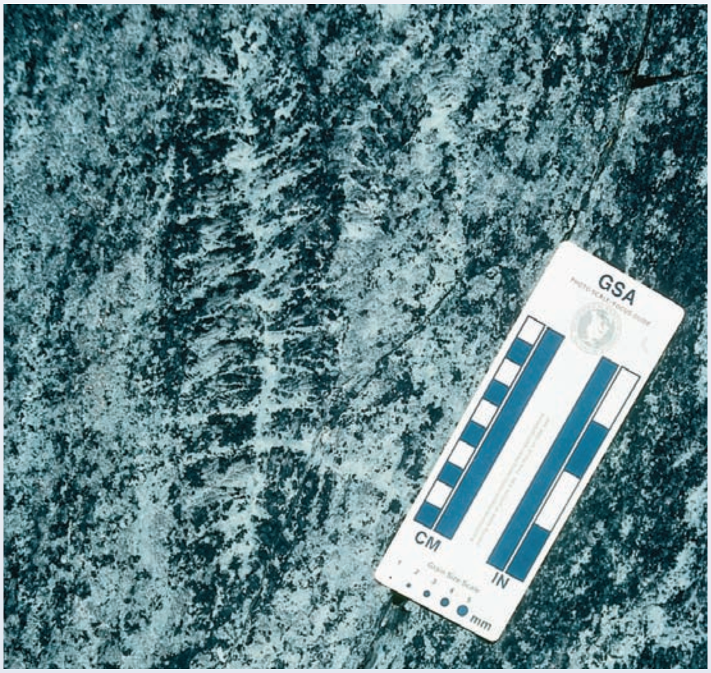
Mount Wapta (peak on left) and the Walcott Quarry (circled) in Yoho National Park, British Columbia.

Photo by Nick Eyles

BOX 20.2 — FIGURE 2

Outcrops of the Mistaken Point Formation, Avalon Peninsula, Newfoundland. This site is now protected as a UNESCO Biosphere preserve. Strata consist of layers of mudstone in which delicate fossils are preserved.

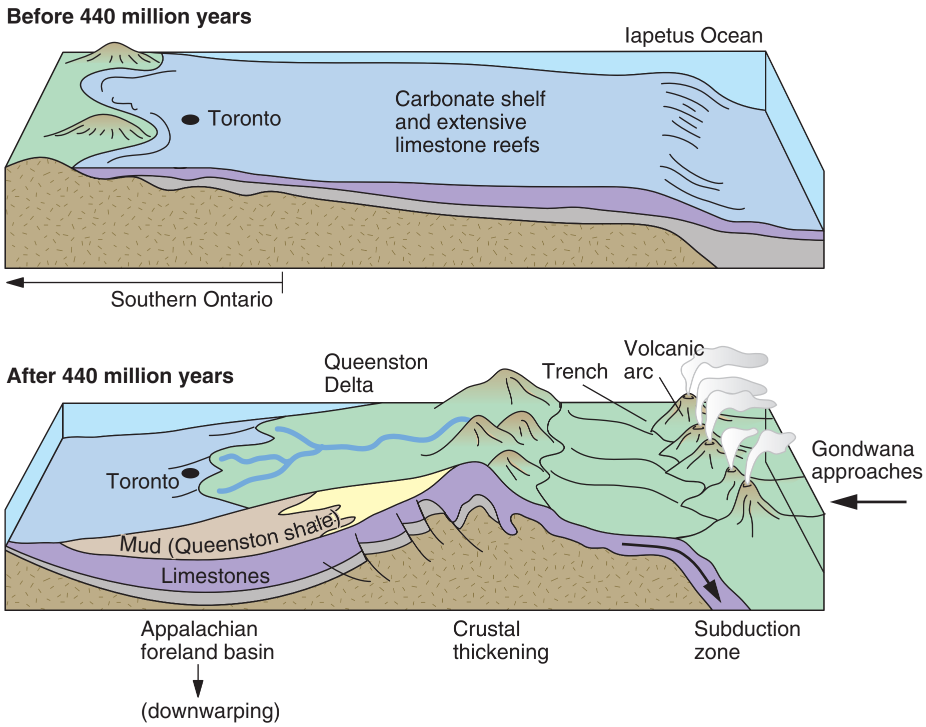
Photo by Nick Eyles



BOX 20.2 — FIGURE 3

Frond-like organisms belonging to the Ediacaran fauna, found in deep-sea rocks at Mistaken Point, Newfoundland.

Photo by Nick Eyles



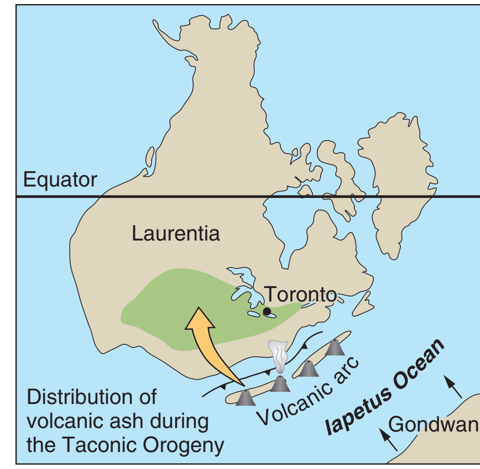


FIGURE 20.11

The Taconic Orogeny. Destruction of the Iapetus Ocean and its floor resulted in crustal thickening along the edge of eastern North America. Associated downwarping at the edge of the shield created shallow seas in which fossiliferous sedimentary strata such as shales, sandstones, and limestones were deposited.

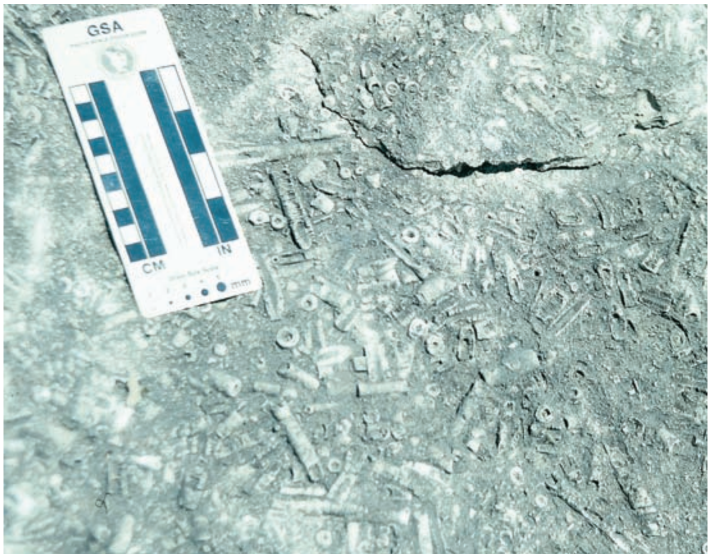
Enormous deltas, such as the Queenston Delta, drained the north slopes of the Taconic Mountains and spread fossiliferous sediment inland, across the outer margins of the North American craton (figure 20.12). At times when little sediment was being transported to the basins, extensive tropical reefs hosting a great wealth of marine organisms flourished in the warm, clear, shallow waters (figure 20.13). Thick limestone deposits are the remains of these reefs and now cover much of Southern Ontario, outcropping spectacularly along the Niagara Escarpment (figure 20.3*C*). The reefs were episodically killed off by influxes of muddy and sandy sediment that deposited shales and sandstones. Canada's first oil strike in 1858 was at Petrolia in southwestern Ontario, where oil is found at shallow depths. It is derived from the breakdown of organic matter in early Paleozoic shales of Devonian age and migrated upward to the ground surface as oil seeps. The commercial pumping of oil at Petrolia heralded the start of the world's oil and gas industry and predated the major discovery at Titusville, Pennsylvania in 1859.

In eastern Canada, the closure of the Iapetus Ocean (figure 20.8*C*,*D*) resulted in portions of the entire ocean floor, including parts of spreading centres and their gabbroic and basaltic rocks, being thrust up as *ophiolites* (see chapter 2). These ophiolites are now preserved high and dry in southern Quebec and along the western coast of Newfoundland (figure 20.14). Geologists can walk over these areas and see first-hand the structure and composition of mid-ocean spreading centres and determine how oceanic crust is produced. Study of these ancient rocks provided important ground truth in support of the emerging plate tectonics ideas of the 1970s. By studying the ancient record much has been learned of the operation of modern processes.

FIGURE 20.12

Brightly coloured, thinly bedded shales and sandstones of the deltaic Queenston Shale, Bronte Creek, Ontario.

Photo by Nick Eyles



A

B

C

FIGURE 20.13

Fossiliferous Paleozoic limestones. (*A*) Broken stems of sea lilies (crinoids). (*B*) Cephalapod fossil. (*C*) Burrows preserved in limestones.

Photos by Nick Eyles

FIGURE 20.14

Pillow lavas, Betts Cove, Newfoundland. Section is approximately 10 metres high. These result from the rapid cooling of basaltic lava erupted on the ancient floor of the Iapetus Ocean. They form part of a larger slab of oceanic crust and sediment (called an ophiolite) that was shoved onto the North American continent when the Iapetus Ocean closed (figure 20.16).

HOW WERE THE ATLANTIC PROVINCES ADDED TO CANADA?

The Taconic Orogeny marks the beginning of the construction of another supercontinent, called *Pangea*. Pangea was completed in the late Carboniferous when Laurasia docked with Gondwana, which consisted of most of the so-called "southern" continents of Australia, South America, India, and Antarctica. This docking event occurred in several stages and involved an initial Devonian-age collision known as the *Acadian Orogeny* and a later Carboniferous collision called the *Alleghenian Orogeny*, which were responsible for the buckling and thrusting of previously deposited sediments. The present-day *Appalachian Mountains* (figure 20.15) are the eroded remnants of these orogenic events. Huge folds and thrust sheets in the Appalachians were created in much the same way as the Canadian Rockies were to be developed much later (see below).

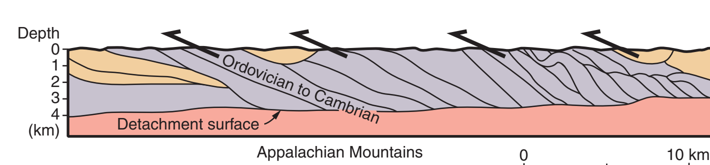


FIGURE 20.15

Geologic cross-section through the modern-day Appalachian Mountains of eastern North America showing folds and thrusts produced during the Acadian and Alleghanian Orogeny, which marked the formation of the supercontinent Pangea.

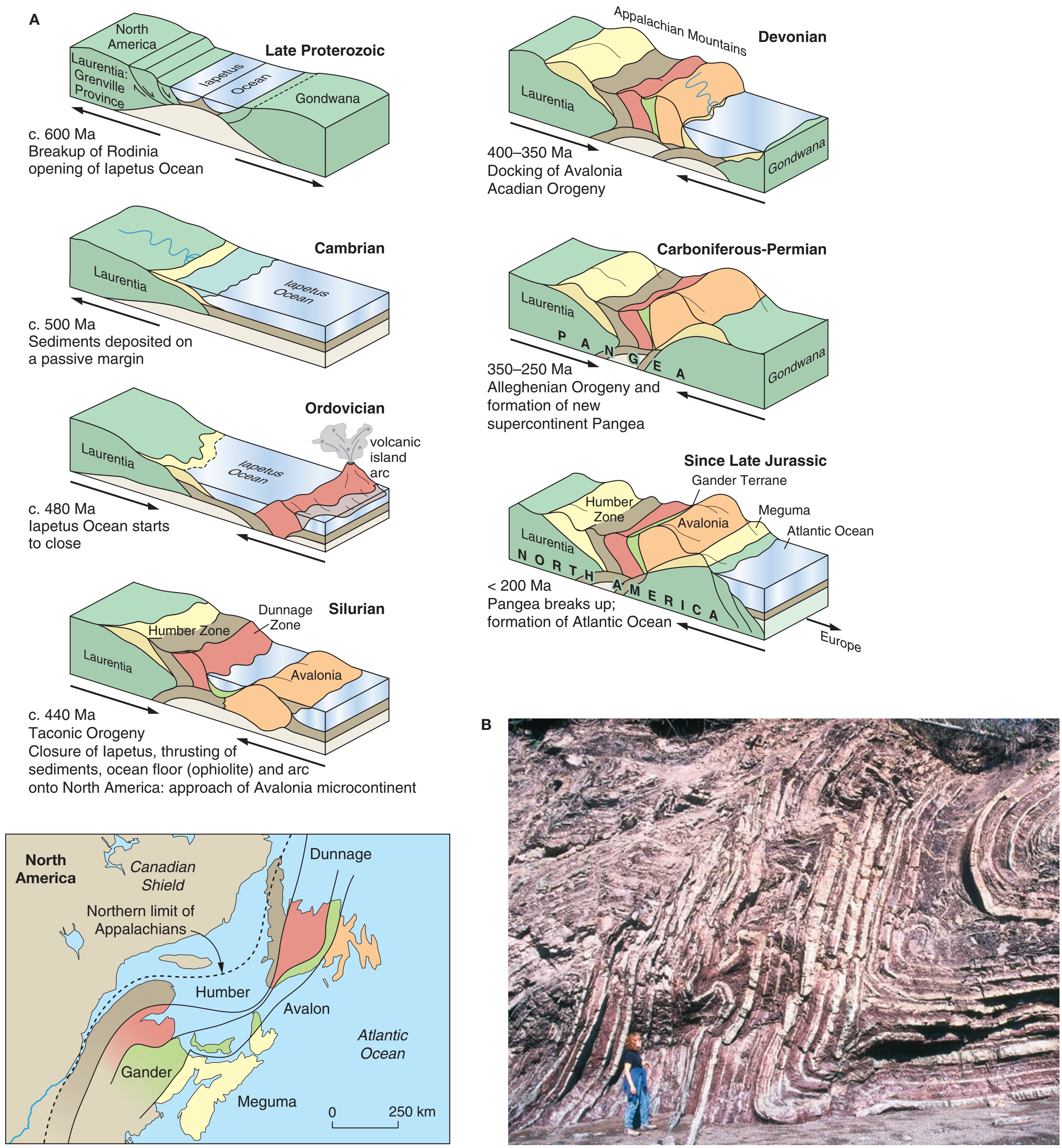


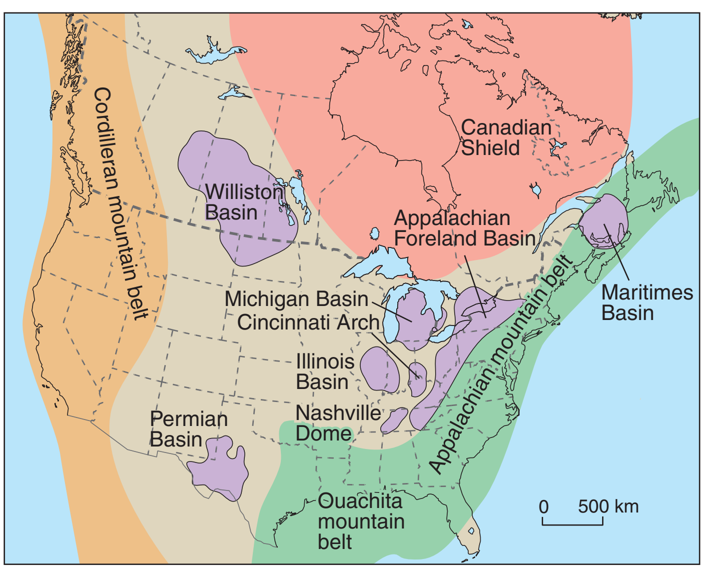
FIGURE 20.16

Formation of Maritime Canada. (*A*) Opening and subsequent closure of the Iapetus Ocean and formation of the Atlantic provinces in the Paleozoic. The sequence of ocean closure, subduction, and accretion of terranes also occurred in western Canada during the Mesozoic (see figure 20.20). Ocean opening and closing is referred to as a Wilson Cycle. The Grenville province records ocean closure during the Proterozoic between 1,300 and 1,000 million years ago. In eastern Canada, the opening of the Iapetus Ocean around 600 million years ago began a new cycle, and the opening of the Atlantic Ocean 200 million years ago marks the beginning of another cycle. (*B*) Folded green and red marine shales at Black Point, west coast of Newfoundland, record closure of the Iapetus Ocean about 400 million years ago.

Photo B by Nick Eyles

In eastern Canada, several large geological blocks (terranes) were added to early North America as micro-continents were thrust and accreted onto the continent during the Taconic and Acadian/Alleghanian Orogenies (figure 20.16). This is how much of what are now the modern-day Atlantic provinces came into being. The most famous of these accreted terranes are the Miramichi-Bras d'Or, Meguma, and Avalon terranes that now make up much of New Brunswick, Cape Breton Island, Nova Scotia, and Newfoundland (figure 20.8*D*). These originated on the far side of the Iapetus Ocean during the Cambrian (figure 20.8*B*,*C*) and now form broad west–east trending geologic belts that lie parallel to the modern Atlantic coastline.

During the late Carboniferous, the Alleghanian Orogeny also produced the extensive **Maritimes Basin** in eastern Canada. This basin was composed of many smaller interconnected basins separated by active faults and lay within the highlands of the Appalachian mountain belt (figure 20.17). The Maritimes Basin extends from central Nova Scotia and southern New Brunswick east into Newfoundland. Huge alluvial fans fed sediment from volcanoes into deep lakes in which microscopic algae thrived. Fine-grained, organic-rich sediments accumulating in these basins would eventually produce oil shales, such as those of southern New Brunswick.



A

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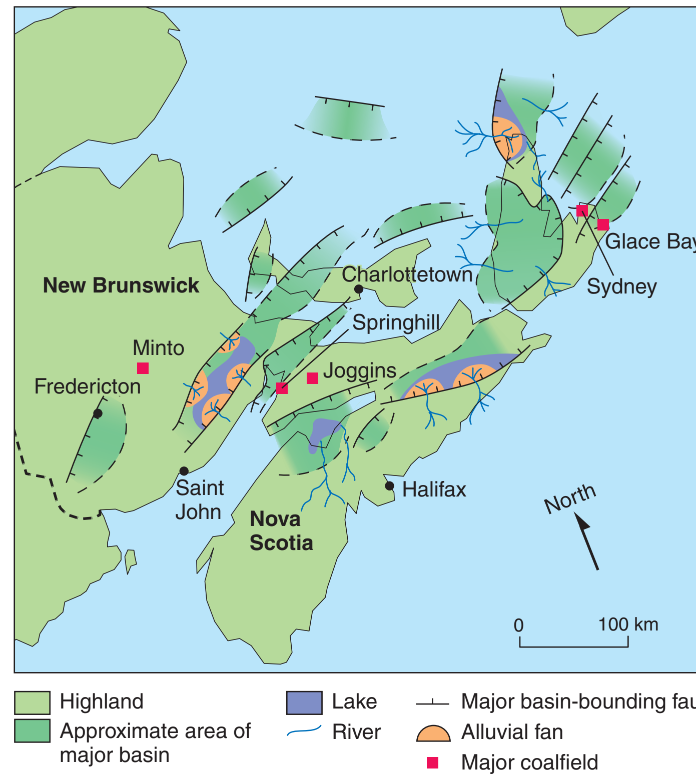


C

D

FIGURE 20.17

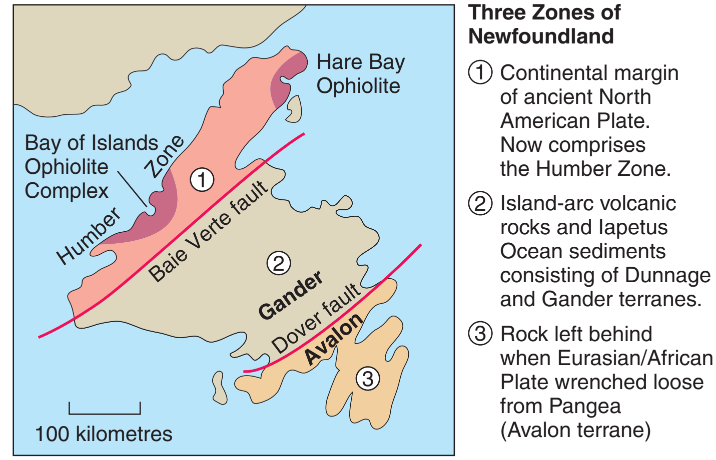
(*A*) Paleozoic orogenies along the eastern margin of North America created several large sedimentary basins separated by basement highs (arches) (e.g., Cincinnati Arch) in the underlying craton. (*B*) Goderich Salt Mine, Ontario. Salt deposits are a prominent component of the Michigan Basin reflecting strong evaporation when mid-continent North America lay across the equator 400 million years ago. (*C*) Maritimes Basin of eastern Canada and major coalfields. (*D*) Famous fossil cliffs at Joggins, Nova Scotia. Lithified tree trunks preserved within these coal-bearing deposits provided the first clues about the origin of coal in the mid-nineteenth century.

C after Atlantic Geoscience Society; Photos B and D by Nick Eyles

By the late Carboniferous (around 325 million years ago), extensive swamps formed in the Maritime provinces, which at that time straddled the equator. Thick peats accumulated in these swamps and eventually compressed and hardened to form coal. The coals are associated with fluvial and shallow marine deposits that record the repeated rise and fall of sea level as large ice sheets grew and waned over the south polar regions of Gondwana. Repeated cycles of coal, fluvial, and marine deposits are called *cyclothems*. The rich coalfields of Nova Scotia, such as those at Sydney, Joggins, and Minto (figure 20.17*C, D*), formed at this time.

The clearest evidence for plate collisions during the closure of the Iapetus Ocean and for the later breakup of Pangea occurs in Newfoundland. The island is made up of three distinct geological zones (figure 20.18*A*). The western part of Newfoundland, including the Great Northern Peninsula, formed the eastern edge of Laurentia at the time of the Iapetus Ocean. In this zone, the Bay of Islands Ophiolite Complex consists of oceanic crust and underlying mantle rocks thrust up and over the margin of North America as the Iapetus Ocean closed (figure 20.16*A*). The contact between the crust and the mantle is known as the Mohorovicic discontinuity (or Moho for short), and an ancient Moho is well exposed on the slopes of Table Mountain in western Newfoundland (figure 20.18*B*).

The central portion of Newfoundland is composed of rocks that made up the floor of the Iapetus Ocean. These rocks were crumpled against North America when the ocean was destroyed during the formation of Pangea as Eurasia and Africa collided with Laurentia (figure 20.16). Much later, as explained below, the Atlantic Ocean opened and a fragment of Eurasia and Africa was left attached to North America to form the eastern third of the island. These rocks can now be found on the Avalon Peninsula (figure 20.18*A*). Matching these rocks with their counterparts on the other side of the Atlantic Ocean provided key evidence to indicate that the modern Atlantic Ocean is a relatively young geological feature resulting from the breakup of Pangea.



A

B

FIGURE 20.18

(*A*) Geology of Newfoundland as established in the 1970s. Areas in black consist of sedimentary, volcanic, and ophiolitic rock and record thrusting of portions of the Iapetus Ocean floor over the ancient margin of North America as the ocean closed during the Taconic Orogeny. Tracing this structure westward into the Atlantic Provinces showed that eastern Canada is made up of accreted terranes (figure 20.16*A*). (*B*) Table Mountain, western Newfoundland; the contact between crust and mantle rocks in the Bay of Islands Ophiolite Complex is shown (dashed line).

Photo B by Nick Eyles

WHERE DID BRITISH COLUMBIA COME FROM?

Stage 5—Canada in the Mesozoic: Pangea Breaks Apart and British Columbia Is Swept Up

Some 200 million years ago, Pangea was beginning to break up, just as Rodinia had done 500 million years earlier. By the middle part of the Jurassic, around 165 million years ago, the northern part of Pangea (Laurasia; see figure 20.19) was beginning to detach from its southern part (Gondwana), forming the narrow equatorial *Tethys Ocean*.

Slowly North America began to move away from Africa, and in the late Jurassic the present-day Atlantic Ocean was born (figure 20.19). This process involved the formation of aulacogens, such as the Ottawa–Bonnechere Graben and the St. Lawrence Rift (see box 2.4). Eastern Canada eventually became a passive continental margin as North America began to track westward. In turn, the former passive margin of western Canada became an active margin characterized by subduction processes. At this time, the area now called British Columbia is thought to have existed as chains of volcanic islands, hot spots, ocean-floor rocks, and microcontinents far offshore in the ancestral Pacific Ocean. These land masses were eventually swept up and accreted onto western North America as the continent drifted westward to form the mountain belts of British Columbia, Alberta, the Yukon, and the Northwest Territories (collectively referred to as the **Canadian Cordillera**). The migration of the land masses that now make up the Cordillera is recorded by

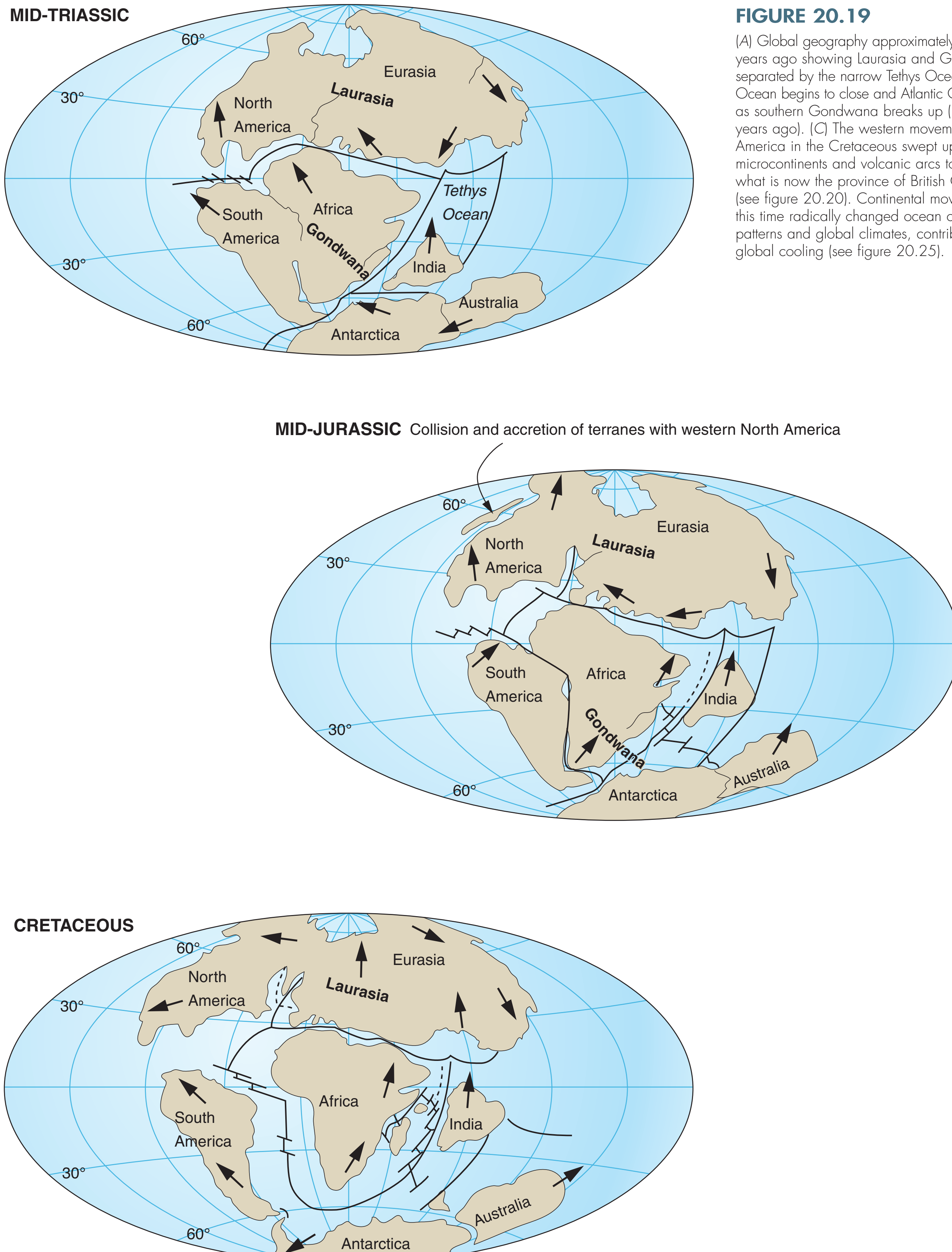
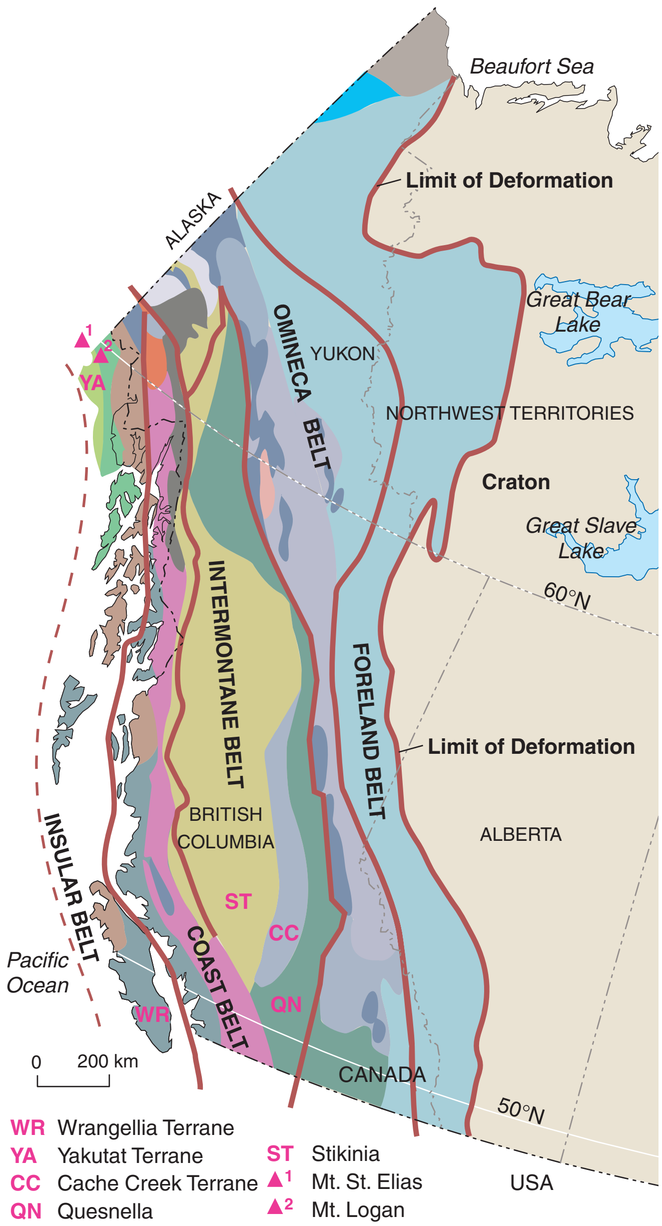


FIGURE 20.19

(*A*) Global geography approximately 220 million years ago showing Laurasia and Gondwana separated by the narrow Tethys Ocean. (*B*) Tethys Ocean begins to close and Atlantic Ocean opens as southern Gondwana breaks up (150 million years ago). (*C*) The western movement of North America in the Cretaceous swept up several microcontinents and volcanic arcs to form what is now the province of British Columbia (see figure 20.20). Continental movements at this time radically changed ocean circulation patterns and global climates, contributing to global cooling (see figure 20.25).



A

B

FIGURE 20.20

(*A*) Major geological belts and terranes of western Canada (in different colours: selected terranes are identified on figure). (*B*) Highly deformed rocks exposed near Cache Creek, southern B.C., contain Permian-age fossils common in Asia. Discovered in 1971, they provided the first clues that much of British Columbia originated elsewhere and was added to western North America as far-travelled blocks of crust called terranes.

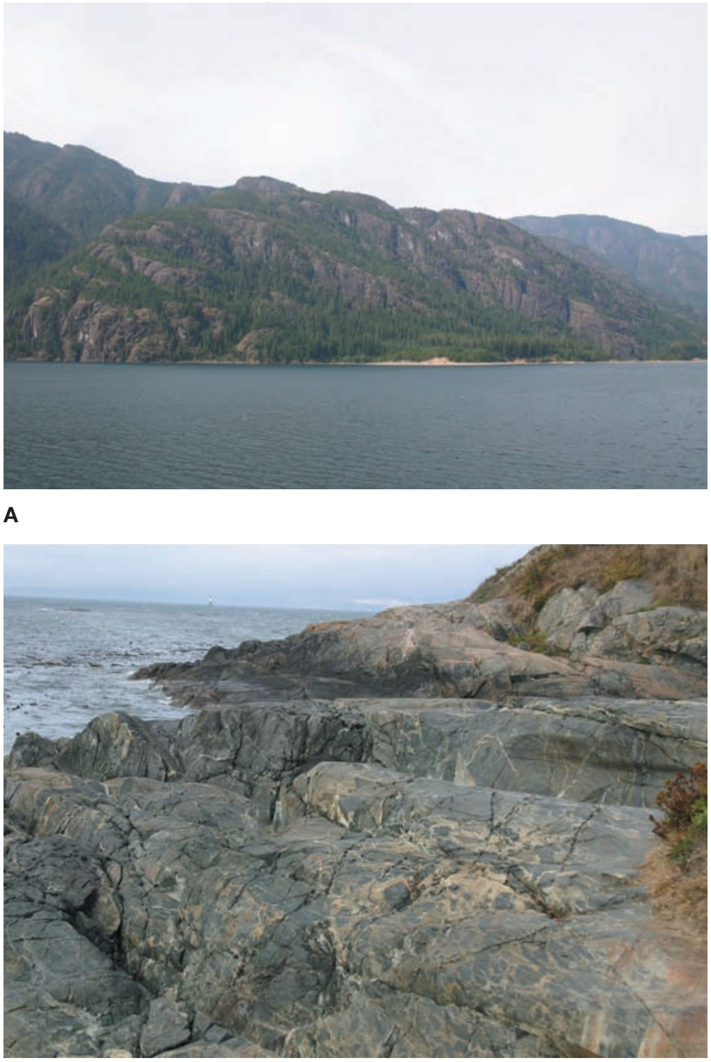
Figure A from www.uni-mainz.de/~mezger/Text/Cordilleran-Belts.jpg; Photo B by Nick Eyles

fossils in sedimentary strata and paleomagnetic data stored in igneous rocks that allow the former source of the land masses to be determined.

The Canadian Cordillera is subdivided into five main geological belts (figure 20.20*A*). The belts result from accretion of far-travelled terranes, which has occurred almost continuously since the mid-Jurassic. The oldest collisional event has historically been referred to as the *Columbian Orogeny*, but this term is slowly disappearing from usage. During this early event the so-called *Intermontane Belt* (consisting of Stikinia, Cache Creek terrane, and part of Quesnellia) docked with western North America, around 185 million years ago. Far to the east, this first phase of thrusting affected rocks of the Foreland Belt (figure 20.20). The Omineca belt marks the boundary or *suture* between the Intermontane and Foreland belts and is a zone of intensely metamorphosed rocks intruded by plutons.

A second major orogenic event, poorly dated, occurred between 150 and 100 million years ago. This event has been called the *Laramide Orogeny*, but geologists now think the orogeny was not a single event and the term is almost abandoned. This time period saw the accretion of the *Insular Belt* consisting of Wrangellia and the Alexander terranes that underlie modern-day Vancouver Island. This collision triggered further eastward thrusting of the rocks that now make up the Rocky Mountains, when resistant Cambrian limestones were thrust over soft Mesozoic shales to form the magnificent panorama of the Front Ranges around Banff. The timing of this second phase cannot be pinned exactly, as the suture between the Insular and Intermontane belts is obscured by the *Coast Plutonic Complex* where the rocks range in age from about 150 to 50 million years.

The many different geologic terranes that now comprise the Canadian Cordillera (figure 20.20) are the squeezed and highly deformed remnants of the accreted land masses. Each terrane has undergone a similar history of being pushed onto North America and then being smeared northward along major intracontinental strike-slip faults. The presence of these faults greatly complicates unravelling the geologic history of British Columbia as terranes have been moved relative to each other over big distances since docking. The large Wrangellia terrane (WR) was broken during faulting and is now found in several different areas of western North America (figure 20.21). Vancouver Island is a large block of Wrangellia that was added to western North America after 200 million years ago. Much of Wrangellia is composed of old oceanic crust, including pillow lavas and



A

B

FIGURE 20.21

(*A*) The Karmutsen Volcanics, west of Campbell River, Vancouver Island, form part of the Wrangellia terrane. (*B*) Highly deformed gneiss exposed on the foreshore below Mile 0 of the Trans-Canada Highway in Victoria, B.C.

Photos by Nick Eyles

FIGURE 20.22

Mount St. Elias (5,540 metres above sea level), on the border between the Yukon and Alaska, is one of several large mountains raised by collision of the Yakutat terrane and the North American continent. Folded strata recordintense compression associated with collision.

Photo by Nick Eyles

FIGURE 20.23

Glaciated mountains of the Coast Belt of British Columbia consist predominantly of eroded granite plutons.

Photo by Nick Eyles

associated volcanic rocks such as those forming the Karmutsen Volcanics west of Campbell River (figure 20.21*A*). Highly deformed metamorphic rocks that represent lower crustal rocks formed at the base of the Wrangellia Terrane are also exposed near Victoria on Vancouver Island (figure 20.21*B*).

Today, the Yakutat Terrane (YA) is in the process of docking against Alaska with its easternmost margin defined by a major strike-slip fault and high mountains. Intense compressive forces between the terrane and North America uplifted the mountain massifs of Mount St. Elias (figure 20.22; 5,540 metres above sea level) and Mount Logan (5,060 metres above sea level), both of which lie on the border between the Yukon and Alaska. Much of the Coast Belt of British Columbia, which lies inboard of the Wrangellia Terrane (figure 20.20*A*) is composed of granite plutons intruded between 170 and 45 million years ago as Wrangellia collided with western North America (figure 20.23). The rounded, dome-like form of the plutons is reflected in the subdued shape of mountains within the Coastal Plutonic Complex of British Columbia, which contrasts with the more sharply etched mountains of the Rockies (refer to figure 20.26 later in this chapter).

The accretionary growth of the Cordillera of western North America in the Mesozoic is very similar in style to the way in which Atlantic Canada was added to North America in the Paleozoic (figure 20.16). Both record the growth of continental crust by collisions of smaller land masses against the North American craton.

During the collisional events that formed the Cordillera, thick successions of strata that had earlier accumulated along the western passive margin of Rodinia were pushed eastward and compressed to form mountains in the interior of British Columbia. Sediment from the eroding mountains was shed eastward into the **Western Interior Sedimentary Basin**. A classic example of a foreland basin (figure 20.24), it extended from modern-day Mexico in the south to the Arctic in the north. Foreland basins develop in response to the weight of thickened thrust belts (on the margins of mountain belts) depressing the surrounding crust (see the examples of the Taconic and Appalachian foreland basins in eastern Canada; figure 20.11).

The Western Interior Sedimentary Basin experienced many changes in water depths allowing alternations of shallow marine sandstones and deeper-water shales. The organic-rich shales, now deeply buried, have acted as source rocks for oil and gas that migrated and collected in porous, shallow-water sandstones, to form large oil and gas reservoirs (see chapter 12). Complex thrust structures created in what is now western Alberta by Cordilleran tectonics far to the west helped to form *hydrocarbon traps*, where oil and gas that would otherwise escape to the Earth's surface became trapped. Western Canada's first major oil discovery took place in 1913 at Turner Valley, south of Calgary. Coal deposits within the Mesozoic strata were discovered near Banff during construction of the Canadian Pacific railway in the 1880s.

In Saskatchewan, rich potash deposits formed as evaporites in the Western Interior Sedimentary Basin. Potassium chloride (the mineral sylvite) is an essential nutrient for plant growth and is a major component of modern fertilizers. Saskatchewan is the world's largest producer of potash.

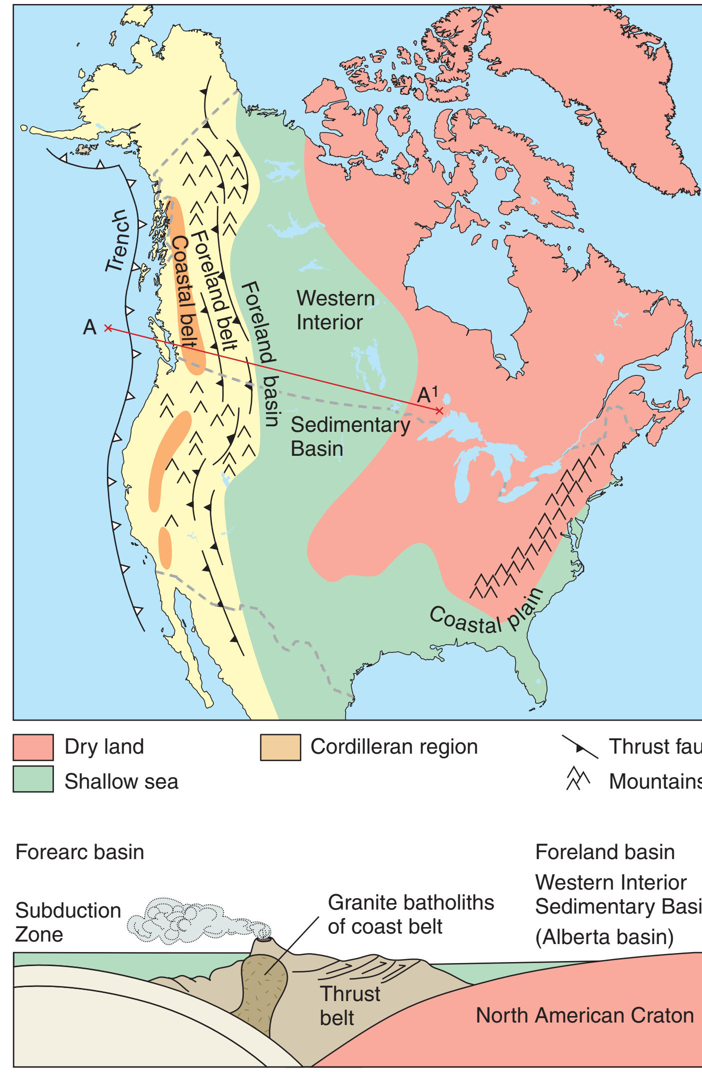


FIGURE 20.24

Paleogeography of western North America during the Late Cretaceous, and schematic cross-section across the thrust belt and Western Interior Sedimentary Basin.

WHERE CAN WE FIND DINOSAURS IN CANADA?

The Western Interior Sedimentary Basin is famous not only for oil and gas but also for its rich fossil remains, principally those of dinosaurs. Dinosaurs roamed subtropical swamps along the shores of the Late Cretaceous seaways. Rapid deposition of sediment in these environments allowed preservation of fossil material, and rich finds of dinosaur fossils are now made in rocks exposed in the many deeply cut valleys of the badlands area of Alberta. More than 150 dinosaur species have been identified in Dinosaur Provincial Park, and the Royal Tyrrell Museum of Paleontology at Drumheller houses many of the major dinosaur discoveries found in the area (figure 20.25). The museum is named after the geologist J.B. Tyrrell, who found the first fossil remains in Alberta in 1884. Important collections of Canadian dinosaurs are also kept at the Canadian Museum of Nature in Ottawa and the Royal Ontario Museum in Toronto (go to http://images.rom.on.ca/public for photos of many specimens).

Dinosaur finds are not restricted to western Canada, and important dinosaur fossils have been found in Nova Scotia. Canada's oldest dinosaur fossils (Triassic age) were found at Burntcoat Head, Nova Scotia, and dinosaur bones and footprints—some made by *Coelophysis*, a small, bipedal dinosaur—were found near Rossway, Nova Scotia. Early Jurassic rocks exposed in the cliffs at Wasson Bluff are particularly rich in dinosaur fossils, including the remains of prosauropods (animals "before the lizard feet") and some of the more agile carnivorous dinosaurs.

FIGURE 20.25

Albertosaurus, one of the large carnivorous dinosaurs found in Dinosaur Provincial Park, Alberta. Late Cretaceous fluvial, deltaic, and shallow marine sediments are widely exposed in the badlands of Alberta and are host to many dinosaur fossils.

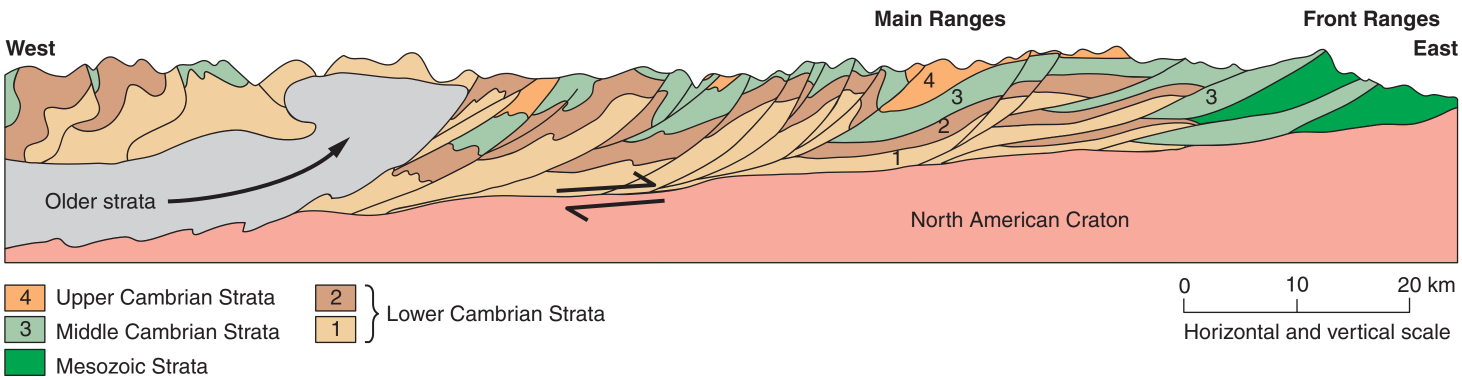
Photo by Nick Eyles

Why Did the Dinosaurs Disappear So Suddenly?

The very youngest Late Cretaceous rocks of Alberta also contain the record of a massive meteorite impact that hit the Yucatan Peninsula about 65 million years ago. The impact is marked in Mexico by the 100-km-wide Chicxulub crater, and at the Cretaceous-Tertiary boundary (K-T boundary) by abrupt global changes in fossil types. This meteorite impact event is thought to have contributed to the demise of the dinosaurs as well as 75 percent of all plant species and 90 percent of the plankton species in the oceans.

HOW DID THE CANADIAN ROCKIES FORM?

In addition to adding what is now British Columbia to North America, the Mesozoic and Cenozoic Orogenies of western North America helped create one of Canada's most spectacular landscapes, the Canadian Rocky Mountains. The Canadian Rockies are formed of layered sedimentary rocks that were displaced eastward by about 150 kilometres as a result of compression caused by collisional events along the western margin of North America. The layered sedimentary rocks detached from underlying granites of the craton and were folded and thrust over one another (figure 20.26). Hard sedimentary rocks, such as limestones that had formed on the margins of Rodinia, were moved as intact slabs over much younger and softer Mesozoic rocks along major thrust faults such as the Rundle and McConnell thrusts. The thrusting process was lubricated by water-rich shale within the Mesozoic rocks. Harder limestones form slab-sided mountains in the Front and Main ranges of the Rockies, such as Mount Rundle near Banff (figure 20.26*B*,*C*). Farther east, in the Foothills, thrusts are composed entirely of the softer and more easily eroded Mesozoic rocks. It is important to bear in mind, however, that the spectacular mountain landscapes we now see in the Canadian Rockies, where deep wide valleys are juxtaposed with steep-sided peaks, developed in only the recent geologic past. The mountains of the Canadian Rockies were formed as a result of deep glacial erosion and mass wasting during the glaciations of the past 2.5 million years. By cutting deep valleys, glaciers can create even bigger mountains. The load on the underlying mantle is reduced, promoting additional uplift of mountains. The Rockies contain old rocks, but they are relatively young mountains.



A

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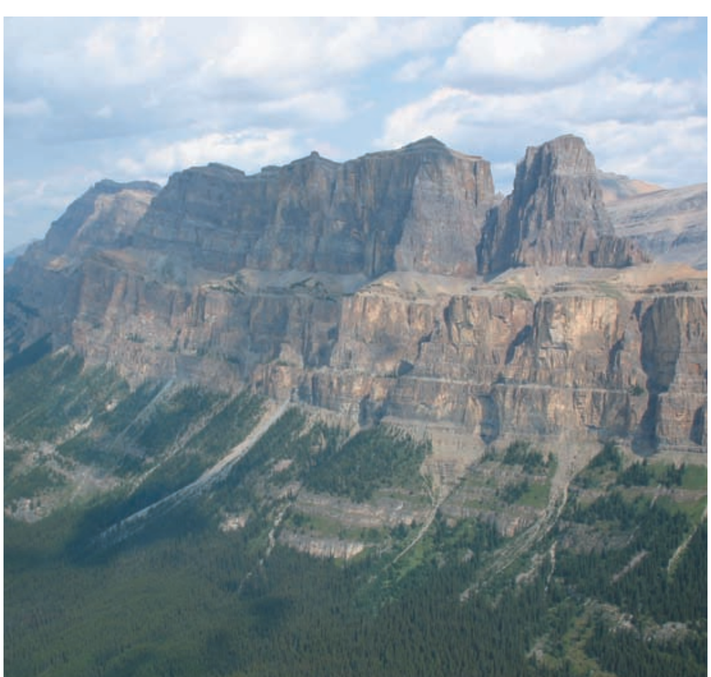


C

FIGURE 20.26

(*A*) Geologic structure of the Canadian Rocky Mountains. These structures were formed as a result of eastward thrusting during the Mesozoic Orogeny. (*B*) Mountain landforms of the Rockies such as these around Banff are relatively young and formed as a result of deep glacial erosion in the last 2.5 million years. Note the steeply dipping rock strata in Mount Rundle (left of centre). The strata were deformed by large thrusts during the Laramide Orogeny (150–100 million years ago), when much of British Columbia was added to western North America. Resistant limestones form the mountains, whereas the valleys have been eroded into softer shales. (*C*) Castle Mountain in the Main Ranges of the Rocky Mountains consists of Cambrian limestones that were thrust eastward as large flat slabs and were gently warped into broad synclines. Glacial erosion has produced a different mountain form to that seen in the Front Ranges.

Photos by Nick Eyles

WHEN DID THE ICE SHEETS DEVELOP?

Canada in the Cenozoic: The Arctic Cools Down

The latest (and unfinished) stage in Canada's ongoing geological evolution did not involve major tectonic events but climate. Climate changes have alternated from full glacial conditions when ice sheets covered most of Canada to interglacial conditions such as the present day. Under interglacial conditions, limited ice masses survive only in the Canadian Arctic, for example on Baffin Island (figure 20.27) or at high elevations in the Rockies. Erosion by ice flowing from the centre of ice sheets to their outer margins profoundly altered Canada's landscapes (see chapter 16).

Global climates during the Mesozoic are considered to have been relatively warm and equable. Paleoclimatic evidence obtained from the sediments that accumulate on the floors of oceans (and thus retain a near-continuous record of global temperatures) indicate that global climates began to cool down around 60 million years ago. As late as 45 million years ago, in the Eocene, warm-loving redwoods and broadleaved trees still flourished in the high Arctic of Canada. The Buchanan Lake Formation of Axel Heiberg Island (almost 80 degrees North latitude) contains 25 layers of mummified (not mineralized) tree stumps and logs and the remains of some of the animals that lived in the forest. Trees were well adapted to living three months in total darkness.

FIGURE 20.27

Buchan Gulf, Baffin Island, seen from Baffin Bay. Deep fjords have been eroded by glaciers draining Baffin Island ice caps.

Photo: GSC Photo 2002–239. Photo by Douglas Hodgson. Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2005 and Courtesy of Natural Resources Canada, Geological Survey of Canada.

Formation of the Antarctic Ice Sheet at about 40 million years ago marked the beginning of more pronounced global cooling (figure 20.28). This cooling phase was to eventually result in the formation of mountain glaciers at high elevations in the northern hemisphere at about 10 million years ago and full-fledged continental ice sheets in North America and Europe at about 2.5 million. Key contributors to this global climate change were radical changes in ocean and atmospheric circulation caused by the closure of the Tethys Ocean as India slammed into Asia (figure 20.19), and the uplift of the enormous Himalayan mountain system. At about 2.5 million years ago, the isthmus of Panama that joins North, Central, and South America formed as a volcanic arc by subduction. Prior to this event water (and heat) could be exchanged from one ocean to another, but development of the isthmus separated the Pacific from the Atlantic, and changed the configuration of ocean currents. Evidence suggests that the Arctic Ocean and Canada's northern coastline first began to freeze over at this time. Arctic Canada became a cold place characterized by widespread permafrost.

Canada in the Quaternary: Ice Sheets Come and Go

Over the past 2 million years or so, Canada has been repeatedly covered by enormous ice sheets. The Cordilleran Ice Sheet grew in western Canada and covered the Rockies and much of British Columbia. Only the highest mountain peaks protruded through the ice (as **nunataks**). Another, much larger ice sheet (the *Laurentide Ice Sheet*) extended from the Prairies through the High Arctic to Labrador and reached down into the United States (see figure 16.33). Newfoundland had its own ice cap, yet other areas—such as the Yukon—were severely cold and ice-free.

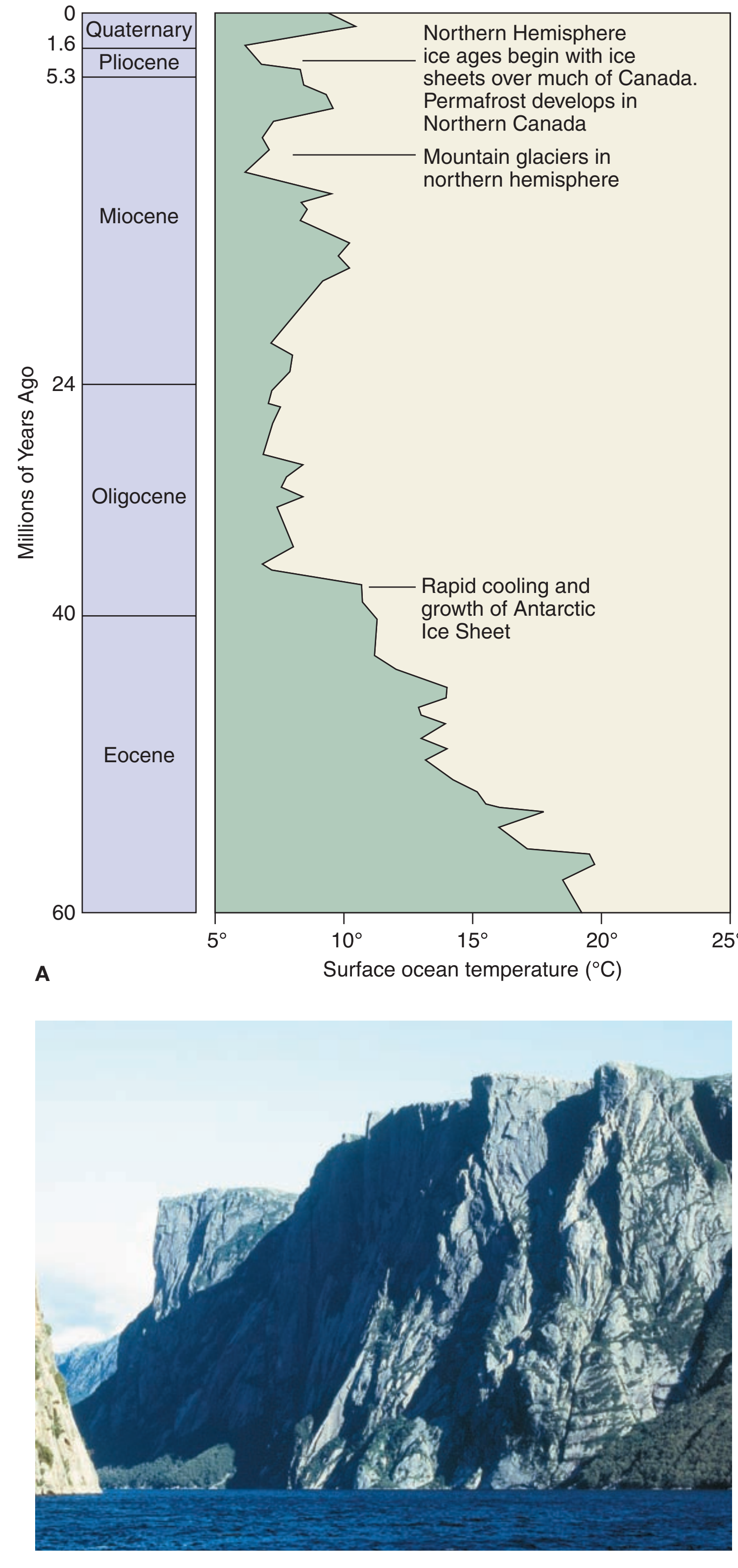


FIGURE 20.28

(*A*) Global climate changes over the past 60 million years. (*B*) Glacially eroded trough incised into high plateau, Gros Morne National Park, Newfoundland. Glacial erosion has unloaded the crust promoting uplift of the plateau, part of the Canadian Shield (figure 20.3).

Photo by Nick Eyles

The thickness of the Laurentide Ice Sheet has been inferred from the amount of depression experienced by the crust below its enormous weight; by reconstructions of its surface profile, or gradient; and by the amount of sea-level lowering created by its growth. At its maximum, the Laurentide Ice Sheet was as much as 3 kilometres thick and had a total volume of about $33 \times 10^6 km^3$. This volume is 50 percent greater than the present-day Antarctic Ice Sheet.

Canadian scientists have played a major role in mapping the former extent of the Laurentide Ice Sheet and reconstructing its history of growth and later retreat. The last major advance of the ice sheet began about 100,000 years ago, over northern Quebec and Labrador. The ice sheet oscillated in size until about 25,000 years ago, when it reached southern Quebec and parts of Ontario, and expanded to its maximum size around 18,000 years ago when its lobate, finger-like margin reached into the northern U.S. Thereafter, the ice sheet began to thin; its last remnants melted in northern Quebec as recently as 6,000 years ago.

Ice flows from central areas of an ice sheet (where it is thickest) to its margins at speeds of up to several hundred metres a year. Armed with rocky debris frozen into its base, or with debris moving as a deforming layer below its base, flowing ice is a very effective agent of erosion and deposition. By abrading underlying bedrock or sediment the ice creates an enormous volume of newly created sediment that is deposited either as a poorly sorted sediment called *till*, or that is transported under and beyond the ice sheet by meltwaters and eventually deposited in lakes or the ocean. Great thicknesses of glaciomarine sediments accumulate offshore from glaciated regions. The wide range of landforms left behind by glacial activity is reviewed in chapter 16 and is only briefly summarized here.

Canadian Landscapes Produced by Glacial Erosion

The most extensive landscape created by large-scale, areal erosion by glaciers and ice sheets is the Canadian Shield, comprising smoothed and eroded bedrock and numerous lakes. The high plateau of Labrador, Newfoundland, and Baffin Island, into which narrow, steep-sided troughs are cut (figure 20.28), forms a classic Canadian landscape. The plateau represents the uplifted margins of the Canadian Shield, which were raised when the Atlantic Ocean opened during the Mesozoic. Rifting allowed the broken edges of the Shield to gently rise in elevation (geologists call this **passive margin uplift**). Fjords are cut by fast-flowing streams of ice descending from the plateau, and their floors have been eroded many hundreds of metres below sea level. The rugged fjord-indented coastline of British Columbia is another example of a classic glaciated landscape.

In western Canada, glacial erosion created the final striking form of the Rocky Mountains, consisting of high angular mountain tops with frost-shattered summits and narrow, glacially excavated troughs (figure 20.26*B*). In many places, the slopes of glaciated valleys are so steep they are unstable and prone to large landslides. Landsliding is also common along the unstable banks of rivers that cross permafrozen ground in Canada's northern regions (figure 20.29).

Thousands of glacially eroded rock basins across Canada trap huge volumes of freshwater and form lakes, such as the Great Lakes (see box 20.5). These freshwater reservoirs, the largest in the world, are of international strategic importance given the growing demand for clean drinking water by expanding urban areas in Canada and the U.S.

FIGURE 20.29

Landslide on the banks of the Mackenzie River, Northwest Territories. Increased landsliding in the area is the result of recent climate change and the melt of deeply frozen ground (permafrost) allowing sediments to slide downslope.

Photo by Nick Eyles

IN GREATER DEPTH 20.3

Tors and Gold: Relics of Early Cenozoic Warmth?

There is some evidence to indicate that during the warmth of the early Cenozoic—around 40 million years ago—the Canadian Shield was exposed to deep chemical weathering that allowed the production of a thick clayey layer called *saprolite*. Saprolite is widespread in the modern tropics and sometimes reaches thicknesses of 500 metres. Unweathered portions of the parent rock survive as *core stones*. As the upper, near-surface parts of the saprolite are eroded with time, core stones are exposed on the surface as *tors*. It is thought by some that many of the rounded boulders of gneiss and granite that are now scattered throughout the tills of southern Canada started off as core stones on the deeply weathered portions of the Canadian Shield only to be moved south by Quaternary ice sheets. Some tors still survive in the Arctic in areas where ice was thin and cold, and glacial erosion was ineffective (box figure 1).

The famous alluvial gold deposits along the Fraser River and in the Cariboo district of British Columbia, and also at Dawson City in the Yukon (site of the famous 1898 Gold Rush), owe something to deep weathering during the early Cenozoic. Gold that was finely dispersed in bedrock was chemically concentrated during weathering leaving large nuggets at the base of the saprolite. When the climate cooled and weathered debris was reworked by rivers and glaciers, the heavy gold nuggets were concentrated in rich placer deposits (box figure 2).

BOX 20.3 ■ FIGURE 1

Marble tors several metres high formed by weathering on the Melville Peninsula, Nunavut.

GSC Photo 2002-480 by Lynda Dredge. Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2005 and Courtesy of Natural Resources Canada, Geological Survey of Canada.

BOX 20.3 ■ FIGURE 2

Placer gold panned from alluvial gold in the Cariboo district of B.C.

Photo by Nick Eyles

Canadian Landscape Features Produced by Glacial Deposition

The extensive deposits of glacial sediment left across northern North America allowed deep soils to develop in the last 10,000 years, creating productive agricultural land. Huge volumes of groundwater are also stored in thick glacial sediments that cover much of southern Canada, forming economically important *aquifers*.

A classic Canadian landscape created by glacial deposition is that of the *drumlin field*. Drumlin fields typically contain many hundreds of elongate hills, some of which are many tens of kilometres in length, up to 100 metres high, and 250 metres wide, while others are much narrower (the narrowest are called *flutes*). Famous drumlin fields in Canada occur in the Peterborough area of southern Ontario and around Yarmouth in Nova Scotia. The magnificent drumlins of the Livingstone Lake drumlin field in northern Alberta are illustrated in figure 20.30.

The well-ordered, streamlined form of drumlin fields contrasts with the haphazard look of glacial deposits forming hummocky moraine. This landscape type covers many thousands of square kilometres of the prairies of central and western Canada (figure 20.31). High-standing hummocks are randomly interspersed with hollows that are often filled with water. This landform may have originated as glacial sediment carried on the surface of stagnant ice (ice that is no longer moving), and was slowly deposited as underlying ice wasted away. Alternately, areas of hummocky moraine may have developed when stagnant ice pressed into soft till below, creating a dimpled surface.

In the mid nineteenth century, as Canadian geologists sought to test Louis Agassiz's newly introduced hypothesis of continental glaciation, many were struck by the presence of "findling boulders," also called **erratics.** These are boulders that have been transported long distances (sometimes almost half a continent) away from their source areas by glacial ice. Some of the best-known erratics include the Foothills Erratics Train of Alberta and the Bleasdell Boulder of southern Ontario (figure 20.32). The former records the collapse of a nunatak near present-day Jasper and the transport of landslide debris on the ice surface. The debris was left scattered out on the prairie as the ice thinned and retreated.

IN GREATER DEPTH 20.4

Cold Winds and Ancient Soils

While the rest of Canada lay under ice as much as 3 kilometres thick, parts of the Yukon Territory (and Alaska) were ice-free. It was simply too dry and cold for glacial ice to build up in these areas. Alaska and the Yukon experienced periglacial conditions (see chapter 16) and large parts of the landscape became buried under deposits of windblown silt and sand (called *loess*), which in places reach considerable thicknesses (box figure 1). During interglacial epsiodes, when the ice sheets largely disappeared from the rest of Canada, soils formed on the surface of these windblown deposits. The soils were subsequently buried when glaciation was renewed and are now preserved within the thick successions of loess. Ancient soils often contain abundant plant and animal fossils and preserve an excellent record of past climatic conditions.

BOX 20.4 ■ FIGURE 1

Thick deposits of windblown silt (loess) have been terraced in this road cut in Alaska.
Photo by Nick Eyles

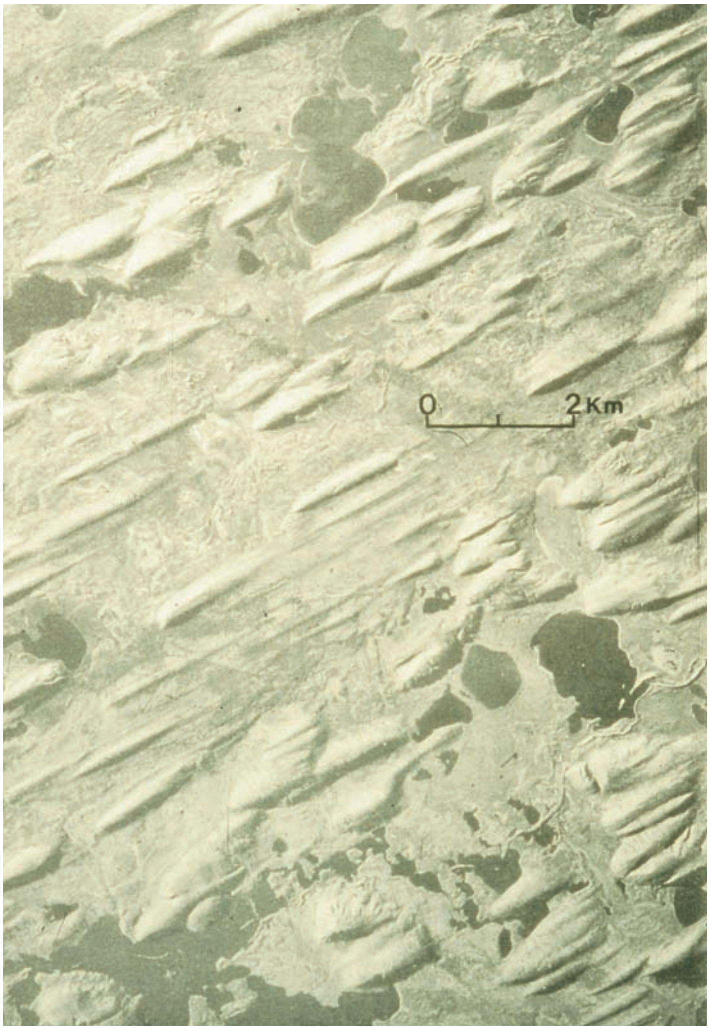


FIGURE 20.30

Drumlins in the Livingston Lake drumlin field in northern Alberta. Ice flows from lower left to upper right of photo. Note the rounded, upglacier ends of the drumlins.

FIGURE 20.31

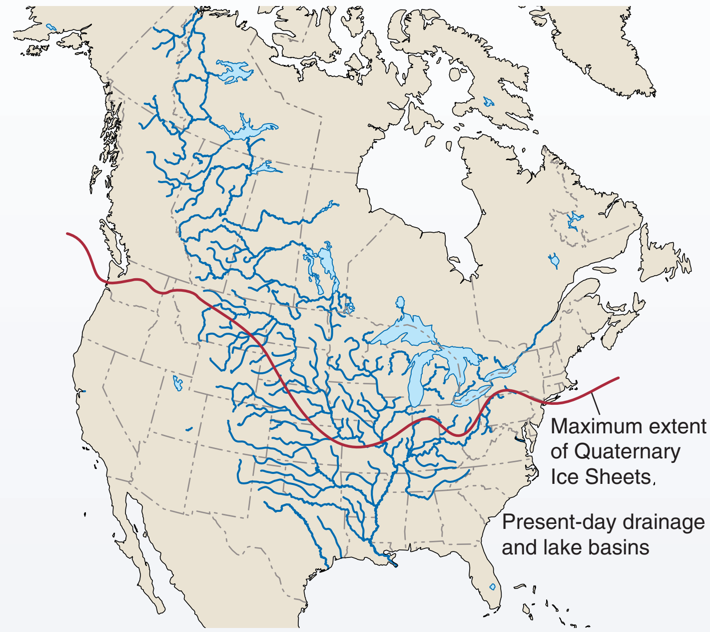
Glaciated landscape consisting of hummocky moraine, central Alberta.
Photo by Nick Eyles

As big as the Okotoks erratics are, they are dwarfed by the enormous slabs of rock (called **megablocks**) that were moved *under* the Laurentide Ice Sheet where it flowed over softer sedimentary rocks in Alberta and Saskatchewan. Some are 100 metres thick and extend over 1,000 square kilometres. They are composed of relatively soft shale, have no surface expression in the landscape, and were discovered only by drilling. Large ice-thrust ridges (figure 20.33) forming broad arcuate belts on the land surface are closely associated with hummocky moraine in central Alberta and Saskatchewan and have a similar origin. These features are examples of *glaciotectonic* deformations and illustrate the ability of ice sheets to quarry and deeply disturb the landscape over which they flow.

IN GREATER DEPTH 20.5

How Did the Great Lakes Form?

Another expression of deep glacial erosion is the Great Lakes of mid-continent North America. The modern lakes fill deep bedrock basins whose floors reach well below sea level. Evidence suggests that the lakes are the result of glacial erosion and overdeepening of a much older mid-continent river system (box figures 1 and 2). Portions of the old river valleys, now plugged and buried by glacial sediment, survive in places. As big as they are, the modern lakes are smaller remnants of much larger lakes that were dammed when the margin of the Laurentide Ice Sheet blocked lake outlets. The biggest of these lakes is called *Glacial Lake Agassiz* (after Louis Agassiz; see chapter 16). Silts and clays deposited in Glacial Lake Agassiz form a huge flat plain that extends over much of Saskatchewan, Manitoba, and Northern Ontario (see figure 16.34). Sediments deposited in much larger precursors of Lake Ontario are exposed in the 100-metre-high Scarborough Bluffs to the east of Toronto (box figure 3). The five Great Lakes (Erie, Huron, Michigan, Ontario, and Superior) form the largest body of freshwater in the world. Lake Superior is the largest of the Great Lakes (and is in fact the largest lake in the world) with a surface area of 82,000 km^2, of which about one-third is in Canada. The Great Lakes watershed covers 766,000 km^2 and is home to 25 percent of Canadians, 10 percent of Americans. The lakes extend 1,200 kilometres from west to east and are unique in that they are interconnected to form a continuous body of freshwater. The St. Lawrence Seaway–Great Lakes Waterway was completed in 1959 and is the world's longest inland waterway, stretching 3,790 kilometres from the mouth of the St. Lawrence River near the Atlantic Ocean to the head of Lake Superior.



BOX 20.5 ■ FIGURE 2

Deep rock basins that now form the Great Lakes were cut by ice sheets only 2.5 million years ago. Note very different drainage patterns in Canada after glaciation.

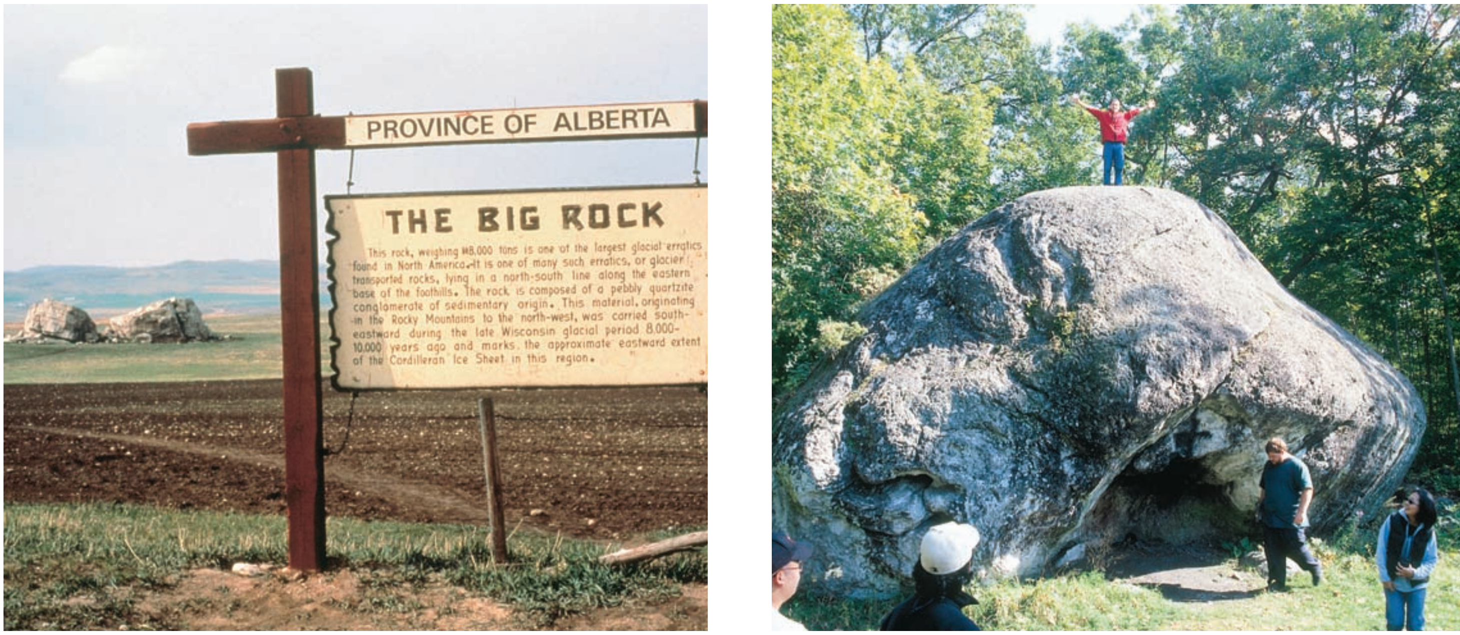
BOX 20.5 ■ FIGURE 3

The Scarborough Bluffs east of Toronto expose a world-famous succession of glacial lake sediments that contain a lengthy record of past lake-level and climate changes.

Photo by Nick Eyles

BOX 20.5 ■ FIGURE 1

Pre-glacial river system of mid-continent North America, around 5 million years ago.

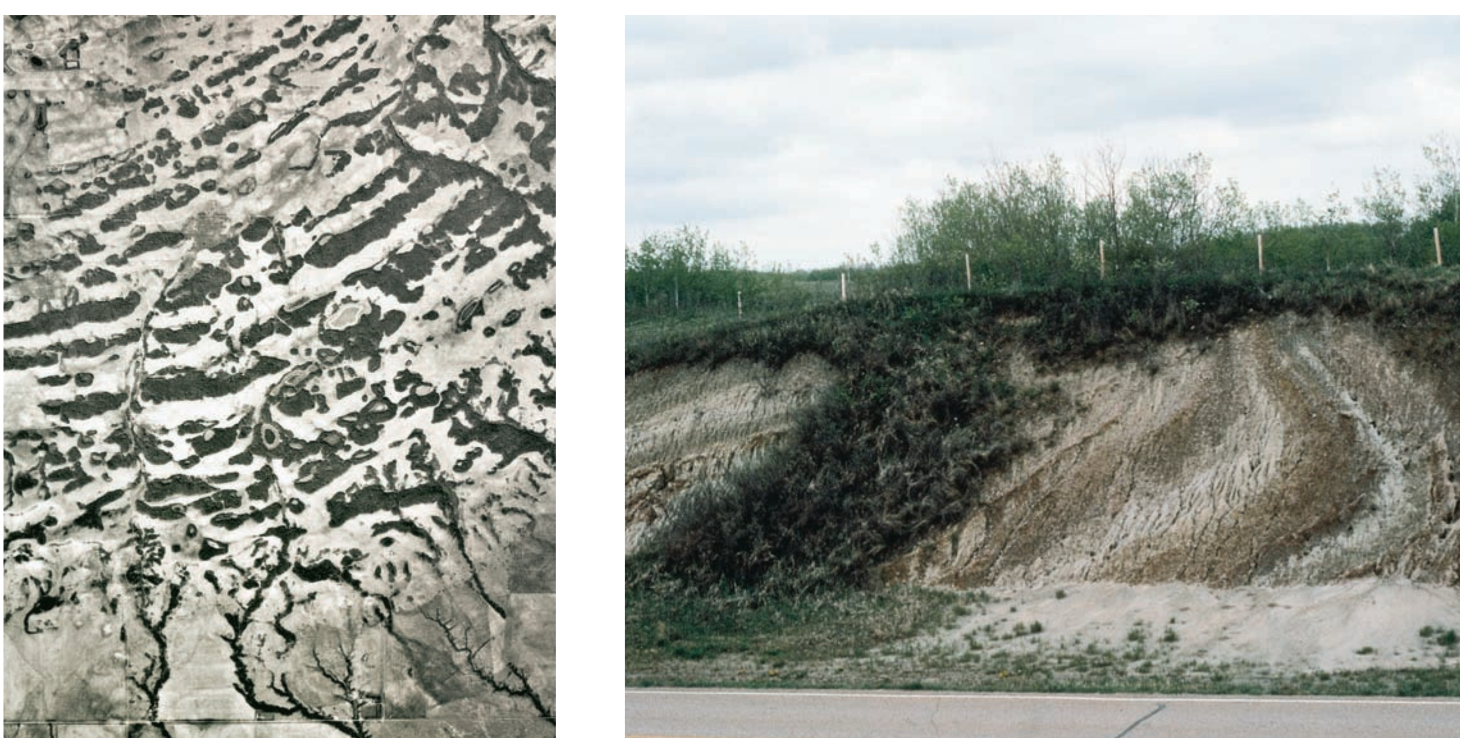


A **B**

FIGURE 20.32

Glacial erratics. (*A*) The Big Rock at Okotoks, Alberta forms part of the Foothills Erratic Train, a series of erratic sandstone blocks transported from their source area near Jasper. (*B*) The Bleasdell Boulder weighs more than 33,000 tonnes and is composed of metamorphosed sedimentary and volcanic rocks derived from the Canadian Shield; near Trenton, Ontario.

Photos by Nick Eyles



A **B**

FIGURE 20.33

Three-kilometre-wide belt of ice thrust ridges, Alberta. (*A*) Arcuate ice thrust ridges associated with hummocky moraine (upper left of photo). (*B*) Steeply dipping ice-thrust Cretaceous bedrock at Stettler, southern Alberta.

Photos by Nick Eyles

FIGURE 20.34

The Lemieux Landslide at South Nation River valley, Ontario. This was a retrogressive landslide that occurred on June 20, 1993.

Lemieux Landslide, Ont. June 1993. Photograph by Greg Brooks. Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2007 and Courtesy of Natural Resources Canada, Geological Survey of Canada.

The soft glaciomarine clays of eastern Canada underlie large areas of the St. Lawrence Valley and are prone to failure as quickclay slides (chapter 13). These clays were deposited on the floor of the Champlain Sea as the Laurentide Ice Sheet was retreating northward about 11,000 years ago (see figure 16.34). Glaciomarine clays are unstable because when deposited they contain salts in their structure derived from sea water. These salts are slowly leached out of the clays by percolating groundwater, weakening the clay structure and leaving them prone to failure if they are disturbed by earthquakes or construction activity. These quickclays give rise to spectacular landslides and mud flows (figure 20.34).

Canada's Geology: A Project in Progress?

Canada's geological evolution continues as the entire country moves westward at velocities of up to 6 centimetres a year (caused by the drift of the North American plate) and surface processes dissect and change its surface. Major earthquakes and intermittent volcanic activity along the west coast testify to ongoing subduction of the Juan de Fuca plate under North America. Other western earthquakes are the expression of continued displacement along the major strike-slip faults separating the various terranes of British Columbia (figure 20.20). The *intracratonic earthquakes* that occur in central and eastern Canada record displacement along buried aulacogens (e.g., the Ottawa-Bonnechere Graben, see box 2.4) and ancient terrane boundaries in the craton. These structures are said to be "reactivated" by within-plate stresses as North America slowly drifts westward.

In addition, although scarcely noticeable to people, large areas of the country continue to slowly rise in elevation recording unloading of the crust (*isostatic rebound*) following the retreat of the ice sheets. More obvious expressions of ongoing geological activity are landslides, rockfalls, and cliff retreat recording the continual processes of mass movement, erosion, and sediment transport.

The major Canadian rivers continue to shape the landscape, eroding gorges at Niagara and depositing vast amounts of sediment to form large deltas on which we depend for resources, agriculture, and urban land. The Fraser River delta in B.C. has grown more than 25 kilometres seaward in the past 10,000 years and now hosts large urban areas and industrial developments, as well as valuable agricultural land and salmon spawning grounds (figure 20.35). Future growth and stability of the delta is now in question as dredging of sand to maintain shipping channels limits sand deposition and parts of the delta front are slowly being eroded. Landslides have occurred on the submarine slope of the Fraser River delta in the past and any future failure could cause damage to the coal port, ferry terminal, or submarine electric cables.

Looking to the future, if climate change continues as it has in the past, Canada will cool down and the next Laurentide Ice Sheet will start to form over northern Quebec and Labrador in about 5,000 years. However, long before then, Canadians might be adapting to a much warmer, but possibly more variable, climate resulting from anthropogenic increases to greenhouse gas concentrations in the atmosphere. The possibility of this global warming raises many questions for Canadians, such as what the future of the Great Lakes and Arctic Ocean are in a warmer climate, and how we can safeguard coastal infrastructure and communities from erosion and flooding as sea level continues to rise.

IN GREATER DEPTH 20.6

4 Billion Years of Canadian Geology in Summary

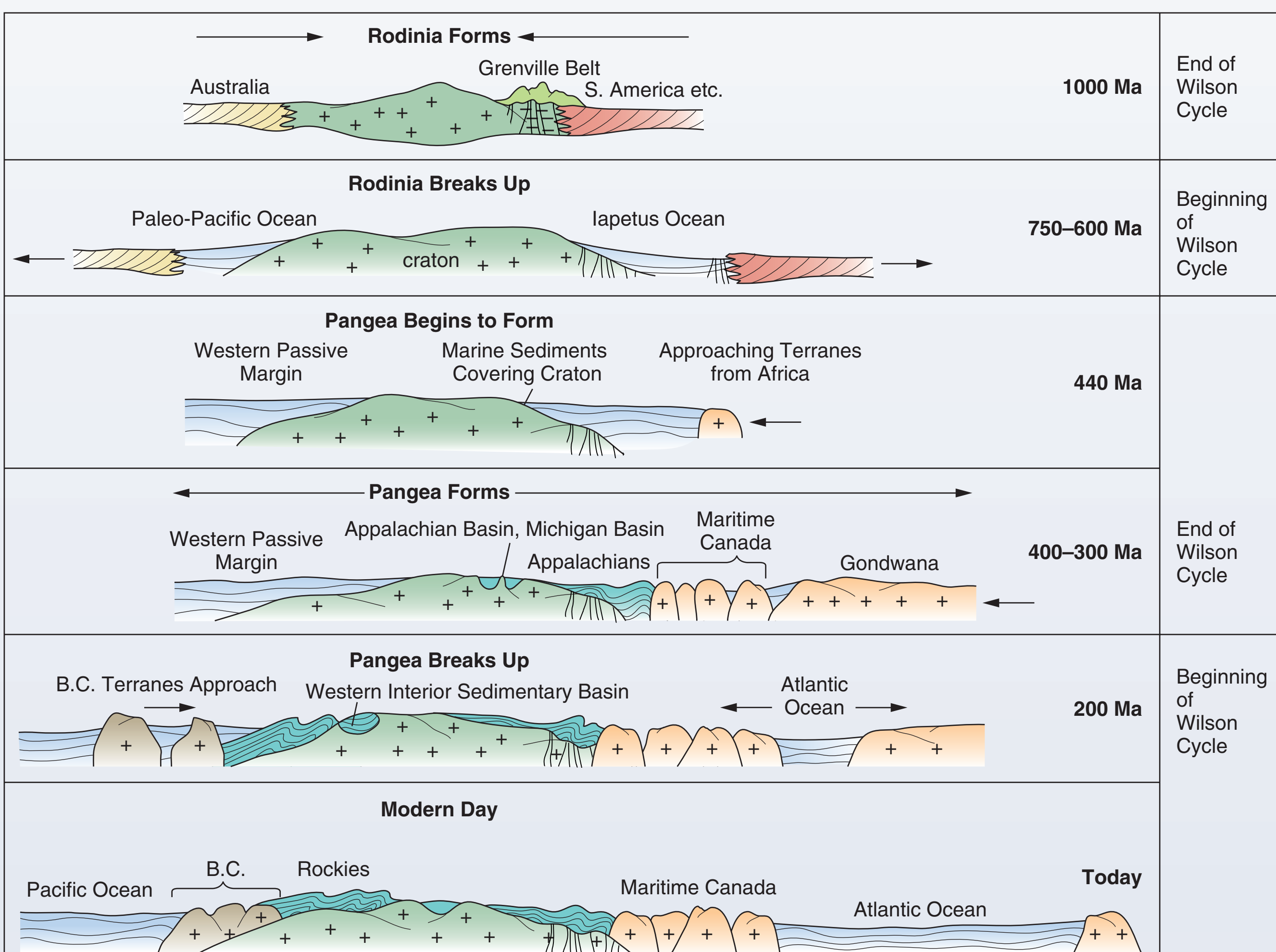
In chapter 2 we showed how the formation and breakup of supercontinents formed a natural repetitive cycle in Earth history; these cycles, repeated many times over the last 4 billion years, are called Wilson Cycles in honour of J. Tuzo Wilson. Canada's complex geology can be simplified using the concept of Wilson Cycles.

Canada's highly varied geology records at least two complete cycles in the last 1,000 million years (box figure 1). The first ended with the formation of *Rodinia* and the addition of the Grenville Belt to eastern North America. Much of present-day central and southern Ontario, Quebec, and Labrador were added at this time.

The breakup of Rodinia started in the west at 750 Ma and somewhat later in the east at about 600 Ma. North America was then surrounded by passive margins along the Paleo-Pacific and Iapetus Oceans. Marine waters and sediments flooded the low-relief interior (the craton), resulting in extensive deposits of richly fossiliferous limestone and shales. Those deposited about 540 to 500 million years ago record the earliest diversification of complex organisms (Burgess Shale etc.).

About 440 million years ago, small crustal blocks (terranes) began to loom into view along the east coast as the Iapetus Ocean began to close. These eventually collided with eastern North America in a series of orogenic events and form the basement of the present-day Maritime Provinces of eastern Canada. Many terranes had an African origin. During ocean closure, old Iapetus Ocean crust was shoved onto North America as an ophiolite complex. These events mark the beginning of the formation of *Pangea*, a second supercontinent. Large basins (e.g., Appalachian and Michigan basins) formed in the interior of the craton pushed down by crustal thickening along its eastern maritime rim. Great thicknesses of sedimentary rocks, including coal, accumulated in these basins derived from the erosion of the Appalachian Mountains and others formed by orogenic activity.

Inevitably, Pangea broke up, forming the early Atlantic Ocean about 200 million years ago. North America began to be pushed westward, colliding with small crustal blocks that were gathering in the Pacific Ocean. Their eventual collision added 500 km



BOX 20.6 ■ FIGURE 1

to North America, forming what is now British Columbia, the Yukon, and much of Alaska. Older marine rocks from the earlier passive margin were shoved eastward and when sculpted by glaciation in the last 2.5 million years produced the Rocky Mountains. The thickened crust produced the Western Interior Sedimentary Basin in what is now Alberta. Dinosaurs languished along its coast until extirpated 65 million years ago. Organic matter deposited and buried in the basin was slowly cooked into oil and gas.

Climate cooling of the last 2.5 million years shaped the landscape, cutting the Great Lakes (among many others), carving deep fiords along the coasts, and leaving thick sediments in which rich soils could develop.

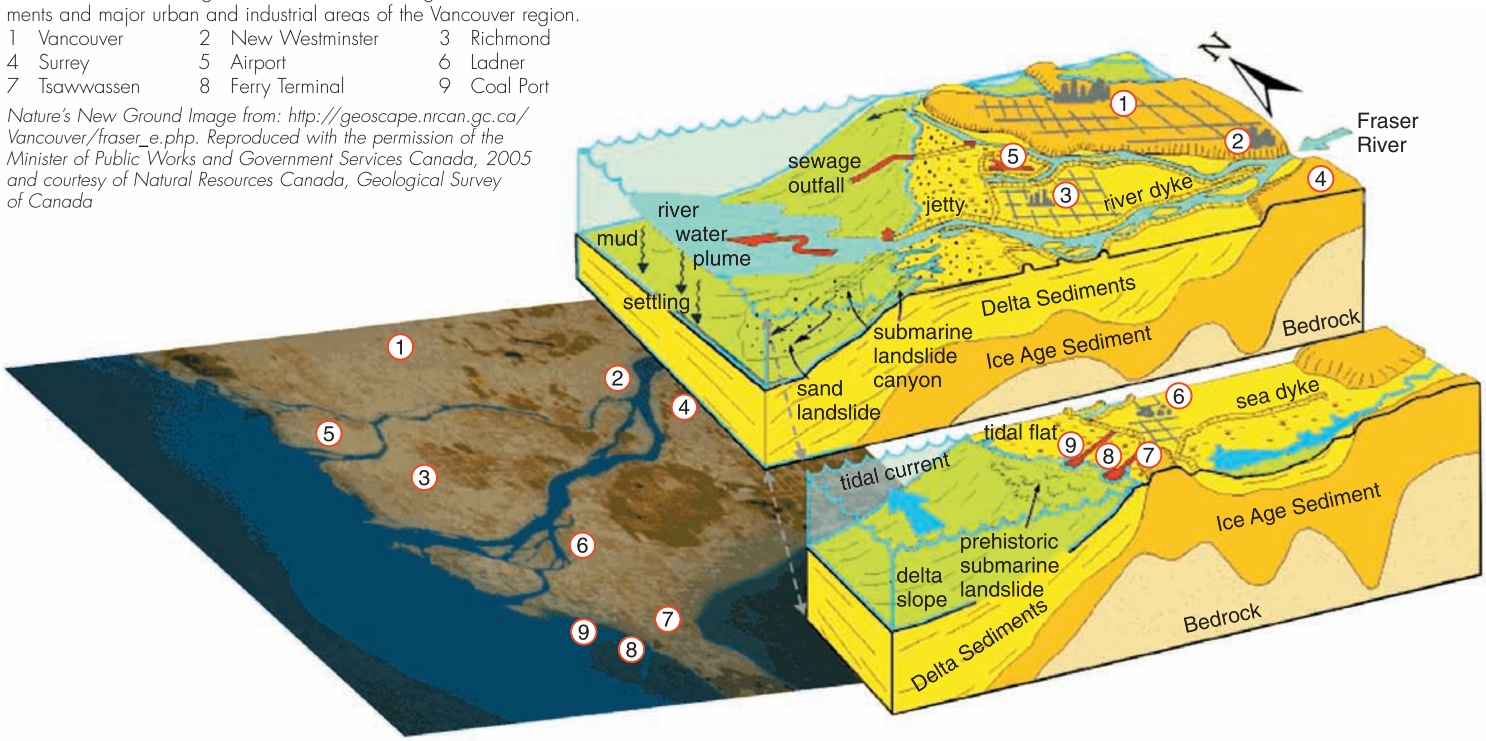
The craton of North America records a series of much older Wilson Cycle extending back to almost 4 billion years beginning with the Acasta Gneiss. The old oceanic crust and volcanic rocks trapped during many collisions of terranes as the craton slowly grew in size are rich in minerals.

FIGURE 20.35

Schematic section through the Fraser Delta showing subsurface sediments and major urban and industrial areas of the Vancouver region.

1 Vancouver	2 New Westminster	3 Richmond
4 Surrey	5 Airport	6 Ladner
7 Tsawwassen	8 Ferry Terminal	9 Coal Port

Nature's New Ground Image from: http://geoscape.nrcan.gc.ca/Vancouver/fraser_e.php. Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2005 and courtesy of Natural Resources Canada, Geological Survey of Canada



WHY IS IT IMPORTANT TO UNDERSTAND THE GEOLOGICAL HISTORY OF CANADA?

Geoscientists carry out a wide range of professional activities where a detailed understanding of Canada's geological history is a fundamental prerequisite. They increasingly work in consulting companies as part of interdisciplinary teams alongside engineers, biologists, and planners. A major part of their work is to conduct environmental assessments designed to minimize the impact of new development and associated land-use changes.

Canada has become one of the world's most urbanized countries, with 80 percent of its population living in urban areas. While this would suggest that we are no longer as reliant on our natural geological environment as we once were, the opposite is true as we try to build cities that are sustainable environmentally. As cities expand, the hazards posed by earthquakes, landslides, and floods increase as a result. Urban expansion and development commonly requires reuse of *brownfield sites* (sites previously used for commercial, industrial, or residential purposes) to spare precious agricultural land. This demands improved ways of mapping contaminants in the subsurface and removing them. The issue of drinking water is now firmly on the Canadian agenda, especially after the tragic events in Walkerton, Ontario in 2001 when drinking water tainted by animal waste killed seven people (see box 15.3). Protection of the quality and quantity of ground and surface waters for future uses, including possible export of Canada's water to the United States, requires detailed understanding of watersheds, their geology, and their functions. Water is the resource of the future, with impending shortages in the U.S. that will place pressure on Canada to export it. The western Prairie Provinces of Canada lie in the lee of the Rocky Mountains, and surface waters derive from snow and ice melt in the mountains (see box 16.1). This source is threatened by climate change. Groundwater is at risk from urbanization in central Canada and agriculture in the western provinces, and this creates a need for effective groundwater protection schemes in many areas (figure 20.36). No longer is groundwater "out of sight, out of mind."

Much new mineral wealth remains to be discovered on the Canadian Shield using new geological techniques and concepts. The recent development of the Canadian diamond mining industry is a classic example of new wealth created as a consequence of the work of geoscientists. Building on experience gained in the Atlantic provinces, renewed oil and gas exploration both in the Arctic frontier and along the British Columbia coast face physical challenges that can be met only with a proper understanding of geological and environmental conditions. The search for our own origins and the history of other organisms and past climates is also dependent on our ability to interpret the geologic record. All of these activities create a need for continuing research and investigation by new generations of geoscience students, armed with new questions and new techniques. What we learn in Canada can also be applied globally.

FIGURE 20.36

Road sign identifying groundwater protection zone.
Photo by Nick Eyles

SUMMARY

Canada's lengthy geologic history began more than 4 billion years ago, when the North American craton began to form. Many separate land masses were fused together by plate tectonics processes over several billion years to create a *craton* consisting of geologically distinct *provinces*. Deformed rocks of the craton identify areas where land masses were sutured together, and are termed *orogens*. These ancient rocks of North America record repeated episodes of supercontinent formation and breakup and are exposed on the *Canadian Shield*.

The outermost margins of the North American craton have been buried by younger *cover rocks*. These sedimentary rocks were deposited in extensive shallow seas (*intracratonic* and *foreland* basins) that covered parts of the craton when it was depressed by the weight of developing mountain ranges. Most of Atlantic Canada originated as parts of other continents that were accreted onto the eastern seaboard of North America through repeated opening and closing of ancestral forms of the Atlantic Ocean. Western Canada also formed by the accretion of many former land masses (*terranes*) onto North America as it slowly drifted westward after the opening of the modern Atlantic Ocean. The Canadian Rockies record compression caused by these collisional events on the western margin. Canadian sedimentary rocks contain a rich fossil record including some of the earliest animal fossils (*Ediacaran fauna*) and numerous species of dinosaur that roamed the swamps around inland seas.

The most recent events in Canada's geologic history involve climate changes that saw the gradual cooling of warm climates, and the repeated growth and decay of enormous ice sheets that covered almost all of Canada. Many of the landscapes most familiar to Canadians are the product of glacial processes active during the past 2 million years. *Glacial erosion* is responsible for the formation of steep-walled glacial troughs and fjords in mountainous areas, streamlined landforms of the Canadian Shield, and excavation of the Great Slave, Great Bear, and Great Lakes basins. *Glacial depositional features* include drumlin fields, hummocky moraine, and extensive plains underlain by till and outwash that host productive aquifers. Canada's geological history continues to evolve as landslides alter the form of mountains and valleys, quickclays fail, deltas develop, and coastal erosion continues.

Terms to Remember

Testing Your Knowledge

Use the questions below to prepare for exams based on this chapter.

1. How did construction of the Canadian Pacific Railroad aid in geologic exploration?
2. Where would you find the oldest rocks in Canada?
3. Why are parts of the North American craton buried by cover rocks?
4. Explain uniformitarianism. Do you think this working principle is always valid?
5. What are thought to be the five stages of evolution of the North American craton?
6. What are the three main types of subprovinces within the Superior Province?
7. What happened in the Grenville Orogeny?
8. Where in Canada would you find the oldest fossil animals?
9. How did the Appalachian Basin form? What kinds of sediment accumulated in the basin and what is the economic significance of these deposits?
10. What happened in eastern North America during the collision of Laurasia and Gondwana?
11. How did the major coal deposits in the Maritimes form? What are cyclothems?
12. Describe the three geological parts of Newfoundland. Why do rocks in Newfoundland provide clues as to the age of the Atlantic Ocean?
13. How does geology and rock type dictate the shape of mountains in western Canada?
14. Explain the formation of the Canadian Cordillera.
15. What is a foreland basin?
16. The Canadian Rockies are young landforms made of old rocks. Explain this statement.
17. Where in Canada would you find fossils indicating warm climatic conditions in the Tertiary?
18. Why are quickclays a problem in eastern Canada?
19. How did the Great Lakes form?
20. What is a Wilson Cycle? How many such cycles are recorded by Canada's geology?

Exploring Web Resources

gsc.nrcan.gc.ca
Geological Survey of Canada Website with links to other geological sites of interest.

http://geoscape.nrcan.gc.ca
Geoscape Canada: Geology and geoscience issues for Canadian cities, including Vancouver.

www.gov.ns.ca/natr/meb/field/start.htm
Virtual field trip of the landscapes of Nova Scotia.

www.tyrrellmuseum.com
Royal Tyrrell Museum, Drumheller Website. Virtual tour, information about local sites.