National Park Service
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Natural Resource Program Center

Acadia National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/232

THIS PAGE:
Visitors navigate along the beautiful Acadia coast. National Park Service photograph by Cynthia Ocel.

ON THE COVER:
Hiking to the tops of summits offers views of ocean and fall colors. Gorham Mtn Trail. National Park Service photograph by Ginny Reams.

Acadia National Park

Geologic Resources Inventory Report

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

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U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Ft. Collins, Colorado

The National Park Service, Natural Resource Program Center publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Contents

List of Figures

List of Tables

Executive Summary

This report accompanies the digital geologic map data for Acadia National Park in Maine, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Arguably one of the most geologically remarkable sites along the Atlantic Coast, Acadia National Park represents the only National Park along the eastern seaboard with a coastline carved by Pleistocene continental glaciers. The park's landscape captures the interplay between older episodes of tectonic deformation, Pleistocene glaciation, and more recent depositional and dynamic erosional processes of the ocean. The park's Mount Desert Island, the largest of many islands located along the coast of Maine, contains Cadillac Mountain, the highest point on the U.S. Atlantic coast.

The official park boundary includes parts of Mount Desert Island, Isle au Haut, and the southern tip of the Schoodic Peninsula about 8 km (5 mi) east of Mount Desert Island. Baker Island, Porcupine Islands, and a small parcel on Little Cranberry Island are federally administered. Other areas protected by conservation easements and managed by the park include all or parts of Swans Island, Ironbound Island, Jordan Island, and Long Island.

Geologic issues relevant to park management include:

- Mass wasting and slope failure
- Coastal erosion
- Sustainability of Sand Beach
- Seismic activity
- Sea level rise
- Visitor impact to natural resources

Rockfalls and slumping close roads and damage trails and campgrounds in Acadia National Park. Precipitation falls in each month in the park, and winter and early spring ice storms are common. The potential for mass wasting and slope failure increases with saturated soils, spring thawing, precipitation, and storm waves.

Storm surge and the relentless pounding of the surf erode coastlines and may damage nearby trails and infrastructure. When storm surge combines with high tides, beach erosion and coastal flooding may damage or destroy sea walls, boardwalks, bulkheads, and piers.

Erosion of a Pleistocene delta deposit may change the composition of Sand Beach. Sand Beach and a beach on Cranberry Island, which is not on park property, are the only two beaches north of Cape Hatteras that contain both dunes and a beach composed almost entirely of calcium carbonate shell fragments. Not only are beaches composed of sand-sized particles rare in Acadia National Park but also calcium carbonate beaches are rare in cold water climates. The delta deposit underlies the Sand Beach parking lot, and quartz and feldspar wash onto the beach. Because quartz and feldspar are naturally harder than calcium carbonate, the quartz and feldspar particles abrade and destroy the calcium carbonate fragments. The shell fragments that currently dominate the beach may diminish over time.

Earthquakes with epicenters close to the park have triggered landslides and damaged roads and trails. Earthquakes occur at a low but steady rate in Maine and generally have magnitudes less than 4.8 on the Richter scale. While smaller than west-coast earthquakes, they do increase the potential for rockfall and mass wasting.

Beach erosion will increase with continued sea level rise. Rising sea level may flood the picnic area on Thompson Island and inundate cobble beaches in the park. If the severity of storms increases, the potential for shoreline erosion and damage to park infrastructure may also increase. Groundwater levels will rise with sea level and may cause leach fields to flood and septic systems to fail. Rising sea level will also change the salinity in estuaries and coastal wetlands.

Acadia National Park is a popular park, and increased visitation has taken its toll on some of the park's natural resources. Trails that were once vegetated are now bare. Visitors illegally collect cobbles from beaches for souvenirs or for landscape decoration. Increased visitation may also be one reason for the decline in anemones in Anemone Cave.

Other potential geologic issues that may impact the park include the rupturing of natural gas pockets in Somes Sound and potential flooding if the glacial moraines that dam Jordan Pond and Long Pond were to fail. Activities external to the park boundaries may also raise management issues in the future. Some of these activities include aquaculture, offshore sand and gravel mining, and alternative ocean energy development.

Bedrock, glaciers, and the sea combined to shape the exceptional landscape of Acadia National Park. The bedrock includes metamorphic, igneous, and sedimentary rocks that record significant tectonic deformation, volcanic activity and the resulting sedimentary response. Acadia National Park offers an excellent outdoor laboratory in which to examine the timing and geologic processes recorded in the bedrock. Excellent examples include the emplacement of previously molten rocks as part of the Cadillac Mountain intrusive complex on Mount Desert Island, the granite on the Schoodic Peninsula, and the volcanic episodes recorded in the Cranberry Island Series. In addition to the pink granite that forms the core of Mount Desert Island, other spectacular features include the shatter zone that borders the Cadillac Mountain granite, diabase dikes that cut the granitic units, and joint sets that fractured the bedrock.

Massive continental glaciers that covered the highest peaks of Mount Desert Island and flowed into the Gulf of Maine created both depositional and erosional features of the landscape. Abrasion by debris in the glacial ice polished the bedrock and carved striations, grooves, and chatter marks in the granite. The grinding force of the glaciers sculpted bedrock knobs known as roches moutonnées and carved characteristic U-shaped valleys that extended to the sea. Meltwater channels within the glaciers transported sediment that was deposited at the glacial margin in fluvial outwash and delta deposits. Debris dumped at the front of melting glaciers became thick moraines of glacial till that dammed the U-shaped valleys. As the glaciers melted, boulders that had been transported far from their place of origin, known as glacial erratics, were left stranded on mountain sides.

The complex interaction between glaciation, crustal rebound, and fluctuations in sea level resulted in features representing both coastal emergence and submergence. As glaciers melted at the end of the Pleistocene, sea level rose rapidly, inundating valleys with sea level reaching approximately 70 m (230 ft) higher than it is today. Remnants of this ancient coastline include boulder beach deposits, sea caves, undercut cliffs, and wave-cut platforms. Exposures of marine clay appear incongruous in present-day terrestrial stream beds indicating an offshore marine depositional environment for those locations. However, sea level did not remain at this elevated level. Unburdened by the weight of the continental ice sheet, the crust rebounded, causing a retreat of sea level to a position approximately 55 m (180 ft) lower than its current position.

Today, the Atlantic surf relentlessly batters the Acadian shoreline. Wave action erodes less resistant rocks, forming such popular attractions as Thunder Hole. Constant hydraulic action modifies the sea cliffs, sea caves, wave-cut platforms, and other coastal features that enhance the grandeur of Acadia National Park.

The glossary contains explanations of many technical terms used in this report, including the Map Unit Properties Table. Figure 26 is a geologic time scale.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Program Center.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Acadia National Park.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Program Center, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory web site (http://www.nature.nps.gov/geology/inventory/).

Regional Information

Unique among all national parks along the Atlantic coast, Acadia National Park protects 64 km (40 mi) of rocky shoreline and contains 19,323 ha (47,748 ac) of rugged, primarily island topography carved and shaped by a succession of continental glaciers (figs. 1 and 2). With its bare, rounded mountain summits, verdant forests, sea cliffs, boulder beaches, deeply indented coastline, carriage trails, pristine ponds and lakes, headlands jutting into the sea, and remote islands, the park captures the extraordinary beauty and charm of the Maine coast.

The glacially-carved ridges and valleys of Mount Desert Island form the core of the park, which lies southeast of Bangor, Maine, and is approximately 113 km (70 mi) southwest of the U.S.–Canada border. The park also includes about half of Isle au Haut, the southern tip of the Schoodic Peninsula about 8 km (5 mi) east of Mount Desert Island, and Federally-owned (fee-owned) properties on nearby islands, including Baker Island, Bar and the Porcupine Islands, Western Ear Island, and Schoodic Island. Additionally, the park manages approximately 207 conservation easements on various islands between Penobscot Bay and the Washington/Hancock county line (fig. 3). Some of the larger islands with conservation easements include Ironbound Island and Jordan Island in Frenchman Bay and Long Island in Blue Hill Bay. For example, the conservation easement on Ironbound Island protects high granite cliffs, nesting eagles, and old growth pine.

Over twenty mountains in the park rise directly from the sea. At 466 m (1,530 ft), Cadillac Mountain, the centerpiece of Mount Desert Island, is the highest point along the Atlantic Seaboard from the international border with Canada to Rio de Janeiro in Brazil. At certain times of the year, sunrise touches the slopes of Cadillac Mountain in Acadia National Park before any other place in the United States. From the rounded, pink granite summit of Cadillac Mountain, a green tapestry of pine and spruce trees stretches to a coastline constantly battered by icy Atlantic waters.

Acadia's lakes and ponds add shimmering contrast to the park's forests and rocky landscape. Lakes and ponds cover about 1,052 ha (2,600 ac) of the park, or approximately 7.4% of its area. Of these, 14 are 'Great Ponds' (natural bodies of water greater than 4 ha [10 ac]). In addition, over 20% of Acadia National Park includes wetlands of all types (marine aquatic beds, intertidal shellfish flat, salt marshes, freshwater marshes, forested wetlands, and peatlands) (National Park Service 2009a).

The rocky shoreline wraps around the irregular border of Acadia National Park (figs. 2 and 4). Waves and currents continually modify the park's shoreline. The

3 to 4 m (10 to 12 ft) tidal range leaves behind tide pools inhabited by diverse and abundant sea life.

The bedrock, past glaciation, and sea combine to give Acadia National Park its exceptional character. The bedrock provided the foundation upon which the glaciers carved the landscape. Each headland, bay, and inlet reveals the magnificent interface between land and sea that allows Acadia National Park to sparkle like a multi-faceted gem.

Geologic Setting

Acadia National Park contains all three basic types of rocks: sedimentary, igneous, and metamorphic (fig. 5). Sedimentary rocks begin as sediments, like the sand on Sand Beach. With burial, sediments compact and squeeze together. In the process of lithification, increased pressure causes some minerals to dissolve and enrich the fluids that occupy spaces between the grains. New minerals precipitate out of the fluid and act as glue or cement to bind the sediments into sedimentary rock. Common cementing materials include quartz, iron oxides, carbonate minerals like calcite, and clay minerals.

The magma that solidifies to form igneous rocks may be produced in two ways. First, deeply buried rocks and sediments associated with ocean plate subduction heat up and release water, which rises and lowers the melting point of rocks in its path to produce magma. This process, for example, is occurring in the subduction zone along the western margin of Washington and Oregon where the oceanic plate is being subducted beneath the North American continent. Mount St. Helens provides proof that magma continues to be generated beneath the Cascade Mountains.

Secondly, magma may also be produced from hot rocks that are under extreme pressure in the mantle. Pressure is released at divergent plate boundaries (Mid Atlantic Ridge and Iceland) and at hot spots (Hawaiian Islands) in the mantle. The rocks melt due to the pressure drop in much the same way that liquid water flashes to steam when the lid of a pressure cooker is removed.

Once magma solidifies, the resulting igneous rocks are classified based on their mineral composition and whether they formed within the earth (intrusive) or solidified on the surface (extrusive). Extrusive igneous rocks cool very quickly and do not have the opportunity to form larger crystals. In general, they have an aphanitic texture (crystals too small to see with the unaided eye). Intrusive igneous rocks cool slowly into a phaneritic texture in which interlocking crystals are clearly visible. Magma may begin cooling slowly below the surface, allowing some larger crystals to form, and then erupt at the surface and cool rapidly, creating a rock with a bimodal texture of large crystals (called phenocrysts) embedded in a fine-grained groundmass. Such a bimodal igneous rock is call porphyritic. Once an igneous rock is identified as either extrusive or intrusive, the minerals are identified and the classification refined.

Granites, which are on one end of the intrusive igneous scale, are silica-rich and contain abundant aluminum, sodium, and potassium. Minerals formed from these elements tend to convey a pink, cream, or greenish-gray color to the granite in Acadia National Park. Granite contains the same minerals as its extrusive equivalent, rhyolite. On the other end of the scale, gabbros are dark colored intrusive igneous rocks with abundant iron, magnesium, and calcium and a lack of silica, aluminum, sodium, and potassium. Basalt is the extrusive equivalent of gabbro.

With increased temperature and pressure, all three types of rocks may undergo recrystallization of some or all of their minerals and metamorphose, without melting, into metamorphic rocks, such as phyllite, schist, and gneiss. Regional metamorphism occurs at great depth and over large areas where rocks encounter increased temperature and pressure. Contact metamorphism occurs near the surface when heat from rising magma bakes the adjacent bedrock (country rock). Limestone that doesn't contain much silt or clay metamorphoses to marble; relatively pure sandstone metamorphoses to quartzite; and siltstone and shale metamorphose to a rock called a hornfels.

In addition to bedrock, Acadia National Park contains glacial deposits and ancient and modern coastal and near-shore sediments. Pleistocene glaciers sculpted the modern landscape of Acadia National Park and the sea continues to modify the present coastline.

Bedrock Units

The 509 million year old Middle Cambrian Ellsworth Schist is the oldest rock exposed on Mount Desert Island (Gilman and Chapman 1988; Gilman et al. 1988; Schulz et al. 2008). The dark- green to gray Ellsworth Schist consists of volcanic sediments that were originally deposited in an extensional (pulling apart) oceanic-continental rift setting similar to today's Gulf of California–Salton Trough and Red Sea–Gulf of Aden rift systems (Schulz et al. 2003; Schulz et al. 2008). This rift setting bordered the coast of a micro-continent called Ganderia. At the time, much of the global landmass formed a larger paleocontinent known as Gondwana that was centered on the South Pole. Ganderia separated from Gondwana and was drifting north towards Laurentia (proto-North America).

During the Early Ordovician, a subduction zone developed along the Ganderia coast. Compression related to subduction coupled with regional metamorphism intensely deformed the volcanic sediments and transformed them into the chlorite-rich Ellsworth Schist (Reusch and Rust 2001; Reusch 2002). These schists contain abundant quartz, muscovite, and chlorite minerals.

Elsewhere in Maine, Late Cambrian rocks overlie the Ellsworth Schist, but these units are missing in Acadia National Park. In the park, the Ellsworth Schist is overlain by the Silurian Bar Harbor Formation, the second oldest rock in Acadia National Park (Wiebe et al.

1997b). The units are separated by an unconformity that represents a gap in time of over 65 million years.

The Bar Harbor Formation derives its name from the excellent exposures of brown to gray siltstones and sandstones along the shoreline at Bar Harbor, Maine. Because of these exposures, Bar Harbor became the type locality for the Bar Harbor Formation. A type locality is the geographic location where a geologic unit is formally defined and described.

Volcanic rocks that define the Cranberry Island series overlie the Bar Harbor Formation (Gilman et al. 1988). Named from exposures on Great Cranberry and Little Cranberry Islands, the Cranberry Island series was considered Silurian and Devonian until those dates were refined by radiometric dates corresponding to the Middle Silurian (approximately 424 million years ago). Field evidence suggests that their deposition is related to the Cadillac Mountain intrusive complex (Seaman et al. 1995; Seaman et al. 1999).

Felsic tuffs (formed from eruptions of volcanic ash) and felsic lava flows define the approximately 1.8 km (1.1 mi) thick lower unit of the Cranberry Island series (Seaman et al. 1999; Seaman 2000). Felsic rocks contain abundant light-colored minerals such as quartz, feldspar, and muscovite. The composition of these Cranberry Island felsic rocks is similar to the composition of the Southwest Harbor granite (Wiebe et al. 1997a). The upper unit, approximately 0.8 km (0.5 mi) thick, consists of mafic basaltic tuffs and basaltic lava flows (Seaman et al. 1999). The mafic rocks, which form the upper unit, are rich in dark-colored minerals containing magnesium and iron.

Since the Cranberry Island series overlies the Bar Harbor Formation, the Bar Harbor Formation must have been deposited before the Cranberry Island series. Previously interpreted to be partly Devonian, the Bar Harbor Formation, like the Cranberry Island series, appears to be restricted to the Silurian. Contrary to previous interpretations (Gilman et al. 1988), Devonian rocks may be absent in Acadia National Park (Berry 2007).

Remarkably, the Bar Harbor Formation and Cranberry Island series underwent little deformation compared to the Ellsworth Schist. Metamorphism resulted in some meta-sedimentary and meta-volcanic units, but these units were not strongly affected by the intense regional metamorphism and compression evident in the folded Ellsworth Schist. Geochemical evidence, the bimodal character of the volcanic rocks in the Cranberry Island series, and the lack of deformation suggest that these stratified deposits originated from tectonic extension rather than compression (Seaman et al. 1999).

Intrusive igneous rocks underlie most of the landscape of Mount Desert Island, the Schoodic Peninsula, and Isle au Haut (Gilman and Chapman 1988; Gilman et al. 1988). The intrusive units in Acadia National Park form the Cadillac Mountain intrusive complex, which, in turn, is part of the Coastal Maine Magmatic Province, a geologic province that consists of over 100 mafic and felsic plutons emplaced over a time span from the Late Silurian to the Mississippian (from approximately 420 million years ago to 360 million years ago) (Hogan and Sinha 1989; Wiebe et al. 1997b). The Cadillac Mountain intrusive complex includes three major units: the Cadillac Mountain granite, a gabbro-diorite unit, and the Somesville granite (Wiebe et al. 1997b). Two minor units include the sheet-like Southwest Harbor granite and irregular masses and dikes (tabular igneous intrusions that cut through older rock) of the Pretty Marsh granite that cut the gabbro-diorite unit.

The Cadillac Mountain intrusive complex was once thought to be emplaced during the Devonian, but recent radiometric data indicate an older, Silurian age for the intrusive complex (Wiebe et al. 1997a, 1997b). The gabbro-diorite unit is about 418 million years old, and the granites range between 424 and 419 million years old (Seaman et al. 1995; Wiebe et al. 1997b). Basaltic magma intruded before, during, and after these granites, and the gabbro-diorite unit was injected multiple times into the Cadillac Mountain magma chamber (Wiebe 1994; Wiebe et al. 1997b). The age and composition of the Cadillac Mountain intrusive complex suggests that the Cranberry Island series may have erupted from these magma bodies (Seaman et al. 1999).

Surficial Units

The surficial deposits in Acadia National Park record a remarkable interaction of glacial activity and sea level fluctuations. Glacial till was deposited directly by glaciers and consists of an unsorted collection of clay, silt, sand, pebbles, cobbles, and boulders. As the glaciers melted, ridges of mixed rock debris (ranging in size from clay to boulders) known as glacial moraines were left along the glaciers' margins. Meltwater streams flowing from melting glacial ice deposited sand and gravel in outwash deposits in front of the glacier or in deltas building along the coast (Lowell and Borns 1988).

About 21,000 years ago, the continental ice sheet reached its maximum extent. The ice sheet flowed across the Gulf of Maine and extended onto the continental shelf approximately 600 km (370 mi) from the present Maine coastline. Because so much water was trapped in the continental ice sheets, sea level fell about 100 m (330 ft) below its current level (Gilman et al. 1988; Kiver and Harris 1999).

In the Acadia region, ice may have been 1.6 km (1 mi) thick. Each acre of ice 1.6-km (1-mi) thick weighs approximately 7 million tons (Kiver and Harris 1999). Continental glaciation displaces the upper mantle so that the land surface subsides about 30 m (100 ft) for every 91 m (300 ft) of ice. During the last period of glacial activity, known as the Wisconsin glaciation, the mass of the ice depressed the coastline (isostatic depression) so that areas on Mount Desert Island that are now above sea level were submerged. At that time, the shoreline on Mount Desert Island lay just south of Jordan Pond, which was approximately 70 m (230 ft) higher than it is today (Gilman et al. 1988).

Glacial melting resulted in a complex interplay between crustal rebound and sea level change. Unburdened from the mass of ice, Maine's crust began to rise. With crustal rebound (isostatic uplift), relative sea level fell. Submerged sediments that had been deposited in marine environments became exposed on the slopes of Mount Desert Island (Lowell and Borns 1988). Sea level lowered to approximately 55 m (180 ft) below its present position, and streams cut valleys into previously submerged coastal areas and continental shelf deposits (Barnhardt et al. 1995).

As crustal rebound slowed, glaciers continued to melt and sea level rose to its present position. Rising sea level drowned the lower ends of valleys and produced the submerged or drowned shoreline typical of New England (fig. 2). With rising sea level, peaks have become islands, and once rocky ridges have been transformed into headlands and peninsulas. The famous offshore fishing ground of Georges Banks, exposed as islands during the height of glaciation, became submerged during this time.

Sea level continues to rise along the Atlantic Coast, and the Atlantic surf relentlessly pounds the Acadia shoreline. Periodically, waves generated by violent nor'easters unleash an enormous amount of energy against the parks' cliffs and headlands. The constant hydraulic action creates and modifies the sea cliffs, sea caves, wave-cut platforms, and other coastal features that enrich the splendor of Acadia National Park.

Cultural History

Native People

For the past 12,000 years, American Indians have inhabited the land now known as Maine, and American Indian encampments in Acadia National Park date back 6,000 years (National Park Service 2006a). Today, the Maliseet, Micmac, Passamaquoddy, and Penobscot (known collectively as the Wabanaki) still consider Mount Desert Island and the surrounding Gulf of Maine area as the center of their traditional homelands. To some of the Wabanaki, Mount Desert Island was known as "Pemetic," meaning "the range of mountains."

The Wabanaki Indians traveled in exquisite birch bark canoes, a craft that would prove indispensible to the French Voyageurs and fur trade in North America. They hunted seals, porpoises, deer, moose, beaver, and birds and fished for sculpin and flounder. They gathered sea urchins, clams, blue mussels and berries and traded with other Wabanaki. Using local resources, the Wabanaki fashioned harpoons, needles, awls, and fishing hooks from animal bone, and chipped arrowheads, knives, scrapers, and heavy wood working tools such as chisels and gouges from local stone. Clay mixed with crushed rock grit or shells was used to make pottery.

In the nineteenth century, Wabanaki people sold handmade ash and birch bark baskets to wealthy travelers, and in the summer, they performed elaborate dances at venues such as Acadia National Park's Sieur de Monts. Wabanaki guides took visitors on canoe trips around Frenchman Bay and the Cranberry Islands (National Park Service 2006a).

Today, each Wabanaki tribe maintains a reservation and has a tribal government headquarters within their territories. The Wabanaki continue their unique association with Mount Desert Island. The National Park Service recognizes the deep history and cultural continuity Wabanaki people have with the landscape and consult with the Tribal Historical Preservation Officers from the Passamquoddy and Penobscot Tribes (Rebecca Cole-Will, Cultural Resources Program Manager, Acadia National Park, written communication, April 23, 2010). The first-ever ethnographic study of the Wabanaki in the Mount Desert Island area was commissioned by Acadia National Park and completed in 2007. The report is now available at the Acadia National Park website (National Park Service 2009b).

European Explorations

In 1524, the Italian explorer, Verranzano, visited the Delaware, Maryland, and Virginia region and named the area "Arcadie" after a pastoral region in ancient Greece. As exploration continued to the north, mapmakers soon started labeling the Nova Scotia area as "L'Arcadie." In later maps, the "r" was dropped. By the 1700s, settlers in eastern Canada were known as Acadians (Hebert 2009).

In 1603, Henry IV, King of France, granted the French explorer, Pierre Dugua, Sieur de Monts, exclusive right to colonize lands in North America between 40° and 60° north latitude. While overseeing the construction of his ill-fated settlement on St. Croix Island, Dugua sent his navigator and cartographer, Samuel de Champlain, to explore the coast further south. Sailing past the bare, rocky summits of Mount Desert Island in 1604, Champlain named the island Isles des Monts Desert—"Isle of Bare Mountains."

Another French adventurer, Antoine Laumet, landed at Mount Desert in 1688. The French government granted Laumet, who called himself Sieur de la Mothe Cadillac, 40,500 ha (100,000 ac) of land along the Maine coast, including all of Mount Desert. Lord Cadillac, however, grew restless and moved inland to establish a settlement that would later be named Detroit.

Settlers, Early Tourism and the Beginning of the Park

Land speculators became interested in the Maine coast after the British defeated the French in 1759. Farming, logging, fishing, and shipbuilding industries blossomed. Paintings by prominent artists of the day attracted visitors to the region, and by 1860, tourism had become the major industry of the area.

In the late 1800s and early 1900s, extremely wealthy people discovered the region and subsequently protected much of the area from logging and unplanned development. Large estates served as summer retreats for such notable families as the Rockefellers, Morgans, Vanderbilts, Carnegies, Fords, Astors, and Kennedys.

Concern about overdevelopment in the Bar Harbor area and the invention of the gas-powered portable sawmill prompted one wealthy landowner, George B. Dorr, to establish a non-profit corporation in 1901 to preserve as much of the Mount Desert landscape as possible. For the next 43 years, Dorr's corporation received land donations and purchased points of interest such as Cadillac Mountain to preserve them for public use. By 1913, Dorr's corporation had acquired 2,400 ha (6,000 ac), and he offered the land to the federal government. In 1916, President Wilson created the Sieur de Monts National Monument.

Dorr continued to acquire property and to push for full national park status. John D. Rockefeller, Jr. donated over 4,000 ha (10,000 ac) and constructed 92 km (57 mi) of narrow carriage roads. Expert stone masons built 17 stone bridges along the carriage roads (fig. 6). In 1919, President Wilson signed the act establishing Lafayette National Park, the first national park east of the Mississippi, and Dorr, whose efforts have been described as "the greatest of one-man shows in the history of land conservation" (qtd. in Rothe 1995), became the first park superintendent (Kiver and Harris 1999; National Park Service 2006a).

In 1929, more area was added to the park and its name was changed to Acadia National Park. In 1986, Congress established a permanent fee boundary for Acadia National Park. At this time, between fee-owned land and conservation easements, Acadia National Park protects over 19,000 ha (47,000 ac). Additional historical information may be found at the Acadia National Park website (http://www.nps.gov/acad).

Figure 1. National Park Service location map for Acadia National Park, Maine. Refer to the detail maps of Mount Desert Island, Isle au Haut and Schoodic Peninsula for more information (fig. 2). National Park Service graphic.

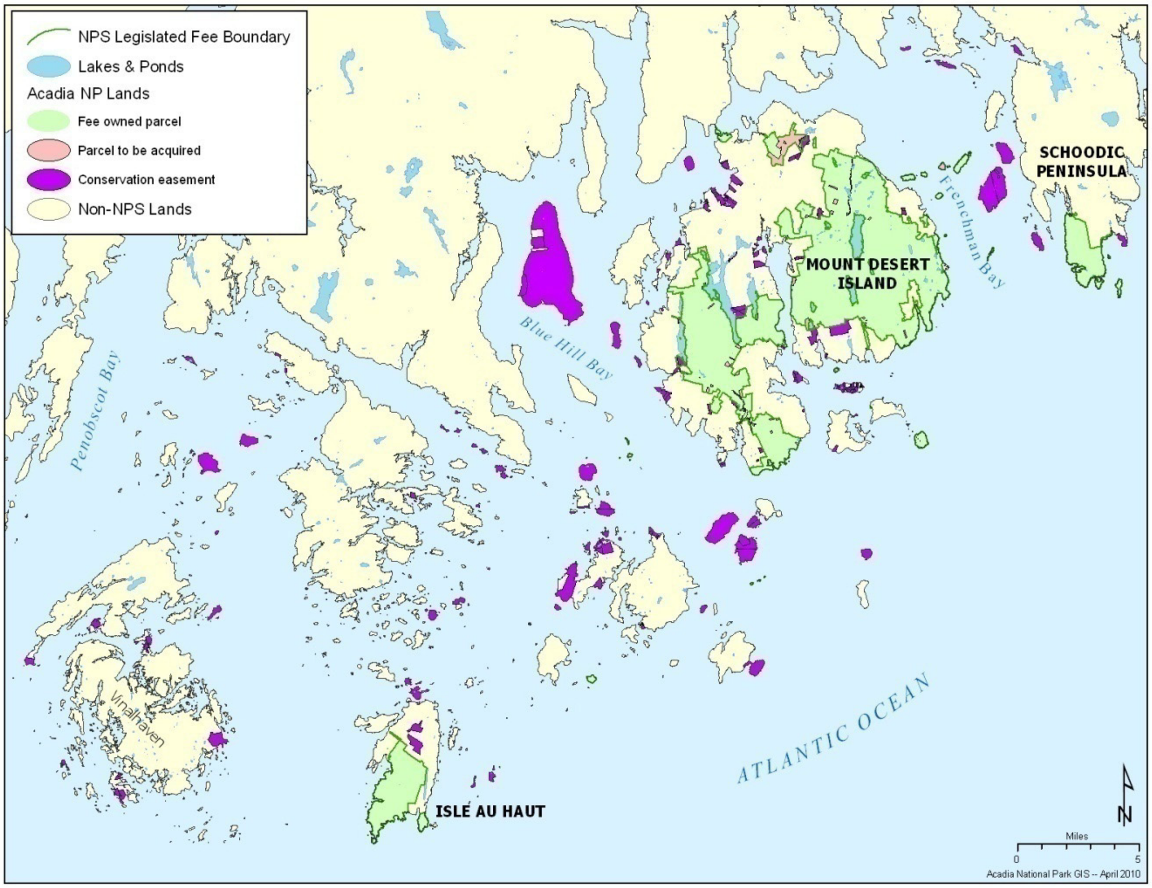


Figure 3. Legislated Acadia National Park boundaries which are known as fee boundaries and conservation easements as of April 2010. National Park Service graphic courtesy Karen Anderson (Acadia National Park).

Figure 4. Blocks of granite form the rocky coastline at Bass Harbor Head on the southwestern side of Mount Desert Island. The coastline of Acadia National Park primarily consists of blocks of granite, steep headland cliffs, or boulder/cobble beaches. Note that the rocks come in a variety of sizes (i.e., poorly sorted) and that abrasion from waves knocking the rocks against one another has rounded their edges. Well-rounded boulders (black arrows) mix with angular rock fragments (yellow arrows). The lighthouse was built in 1858 and stands 17 m (56 ft) above mean high water. National Park Service photograph by John Chelko, available online: http://www.nps.gov/acad/photosmultimedia/scenic.htm (accessed January 7, 2010).

Era	Period*		Formation/Unit	Description	Geological Events	
CENOZOIC	Quaternary	Holocene Epoch	Alluvial and coastal sediments; Talus (angular rock fragments).	Beach, fluvial (river), marsh deposits of sand, gravel, and organic-rich sediments. Talus forms at the base of cliffs.	Opening of present-day Atlantic Ocean.	Crustal rebound, rising sea level, and formation of present-day landscape and shoreline.
CENOZOIC	Quaternary	Pleistocene Epoch	Glacial Deposits and Emerged Marine Deposits.	Glacial till, outwash, and delta sediments. Marine deposits of clay, silt, sand, gravel, cobbles, and boulders.		Continental glaciation. Glacial melting. Fluctuating sea level and shoreline.
CENOZOIC	Tertiary	Neogene	Unconformity (Represents over 413 million years of missing time)			Extensive uplift and erosion. (Gilman and Chapman 1988).
CENOZOIC	Tertiary	Paleogene				
MESOZOIC	Cretaceous					
MESOZOIC	Jurassic					
MESOZOIC	Triassic					
PALEOZOIC	Permian					
PALEOZOIC	Pennsylvanian					
PALEOZOIC	Mississippian					
PALEOZOIC	Devonian				Acadian Orogeny: Collision of Avalon micro-plate with North America. Closing of Iapetus Ocean.	
PALEOZOIC	Silurian		Cadillac Mountain Intrusive Complex (CMIC); Cranberry Island Series; Granite of Schoodic Peninsula	CMIC: Pink, greenish-gray,light- gray, fine- to coarse-grained granite and dark-colored gabbro and diorite. Cranberry Island Series Lower unit: Felsic rocks. Upper unit: Mafic rocks. Granite of S.P.: Felsic granite; diabase dikes.	Granite and pegmatite emplacement. Shattering and contact metamorphism. Hydrothermal activity. Intrusive dikes and sills. Recrystallization. Intrusions accompanied by volcanic activity.	
PALEOZOIC	Silurian		Bar Harbor Formation	Siltstones and sandstones.	Marine sedimentation.	
PALEOZOIC	Ordovician		Unconformity		Folding, metamorphism, uplift and erosion of Ellsworth Schist.	
PALEOZOIC	Cambrian		Ellsworth Schist	Dark- green or gray schist. Streaked appearance	Marine deposition of volcanic rocks in a rift (extension) setting.	
PALEOZOIC	Cambrian		Unconformity			

* See the geologic timescale (fig. 26) for absolute age boundaries of geologic eras and periods.

Figure 5. Bedrock and surficial geologic units in Acadia National Park. The Cadillac Mountain intrusive complex (CMIC) has been updated from the data used for the GIS map and includes all of the igneous intrusive units of Gilman and Chapman (1988). The columns are not to scale with regards to geologic time intervals.

Figure 6. Stone bridge along a carriage road, Mount Desert Island, Acadia National Park. Constructed in 1920, the bridge is one of 17 stone bridges within the park. Melanie Ransmeier, NPS Air Resources Division, for scale. Photograph by John Graham (Colorado State University).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Acadia National Park on June 9–10, 2008, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Participants attending the 2008 scoping workshop identified the following geologic issues as relevant to park management:

- Mass wasting and slope failure
- Coastal erosion
- Sustainability of Sand Beach
- Seismic activity (earthquakes)
- Sea-level rise
- Visitor impact to natural resources

Mass Wasting and Slope Failure

Rain falls every month in Acadia National Park. Although temperatures can fall to below -18° C (0° F), frequent thawing periods prevent large, long-term snow accumulations. Ice storms are common in winter and early spring (National Park Service 2006b). Every spring, saturated soils, thawing, precipitation, and storm waves lead to rockfalls that impact the Park Loop Road on Mount Desert Island and slumping along coastal bluffs. Undercutting of the paved surface above the path leading to Thunder Hole has caused the slope to fail and required the installation of a safety fence (fig. 7).

Mass wasting of marine clay (deposited at a time when sea level was much higher) occurs along Hunters Brook, which drains into the cove protected by Hunters Head on Mount Desert Island. Slumping of the greenish- gray clay has destabilized the stream bank and changed the course of the stream (fig. 8). Exposures of eroded and gullied slopes, characteristic of this marine clay, may also be found on the eastern end of the beach at Otter Cove. Potential mass wasting and slope failure may be an issue wherever this marine clay is exposed on Mount Desert Island (Lowell and Borns 1988).

On the Schoodic Peninsula, slumping occurs along Frazer Creek, south of the park entrance, and erosion cuts into the picnic area. Monitoring these areas may help to predict future mass wasting and erosion.

Earthquakes also may trigger landslides (see the "Seismic Activity" section below for more information on Maine's potential for earthquakes). The park contains over 160 km (100 mi) of trails, some of which are along steep cliff faces. Dislodged, mega-blocks of Cadillac Mountain granite and other debris from an October 2006 earthquake closed the Precipice Trail, East Face Trail on Champlain Mountain, and Homans Path on Dorr Mountain (fig. 9A). Homans Path and Precipice Trail reopened in 2007. Landsliding blocks of granite closed the Park Loop Road for one day (fig. 9B).

Several large boulders tumbled off the mountainside, crashing through a job site, while crews worked on a section of the East Face Trail (renamed the Orange and Black Path) in October 2007. Deanna Greco (NPS Geologic Resources Division) performed an on-site analysis, and found that the 2006 earthquake had opened new fractures in the bedrock and destabilized rocks and boulders on the slope above the trail. To allow the slopes to stabilize, the trail remained closed until October 8, 2009.

Landslides related to the 2006 earthquake generated interest in assessing potential movement along the abundant horizontal to gently sloping joint surfaces in Acadia National Park (Vollmer 2009). This research may prove useful to park management in the future.

Wieczorek and Snyder (2009) have suggested monitoring strategies for slope stability.

Coastal Erosion

Regardless of the season, the North Atlantic surf continues its relentless modification of the coastline, buffeting headlands and redistributing beach sediment. Occasionally, hurricanes pound the coastline. On August 23, 2009, waves from Hurricane Bill hammered the Acadia coastline (fig. 10A). These waves battered the rocky headlands and flooded Sand Beach (fig. 10B). Swells 4 to 5 m (12 to 15 ft) high combined with high tide to produce exceptionally dangerous surf conditions requiring the closure of Sand Beach and the Thunder Hole viewing platform. An estimated 10,000 people converged on the Park Loop Road, trying to get a good view of the violent waves, some of which were more than 5 m (15 ft) high. Ignoring park rangers' warnings, visitors crowded close to the rocky coastline. Suddenly, an unusually large wave careened against the cliffs and the cavernous inlet of Thunder Hole, washed over a crowd of spectators, and swept seven visitors into the ocean. Tragically one of the seven was lost to the sea (National Park Service 2009c).

A tremendous amount of beach erosion and coastal flooding occurs when storm surges combine with high tides. The 1991 Perfect Storm (October 31, 1991) generated sustained winds of 49 to 53 knots (91 to 98 km/hr; 56 to 61 mph) with gusts up to 65 knots (120 km/hr; 75 mph) and wave heights of 9 to 12 m (31 to 39 ft). Sea walls, boardwalks, bulkheads, and piers were heavily damaged or destroyed all along the eastern seaboard from North Carolina to Nova Scotia. Total damage was in the hundreds of millions of dollars (National Oceanic and Atmospheric Administration 2008).

During the Patriots Day Storm on April 16-17, 2007, tidal flooding in Maine was greater than the storm tide of the Perfect Storm (National Oceanic and Atmospheric Administration 2007). High tide in Portland, Maine, was the 7th biggest tide on record at 4.05 m (13.28 ft).Waves 9 m (30 ft) high pounded the coastline and caused extensive damage to homes, businesses, coastal roads, and beaches.

Such storm surges may damage trails and infrastructure. On Mount Desert Island, major storms have caused boulders to wash onto the road at Seawall Beach. If shoreline erosion and retreat continue, sections of the Park Loop Road may have to be moved (Joseph Kelley, University of Maine, personal communication, June 10, 2008). At Thunder Hole, high energy waves erode the retaining wall so that the trail and stairs often need repair (National Park Service 2008). Storm surges coupled with high tide and overall rising sea level present significant future potential danger to the park. In general, rising sea level is causing the shoreline to migrate inland.

Coastal erosion is a natural process at Acadia National Park. The hydraulic energy of the waves at high tide may present management issues for the park, but the tremendous force of the waves also creates some of the remarkable features found along the park's coastline, such as undercut cliffs, sea arches, sea caves, boulder beaches, sea stacks, wave-cut platforms, and thunder holes (fig. 11).

Bush and Young (2009) have suggested monitoring strategies for coastal features and processes.

Sustainability of Sand Beach

Sea level rose following the melting of the Pleistocene glaciers so that sand accumulation along the coast of Acadia National Park has been minor. Sandy beaches are relegated to small pockets in coves and a few sandbars in protected areas. Most of the pocket beaches contain more cobbles than sand. Sustaining Sand Beach is important not only because the beach is one of the few sandy beaches on Mount Desert Island but also because of the composition of its sand.

Sand Beach, sheltered between Great Head and Otter Cliff, is exceptional because its sand is composed of sand-sized shell fragments (calcium carbonate) and not quartz. Deposited by waves, these shell fragments are thousands of years old. Sand Beach and a beach on Cranberry Island (not on park property) hold the distinction of being the only beaches along the Atlantic coastline north of Cape Hatteras, North Carolina, that contain both dunes and beaches composed almost entirely of calcium carbonate sand.

Sand Beach also provides an important visitor contact area for interpretation. Ranger-led interpretive walks begin at Sand Beach, and educational signs are posted in the area.

Recently, the beach has become threatened by sediments eroded from a Pleistocene delta deposit that underlies the Sand Beach parking lot (fig. 12). Both natural processes and human activity have exposed the slope leading to the beach. Eroded slope sediments contain abundant quartz and potassium feldspar. With constant wave action, the harder quartz and feldspar grains abrade the softer calcium carbonate fragments breaking them down. Over time, the amount of shell fragments that currently dominate the beach may diminish. Monitoring and mitigating slope erosion in this area may help sustain the calcium-carbonate composition of Sand Beach.

Because natural processes are allowed to take place along the shoreline at Sand Beach, the beach may appear to be deteriorating at an alarming rate during certain storm events. Erosion of beach sand during storms in 2007 exposed a rocky boulder deposit at the base of the steps leading to the beach (fig. 13A). Access to the beach became a visitor safety issue. However, the sand was naturally restored to the beach (thus eliminating the safety issue within a few months) (fig. 13B).

In the past, visitors were allowed to cross the dune area, and trampling damaged the dunes and their distinctive vegetation. A fence now prevents foot traffic and human-induced erosion of the dunes (fig. 14).

At times, sediment chokes the tidal inlet connecting the sea to the lagoon behind the dunes, preventing tidal flushing of the lagoon (fig. 12). Without tidal flushing, bacterial levels in the lagoon can rise to unsafe levels. However, the park monitors bacteria levels in the lagoon on a weekly basis, and has yet to find levels sufficiently high to close the beach.

Seismic Activity

According to the Maine Geological Survey, earthquakes occur at a low but steady rate in Maine, which is typical of seismic activity in New England (Berry 2006). Earthquakes have been reported from all counties in Maine although higher activity occurs in the eastern, central, and southwestern parts of the State. In 1904, chimneys collapsed in Calais and Eastport during the largest earthquake recorded in Maine (estimated magnitude of 5.1 on the Richter Scale) (U.S. Geological Survey 2009). This earthquake was felt over approximately 390,000 sq km (150,000 sq mi). Magnitude 5.0 earthquakes occur in Maine at an estimated average of once in 52 years. By comparison, magnitude 6.0 earthquakes are estimated to occur, on average, once in 363 years and magnitude 7.0 earthquakes occur once in about 2,512 years (Berry 2006).

However, it is important to note that these are not actual rates of earthquake occurrence. These numbers represent probabilities of occurrence rather than predictions of frequency. Because of historical averages, the probability that a 7.0 earthquake will happen more than once in 2,512 years is low, but that does not mean 7.0 earthquakes could not occur several times in one decade. Likewise, a 5.0 magnitude earthquake may not occur for a thousand years, although historical averages suggest at least one 5.0 magnitude earthquake will occur within 52 years of the previous one.

The largest accurately measured earthquake was a magnitude 4.8 recorded on June 15, 1973 on the Quebec side of the border across from Oxford County, Maine. From April 29, 1997 to February 26, 2007, 49 earthquakes occurred in Maine. The epicenters of all but 6 of these were located in Maine, and magnitudes ranged from 1.3 to 4.2. Magnitudes of all but 14 of these earthquakes were less than or equal to 3.0. Of 507 earthquakes that occurred from 1747 to 1992, only one originated beneath Mount Desert Island.

On October 2, 2006, a 3.8 magnitude earthquake triggered landslides and rockfalls in Acadia National Park and damaged roads and trails (fig. 15). The Precipice, Homans, and East Face trails were closed, and rocks fell onto the Park Loop Road (fig. 9B).

The 2006 earthquake also caused the water level in a U.S. Geological Survey monitoring well to drop more than 0.76 m (2.5 ft). Although earthquakes often cause minor changes in water levels in wells, a decrease of this magnitude was dramatic for Maine (U.S. Geological Survey 2006). The well, located in Acadia National Park in Bar Harbor, was drilled 30 m (98 ft) into bedrock, and on a normal day, water level fluctuates about 8 to 10 cm (3 to 4 in).

The epicenter of the 2006 earthquake was in the Atlantic Ocean, just off Great Head on the eastern side of Mount Desert Island. The earthquake followed several smaller aftershocks produced by a magnitude 3.4 earthquake on September 22, the epicenter of which was approximately located near the Precipice Trail parking area on the Park Loop Road. No damage was reported from this earthquake.

Maine lies along a passive tectonic margin, and in general, passive margins have a low rate of seismic activity. The cause of earthquakes in the Northeast involves movement along preexisting faults in the ancient bedrock. These faults formed millions of years ago when the eastern seaboard collided with the ancient Gondwana landmass to form the supercontinent known as Pangaea. Later, tectonic forces rifted Pangaea causing the present-day Atlantic Ocean to open. Precisely identifying individual geologic faults and fractures that are directly responsible for modern earthquakes has proven difficult though investigation continues (Kafka 2008). Braile (2009) has suggested monitoring strategies for seismicity.

Global Climate Change

Sea-level rise and a possible increase in storm intensity and frequency due to global warming may increase beach erosion, modify the hydrodynamics of tidal flushing in the Sand Beach area, and negatively impact many of the park's iconic visitor destinations. Some significant cultural resources that are located immediately in the coastal zone may also be damaged. According to the Intergovernmental Panel on Climate Change, global sea level will rise an estimated 0.19 to 0.58 m (7.5 in to 1.9 ft) by 2100 (Meehl et al. 2007; Karl et al. 2009). Sea-level is expected to rise 36 cm (14 in) by 2100 along the mainland coast west of Isle au Haut (New England Climate Coalition 2003).

Most of the Acadia National Park's coast consists of rocky cliffs. In general, Maine's coast shows a relatively low vulnerability to future sea-lever rise due to steep coastal slopes, rocky shorelines, and large tidal range (Thieler and Hammar-Klose 1999). Most of the park's coastal zone lies at least 3.5 m (11 ft) above mean sea level and may be less vulnerable to relative sea level rise than the areas on the eastern coast of Mount Desert Island that are less than 1.5 m (4.9 ft) above mean sea level (Titus and Richman 2001). Low areas that might be flooded by rising sea level include Sand Beach, the cobble beaches in the park, and the picnic area on Thompson Island (fig. 16).

The few coastal marshes and estuaries in Acadia National Park will also be impacted by rising sea level. As sea level rises, the salinity will change in the salt marsh behind the dune ridge at Sand Beach. Salinity may increase in Seawall Pond and the freshwater ponds in the Seawall area. Outside of the park boundaries on Mount Desert Island, salinity changes may occur in the saltwater marshes at Seal Cove, Pretty Marsh Harbor, and Fresh Meadow.

If storms become more frequent and more intense with climate change, coastal zone erosion and damage to park infrastructure, visitor sites, and cultural resources may also increase. Some areas likely to be negatively impacted by rising sea level and storm frequency include Thunder Hole, parts of the Park Loop Road, and the Otter Cove Causeway and bridge. In addition, many park septic systems currently located near the coast or in areas with high groundwater will be damaged by rising sea levels. As sea level rises, groundwater levels will also rise, causing potential flooding of leach fields, subsequent pollution, and/or non-functioning restroom facilities (David Manski, Chief of Resource Management, Acadia National Park, written communication, April 19, 2010).

Refer to the National Park Service Climate Change Response Program web site for additional information and links: http://www.nature.nps.gov/climatechange/index.cfm (accessed 5 August 2010).

Visitor Impact to Natural Resources

Cobble Collecting

Visitors collect cobbles as souvenirs and for landscaping purposes. Although signs in the park discourage illegal cobble collecting, cobble theft continues. Because many cobble beaches and access points exist in the park, monitoring cobble theft presents a difficult and time-consuming task. Relatively few citations are issued each year for cobble theft.

Anemone Cave

The population of anemones in Anemone Cave has declined dramatically since 1999. Anemone Cave, one of the few sea caves in Acadia National Park and along the Maine coast, contains the most anemones in the park and is especially accessible to visitors. Consequently, the sea cave has been a popular visitor attraction for years. High visitor impact has been proposed as one possible reason for the decline in the anemone population in Anemone Cave.

In the 1960s to early 1970s, the park removed all references to Anemone Cave from maps and the parking lot. Visitor developments, such as the handrail, were also removed, thereby inhibiting easy access to the cave. Unless specifically asked about the Anemone Cave, park rangers avoid mentioning the cave to visitors.

Fresh water runoff from the parking lot may be a second reason for the decline of anemones. Fresh water influx can decrease the salinity of the tide pools, required to sustain anemones. Additional data are needed to determine if a relationship exists between fresh water input and the decline in anemones in Anemone Cave (Petraitis et al. 2002).

Overuse

Some of the geologic features, such as Cadillac Mountain summit and Bubble Rock, a large and highly visible glacial erratic, are quite popular and attract a large number of visitors each year. The popularity of these sites results in erosion and trampling of the naturally thin soils and sensitive sub-alpine vegetation (fig.22B).

Other Potential Issues

Gas pockets in Somes Sound

Abundant organic matter has generated pockets of natural gas in the sediments of Somes Sound. If these pockets of gas were disturbed (by earthquakes, for example), the resulting pressure release may form craters in the marine embayment. Waves generated from these releases could have unusual, though brief, erosive potential. Existing craters that have been mapped in the sound are quite deep, although whether or not these craters originated from violent outbursts of natural gas remains to be determined (Robert Marvinney, Maine State Geologist, written communication, April 16, 2010).

Potential Flooding if Glacial Moraines Erode

Glacial moraines—composed of a thick unit of relatively impermeable glacial till—form natural dams at the southern ends of both Jordan Pond and Long Pond on Mount Desert Island. At the scoping meeting in 2008, park participants noted that flooding may negatively impact park infrastructure, primarily roads, if the moraines ceased to act as dams. However, no evidence exists to indicate that erosion is causing these moraines to deteriorate or that they may cease to act as dams in the near future. Responsibility for maintaining the damming effect of the moraines does not lie with Acadia National Park, but park management may wish to contact the National Park Service Safety Manager regarding potential dam failure, response options should a dam rupture, and any monitoring data.

Mining

No mines are active in the park, and mining is not a major issue of concern for park management. At one time, copper was produced from a mine on Beech Hill, Mount Desert Island. No tailings are associated with this mine. A mine on Stave Island, located off the west coast of the Schoodic Peninsula, produced copper and silver, but Stave Island is not managed by Acadia National Park. The Schoodic Peninsula once contained active gold and silver mines, but their locations with regard to Acadia National Park's current boundary are unknown (National Park Service 2008).

In the late 1800s and early 1900s, Somesville granite, exposed on the western portion of Mount Desert Island, was extensively quarried for building stone (Gilman et al. 1988). The Hall Quarry on Mount Desert Island supplied large quantities of Somesville granite to many major cities. Today, historic quarries in the area still provide rock that is used to maintain the trails and roads that were originally built with local stone. Active boutique quarries on the Schoodic Peninsula outside of the park still provide sculpture and building stone.

In 1993, the Geologic Resources Division (GRD) of the NPS conducted on-site surveys of granite quarry sites within and immediately adjacent to Acadia National Park. In order to accelerate long-term recovery, minor reclamation was recommended for six of twelve internal sites, although total restoration was not recommended due to the historic significance of the quarries. At the time, the park was encouraged to pursue assistance from Bar Harbor's Planning Director on two external sites that were not grandfathered or exempt from the city's cleanup regulations (John Burghardt, NPS Geologic Resources Division, written communication, February 8, 2010).

Also in 1993, the GRD conducted a Level I Hazardous Materials Survey of a 1980 Canadian molybdenum exploration program that had occurred on Long Island, located between the mainland and Mount Desert Island. The core-drilling program consisted of 6 drill holes totaling 621.2 m (2,038 ft). With the exception of a discarded pile of drill steel, the site had been thoroughly cleaned (John Burghardt, GRD NPS, written communication, February 8, 2010). Since 1993, Long Island, which is the large island east of Mount Desert Island (fig. 3), has been added as a conservation easement to the park.

In the future, offshore sand and gravel deposits may become potential mining targets. Although they now lie in coastal waters, these deposits consist of river and delta sediments that are a legacy of the Pleistocene ice age when sea level was much lower than today.

Alternative Ocean Energy Development

The Gulf of Maine may prove to be an exceptional resource for both wind and tidal energy. Offshore wind facilities benefit from greater and more constant wind velocities, and if placed far enough from shore, they have little or no aesthetic impact on coastal landowners. At water depths of 60 to 80 m (197 to 262 ft), optimal wind velocities may exceed 9.5 m/s (21 mph). Wind energy potential for the Gulf of Maine is estimated to be approximately 100 gigawatts, approximately 10% of the United States' energy needs for one year (Waterman 2008).

In order to comply with legislation passed by the Maine State Legislature in June, 2009, the Maine Department of Conservation (MDOC), in consultation with the Maine State Planning Office and following a comprehensive public outreach effort, designated three locations (Boon Island, Damariscove Island, and Monhegan Island) as "Ocean Energy Testing Areas" on December 15, 2009 (Maine Department of Conservation 2005). Monhegan Island, which lies approximately 60 km (40 mi) southeast of Isle au Haut, was the closest location to Acadia National Park. However, the Monhegan Island site was subsequently dropped from consideration (David Manski, Chief of Resource Management, Acadia National Park, written communication, August 10, 2010). The sites were chosen because they lie within state boundaries, have an average annual wind speed of 27 km/hr (17 mph), a water depth of 60 m (200 ft) or more, and they are free of obstructions. In October 2009, the U.S. Department of Energy extended grants to the University of Maine for offshore wind energy research.

The MDOC worked to designate sites that would result in minimal disruption and inconvenience to existing offshore users, including fishermen, sailors, birds, marine life, and others. In 2001, environmental and economic concerns blocked a proposed wind farm off the coast of Cape Cod (Waterman 2008).

In 2009, Statoil, a Norwegian oil and energy firm, installed the world's first full-scale floating wind turbine about 10 km (6 mi) off the southwest coast of Norway. The University of Maine is consulting with Statoil about their Gulf of Maine project. To date, no impact on Acadia National Park has occurred.

Tidal energy potential lies primarily in the Bay of Fundy, an embayment shared by Maine, New Brunswick and Nova Scotia. More than 115 billion tons of water each day is channeled through the Bay of Fundy. With a tidal range that can reach 15.2 m (49.9 ft), the embayment holds abundant potential energy (Waterman 2008). There is some interest in tidal energy research near the park boundary, and a research permit application may be filed (David Manski, Chief of Resource Management, Acadia National Park, written communication, August 10, 2010).

Water Quality and Quantity

Acadia National Park contains near-pristine water resources and protects some of the last remaining undeveloped portions of New England's coastal mountains, islands, and coastline. The water resources in Acadia National Park provide visitors with a variety of recreational activities including fishing, canoeing, sailing, swimming, and sightseeing. In addition to the 14 Great Ponds, Acadia and the surrounding area contain 10 smaller lakes, more than 24 named streams, and 10 named wetland areas (National Park Service 2006c). Major water quality concerns for park management include private water well development, salt water intrusion into the groundwater aquifer, and contamination of water resources from septic systems.

Since the early 1980s, park staff have been monitoring Acadia's lakes. Most lakes have excellent water quality. Three remote springs in the park (Sieur du Mont Spring, Birch Spring, and Maple Spring) reported high metal content in some samples, but the high levels may be the result of dissolution of bedrock (National Park Service 2008). Two primary concerns for resource managers result from sources beyond the park's boundaries: mercury and acid precipitation.

Industrial emissions from sources far removed from the park contribute to mercury levels in Acadia's surface water. Maine's fish, loons, and eagles contain mercury levels that are among the highest in North America (Maine Department of Environmental Protection 2005).

Exhaust from industrial smokestacks and vehicle tailpipes contribute to atmospheric sulfur dioxide and nitrogen oxides, the primary contributors to acid rain (Maine Bureau of Air Quality 2005). Acid precipitation from rain, snow, and fog alters lake and stream chemistry. Park monitoring indicates that most of the surface water in Acadia has near-neutral pH levels (National Park Service 1994, 2006c).

The ponds on Mount Desert Island are bordered by Cadillac Mountain granite, and the bedrock on Isle au Haut consists of granite, gabbro, and diorite. These igneous rocks do not act as buffering agents to acid deposition. If acid precipitation increases, the park's soil and bedrock have little buffering capacity.

The NPS Water Resources Division (WRD) addresses water quality and quantity issues in the nation's parklands. For baseline surface-water-quality data refer to National Park Service (1994). Contact the WRD for additional information or technical assistance regarding water issues within the park.

Figure 7. Slumping above the path to Thunder Hole due to undercutting of the pavement and the stone wall. A fence has been installed for visitor safety. Bedrock consists of Cadillac Mountain granite. View is from the path to Thunder Hole, June 10, 2008. Photograph by John Graham (Colorado State University).

Figure 8. Slope failure and slumping along Hunters Brook, Mount Desert Island. Erosion of the greenish- gray marine clay (foreground) undercuts the overlying slope, causing slumping and further instability, including collapse of large trees into the stream (June 10, 2008). Photograph by John Graham (Colorado State University).

A) Large slab of rock overhangs Homans Path.

B) Park Loop Road debris.

Figure 9. Examples of mass wasting on Mount Desert Island caused by the October 2006 earthquake. A) A great slab of granite, dislodged by the earthquake, overhangs Homans Trail. The person (indicated by the white arrow) poking his head through the opening is standing on the old trail. B) Blocks of Cadillac Mountain granite close the Park Loop Road. National Park Service photographs, available online: http://www.nps.gov/acad/photosmultimedia/earthquakephotos.htm (accessed January 8, 2010).

A) Waves from Hurricane Bill at Thunder Hole.

B) Waves from Hurricane Bill at Sand Beach.

Figure 10. Waves from Hurricane Bill come ashore at Mount Desert Island, August 23, 2009. A) Thunder Hole. Spray and splash reached in excess of 30 m (100 ft). B) Sand Beach minutes before park rangers cleared the beach of spectators and the sea swept across the entire beach. Photographs used with permission from DownEast Maine Online, available online: http://www.downeastmaineonline.com/HurricaneBill-Acadia-Natonal-Park.htm (accessed January 8, 2010).

Figure 11. Winter seas hammer the coastline of Acadia National Park. Storms and high seas continually modify the coastline by eroding headlands and transporting and abrading rock material. Waves such as these can easily move the boulders found on the beaches in the park. National Park Service photograph by S. West, available at: http://www.nps.gov/acad/photosmultimedia/seasonphotos.htm, (accessed January 8, 2010).

Figure 12. Aerial view of Sand Beach, Mount Desert Island, Acadia National Park. Erosion of quartz and potassium feldspar from the slope adjacent to the parking lot (left) diminishes the proportion of calcium carbonate sand on the beach. The lagoon (salt marsh) lies behind the dune ridge. Periodically, the stream connecting the lagoon to the sea is blocked by sand. Aerial imagery from U.S. Geological Survey Seamless Server (http://seamless.usgs.gov).

A) Erosion of Sand Beach following a 2007 storm.

B) Deposition of sand on Sand Beach one month after the 2007 storm in (A).

Figure 13. Erosion and deposition of Sand Beach. A) A 2007 storm eroded beach sand and exposed boulders at the base of the stairway leading to the beach from the parking lot, creating an unsafe condition. B) After only 1 month, sand was beginning to cover the boulders. The black arrow points to the same boulder in each photograph. Photographs courtesy of Joseph Kelley (University of Maine).

A) Dune ridge prior to the dune fence.

B) Dune ridge after installation of the dune fence

Figure 14. Erosion of the dune ridge (A) was substantially reduced with the installation of a dune fence (B) at Sand Beach. Photograph (A) courtesy of Joseph Kelley (University of Maine). Photograph (B) courtesy of the author.

Figure 15. Boulders dislodged by the 2006 earthquake twisted this iron railing on Precipice Trail and made the footbridge impassable. Bedrock consists of Cadillac Mountain granite. The sheer cliff face resulted from glacial plucking along vertical fractures in the rock. National Park Service photograph, available at: http://www.nps.gov/acad/photosmultimedia/earthquakephotos.htm (accessed January 8, 2010).

Figure 16. Flooded shoreline and fire rings Nos. 2, 3, 4 at the Thompson Island picnic area at high tide during the Patriots Day storm, April 17, 2007. Photograph courtesy of Joseph Kelley (University of Maine).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Acadia National Park.

Tectonic activity, glaciation, and the relentless erosion of the sea formed the geologic features in Acadia National Park. The bedrock records episodes of marine deposition, igneous activity, and intense deformation that occurred hundreds of millions of years ago. Pleistocene continental ice sheets sculpted the present landscape and left both erosional and depositional features. The modern sea coast serves as an analogue to coastal features found well inland that testify to a time when sea level was much higher than it is today.

Bedrock Features

Bedrock that forms the archipelago and Schoodic Peninsula of Acadia National Park includes an assortment of igneous, metamorphic, and sedimentary rocks. Igneous rocks of the Cadillac Mountain intrusive complex and the granite on the Schoodic Peninsula are the primary rock types in the park (Appendix A). The granitic plutons, dikes, and unique shatter zone on Mount Desert Island provide an exceptional glimpse into a magma chamber that was once 5 to 7 km (3 to 4 mi) beneath the surface (Wiebe et al. 1997b). The igneous rocks of the Cranberry Island series are the extrusive compliment to the Cadillac Mountain intrusive complex.

Metamorphic rocks, the oldest rocks in the area, border the western margin of Mount Desert Island. Sedimentary rock units exposed along the northeastern shoreline of Mount Desert Island take their name from Bar Harbor, Maine. All of these rock units record numerous tectonic events that affected eastern North America.

Cadillac Mountain Intrusive Complex

Granitic exposures in Acadia National Park continue to provide clues to the coastal evolution of North America's eastern seaboard. Research over the last 20 years redefined an age (Silurian) for the Cadillac Mountain intrusive complex and defined its components (Wiebe et al. 1997a; Wiebe et al. 1997b). Radiometric age dates and field evidence established a significant genetic relationship among the individual igneous intrusive bodies and the extrusive units of the Cranberry Island Series (Seaman et al. 1995; Wiebe et al. 1997a; Wiebe et al. 1997b; Seaman 2000).

Mount Desert Island offers excellent exposures of the three major units (Cadillac Mountain granite, a mixed gabbro and diorite unit, and the Somesville granite) and the two minor units (Southwest Harbor granite and the Pretty Marsh granite) of the Cadillac Mountain intrusive complex (Gilman and Chapman 1988; Wiebe et al. 1997a; Wiebe et al. 1997b). Analysis of the crystallization process indicates that the emplacement of the Cadillac Mountain intrusive complex took place at approximately 5 km (3 mi) below Earth's surface. This relatively shallow emplacement of the intrusive complex appears to have been controlled by the unconformity between the Ellsworth Schist and the gently dipping Bar Harbor Formation (thus making the Ellsworth Schist and Bar Harbor Formation older than the units in the Cadillac Mountain intrusive complex).

The older Southwest Harbor granite sharply intrudes the Ellsworth Schist and the Bar Harbor Formation. The fine grained, light-gray granite forms a sheet-like mass that is overlain by a sheet of gabbro. Minor amounts of the dark-colored ferromagnesian minerals biotite and hornblende speckle the granite of Southwest Harbor, whereas the primary accessory mineral in Cadillac Mountain granite is hornblende. Isle au Haut contains granite similar to Southwest Harbor granite.

Cadillac Mountain granite forms the bedrock of most of Mount Desert Island (figs. 9 and 15). In contrast to the fine-grained Southwest Harbor granite, the coarse-grained Cadillac Mountain granite contains easily visible grains of translucent, gray, glassy-looking quartz and pink or gray feldspar. The granite's color derives from a distinctive type of feldspar known as perthite, which is pinkish when weathered and greenish on a freshly exposed surface (Gilman et al. 1988).

Exposures of the Cadillac Mountain granite and the gabbro-diorite unit on Bartlett Island and near Crystal Cove indicate that the 2 to 3 km (1.2 to 1.9 mi) thick gabbro-diorite unit overlies a lower unit of Cadillac Mountain granite that has an unknown thickness. On the western part of Mount Desert Island, an upper unit of Cadillac Mountain granite, which is approximately 3 km (1.9 mi) thick, overlies the gabbro-diorite unit (Wiebe et al. 1997a). South of the Somesville granite, upper Cadillac Mountain granite is interlayered with gabbro-diorite. Once the granite solidified, hydrothermal solutions flowed into fractures and formed the quartz veins that are a common feature in the Cadillac Mountain granite (Wiebe et al. 1997**b**).

Sparsely distributed blobs of mafic rock material (enclaves) occur in the Cadillac Mountain granite. These enclaves range in size from less than 1 cm (0.4 in) to over 1 m (3.3 ft) in diameter. The enclaves are strongly flattened, suggesting that they conform to the shape of the magma chamber floor (Gilman et al. 1988; Wiebe et al. 1997b). Research continues into the origin of the enclaves, but initial data from Mount Desert Island indicates that the enclaves formed at different times during the evolution of the granite and that the chemical character of the enclave sources also changed with time (Wiebe et al. 1997b).

The gabbro-diorite unit resulted from multiple injections of basaltic magma into the Cadillac Mountain magma chamber (Symchych 1994; Wiebe et al. 1997a). The unit consists of layers, typically 2 to 50 m (6.6 to 160 ft) thick, that grade upward from fine-grained, rapidly-cooled gabbro to coarser-grained gabbroic, dioritic, or granitic rocks (Wiebe et al. 1997a). Silica-rich pipe-like intrusions extend through the lower Cadillac Mountain granite and into the gabbro-diorite unit. Orientation of these silicic pipes indicate that the gabbro-diorite layers were originally deposited close to horizontal and subsequently bowed downward as the magma chamber evolved (Wiebe et al. 1997a).

Dark gray, coarse-grained gabbro and lighter gray diorite outcrop primarily on the northwest side of Mount Desert Island and on the east side of Isle au Haut (Gilman and Chapman 1988). Good exposures of diorite occur along Route 3 west of Salsbury Cove on the north side of the island. Exposures of gabbro – diorite may also be found in Hulls Cove and on the summit of Great Head on the east side of Mount Desert Island. On the Porcupine Islands, the gabbro – diorite occurs as thick layers that intrude into the Bar Harbor Formation.

The pink, medium-grained Pretty Marsh granite is named for exposures bordering Pretty Marsh Harbor, western Mount Desert Island. As with the above igneous intrusions, the Pretty Marsh granite displays evidence of mechanical mixing with rapidly cooling basaltic magma (Wiebe et al. 1997a).

Somesville granite occurs at the head and to the west of Somes Sound. At first glance, the pink and gray Somesville granite appears to be similar to the granite of Cadillac Mountain. However, the Somesville granite has smaller mineral grains, a different type of feldspar, and minor amounts of biotite mica rather than hornblende (Gilman et al. 1988; Schuh 1994). In addition, the Somesville granite cuts the upper Cadillac Mountain granite along steep contacts that appear to dip about 60° to 70° inward towards the center of the Cadillac Mountain Intrusive Complex (Wiebe et al. 1997a). Extensive quarrying of Somesville granite (from quarries that are now in the park) supplied building stones to many major cities in the early part of the twentieth century.

Acadia National Park offers a unique opportunity to study the evolution of shallow plutons over a large, relatively undeveloped area. Research on the Cadillac Mountain intrusive complex has provided a record of the beginning, development, and solidification of a shallow-level silica-rich magma chamber that existed in an extensional terrane during more or less continuous basaltic magmatism (the development and movement of magma, and its solidification to igneous rock).

Extrusive Igneous Rocks: Cranberry Island Series

The lower felsic (light-colored; rich in silica) unit and upper mafic (dark-colored; low in silica) unit of the approximately 2.6-km (1.6-mi) - thick Cranberry Island series can be subdivided into eight informal members (table 1) (Seaman 2000). Rhyolite dominates the lower six members while basalt is the primary volcanic rock in the overlying two members. The voluminous amount and type of volcanic deposits suggest the evolution of a caldera-like eruptive sequence typical of a setting involving crustal extension (Seaman 1994; Seaman et al. 1995; Seaman et al. 1999; Seaman 2000).

Table 1: Cranberry Island series (SDcif, SDcit, and SDcis on the Map Units Property Table)

Felsic (F) and Mafic (M) units	General Description
M2	Basaltic lava flows with possible pillow structures
M1	Basaltic and andesitic ignimbrites with some sedimentary layers
F6	Rhyolitic ignimbrite with abundant inclusions of basalt
F5	Andesitic ignimbrite with rare pods of basaltic inclusions
F4	Rhyolite ignimbrite lava flow
F3	Flow-banded rhyolite lava flow
F2	Rhyolite ignimbrite (pyroclastic flow)
F1	Clast-supported lahar (volcanic mudflow with rhyolite, siltstone, basalt, and granite fragments)

In the table, the sequence from rhyolite (F1 through F4) to andesite (F5) to basalt (M1 and M2) represents a classification based on composition in which rhyolite lacks iron and magnesium-rich minerals, but contains abundant quartz and feldspar; basalt is rich in iron and magnesium-rich minerals; and andesite is a transition between the two end members. Pillow basalts are pod- or pillow-shaped and form as basaltic magma rapidly cools upon emerging from an underwater fissure. The series represents a classic inversion pattern showing the initial extrusion of the felsic top of the magma chamber and evolving to the extrusion of the more dense, basic lava that forms near the base of the magma chamber.

Previous interpretations subdivided the Cranberry Island series into the three members that are listed in the Map Units Property Table (Gilman et al. 1988). However, the unit of felsites and flows (SDcif), which occurs only on Mount Desert Island, has been reinterpreted as a shallow intrusive unit that may be related more to the Cadillac Mountain intrusive complex than to the Cranberry Island volcanic sequence (Seaman 2000).

In the park, exposures of the Cranberry Island series occur on Isle au Haut and near Seawall campground. The most complete section of the Cranberry Island series lies outside the park, along the shore of Great Cranberry Island (Gilman and Chapman 1988; Seaman 2000). The north side of Little Cranberry Island also contains excellent exposures.

Granite of the Schoodic Peninsula

Previously considered to be part of the Cadillac Mountain intrusive complex, the Late Silurian (approximately 419 million years old) granite that forms the landscape of the Schoodic Peninsula contains a significantly different composition than the Cadillac Mountain granite and lacks a shatter zone (Chris Koteas, University of Massachusetts, personal communication, June 9, 2008). The contact between the Schoodic Peninsula granite and the Cadillac Mountain intrusive complex lies within Frenchman Bay.

The Schoodic Peninsula contains excellent exposures of the upper portion of the magma chamber and mafic dike swarms that show an intermingling of two hot, plastic magma bodies (fig. 17A). Pulsed injections of mafic magma into the magma chamber produced zones of mingling of intermediate magma with felsic magma. These zones point to a long-lived, dynamic episode of volcanism. Rounded blocks of greenstone (metamorphosed mafic igneous rock) found within the diorites of the Schoodic Peninsula and the lack of a shatter zone indicate that the Schoodic Peninsula granite formed from a different method of intrusion than did the Cadillac pluton.

Diabase Dikes

Stripes of fine-grained, black diabase dikes are especially noticeable in the light-colored Schoodic Point granite (fig. 17A). Chemically similar to gabbro and basalt, diabase is a fine-grained intrusive igneous rock that forms a transition between deeply-buried gabbros and extrusive basalts. The dikes are mostly less than 3 m (10 ft) wide. However, some exceed 18 m (60 ft) in width (Gilman et al. 1988). In all units of the Cadillac Mountain intrusive complex, the dikes trend roughly north-to-south to 340° (Wiebe et al. 1997a). They appear to be more abundant in the Cadillac Mountain granite than in the younger Somesville and Pretty Marsh granites.

Schoodic Point and Cadillac Mountain offer excellent exposures of diabase dikes (fig. 17B). Two 1.5- to 3-m (5- to 10-ft)-wide dikes cut through the granite at the hairpin turn 2.9 km (1.8 mi) from the entrance gate on Cadillac Mountain Road (Gilman et al. 1988). The trail on the south side of the mountain that leads to Black Woods Campground offers excellent exposures of the black dikes. The southern end of the Schoodic Peninsula also offers exceptional exposures of the dikes as well as their cross-cutting relationships.

Other Schoodic Peninsula Dikes

On the Schoodic Peninsula, dikes with three different compositions have been identified. These include: 1) fine-grained felsic dikes, 2) felsic dikes with plagioclase phenocrysts, and 3) banded rhyolite dikes (Chris Koteas, University of Massachusetts, personal communication, June 9, 2008). Blobs and chunks of granite that only partially dissolved appear to ‘float’ within the dikes, and some of the granite within the dikes contains the mineral hornblende that formed within the granite from the heat of the intrusion. Some of the dikes on the Schoodic Peninsula appear to have intruded into granite and then reversed their flow direction to inject back on themselves, indicating a dynamic process of intrusion.

Shatter Zone (Intrusive Breccia)

One of the most spectacular features on Mount Desert Island is the shatter zone that borders the Cadillac Mountain granite to the north, east, and south (Gilman et al. 1988; Gilman and Chapman 1988). Ranging in width from 300 m (1,000 ft) to more than 1.6 km (1 mi), the shatter zone consists of severely shattered, angular fragments of gabbro-diorite, Ellsworth Schist, volcanic and sedimentary rock from the Bar Harbor Formation, and other rock rubble from veins and dikes all congealed in a matrix of granite (fig. 18). The rock pieces surrounded by granite are up to hundreds of meters across (Gilman et al. 1988).

Investigation continues into how the shatter zone formed. Current data suggests that the shatter zone formed suddenly, perhaps associated with an explosive eruption triggered by an influx of basaltic magma into the Cadillac Mountain granite chamber (Coombs 1994).

Gilman and others (1988) proposed that roof pendants (rocks above the magma chamber) and fractured country rock adjacent to the chamber walls became weakened by the intrusion and began to sag and sink into the magma. The magma then surged upward, filling spaces created by the foundering country rock in a process called cauldron subsidence. The inclusions of country rock appear to have settled to the floor of the magma chamber as the magma crystallized, (fig. 19). The shatter zone would then represent the outermost edge of a collapsed central region and contain brecciated country rock that did not completely assimilate into the magma (Gilman et al. 1988; Kiver and Harris 1999).

Excellent exposures of the shatter zone are present at Otter Cliffs, Western Point south of Black Woods Campground, and in Little Hunters Cove (fig. 18). The east end of Sand Beach also offers good exposures as does the parking lot for the overlook at Schooner Head.

Regional Metamorphic Rocks: Ellsworth Schist

Schist (from the Greek word meaning “to split”) refers to a metamorphic rock that is layered (foliated) and splits along this layering. While the Ellsworth Schist may exist elsewhere in Maine, in Acadia National Park, the Ellsworth Schist has undergone a higher degree of regional metamorphism to forming a gneiss. The gneiss contains complexly-folded bands of light and dark-colored minerals. In the Ellsworth Schist, darker layers of the mineral chlorite and lighter layers of quartz and feldspar give the rock its distinctive streaked appearance (fig. 20A).

Composed of intensely deformed and metamorphosed volcanic rocks, the Ellsworth Schist records two significantly different tectonic regimes: 1) an extensional regime in a rift setting, and 2) a compressional regime resulting from plate subduction along an active margin (Reusch 2002; Schulz et al. 2007; Schulz et al. 2008). The Ellsworth Schist consists of basalt and rhyolite, volcanic rocks with quite different mineral compositions. Ellsworth basalts have compositions similar to mid-ocean-ridge basalts that originate from the asthenosphere while the rhyolite tuffs that are interlayered with the basalts reflect a shallower source in the crust. The compositional similarity of the Ellsworth basalt to others found in the present Gulf of California suggests that the Ellsworth evolved in a similar extensional tectonic regime (see the "Geologic History" section).

Detailed measurements of larger scale asymmetrical folding (fig. 20A), analysis of the orientation of small scale foliation (called crenulation cleavage), and analysis of the metamorphic grade (i.e., low temperature but high pressure) suggest that the Ellsworth Schist was intensely deformed during regional metamorphism associated with a subduction zone that formed along an active plate margin (see the "Geologic History" section) (Reusch and Rust 2001; Reusch 2002).

Across the bridge from the mainland to Mount Desert Island, the Ellsworth Schist is the first rock exposed along the shore. Excellent exposures of the Ellsworth Schist may be found at the picnic area opposite the Acadia National Park information center on Thompson Island, on the northwest side of Mount Desert Island, and on the west side of Bartlett Island (Gilman and Chapman 1988).

Stratified Sedimentary Rocks: Bar Harbor Formation

The second oldest group of rocks in the park, the Silurian Bar Harbor Formation consists of siltstone and sandstone beds generally a few centimeters to 1 m (3.3 ft) thick. These sedimentary rocks are stratified, forming relatively undeformed layers in comparison to the Ellsworth Schist (fig. 20B). However, like the Ellsworth Schist, Bar Harbor sediments were products of offshore, marine deposition. Volcanic material, transported by waves and currents in an ancient sea, form thin white layers in the formation (Harris et al. 1997). Contact metamorphism from the emplacement of the Cadillac Mountain intrusive complex fused the grains of the Bar Harbor Formation but did not change its mineral composition. Because the grains have been welded together by contact metamorphism, the unit is referred to as a metasedimentary rock.

Coarser-grained beds in the Bar Harbor Formation may contain quartz pebbles up to 0.64 cm (0.25 in) in diameter. Some individual beds display graded bedding, which shows a gradual change from coarse material at the bottom of the layer to fine silt at the top. Graded bedding results from a sediment gravity flow where different-size particles settle through the sediment-water mix. In these conditions, the graded beds likely resulted from a pulse of sediment. The triggering mechanism for the pulse of sediment that produced these normally graded beds (coarser at the base and fining upward) may have come from a variety of sources including earthquakes, volcanic eruptions, channel margin collapse from channel undercutting, collapse of oversteepened beds, and erosion caused by intense rain storms.

Graded bedding is extremely useful for telling directionality and patterns of sediment transport within a basin. Using graded bedding, geologists can also tell if the rock layers have been overturned during a deformational event. The rock strata at Bar Harbor are right-side-up, suggesting they have undergone little deformation since they were deposited approximately 420 million years ago. Alternatively, the strata may have been tilted during one deformational event and returned to a relatively original position during a subsequent deformational event.

Bar Harbor, Maine, was designated as the type locality for the Bar Harbor Formation because of excellent exposures along the shoreline. In this area, bedding is inclined gently toward the ocean, and the strata lack any folding or complex faulting (Gilman et al. 1988). Rocks exposed along the shore at The Ovens and on the north side of Mount Desert Island in road-cuts along Route 3 at Ireson Hill also belong to the Bar Harbor Formation. However, bedding in these locations is difficult to distinguish, and the rock is more flint-like than the strata at Bar Harbor. Some of the beds may be accumulations of ash that settle out of the atmosphere following a volcanic eruption (Gilman et al. 1988).

Joints and Faults

On Cadillac Mountain, prominent vertical joint sets have directions of 90° (east-to-west), 40° (northeast-to-southwest), and 335° (northwest-to-southeast) (Gilman et al. 1988). Joints typically form in conjugate joint sets where two joints intersect at acute angles of roughly 60° and obtuse angles of 120° (fig. 17). Conjugate joint sets are compressional features and may resemble a squashed "X". Regional study of conjugate joint sets gives tremendous insight to the tectonic regime at the time deformation took place.

The broad exposures of smooth, gently sloping rock on Cadillac Mountain, Pemetic Mountain, and Dorr Mountain originated from horizontal joints during a process known as exfoliation. As erosion removed the weight of overlying rock, the underlying rock expanded and cracked parallel to the surface. Recent field studies have shown that the three mountains are part of a single exfoliation dome that formed prior to glaciation (Vollmer 2009). Glaciers carved the exfoliated sheets of rock that had been weakened by vertical and horizontal fractures, leaving behind today's smooth, gently rounded topographic domes of Mount Desert Island (Gilman et al. 1988).

Very little movement or displacement took place along the joints, but in some situations, forces not only fractured the rock, but also displaced it, forming a fault. Faults are not as easily found on Mount Desert Island as are joints for several reasons. Faults usually contain ruptured and broken rock, which weathers easily, so that many faults now lie in low areas, covered by soil, vegetation, or glacial material. The limited amount of bedrock exposures also limits the number of faults exposed at the surface (Gilman et al. 1988).

Along the north shore of Mount Desert Island, several small, nearly vertical faults interrupt the bedding in the Bar Harbor Formation. Vegetation obscures the faults farther inland. Inference of a larger fault may be found at Salsbury Cove where sheared and broken Ellsworth Schist terminates abruptly against the gabbro-diorite. The eastern boundary of the Ellsworth Schist south of Salsbury Cover may be a continuation of this fault.

Both chemical and physical weathering processes tend to enhance the fractured bedrock surfaces. Water percolates into the fractures, dissolving some of the mineral cements, and then expands upon freezing, forcing individual grains apart. When the ice thaws, water washes away the loosened pieces of granite from the widening fractures. More water is trapped, and the cycle repeats. Fractures are also desirable habitats for lichen and plants whose roots contribute to the physical destruction of bedrock.

Glacial Features

In the Devonian, continental collision resulted in the northern Appalachian Mountain Range. In the Triassic, the supercontinent, Pangaea, began to rift apart as the Atlantic Ocean opened. In the Pleistocene, continental glaciers sculpted today's New England landscape. The last glacier to extend into the Gulf of Maine left two major types of geologic features, erosional features and depositional features summarized in table 2.

Table 2: Glacial features in Acadia National Park.

Erosional Features	Depositional Features
Glacial polish, striations, grooves and chatter marks (abrasion)	Glacial till
Cliffs (plucking)	Moraines
Roches moutonnées	Glacial erratics
U-shaped valleys	Deltas
Fjard of Somes Sound	Outwash deposits
Meltwater channels	

Glacial Polish, Striations, Grooves, and Chatter Marks

The major landforms seen today in Acadia National Park owe their origin to glacial erosion caused by south-flowing ice sheets during the Pleistocene. Rock fragments dragged along by the Wisconsinan-aged glacier acted like grit on sandpaper to scratch, gouge, grind, and polish the underlying bedrock (fig. 21A). Abrasion was stronger on the north sides of hills, which offered more resistance to the southward-flowing ice. Striations (scratch marks), which are oriented parallel to ice flow, may be used to plot the direction of glacial movement. On Mount Desert Island, glacial grooves and striations show a generally north-south orientation (Lowell and Borns 1988). Boulders and rocks embedded in the ice may bear down against a bedrock surface to produce crescent-shaped grooves known as chatter marks. Chatter marks document areas where some of the greatest pressures were exerted against the bedrock (Gilman et al. 1988).

Glacial-derived Cliffs

Glacial plucking removed large amounts of rock and produced many of the spectacular cliffs in Acadia National Park (fig. 15). Because the glacier was advancing from the north, increased pressure on the north side of hills caused ice to melt at the bottom of the glacier. Meltwater seeped into fractures and refroze on the southern side of hills. Upon freezing, the ice expanded and forced the rock apart. Blocks of bedrock pried loose in this manner were subsequently frozen into the glacier and carried away. The prominent cliffs along the Precipice Trail and on the southeast side of The Bubbles are examples of cliffs created by glacial plucking (Gilman et al. 1988).

Roches Moutonnées

Glacial abrasion and plucking caused many of the hills in Acadia National Park to develop a distinctly asymmetric profile. Abrasion smoothed and polished the north sides that faced into the ice flow. Glacial plucking generated a steep, rugged south side. These glacially sculpted bedrock knobs form roches moutonnées, a term coined by Horace-Bénédict de Saussure, a French alpine explorer in the eighteenth century. De Saussure thought the rocks (roche) looked like the fashionable wigs of the day that were smoothed with mutton fat (moutonnée) to keep the hair in place.

Because of its shape, a roche moutonnée is also known as a whaleback or sheepback. The roches moutonnées on Mount Desert Island tend to be elongated and streamlined in a north-south direction, relatively parallel to the direction of ice movement. Two of the more famous roches moutonnées in the park are The Bubbles, the two rounded mountains located north of Jordan Pond (fig. 21B). Viewed from the side, The Bubbles appear asymmetrical, with the steeper side to the south.

U-shaped Valleys

While streams tend to erode an alpine valley into a characteristic V-shape, glaciers cut flat-bottomed, steep, relatively straight, distinctive U-shaped valleys (fig. 21B). Like the striations and roches moutonnées, the U-shaped valleys on Mount Desert Island trend north to south (Gilman et al. 1988). When the glaciers melted, lakes formed in the U-shaped valleys. Sargent Mountain Pond became the first post-glacial lake in Maine. Jordan Pond, which covers 76 ha (187 ac) and reaches a maximum depth of 46 m (150 ft), holds the distinction of being Maine's clearest lake with normal visibility reaching 14 m (46 ft) and occasionally up to 18 m (60 ft). Other lakes that formed in U-shaped valleys include Seal Cove Pond, Long Pond, Echo Lake, and Eagle Lake.

Fjard

In the past, Somes Sound, one of the most magnificent bays on the Maine coast, has been categorized as a fjord (Gilman et al. 1988; Harris et al. 1997). Fjords are long, narrow, glacially-eroded arms of the sea, usually hundreds of meters deep, with steep rock cliffs and a shallow sill at the entrance to the ocean. The great depths of fjords inhibit mixing of marine waters so that the bottom is anoxic.

Although glacially derived, Somes Sound lacks features required by the strict definition of a fjord. The relief of Somes Sound, almost 300 m (980 ft), is relatively small compared to the 1,000 m (3,300 ft) relief of fjords found in Norway. Somes Sound opens to the sea through The Narrows, an entrance sill similar to those found in fjords. However, The Narrows is not large enough to alter the circulation within the sound, and the bottom of the sound remains oxygenated.

The Scandinavian term, fjard, may be a more accurate description of Somes Sound. Smaller, shallower, and broader in profile than a fjord, a fjard is simply a glacially carved embayment that is drowned by the sea (Maine Geological Survey 2005a).

Meltwater Channels

Near the close of the Pleistocene, the climate warmed and the glaciers melted, vast amounts of water flowed either directly off the glacial surface or found its way to the bottom of the ice (Gilman et al. 1988). Strong currents and abundant sediment in these internal meltwater channels eroded trough-like features into the bedrock hills. All the mountains on Mount Desert Island contain evidence of meltwater channels. A meltwater channel formed the notch between Cadillac Mountain and Dorr Mountain and is visible from the Park Loop Road where it crosses Otter Cove (Lowell and Borns 1988).

Glacial Till

Glaciers transport all sizes of debris, from fine dust to boulders, and deposit this debris along its sides, on the valley floor through which it flows, and at its farthest extent. The general term for the poorly sorted mixture of fine to coarse rock debris deposited by melting ice is till (fig. 22A). On Mount Desert Island, intense grinding and crushing pulverized much of the rock debris carried near the base of the last glacier, resulting in a basal till of compact, fine-grained sediment containing many striated stones (Gilman et al. 1988). Glacial till has been mapped throughout the northern part of Mount Desert Island, and although hidden by vegetation, till may be exposed in new construction, fresh road cuts, or along the borders of many lakes.

Terminal Moraines

Terminal moraines are landforms that are shaped by rock debris that is carried along by the flowing ice, as if on a conveyor belt, and dumped at the front edge of the ice as glaciers melt. Terminal moraines cap Clark Ridge and dam the southern end of Long Pond, Echo Lake, and Jordan Pond on Mount Desert Island (Lowell and Borns 1988). Jordan Pond House was constructed on the crest of a terminal moraine. The moraine consists of rock debris ranging in size from clay to the boulders strewn about the field below the manicured lawn (fig. 21B).

Glacial Erratics

Glacially plucked rocks transported away from their point of origin are termed glacial erratics. Flowing ice carried boulders of Cadillac Mountain granite to the southern part of Mount Desert Island and into the Gulf of Maine. In addition, rock fragments from the mainland were transported onto Mount Desert Island. Gray granite boulders on the top of Cadillac Mountain, for example, came from the Lucerne granite, located 31 km (19 mi) to the north. One of the most far-traveled erratics in Acadia National Park is the famous balanced boulder called Bubble Rock perched high on the side of South Bubble Mountain (Gilman et al. 1988). Bubble Rock is composed of white granite with large feldspar crystals, which is clearly different from the pink granite that forms the surrounding mountains. Its location provides evidence that the glaciers were as thick as the island's present mountain tops (fig. 22B).

Glacial Outwash Deposits and Deltas

During periods of glacial retreat, meltwater streams produced outwash deposits from the front of the glacier. These consist primarily of mixtures of sand and silt. Streams transported silt and clay particles out to sea, but larger clasts were left behind as lag deposits. One of the better exposures of outwash on Mount Desert Island extends from Bubble Pond southward along Hunter Brook (Lowell and Borns 1988). Outwash deposits may also be found at the north end of Upper Hadlock Pond and near the campground southeast of Long Pond.

In three locations on southern Mount Desert Island (south of Jordan Pond, south of Jordan Ridge, and south of Upper Hadlock Pond), the sand and gravel entered the ocean and built up to the water surface, forming flat-topped delta deposits (Lowell and Borns 1988). Herodotus, the Greek historian, coined the term "delta" because the mouth of the Nile River formed a feature shaped like the upper-case Greek letter Delta, Δ. As they do today, deltas in the Pleistocene formed at the shoreline. Thus, the deltas on Mount Desert Island establish the location of at least one shoreline during the Wisconsin glacial period.

The delta deposit southeast of Jordan Pond began to form when the ice margin stood behind the Jordan Pond moraine (Gilman et al. 1988). The flat-topped delta documents a time when sea level was approximately 70 m (230 ft) higher than it is today.

Coastal Features

Before the coast of Maine rebounded following deglaciation, the sea flooded much of the low-lying portion of Mount Desert Island. As a consequence, Acadia National Park contains features representing both ancient and modern coastlines.

Emergent Shorelines of an Ancient Coast

Acadia National Park preserves significant exposures of ancient sea stacks, sea caves, sea cliffs, boulder beaches, and thunder holes that record the dynamic interaction between post-glacial shorelines and sea level change. The pockets of offshore marine clay that once blanketed the low areas on Mount Desert Island provide the most widespread evidence of a past high-stand (transgression) by the sea. Exposures of marine clay occur along Ocean Drive, on the east side of Otter Cove where it is crossed by Park Loop Road, at the east end of Sand Beach, and along Hunters Brook (fig. 8).

In places, the marine clay contains fossil shells of clams, mussels, and other mollusks (Tweet et al. 2010). Some species of these invertebrates live today in cold, subarctic waters, indicating that the late-glacial marine environment of coastal Maine probably resembled that of present-day southern Greenland. Carbon-14 radiometric age analysis from some shells found in a clay deposit in Goose Cove establish an approximate age of 12,250 years old for these deposits (Gilman et al. 1988).

Concentrated deposits of pebbles, cobbles, and boulders exposed at higher elevations in the park document ancient shorelines. Similar to modern beach deposits, well-rounded boulders on the east side of Day Mountain have been tossed about and rounded in the former surf zone when sea level was approximately 64 m (210 ft) higher than its present level (Gilman et al. 1988). A wave-cut platform, an undercut notch in a cliff of granite, a sea stack (known as Chimney Rock) and a sea cave similar to those found along the present coastline of Mount Desert Island are exposed on Cadillac Cliffs, along the Gorham Mountain Trail above Monument Cove (fig. 23A). The entrance to the sea cave cut into the granite sea cliff measures approximately 10 m (33 ft) high. Seaward of the cliff, rounded boulders are reminiscent of the boulder beach at Monument Cove (Maine Geological Survey 2005b).

Remarkably, a rounded boulder, approximately 1 m (3.3 ft) in diameter, is lodged securely in the back of the ancient sea cave (fig. 23B). This boulder may have been hurled into the cave during a storm 13,000 years ago, or it may represent a post-glacial tsunami deposit along a coastline located much higher than it is today (Joseph Kelley, personal communication, June 10, 2008). Another possibility involves ice rafting. If the boulder was embedded in ice and currents or storm waves pushed the ice toward the back of the cave, the ice may have melted or cracked and dropped the boulder.

Modern Sea Coast

The sea continually modifies the coastal landscape of Acadia National Park. The sea erodes the coast in a process known as differential erosion, which means that areas of weakness erode more quickly than other areas. Fractures, joints, and intrusive dikes have made some of the igneous rocks in the park less resistant than others (fig. 17A). Currents and waves transport eroded rock debris away from high-energy zones and deposit the material in areas of quiet water. Some of the more spectacular features along the park's coastline include the sea cliffs, a variety of beaches, sea caves, sea arches, wave-cut platforms, and other features developed along the shore from the process of differential erosion.

The dense, granitic bedrock in the park forms the characteristic sea cliffs exposed along the park's coastline. With glacial melting and sea level rise, headlands such as Great Head, Otter Cliff, and Schooner Head on Mount Desert Island resisted erosion and now extend prominently out to sea. Waves batter the headlands and sea cliffs, and their hydraulic action dislodges blocks of granite that pulverize and abrade less resistant or fractured rock (fig. 4).

Rounded by constant rolling, the boulder and cobble beaches in Acadia National Park pay tribute to the incessant pounding by North Atlantic swells. Storm waves (fig. 11) tumble boulders into near-spherical shapes, such as those on the boulder beach in Monument Cove (fig. 24). The classification for a boulder is a rock that is greater than 25.6 cm (10 in) in diameter, about the size of a volleyball. A cobble measures from 6.4 to 25.6 cm (2.5 to 10 in) in diameter. In Acadia National Park, some of the boulders reach 0.5 to 1 m (1.6 to 3.3 ft) in diameter. Typically the beaches grade from boulders near the cliff edge to cobbles closer to the surf.

Sandy shores are rare at Acadia National Park. Even more scarce are beaches like Sand Beach that are composed of sand-sized particles of calcium carbonate. Nestled between the headlands of Great Head and Otter Point on eastern Mount Desert Island, the 265-m (870-ft) -long Sand Beach presents the longest continuous stretch of sandy beach in the park (fig. 12). Calcium carbonate forms slowly in cold waters, such as those found in the Gulf of Maine so that marine invertebrates encased in calcium-carbonate shells are not as common as they would be in warm, tropical, shallow marine environments. South of Cape Hatteras (North Carolina), carbonate beaches are composed of shell fragments from recently deceased invertebrates, but at Sand Beach, some of the shell fragments are from animals that lived thousands of years ago. In addition to the beach, geomorphic features at Sand Beach include a dune ridge, tidal creek, and lagoon (figs. 12, 13, and 14).

The sea stack at the eastern end of the boulder beach in Monument Cove looks remarkably similar to Chimney Rock, which now lies along the Gorham Mountain Trail 60 m (200 ft) above present sea level (fig. 24). Wave erosion focused on vertical fractures in this column of granite and eventually separated it from the mainland.

The boulder beach also contains a minor exposure of hydrothermally altered granite. Flecks of molybdenite may be found embedded in some of the granite boulders along the beach. In 1980, exploration for molybdenite, an alloy in stainless steel, occurred on Long Island, which is now a conservation easement in the park and protected from mining activities (see “Mining” in the “Geologic Issues” section).

Boulders at Seawall Beach in Southwest Harbor may wash onto the road when major storms occur. Raised ridges of gravel form a natural seawall (Lowell and Borns 1988). The boulder beach in Little Hunters Cove also provides access to excellent exposures of the shatter zone.

Sea caves are rare in Acadia National Park. Anemone Cave remains a spectacular exception, and sea caves are currently forming on the Schoodic Peninsula and above the high tide line in Frenchman Bay at Ironbound Island due to differential erosion. Ironbound Island is currently protected by a conservation easement.

Thunder Hole, a popular site for visitors, formed from waves battering against an intrusive, less resistant diabase dike and joints in the adjacent Cadillac Mountain granite (fig. 25). The narrow, vertical-walled slot and sea cave booms like thunder when an exceptionally large wave suddenly compresses the air and displaces it from the cave.

Although not on park property, the craggy cavities known as The Ovens on the northeastern coast of Mount Desert Island have piqued the curiosity of visitors for years. Located on the headland between Salsbury Cove and Hulls Cove, The Ovens form a series of natural arched caves in the Bar Harbor Formation. At The Ovens, a massive, more resistant rock layer overlies a thinly stratified unit. Long, vertical fractures cut through the massive layer and combine with small, inclined faults to break apart the thin horizontal layers so they can be excavated by the sea. The mechanical breaking and erosion by the ocean proves to be an effective agent at removing broken material and carving the caves that stretch along the base of the cliff.

Where sea caves enlarge sufficiently to penetrate through a headland, sea arches form. At Sand Point, northeastern Mount Desert Island, erosion along a prominent vertical fracture created a high narrow arch (Kiver and Harris 1999).

The relentless hydraulic action of waves continues to undercut sea cliffs and bevel the bedrock into modern examples of the emergent wave-cut platform and undercut cliff exposed on the Gorham Mountain Trail. South of Thunder Hole, Otter Cliffs rise vertically 33 m (107 ft) above a smooth, well-developed wave-cut bench or platform. At Schoodic Point, waves continue to wash over a smooth platform cut into the granite bedrock.

Table 3 summarizes the geologic features visible within Acadia National Park.

A) Diabase dike on Schoodic Point.

B) Diabase dike intruding Cadillac Mountain granite.

Figure 17. Igneous diabase dikes in Acadia National Park. A) A massive diabase dike intrudes light-colored granite on Schoodic Point, Acadia National Park. Note the preferential weathering that has eroded the contact between the dike and granite. Also visible are horizontal joints that form “steps” and vertical joint sets that form an “X” pattern in the granite. Photograph by John Graham (Colorado State University). B) Diabase dike cutting through (intruding) the Cadillac Mountain granite on Mount Desert Island, Maine. The granite is fractured by intense horizontal jointing. Photograph from Gilman and others (1988), available on the Maine Geological Survey website, http://www.maine.gov/doc/nrimc/mgs/explore/bedrock/acadia/igneous.htm (accessed February 20, 2010).

Figure 18. The shatter zone at Little Hunters Cove, Mount Desert Island. Exotic deformed and angular fragments of rock create a unique rock unit associated with the intrusion of the Cadillac Mountain intrusive complex. Mechanical pencil is 14.5 cm (5.7 in), for scale. Photographs courtesy of the author.

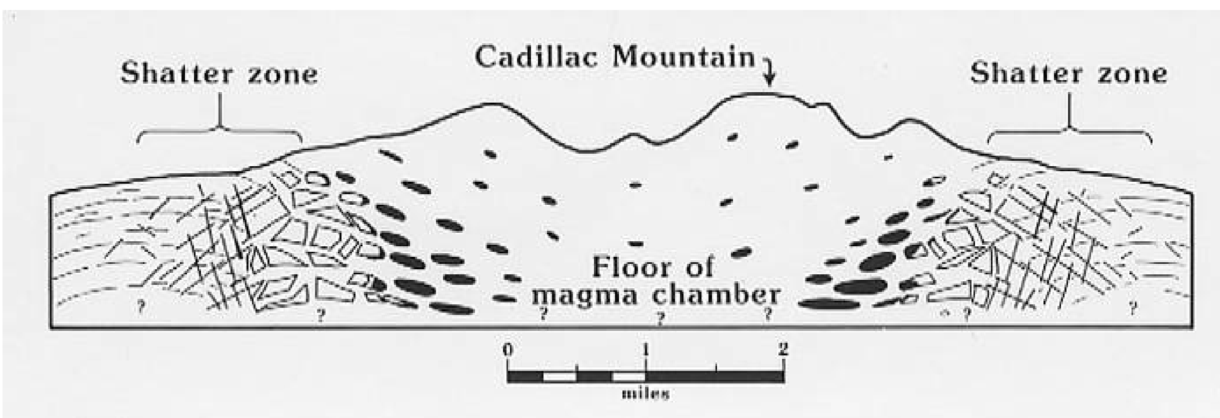


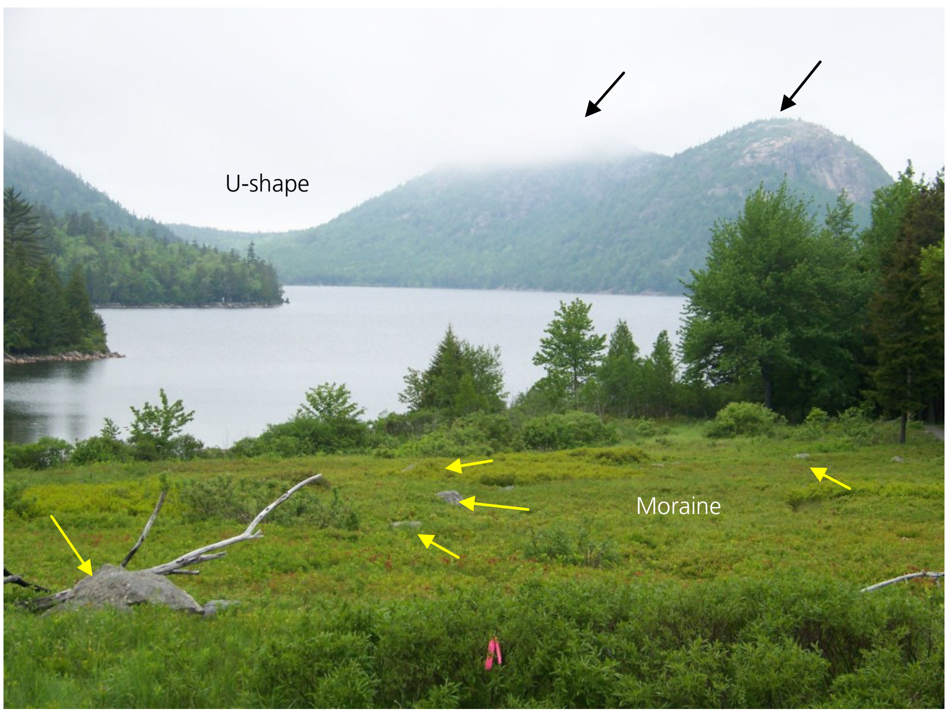
Figure 19. Schematic cross section through Cadillac Mountain granite illustrating one possible origin for the shatter zone. The granitic intrusion fractures the country rock, causing angular pieces of country rock to be surrounded by intruding magma. When the magma chamber's roof collapses, a process called cauldron subsidence, magma fills the spaces. The inclusions of country rock settle to the floor of the magma chamber. Support for this idea comes from the orientation of the inclusions, which are essentially horizontal in the interior of the granite body, but tilt downward towards the interior on the outside margin of the granitic body. Diagram from Gilman and others (1988), available on the Maine Geological Survey website, http://www.maine.gov/doc/nrimc/mgs/explore/bedrock/acadia/igneous.htm (accessed July 30, 2010).

A) Ellsworth Schist

B) Bar Harbor Formation

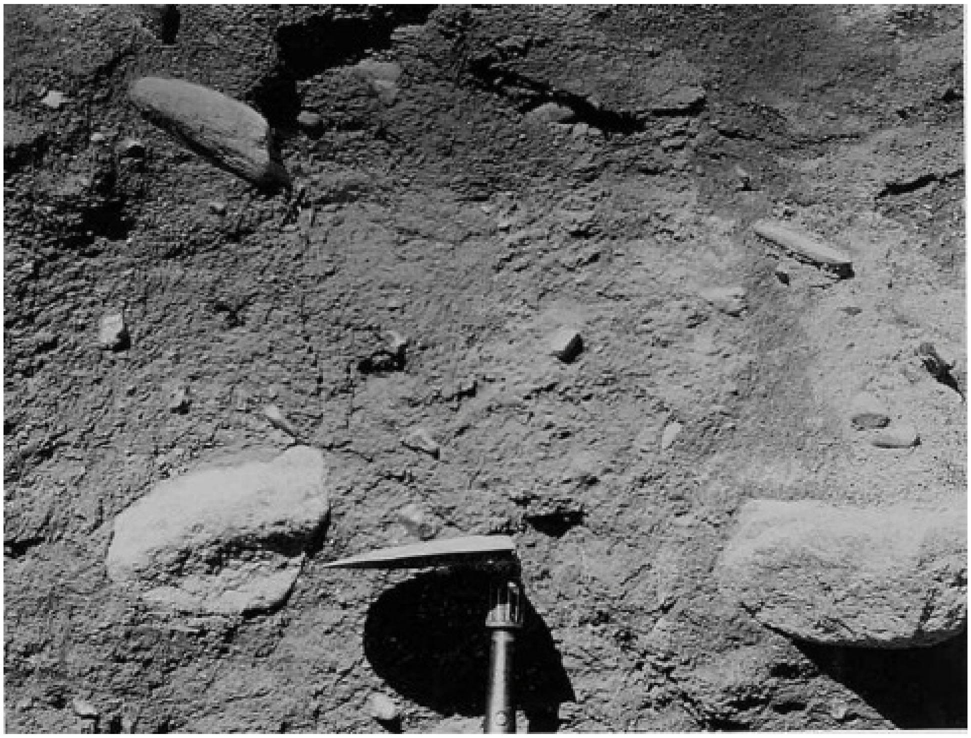
Figure 20. Metamorphic and sedimentary bedrock features in Acadia National Park. A) Ellsworth Schist. Deformation during metamorphism contorted the thin layers into complex, asymmetric folds with one limb of the fold steeper than the other. Measurement of these folds can provide clues as to the direction of compression. Quartz and feldspar compose the light-colored layers; chlorite and other mica minerals form the dark bands. Note the penny in the center of the photograph for scale. Photograph from Gilman and others (1988), courtesy of the Maine Geological Survey and available online: http://www.maine.gov/doc/nrimc/mgs/explore/bedrock/acadia/strat.htm, (accessed January 8, 2010). B) Strata (layers) in the Bar Harbor Formation along the shoreline near Bar Harbor, Maine. The Bar Harbor Formation changes from regular thin and medium bedded sedimentary rock, as seen here, to a massively-bedded unit at The Ovens, farther north along the coast. Photograph courtesy of the Maine Geological Survey, available online: http://www.maine.gov/doc/nrimc/mgs/explore/bedrock/sites/jul03.htm, (accessed January 8, 2010).

A) Glacial polish, striations, and chatter marks.



B) The Bubbles.

Figure 21. Glacial erosional features in Acadia National Park. A) Abrasion from rock material carried by the glaciers polished the bedrock and left chatter marks (arc-shaped indentations) and striations (lines scratched into the rock surface). Striations are parallel to the pen (for scale) and indicate the direction of the flowing ice. Photograph from Gilman and others (1988), courtesy of the Maine Geological Survey and available online: http://www.maine.gov/doc/nrimc/mgs/explore/bedrock/acadia/strat.htm, (accessed January 8, 2010). B) View to the north across Jordan Pond to The Bubbles (left Bubble summit shrouded in clouds), two roches moutonnées in the park. Glacial plucking shaped the steep, southern slopes of The Bubbles, seen in this photograph (black arrows). The vegetated, hummocky terrain in the foreground is the glacial moraine that dammed the U-shaped valley to form Jordan Pond. Note the boulders (yellow arrows) strewn randomly upon the typical hummocky surface of a moraine. Boulders are common in the poorly sorted glacial till. Photograph by John Graham (Colorado State University).

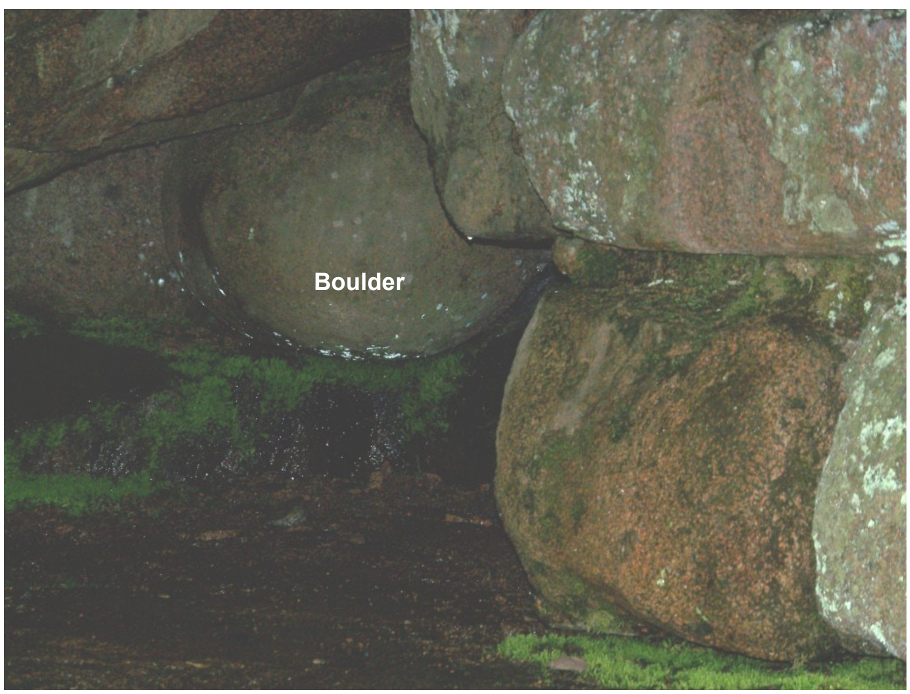


A) Glacial Till.

B) Bubble Rock.

Figure 22. Glacial depositional features in Acadia National Park. A) Glacial till exposed during the construction of the Jordan Pond House. Tills are poorly sorted, containing a wide range of particle sizes from clay to boulders. Note the rounded edges to some of the boulders, indicating abrasion during transportation prior to deposition. Shovel blade is 18 cm (7 in) across. Photograph from Gilman and others (1988), courtesy of the Maine Geological Survey and available online: http://www.maine.gov/doc/nrimc/mgs/explore/bedrock/acadia/strat.htm, (accessed January 8, 2010). B) Bubble Rock, a glacial erratic over 3 m (10 ft) tall. Composed of white granite with large feldspar crystals, Bubble Rock probably came from the Lucerne plutonic complex, approximately 31 km (19 mi) to the north. Bubble Rock is a popular attraction, and trampling has destroyed the vegetation that once covered the trail. National Park Service photograph by Charlie Jacobi (Acadia National Park).

A) Emergent coastline feature; a sea cave on Gorham Mountain Trail.



B) Boulder lodged in emergent sea cave on Gorham Mountain Trail.

Figure 23. Emergent coastline features exposed along Cadillac Cliffs on the Gorham Mountain Trail, Mount Desert Island, Acadia National Park. A) Features similar to those found at the present sea coast include the steep sea cliff, previously undercut by the hydraulic action of waves, and the smooth wave-cut platform at the base of the cliff. Visitors are standing on an ancient shore and staring at a sea cave that formed along the post-glacial coastline. B) In the recesses of the sea cave, a rounded boulder, approximately 1 m (3.3 ft) in diameter, remains securely lodged within the horizontally fractured Cadillac Mountain granite. One interpretation suggests that a tsunami transported the boulder into the sea cave. Photographs courtesy of the author.

Figure 24. Boulder beach and sea stack (indicated by the yellow arrow) at Monument Cove, Mount Desert Island. Note that some of the boulders are larger than others and some are more rounded, indicating various abrasion and transportation histories. Wave erosion, focused on the vertical fractures in the rocks, has separated the sea stack from the mainland. Photograph by John Graham (Colorado State University).

Figure 25. Thunder Hole slot and sea cave on Mount Desert Island, Acadia National Park. The narrow slot formed as waves eroded the contact between the dike (containing the viewing platform) and the Cadillac Mountain granite. The yellow lines indicate the planes of two near vertical joints that intersect each other at an acute angle of approximately 45 degrees, further reducing rock stability. Paired joint sets such as these, which are common on Mount Desert Island, are known as conjugate joint sets. Waves rushing into the cave (below the photographer) displace air, which produces a booming, thunderous sound. Photograph by John Graham (Colorado State University).

Table 3: Summary of geologic features and processes visible within Acadia National Park

Bedrock Features	Cadillac Mountain Intrusive Complex • Cadillac Mountain Granite • Gabbro – Diorite Unit • Somesville Granite • Southwest Harbor Granite • Pretty Marsh Granite
	Regional Metamorphic Rocks: Ellsworth Schist
	Stratified Sedimentary Rocks: Bar Harbor Formation
	External Igneous Rocks: Cranberry Island Series
	Granite of Schoodic Peninsula
	Diabase (and other) Dikes
	Shatter Zone
	Joints and Faults
Glacial Features	Erosional Features • Glacial polish, striations, grooves and chatter marks (process of glacial abrasion) • Cliffs (process of glacial plucking) • Roches moutonnées • U-shaped valleys • Fjard of Somes Sound • Meltwater stream channels
	Depositional Features • Glacial till • Moraines • Glacial erratic • Deltas • Outwash Plains
Coastal Features	Emergent Shorelines: sea cliffs, sea caves, boulder beaches, wave-cut platforms, sea caves, marine clay
	Modern Coastline: sea cliffs, sea caves (including Thunder Hole and The Ovens), Sand Beach, boulder beaches, sea arch, examples of differential erosion

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Acadia National Park. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Acadia National Park provided information for the Geologic Issues, Geologic Features and Processes, and Geologic History sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, other natural resources, and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps, and do not show soil types, but they do show parent material—a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 26) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table is conjectural and meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following references are the sources for the GRI digital geologic data for Acadia National Park:

Gilman, R. A. and C. A. Chapman. 1988. Bedrock geology of Mount Desert Island. Bulletin 38. Maine Geological Survey, Augusta, Maine, USA (scale 1:50,000).

Lowell, T. V. and H. W. Borns, Jr. 1988. Surficial geology of Mount Desert Island. Bulletin 38. Maine Geological Survey, Augusta, Maine, USA (scale 1:50,000).

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, and increases the overall utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase and shapefile GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map and connects the help file directly to the map document. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Acadia National Park, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

In general, the bedrock and surficial deposits of Acadia National Park record two major events in the evolution of eastern North America: the growth of the Paleozoic Appalachian mountain chain and the sculpting of the landscape by much younger Pleistocene glaciers (fig. 26). The Appalachian chain extends from eastern Canada to encompass the Oachitas of west Texas ending in Big Bend National Park and evolved as a result of three main mountain-building episodes (orogenies): the Taconic (Ordovician), Acadian (Silurian and Devonian), and Alleghanian (Carboniferous and Permian) orogenies (fig. 26). Although relegated to specific geologic periods for convenience, the three orogenies represent an active tectonic margin that existed along the eastern seaboard of North America throughout most of the Paleozoic (542 to 251 million years ago). The Avalonian Orogeny occurred far from the proto-North American continent, but its history can be found in rocks exposed in Newfoundland, eastern New England, and the southern Appalachian Piedmont region (Suppe 1985).

Bedrock exposures in Acadia National Park document a complex early Paleozoic history involving regional and contact metamorphism, igneous intrusions, volcanism, and intricate folding from intense deformation. Events involving both active tectonic margins and passive tectonic margins established the foundation upon which the glaciers of the last ice age carved the present landscape.

Geologic events over time have been accurately dated using rock geochemistry, paleontological classification of organisms from cores, and radiocarbon analyses on mollusk shells and on bulk organic material from cores.

Paleozoic Era (542 to 251 million years ago)

The geologic units that compose the bedrock of Acadia National Park originated far from the eastern seaboard of North America. By the beginning of the Cambrian period, most of the global continental landmass clustered around the South Pole as part of the supercontinent, Gondwana. Exceptions included smaller continents to the north, such as Laurentia, which formed the continental core of North America, and Baltica, the core of Western Europe (fig. 27).

In the Middle Cambrian, approximately 509 million years ago, micro-continents began to separate from northern Gondwana. Similar to what is currently occurring in the Gulf of California, rifting pulled apart the crust to create a submarine rift system that allowed basaltic magma to erupt through fissures onto the sea bed. Between eruptions, felsic deposits of rhyolite tuff settled over the basalt (Reusch 2002; Schulz et al. 2007; Schulz et al. 2008). These deposits would later be metamorphosed into the Ellsworth Schist.

Eventually, the rift widened and Ganderia, along with other micro-continents such as Avalonia (which would become the coast of Maine) and Meguma (modern-day Nova Scotia), split away from northern Gondwana (Murphy et al. 2006). Sometime between the Late Cambrian and Early Ordovician, the leading edge of Ganderia changed from a passive margin to an active margin with a subduction zone and a chain of volcanic islands, called the Penobscot arc, forming above the down-going slab of crust. Collision of the Penobscot arc with the Ganderia mainland, which lay many kilometers east of Laurentia, resulted in regional metamorphism and deformation that transformed the interlayered basalt and rhyolite into the Ellsworth Schist (Reusch 2002; van Staal 2007).

Ganderia, Avalonia, Meguma and the other micro-continents formed an island chain bordered by the Iapetus Ocean to the north and the Rheic Ocean to the south (fig. 27). The ocean names are based upon Greek mythology: Iapetus was the father of Atlas, just as the Iapetus Ocean was the predecessor of the Atlantic Ocean. Rhea was the sister of Iapetus. As Ganderia and the other micro-continents drifted away from Gondwana, the Iapetus Ocean between Laurentia and the micro-continents narrowed (Bradley 1997; Murphy et al. 2006).

During the Late Cambrian to Middle Ordovician, a convergent boundary with an east-dipping subduction zone developed along the northeastern margin of this island chain. Partial melting of the down-going slab of crust generated magma, which returned to the surface to form a volcanic island arc system between the micro-continents and Laurentia. By the Late Ordovician, igneous and sedimentary rocks in the volcanic arc had been folded, faulted, metamorphosed and accreted to Laurentia as part of the Taconic Orogeny, named for exposures in the Taconic Mountains of New York and Vermont (fig. 28). Today, these rocks form the fold-and-thrust belt of western Vermont, eastern New York, and northernmost Maine (Bradley 1997).

As the volcanic arc accreted to the Laurentian mainland, Ganderia and the other micro-continents were approaching from the east. Sediments eroded from Ganderia were deposited offshore and solidified into the Silurian Bar Harbor Formation. An unconformity (gap in time in the geologic record) separates the Bar Harbor Formation from the Ellsworth Schist, signifying a period of either nondeposition or uplift followed by erosion.

Episodic deformation of the Northern Appalachians occurred from the southeast as the Acadian Orogeny progressed across Maine and adjacent areas (fig. 29) (Bradley et al. 2000). The first micro-continent to collide with Laurentia in the developing Acadian Orogeny was Ganderia during the Late Silurian (a pre-Acadian phase also referred to as the Salinic Orogeny) (van Staal 2007). The docking of Avalonia soon followed in the Late Silurian or Early Devonian (van Staal et al. 2002). Discussion continues regarding whether or not Ganderia became part of Avalonia before it became attached to Laurentia in the Silurian (van Staal et al. 2002; Murphy et al. 2007). In the Late Devonian or Early Mississippian, Meguma became part of Laurentia (a phase also known as the Neoacadian Orogeny) (van Staal 2007).

Magmatic and plutonic activity associated with the Acadian Orogeny resulted in the emplacement of over 100 mafic and felsic plutons in the Coastal Maine Magmatic Province, which includes the Cadillac Mountain intrusive complex (Hogan and Sinha 1989; Wiebe et al. 1997). Field evidence and radiometric data suggest the following sequence for the emplacement and solidification of the granitic units within the Cadillac Mountain intrusive complex (Wiebe et al. 1997b):

- Somesville granite (emplaced last)
- Pretty Marsh granite
- Cadillac Mountain granite
- Southwest Harbor granite (emplaced first)

Basaltic magma intruded before, during, and after these granites, and the gabbro-diorite unit injected multiple times into the Cadillac Mountain magma chamber (Wiebe 1994; Wiebe et al. 1997b). Heat from the emplacement of the Cadillac Mountain intrusive complex hardened the Bar Harbor Formation into meta-sedimentary rocks.

The Cranberry Island Series may represent the extrusive equivalent of the Cadillac Mountain intrusive complex. Debate continues regarding the tectonic setting for the Cranberry Island Series, with some geologists proposing a compressional origin while others suggesting crustal extension. Currently, geochemical and outcrop data support an origin involving an extensional tectonic setting (Seaman and Wobus 1995; Wiebe et al. 1997; Seaman et al. 1999; Seaman 2000). In an active margin setting, magmatism associated with extension may occur in backarc basins (the region between a volcanic arc and the mainland), in association with transcurrent faulting, or with rifting of the coastal Maine volcanic belt from another continental margin (Hogan and Sinha 1989; Seaman et al. 1999; Seaman 2000)

The tectonic welding of Gondwana with Laurentia closed the Iapetus Ocean (fig. 29). Similar to the on-going collision between India and Asia, this continent-to-continent collision in the Devonian resulted in an impressive Acadian mountain range. The Pennsylvanian-to-Permian Alleghanian Orogeny brought closure to the Rheic Ocean and established the Southern Appalachian and Ouachita mountains. Gondwana finished colliding with Laurentia and together, they formed the supercontinent, Pangaea (fig. 30).

Mesozoic Era (251 to 65.5 million years ago)

Over 300 million years of erosion following the Devonian left little record to decipher prior to the Pleistocene. Approximately 200 million years ago, (fig. 26), the impinging plates relaxed and Pangaea began to rift apart. Plate separation produced Triassic and Jurassic rift basins, including one under the Bay of Fundy about 240 km (150 mi) northeast of Mount Desert Island (Bradley 1997; Harris et al. 1997; Kiver and Harris 1999). By the Jurassic, plates had separated enough to open the North Atlantic. The Atlantic Ocean continues to widen at approximately 2.5 cm (1 in) per year (Gilman et al. 1988).

In general, the eastern landmass detached along zones of weakness, primarily along old fault planes. Separation left behind pieces of the microplates. For example, the Meguma terrane (Nova Scotia) was left behind when North Africa drifted away from North America (Bradley 1997). Similarly, rocks once contiguous with Scotland remain in Maine and Quebec.

With the end of the Alleghanian Orogeny, the opening of the Atlantic Ocean, and the creation of the mid-Atlantic Ridge system, the eastern seaboard of North America became a passive tectonic margin on the trailing edge of the North American plate. Extensive erosion wore away the mountain peaks and eventually exposed the igneous intrusions that had originally cooled several kilometers below Earth's surface.

Cenozoic Era (the past 65.5 million years)

Paleogene and Neogene (Tertiary)

Erosion in the Paleogene and Neogene (Tertiary) (fig. 26) may have created a landscape where resistant, deep-seated rocks such as those in the Mount Desert Range stood high above the surrounding landscape. The term for such a rock island surrounded by low country is monadnock, which is Algonquin for "a mountain that stands alone." Uplift during the Tertiary rejuvenated streams, which deepened valleys. Valleys were aligned in a north-to-south direction, parallel to the main, vertical fractures.

Approximately 2.6 million years ago, the Mount Desert area probably formed an east-to-west trending peninsula attached to the mainland (Gilman et al. 1988; Harris et al. 1997; Kiver and Harris 1999). As erosion removed the overlying rock that buried the massive granites, the confining pressure decreased, and fractures developed that paralleled the rock surface in a process known as exfoliation. By the end of the Neogene, the stage was set for the continental glaciers that would put the final touches on the landscape that forms today's Acadia National Park.

Pleistocene Glaciation

Preglacial topography strongly influenced glacial flow. Valleys deepened and widened, soil and loose debris was relocated, and eventually continental ice overtopped the highest mountains in New England. In Acadia National Park, the Wisconsin glaciation, the last period of ice advance, destroyed most of the evidence of older glaciations (fig. 31). During times of maximum glaciation, glaciers locked up such vast amounts of water that sea level fell by as much as 100 m (330 ft) (Gilman et al. 1988; Kiver and Harris 1999). When the ice melted during interglacial episodes, outwash and glacial lake sediments filled lowlands. Retreating glaciers left behind local deposits of glacial till and glacial erratics.

On Mount Desert Island, an advancing ice lobe scoured a particularly deep trough that is now occupied by Somes Sound. Other ice lobes carved the U-shaped, elongate valleys that are filled today by Jordan Pond, Eagle Lake, Echo Lake, Long Pond, and Seal Cove Pond. Ice continued to thicken on Mount Desert Island so that by 21,000 years ago, glaciers covered the entire island, including Cadillac Mountain. Glacial plucking removed fractured bedrock from the hillsides. Abrasion and plucking began to shape the present landscape.

About 18,000 years ago, glaciers began thinning and melting to the extent that more ice melted than was being replenished. Between 14,000 years and 13,000 years before present, the ice-margin retreated approximately 20 km (12 mi) (Kaplan and Borns 1994). The relatively slow, overall rate of approximately 20 to 30 m (66 to 98 ft) per year was accompanied by minor ice-margin re-advances and numerous times when relative sea level did not fluctuate greatly. By 13,000 to 14,000 years ago, the rocks of Mount Desert Island began to be exposed. Sargent Mountain, which lies south of the higher Cadillac Mountain, emerged as the first visible landform above the massive glacial ice in the Acadia National Park region.

Global sea level rose as water returned to the ocean. Eventually, rising sea level caused the seaward edge of the ice sheet to float and disintegrate into icebergs. As the glaciers melted, meltwater streams emerging from the toe of the glaciers deposited extensive outwash material. Deltas formed at the edge of the sea. Receding glaciers left behind mounds of glacial till. By 12,500 years ago, the continental glacier had receded from the area, leaving behind a tongue of ice in Jordan Pond valley. The ocean flooded the depressed land surface, and marine clay settled on the ocean floor. As the continental glaciers melted, sea level rose to approximately 60 m (200 ft) above its present level.

Glacial till left behind by the receding ice formed a moraine at the southern end of Jordan Pond valley (Jordan Pond House is constructed on the Jordan Pond moraine). By 11,000 years ago, the ice had disappeared from Jordan Pond valley. Jordan Pond formed behind the natural dam created by the southern moraine. Sea level dropped and the delta that had formed south of Jordan Pond began to emerge (Gilman et al. 1988).

Holocene (Post-Glacial) History

Over the past 14,000 years, the coast of Maine and the inner continental shelf record two marine transgressions (relative sea level rise) separated by a regression (relative sea level fall) (Belknap et al. 1987; Barnhardt et al. 1995). Initially, the sea transgressed across the depressed crust following the retreating ice (Kaplan and Borns 1994). Crustal rebound halted this transgression approximately 13,000 years ago (Barnhardt et al. 1995). Sea level fell rapidly, passing the present coast by approximately 11,500 years ago (Anderson et al. 1990; Barnhardt et al. 1995). Relative sea-level fluctuations in the Gulf of Maine and Atlantic Canada vary widely, but in Maine, the short-lived, relative sea-level lowstand reached 55 m (180 ft) below the current shoreline at 10,500 to 11,000 years before present (Barnhardt et al. 1995). Regression led to a reworked littoral zone and deep fluvial valleys cut into the inner continental shelf (Belknap and Kelley 1993). These valleys often connect to present estuaries and embayments, or they lie just offshore of rivers.

Sea level rose rapidly to 20 m (66 ft) below modern sea level approximately 9,000 years ago and then rose slowly for another 2,000 years. By 6,000 years before present, sea level had risen to -15 m (-49 ft) and continues to rise slowly in the late Holocene (Belknap and Kelley 1993). Modern beach deposits are being created and the relentless erosive power of the sea continues to modify the shoreline.

Acadia National Park preserves one of the premier places in the world to observe evidence of such dramatic crustal rebound and sea level changes. For example, the paleo-sea stacks, paleo-sea caves, and paleo-thunderholes that are exposed along Gorham Mountain Trail provide evidence of the post-glacial shoreline. Such features as moraines, glacial erratic, whalebacks, U-shaped valleys, glacial polish, and striations provide silent reminders of the dynamic and formidable effects of past glacial activity.

Today, Acadia National Park is dominantly an erosional landscape. Notches in bedrock cliffs and sea caves form from wave action along the high tide mark. Differential erosion causes less resistant rocks such as diabase and schist to erode more easily than granite, forming such features as Thunder Hole and Anemone Sea Cave. Acadia National Park preserves a magnificent outdoor laboratory where geological processes of the past may be studied along with similar terrestrial and marine processes that are shaping the current landscape.

Eon	Era	Period		Epoch	Ma		Life Forms	North American Events
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01	Age of Mammals	Modern humans	Cascade volcanoes (W)
				Pleistocene	2.6		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary	Neogene	Pliocene	5.3		Large carnivores	Sierra Nevada Mountains (W)
				Miocene	23.0		Whales and apes	Linking of North and South America Basin-and-Range extension (W)
			Paleogene	Oligocene	33.9			
				Eocene	55.8		Early primates	Laramide Orogeny ends (W)
				Paleocene	65.5			
	Mesozoic	Cretaceous			145.5	Age of Dinosaurs	**Mass extinction** Placental mammals Early flowering plants	Laramide Orogeny (W) Sevier Orogeny (W) Nevadan Orogeny (W)
		Jurassic			199.6		First mammals	Elko Orogeny (W)
		Triassic			251		**Mass extinction** Flying reptiles First dinosaurs	Breakup of Pangaea begins Sonoma Orogeny (W)
	Paleozoic	Permian			299	Age of Amphibians	**Mass extinction** Coal-forming forests diminish	Supercontinent Pangaea intact Ouachita Orogeny (S) Alleghanian (Appalachian) Orogeny (E)
		Pennsylvanian			318.1		Coal-forming swamps Sharks abundant	Ancestral Rocky Mountains (W)
		Mississippian			359.2		Variety of insects First amphibians First reptiles	Antler Orogeny (W)
		Devonian			416	Fishes	**Mass extinction** First forests (evergreens)	Acadian Orogeny (E-NE)
		Silurian			443.7		First land plants	
		Ordovician			488.3	Marine Invertebrates	**Mass extinction** First primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian			542		Early shelled organisms	Avalonian Orogeny (NE) Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian			2500		First multicelled organisms Jellyfish fossil (670 Ma)	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean					≈4000		Early bacteria and algae	Oldest known Earth rocks (≈3.96 billion years ago)
Hadean					4600		Origin of life?	Oldest moon rocks (4–4.6 billion years ago) Formation of Earth's crust Formation of the Earth

Figure 26. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/ with additional information from the International Commission on Stratigraphy. http://www.stratigraphy.org/view.php?id=25.

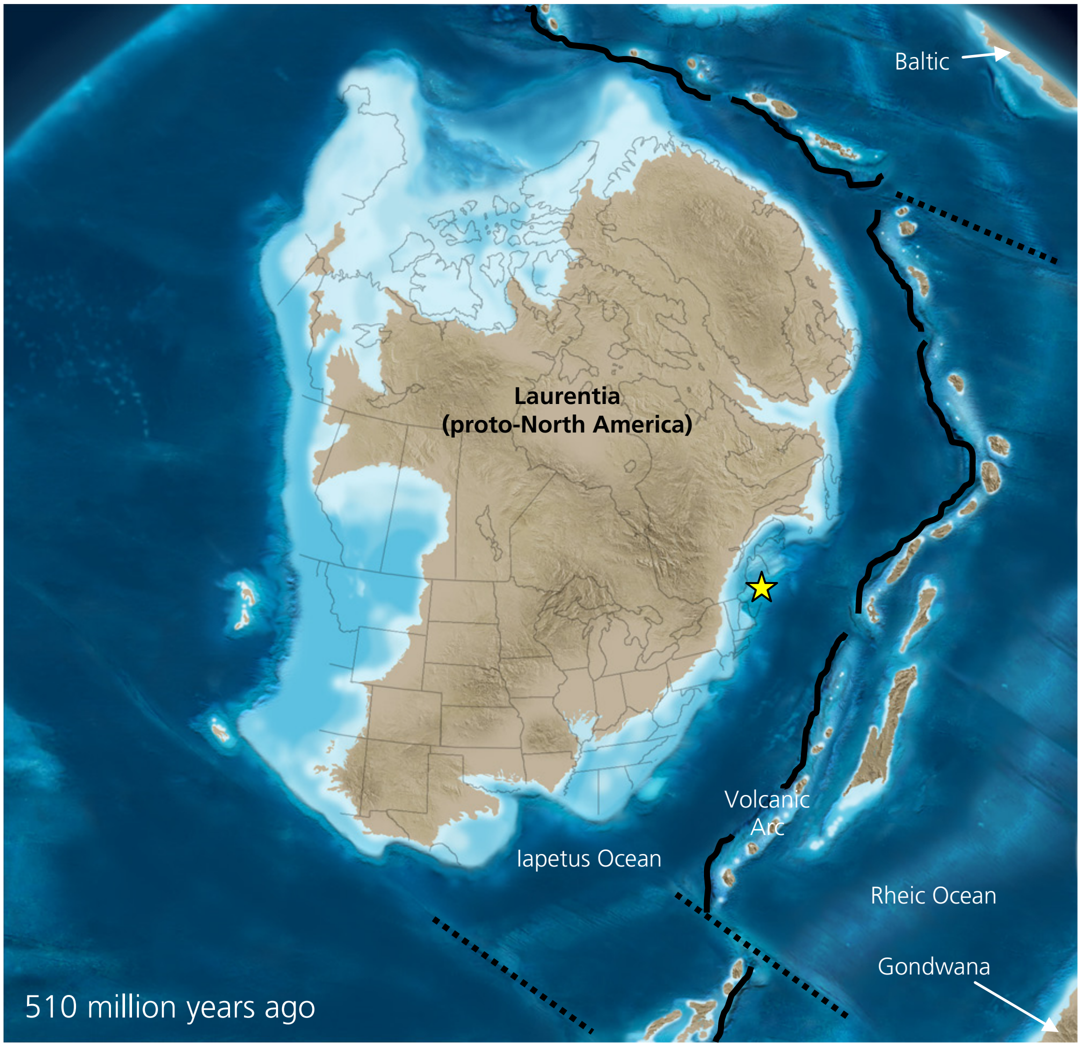


Figure 27. Middle Cambrian paleogeographic map. Approximately 510 million years ago, a volcanic arc (VA) and micro-continents separated the Iapetus Ocean and Laurentia from the Rheic Ocean and Gondwana. The black lines represent approximate locations of paleo-subduction zones (dashed lines are possible paleo-transform faults). At this time, the Baltic landmass was closing on Laurentia. The yellow star (not to scale) marks the approximate location of today's Acadia National Park. Modified from the Middle Cambrian map of Ron Blakey (Northern Arizona University), available online at: http://jan.ucc.nau.edu/rcb7/namC510.jpg, (accessed January 9, 2010).

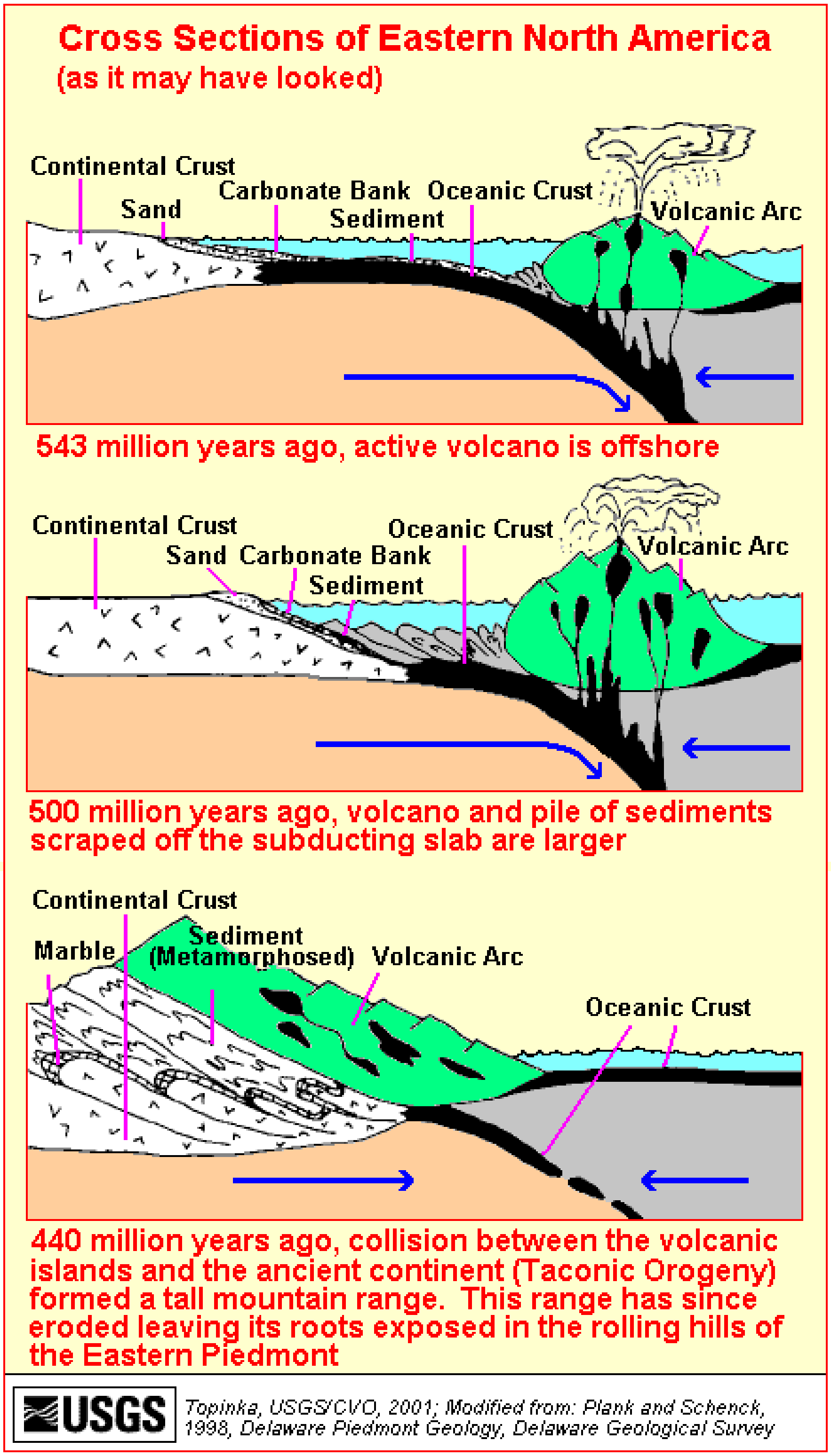


Figure 28. Schematic illustration of the Taconic Orogeny. The volcanic island chain that lay between the micro-continents and Laurentia eventually collided with the eastern seaboard as the Iapetus Ocean closed. Illustration courtesy of the U.S. Geological Survey, available at: http://vulcan.wr.usgs.gov/LivingWith/VolcanicPast/Notes/taconic_orogeny.html, (accessed January 9, 2010).

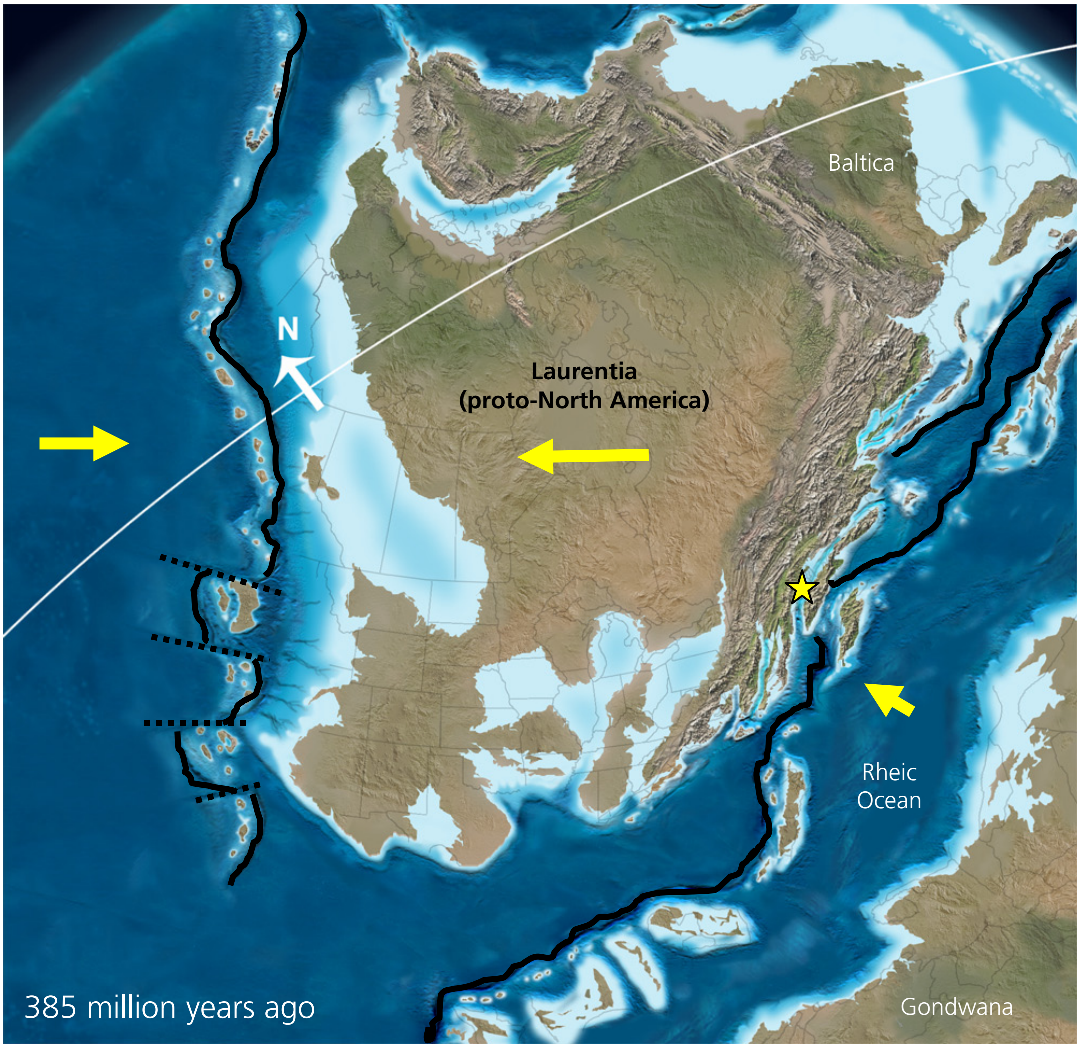


Figure 29. Middle Devonian paleogeographic map. Approximately 385 million years ago, during the Acadian Orogeny, Avalonia and other micro-plates were accreting to the eastern seaboard of Laurentia. The suture zone of Baltica to Laurentia is marked by a Canadian mountain range. The east-to-west closure of Laurentia with Gondwana was closing the Rheic Ocean. The black lines represent approximate locations of paleo-subduction zones. By this time, the western margin of Laurentia had also become an active tectonic margin. Note that the global landmasses were converging near the equator. The yellow arrows suggest the direction of movement of the lithospheric plates; the white arrow indicates the direction of north in the Middle Devonian. The white line is the paleo-Equator. The yellow star (not to scale) marks the approximate location of today's Acadia National Park. Modified from the Middle Devonian map of Ron Blakey (Northern Arizona University), available online at: http://jan.ucc.nau.edu/rcb7/namD385.jpg, (accessed January 9, 2010).

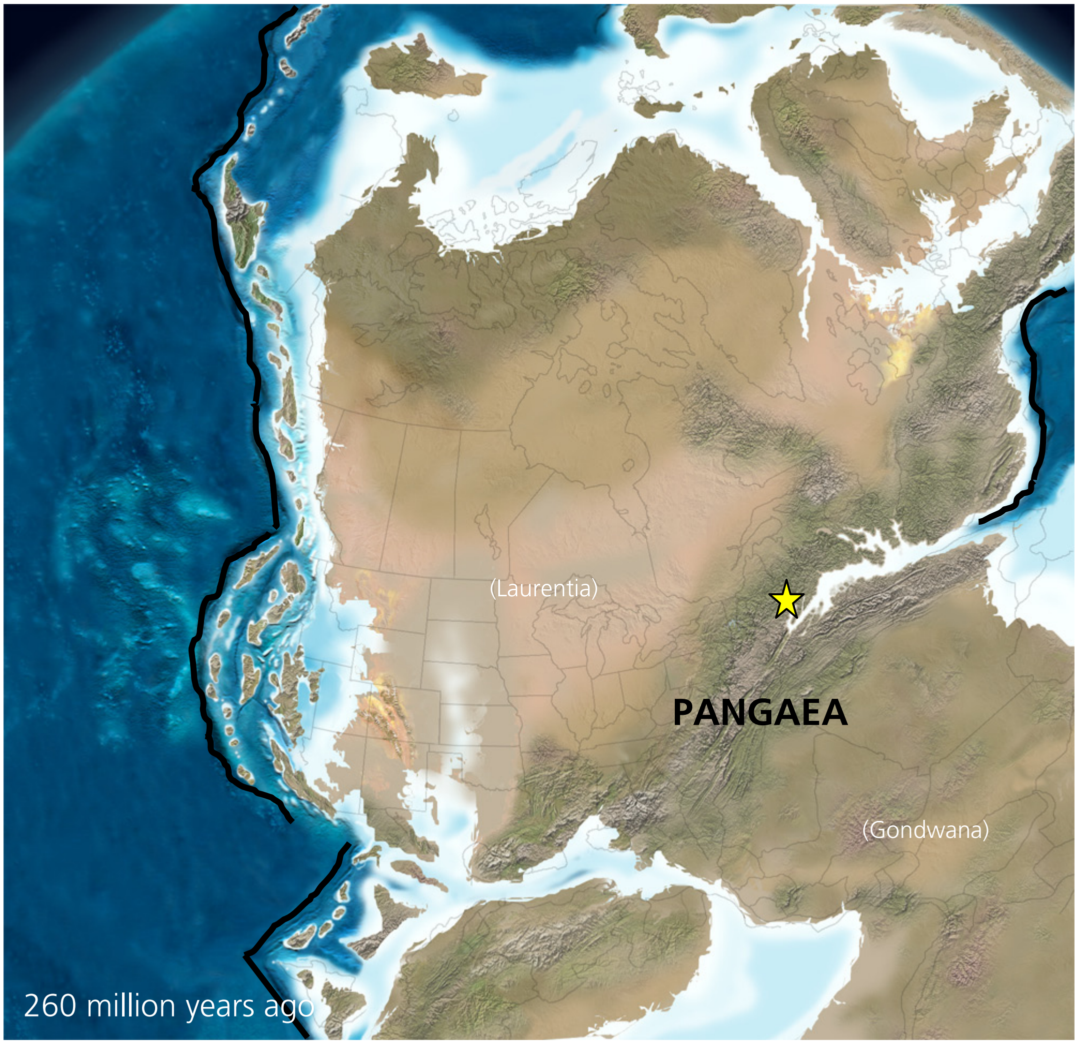


Figure 30. Late Permian paleogeographic map. Approximately 260 million years ago, Gondwana and Laurentia collided to form the supercontinent, Pangaea. Collisions throughout the Paleozoic had created the Appalachian Orogen, which stretched from Canada to west Texas. The black lines represent approximate locations of paleo-subduction zones. The yellow star (not to scale) approximates the location of today's Acadia National Park. Modified from the Late Permian map of Ron Blakey (Northern Arizona University), available online at: http://jan.ucc.nau.edu/rcb7/namP260.jpg, (accessed January 9, 2010).

Figure 31. Quaternary paleogeographic map of North America. Approximately 126,000 years ago, during the Pleistocene ice age, continental glaciers flowed southward and covered the upper Midwest and New England. The yellow star is the approximate location of today's Acadia National Park (not to scale). Modified from the Quaternary map of Ron Blakey (Northern Arizona University), available online at: http://jan.ucc.nau.edu/rcb7/namQ.jpg, (accessed January 9, 2010).

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

alluvium. Stream-deposited sediment.

andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

batholith. A massive, discordant pluton, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.

beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

beach face. The section of the beach exposed to direct wave and/or tidal action.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

biotite. A widely distributed and important rock-forming mineral of the mica group. Forms thin, flat sheets.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cauldron subsidence. The process in which a more or less cylindrical block of rock above a magma chamber collapses into the space left as the magma moves toward the surface.

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

coastline. A broad zone of land and water extending indefinitely both landward and seaward from a shoreline.

concordant. Strata with contacts parallel to the orientation of adjacent strata.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

continental shield. A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust.

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

convergent boundary. A plate boundary where two tectonic plates are colliding.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

crystal tuff. A tuff that consists chiefly of crystals and fragments of crystals.

dacite. A fine-grained extrusive igneous rock similar to andesite but with less calcium-plagioclase minerals and more quartz.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

discordant. Describes contacts between strata that cut across or are set at an angle to the orientation of adjacent rocks.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

dune. A low mound or ridge of sediment, usually sand, deposited by wind.

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix; many estuaries are drowned river valleys caused by sea-level rise (transgression) or coastal subsidence.

exfoliation. The breakup, spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by differential stresses due to thermal changes or a reduction in pressure when overlying rocks erode away.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

felsite. A general term for any light-colored, fine-grained extrusive rock composed chiefly of quartz and feldspar.

fjard. A small, narrow, irregular inlet or bay, typically formed by submergence of a glacial valley excavated in a lowland along the margin of a flat rocky coast. A fjard is shorter, shallower, and broader in profile than a fjord.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral; also any break in a rock (e.g., crack, joint, or fault).

gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

hanging wall. The mass of rock above a fault surface (also see "footwall").

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

hornfels. A fine-grained rock composed of a mosaic of grains that are the same size in each dimension without preferred orientation. Typically formed by contact metamorphism, which occurs near the contact with an intrusion of molten material.

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

isostacy. The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere. Crustal loading (commonly by large ice sheets) leads to isostatic depression or downwarping; removal of the load leads to isostatic uplift or upwarping.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

keratophyres. A term applied to salic (silicon or aluminum-rich minerals) or hypabyssal rocks.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

lithic tuff. A dense deposit of volcanic ash in which the fragments are composed of previously formed rocks that first solidify in the vent and are then blown out.

lithification. The conversion of sediment into solid rock.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

littoral zone. The benthic ocean environment or depth zone between high water and low water.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.
mantle. The zone of Earth's interior between the crust and core.
mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.
matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.
mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."
member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.
meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.
metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.
metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.
mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margin(s) in Earth's oceans.
mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.
normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.
obduction. The process by which the crust is thickened by thrust faulting at a convergent margin.
oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.
orogeny. A mountain-building event.
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.
outwash. Glacial sediment transported and deposited by meltwater streams.
paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.
parent material. Geologic material from which soils form.
passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").
perthite. A variety of feldspar consisting of parallel or subparallel intergrowths in which the potassium-rich phase (usually microcline) appears to be the host from which the sodium-rich phase (usually albite) separated at a critical temperature.
plastic. Capable of being deformed permanently without rupture.
plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.
pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.
porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.
potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).
pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.
radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.
radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.
regression. A long-term seaward retreat of the shoreline or relative fall of sea level.
relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.
reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").
rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.
roche moutonnée. An elongate, eroded ridge or knob of bedrock carved by a glacier parallel to the direction of motion with gentle upstream and steep downstream surfaces.
rock. A solid, cohesive aggregate of one or more minerals.
sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).
sandstone. Clastic sedimentary rock of predominantly sand-sized grains.
seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.
sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.
sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.
shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.
silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.
sill. An igneous intrusion that is of the same orientation as the surrounding rock.
silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).
siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

stock. An igneous intrusion exposed at the surface; less than 100 km^2 (40 mi^2) in size. Compare to “pluton.”

strata. Tabular or sheet-like masses or distinct layers of rock.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be “sinistral” (left-lateral) if relative motion of the block opposite the observer appears to be to the left. “Dextral” (right-lateral) describes relative motion to the right.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth’s surface.

suture. The linear zone where two continental landmasses become joined via obduction.

tectonic. Relating to large-scale movement and deformation of Earth’s crust.

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

theory. A hypothesis that has been rigorously tested against further observations or experiments to become a generally accepted tenet of science.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

topography. The general morphology of Earth’s surface, including relief and locations of natural and anthropogenic features.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trend. The direction or azimuth of elongation of a linear geologic feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth’s surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

weathering. The physical, chemical, and biological processes by which rock is broken down.

Literature Cited

This section lists references cited in this report. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.

Anderson, R. S., N. G. Miller, R. B. Davis, and R. E. Nelson. 1990. Terrestrial fossils in the marine Presumpscot Formation: Implications for late Wisconsinan paleoenvironments and isostatic rebound along the coast of Maine. Canadian Journal of Earth Sciences 27: 1242-1246.

Barnhardt, W. A., W. R. Gehrels, D. F. Belknap, and J. T. Kelley. 1995. Late Quaternary relative sea-level change in the western Gulf of Maine: Evidence for a migrating glacial forebulge. Geology 23 (4): 317-320.

Belknap, D. F. and J. T. Kelley. 1993. Late Quaternary evolution of the northern Gulf of Maine. Geological Society of America Abstracts with Programs 25 (6): 335.

Belknap, D. F., B. G. Andersen, R. S. Anderson, W. G. Anderson, H. W. Borns, Jr., G. W. Jacobson, J. T. Kelley, R. C. Shipp, D. C. Smith, R. Stuckenrath, Jr., W. W. Thompson, and D. A. Tyler. 1987. Late Quaternary sea-level changes in Maine. Pages 71-85 *in* D. Nummedal, editor. Sea-level fluctuation and coastal evolution. Society for Sedimentary Geology, Special Publication 41, Tulsa, Oklahoma, USA.

Berry, H. N. 2006. Earthquakes in Maine. Maine Geological Survey, Augusta, ME. (http://www.maine.gov/doc/nrimc/mgs/explore/hazards/quake/quake.htm). Accessed 28 July 2010.

Berry, H. N. 2007. A review of coastal Maine stratigraphy. Geological Society Abstracts with Programs 39 (1): 48.

Bradley, D. C. 1997. The Northern Appalachians. Pages 445-450 *in* B.A. van der Pluijm and S. Marshak, editors. Earth Structure. WCB/McGraw-Hill, Dubuque, Iowa, USA.

Bradley, D. C., R. D. Tucker, D. R. Lux, A. G. Harris, and D. C. McGregor. 2000. Migration of the Acadian Orogen and foreland basin across the Northern Appalachians of Maine and adjacent areas. Professional Paper 1624. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/pp/pp1624). Accessed 29 July 2010.

Braile, L. W. 2009. Seismic monitoring. Pages 229-244 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA.

Bush, D. M and R. Young. 2009. Coastal features and processes. Pages 47-67 *in* R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado, USA.

Coombs, M. L. 1994. Petrology and geochemistry of the southern intrusive breccia zone, Cadillac Mountain pluton, Mount Desert Island, Maine. Geological Society of America, Northeastern Section, Abstracts with Programs 26 (3): 12.

Gilman, R. A., C. A. Chapman, T. V. Lowell, and H. W. Borns, Jr. 1988. The geology of Mount Desert Island: A visitor's guide to the geology of Acadia National Park. Bulletin 38. Maine Geological Survey, Augusta, Maine, USA.

Gilman, R. A. and C. A. Chapman. 1988. Bedrock geology of Mount Desert Island. Bulletin 38. Maine Geological Survey, Augusta, Maine, USA (scale 1:50,000).

Harris, A. G., E. Tuttle, and S. D. Tuttle. 1997. Geology of national parks. 5th ed. Kendall/Hunt Publishing Company, Dubuque, Iowa, USA.

Hebert, T. 2009. Acadian-Cajun genealogy and history: Origins of the Acadians. (http://www.acadian-cajun.com/origin.htm). Accessed 27 July 2010.

Hogan, J. P. and A. K. Sinha. 1989. Compositional variation of plutonism in the coastal Maine magamatic province: Mode of origin and tectonic setting. Pages 1-33 *in* R. D. Tucker and R. G. Marvinney, editors. Studies of Maine Geology: Igneous and Metamorphic Geology. Maine Geological Survey, Department of Conservation, Augusta, Maine, USA.

Kaplan, M. R. and H. W. Borns, Jr. 1994. The deglaciation of southeastern coastal Maine. American Quaternary Association Program and Abstracts 13: 106.

Kafka, A. L. 2008. Why does the Earth quake in New England? Boston College, Weston Observatory, Department of Geology and Geophysics, Boston, Massachusetts, USA. (http://www2.bc.edu/~kafka/Why_Quakes/why_quakes.html). Accessed 29 July 2010.

Karl, T. R., J. M. Melillo, and T. C. Peterson, editors. 2009. Global climate change impacts in the United States. Cambridge University Press, New York, New York, USA. (http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/full-report) Accessed 15 July 2010.

Kiver, E. P. and D. V. Harris. 1999. Geology of U.S. parklands. 5th ed. John Wiley & Sons, Inc., New York, New Yord, USA.

Lowell, T. V. and H. W. Borns, Jr. 1988. Surficial geology of Mount Desert Island. Maine Geological Survey, Augusta, Maine, USA (scale 1:50,000).

Maine Bureau of Air Quality. 2005. Acid rain. Bureau of Air Quality, Augusta, Maine, USA. (http://www.maine.gov/dep/air/acidrain). Accessed 28 July 2010.

Maine Department of Conservation. 2005. Testing ocean energy in Maine. Department of Conservation, Augusta, Maine, USA. (http://www.maine.gov/doc/initiatives/oceanenergy/oceanenergy.shtml). Accessed 28 July 2010.

Maine Department of Environmental Protection. 2005. Mercury: A significant environmental problem. Department of Environmental Protection, Augusta, Maine, USA. (http://www.maine.gov/dep/mercury). Accessed 28 July 2010.

Maine Geological Survey. 2005a. Somes Sound, Mount Desert Island. Department of Conservation, Augusta, Maine, USA. (http://www.maine.gov/doc/nrimc/mgs/explore/marine/sites/nov98.htm). Accessed 28 July 2010.

Maine Geological Survey. 2005b. Sea-level change on Mount Desert Island. Department of Conservation, Augusta, Maine, USA. (http://www.maine.gov/doc/nrimc/mgs/explore/marine/sites/mar02.htm). Accessed 29 July 2010.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, and Z. –C. Zhao. 2007. Global Climate Projections. *in* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA. (http://www.ipcc-wg1.unibe.ch/publications/wg1-ar4/wg1-ar4.html) Accessed 27 July 2010.)

Murphy, J. B., G. Gutierrez-Alonso, R. D. Nance, J. Fernandez-Suarez, J. D. Keppie, R. A. Strachan, and J. Dostal. 2006. Origin of the Rheic Ocean: Rifting along a Neoproterozoic suture? Geological Society of America, Northeastern Section, Abstracts with Programs 38 (2): 21.

Murphy, J. B., J. D. Keppie, and R. D. Nance. 2007. What is the Acadian Orogeny? Geological Society of America, Northeastern Section, Abstracts with Programs 39 (1): 69.

National Park Service. 1994. Baseline water quality data inventory and analysis: Acadia National Park. Water Resources Division, National Park Service, Fort Collins, Colorado, USA. (http://nrdata.nps.gov/ACAD/nrdata/water/baseline_wq/docs/ACADWQAA.pdf). Accessed 28 July 2010.

National Park Service. 2006a. History and culture: *Stories*. Acadia National Park website, Bar Harbor, Maine, USA. (http://www.nps.gov/acad/historyculture/stories.htm). Accessed 27 July 2010.

National Park Service. 2006b. History and culture: Weather. Acadia National Park website, Bar Harbor, Maine, USA. (http://www.nps.gov/acad/naturescience/weather.htm). Access 27 July 2020.

National Park Service. 2006c. Acadia National Park: Water quality. Acadia National Park website, Bar Harbor, Maine, USA. (http://www.nps.gov/acad/naturescience/waterquality.htm). Accessed July 31, 2010.

National Park Service. 2008. Geologic Resource Evaluation Scoping Summary: Acadia National Park, Maine. National Park Service, Geologic Resources Division, Lakewood, Colorado, USA. (http://www.nature.nps.gov/geology/inventory/publications/s_summaries/ACAD_scoping_summary_2006-0922.pdf). Accessed 28 July 2010.

National Park Service. 2009a. Nature and science. Acadia National Park website, Bar Harbor, Maine, USA. (http://www.nps.gov/acad/naturescience/index.htm). Accessed 27 July 2010.

National Park Service. 2009b. History and culture: Wabanaki ethnography. Acadia National Park website, Bar Harbor, Maine, USA. (http://www.nps.gov/acad/historyculture/ethnography.htm). Accessed 27 July 2010.

National Park Service. 2009c. Park news: High surf washes visitor into ocean at Acadia National Park. Acadia National Park website, Bar Harbor, Maine, USA. (http://www.nps.gov/acad/parknews/high-surf-washes-visitor-into-ocean.htm). Accessed 28 July 2010.

National Oceanic and Atmospheric Administration. 2007. The Patriot's Day Storm of 2007. National Weather Service Forecast Office, Gray, Maine, USA. (http://www.erh.noaa.gov/gyx/patriots_day_storm_2007.htm). Accessed 28 July 2010.

National Oceanic and Admospheric Administration Satellite and Information Service. 2008. The perfect storm: October 1991. National Climatic Data Center, Washington, D.C. (http://www.ncdc.noaa.gov/oa/satellite/satelliteseye/cyclones/pfctstorm91/pfctstorm.html). Accessed 28 July 2010.

New England Climate Coalition. 2003. Global warming in New England states. (http://www.newenglandclimate.org/effectsbystate.htm). Accessed 28 July 2010.

Petraitis, P. S., S. R. Fegley, and B. F. Beal. 2002. Ecological assessment of the Anemone Cave in Acadia National Park. Acadia National Park files.

Reusch, D. N. 2002. The Ellsworth Schist, Maine: Acadian-telescoped rift sequence or Penobscottian accretionary complex? Geological Society of America, Northeastern Section, Abstracts with Programs 34 (1): 76.

Reusch, D. N. and K. L. Rust. 2001. Post-rifting fate of the peri-Gondwanan Ellsworth Schist, Newbury Neck, Maine. Geological Society of America, Northeastern Section, Abstracts with Programs 33 (1): 79.

Rothe, R. 1995. Acadia: The story behind the scenery. KC Publications, Las Vegas, Nevada, USA.

Seaman, S. J. 2000. Physical volcanology and petrogenesis of the Late Silurian Cranberry Island series, coastal Maine. Pages 23-37 *in* M. G. Yates, R. R. Lux, and J. T. Kelley, editors. Guidebook for field trips in coastal and east-central Maine. University of Maine, Orono, Maine, USA.

Seaman, S. J. and R. A. Wobus. 1995. The Cranberry Island Series of coastal Maine: Bimodal volcanism on pre-Acadian Avalon. International Union of Geodesy and Geophysics Abstracts 21: 439.

Seaman, S. J., R. A. Wobus, R. W. Wiebe, N. Lubick, and S. A. Bowring. 1995. Volcanic expression of bimodal magmatism: The Cranberry Island – Cadillac Mountain Complex, coastal Maine. Journal of Geology 103 (3): 301-311.

Seaman, S. J., E. E. Scherer, R. A. Wobus, J. H. Zimmer, and J. G. Sales. 1999. Late Silurian volcanism in coastal Maine: The Cranberry Island series. Geological Society of America Bulletin 111 (5): 686-708.

Schuh, K. J. 1994. Petrology of the Somesville granite, Mount Desert Island, Maine. Geological Society of America, Northeastern Section, Abstracts with Programs 26 (3): 71.

Schulz, K. J., D. B. Stewart, and R. D. Tucker. 2003. Geochemistry of the Cambrian Ellsworth Schist and Castine Volcanics, Penobscot Bay area, Maine: Implications for paleotectonic setting. Geological Society of America, Northeastern Section, Abstracts with Programs 35 (3): 78.

Schulz, K. J., D. B. Stewart, R. D. Tucker, J. C. Pollock, and R. Ayuso. 2008. The Ellsworth Terrane, coastal Maine; geochronology, geochemistry, and Nd-Pb isotopic composition: Implications for the rifting of Ganderia. Geological Society of America Bulletin 120: 1134-1158.

Suppe, J. 1985. Principles of Structural Geology. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA.

Symchych, E. M. 1994. Evidence of periodic basaltic injections into the crystalline mush of the Cadillac Mountain granite magma chamber, Mount Desert Island, Maine. Geological Society of America, Northeastern Section, Abstracts with Programs 26 (3): 75.

Thieler, E. R. and E. S. Hammar-Klose. 1999. National assessment of coastal vulnerability to sea-level rise: Preliminary results for the U.S. Atlantic coast. Open-File Report 99-593. U.S. Geological Survey, Reston, Virginia, USA. (http://pubs.usgs.gov/of/1999/of99-593/index.html). Accessessed February 19, 2010.

Titus, J. G. and C. Richman. 2001. Maps of lands vulnerable to sea level rise: Modeled elevations along the U.S. Atlantic and Gulf coasts. Climate Research 18 (3): 205-228. (http://www.int-res.com/articles/cr/18/c018p205.pdf). Accessed 29 July 2010.

Tweet, J. S., V. L. Santucci, and J. P. Kenworthy. 2010. Paleontological resource inventory and monitoring: Northeast Temperate Network. Natural Resource Technical Report NPS/NRPC/NRTR—2010/326. National Park Service, Fort Collins, Colorado, USA.

U.S. Geological Survey. 2006. Maine earthquake lowers ground water. U.S. Geological Survey Newsroom, Reston, Virginia, USA. (http://www.usgs.gov/newsroom/article.asp?ID=1562). Accessed 28 July 2010.

U.S. Geological Survey. 2009. Maine: Earthquake history. U.S. Geological Survey, Earthquake Hazards Program, Reston, Virginia, USA. (http://earthquakes.usgs.gov/earthquakes/states/maine/history.php). Accessed 28 July 2010.

Van Staal, C. R. 2007. Pre-Carboniferous tectonic evolution and metallogeny of the Canadian Appalachians. Pages 793-818 in W. D. Goodfellow, editor. Mineral deposits of Canada: A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods. Geological Association of Canada, Special Publication 5, St. John's, Newfoundland, Canada.

Van Staal, C. R., S. M. Barr, L. R. Fyffe, V. McNicoll, J. C. Pollock, D. N. Reusch, M. Thomas, P. Valverde-Vacquero, and J. Whalen. 2002. Ganderia – an important peri-Gondwanan terrane in the northern Appalachians. Geological Society of America, Northeastern Section, Abstracts with Programs 34 (1): 28.

Vollmer, F. W. 2009. Relationship between exfoliation dome geometry and topography on Cadillac Mountain, Mount Desert Island, Maine. Geological Society of America, Northeastern Section, Abstracts with Programs 41 (3): 14.

Waterman, M. 2008. Harnessing the Gulf's winds, tides for reliable energy independence. *Gulf of Maine Times* 12 (3). (http://www.gulfofmaine.org/times/fallwinter2008/energy.php). Accessed 28 July 2010).

Wiebe, R. A. 1994. Silicic magma chambers as traps for basaltic magmas: The Cadillac Mountain intrusive complex, Mount Desert Island, Maine. Journal of Geology 102: 423-437.

Wiebe, R. A., J. B. Holden, M. L. Coombs, R. A. Wobus, K. J. Schuh, and B. P. Plummer. 1997a. The Cadillac Mountain intrusive complex, Maine: The role of shallow-level magma chamber processes in the generation of A-type granites. Pages 397-418 in A. K. Sinha, J. B. Whalen, and J. P. Hogan, editors, The nature of magmatism in the Appalachian Orogen. Geological Society of America Memoir 191, Boulder, Colorado, USA.

Wiebe, R. A., D. Smith, M. Sturm, E. M. King, and M. S. Seckler. 1997b. Enclaves in the Cadillac Mountain Granite (coastal Maine): Samples of hybrid magma from the base of the chamber. Journal of Petrology 38 (3): 393-423.

Wieczorek, G. F. and J. B. Snyder. 2009. Monitoring slope movements. Pages 245-271 *in* Geological Monitoring. Geological Society of America, Boulder, Colorado, USA.

Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of August 2010.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado). http://nature.nps.gov/geology/

NPS Geologic Resources Inventory. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

U.S. Geological Survey Geology of National Parks (includes 3D photographs). http://3dparks.wr.usgs.gov/

Harris, A. G., E. Tuttle, and S. D. Tuttle. 2003. Geology of National Parks. Sixth Edition. Kendall/Hunt Publishing Co., Dubuque, Iowa, USA.

Kiver, E. P. and D. V. Harris. 1999. Geology of U.S. parklands. John Wiley and Sons, Inc., New York, New York, USA.

Lillie, R. J. 2005. Parks and Plates: The geology of our national parks, monuments, and seashores. W.W. Norton and Co., New York, New York, USA. [Geared for interpreters].

NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program. http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf.

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual
R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado.

[Website under development]. Contact the Geologic Resources Division to obtain a copy.

NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

State Geological Survey Websites

Maine Geological Survey: http://www.maine.gov/doc/nrimc/mgs/mgs.htm

Association of American State Geologists: http://www.stategeologists.org/

Geological Societies

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

Unites States Geological Survey (USGS):

U.S. Geological Survey: http://www.usgs.gov/

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey Seamless Server (download digital data, including imagery, elevation, boundaries): http://seamless.usgs.gov

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.usgs.gov

U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix A: Overview of Digital Geologic Data

The following page is an overview of the digital geologic data for Acadia National Park. For a poster-size PDF of this overview and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Appendix B: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Acadia National Park, held on June 9–10, 2008. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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