
Abstract

The geology of the northeastern United States begins with the late Mesoproterozoic, over 1 billion years ago, when the Grenville suite of metamorphics (including the Grenville Marble) of the Adirondack Mountains was formed during the assembly of the supercontinent of Rodinia. Cambrian and early Ordovician carbonates, along with clastics, were deposited in continental shelf conditions until the mid-Ordovician Taconic Orogeny, when those carbonates were metamorphosed to marbles in eastern New York, southwestern Vermont, western Massachusetts and southeastern Connecticut. In central New York, those carbonates were unaffected, and from the late Silurian through the early Devonian, the Helderberg Group carbonates were deposited, shifting to clastics and back to the Onondaga Limestone by mid-Devonian. The onset of the Acadian Orogeny to the east in the late Silurian progressed westward, shedding clastics and eventually greatly deforming the Devonian carbonates along the Hudson River Valley. Other than Holocene calcareous tufa, no further carbonates were deposited on the region; clastic units of the Catskills migrated westward as the Alleghenian Orogeny ended the Paleozoic with the completion of the supercontinent of Pangea. Triassic rifting influenced southern New York and formed the Connecticut River valley, and Mesozoic intrusions developed farther east in New Hampshire and Maine. Erosion and peneplanation dominated the region from the Mesozoic through the Cenozoic until the onset of continental glaciation in the Pleistocene. Late Cenozoic doming brought the Adirondack Mountains upward, the region's oldest rocks becoming the youngest tectonic feature. Caves and karst as visible today may have initiated in the late Pliocene.

To understand the karst of the northeastern United States it is important to know the events that shaped the region, from the Precambrian and Paleozoic orogenic events, to the Quaternary glaciations. These events created the various physiographic provinces of New York and New England (Fig. 2.1), each with differing

geology shaped by these events. Mountain building events in the Precambrian and Paleozoic have created the basement rocks of the region; developed basins in which sediments have been deposited, and deformed preexisting sedimentary rocks, in some cases metamorphosing them. Rifting in the region has also created



Fig. 2.1 The physiographic provinces of New York and New England follow their underlying geology. The Appalachian Plateaus province is characterized by flat lying, Siluro-Devonian strata in New York. The Valley and Ridge province contains deformed Siluro-Devonian strata, modified through multiple orogenic events. The lowland provinces that rim the Great Lakes, St. Lawrence River, and Lake Champlain contain relatively flat lying Cambrian, Ordovician, and Silurian strata, though some Precambrian exposures exist. The Adirondack province is composed of Precambrian metamorphic units. The New England province consists mainly of metamorphosed Paleozoic strata, as well as Mesozoic plutonic rocks. The Piedmont and Coastal Plain provinces do appear in the region, but are limited. These different provinces correspond to the differing karst regions explored here; the Helderberg Plateau region exists in the Appalachian Plateau, the Hudson Valley Fold-Thrust Belt region exists in the Valley and Ridge, and the northern New York Lowlands exist in the Central Lowland, St. Lawrence Valley, and Appalachian Plateaus. The Adirondacks and New England karst regions correspond to their respective provinces

basins during the breakup of Pangea, and preserves some sedimentary rocks from the Triassic Period. Igneous rocks have also formed from plutonism during mountain building and rifting. While igneous rocks do not form karst they do form pseudokarst and non-dissolution caves (Chap. 4). In the New England states with low karstic rock extent (Chap. 1, Fig. 1.1), non-dissolutional caves are the primary cave type.

Geomorphically New York and New England have been shaped by erosion of the previously high-relief mountain ranges, as well as the low relief plateaus of non-deformed areas. Erosion has included long-scale fluvial erosion, as well as the glacial erosion of the Quaternary.

Of importance for the discussion of the karst of northeastern United States are the creation of basins, the deposition of limestone and dolomite and their adjacent non-soluble units, the deformation of these units and their metamorphism, and the erosion of these units to their modern extent by fluvial and glacial processes.

2.1 Precambrian—Grenville Orogenic Events

The oldest rocks in New York and New England are the Precambrian Grenville-aged metamorphic and igneous rocks. These rocks make up the basement rock of much of the eastern United States as the Laurentian Craton, and crop out in New York in two areas: the Adirondack Mountains, and the Hudson Highlands (Isachsen et al. 2000). This suite of rocks is composed of metamorphosed sedimentary rocks that were deposited in the shallow pre-Grenville seas, metamorphosed anorthosites in the Adirondacks, and granites in the Hudson Highlands. The Grenville orogeny is associated with the formation of the supercontinent Rodinia (Fig. 2.2), and occurred in multiple events between 1.3 and 1.0 Ga (Tollo et al. 2004). Dates from

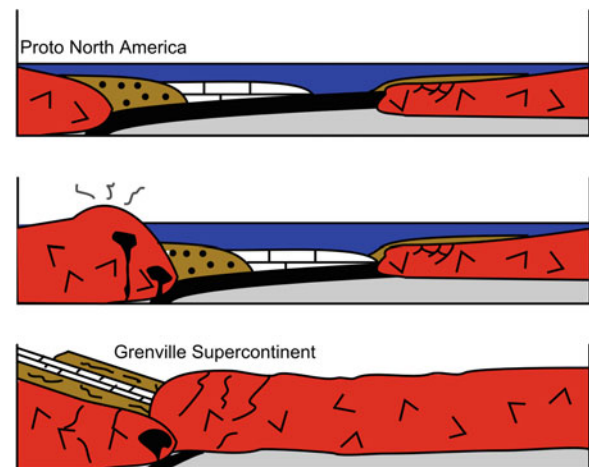


Fig. 2.2 Formation of the Grenville supercontinent during the Grenville Orogeny (1.3–1.1 Ga). Clastics and carbonates were deposited in the pre-Grenville ocean off of Proto North America. These units were metamorphosed and are the basement rock of much of eastern North America, outcropping in the Adirondack Mountains, as well as the Hudson Highlands

exposed rocks in New York associate them with the 1.1 Ga orogenic phase. While the rocks associated with the Grenville Orogeny are the oldest in the region, their exposure is recent in the Adirondack Mountains as dome uplift continues to this day, making them the youngest mountains in the region.

The variety of rocks within the Grenville metamorphics includes schist, gneiss, marble, and meta-anorthosite. Igneous rocks include a variety of granites that comprise the Hudson Highlands. The metamorphic rock units crop out in both southeastern New York, and in the Adirondacks, though these units have a larger extent in the Adirondacks. Caves and karst have formed in the marble distributed around the Adirondacks, and the marble units tend to be sandwiched between two schist units, analogous to the stripe-karst seen in Norway, though they do not produce the multi-level network mazes displayed in the Norwegian examples (Faulkner 2009; Chap. 9).

While not karst forming, the igneous and metamorphic rocks of the Grenville suite do produce non-dissolution caves. When over-steepened, these rock slopes can produce crevice caves on initial fracture, and talus piles and caves upon fracture failure (Chap. 4).

Additional exposed Precambrian rocks in New England include those of the Berkshire Massif, a series of metamorphic rocks that crop out in Connecticut, Massachusetts and Vermont. Other karst forming Precambrian units includes the Sherman Marble (Porter 2009) of Massachusetts and Vermont.

2.2 Paleozoic Mountain Building and Deposition

2.2.1 Cambro-Ordovician—Taconic Orogenic Events

After the Grenville orogeny, the subsequent period of the Rodinia supercontinent rifting occurred creating the Iapetus Ocean, and defined the beginning of the continent of Laurentia (North America and Greenland). This rifting created basins in which sediments were deposited and preserved. In some eastern parts of New York and in New England the Cambrian sedimentary rocks were later metamorphosed, including limestone into marble where karst has formed (Chap. 8). In the Lake Ontario—St. Lawrence—Lake Champlain lowlands, Mohawk Valley, and west of the Taconic Mountains

along the Hudson River Cambro-Ordovician limestones crop out. Those Cambro-Ordovician units close to the Taconic Mountains have been deformed, but not metamorphosed, while those in northern New England, the northern New York lowlands and Mohawk Valley are minimally deformed (Isachsen et al. 2000).

During the Cambrian and Ordovician eastern Laurentia was covered in shallow, epicontinental seas in passive margin conditions. Sedimentation during this time can be broken into two sequences: the clastic Taconic Sequence, and the Carbonate or Shelf Sequence (Zen 1961; Isachsen et al. 2000). Initial sedimentation in the basins occurred from the erosion of Grenville-aged material generating quartz sands in both the carbonate/shelf sequence, and the Taconic sequence. The Taconic Sequence (Fig. 2.3) contains a variety of clastic formations with outcroppings in New York, Massachusetts, Connecticut, and Vermont. This sequence of clastics originates from the approaching

Ordovician	Upper Ordovician	Snake Hill Shale	
	Middle Ordovician	Normans-kill	Austin Glen
			Mount Merino
			Indian River
Cambrian	Lower Ordovician	Deep Kill	
	Upper Cambrian	Hatch Hill	
	Middle Cambrian		
	Lower Cambrian	M. Granville Browns Pond Mudd Pond	Diamond Rock
		Mettawee Zion Hill	Nassau Curtis Mtn.
		Mettawee Bomoseen Rensselaer	Nassau

Fig. 2.3 Stratigraphic column of the Taconic sequence of clastics that eroded from the Taconic/Iapetus terrane. While there are no carbonate units in this clastic sequence, carbonates were deposited contemporaneously to the west

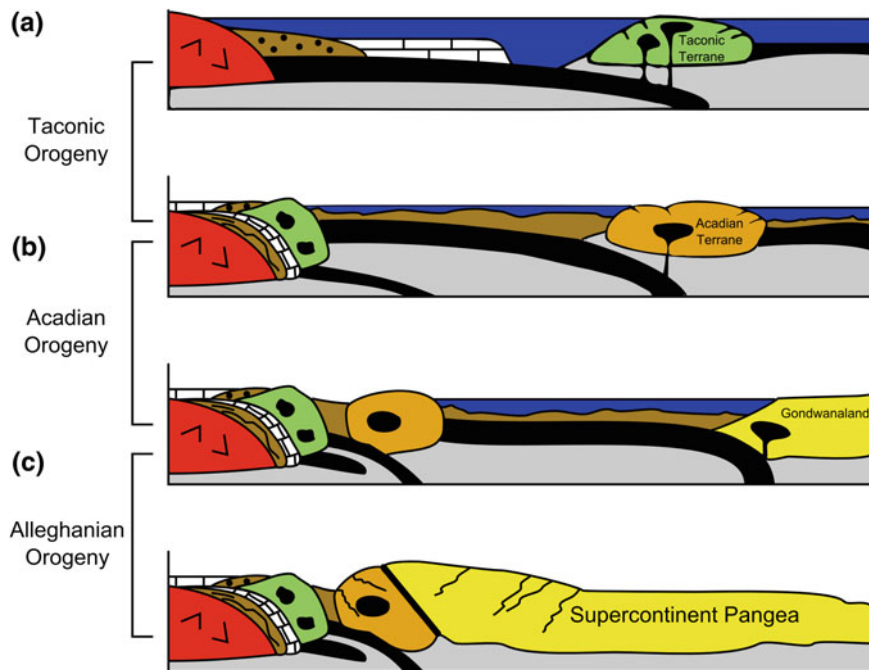


Fig. 2.4 The northeastern United States has been affected by several orogenic events. **a** The Taconic orogeny, involving the Grenville province and volcanic arc Taconic Terrane. **b** The Acadian orogeny, involving Laurentia, and the Acadian Terrane. The Acadian orogeny added parts of Connecticut, New

Hampshire, and Maine, as well as the entirety of Rhode Island onto the eastern margin of Laurentia. **c** The Alleghanian orogeny occurred between Laurentia and Gondwanaland, closing the Iapetus Ocean and forming the supercontinent Pangea

volcanic Iapetus Terrane (Fig. 2.4a). As clastic input generally shuts down carbonate production, the Taconic Sequence is lacking in carbonate units, and therefore does not develop karst. Some of these continuous or equivalent units have differing stratigraphic names depending on the state, and some units have confusing multiple names due to their fragmentary outcrop nature resulting from deformation (Vollmer and Walker 2009).

Of greater interest for karst development, the Carbonate Sequence (Fig. 1.2) of the Cambrian and Ordovician generated several extensive limestone and dolomite units, some of which have been subsequently metamorphosed into marble. Paleogeographically, Laurentia was located along the equator at this time (Fig. 2.5), allowing the deposition of these carbonates in shallow epicontinental seas, and out to the paleo-shoreline in modern day Vermont, Massachusetts, and Connecticut. In southeastern New York and western New England the earliest unit deposited in the Cambrian was the Stockbridge Group (called the Wappinger Group in New York). In the lowlands of northern

New York and northwestern New England the Beekmantown Group was deposited contemporaneously

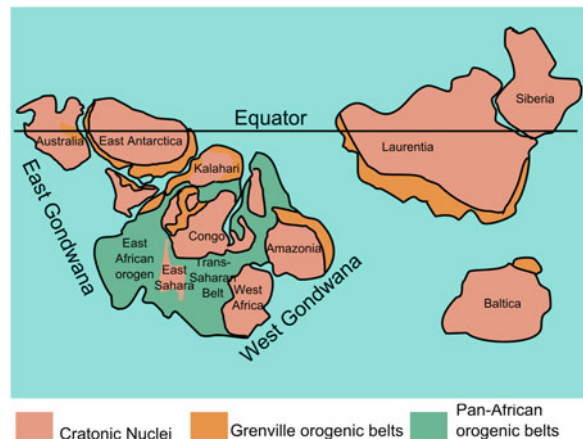


Fig. 2.5 Paleogeographic map for the Cambrian. During this time most of the continents were tied up near the South Pole. Laurentia's position is near the equator, allowing the formation of carbonates during this period, and subsequent time periods of the Paleozoic. (Redrawn from Technical Report USGS-TR-98-3)

with the Stockbridge Group. Karstic units within the Beekmantown Group include the Bascom Formation (Porter 2009) and the Little Falls Formation (Engel 2009). Both of these groups have karstic units (Plante 1990; Engel 2009), and the Stockbridge Group forms most of the karst in the Berkshires where it was metamorphosed into marble during the Taconic and subsequent orogenic events. Deposition of these units continued into the Lower Ordovician.

Through the Middle Ordovician, deposition of carbonates continued in the shallow seas of Laurentia. One of the most extensive carbonate units of the Middle Ordovician is the Chazy Group. Outcrops of the formations within the Chazy Group extend from the Champlain lowlands of northern New York, through Vermont, and into Newfoundland. This group represents some of the earliest fossilized reefs. The karst units within the Chazy Group such as the Valcour Limestone contain several caves in northeastern New York and western Vermont.

Through the Middle Ordovician the Taconic Orogeny began influencing eastern Laurentia causing greater clastic input along the paleo-shoreline. Throughout the beginnings of orogeny, however, some periods of tectonic quiescence existed, allowing deposition of carbonates of the Walloomsac Formation, an irregularly appearing karst forming formation ranging from modern day western Massachusetts to southeastern New York in the Stockbridge Valley (Plante 1990; Isachsen et al. 2000), and the karst forming Middlebury and Chipman formations in Vermont (Porter 2009; Scott 2013). Continued mountain building in this area during the Middle Ordovician formed the Taconic Mountains, and the Berkshire Mountains (termed Green Mountains in Vermont), and metamorphosed the clastics of the Taconic Sequence, and the carbonates of the Carbonate Sequence in eastern New York, western Massachusetts, and western Vermont (Fig. 1.3) producing a Barovian metamorphic sequence from the clastics (Vollmer and Walker 2009), and the Stockbridge Group and Walloomsac marbles.

Despite the mountain building towards the east, carbonate deposition continued in the northern lowlands and Mohawk Valley of New York, including the Black River Group and Trenton Group. These groups represent up to 140 m of carbonates (Isachsen et al. 2000), deposited in intertidal to deep environments. Both groups are karstic, and contain extensive maze

caves in the Lake Ontario—St. Lawrence lowlands along the Black River, and Perch River, along with other smaller caves. These units are relatively non-deformed, but do contain some folds, and monoclines form important control on geomorphic development (Cushing et al. 1910), including karst development (Chap. 7).

The Taconic orogenic events ceased by 440 Ma (Isachsen et al. 2000), leaving the Iapetus Terrane accreted to Laurentia. This accreted terrane enlarged Laurentia and moved the paleo-shoreline to eastern Massachusetts and added substantial portions of New England including much of Connecticut and Vermont, as well as most of New Hampshire and Maine. At this time Greenland, northern Ireland, northwestern Scotland, and northern Scandinavia were also part of Laurentia (Torsvik et al. 1996). Sedimentation in basins during the Late Ordovician ceased in the western parts of the region as the Taconic and Berkshire Mountains were built and were eroding, but continued in western New York, depositing shales and sandstones such as Queenston Formation. Deposition during Late Ordovician and Early Silurian was mainly shut off ending the Sauk megasequence (Sloss 1963), due to eustatic sea-level lows associated with tectonics and Ordovician glaciation (Isachsen et al. 2000).

2.2.2 Siluro-Devonian—Acadian Orogenic Events

Sea level began to rise again in the Early Silurian, allowing marine sedimentation to occur and be preserved. Early Silurian units preserved in New York and New England outcrop in western New York, New Hampshire, Vermont, Massachusetts, and Maine. Early Silurian units in western New York along the Allegheny Plateau and Erie-Ontario Lowlands are those of the Medina and Clinton groups, with the Shawangunk Conglomerate in the east along the eastern edge of the Alleghany Plateau (Chap. 1, Fig. 1.2; Isachsen et al. 2000). The Medina Group and Shawangunk Conglomerate are both entirely clastic as erosion of the Taconic Mountains supplied vast amounts of clastic sediment, therefore shutting off carbonate production. The Shawangunk Conglomerate is over 300 m thick at its maximum, representing braided stream deposits of quartz sands and conglomerate. The Medina Group to the west contains

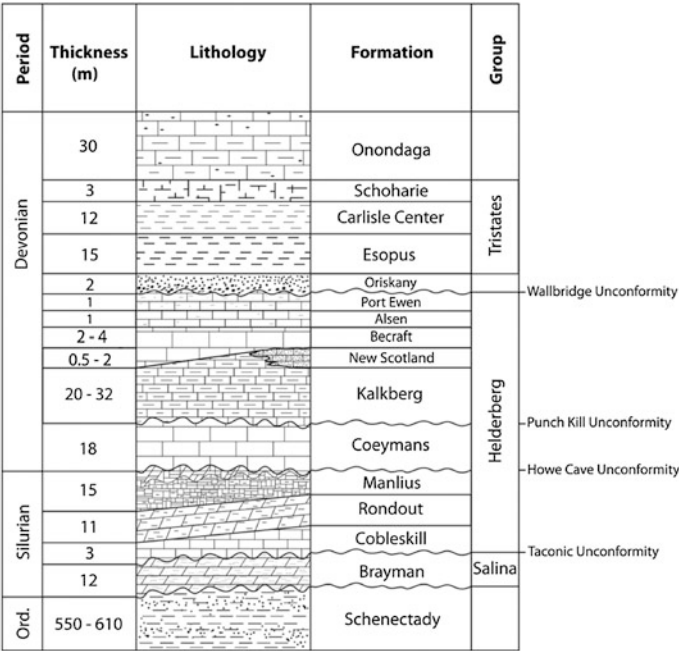
units that are fluvial to offshore. The Clinton Group continues the trend of clastic rocks deposited in shallow and open shelf, though it does contain several carbonate units including the Irondequoit Limestone and the DeCew Dolostone that display limited karst development. In New England, Early Silurian deposition was also clastic, with some volcanics. These, like the New York strata are a mixture of braided stream to offshore facies (Thompson 1985), though unlike in New York the Acadian and Allegheny orogenies have metamorphosed the New England units.

In the Late Silurian clastic deposition continued in eastern New York, also represented by the thick Shawangunk Conglomerate. In the west carbonate production was reinitiated with the karst-forming Lockport Group (Engel 2009), containing limestone and dolomite. The Late Silurian also continued clastic deposition in New England. As the Late Silurian continued, sea-level transgression and low relief of the region changed clastic deposition to evaporative coastal plain and nearshore environments of the Salina Group in eastern and western New York and New England. The Salina Group in western New York contains evaporates including gypsum and rock salt, though no known evaporate karst exists within these rocks. Following this deposition, the Taconic Mountains were eroded to very low relief, shutting off clastic

input and renewing carbonate deposition in eastern New York (Isachsen et al. 2000), and parts of Massachusetts and New Hampshire (Thompson 1985). Late Silurian carbonate units include the occasionally karstic Rondout Formation and early Helderberg Group in New York, and the Fitch Formation in Massachusetts and New Hampshire.

The beginning of the Devonian is marked by a transition to completely carbonate deposition in the form of the Helderberg Group (Fig. 2.6) in New York. Carbonate deposition also occurred in the Early Devonian of Massachusetts with the Gile Mountain and Waits River formations, and in Vermont with the Waits River Formation. The Early Devonian carbonate and clastic units of New England are, like most units in this region, metamorphosed. The Helderberg Group in New York contains several limestone formations above the Rondout Dolomite: the Manlius, the Coeymans, the Kalkberg, the New Scotland, the Becraft, the Alsen, the Port Ewen, and the Oriskany. These units outcrop in the eastern border of the Allegheny Plateau, and along the northern border of the Allegheny Plateau, particularly in the Helderberg Plateau. These units represent several facies: the intertidal Manlius, the shallow shelf Coeymans, the deeper water, chert-rich Kalkberg, and the fossil rich, deeper water New Scotland (Isachsen et al. 2000). The Becraft, Alsen,

Fig. 2.6 Stratigraphic column of the Siluro-Devonian units outcropping in the Helderberg Plateau, and elsewhere in the Appalachian Plateaus. (From Weremeichik 2013)



and Port Ewen formations are a repeat of the Coeymans, Kalkberg, and New Scotland facies respectively. The Helderberg Group is continuous in the east representing the full transgressive, regressive, and the following additional transgressive stratigraphic sequence, but to the west in the Helderberg Plateau the New Scotland, Alsen and Port Ewen formations are not extant, or were never deposited (Mylroie 1977). The Port Jervis Limestone only exists in Port Jervis, New York and represents the New Scotland facies. The time-transgressive nature of the Helderberg Group westward means that the Silurian-Devonian boundary moves downward through the Manlius and Rondout formations as the marine transgression proceeded west (Ebert and Elliot 2003). There is some disagreement in the literature regarding whether or not the Rondout Formation is part of the Helderberg Group; the confusion is in part because the Lower Manlius is now recognized to be Silurian in the eastern part of New York, but transitions to Devonian proceeding west. Ebert and Elliot (2003) provide a review of the situation. Isachsen et al. (2000) treat the Rondout as separate from the Helderberg Group; from a cave and karst viewpoint, the Rondout behaves as part of the Helderberg Group.

The Helderberg Group, particularly the Manlius Formation contains the most well developed caves and karst in the northeastern US, as the units are extensive and thick. The Manlius and overlying Coeymans Formations are particularly well suited for karst development as the Manlius is a very pure, thin-bedded micrite and the Coeymans is a massive, soluble caprock (Mylroie 1977). Other units of the Helderberg Group do form karst and caves, but not as extensively as the Manlius and Coeymans Formations. High chert content in units of the Kalkberg facies especially do not form extensive karst, but provide insoluble material that can guide flow paths.

The Port Jervis Formation marks the end of the Tappan megasequence, and thus begins a period of erosion and the Wallbridge Unconformity (Sloss 1963) due to eustatic sea level lows. This formation is one of the only extant units from this time period. Following the Port Jervis formation are those of the Tristates Group (Fig. 2.6), a mixture of clastics and carbonates. Units that were deposited and preserved as sea level began to rise again are terrestrial clastics, including the Oriskany Sandstone and Connelly Conglomerate, as well as the marine Glenora Limestone (Kalkberg

facies). The Oriskany Sandstone imposes an important control on karst formation, as this sandstone allows allogenic recharge to the limestones below, and can allow formation of sandstone-capped maze caves in the underlying Becraft Limestone (Cullen et al. 1979). These low sea-level clastics were preserved as sea level rose, burying them with marine sediments of the Esopus Formation (Isachsen et al. 2000). The Esopus Formation is a shale unit, containing bentonites formed from volcanic ash. The combination of volcanoclastics and erosional clastics in the Esopus Formation mark the first phase of the Acadian Orogeny. This orogeny involved Laurentia, the advancing Avalonia Terrane, and the attached continent of Baltica (Figs. 2.4b and 2.7; Torsvik et al. 1996). The Avalonian Terrane includes what are now parts of Connecticut and Maine, and the entirety of Rhode Island, southern Britain and Ireland, and western Europe. Baltica at this time included Fenno-Scandinavia, eastern Europe, and northwestern Russia.

Units above the Esopus Shale in the Tristates Group are a mixture of carbonates and clastics, with the Schoharie and Rickard Hill formations being a mixture of both. The Onondaga Formation is a karstic limestone unit with several members that are repeats of facies of the Helderberg Group: the Edgecliff Member (Coeymans), the Nedrow Member (New Scotland), the Moorehouse Member (Kalkberg), and the Seneca Member (New Scotland) (Isachsen et al. 2000). The Nedrow and Moorehouse members, like their respective Helderberg facies contain abundant chert. The Seneca Member contains the Tioga volcanic ash beds, again indicating the beginning of another phase of the Acadian Orogeny. The Onondaga Formation is another dominant karst former along the Allegheny Plateau, and extends farther west than the Manlius Formation, though it also forms caves in areas where the Manlius Formation exists such as the Helderberg Plateau.

After deposition of the Onondaga Formation, the Acadian Orogeny continued, causing mountain building in the east, and tacked on parts of Avalonia as Rhode Island, and parts of the eastern coast of Maine, Connecticut, and Massachusetts. The mountain building of the Acadian Orogeny caused the formation of the Acadian Mountains, the deepening of the Appalachian Basin, deformation and metamorphism of sedimentary rocks in New York and New England, and plutonism forming granites and other igneous

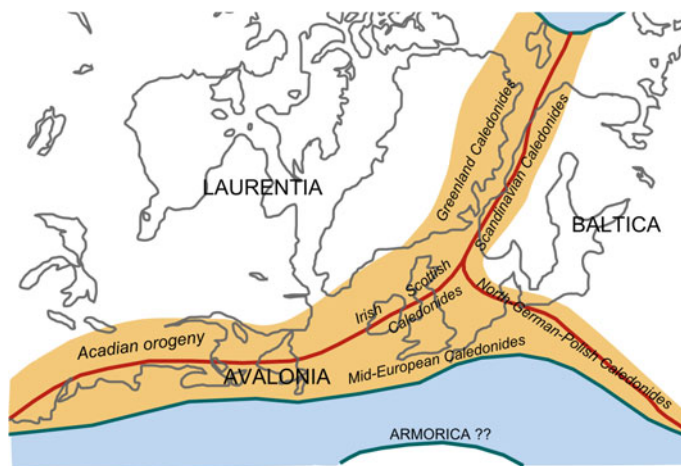


Fig. 2.7 The Caledonian/Acadian orogeny involving Laurentia, Avalonia, and Baltica. The Acadian orogeny added much of New England to the coast of Laurentia. The Caledonides in Ireland, Scotland, Greenland, and Scandinavia are a continuation of the Acadian mountain building event in those regions. This orogeny, combined with the Alleghenian has deformed and

metamorphosed the sedimentary rocks of eastern North America, and the countries mentioned above. Map from Woudloper, using data from Torsvik et al. (1996). Image license is Creative Commons ShareAlike 1.0 [<http://creativecommons.org/licenses/by-sa/1.0/>]

rocks in Maine, New Hampshire, and eastern portions of the other New England states. Accompanying the Acadian Orogeny is the renewal of clastic deposition, a trend continued through the Late Devonian and into the later Paleozoic periods (Fig. 2.6). This deposition occurred in the Appalachian Basin in New York, as the rocks of New England eroded. Little to no preserved deposition exists in New England from the Middle Devonian to the end of the Paleozoic.

In the east deposition occurred in deltaic and fluvial environments in the form of the Catskill Delta, with deep water shales such as the Marcellus Shale to the west. As sea level dropped and sedimentation continued, facies migrated westward. In the eastern portions of the Allegheny Plateau hundreds of meters of this clastic material are preserved, tapering towards the west (Isachsen et al. 2000). Continued sea level fall, and subsequent rise, allowed the preservation of the large amount of terrestrial sediments. The return to sea level rise occurred after the deposition of the Hamilton Group, and continued deposition westward. Following this unconformity, sea level transgression shut off clastic input towards the west, allowing carbonate production briefly with the Tully Limestone. Some small caves have formed in the Tully Limestone in western New York. In the east terrestrial clastic deposition continued, with additional building of the Catskill

Delta. Continued transgression and regression slowly moved facies westward, through the Late Devonian.

2.2.3 Mississippian, Pennsylvanian, and Permian—Allegheny Orogeny

Deposition continued to occur into the Mississippian, Pennsylvanian, and Permian periods in the Appalachian Basin. Little sedimentary rock from these periods remains, however, in the Allegheny Plateau of New York, as erosion during the Mesozoic and Cenozoic stripped these units away (Isachsen et al. 2000). Units from this time period in the Appalachian Basin do exist towards the south, including extensive carbonates from the Mississippian in the Virginias and to the south and west. Northwards clastic deposition continued in Pennsylvania and New York, with preservation to the current day in Pennsylvania. In New York, only minor Mississippian and Pennsylvanian units persist along the southern portion of the Allegheny Plateau in the state.

During the Mississippian another orogenic event began, the Allegheny Orogeny. This orogeny occurred between Euramerica (Laurentia, Avalonia, and Baltica) and Africa (at that point part of Gondwana), and began the formation of the supercontinent Pangaea

(Fig. 2.4c; Torsvik et al. 1996). Orogeny continued through the Pennsylvanian and into the Permian. In New England this orogeny increased the height of the Acadian Mountains, and continued deformation and metamorphism in the northeast. In New York deformation occurred in the southeast, affecting the eastern reaches of the Allegheny Plateau. This deformation includes carbonate units, and in this area deformation structures greatly influence cave development (Chap. 6). Westward in New York, however, little deformation occurred (Isachsen et al. 2000), though several structural effects exist, including those important to karst development (Kastning 1975; Mylroie 1977). Jointing and cleavages have developed in the carbonate units of the Allegheny Plateau (Marshak and Engelder 1985; Isachsen et al. 2000). Cave development in this region is highly influenced by jointing (Chap. 5), as joints guide flow paths of initial cave enlargement (Palmer 1991).

The Late Permian in the northeastern US lacks a sedimentary record, as glaciation lowered sea level globally (Knoll et al. 1997), and the relief along the mountains formed by the Allegheny Orogeny lowered.

2.3 Mesozoic Rifting and Deposition

2.3.1 Triassic and Jurassic—Rifting

During the Triassic rifting began around 220 Ma (Isachsen et al. 2000), breaking apart Laurentia from Africa, forming the Atlantic Ocean. During the period of rifting failed rift basins formed (Fig. 2.8), as faulting allowed blocks to move downward. Along with this rifting, diabases and basalts were formed and preserved in these basins, such as the Palisades Sill diabase along the southern Hudson River, along with deposition of terrestrial clastics including redbeds of sandstone, conglomerate, siltstone, and shale. Basins of this time include the Newark Basin, the largest of the failed rift basins, as well as the Hartford, New York Bight, and other basins. Deposition continued through the Jurassic, including flood basalts (McHone 1996) in Connecticut, Maine, Massachusetts, Rhode Island, and New York. Elsewhere in New York and New England, high relief conditions continued.

After the failed rifts of the Triassic, the Atlantic Ocean began to fully open in the Early Jurassic, beginning deposition off of the northeastern coast,

continuing into the Cretaceous. Erosion continued during this time, forming a hypothesized peneplain in New York during the Middle Jurassic (Isachsen et al. 2000). Jurassic granites also formed in New Hampshire as a result of the New England hotspot (Duncan 1984).

2.3.2 Cretaceous—Plate Movement, Erosion, and Deposition

During the Cretaceous the Atlantic Ocean continued enlarging, and active margin conditions transitioned to passive margin conditions. Erosion of high relief areas of New York and New England continued, depositing sediments in the Atlantic Ocean along the eastern coast in the Coastal Plain region. Most deposition in this time period occurred in the warm seas south along the east coast of North America, though some Cretaceous deposits exist along the New York and New

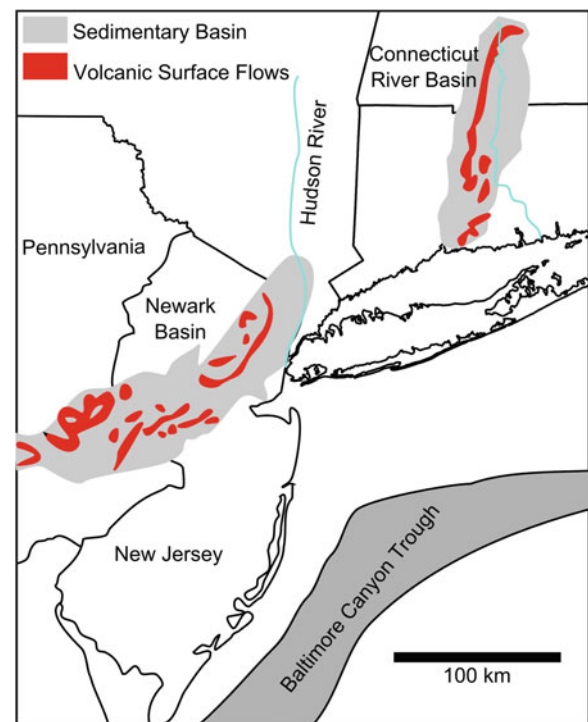


Fig. 2.8 During Triassic rifting basins were formed along the eastern margin of North America. These basins contain clastic sedimentary deposits, mainly red sandstones, as well as volcanic lava flows and dikes. (Modified from USGS [<http://3dparks.wr.usgs.gov/nyc/mesozoic/mesozoicbasins.htm>], accessed 2015-01-20)

England coast, including the original sedimentation underlying Long Island. Erosion continued through the Cretaceous as the region was uplifted, beginning dissection of the hypothesized Middle Jurassic peneplain (Isachsen et al. 2000).

By the end of the Cretaceous North America was mostly the same shape as it is now, as rifting continued in other areas and Pangaea broke apart. During this movement North America continued to move over the New England hotspot, forming the White Mountains due to plutonism (Duncan 1984), and the New England (also known as the Kelvin) Seamount chain to the east in the Atlantic Ocean.

2.4 Cenozoic Geomorphic Development

2.4.1 Paleogene and Neogene—Erosion

Few deposits exist from the Paleogene and Neogene in New York and New England, as erosion continued during this time. Those deposits that do exist include early Paleogene lignite deposits in Vermont. The erosion of this time continued to downcut the hypothesized Jurassic peneplain, establishing much of the current large drainage patterns (Fig. 2.9). These drainage patterns reflect the underlying geology established during the Precambrian, Paleozoic, and Mesozoic. Where structural deformation exists gradients are high, and channel drainage moved into weaker units, as exemplified by the Hudson River following the western edge of the weathered Taconic Mountains. In the Allegheny Plateau drainage patterns reflect little structural control and thus are mostly stratigraphically controlled. This plateau was dissected, forming sedimentary “mountains” by removing material, causing isostatic rebound, in turn causing more erosion.

The erosion of the Paleogene and Neogene drove additional uplift, bringing the current stratigraphy now seen in the northeastern US to the surface. Most of the current bedrock exposure seen today was carved out due to this erosion, except for possibly the continually uplifting Adirondack dome (Isachsen et al. 2000).

The Late Neogene is marked by a decrease in global temperatures, as they dropped from the Cretaceous and through the Paleogene. Late Neogene cooling, plate arrangement, and ocean currents were set on course for the “just right” conditions to begin an

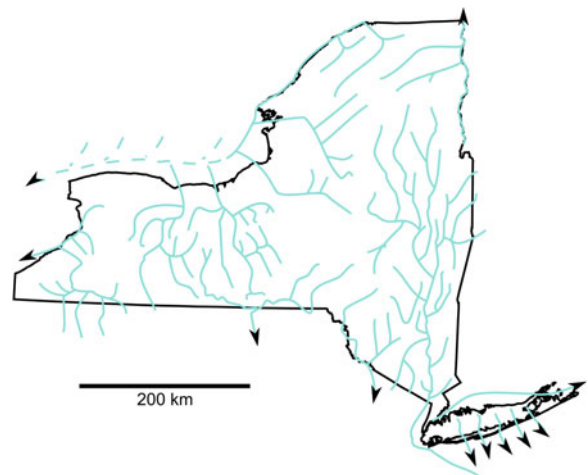


Fig. 2.9 An interpretation of the pre-Quaternary drainage of New York State. This loose interpretation is based on remaining, relict stream valleys. The Hudson River maintains much of its pre-glacial course. The Finger Lakes and Lake Champlain are interpreted to be former river channels. (Adapted from Isachsen et al. 2000)

ice age, similar to those seen before in the Proterozoic, Ordovician, and Permian.

2.4.2 Quaternary—Ice Age

The Quaternary Period is a time of ice ages following the Neogene (Chap. 1). In New York and New England there are multiple glacial, deglacial, and interglacial cycles, the most recent being the Wisconsinan glaciation, an advance of the Laurentide ice sheet covering Canada, almost all of New York and all of New England, northern New Jersey and northern Pennsylvania, and other northern US states (Fig. 2.10). The Quaternary is broken into the Pleistocene, and the current interglacial, the Holocene.

2.4.2.1 Pleistocene—Glacials and Interglacials

The Pleistocene contains several glacial and interglacial time periods. In eastern portions of North America the most recent are named, from youngest to oldest: the Wisconsinan glacial, the Sangamonian interglacial (MIS 5e, Chap. 1), the Illinoian glacial, and the Pre-Illinoian glacials and interglacials (Muller and Calkin 1993). The geomorphologies of Pre-Illinoian cycles have been overridden by the subsequent Illinoian and Wisconsinan glaciations, and are pieced

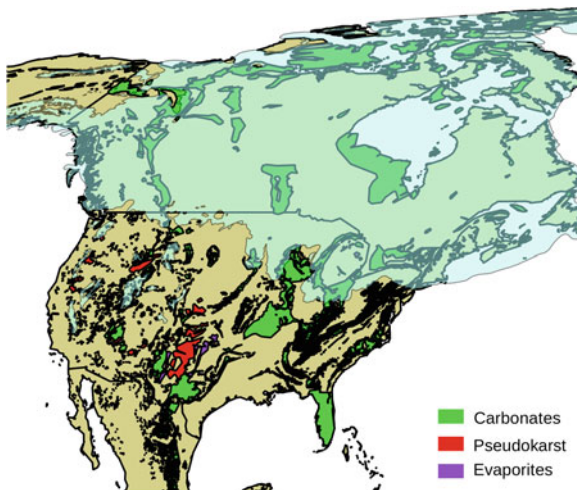


Fig. 2.10 Map of ice extent during the last glacial maximum (LGM) in North America, combined with potentially karstic and pseudokarstic rock exposure. All karst regions in Canada have been glaciated, either by continental glaciation from the Laurentide ice-sheet, or by alpine glaciation in the Canadian Rockies. The entirety of New York and New England was glaciated during the previous (Wisconsinan) glaciation, as well as further south in New Jersey and Pennsylvania, though karst regions of these states were not overridden by ice. Other northern states in the US were continentally glaciated, including those containing karstic rocks; continentally glaciated karst exists in states such as Michigan. Alpine glaciation also affected karst development in the Rocky Mountains, in states such as Colorado, and in areas such as the Tetons

together from marine isotope data. Both the Illinoian and Wisconsinan glaciations can be divided into further substages, with advance and retreat of various ice lobes. Glaciation here will be treated as a whole for pre-Wisconsinan as the Wisconsinan glaciation in New York and New England has reset prior surficial geology almost entirely. The Illinoian glaciation is known to have taken place in New York and New England as landforms associated with this glaciation exist southward in New Jersey, beyond the Wisconsinan glacial limit.

Large-scale glacial landforms in the northeastern United States were likely shaped over multiple glacial advances, such as the Great Lakes, Finger Lakes, and Long Island. The multiple glacial advances slowly eroded more and more material away, causing uplift bringing older rocks to the surface, even to the basement Grenville rocks in the Adirondacks. This erosion can remove shallow caves and cave passage, though

the process can also bring more soluble rock to the surface. Smaller scale glacial landforms of previous glacial advances are reset upon subsequent glaciation, and as such the current erosional and depositional features represent the last glacial advance (Muller 1977), unless protected outside of the last glacial limit. The removal of glacial landforms makes it nearly impossible to precisely date and locate ice-limits of previous glaciations, though large-scale advance and retreat can still be dated using ice-core data, as well as deep-sea sediment core data. Speleothem data can also offer some timing controls.

While surficial deposits of previous glaciations were removed by subsequent glaciation, glacial deposits can be preserved in caves (Palmer 1975; Mylroie 1984; Weremeichik and Mylroie 2014). Some of these deposits can be dated to pre-Wisconsinan time (Dumont 1995; Lauritzen and Mylroie 2000; Perzan et al. 2014). As caves are preservational environments it may be possible to date and locate previous ice-limits using preserved material. Dumont (1995) and Lauritzen and Mylroie (2000) calculated age-dates of speleothems using U/Th age dating. Using this method it may be possible to date ice-advance and retreat as advance shuts off speleothem growth, and growth is renewed upon retreat (Lauritzen and Mylroie 2000). These methods are limited however, as they only apply to karst areas, and Lauritzen and Mylroie (2000) note that their data were not abundant enough to precisely map ice-advance and retreat, but it may still be a possibility if more data were collected from a larger range of sites. They were able to recognize a mid-Wisconsinan interstadial (MIS 3) as speleothem growth resumed for a brief time in the Hudson River valley, starting before, and ending later, than an even shorter speleothem growth pulse to the north in the Helderberg Plateau, during that interstadial.

The appearance of landscapes during previous interglacials likely resembled the current post-glacial (used here to mean Holocene) time period, with similar on-going processes.

The multiple readvances and retreats, and ultimate deglaciation of the Wisconsinan glaciation can be accurately mapped, and timed. In New York and New England multiple ice-lobes existed from the Laurentide ice sheet, including the Ontario, Hudson, Champlain, Connecticut Valley, Buzzards Bay, and Cape Cod lobes (Ridge et al. 1991; Dyke et al. 2002). These individual

lobes also contain multiple sub-lobes. Ice flow direction of these lobes can be accurately mapped by drumlin orientation (e.g. Dineen 1986), and ice-advances and retreats can be mapped by end-moraine positions. Pollen stratigraphy and paleomagnetism can be used to date end-moraines, and associated times of advances and readvances (e.g. Ridge 2004). The last glacial maximum of the Wisconsin glacial maximum occurred 28–24 ka, and glaciers had completely retreated from New York and New England by 12 ka (Ridge 2004). Ridge (2004) mapped deglaciation times for New England, giving accurate timings for ice-retreat (Fig. 2.11).

Glacial landforms that persist into the Holocene in New York and New England are associated with the Wisconsin glacial maximum and deglaciation. These landforms are numerous, and exist at a variety of scales. The most important glacial features in the discussion of karst development are glacially downcut valleys and infilled valleys, which both change base level, but in different directions (Palmer 1976), and deranged drainage guided by erosional and depositional landforms, as these affect the recharge of cave systems, both of adjusted pre-glacial (used here to mean pre-Wisconsin) caves (Myroie and Carew 1987), and post-glacial caves (Cooper and Myroie 2014).

2.4.2.2 Holocene—The Current Interglacial

The Holocene began at 11.7 ka, and is the current epoch. The surficial geology of the Holocene in the northeastern US is the result of Wisconsin glacial maximum, and unlike non-glaciated areas many forms of the pre-Pleistocene landscape have been removed (Muller 1977). Pre-Pleistocene rivers have been rerouted by glacial erosion or damming by glacial deposition (Fig. 2.12). Several landforms have been preserved however, allowing a rough reconstruction of the pre-Pleistocene landscape. Such landforms include valleys that have been preserved as a result of infilling by sediment (e.g. Palmer 1976). Larger rivers, like the Hudson River and the St. Lawrence River likely have similar paths to their pre-glacial state, though the drainage basin of the St. Lawrence has been adjusted by glaciation (e.g. Cushing et al. 1910). Smaller streams may also maintain a general course, such as Onesquethaw Creek (e.g. Dineen 1987).

The Holocene time in the northeastern US displays a return to erosion and deposition by fluvial processes, rather than by glaciation, as such is the style in many non-glaciated terrains. On the small scale, routing of water is guided through deranged drainage by glacial landforms, and this water downcuts the landscape.

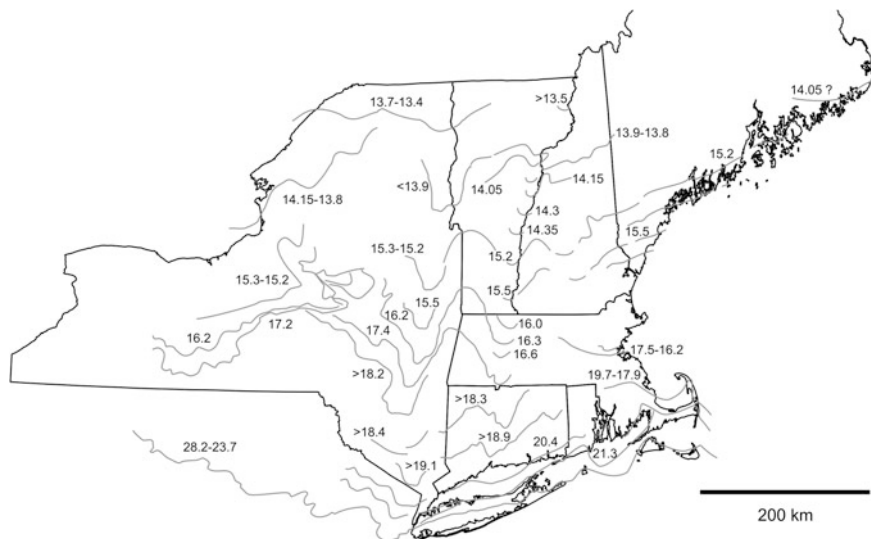


Fig. 2.11 Map of deglaciation of the northeastern United States. Gray isolines indicate time of withdrawal of ice-lobes indicated by end moraines. These dates are adjusted from calibrated ^{14}C dates of pollen located within moraines, and are

in ka BP. The terminal moraine indicates the LGM in this region, and forms part of Long Island, New York. Ice-withdrawal from the region was complete by 13 ka BP. (Redrawn with data from Ridge 2004)

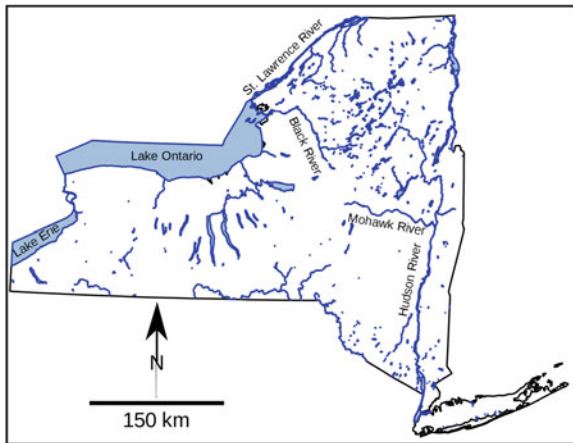


Fig. 2.12 Map of the modern drainage of New York State, showing modification by repeated glaciation. An example of this is the Finger Lakes, which were once river valleys (Fig. 2.9) but have been adjusted by glaciation. Several rivers such as the St. Lawrence and Hudson rivers have largely maintained their course, though with some adjustment

Sediment and organic material are also deposited in the many lakes of the post-glacial landscape, including within swamps caused by inefficient drainage of glacially carved depressions. Quaternary deposits in New York and New England are Holocene in age, or are from the Wisconsin glaciation (Muller 1977). In some cases till deposits have been well compacted, though their surficial nature leaves them prone to removal by subsequent glaciation.

While glaciers are not in-place over the northeastern US during the Holocene, the effects of the glaciers still impacted the early Holocene. When the ice-sheets were in place, the crust was isostatically depressed. Removal of the ice-sheets, as well as the erosion provided by advancing ice, removed mass, and therefore caused isostatic rebound. Rebound has important impacts in post-glacial geomorphology, as it expands joints mechanically (Harland 1957), uplifts the terrain causing rapid fluvial downcutting, and can cause neotectonic earthquakes. Rebound, combined with glacial forms such as over-steepened slopes also influence post-glacial geomorphology as these can cause slope failure, and create features such as talus piles, common in the northeastern US in mountains, and along escarpments. Lake Champlain was converted from a marine inlet to a fresh-water lake by isostatic rebound.

While during interglacial times New York and New England are shaped by the same geomorphic processes as non-glaciated areas, the surficial geology, and thus karst development, is shaped by glaciation. The current surficial and shallow subsurficial forms in the northeastern US are transient in nature, and are limited in time to the relatively short interglacials.

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