

The Geology of Vermont

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Vermont does not give up its geology easily. The once lofty and grandiose Appalachians have been modified by millions of years of erosion and extensive reshaping by great mile-thick ice sheets over the last tens of thousands of years. Therefore, glimpses of Vermont's early geologic history come from scattered outcrops on mountain tops, in stream valleys, and in hummocky pasture lands that offer insights to a remarkable geologic history and a rich diversity of geologic settings and landscapes. Evaluating the bedrock evidence in the context of plate-tectonic processes operating today throughout the world brings new understanding of the enormity of the geologic history recorded in the rocky infrastructure beneath the Vermont landscape.

Take, for example, the rocks cropping out around the shore lines and islands of Lake Champlain. Fossils within these rocks, which date back to the Paleozoic Era, speak of shallow-to-deep marine environments, similar to present-day environments in the Bahamas, the Florida Keys, or in Timor. How could this be Vermont's past?

Look at the great overthrust at Lone Rock Point in Burlington, Vermont, which is but a small segment of a once continuous fault that brought earliest Paleozoic rocks up and over rocks more than 100 million years younger than the rocks above the fault. Such features require plate-scale compressive forces that are present today only at active plate boundaries. Active tectonic activity is also needed to explain the presence of the Taconic Mountains of southwestern Vermont, eastern New York, and western Massachusetts, which according to the fossil record and the geologic setting, have been transported tens of kilometers westward over the rocks of the Champlain Valley.

To consider these and other aspects of Vermont's geology, it seems best to begin by defining the state's physiographic provinces. These subdivisions will serve as reference areas to explain the geology.

Vermont Physiographic Provinces

The Vermont landscape varies along sinuous elongate north-south belts following the general "grain" of the Appalachian Mountains, which extend from Newfoundland to at least Georgia. On the west is the low-lying Champlain Valley, which is characterized by the rolling hills and gently tilted strata on the Vermont side of Lake Champlain. These rocks preserve the best fossil record in the state; indeed, the ancient Paleozoic (ca. 450 million years before present) reefs of Isle la Motte on Lake Champlain are world renowned for the preservation and size of their fauna. The Champlain Valley province is abruptly interrupted to the south by a large mass of generally older rocks of the Taconic Mountains, an important part of Vermont geological history and host to quarries producing some of the world's highest-quality slate.

A central belt of rocks defines the Green Mountains, which are underlain by metamorphosed equivalents (schists and phyllites) of ancient sediments, lava flows, and slivers of ancient oceanic crust and mantle. These rocks host Vermont's high-quality talc and asbestos deposits, including the famous Belvidere Mountain locality in Lowell described elsewhere in this issue.

All of these rocks were originally deposited directly upon, or were transported onto, an ancient "basement" complex of rocks. This ancient basement, more than 1 billion years in age, is exposed along the spine of the Green Mountains in central and south-central Vermont. This basement core represents the only known Precambrian rocks in the state.

A narrow valley (the Vermont Valley of fig. 2) runs between the Taconic Mountains to the west and the Green Mountain belt to the east. This valley is composed of rocks similar to those underlying the Champlain Valley to the north (fig. 1) and includes most of the famous Vermont marble quarries.

The eastern third-to-half of the state is underlain by a continuous and somewhat younger belt of ancient rocks of the Connecticut Valley-Gaspé Basin. This ancient sedimentary basin is characterized by thick deposits of calcareous (calcite-bearing) sediments that extend at least from Connecticut to the end of the Gaspé Peninsula of Quebec. These Silurian and Devonian rocks are noted for the felsic intrusions from which Vermont's famous granites continue to be quarried.

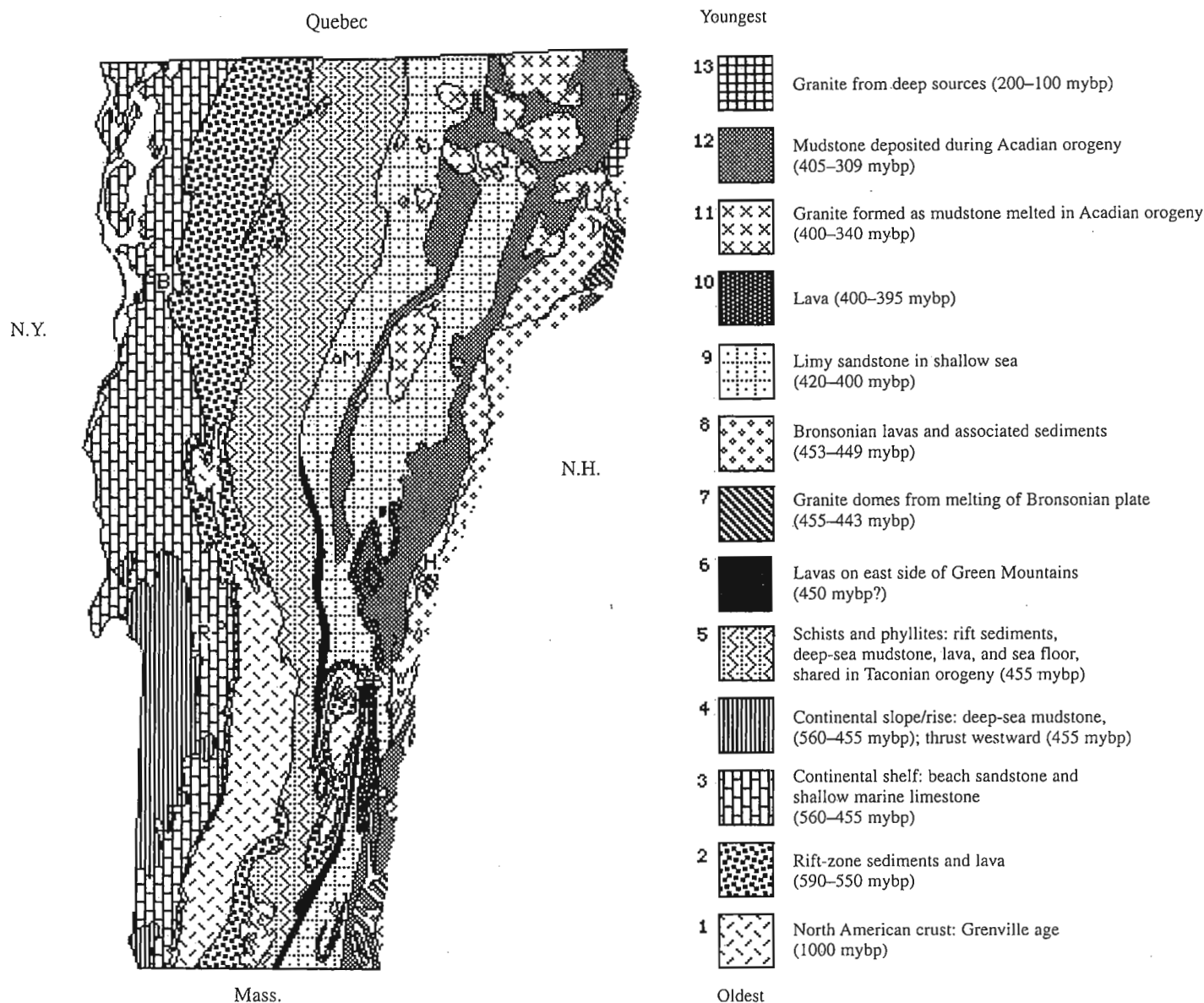


Figure 1. Generalized geologic map of Vermont. Modified after computer-generated map of Vermont and New Hampshire produced by David Lang, 1992. MYBP = Millions of years before the present. B = Burlington, M = Montpelier, R = Rutland, W = Windsor, H = Hanover, New Hampshire.

STORY OF THE ROCKS

First there is a mountain, then there is no mountain, then there is ...

Donovan, ca. 1960

It is difficult to say when Vermont was without mountains. Certainly before the Appalachians formed, a much older and perhaps even grander mountain system existed. This earlier mountain range is evidenced by the exposure of its precambrian roots in the present core of the Green Mountains. These ancient mountain roots have been greatly modified by the processes responsible for the formation of the younger Appalachians; thus, little of the record of these early mountains is preserved. To understand the early mountains, Ver-

monters look west to the Adirondack Mountains of New York that display similar rocks, apparently little modified by Appalachian events.

The Adirondack Mountains are part of an extensive mountain-building phase referred to as the Grenville orogeny (orogeny is used synonymously with mountain building). A basic geologic premise holds that older mountains must, by the necessities of erosion and time, be lower than newer mountains. The fact that the Adirondacks are both higher and older than the Appalachians requires that either the original Grenville Mountains stood much higher than the Appalachians

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or that other processes have kept the Adirondack Mountains elevated.

Geologists in New York have proposed that the Adirondacks may in fact be higher today than they were even 600 million years ago. The evidence is based on relevelling surveys completed on topographic markers by the U.S. Coast and Geodetic Survey. This study suggests that the Adirondacks may be presently rising at a rate of 3 mm per year! If true, the present elevation of the Adirondack Mountains could be explained by uplift in the recent geologic past (on the order of the past 1 million years). The most likely explanation for this phenomena is a heat source in the upper mantle of the earth situated directly below the Adirondack Mountains. The present-day and geologically recent uplift history may be responsible for the oval shape of the Adirondack Highlands as well as present-day seismic activity along its boundaries.

Whatever the post-Grenville history of the Adirondacks, it is clear from the rocks exposed in these mountains that the Grenville orogeny was a major mountain-building event. The present-day roots of this mountain system indicate that at least 35 kilometers of rock once overlay the Adirondack Mountains and perhaps much of the exposed Grenville roots of Canada and elsewhere. Since the continental crust beneath the present-day Adirondacks is known to be at least 35 kilometers thick, a crustal thickness of at least 70 kilometers must have existed at the climax of the Grenville mountain-building stage. Such crustal thicknesses are unusual but exist today in the Himalayas. The Adirondacks are geologically analogous to the continental crust of the India plate, which is presently being forced under (subducted) the continental crust of the Asian plate along the axis of the Himalayan Mountains system. The Grenville orogeny is the oldest event that has been recorded with confidence in Vermont history. The dates, obtained by radiometric decay studies on both rocks and minerals, range from 1.3 to about 1.0 billion years before the present.

Little is known about the history of Vermont over the geologic time span from 1 billion years to approximately 580 million years ago. It can only be stated that the Grenville Mountains were probably high and undergoing active erosion. The rock record rarely preserves erosion processes; a site for deposition of the erosion products is necessary to preserve such events. In Vermont—and, indeed, everywhere along the western side of what is now the Appalachian Mountains system—deposition sites (i.e., sedimentary basins) are known to have developed in dramatic fashion approximately 590–570 million years ago.

The First Basins . . .

Precursors to the Vermont Rock Sequences

Sedimentary basins large enough and long lived enough to preserve sediments form when the rigid upper layer of the earth (i.e., the earth's lithosphere) subsides. The fact that Vermont has a rather complete sedimentary record spanning more than 100 million years prior to the first emergence of the Appalachian Mountains indicates that Vermont, and, indeed, the entire region marking the axis of the present Appalachian Mountains, must have undergone major periods of subsidence.

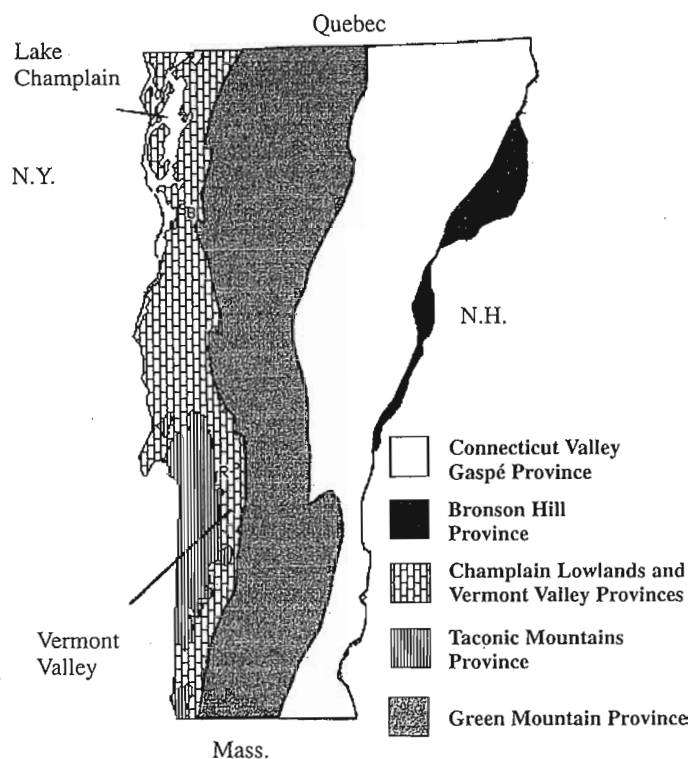


Figure 2. Geo-physiographic provinces of Vermont.

The first great sediment input into basins in Vermont occurred during the period of 580–560 million years before the present. Within the ancient North American lithosphere, a major extensional (or rifting) event occurred that thinned the lithosphere along a general trend subparallel to the present axis of the mountain belt.

In northern Vermont and southern Quebec, the rifting event was accompanied by voluminous outpourings of basalt and locally rhyolite (e.g., the Tibbit Hill Formation of Doll et al. 1961), both of which characterize the igneous activity in modern-day rift environments. Relatively thin deposition of sandstones and greywackes (e.g., the Pinnacle Formation of Doll et al. 1961) followed the volcanic outpourings.

In central Vermont, volcanic eruptions were relatively minor and synchronous with thick sequences of coarse-grained sediment that mimic river deposits or sediments deposited as alluvial fans at the edges of steep-sided valley walls.

These rift-related deposits occur throughout the length of Vermont. The thicknesses, grain sizes, and association of the rock types present in these early rift basins support a view of Vermont as being much like the modern-day rift environments in the East Africa Rift systems of Kenya, Ethiopia, and Mozambique. Very little evidence in the Vermont rocks of this stage indicates that the rift basins formed in a marine environment. As in East Africa, continental lithosphere supplying the Vermont sedimentary basins came from both sides of the basins; in modern-day coordinates, this would suggest that sediments came from both the New York side and the area now occupied by New Hampshire. The source rock from both sides was very likely the Precambrian basement that was a product

of the Grenville orogeny that occurred a half-billion years before formation of the rift grabens. Although some of the sediments show rapid infilling with local occurrences of large cobble- and even boulder-sized rocks deposited in the basins, there is no evidence from the record that the Grenvillian Mountains were a large topographic feature of the Vermont landscape. Indeed, at the time the rift basins were forming, the Grenvillian Mountains had undergone 500 million years of erosion; thus, their elevation was conceivably considerably less than the topography of the present Green Mountains.

Invasion onto the Vermont Landscape by Paleozoic Oceans

At the time of deposition of the fluvial and alluvial sediments during the earliest Paleozoic, there is no indication of invading seas. The environment was likely hot (within 30 degrees of the equator), lifeless (no terrestrial plants or animals at this time), and subject to flash flooding by heavy rains and runoff into rift valleys. Volcanic activity, so prevalent in northern Vermont and southern Quebec, may also have been prevalent in the eastern parts of the Green Mountain province (fig. 2) of central and southern Vermont. These eastern sediments, now schists and phyllites, are not well preserved in the Vermont rock record. Nonetheless, the stage was set for this landscape to subside thousands of meters during the next several hundred million years, during which an influx of marine waters resulted in deposition that provides a history of life and sedimentation of that period.

The marine invasion followed the development of active spreading centers in the rift basins. In today's world, mid-oceanic spreading centers are fundamental first-order features of our globe. In the early Cambrian Period of the Paleozoic Era (550 million years before present—mybp), spreading centers were also common. In Vermont, and the rest of the Appalachians, establishment of these spreading centers coincided with the birth of a new ocean basin referred to by Appalachian geologists as Iapetus (after the mythological father of Atlantis).

Spreading centers in Iapetus led to movement of rifted crust away from the active spreading centers, thereby cooling the older, thinned lithosphere covered with the earlier rift deposits. Cooling increased the density of the lithosphere, which led to further subsidence. This second stage (drift stage) of subsidence lasted for approximately 100 million years. Rift-stage deposits largely of continental origin thus became covered by marine sediments as the subsiding crust was drowned by seas transgressing over the ancient Vermont coastline.

The first sign of marine deposits on the Vermont landscape was the blanket of beach or tidal-flat sandstones (referred to as the Cheshire Quartzite by Doll et al. 1961), which are sporadically exposed along the full length of Vermont. Similar Cambrian quartzites are also found in the same stratigraphic position from Newfoundland to Alabama, attesting to the widespread success of the rifting event in producing the Iapetus Ocean adjacent to the ancient North American continental margin. The timing of these first marine deposits coincides with the evolution of the first shelly fossil record in the paleontological record. In the Champlain Valley of Vermont, these

Cambrian fossils are characterized by trilobites such as *Ollenelus*.

Beach deposits are followed by other near-shore and shallow marine tidal-flat deposits composed of carbonate and siliciclastic formations—the Dunham Dolomite, Monkton Quartzite, Winooski Dolomite, Danby Quartzite, and Clarendon Springs formations (Mehrtens 1985). These deposits were followed by limestones of Ordovician age. All of these rocks comprise a thick (up to 3,000 meters), well-developed Cambrian-Ordovician platform that bordered the ancient continental margin. This platform is best developed in westernmost Vermont where the subsidence rate due to cooling was balanced by sediment deposition, either direct precipitation of limestone or influx of reworked sediment carried across the platform in tidal channels and submarine river channels.

Basinward of the platform, subsidence exceeded the rate of sediment input. These parts of the deep sedimentary basin are referred to as “starved basins” because of the relatively low sediment supply and large subsidence rate. These starved basins are directly analogous to the continental rise deposits that occur beyond passive margin platform sequences in today's oceans.

Thus, by the middle of the Ordovician Period (445 mybp), Vermont was situated on the ancient continental margin of eastern North America—virtually all the rocks of the Champlain Valley, Taconic Mountains, Vermont Valley, and Green Mountain physiographic provinces had originated from processes leading to the formation of this ancient shelf slope and rise sequence adjacent to the North American Paleozoic landmass.

No rocks east of the Green Mountain belt can be linked to the development of the continental margin of ancient North America. Vermont geologists still debate the eastern extent of rocks having North American sources. Most of the rocks east of the Green Mountain province are younger and originated after the major mountain-building event that destroyed the ancient continental margin—i.e., the Taconic orogeny.

The Taconic Orogeny: Destruction of the Ancient Continental Margin and Formation of “New” Mountains

During the middle Ordovician Period (about 445 mybp), a thick blanket of mud was deposited on top of the stable platform of carbonates and sandstones. These muds, now cropping out in the Champlain Valley as shales and slates, were derived from uplifted source rocks to the east . . . the area that, in earlier times, was underlain by deep ocean sediments. These shales mark the first evidence in the rock record that the ancient continental margin of Vermont was being drowned to depths that precluded the deposition of shallow marine sands and carbonates. Such rapid change in water depth of a carbonate bank, which for over 100 million years existed in a shallow marine environment, has led geologists to link this event to subduction of the ancient continental margin of North America down a trench (compare today with the subduction of the northern continental margin of Australia beneath the Timor Trench). Under this interpretation, oceanic rocks on the outer

part of the subduction zone collected into stacked slices of folded and deformed rocks. The ultramafic rocks of Belvidere Mountain are representative of some of the earliest slices of oceanic crust and mantle that were stacked on top of each other deep within the subduction zone. Rocks of the earlier-formed deep rift basins were scraped off the downgoing continental margin and sandwiched between the platform rocks to the west and the oceanic slices to the east. The rising prism of deformed sediment and oceanic material incorporated above the subduction zone rose first to the status of islands and, eventually, to a significant landmass that lay east of the ancient North American margin. The source of the shales is thus not a mystery. They clearly are associated with the subduction of the continental margin, which provided the processes necessary to create a new landmass oceanward of the continental margin; erosion from the landmass contributed the material that filled the space created by the subducting continental margin. That is to say, in plate-tectonic terms, the environment changed from that of a spreading ocean basin and passive continental margin to an environment of compression, subduction, and trench development.

The change in tectonic activity during the Ordovician was related to a major reconfiguration of lithospheric plates. Its effects were felt well beyond the confines of Vermont. Indeed, the entire Appalachian Mountains system of North America from Georgia to Newfoundland as well as the continuous Caledonian Mountains of Scotland and northern England and Scandinavia were involved. Although the exact timing of the compression may not have been the same everywhere, in North America this major tectonic event is named the Taconic orogeny because of the evidence in the Taconic Range of Vermont and eastern New York.

The Taconic Mountains

The Taconic Mountains have had a long history of geologic study and controversy. Before the paradigm of plate tectonics, it was difficult to reconcile what appeared to be contrary evidence that field geologists found in outcrops. To briefly summarize the dilemma: Deep-water slates and chert dating back to the Cambrian Period and even older are presently situated *on top of* younger shales that overlie the carbonate platform of the Champlain Valley. Some believed the rocks on top were younger because finding the fault contact separating rocks of similar composition (shales and slates) was difficult at best. How could such a large mass of old rocks be placed on top of the younger muds? The Taconic orogeny was invoked to describe the event in the Taconic Mountains that was responsible for the transport of the deep-water sediments onto the plat-

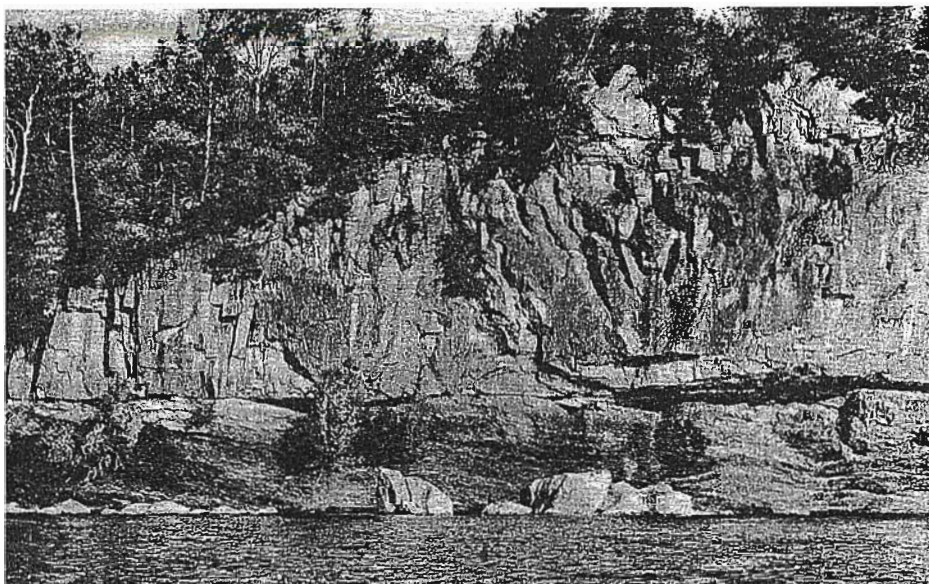


Figure 3. Photograph of the Champlain Thrust at the classic locality: Lone Rock Point, Burlington, Vermont. The massive, vertically fractured, light-colored rocks above the fault are dolostones of the Dunham Formation. These Early Cambrian-age rocks are thrust over rocks of the Iberville Formation (shales approximately 100 million years younger than the Dunham). The Champlain Thrust extends from the international border with Quebec as far south as the Albany area of New York.

form. The plate-tectonic theory can be invoked to explain the event: The subduction zone brought oceanic rocks over the early rift deposits and caused the drowning and collapse of the platform, thus scraping up and transporting ancient continental slope-and-rise deposits over the continental margin. Rocks that are presently found in places where they were not originally deposited must be moved to their present positions (the term *allochthons* is given to such masses of transported rocks). Recognition of allochthons in the Taconics led geologists to compare similar “out-of-place” rocks in Quebec, Newfoundland, and Pennsylvania. In each case, the story was the same. Older rocks, once part of the deeper portions of the ancient continental margin, were moved as allochthonous stacks and

No part of Vermont has escaped the imprint of the glacial record.

slices (perhaps for distances of 100 kilometers in some places) westward over the ancient continental platform. In the case of the Taconic Mountains, these rocks continued to be deformed by folding after their arrival onto the platform. The resulting cleavage in the slates of the Taconics is nearly perfect for the production of some of the world's best commercial slate, which is known not just because of its ability to cleave smoothly, but also because of its diverse colors—green, gray, purple, and red. These colors reflect slightly different environments present when the muds were accumulating oceanward of the ancient continental platform during the Cambrian and Ordovician periods.

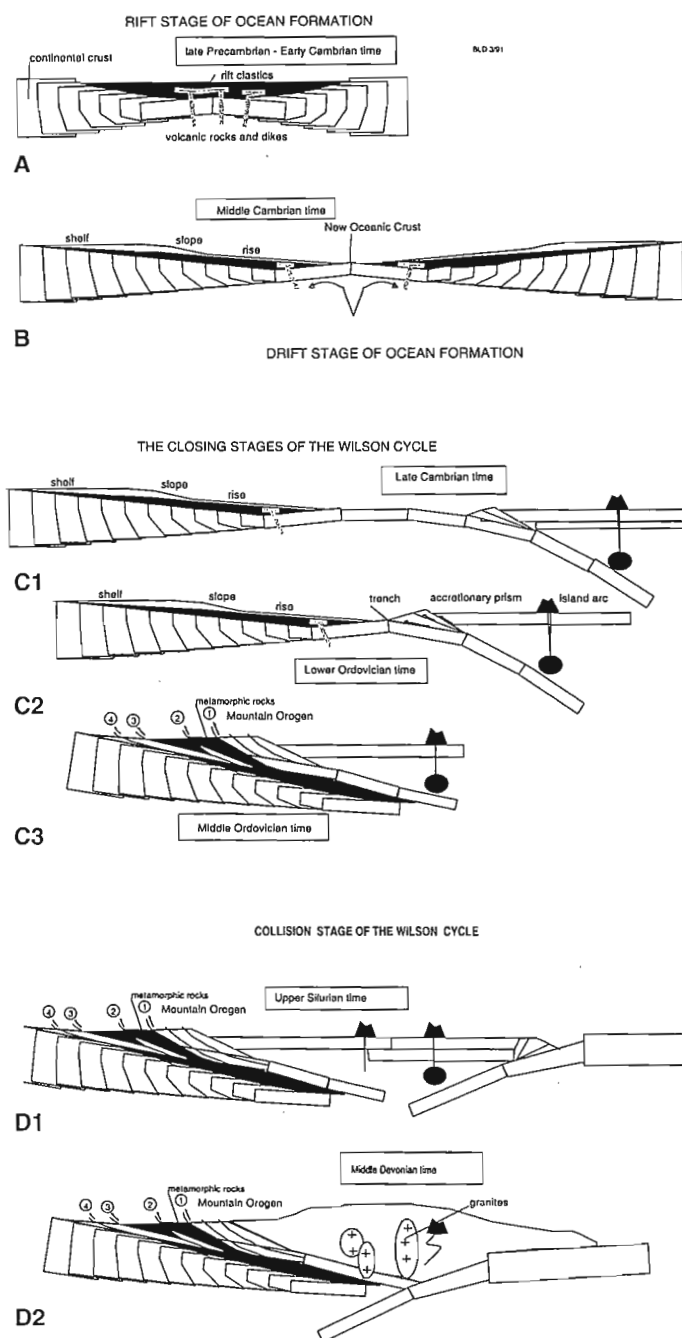


Figure 4. Plate tectonic reconstruction of Vermont geology in the Paleozoic Era.

The effects of the Taconic orogeny were profound throughout western Vermont, not just within the Taconic Mountains. Thrust faults such as the Champlain Thrust, which can be seen at the famous Lone Rock Point locality in Burlington (figs. 1 and 3), brought Cambrian-age platform rocks tens of miles in a generally westward direction over the younger shales that blanketed the platform in the Middle Ordovician. Faults and folds that can be observed east of the Champlain Valley occur in rocks that were caught deeper in the subduction zone. The axis of the mountains, which forms a major spine down the full length of the state, corresponds with the location of the most

A. Rift stage of the Wilson Cycle (Late Precambrian to Early Cambrian time, ca. 590–555 mybp). Ancient North America rifts apart to form deep valleys that fill with eroded materials off adjacent highlands; eruptions are locally abundant, especially in northern Vermont and adjacent Quebec.

B. Drift stage of the Wilson Cycle (Early Cambrian to Middle Ordovician time). A new spreading center develops between two continental masses that are “drifting” away from each other. A mid-oceanic ridge develops in the newly formed Iapetus Ocean. On each side of the ocean, fully developed continental margins consisting of shelf, slope, and rise develop over a 100-million-year period. These continental margins are major centers for sediment accumulation.

C. Closing stages of the Wilson Cycle.

C1 to C3: The Iapetus Ocean closes by subduction of oceanic crust beneath a trench (C1 and C2). Material on the ocean floor as well as fragments of oceanic crust are scraped together into an accretionary prism during the closure. The mountain orogen develops when the large accumulations of sediment along the continental margin are incorporated into the accretionary prism. (C3). Although an island arc is shown to be present throughout this time period (C1 to C3), the Bronson Hill rocks of western New Hampshire (see fig. 1) were formed only during the last stages of the Taconic orogeny. Thrust faults develop in the accretionary prism and generally develop from the orogen side of the complex toward the continent (i.e., in C3 fault 4 develops before fault 3, which develops before fault 2, etc). Faults like these were responsible for carrying the Taconic Mountains over the rocks of the Champlain Valley domain.

C3 is the culmination of the Taconic orogeny, which concluded approximately 445 mybp.

D. Collision stage of the Wilson Cycle.

D1. Development of the Connecticut Valley Gaspé Basin. Following the Taconic orogeny, a new basin develops east of the Taconic Mountains (Connecticut Valley Gaspé Basin). A new trench is active on the eastern edge of the Iapetus Ocean that dips toward the ancient Taconic Mountains. A large continental mass (actually eastern New England on this cross section) lay east of the trench.

D2. Collision of the Vermont and eastern New England landmasses with metamorphism and intrusion and uplift in the axial region of the collision zone. The famous Barre Granite and related intrusions formed by melting of sediments and crust during this collision. This culmination of the Wilson Cycle in the Middle Devonian is referred to as the Acadian orogeny.

highly deformed and the most deeply buried rocks within the ancient subduction-zone complex of rocks. From Jay Peak south through Mt. Mansfield, Camels Hump, Mt. Ellen, and Mt. Grant, this axial zone is underlain by schists and phyllites, which were formed by the metamorphism of older rift sediments and volcanic rocks caught deep within the Taconic orogeny subduction zone. In the vicinity of Mt. Holly and southward into the Berkshire Mountains of Massachusetts, the axial zone is underlain by the ancient (Grenvillian) basement, which formed the original substrata for the ancient continental margin deposits. Mixed in with these rocks, especially on the

east side of the Green Mountain axis, are slivers, patches, and fragments of oceanic material, many of which contain talc and serpentine deposits. These mixtures provide geologists with a window into the inner workings of subduction zones of the past and are used to complement the studies of active subduction zones that appear to be operating today.

Post-Taconic History: Continent-Continent Collisions

The size of Vermont was greatly enlarged during the Taconic orogeny. Still, Vermont was situated on the western shore of what remained of the ancient ocean of Iapetus following the Taconic orogeny (440–430 mybp). It seems likely that an archipelago of volcanoes above the east-bending subduction zone lay to the east in the present vicinity of the Vermont-New Hampshire border. Throughout the Silurian and Lower Devonian Period (approximately 430–400 mybp), lands east of the Green Mountains began to stretch and subside to form a large elongate basin that extended throughout New England and Quebec as far north as the Gaspé Peninsula. The resulting sedimentary basin, referred to as the Connecticut Valley–Gaspé Basin (CVG; see figs. 1 and 2), was inundated with shales, limestones, and sand that came from the highlands to the west. Basins of this extent and longevity are thought to result from plate-tectonic processes that in this case represent continuation of the geologic settings established during the Taconic orogeny. Although volcanic activity was not abundant within the basin, volcanic arc activity was present along the Bronson Hill area, a terrane of rocks presently exposed just east of the Connecticut River in New Hampshire. This suggests that subduction shifted eastward to the east side of the CVG. By Early Devonian times, evidence from New Hampshire and Maine suggests that all remnants of the ancient Iapetus Ocean were disappearing rapidly. Continental masses along the eastern seaboard of ancient North America were converging onto the newly formed mountains of Vermont and its subjacent basin filled with Silurian and Devonian sediments.

The convergence began from the east in what is now central New Hampshire. As the basin between the developing landmass to the east and the CVG to the west closed, large masses of rocks were folded into *nappes* pushed from east to west (picture a 9 by 12-foot rug folded lengthwise into three flat-lying folds of 3 by 12-foot size; imagine this rug in miles instead of feet, and you begin to appreciate the scale of *nappes*). The entire Bronson Hill Terrane and much of the CVG were involved in this major compressional event. The central belt of the entire Appalachian chain was part of the collision, which involved not only the sedimentary cover but presumably also the underlying basement. Melting in this convergence zone produced large quantities of granite both during and immediately following the collision. In Vermont, these granites included the famous Barre Granite and related intrusions of Mid-to-Late Devonian age (approximately 355 mybp).

This major convergence event in the Appalachians is referred to as the Acadian orogeny. Its effects are manifest by the complex fold patterns, metamorphism, and intrusion of the shales, limestones, and sandstones (now schists, phyllites,

quartzites, and marbles) throughout the CVG Basin. Further west, the Acadian event refolded the earlier-formed mountains in the Green Mountain domain and raised the earlier-formed deep-seated rocks along the Green Mountain axis. The size of the Acadian Mountains was significant judging from the tremendous quantities of erosional debris shed from these highlands. The quartz-rich debris was carried far across New York and Pennsylvania and deposited in what geologists refer to as the Catskill Delta; eroded remnants of these deposits occur in the Catskill Mountains of eastern New York.

The Acadian orogeny brought together all of the land that we now know as New England, Maritime Canada, and much more. Further convergence in the southern Appalachians during the Carboniferous (Alleghenian orogeny), which had little effect on Vermont geology, marked the final stage of convergence for the Appalachians orogen as a whole. In any case, Vermont at the close of the Acadian and Alleghenian orogenies was located in the core of the large continent of Pangea, a great distance from oceans of any kind. That is to say, the Vermont Appalachians had a location rather analogous to the present-day Ural Mountains, which are located near the center of Eurasia.

During the Mesozoic and Cenozoic eras, Vermont was a landmass undergoing erosion much as it is today. The geologic record is scanty because of the lack of significant depositional basins within the area. The Mesozoic was, however, an active time tectonically for the Appalachians, since it marked the breakup of the supercontinent of Pangea and formation of the present Atlantic Ocean. The effects in Vermont, however, may have been more extreme than now assumed. Certainly, the evidence of large-scale extension of the North American continent was felt in Vermont, as is evidenced by the abundance of Mesozoic dikes that are located throughout the state and that are especially well preserved in the Champlain Valley. Normal faults, also the product of extension, are also abundant in the Champlain Valley; these faults, many of which were active in the Ordovician Period, may have been reactivated in the Mesozoic, creating the down-dropped grabens that were precursors to present-day Lake Champlain.

In the Cenozoic, the geologic record changes its character. The only rock record, *per se*, preserved is the interesting Brandon Lignite deposits that contain abundant plant fossils, seeds, and pollen grains, attesting to warm and humid climates during the Eocene. During the Pleistocene Epoch, the geologic history of Vermont is preserved in the sands, gravels, and muds. These sediments are part of a story of advance and retreat of mile-high ice sheets over the Vermont landscape during the last twenty thousand years. No part of Vermont has escaped the imprint of the glacial record, which includes major fresh water and marine inundations of the Champlain Valley that led to the formation of Lake Champlain as we know it today.

Epilogue

The plate-tectonic paradigm has helped all of us appreciate the rich geologic past recorded in the rocks and minerals of the state of Vermont. Without the paradigm, interpretation of the

long history of tectonic cycles would be difficult, if not impossible, to piece together from the evidence in the rock record alone. For the future, plate tectonics predicts that there is more to come. Eventually, the Atlantic will close and the history of the Grenvillian, Taconian, and Acadian orogenies of Vermont's past will serve as templates to envision the future evolution of the Vermont-New England landscape.

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