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HISTORY OF RESEARCH ON GLACIATION IN THE WHITE MOUNTAINS, NEW HAMPSHIRE (U.S.A.)

Woodrow B. THOMPSON*, Maine Geological Survey, 22 State House Station, Augusta, Maine 04333-0022 U.S.A.

ABSTRACT The glacial geology of the White Mountains in New Hampshire has been the subject of many investigations since the 1840's. A series of controversies evolved during this period. First was the question of what geologic processes were responsible for eroding the bedrock and depositing the cover of surficial sediments. By the 1860's, the concept of glaciation replaced earlier theories invoking floods and icebergs. Research in the late 1800's concerned the relative impact of continental versus local glaciation. Some workers believed that surficial deposits in northern New Hampshire were the product of valley glaciers radiating from the White Mountains, but in the early 1900's continental glaciation was established as the most important process across the region. Debate over the extent and timing of alpine glaciation in the Presidential Range has continued until recent years. The most intensely argued topic has been the manner in which the Late Wisconsinan ice sheet withdrew from the White Mountains: whether by rapid stagnation and downwastage, or by progressive retreat of a still-active ice margin. The stagnation model became popular in the 1930's and was unchallenged until the late 1900's. Following a research hiatus lasting over 40 years, renewed interest in the glacial history of the White Mountains continues to inspire additional work.

RÉSUMÉ *Histoire de la recherche sur les glaciations dans les White Mountains du New Hampshire (É.-U.A.).* La géologie glaciaire des White Mountains au New Hampshire a fait l'objet de nombreuses études de 1840 à 1940. Les recherches ont donné lieu à différentes controverses au cours de cette période. Il y a d'abord eu la question des processus géologiques responsables de l'érosion du substratum et de la mise en place des sédiments de surface. Vers les années 1860, l'hypothèse des glaciers a prévalu sur les théories évoquant les inondations et les icebergs. La recherche à la fin du XIX^e^ siècle cherchait à déterminer l'apport relatif des glaciations continentales et des glaciations locales. Certains chercheurs croyaient que les dépôts de surface dans le nord du New Hampshire provenaient de glaciers alpins issus des White Mountains, mais au début du XX^e^ siècle le concept de la glaciation à l'échelle continentale a été établie comme étant le processus principal dans la région. Toutefois, le débat sur l'extension et le déroulement des glaciations alpines dans le Presidential Range s'est poursuivi jusqu'à récemment. La question la plus discutée concerne la façon dont s'est fait le retrait de l'inlandsis wisconsinien : stagnation et ablation rapides du front ou retrait progressif d'une marge glaciaire encore active. Le modèle de la stagnation l'a emporté dans les années 1930 et est demeuré incontesté jusqu'à la fin du XX^e^ siècle Après une interruption de plus de quarante ans, un intérêt renouvelé a inspiré des travaux additionnels sur la question.

ZUSAMMENFASSUNG *Geschichte der Forschung über die Vergletscherungen in den White Mountains, New Hampshire.* Die glaziale Geologie der White Mountains in New Hampshire ist seit 1840 Thema vieler Studien gewesen. In dieser Zeit entstand eine Reihe von Kontroversen. Die erste Frage war, welche geologischen Prozesse für die Erosion des anstehenden Gesteins und die Ablagerung der Decke von Oberflächensedimenten verantwortlich waren. In den 60er Jahren des letzten Jahrhunderts ersetzte das Konzept einer Vergletscherung frühere Theorien, die Überschwemmungen und Eisberge ins Feld führten. Die Forschung im späten 19. Jahrhundert beschäftigte sich mit der relativen Auswirkung der kontinentalen im Verhältnis zur lokalen Vergletscherung. Einige Forscher glaubten, dass Oberflächenablagerungen in Nord-New Hampshire das Produkt von Talgletschern waren, die von den White Mountains ausgingen, aber zu Beginn des 20. Jahrhunderts bestimmte man die kontinentale Vergletscherung als den wichtigsten Prozess in der ganzen Region. Die Debatte über die Ausdehnung und den zeitlichen Ablauf der alpinen Vergletscherung in der Presidential Range hat bis vor kurzem fortgedauert. Am intensivsten hat man darüber gestritten, wie die Spät-Wisconsin-Eisdecke sich von den White Mountains zurückgezogen hat : entweder durch schnelles Stagnieren und Abwärtszehrung oder durch progressiven Rückzug eines immer noch aktiven Eisrands. Das Stagnier-Modell wurde in den 30er Jahren unseres Jahrhunderts populär und blieb bis gegen Ende des 20. Jahrhunderts unumstritten. Nach einer über 40 Jahre dauernden Unterbrechung der Forschungen beginnt ein neues Interesse an der glazialen Geschichte der White Mountains wieder zusätzliche Forschungen einzuleiten.

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* E-mail address: woodrow.b.thompson@state.me.us

INTRODUCTION

New Hampshire's White Mountains (Fig. 1) have attracted scientists since the early 1800's. The first geologists and botanists who worked in the region were explorers as well as researchers. Their pioneering work through the mid to late 1800's was intertwined with the economic development of the White Mountains and the growth of a major tourism industry. Fundamental concepts and problems in New England glacial geology were tested here as researchers built upon knowledge accumulated by previous generations.

This paper reviews the evolution of glacial studies and controversies in the White Mountains. The time period covered here spans slightly more than 150 years. It begins with introduction of the glacial theory in the 1840's and extends to recent and ongoing investigations of the 1990's. The author has concentrated mainly on the first century of research (1840-1940). This was an important period when glacial theories and field methods were developed in the White Mountains, and for which a synthesis has not been previously published.

Early geologic work in the White Mountains addressed the question of whether glaciers formerly existed in this part of the world. Following the acceptance of glaciation, two controversies dominated glacial studies from the late 1800's until 1940. First was the issue of determining the origin and magnitude of glaciation. Was the area affected mainly by alpine glaciers, a local ice cap, a continental ice sheet, or some combination of these types of glaciers? The other problem was to understand the style of deglaciation, which has been a persisent research theme in the White Mountains. Stratigraphic exposures recording pre-Late Wisconsinan glacial cycles are rare in northern New Hampshire, so much attention has focused on the evidence of Late Wisconsinan ice recession. Arguments surrounded the question of whether there was a distinct northward-retreating ice margin, which presumably was associated with active glacial flow, as opposed to rapid stagnation of the entire ice sheet due to thinning and separation over the mountainous terrain.

The deglaciation controversy peaked in the 1930's, followed by a period of inactivity extending nearly four decades. It seemed that the stagnationists had won the debate, and glacial geologists looked to other parts of the world for new problems. However, interest in the White Mountains has experienced a resurgence during the last 20 years. Student theses and detailed investigations of glacial deposits by workers from academic institutions and government agencies have shown that much remains to be learned about this familiar part of New England. Another recent development has been the completion of large-scale (1:25000 metric series) topographic mapping by the U. S. Geological Survey. Unfortunately, these maps often show the terrain with less detail and accuracy than the older 1:62,500 quadrangles.

The geologists who worked in the White Mountains have often been as interesting as the theories they advocated.

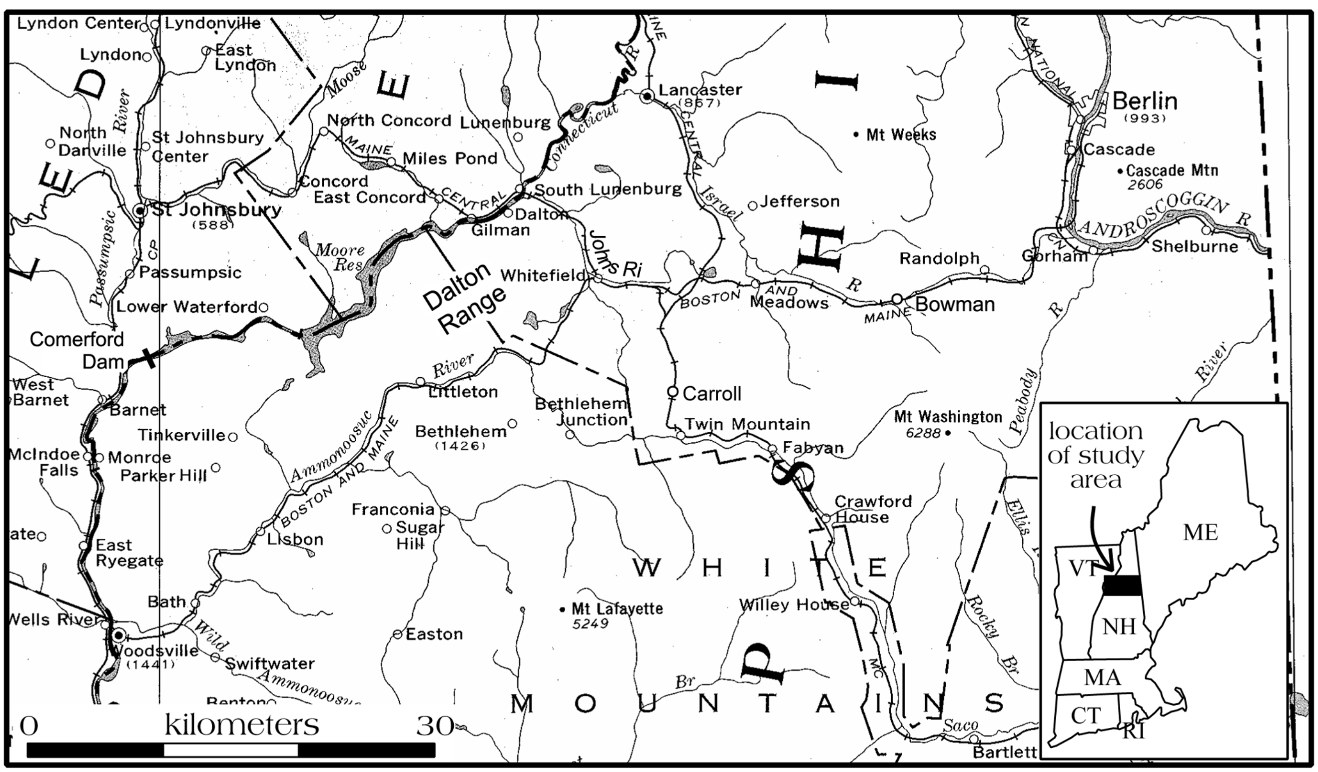


FIGURE 1. 1:500,000-scale map of the White Mountain region, showing principal towns and rivers mentioned in the text.

Carte à 1/500 000 de la région des White Mountains, montrant les principales villes et rivières mentionnées dans le texte.

Detailed characterization of these scientists is beyond the scope of this paper, but the biographic references cited here provide further details about them. The reference section also includes a comprehensive list of publications on glacial studies in the White Mountains, which is intended to be useful to both geologists and historians. Unfortunately, the research for this paper has uncovered few photographs or field notes documenting the day-to-day activities of early geologists in the White Mountains. The author has assembled a gallery of their portraits (Fig. 2), but candid photographs taken in the field are scarce. This lack of original source materials has made it difficult to reconstruct what was actually seen at controversial localities mentioned in published literature.

THE DRIFT PROBLEM

Explorations of the natural history of the White Mountains during the early 1800's were concerned mainly with the inventory of geographic and botanical features. Kilbourne (1916) presented a good summary of this pioneering work. The early writings on New Hampshire mentioned products of glaciation, but the true origins of these features were not recognized. Large or unusually situated boulders have long attracted the attention of both residents and tourists (Fig. 3). In his famous history of the state, Jeremy Belknap remarked on the occurrence of boulders that had been "detached from the mountains", but he thought these stones had rolled into their present positions after being shaken loose by earthquakes (Belknap, 1812). Belknap's observation that earthquakes had been frequent in New England from 1755 to 1774 may have been a factor in his explanation of boulder movement.

Toward the mid 1800's, the growing transportation network and availability of lodging helped open the White Mountains to geologic investigation. In 1839 the New Hampshire legislature authorized the first geological survey of the state, with an annual budget of $2000 for three years. Charles T. Jackson (1805-1880), a Massachusetts physician who had just completed a geological survey of Maine, was hired as State Geologist and held that position until 1844. Like many other prominent 19th century geologists, Jackson had a wide range of scientific interests along with the time and financial means to pursue them. He was also one of the most controversial figures in New England geology. He became embroiled in bitter priority disputes over the invention of the telegraph and discovery of the use of ether as a surgical anesthetic. In retrospect Jackson has been variously described as irritable and paranoid (Gifford, 1973) and "among the first of American scientists" (Maine Mining Journal, 1880).

When Jackson began his field work in New Hampshire, his warm reception showed the esteem in which scientific endeavors were held in those days. In his first annual report he remarked that "not infrequently the towns had, before our arrival, appointed committees to aid us in the work, and sometimes a large number of citizens have gone forth with us among the mountains, to assist in collecting specimens of minerals for examination" (Jackson, 1841, p. 12). Jackson stayed at T. J. Crawford's Notch House, which was one of the earliest hostelries in the White Mountains. In 1840 he and the mountain guide Abel Crawford made the first horseback ascent of Mount Washington (the highest mountain in New Hampshire, with a summit elevation of 1917 m).

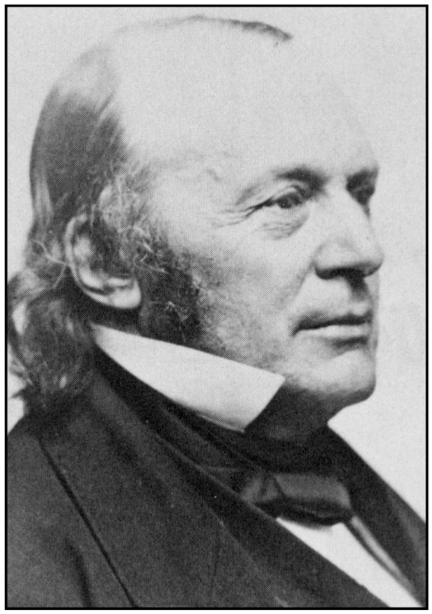
Jackson and his contemporaries referred to surficial sediments as "diluvium" or "drift". He adhered to a theory that was popular at the time, that these sediments were deposited by a marine flood carrying icebergs. Strong ocean currents were assumed to have dragged rocks across ledges, producing grooves on their surfaces. Although he never concluded that New Hampshire had been glaciated, Jackson at least made significant observations on what were later shown to be glacial phenomena. He measured the SSE trend of "diluvial furrows" on Pigwacket Mountain (now called Kearsarge North) near North Conway (Jackson, 1841). In his final report he noted that "... the scratched rocks and transported materials indicate the northern origin of the drift..." (Jackson, 1844, p. 244).

Jackson apparently expected that any former glaciers in the White Mountains would have behaved like alpine glaciers that could still be seen in other parts of the world. He claimed that the lack of a groove pattern radiating outward from the White Mountains is evidence that glaciers never existed in this area. He mentioned Agassiz's glacial theory of 1837 but made the memorable statement that "the glacial theory of drift is absurd" (Jackson, 1844, p. 25).

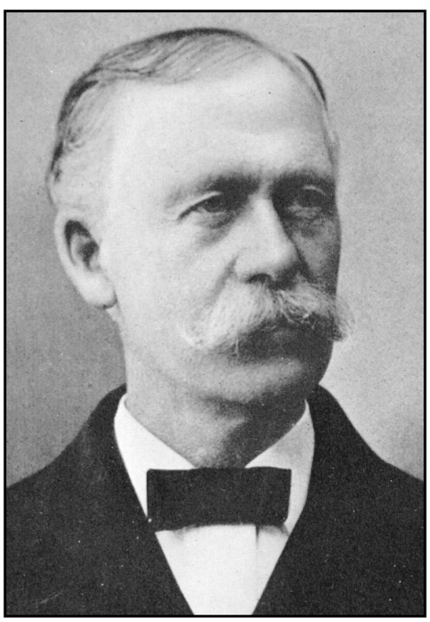
Edward Hitchcock (1793-1864) held views similar to those of Jackson. He was the first president of Amherst College and State Geologist for Massachusetts and Vermont (Foose and Lancaster, 1981). Hitchcock (1841) observed that "drift" had been carried to the south or southeast and noted its presence at elevations up to about 4000 ft in the New England mountains. He favored the glaciation theory, saying that it could explain "ancient moraines", the abrasion of bedrock, and the presence of angular boulders on mountain summits. However, Hitchcock had difficulty visualizing an ice sheet of continental scale that could overrun mountains and spread far across gentle slopes. He concluded that drift resulted from "glacio-aqueous action"—the "joint action of ice and water, without deciding which has exerted the greatest influence" (1841, p. 258).

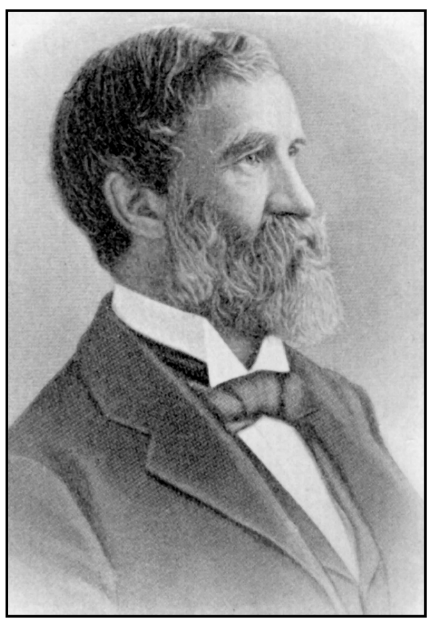
Another eminent geologist who supported the combined action of ocean waters and icebergs in forming drift was Charles Lyell (1797-1875). He believed that erratic boulders and striated bedrock in New England were produced by icebergs melting and running aground, respectively (Brice, 1981). It is particularly interesting to read Lyell's (1849) account of his explorations in the White Mountains during the fall of 1845. He and his wife travelled through the mountains via Conway, Crawford Notch, Bethlehem, Franconia Notch, and Plymouth. The "elder Crawford" (presumably Abel Crawford) guided Lyell to the site of the famous Willey House landslide in Crawford Notch, where he examined bedrock scratches in the path of the slide to compare them with the types of grooves that other people attributed to glaciers. Lyell found that the landslide scour marks were not as con-

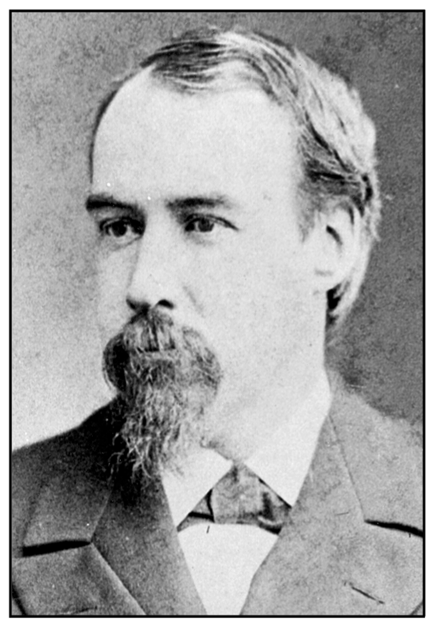

Charles Thomas Jackson
1805 - 1880


Jean Louis Rodolphe Agassiz
1807 - 1873


George Leonard Vose
1831 - 1910


Charles Henry Hitchcock
1836 - 1919


Alpheus Spring Packard
1839 - 1905


George Hapgood Stone
1841 - 1917

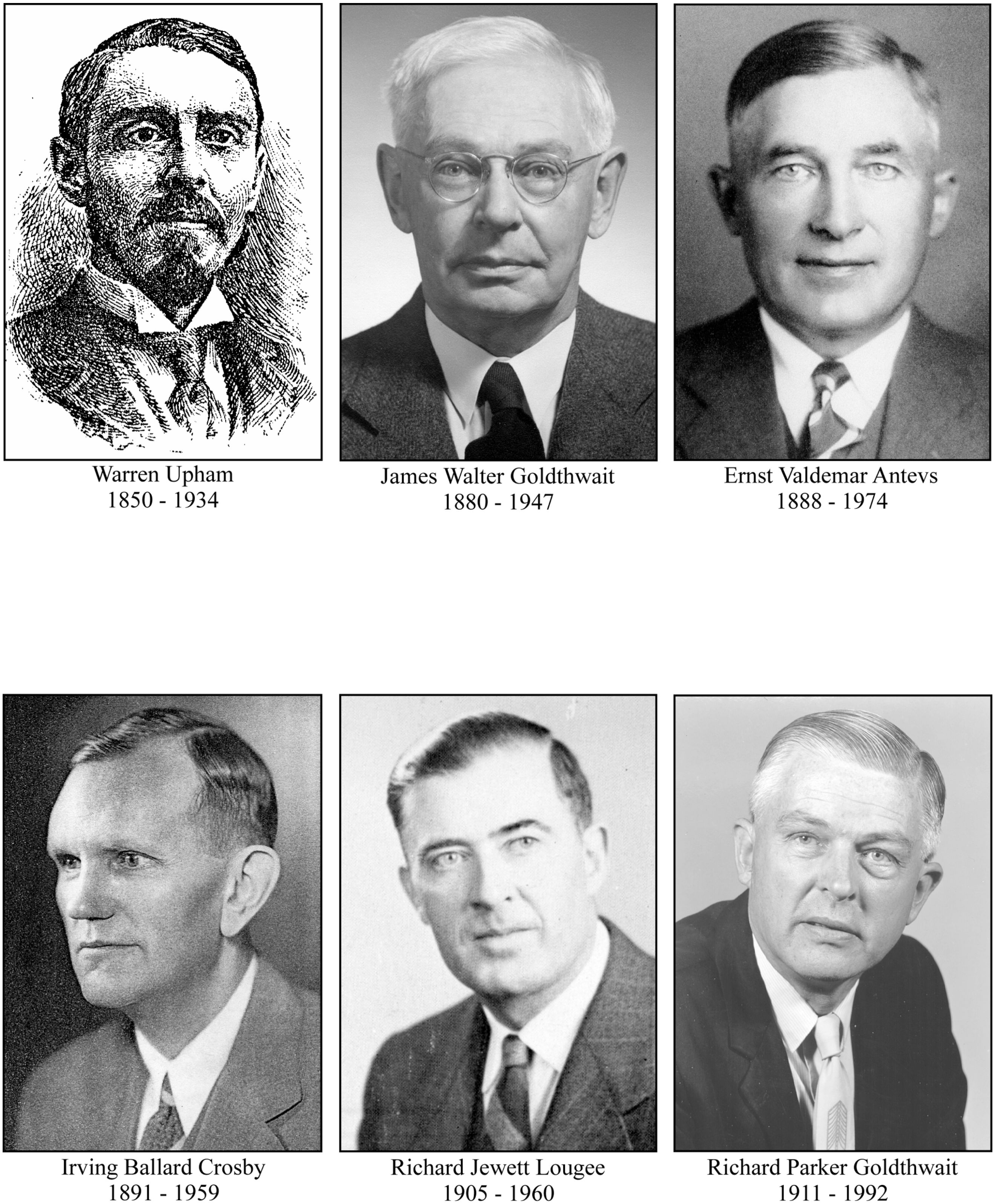


FIGURE 2. Geologists who investigated glaciation in the White Mountains during the period 1840-1940.

Les géologues qui ont étudié la glaciation dans les White Mountains de 1840 à 1940.

tinuous and parallel as those thought to have been made by glacial ice elsewhere. This led him to conclude that stony mudflows could be too easily deflected by obstacles to cause long straight furrows.

Lyell then spent several days at Fabyan's Hotel, which the botanist William Oakes was using as a base for his work in the White Mountains. Oakes and the Lyells were treated to the demonstration of mountain echoes that Fabyan liked to produce for his guests by playing loud "notes" on his horn, and they joined a party to climb Mount Washington on horseback. At the time of Lyell's visit, a prominent esker segment called "The Giant's Grave" (since removed) existed near Fabyan's Hotel. Lyell described this feature as "a long superficial ridge of gravel, sand, and boulders, having the same appearance as those mounds that are termed 'osar' in Sweden" (Lyell, 1849, p. 65). This may have been the first suggestion that eskers exist in the White Mountains, although he stopped short of saying that the Giant's Grave was indeed an osar.

On the final leg of his White Mountain journey, Lyell travelled south from Franconia to Plymouth. Along the way he noted "roches moutonnées" in the Pemigewasset River valley. He likened these to similar landforms in the Alps, but again there was no mention of how they might have formed.

The renowned Swiss naturalist Jean Louis Rodolphe Agassiz (known as Louis Agassiz; 1807-1873) may have been the first major proponent of glaciation in the White Mountains. Agassiz came to the United States in 1846 to lecture at Harvard University. He had already published, in 1840, an important pioneering work on modern alpine glaciers—*Études sur les glaciers*. In 1847 he visited the White Mountains with a group of Harvard students to look for evidence of glaciation (Lurie, 1988). This probably was one of the first collegiate geology field trips to the area! In a letter to Elie de Beaumont, dated August 31, 1847, Agassiz said that "The absence of moraines, properly so-called, in a country so little broken, is not surprising; I have, however, seen some very distinct ones in some valleys of the White Mountains and in Vermont" (E. Agassiz, 1885).

Agassiz's paper on White Mountain glaciation did not appear until 1870, when he returned to the region to examine a problem that had made him hesitant to publish sooner—the relationship of the regional drift cover to the products of what he supposed were local mountain glaciers. Agassiz made several key points in this paper. He proposed that the "northern drift" (till deposited by a large ice sheet from the north) occurs throughout the White Mountains, and thus the mountains were overriden by this ice sheet. He gave a graphic description of the till, including striated and faceted stones. Agassiz thought that large erratic boulders overlying the northern drift in the White Mountains were deposited by younger alpine glaciers. He was the first to propose that a series of drift ridges in Bethlehem are moraines, which he attributed to a local glacier flowing north from the Franconia Range. Agassiz likewise believed that other presumed moraines south of the mountains, in the Center Harbor and Squam Lake areas of central New Hampshire, were deposits of the younger alpine glaciers radiating from the White Mountains.

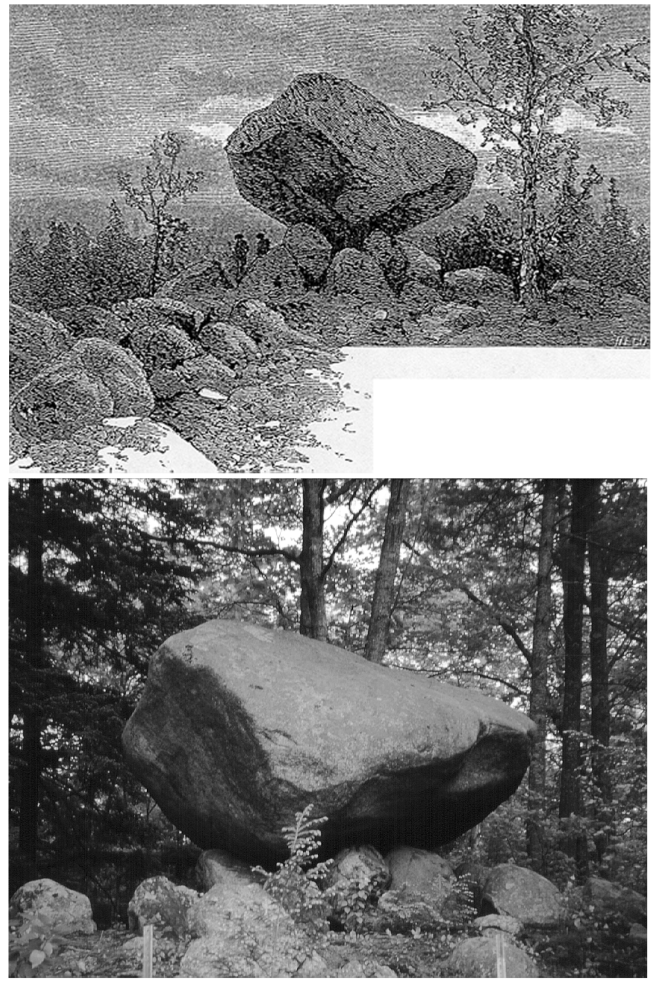


FIGURE 3. This boulder in Bartlett, N.H. was formerly a tourist attraction. It was glacially transported, and as the ice melted was lowered onto four smaller boulders. (a) The boulder as it appeared during the Victorian era (from Drake, 1882). (b) The Bartlett Boulder today. It is approximately 3.7 m wide.

Ce bloc situé à Bartlett (New Hampshire) a déjà constitué un attrait touristique. D'abord transporté par les glaciers, le bloc a été déposé sur quatre pierres à la fonte des glaces. a) Le bloc tel qu'il apparaissait à l'époque victorienne (de Drake, 1882) ; b) le bloc de Bartlett, aujourd'hui. Il mesure environ 3,7 m de largeur.

The area of inferred moraines in the Ammonoosuc River basin north of Bethlehem village later became the most debated glacial feature in the White Mountains. Agassiz remarked that "The lane starting from Bethlehem Street, following the Cemetery for a short distance, and hence trending northwards, cuts sixteen terminal moraines in a tract of about two miles. Some of these moraines are as distinct as any I know in Switzerland" (Agassiz, 1870, p. 164). Despite the existence of many drift ridges nearby, subsequent investigators have not been able to locate and verify an obvious moraine cluster in this part of Bethlehem. The problem with re-locating Agassiz's moraines probably was responsible for the later skepticism as to whether moraines could be found anywhere in the region.

TRACES OF ANCIENT GLACIERS

Two multi-talented individuals advanced the study of glacial geology in the White Mountains during the late 1860's. Alpheus S. Packard, Jr. (1839-1905) received his M.D. degree from Bowdoin College in 1864 and then studied under Agassiz at Harvard. He led a varied and illustrious career, co-founded *The American Naturalist* in 1867 (Norland, 1974), and was especially active in the field of entomology (National Cyclopaedia of American Biography, 1893). George L. Vose (1831-1910) studied civil engineering at Harvard and became a prominent author in the engineering and railroad fields. He later taught at Bowdoin College and M.I.T. (Vose, 1932). Vose also worked on Charles Hitchcock's geological survey of New Hampshire in 1869 (see below).

Geology appears to have been a sideline, perhaps a hobby, with these two scientists. They probably were acquainted with each other through their involvement with Bowdoin College, where Packard was a lecturer, or their mutual assocation with Hitchcock in his surveys of Maine and New Hampshire. Both Packard and Vose carried out much of their glacial geology field work in the eastern White Mountains and western Maine. One of their most important contributions was to use glacial striations and erratics as a record of ice-flow history. It is not clear whether they worked in the field together, but they did exchange correspondence regarding field observations (Packard, 1867a).

Packard (1867a) conceived of "continental glaciers" as a series of ice caps on the high mountains of eastern North America, from which valley glaciers radiated into the surrounding lowlands. He believed that the proposed White Mountain ice cap was not thick enough to cover the Presidential Range and soon subdivided into local glaciers. Packard claimed that valleys issuing from the mountains were occupied by deep glacial lakes impounded behind "terminal" moraines. He cited the Peabody, Ellis, Saco, Ammonoosuc, and Moose River valleys as examples. Although his evidence for glacial lakes in these valleys was not stated, subsequent investigations have confirmed that lakes existed in most of them. Packard (1867b) was the first to propose that the Saco River valley contained a series of postglacial lakes in which reworked glacial sediments were deposited. This conclusion was likewise verified by later workers.

Packard also provided the earliest published reference to complex sections of till and glaciolacustrine deposits along the north-draining Peabody River (east of the Presidential Range), which continue to be studied today (Fowler, this volume): "In passing from Gorham, N.H., to the Glen House we see on each side of the road, fine examples of true glacial moraines which apparently have never been modified by the sea. These moraines, presenting vertical cliffs from fifty to one hundred feet high, of clay and mud and gravel, are mixed in confusion, though near the top of the deposit there is a rude stratification probably similar to what has been noticed in the ancient moraines in the Alps" (Packard, 1867a, p. 238).

Vose (1868) devoted much of his work to understanding the striation record in the eastern White Mountains. He wrote a short primer on how to measure striation azimuths, including what may be the first reference to the technique of rubbing a polished ledge surface with a pencil or similar agent to reveal fine scratches: "Glacial traces may be rubbed off from the stone itself, when it is somewhat smooth, in the same manner as children obtain the figure from a coin" (1868, p. 291). Vose's paper was accompanied by the first known striation map of the region, covering an area south of the Androscoggin River and extending from the Presidential Range east to Kezar Lake in Maine (Fig. 4).

Vose recognized that there had been a widespread ice flow across New England in a south-southeast direction. He presented data on anomalous striation trends that were thought to indicate the flow of valley glaciers issuing from local ice masses in the White Mountains. Vose cited field evidence supporting Packard's (1867b) theory that a valley glacier from the Presidential Range flowed down the Peabody River valley and joined the "Androscoggin glacier" at Gorham. In this valley he noted NE-SW striations which he believed to have resulted from the northeast flow of the local glacier. Vose also recorded striations following the general eastward path of the Androscoggin Valley between Gorham and Bethel, Maine, and assigned them to the local Androscoggin glacier (in contrast to nearby south-trending striations that were prominent at higher elevations). However, he was not able to establish the age relation between the New England ice movement and the presumed local glaciers of the White Mountains.

THE HITCHCOCK SURVEY

Charles H. Hitchcock (1836-1919) was the son of Edward Hitchcock. He first studied theology and then became a geologist, earning several degrees from Amherst College. Like C. T. Jackson, Hitchcock conducted a geological survey of Maine, where he was State Geologist in 1861-1862, and then worked in New Hampshire. In 1869 he was appointed as both State Geologist and Professor of Geology and Mineralogy at Dartmouth College. Hitchcock's survey of New Hampshire occupied 10 years and is remembered as one of his greatest achievements (Upham, 1920). He also helped establish the first year-round weather station on Mount Washington, which was occupied through the winter of 1870-1871.

Among his other interests, Hitchcock was a charter member of the Appalachian Mountain Club (AMC) and offered popular lectures and field trips for Dartmouth students and the general public (Naslund, 1985; Wallace, 1995). His report titled "Glacial markings among the White Mountains" was one of the first of many scientific studies published in the AMC journal *Appalachia* (Hitchcock, 1878c).

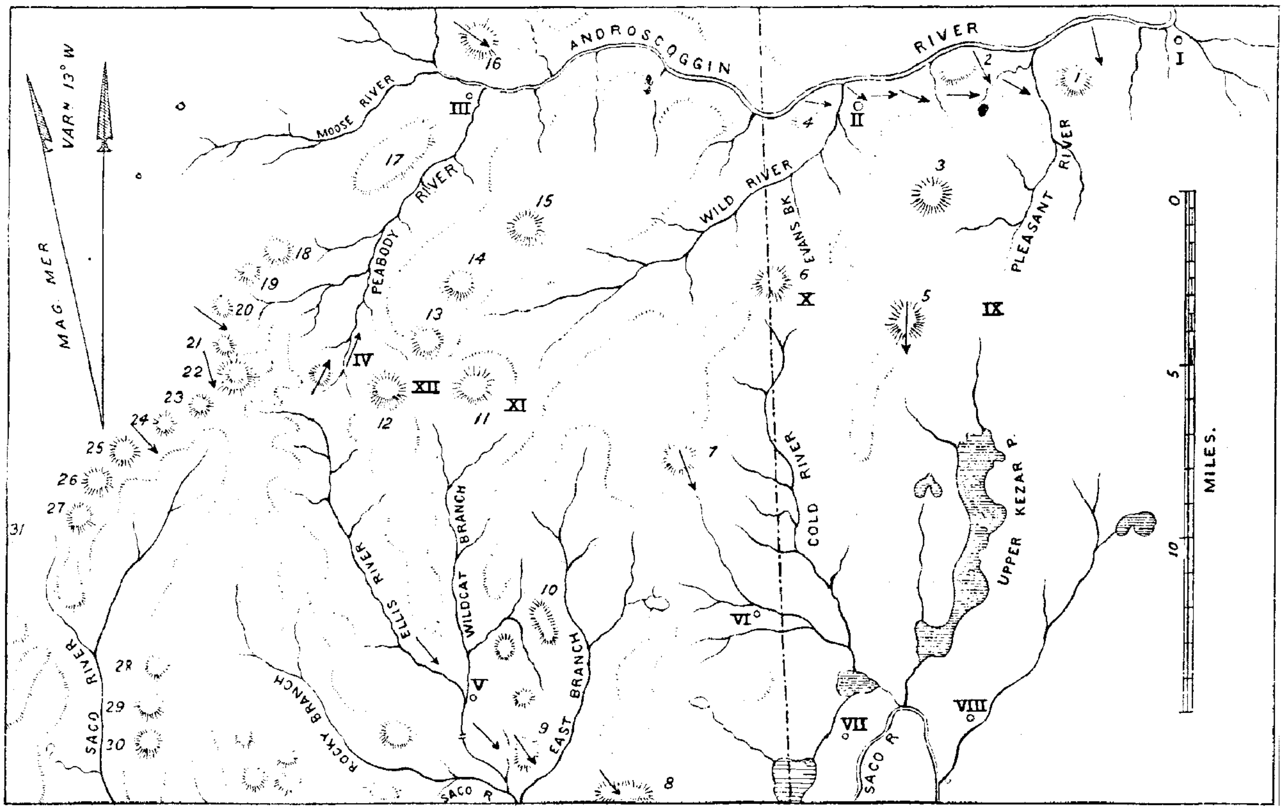


FIGURE 4. Map by George Vose (1868), showing glacial striation localities in the White Mountain region. Arrows indicate inferred ice-flow directions.

Carte de George Vose (1868) montrant les sites où l'on avait trouvé des marques glaciaires dans les White Mountains. Les flèches donnent les directions probables de l'écoulement glaciaire.

Hitchcock's New Hampshire survey resulted in preliminary annual reports for 1869-1873, an elegant series of three large volumes with final results (published in 1874, 1877, and 1878), and an accompanying atlas of geologic maps in 1878. The preliminary reports contain interesting insights concerning his work. As in Jackson's time, scientists were accorded great respect by the citizenry. Hitchcock said that his field party often received lodging free or at reduced cost, along with offers of assistance and transportation. He remarked that "...for six weeks so many carriages were placed at our disposal that there was no occasion to hire a team" (Hitchcock, 1869). Hitchcock's 1878 volume included much new information on the glacial geology of New Hampshire (Hitchcock, 1878a), and his atlas contained the first surficial geologic maps of the state. These maps were hand-colored and showed striation data as well as the distribution of stratified drift (Hitchcock, 1878b).

Several highlights stand out among Hitchcock's observations on the glacial geology of the White Mountains. He contributed to understanding the behavior of the continental ice sheet and the extent of glaciation on Mount Washington. Previous workers such as E. Hitchcock (1841) and Packard (1867a) thought that the summit cone of Mount Washington was not affected by glaciers or other forms of ice activity that had scoured the surrounding peaks and valleys. However, Hitchcock showed that this mountain, too, had been overriden by glacial ice. The evidence that he found very close to the top of Mount Washington included erratic stones transported from the north, and a roche moutonnée. Hitchcock also found till in the foundation hole under the summit hotel, and he reported faint SE-trending striations in the immediate vicinity of the summit (Hitchcock, 1876, 1878a, c).

Hitchcock shared the opinion of previous workers who believed that the White Mountains had experienced local glaciation as well as being covered by a continental ice sheet. He commented on the relative ages of alpine and continental glaciation, saying that "local glaciers occupied the flanks of the White Mountains during the decline of the ice period" (1878a, p. 208). He also agreed with Agassiz's observations of moraines north of Bethlehem village and the assertion that they were deposited by local ice flowing north from the vicinity of the Franconia Range. Hitchcock (1872) reported that he had prepared a "topographical model" of the mountains around Bethlehem and Franconia to illustrate Agassiz's proposed northward glacial transport of erratic boulders, and he sent it to the Secretary of State for New Hampshire (John H. Goodale). Although other plaster relief models constructed by Hitchcock have survived, the present author has not been able to locate this glacial model.

Despite his belief in local glaciers, Hitchcock refuted the claims of Packard and Vose that one such glacier had flowed northward down the Peabody River valley near Gorham. He remarked on the anomalous NNE-SSW striations in this valley, but pointed out that stoss-and-lee erosion of bedrock outcrops indicates these striations were engraved by the regional ice sheet flowing up the valley to the southwest (Hitchcock, 1878a, c).

Several other geologists participated in the survey led by Hitchcock, including Warren Upham (1850-1934). Upham graduated from Dartmouth College in 1871. He worked on the New Hampshire survey from 1874 to 1878, then joined the Minnesota Geological Survey and was later employed by the USGS (1879-1895). Upham published many papers on glacial subjects, but switched to archaeological and historical work later in his career (Malone, 1936).

During his tenure with the Hitchcock survey, Upham conducted some of the earliest investigations of glacial meltwater deposits in New Hampshire. He used the term "modified drift" for all of the water-laid sediments in valleys. This material was said to have resulted from "the melting of an immense sheet of ice" (Upham, 1878). Upham also made observations on till deposits. He distinguished "Lower Till", which formed beneath the ice, and "Upper Till", described as a loose, gravelly variety derived from higher in the ice sheet.

Upham (1878) found "kames" in the upper Ammonoosuc valley, including the Giant's Grave at Fabyan (noted earlier by Lyell), but he did not recognize the esker segments described by more recent workers. Both kames and morainic boulders were attributed to local ice flowing westward down the valley from the Mount Washington area. Upham further proposed that a late-glacial lake existed in the Ammonoosuc valley. This was the first recognition of what was later called glacial Lake Ammonoosuc.

THE SEARCH FOR MORAINES

George H. Stone (1841-1917) was the son of a Methodist minister from central New York. Following a tour of duty with the Union army in the Civil War, Stone earned his B.A. and M.A. degrees from Wesleyan University and became a teacher. He taught at Genesee Wesleyan Seminary in Lima, New York (1869-1873) and then at Maine Wesleyan Seminary (now Kents Hill School) in Kents Hill, Maine (1874-1881). Then he was a professor of geology at Colorado College (1881-1888). Stone worked for the U. S. Geological Survey from 1884 to 1898 and spent the last part of his career as a mining geologist and civil engineer in Colorado (Bartlett, 1926).

While Stone was in Maine, he carried out field investigations of glacial deposits across much of the state. This project culminated in publication of a large USGS monograph on eskers and other glacial meltwater deposits titled *The Glacial Gravels of Maine* (Stone, 1899). Most of Stone's writings on glacial geology are outside the scope of this paper, but his investigation of moraines in the upper Androscoggin River valley (on the Maine-New Hampshire border) are important to understanding the deglaciation of the White Mountains.

The nineteenth century geologists working in the White Mountains assumed that former glaciers in this region, whether local glaciers or a large ice sheet, were dynamic and capable of building end moraines as they receded. Stone was familiar with the work of Packard, Vose, and Hitchcock, including their speculation that a local glacier flowed eastward along the Androscoggin Valley between Gorham and the New Hampshire border. In June, 1879, he found large moraine ridges on both the north and south sides of the valley in the vicinity of the state line (Stone, 1880, 1899). Leavitt and Perkins (1935) claimed that the SE-trending ridge north of the river was merely a drift tail, but these authors evidently were unaware of Stone's 1880 paper describing companion ridges projecting from the south side of the Androscoggin Valley.

Interest in finding and correlating moraines continued through the end of the century. In a short discussion of "terminal moraines in New England", Hitchcock (1892) mentioned the Bethlehem moraines, as well as others a short distance farther east (in the town of Carroll) that were not specifically located. In Hitchcock's later discussion of moraines deposited across the northeastern states by the "Laurentian ice sheet", he suggested that "Another line may be indicated in the morainic piles south of Gorham, Carroll, Whitefield, and Littleton" (Hitchcock, 1897, p. 31). It is noteworthy that Hitchcock was the first to place these deposits in the context of continental ice receding northward, rather than invoking local glaciers to form them (as he had previously done with the Bethlehem moraines).

After his work with the Hitchcock survey, and some consulting for the railroad extension to the base of Mount Washington, Upham returned in 1901 to study moraines in the White Mountains. He examined drift ridges in the area described by Agassiz (1870), and formally named them as the "Bethlehem Moraine" (Upham, 1904). Upham's study of this controversial moraine complex was one of many between Agassiz's 1847 visit and the 1930's. While Upham agreed with Agassiz that the moraines were deposited by ice flowing north from the nearby mountains, he said they lacked the well-defined morphology expected of moraines produced by valley glaciers. Upham called the Bethlehem deposits a "promiscuous morainic belt" similar to those found in the Midwest.

Upham (1904) concurred with Agassiz that the moraines in Bethlehem were equivalent to alleged moraines in the lakes region just south of the White Mountains. He extended the definition of the Bethlehem Moraine to comprise a concentric morainal network that he thought could be traced around the entire perimeter of the mountains. Other workers have restricted the Bethlehem Moraine to the vicinity of Bethlehem, or at least to the north side of the White Mountains. Upham believed that the morainal belt resulted from the radial flow of a single large ice cap, rather than individual valley glaciers. In addition to working on moraines, Upham (1904) recognized the sand and gravel ridges in the upper Ammonoosuc valley as an esker series. However, he misinterpreted the flow direction and source of the glacial stream system, which he thought was westward (downvalley) from the diminishing White Mountain ice cap.

CONTINENTAL VS. LOCAL GLACIERS: DISCOVERIES BY J.W. GOLDTHWAIT

James W. Goldthwait (1880-1947) advanced the study of White Mountain glacial geology to an unprecedented degree. He received his Ph.D. in geology from Harvard University in 1906, and was invited to teach at Dartmouth College upon Hitchcock's retirement in 1908. Goldthwait began part-time work for the State Highway Deparment in 1917, inventorying gravel resources and examining glacial deposits with the aid of new topographic maps (White, 1949). This field experience shaped his understanding of the Pleistocene history of the state.

Goldthwait's 1912 field season in the Mount Washington area yielded the first analysis of cirques in the Presidential Range and their relationship to continental glaciation. He published the results of this work both in the *American Journal of Science* and as a popular-interest article in *Appalachia* (Goldthwait, 1913a, b). The latter report is especially interesting for its informal account of camping and working conditions experienced by Goldthwait's field party. It also indicates the continuing role of the Appalachian Mountain Club in promoting and publishing scientific research in the White Mountains.

Goldthwait remarked that Hitchcock apparently did not recognize the origin of the Presidential Range cirques. He described how the alpine zone has been dissected by both fluvial and glacial erosion, and demonstrated that the cirques were cut by alpine glaciers rather than continental ice, stream, or frost activity. Goldthwait found no evidence that valley glaciers radiated out of these mountains to the extent proposed by earlier workers. He cited the northern provenance of till in the Presidential Range cirques, the absence of moraines in these basins, and the asymmetric erosion of valley sides by obliquely overriding ice as proof that continental glaciation followed cirque cutting. He also suggested that the cirques formed as early as Kansan time (Goldthwait, 1913a).

Despite the evidence presented by Goldthwait, his proposed absence of late-glacial cirque development was not universally accepted. The geomorphologist Douglas Johnson published two papers arguing that cirque glaciation followed the demise of the last continental ice sheet. His first paper stated that the White Mountain cirques could have been cut largely in late-glacial time (Johnson, 1917), but he subsequently moderated this position. Johnson (1933) noted glacial valleys in alpine regions that have never experienced continental glaciation, and where morainal deposits are nevertheless sparse. He used these examples to show that the lack of moraines in the Presidential Range cirques does not exclude the possibility of late ice activity.

In the summer of 1915, with field support from the Dartmouth Outing Club, Goldthwait worked on the problem of local versus continental glaciation at lower elevations. He concentrated on the Ammonoosuc River basin, which continued to be a proving ground for the latest theories on regional glacial history. Goldthwait refuted the view of Agassiz (1870), Hitchcock (1878), and Upham (1904) that local White Mountain ice deposited the Bethlehem Moraine (although he seems to have overlooked Hitchcock's implicit retraction of this theory in 1897). Goldthwait also showed that there is no indication of northward ice flow from the Franconia Range. The morphology and provenance of the moraine ridges in Bethlehem, along with evidence of meltwater ponding in the Ammonoosuc valley, favor a continental ice margin receding to the northwest (Goldthwait, 1916).

Still believing in the existence of the moraines in Bethlehem, Goldthwait provided a more detailed description of these deposits than previous workers had given, and he published the first map of the moraine complex. He also described "kame plains" (deltas) just north of Twin Mountain (Goldthwait, 1916). Goldthwait said that both the moraines and kame plains were deposited into a glacial lake dammed by the retreating continental ice margin in the lower Ammonoosuc valley to the west. He named this water body "Lake Ammonoosuc". The esker system in the upper part of the valley was likewise reinterpreted as a continental ice-sheet deposit.

CONTRIBUTIONS OF ANTEVS, LOUGEE, AND CROSBY

Ernst V. Antevs (1888-1974) was born in Sweden and received his Ph.D. from the University of Stockholm in 1917. In 1920 he came to the United States with Baron Gerard De Geer (who established the Swedish varve chronology) and began a series of varve correlations in both this country and Canada. Antevs spent only a short portion of his career in New England, but in 1921 he carried out a tremendous amount of field work on the varve chronology of glacial Lake Hitchcock in the Connecticut River valley. His chronology has become particularly useful in recent years, as workers have begun to calibrate the varve sequence with radiocarbon dates from lake sediments (*e.g.* Ridge and Larsen, 1990; Ridge *et al.*, 1996, this volume).

Antevs' varve records from Lake Hitchcock sediments indicate an average ice-margin retreat rate of 73 m/yr between Hartford, Connecticut, and St. Johnsbury, Vermont. His study is significant to White Mountain glacial history because Antevs found a site in the Connecticut valley west of Littleton (near the present Comerford Dam; Fig. 1) where the absence of a particular series of varves at the base of the lacustrine section suggested a stillstand of the ice margin lasting approximately 280 years. He tentatively correlated the interruption of glacial retreat with deposition of the nearby Bethlehem Moraine (Antevs, 1922).

In 1928 Antevs worked in the Mount Washington area. He presented the results of this research in a book titled *Alpine Zone of Mt. Washington Range*, which is a natural history of the Presidential Range (Antevs, 1932). Antevs' book discusses the timing of cirque glaciation relative to the most recent continental glaciation and presents much information on frost action in the zone above timberline. Figure 5 shows Antevs on Mount Washington with Michigan geologist Frank Leverett. This photo was taken by J.W. Goldthwait and is dated 1929. An accompanying note to the present author from R.P. Goldthwait states that "I was there. Antevs had hiked up and lived at Lakes of the Clouds AMC hut. Leverett came up for the day by Cog Railroad, dressed in his usual [formal] field visiting garb!"

Richard J. Lougee (1905-1960) graduated in 1927 from Dartmouth College, where he presumably was a student of J.W. Goldthwait. He entered a teaching career in New England and received his Ph.D. from Columbia University in 1938. Lougee taught at Dartmouth (1927-1928), Colby College (1936-1947), and Clark University (1947-1960).

Lougee's publications on the White Mountains are mentioned below, but one of his earliest and most informative reports was never published. This manuscript was based on work that he did in 1930 as part of a statewide inventory of gravel deposits for the New Hampshire Highway Department (Lougee, n.d.). J.W. Goldthwait directed the project, and Lougee's field area comprised a group of 15-minute quadrangles in the White Mountain region. Among his assistants were Lincoln Page and Richard Goldthwait, who later became two of the state's most famous and accomplished geologists.

Lougee's field report for the gravel survey (*ca.* 1930) presented much new information on glacial deposits, lakes, and meltwater spillways. He proposed and named glacial lake stages for the first time, especially in the Littleton-Jefferson-Lancaster area on the northwest flank of the White Mountains. Lougee's working hypothesis was that lakes were impounded by the receding ice margin as the west-sloping valleys in this area were deglaciated. Continued ice retreat opened progressively lower spillways in each river basin, resulting in lowering and eventual emptying of the lakes. Lougee's analysis of meltwater drainage systems foreshadowed the morphosequence mapping concept now used to reconstruct the deglaciation sequence over much of New England (*e.g.* Koteff and Pessl, 1981). His detailed analysis of the stages of glacial Lake Ammonoosuc has needed only minor refinements to the present day (Thompson *et al.*, this volume).

Irving B. Crosby (1891-1959) received his B.S. degree from the Massachusetts Institute of Technology in 1918. His interest in the White Mountains was already evident during his undergraduate years, since he did a bachelor's thesis on the geology of the town of Randolph and the northern Presidential Range. Crosby received an M.S. degree from Harvard University in 1920 and spent his entire career as a consultant in the field of engineering geology (Shrock, 1972). He was interested in glacial stratigraphy and geomorphology, and pursued these topics as part of his consulting work on dam sites.

Crosby (1934a) conducted the feasibility study for Comerford Dam on the Connecticut River west of Littleton (Fig. 1). This dam was constructed during 1928-1930 as part of New England Power Association's "Fifteen Mile Falls Development". On the New Hampshire end of the dam site, Crosby found two tills separated by thrust-faulted sand. He claimed that the upper till resulted from a glacial readvance that followed the local westward trend of the Connecticut valley and terminated in a lake (Crosby, 1934b). Crosby equated the readvance at Comerford Dam to the readvance inferred by Antevs (1922) from nearby varve localities. He further suggested that the Bethlehem Moraine was the same age as this event and could be traced west through intervening morainal deposits to the Connecticut River valley. Crosby also correlated the Bethlehem Moraine with "outwash" deposits farther east at Twin Mountain, which had been described by Goldthwait (1916), and with more distant morainal deposits in Jefferson and the Peabody River valley at Gorham (Crosby, 1934b).

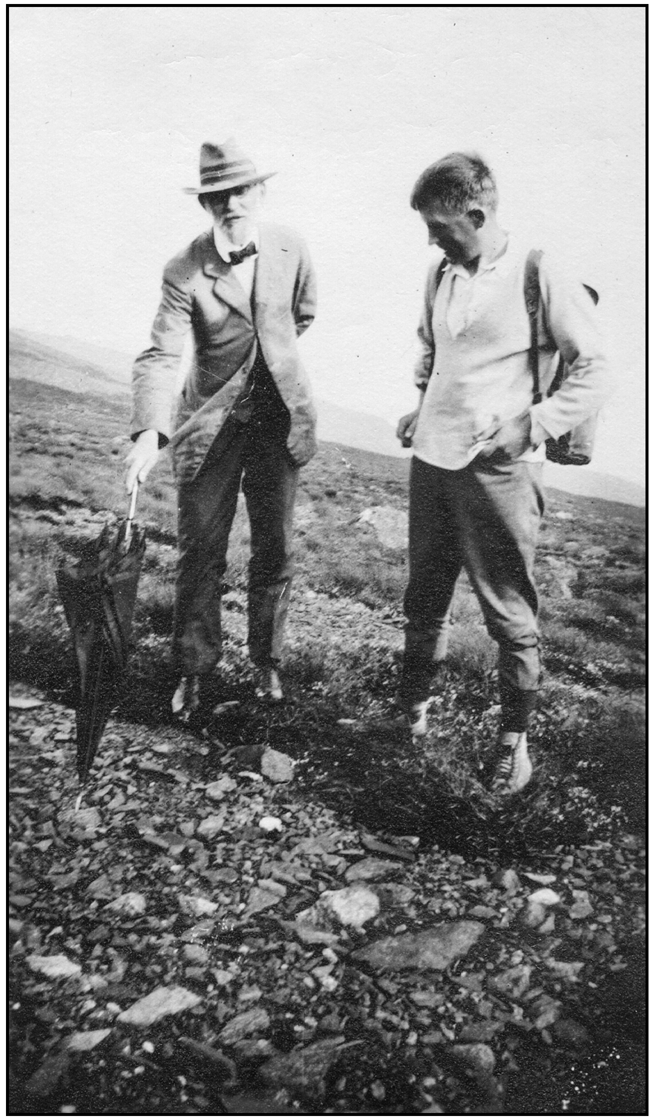


FIGURE 5. Ernst Antevs (right) and Frank Leverett examining patterned-ground features on Mount Washington.

Ernst Antevs (à droite) et Frank Leverett observant des formes de sols structurés sur le mont Washington

Shortly after construction of Comerford Dam, Lougee (1935) found a new section at the lower end of the spillway channel on the Vermont side. This section revealed deformed varved clay between till units. Lougee correlated the lowest 52 varves with Antevs' varve stratigraphy, and concluded that deposition of these varves commenced 270 years before the varves overlying nearby till sections. From this span of time, he subtracted 119 years represented by the varves between the tills, and arrived at 151 years for the duration of the readvance at the dam site. Since Lougee referred to the readvance as the "Littleton oscillation", it appears that he also took this as the time span during which the moraines in Littleton and Bethlehem were formed.

THE 1930'S REVOLUTION

Until about 1930 it was generally assumed that glaciers in the White Mountains were internally active and remained capable of depositing end moraines during their retreat. This was the preferred model when J.W. Goldthwait published *The Geology of New Hampshire* in 1925. However, when the New England Intercollegiate Geological Conference (NEIGC) held its annual field gathering for 1929 in the Littleton area, a paradigm shift was occurring in New England glacial geology. A report on this meeting noted that "During the last year there has been a tendency to postulate a stagnation of the ice sheet in New England, and some have doubted whether the deposits at Bethlehem, N.H., were true recessional moraine" (Foye, 1929, p. 454). This remark hinted at the growing controversy over the mode of deglaciation that became an intense argument in the 1930's.

Richard Foster Flint of Yale University exerted a strong influence on glacial geologists, and he triggered a departure from the active-ice deglaciation model. Flint claimed that the last ice sheet in New England reached its maximum extent and then "lost its motion and melted away in place" (Flint, 1929). J.W. Goldthwait referred to this paper in saying that "The first real challenge to the theory of orderly recession in New England came in 1929, when Flint held that the 'recessional moraines' of this region were fictitious and that the deposits of western Massachusetts and Connecticut required stagnation and irregular downwastage of the ice" (Goldthwait, 1938, p. 370). Richard Goldthwait (1939a) similarly observed that "A few field workers objected from time to time [to the orderly retreat model], but none made such impact as did Richard Flint in 1930". The latter remark probably alluded to Flint's bulletin on the glacial geology of Connecticut (Flint, 1930).

Flint (1929) cited statements in Goldthwait's 1916 paper that he interpreted as favoring a stagnation model for deposition of the Bethlehem Moraine and other ice-contact features in the White Mountains. There was further evidence of the new model in Marland Billings' bulletin on the geology of the Littleton and Moosilauke quadrangles (Billings, 1935). The section of Billings' report on glacial geology contained information supplied mainly by J.W. Goldthwait. It is evident that by this time Goldthwait had shifted toward the concept of widespread stagnation of the Laurentide Ice Sheet during its recession.

Goldthwait published a landmark paper in 1938, completely reversing many of the opinions that he previously held concerning the deglaciation of New Hampshire. Based on his gravel survey for the State Highway Department, he now claimed that ice-contact deposits in valleys "... are much more strongly aligned in the direction of ice motion than transverse to it. Both individually and collectively these records of late-glacial drainage imply downwastage of the ice surface almost to the valley floors instead of orderly 'retreat' of a single wall or 'front'" (Goldthwait, 1938, p. 347). This remark framed the great debate that was in progress concerning "normal retreat" versus "downwastage" of the Late Wisconsinan ice sheet. Goldthwait no longer regarded the Bethlehem deposits as moraines and instead called them "a zone of massive kettled outwash".

Considering Flint's persuasive arguments, it may be no surprise that Lougee's manuscript supporting systematic glacial recession in the White Mountain's remained unpublished. However, Antevs and Lougee continued to support active-ice retreat. The provocative introduction to Antevs' rebuttal paper shows the intensity of the debate: "In a recent paper on the mode of the late Glacial ice waning in New Hampshire Professor Goldthwait eagerly repudiates what he observed and wrote prior to 1929 and cheerfully goes to battle without ascertaining whether the attacked views are real or fancied" (Antevs, 1939, p. 503).

Antevs (1939) said that Goldthwait had misrepresented him as believing that the last ice sheet simply retreated by recession of a marginal ice cliff without concurrent thinning behind the margin. He carefully described his deglaciation model, which was very similar to the stagnation-zone retreat concept of later New England workers such as Koteff and Pessl (1981). Antevs took a moderate position that he felt was realistic in light of variable conditions on modern glaciers. He concluded that "In some regions there was a belt of stagnant ice off the continuous ice edge. The existence of such a zone and its width depended on the trend and degree of the relief, the rate of the forward motion of the ice, the attenuation of the marginal belt of the ice sheet by melting and undernourishment, the rate of retreat of the solid ice edge, and the durability of the severed ice blocks...The fact that a belt of dead-ice topography may be 25 or more miles wide does not imply that there was so broad a belt of stagnant ice at any one time" (Antevs, 1939, p. 508).

Following the publication of Goldthwait's 1938 paper, Lougee likewise continued to support the active-ice model for deglaciation of the White Mountains. In a little-known article on the geology of the upper Connecticut River watershed, he claimed that a series of ice-dammed lakes were impounded between the retreating glacier margin and the northwest flank of the mountains. This article included a map of the proposed glacial lakes and the first published photograph (Fig. 6) showing part of the Bethlehem Moraine (Lougee, 1939). Lougee observed that hillside meltwater channels often connect the glacial lake basins, and he thought they were carved by episodic drainage of the lakes.

In 1940 Lougee published a paper making his final case for persistent active ice during deglaciation of New England. Like so many previous studies, much of this paper was concerned with the Bethlehem Moraine and related deposits of glacial Lake Ammonoosuc north of Twin Mountain village (in the town of Carroll; Fig. 1). Lougee noted that some of the clearest moraine ridges in the Bethlehem complex are just south of U.

FIGURE 6. Photograph from Lougee (1939) showing bouldery ridges comprising part of the Bethlehem Moraine. Location not specified, but presumably in Bethlehem or Littleton, N.H.

Photographie tirée de Lougee (1939) montrant des crêtes morainiques qui comprennent une partie de la Moraine de Bethlehem. La localisation n'est pas précisée, mais il s'agit vraisemblablement de Bethlehem ou de Littleton (New Hampshire).

S. Route 302, near the Littleton-Bethlehem town line (Lougee, 1940, p. 196; described by Thompson *et al.*, 1996, p. 223-224). He also demonstrated that the ice-contact delta built into Lake Ammonoosuc at Carroll is part of an assemblage of features indicating progressive northward retreat of a discrete glacier margin, and not the irregular downwastage of the ice advocated by Goldthwait. Lougee's paper includes a detailed block diagram showing the inferred distribution of glacial ice when the Carroll delta was deposited (reproduced by Thompson *et al.*, this volume).

The controversy over the style of deglaciation disappeared from White Mountain literature shortly after 1940. Probably most New England geologists and the participants themselves had grown weary of the debate by this time. It might not be accurate to say that either side "won" the argument, although the stagnation model prevailed for the next few decades. Douglas Johnson offered a mediation in 1941 as he attempted to clarify the confused terminology that had been used to describe glacial retreat, especially the erroneous tendency of previous authors to assume that "normally retreating" ice had to be live and "down-wasting" ice was stagnant. Johnson noted that lowering of the ice-sheet surface must have accompanied recession of the glacier margin, regardless of whether the ice was still internally active. The trend of the ice margin would have been very irregular in mountainous terrain, so any moraines or other ice-marginal deposits would not be expected to show alignments over long distances (Johnson, 1941). In these respects, Johnson's characterization of the ice sheet was similar to that of Antevs (1939).

REVISITING THE PRESIDENTIAL RANGE

One of J.W. Goldthwait's sons, Richard P. Goldthwait (1911-1992), devoted his career to glacial geology. R.P. Goldthwait graduated from Dartmouth College and received M.S. and Ph.D. degrees in geology from Harvard University in 1937 and 1939, respectively. He taught at Brown University from 1939 to 1943, and at Ohio State University from 1946 until his retirement in 1977. Goldthwait conducted glacial research in many areas of the world besides New Hampshire (White, 1993).

R.P. Goldthwait shared his father's interest in the White Mountains and further defined the relationship between alpine and continental glaciation in the Presidential Range. He authored several popular and scholarly publications on this area between 1939 and 1970. The first was an article in *New England Naturalist*, in which he summarized the evidence for overriding of Mount Washington by the latest continental ice sheet subsequent to formation of the cirque basins (Goldthwait, 1939b). This article describes erratic stones that were transported southward onto the Presidential Range and the abrasion of the cirques by the ice sheet. Goldthwait's observations generally supported his father's views, although he believed that the freshness of the cirques indicated they were cut at least in part during Wisconsinan time.

Goldthwait also described the glacial history of the Mount Washington area in a 1940 bulletin published by the New Hampshire Academy of Science. This well-illustrated report contained much information on frost action, and it included the first detailed topographic map showing glacial features in the entire Presidential Range. Goldthwait argued that the Wisconsinan continental ice sheet dissipated by irregular downwasting in the White Mountains, because meltwater deposits are concentrated in the bottoms of the valleys and northeast-trending morainal belts were thought to be absent. He did acknowledge an overall retreat of the ice toward the northwest, since meltwater streams flowed south and east in the lowlands surrounding the Presidential Range (Goldthwait, 1940).

In 1970 Goldthwait again reviewed the problem of determining the relative age of cirque glaciation in the Presidential Range and presented the most detailed analysis of this topic that had yet been published (Goldthwait, 1970a). He said the sharpness of cirque rims indicates that alpine glaciers were active in early Wisconsinan time, but the overall volume of the basins suggests they were being eroded in Illinoian time as well. On the other hand, Goldthwait speculated that the preservation of large remnants of preglacial uplands (above the cirques) implies that cirque development has not continued throughout Pleistocene time.

RECENT GLACIAL STUDIES

There was little original research on glacial features in the White Mountains during the three decades from 1940 to 1970. However, there has been renewed interest in this region in more recent years, beginning with student thesis research and studies by local residents in the 1970's. In 1971, Guy Gosselin (then Chief Observer of the Mount Washington Observatory) published an informal account of glacial lake deposits in the Peabody and Rattle River valleys near Gorham.

Thomas B. Goldthwait (Richard Goldthwait's son) conducted stone counts and fabric analysis at the Peabody River sections, which had been noticed by geologists as long ago as the 1860's (Packard, 1867a). Despite over a hundred years of prior work in the White Mountains, his undergraduate paper on the Peabody sections may be the first recorded description of a stratigraphic section to which we can refer today (Goldthwait, 1971). This study helped initiate a new trend toward lithofacies analysis of glacial sediments to better understand the glacial record in northern New Hampshire. T. B. Goldthwait (1971) recognized three units in the Peabody valley: a lower "basal till" separated from the overlying "ablation till" by a sequence of "varved lacustrine clays". He proposed that both tills were deposited by ice from the northwest during a single glaciation.

George M. Haselton (1975) studied the glacial geology of the Mount Moosilauke area in the southwestern White Mountains. He recorded striations indicating continental ice flow from directions between north and west, and found two till facies. Haselton also described cirques on Mount Moosilauke and suggested that similar evidence of alpine glaciation may exist on other peaks in the White Mountains besides the Presidential Range. He did not find any moraines in the Moosilauke ravines, but left open the possibility that there may have been some cirque glacier activity in late-glacial time.

In the late 1970's, Robert F. Gerath reconstructed the sequence of deglaciation in the Berlin-Gorham region. He discovered a thick sequence of ice-contact deposits on the northwest flank of the Mahoosuc Range and called them the "Success Moraine". This moraine includes both fluvial and lacustrine sediments, locally deformed and overlain by till. A smaller sand and gravel ridge northwest of Berlin was named the "Copperville Moraine" (Gerath, 1978). Gerath speculated that deglaciation of the Berlin-Gorham area was completed between 12,600 and 12,100 BP.

Gerath *et al.* (1985, p. 23) noted the open terrain northwest of the Success and Copperville moraines and said "... it is likely that the moraines formed at the frontal margins of ice streams sustained by regional ice in the upper Androscoggin and Connecticut River basins." They thought that rapid stagnation and melting of the ice occurred over much of the high-relief terrain. Gerath (1978) commented on the similarity between meltwater channels and eskers on the lower northwest slopes of the Mahoosuc Range and modern features associated with downwasting and stagnating ice in Alaskan valleys. However, the inclusion of late-glacial ice streams in Gerath's deglaciation model allowed a broader spectrum of ice retreat mechanisms than the stagnationist views of Flint and J.W. Goldthwait.

R.P. Goldthwait and David M. Mickelson (1982) compared deglacial events in the White Mountains with the Glacier Bay area in Alaska. These authors recognized four successive and diachronous phases of ice retreat in the mountainous terrain of both regions: (1) the "nunatak phase", when mountain tops began to protrude from the ice sheet and high-altitude meltwater channels were cut; (2) the "channel phase", during which groups of progressively lower meltwater channels were eroded on hillsides adjacent to thinning ice; (3) the "esker phase", when subglacial chutes conveyed water and sediment downslope into meltwater tunnels where eskers were deposited; and (4) the "kame terrace or lacustrine phase", marked by uncovering of valley floors and low-level deposition of ice-contact sediments. Goldthwait and Mickelson presented a map of meltwater channels and ice-contact deposits in the Israel River valley (north of Mount Washington; Fig. 1) to support their concept of downwasting and stagnating ice in the White Mountains.

Dwight C. Bradley (1981) revived the debate over timing of cirque glaciation. On the northern slopes of the Presidential Range, Bradley found a diamict whose stone provenance indicated a source area to the south. He interpreted this unit as till deposited by local glaciers issuing from King Ravine and two other cirques in the northern Presidentials. Bradley proposed that these glaciers were confluent with a continental ice stream flowing eastward down the Moose River valley to Gorham, where it supposedly joined another ice stream in the Androscoggin River valley. This system of valley glaciers was said to have formed the morainic deposits described by previous workers in the lower Peabody River valley (south of Gorham), as well as recessional "lateral moraines" in the lower Moose River valley (Bradley, 1981).

Gerath and co-worker Brian K. Fowler refuted Bradley's hypothesis of late valley glaciation. He and Brian K. Fowler asserted that moraines do not exist in the Moose River valley, and the Peabody valley deposits lack sufficient topographic expression to be called moraines (Gerath and Fowler, 1982). These authors questioned Bradley's stone counts and reinterpreted the diamict downvalley from King Ravine as a poorly sorted debris fan. Fowler (1984) conducted a more detailed study of the latter deposits in the vicinity of Durand Lake in Randolph. Based on new stone counts and a variety of textural and morphologic evidence, he concluded that the diamict is a debris flow deposit. It was found to have a southerly provenance, but many of the stones probably came from sources downvalley from the King Ravine cirque.

Richard B. Waitt and P. Thompson Davis (1988) likewise studied the sediments near Durand Lake and reached the same conclusion as Fowler. They also documented northward mass-wasting transport of clasts in an adjacent V-shaped valley that does not drain a cirque. Waitt and Davis studied other mountainous regions in Maine and Vermont and found no evidence that cirque glaciers were active in northern New England after recession of the Late Wisconsinan continental ice sheet.

Further evidence concerning the mode of deglaciation in the White Mountains continued to emerge in the 1980's. Thompson (1983a, b) investigated moraine ridges in the Androscoggin River valley, on the Maine-New Hampshire border. Stone (1880, 1899) had recognized some of these deposits as moraines, but in the revisionist atmosphere of the 1930's, Leavitt and Perkins (1935) dismissed one of the more prominent ridges as a drift tail or kame terrace. However, Thompson verified Stone's observations that moraines exist on both sides of the valley. He discovered a 30-m high moraine ridge projecting east from Stock Farm Mountain on the south side of the river. Thompson assigned the name "Androscoggin Moraine" to the arcuate series of sharp-crested bouldery drift ridges comprising the moraine complex.

Thompson and Fowler (1989) conducted further studies of the Androscoggin Moraine. They extended the known limits of the complex and determined the composition of several of the ridges. The deposits were found to consist of interbedded diamicts (flowtills) and waterlaid sediments. Thompson and Fowler proposed that the Androscoggin Moraine was deposited by a late-glacial active ice tongue issuing from the Laurentide Ice Sheet in the Connecticut River basin to the west. Based on the small number of radiocarbon dates from the region, they suggested that the moraine complex formed sometime between 14,000 and 13,000 ^{14}C yr BP.

The interbedded till and lacustrine sediments of the Peabody River sections continue to attract interest (Fowler, this volume). Haselton and Fowler (1991) attributed these deposits to oscillation of a Late Wisconsinan ice tongue from the nearby Androscoggin Valley. They concluded that the provenance and fabrics of the diamict units indicate southwestward ice flow, in contrast to T. B. Goldthwait's proposed southeastward flow (Goldthwait, 1971).

Other factors have contributed to the growing interest in White Mountain glacial geology in recent years. In 1993 the Mount Washington Observatory sponsored a symposium on "The Ice Age in the White Mountains", which led to preparation of the present volume. Several recent field trips have focused on the Quaternary history of the White Mountains, including excursions by the American Quaternary Association (Davis *et al.*, 1988), the Geological Society of America (Davis *et al.*, 1993), and the New England Intercollegiate Geological Conference (Van Baalen, 1996). The latter conference reexamined the deposits of glacial Lake Israel, Lake Ammonoosuc, and the Bethlehem Moraine complex. Thompson *et al.* (1996) supported the contention of Lougee (1940) and earlier workers that deglaciation of the northwestern White Mountains involved the progressive retreat of an active ice margin. At this same meeting, Ridge *et al.* (1996) presented evidence validating Antevs' (1922) varve chronology and glacial readvance in the Connecticut River valley west of Littleton.

FUTURE PROSPECTS

The conclusion of the twentieth century is an appropriate time to reflect on what has been accomplished in understanding the glacial history of the White Mountains and look ahead to new research opportunities. Considering all the studies summarized here, it might appear that little new information can be extracted from this part of New Hampshire. That seemed to be the unspoken sentiment in 1940, following the exhausting debate over the mode of deglaciation. However, the extent of field work done in the White Mountains remains limited. Early investigators of glacial landforms took advantage of cleared farmland in small parts of the region, such as the Littleton-Bethlehem area, but they were hampered by the scarcity of borrow pits that would reveal the stratigraphy of glacial deposits. Pit exposures have become more numerous with the advent of highways and modern excavating equipment, but much of the White Mountain region is still forested. Large natural sections like those along the Peabody River are rare or remain undiscovered over most of the area.

Many glacial studies have concentrated on the north side of the White Mountains, between Gorham and Littleton. This is partly due to good road access in the latter area, but is also the consequence of preferential development of moraines, deltas, and drainage channels where ice retreat was accompanied by meltwater ponding in river basins that sloped toward the ice margin. The resulting suite of ice-recessional features in the northern White Mountains provides a better record of deglaciation than many of the freely draining valleys on the south side of the mountains. Nevertheless, there are probably many interesting glacial features remaining to be discovered in the vast central wilderness of the White Mountain National Forest, as well as in the Gale River valley and other relatively unexplored river basins where the glacial lake sequences have not been studied.

The concluding remark of Gerath *et al.* (1985) is still true: "More studies with systematic mapping are needed in the White Mountain region. The topics mentioned above and the rugged mountain topography present challenges for future workers in this portion of New England".

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