THE GEOLOGY OF THE
HANOVER QUADRANGLE
NEW HAMPSHIRE

by

JOHN B. LYONS

Published by THE NEW HAMPSHIRE STATE PLANNING AND DEVELOPMENT COMMISSION

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Foreword

This is the eighteenth of a series of non-technical pamphlets on the geology of various quadrangles in New Hampshire which have been issued by the New Hampshire State Planning and Development Commission since 1935. In order to make the report understandable to those unfamiliar with geologic terminology, an effort has been made to avoid technical words. Where this has not been feasible, the term has either been defined in the text, or in the glossary at the end of the pamphlet. Discussion of the geology necessitates the use of a geologic map of the bedrock, and this has been provided in the pocket of the back cover.

The geologic study on which this report is based was carried out from 1947 to 1949 on a research grant from the Geological Society of America. That organization also cooperated with the New Hampshire Planning and Development Commission in underwriting the heavy expense of printing the colored geologic map. The writer was assisted in the field by H. C. Coulter, J. F. Murphy, and H. H. Woodard, former students at Dartmouth College.

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By John B. Lyons

INTRODUCTION

The Landscape

The face of the earth mirrors the accidents of geology. The wide expanse of the Great Plains, for example, reflects the flat-lying strata beneath them, and a relatively uneventful geologic past. By contrast, the lofty Alpine-Himalayan chain owes its ruggedness to cataclysmic events which, geologically speaking, happened only yesterday.

Most of northern New England is characterized by a rolling, sub-mountainous topography. To the practiced eye this is an almost-certain indication of an area of moderate geologic antiquity, reduced by erosive processes from its former mountainous magnificence. Even Mt. Washington (el. 6,288) and the other peaks of the White Mountains are mere nubs of what they once were; New England may, at one time, have been dotted with peaks as lofty as Everest.

Geologically, New England is a part of the Appalachian Mountain system. It is older, however, than the mountainous belt extending from New York to Alabama, and most of the events important in its development occurred in the interval between 450 and 300 million years ago. In the more southerly part of the Appalachians, much of the mountain building went on as recently as 180 million years ago.

The geology of the Hanover quadrangle, to be described in this booklet, is typical of much of that in the areas bordering the Connecticut River in northern New England. The region is one of moderate relief. Griggs Mountain in the township of Norwich, Vermont is, at 1,800 feet, the highest elevation in the area. Its lowest elevation, 300 feet above sea level, is along the banks of the Connecticut, in the southern part of the area described in this report. The White and Ottauquechee Rivers of Vermont and the Mascoma River of New Hampshire are important tributaries joining the Connecticut within the quadrangle boundaries.

THE BEDROCK, AND ITS HISTORY

The Geological Map, and How to Read It

In order to allow the reader to better understand the geology, a colored map has been inserted into an envelope at the back of this pamphlet. Each color pattern on the map represents a group of rocks (a so-called formation) whose characteristics are recognizable in outcrops, and are distinctive from those of other rock units. The areal distribution of these formations is indicated by the map. Their structural arrangements are shown on the map by a series of symbols whose meanings are explained on the map legend, and by a series of cross-sections at the bottom of the map. These sections indicate the probable arrangements of the formations which we should discover were we able to slice trenches a mile deep through the bedrock. On both the map and the cross-sections the distribution of the soil and glacial deposits is not shown, although these unconsolidated materials have local thicknesses of as much as a few hundred feet.

The bright red lines marked "Isograds" on the map define boundaries where critical rock-forming minerals (such as biotite, garnet, etc.) are first encountered in the field in progressing from areas of lesser metamorphism to those of greater metamorphism. The significance of the isograds is discussed in a later section.

The geologic map has been overprinted on a topographic map in order that we may not only obtain a picture of the geology, but also of the shape of the earth's surface. The brown contour lines have their elevations above sea level indicated at appropriate intervals on the map. Contours may be thought of, for convenience, as marking the map positions of a series of shorelines which would be developed in the Hanover region should the land subside in successive intervals of 20 feet, and the sea progressively flood the area. Contour lines in northern New England generally have little direct relation to the bedrock geology. The reader should be cautioned that the topographic map of the Hanover quadrangle was published in 1906, and that for this reason the positions of new or rerouted roads are not indicated on the geologic map.

In the discussions to follow, reference will frequently be made to dates or time spans in terms of millions of years. The basis for these time determinations is described on page 19.

Table 1

GEOLOGIC TIME SCALE WITH SEQUENCE OF EVENTS IN THE HANOVER REGION

Oldest Event is at Bottom of Chart; Youngest is at Top

Era	Period	Time in Millions of Years	Sequence of Events
Cenozoic	Quaternary	0-1	Recent erosion in last 11,000 years Pleistocene glaciation; deposition of till, varved clay, and fluvio-glacial material
	Tertiary	1-60	Renewed uplift and erosion. Brown coal bed at Brandon, Vermont indicates warm moist climate 30 million years ago
Mezozoic	Cretaceous	60-130	Erosion; land reduced to a low level
	Jurassic	130-155	Erosion
	Triassic	155-185	Erosion and faulting; possible deposition of some red beds, as in lower Connecticut Valley of Massachusetts and Connecticut
Paleozoic	Permian	185-210	Intrusion of igneous rocks of the White Mtn. series; evidence of glaciation in Boston area
	Pennsylvanian	210-230	Warm moist climate in New England; erosion
	Mississippian	230-265	Erosion
	Devonian	265-320	Erosion
			Final withdrawal of oceans from New England
			Faulting
			Intrusion of Lebanon granite and metamorphism (300 m.y. ago)
			Folding and metamorphism of rocks begins; some dikes injected
			Littleton formation deposited
	Silurian	320-360	Deposition of Fitch and Clough formations; these rocks not exposed in Hanover quadrangle
			Renewed geosynclinal subsidence and marine invasion
	Ordovician	360-440	Erosion
			Intrusion of granite (380 m.y. ago), followed by brief period of uplift and erosion
			Deposition of Partridge, Ammonoosuc and Albee formations; these rocks not exposed in Hanover region
			Deposition of Orfordville formation Deposition of Gile Mtn. formation Deposition of Waits River formation Deposition of older unexposed formations
	Cambrian	440-550	Deposition of older unexposed formations Beginning of geosynclinal sedimentation and marine invasion
Precambrian		550-5500	Complex but unknown history

Ancient Marine Invasions, and the Formation of the Bedrock

The rocks thought to be the oldest in the Hanover quadrangle constitute the Waits River formation, and occur only in the western part of the area. These rocks, originally deposited on the ocean floor as flat-lying limey muds and silts with an aggregate thickness in excess of 4,000 feet, were first hardened into limestones and shales, and then crumpled and transformed into calcareous schists and mica schists.

The Waits River formation is widespread throughout eastern Vermont, and underlies a small portion of northwestern New Hampshire. Near Montpelier and near Westmore, Vermont, fossil corals, crinoids, gastropods, and cystoids have been discovered in the formation by C. A. Doll. Their importance is twofold: they indicate, first, that at the time of deposition of the Waits River beds Vermont and New Hampshire were inundated by the ancient Atlantic Ocean; secondly, their presence should allow us to date the formation geologically. Unfortunately, the fossils are not in an excellent state of preservation, and there is debate as to their precise age. It is certain, nevertheless, that they belong to the Ordovician, Silurian, or Devonian periods, and can be no older than 440 million nor younger than 260 million years.

The geography of New England during Waits River time was far different than it is today. The Adirondacks and that part of Quebec north of the St. Lawrence were the western shoreline of the Atlantic. An unstable archipelago, or a series of unstable archipelagoes probably existed in what is now the western Atlantic, extending southward from offshore Newfoundland to offshore Georgia. These landmasses finally disappeared beneath the Atlantic approximately 180 million years ago but while in existence served as source areas for some of the sedimentary material which afterward became the hard crumpled rocks of the Appalachian mountains.

The uppermost portion of the Waits River formation consists of a distinctive dark green hornblende schist, 125 to 650 feet thick, indicated on the geologic map as the Standing Pond amphibolite. Prior to metamorphism the amphibolite consisted of detritus eroded away from one or several basaltic volcanoes, and spread by ocean currents as a thick layer on top of the limey muds of the Waits River formation. The precise location of these ancient volcanoes is unknown.

Overlying the Waits River formation is a 6,500-foot thickness of tan to gray quartz-mica schists and quartzites which grade upward into a 1,000-foot thickness of black mica schist and phyllite. Collectively these rocks form the Gile Mountain formation; its uppermost part is the Meetinghouse slate member of the formation. The rocks which are now quartz-mica schists and quartzites were once marine sands; the black schists were black marine muds. The Gile Mountain is the most widespread of the formations of the Hanover quadrangle, and is excellently exposed along the White River, between the villages of Hartford and West Hartford, Vermont.

At South Strafford, Vermont (9 miles north-northwest of Hanover, and beyond the boundaries of our map) C. A. Doll has discovered what may be a fossil brachiopod of Devonian age (320-260 million years old) in the Gile Mountain formation. The fossil identification is in dispute, however, and because of its regional geologic relations the Gile Mountain is considered in this report to be of probable Ordovician age (440-360 million years). Regardless of its precise age, all geologists who have studied the formation are agreed that it was once a sandy marine-type deposit, which has been highly deformed and metamorphosed.

Underlying much of the area along and east of the Connecticut River is the non-fossiliferous Orfordville formation. In the northern part of the Hanover quadrangle this unit is separated from the Gile Mountain formation by the Monroe fault (see geologic map). Where the two formations are in apparent sedimentary contact south of the village of Hartland, Vermont, it appears that the Orfordville rocks are younger than the Gile Mountain rocks. From its relations to other formations in New Hampshire it is assumed that the Orfordville formation is of probable Ordovician age (440-360 million years) and was deposited on top of the Gile Mountain beds.

The lower part of the Orfordville consists of approximately 2,000 feet of black mica schist (originally a black mud), toward the base of which is some marble (Ooc on the geologic map) and a white quartz conglomerate member, 0-350 feet thick. The conglomerate crops out prominently at French's Ledge, southwest of Meriden, New Hampshire, but derives its name, the Hardy Hill quartzite, from the outcrops at Hardy Hill, Lebanon, New Hampshire (2 miles east of the map boundary). The upper part of the Orfordville formation, the Post Pond volcanic member, is a

3,500- to 4,000-foot thickness of green chlorite or hornblende schist. Some of these schists have "ghosts" or relicts of the structures which characterized them prior to metamorphism. These include amygdules (small almond-shaped mineral aggregates filling former gas cavities), pillows (ellipsoidal blobs, several feet in maximum diameter), and sub-angular blocks. Pillow structures are characteristic of submarine lava extrusions, and there is little doubt that the Post Pond volcanics are metamorphosed basalts, originally poured out as submarine lava flows on top of the black marine muds of the lower Orfordville formation.

Approximately a half square mile of the extreme southeastern portion of the Hanover quadrangle is underlain by black schists of the Littleton formation. These are almost identical in appearance with the Orfordville black schists but are of Devonian age (320-260 million years) and are here separated from Orfordville schists by the Northey Hill fault. The Albee, Ammonoosuc and Partridge formations (Ordovician) and the Clough and Fitch formations (Silurian) normally intervene between outcrops of the Orfordville and Littleton formations where no fault is present. None of these five missing formations occurs within the limits of the Hanover quadrangle, but they are well exposed in areas to the north and east.

The aggregate thickness of the Waits River, Gile Mountain, and Orfordville formations is approximately 16,500 feet. We know, furthermore, that in eastern Vermont there are approximately 21,000 feet of metamorphosed sedimentary and volcanic rocks underlying the Waits River formation, and ranging in age from 550 to 400 million years old (i.e. of Cambro-Ordovician age). In New Hampshire there are approximately 15,000 to 22,000 feet of metamorphosed sedimentary and volcanic rocks overlying the Orfordville formation, and ranging in age from approximately 360 to 300 million years old (i.e. of Ordovician, Silurian, and Devonian age). Thus northern New England, in the interval from 550 to 300 million years ago received a blanket of approximately 60,000 feet (11 miles) of marine sediments and volcanics. To borrow a phrase, this staggers the imagination.

Two questions arise from a consideration of the stratigraphic record. What was the source of the material, and how deep were the oceans covering New England? An analysis of existing rates of erosion and sedimentation indicates that there is nothing extraordinary in an accumulation of an 11-mile thickness of rock over a period of 250 million years. In the last 60 million years, for example, a maximum thickness of 40,000 feet of sedimentary material has been deposited in the Gulf of Mexico at the mouth of the Mississippi. The streams flowing from the Canadian shield, the Adirondacks, and the archipelagoes in the Atlantic could, it seems, have easily transported a 50,000-foot thickness of sediment into the great portion of the Atlantic covering New England during the early Paleozoic. An additional 10,000 feet of volcanic material could have been added from volcanoes erupting in the ancient ocean bottom during portions of the same 250-million year period. Iceland, to cite an analogy, is an active volcanic region in which a 10,000-foot thickness of lavas has been built up within the last 50 million years.

Even more interesting than the problem of the origin of the material which made up a 60,000-foot blanket of rock in northern New England is the question of the depth of the ancient ocean and the behavior of the earth's crust under this enormous load. In modern oceans the deepest known trench is 35,640 feet below sea level, in the Mariana Trench south of Guam. Such deeps, however, are not only relatively uncommon, but are also quite narrow. We know of no oceanic deeps comparable in width to New England; we have good reason for believing that no such deeps have existed in the geologic past. The fossils which have been sparingly found in the New England metamorphic rocks, and the nature and structure of these bedded rocks clearly indicate that they were deposited in relatively shallow marine waters. This being true, it follows that the accumulation of a great thickness of sedimentary and volcanic rocks was possible only because the earth's crust gradually sagged as the sedimentary and volcanic load was placed upon it. Sagging of the earth's crust under such a load is known to be possible because of plastic flowage which may occur in a weak shell of the earth commencing at a depth of 30 to 40 miles below the surface. It is also a well established principle in geology that those areas where long linear mountain belts have been developed are, in their first stages, slowly subsiding downwarps in the earth's crust (known geologically as geosynclines) where great thicknesses of rock are deposited. Mountain belts follow a similar evolutionary pattern; they commence as great, linear, sediment-filled downwarps; they are next squeezed, and their rocks folded; they are elevated into lofty alpine belts; and they are eventually destroyed by erosion.

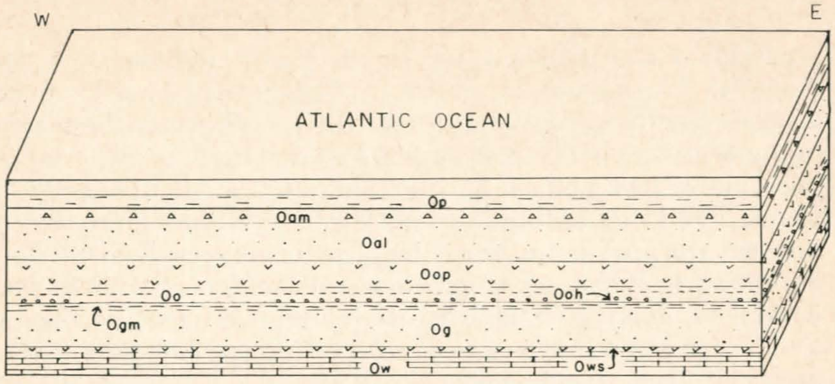

Fig. 1. Hanover region toward the close of the Ordovician period (i.e. 400-380 million years ago). *Ow* is Waits River formation; *Ows* Standing Pond amphibolite member of the Waits River; *Og* Gile Mountain formation, and *Ogm* the Meetinghouse member of the Gile Mountain; *Oo* Orfordville formation, and *Ooh* Hardy Hill member and *Oop* the Post Pond members of the Orfordville; *Oal* Albee formation; *Oam* Ammonoosuc volcanics; *Op* Partridge formation.

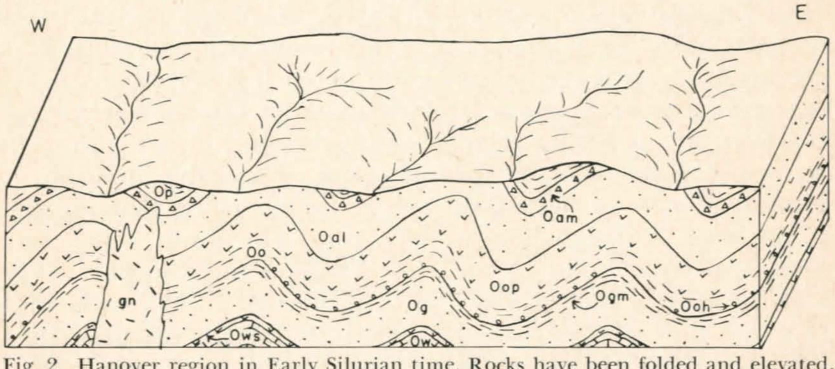

Fig. 2. Hanover region in Early Silurian time. Rocks have been folded and elevated, temporarily, above sea level. Granite *(gn)* has also been intruded into the rocks during the Late Ordovician Taconic orogeny (370 million years ago).

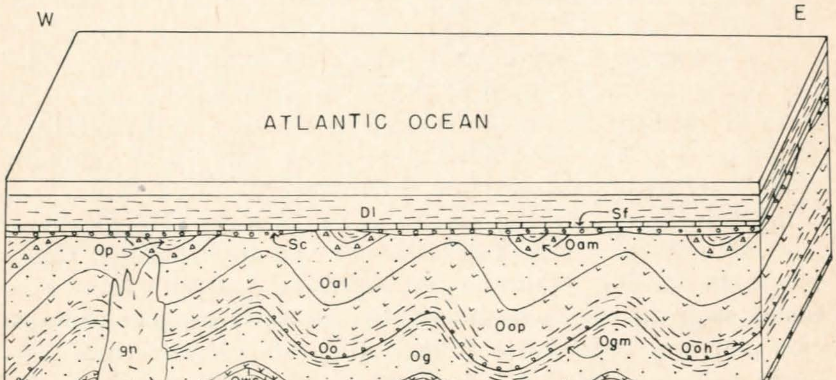

Fig. 3. Hanover region in Early Devonian time. Region was resubmerged in Middle Silurian time, and has had the Clough *(Sc)* and Fitch *(Sf)* formations (Middle Silurian) and Littleton *(Dl)* formation (Lower Devonian) deposited upon the older rocks.

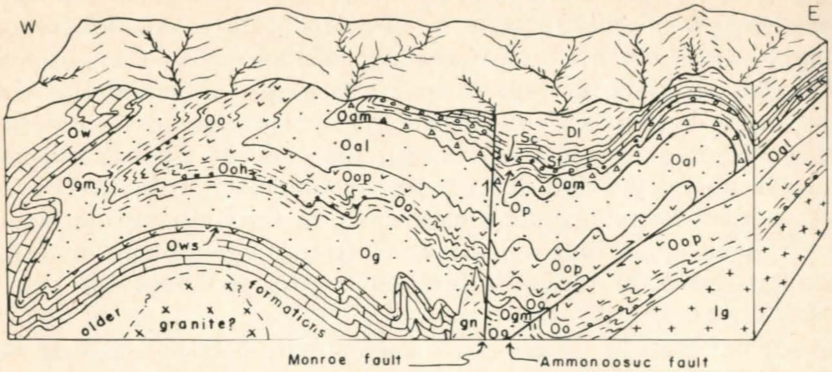

Fig. 4. Hanover region in Late Devonian time. Rocks were folded in the Middle to Late Devonian Acadian orogeny (300 million years ago), intruded by the Lebanon granite *(lg)*, metamorphosed, and elevated above sea level. Erosion is actively reducing the area.

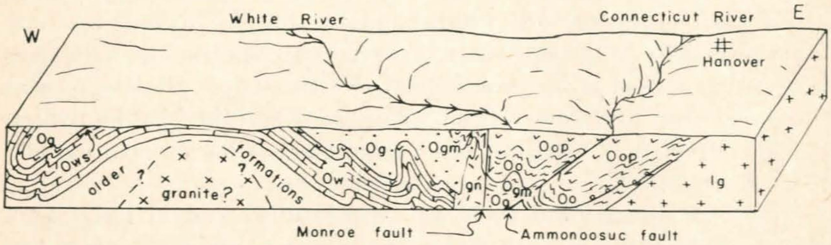

Fig. 5. Hanover region at present. Approximately 5 miles of bedrock have been stripped from the area.

Folding, Metamorphism, and the Emplacement of Granites

Geologic reasons behind the development of geosynclines and their eventual squeezing into belts of highly folded rocks are, as yet, matters of scientific debate. The gigantic forces operative in crustal deformation invariably act, nevertheless, as a great vise, the maximum compressive forces being oriented in a direction perpendicular to the trend of the geosyncline. Thus, in New England, the northward-trending geosyncline was crushed by east-west stresses, and the soft flat-lying sediments and volcanics were hardened and crumpled into tight northerly-trending folds. So intensive were the forces which squeezed the crust of New England that parts of the bedrock were also torn loose from adjoining sections, and great blocks of the earth's crust were moved past other blocks for distances of several thousand feet. The fracture surfaces along which these movements occurred are known as faults, and three such faults, the Monroe, Ammonoosuc, and Northey Hill are indicated on the geologic map.

In the Hanover region the rocks were compressed on two separate occasions. One of the periods of crustal deformation, the Taconic orogeny, occurred toward the close of the Ordovician period, some 370-350 million years ago. We have little direct evidence of this cycle of deformation within the limits of the Hanover quadrangle, but are aware of it through the outstanding geologic work of M. P. Billings in the region about Littleton, New Hampshire.

The Acadian orogeny, the major deformational episode in New England, occurred in the Middle to Late Devonian, approximately 300 million years ago. This second period of folding, far more intensive than the first, was accompanied by another significant event — the final elevation of New England above sea level. From this time onward, New England has been part of continental North America; instead of receiving sedimentary detritus from other areas, it has itself been subjected to ceaseless erosive attack. Despite intervals of re-elevation between the Mid-Devonian and the present, the region has been slowly worn down to a subdued topography.

Because the folded rocks of the Hanover region have been deeply eroded, the structural arrangements of the formations are not apparent in most outcrops. The geometry of the folds, however, may be reconstructed from the dip and strike symbols, and the map patterns of the various formations. Three major anticlines dominate the region, all of them extremely complex, with many minor folds superimposed on the major upwarps. The core of one of the major anticlines is occupied by the Lebanon granite, an unusual fold in that the beds which wrap around its southern nose have been inverted by the intrusive pressures developed during the injection of the granite. Another major anticline, plunging northeasterly, is conspicuous from the mapped geology of the southeastern ninth of the quadrangle. The third major anticline, deceptively simple in map pattern, is outlined by the Standing Pond amphibolite in the northwestern part of the area, and has been named the Pomfret dome. This dome is the smallest of six or more similar structures extending en echelon from western Massachusetts through eastern Vermont, on the west side of the Connecticut. The detailed structural geology of all of the domes is extraordinarily complicated (see Figure 8), probably because the origin of the domes is ascribable to a punch-up of material from the depths of the earth into already-folded rocks. Part of the incredibly complex fold pattern is indicated diagrammatically in the cross sections at the bottom of the geologic map. Section B-B′ is worthy of particular comment. This shows, near its western end, what appears to be an anticline, with the Gile Mountain formation in its core, and overturned toward the west. Actually, the fold is a syncline, with its trough bent around and dragged upward and westerly, probably by the rise of the great Chester dome immediately southwest of the Hanover region. Recumbent folds of the type shown in Section B-B′ are known in relatively few areas of the world, one of the classic localities being the Alps.

Two other phenomena normally accompany the folding of a geosyncline: 1. metamorphism of the rocks, and 2. intrusion of granites. All of the rocks of the Hanover quadrangle, aside from some of the granites and some rare dikes, have been metamorphosed. This means that they have been so thoroughly transformed, by recrystallization, that their original characteristics are largely obliterated. Metamorphic rocks are denser and generally coarser than their sedimentary and volcanic progenitors. They contain distinctive minerals, and they frequently have these minerals aligned in parallel planes — whence the names *"schist"* and *"gneiss"* which are descriptively applied to them. A combination of field and experimental laboratory experience has taught geologists that certain critical metamorphic minerals may be recognized and mapped in the field, and that these minerals are temperature indicators. On the geologic map of the Hanover quadrangle the hachured red lines labelled *"Isograd"* indicate the locations where the silicate minerals chlorite, biotite, garnet, staurolite, and kyanite may be first recognized as one proceeds from areas of lower to higher metamorphic intensity. In this series, chlorite-zone rocks represent recrystallization temperatures of approximately 200°C (380°F); kyanite-zone rocks, of approximately 600°C (1100°F). A rock in the garnet zone may contain chlorite or biotite, but its recrystallization temperature will have been too low to permit the development of kyanite or staurolite. Despite the relatively high temperatures at which regional metamorphism occurs, rocks are not melted down during their transformation; consequently they have preserved within them traces or relicts of their original structures, such as bedding planes in the rocks of sedimentary origin, and pillow structure in rocks of volcanic origin. Had there been no metamorphism of the rocks of the Hanover region we should now have such common bedrock types as shale, sandstone, limestone and basalt. During recrystallization the shale has been transformed into mica schist or phyllite, the sandstone into quartzite, the limestone into calcareous schist and marble, and the basalt into hornblende or chlorite schist.

It is an interesting and significant fact that the highest-temperature metamorphic rocks of the Hanover region occur either peripherally to the Lebanon granite, or in an area of domal upwarp in the northwestern portion of the mapped area. There, geophysical measurements of the intensity of gravitation (made by R. J. Bean) suggest the probability of unexposed granite within 2,500 feet of the present surface. The close areal relationship between the granites and the highest-temperature metamorphic rocks of the Hanover region is repeated in numerous metamorphic terranes throughout the world. It is reasonable to conclude that regional metamorphism is induced only in small part by the deformational stresses which contort geosynclinal rocks. Much of the metamorphic heat must be contributed by masses of hot granite shouldering their way upward through the folded rocks, and much of it is ascribable to the fact that the geosynclinal rocks are depressed toward the earth's hot interior.

The intrusion of granites into the rocks of the Hanover region occurred in two cycles, separated by a time span of approximately 70 million years. The older granites, indicated on the map by the symbol "gn" were emplaced at the close of the Taconic orogeny, toward the close of the Ordovician period. These granites are exposed at White River Junction, Vermont, and in an area approximately 3½ miles northeast of Plainfield, New Hampshire. The exposures of the granites which crop out both north and south of White River Junction show particularly good evidence of having been emplaced by the injection of numerous sheets of granitic magma into the cleavage planes of the Post Pond volcanic member of the Orfordville formation. Typical outcrops of the granite show an alternation of layers of the chlorite schist country rock with layers of the granite, and constitute what is known geologically as a lit-par-lit (bed-by-bed) complex. Unlike the younger granites, the Ordovician granites have been subjected to the same regional metamorphism that has recrystallized the other rocks of the region.

The younger, unmetamorphosed granites are confined chiefly to the elliptical outcrop area of the Lebanon granite. Structures in the granite and its adjacent metamorphic rocks, as well as the results of a gravity geophysical survey made by R. J. Bean show that the Lebanon granite has the shape of a cone, tilted northwestward. The apex of the cone has been removed by erosion but must, at the time the granite was emplaced, have been situated approximately 10,000 feet above the present site of the village of Lebanon. The granite was injected as a magma or as a plastic mass, and moved upward and southeastward through the country rock. So intensive were the intrusive pressures that the rocks south of the Lebanon granite were pushed upward and rotated through an angle of more than 90 degrees. Minor folds in these rocks now plunge northward at high angles in places where, prior to the intrusion of the Lebanon granite, they plunged gently southward.

Radioactive determination of the ages of the granite at White River Junction and of the Lebanon granite have been recently carried out by the writer and others at the laboratories of the United States Geological Survey, using a method developed by Dr. E. S. Larsen. To make an age determination, one concentrates by heavy-liquid and electro-magnetic techniques approximately 25/100,000 of a pound of the mineral zircon from an initial sample of 25 to 30 pounds of granite. Zircon itself contains a small amount of uranium and thorium, and of radiogenic lead. By measuring the amounts of uranium, thorium and lead, it is possible to calculate the age of the zircon, and hence of the granite of which it is a minor but important constituent. The granite at White River Junction belongs to a group of granites whose mean age is approximately 385 million years (Upper Ordovician), and the Lebanon granite to a group of granites whose mean age is approximately 311 million years (Middle Devonian). These direct determinations of the ages of the granites are in excellent agreement with geologic ages previously assigned them on the basis of regional mapping and correlation with fossiliferous rocks near Littleton, New Hampshire.

Faulting

A fault is a great fracture in the earth's crust, induced by enormous tensile or compressive stresses which have exceeded the strengths of rocks. One block of the earth's crust moves relative to the other along the fault surface, and the displacement may be in any direction parallel to the plane of the fault surface. Slippage along faults is slow and intermittent, some faults remaining active for millions of years, and having total displacements measurable in tens of miles. Movements along active faults, such as the San Andreas rift of California, are sometimes responsible for great and destructive earthquakes. Fortunately, all of the known faults in New Hampshire have been inactive for many millions of years.

Three faults, all indicated on the geologic map, have been traced into the Hanover area from regions 40 to 60 miles to the north. Two of these, the Monroe and Northey Hill faults, developed as the rocks of the region were being folded, and prior to their metamorphism. The third, the Ammonoosuc thrust, was developed subsequent to the regional metamorphism and the intrusion of the Lebanon granite. It is more easily recognized than the others because there is a sharp change in the character of the bedrock on the footwall (lower) and hanging wall (upper) blocks of the fault, and also because the rocks at the fault plane are highly crushed and fractured.

The Monroe fault is the plane separating the Meetinghouse slate member of the Gile Mountain formation on the west from the Post Pond member of the Orfordville formation on the east. The fault surface itself has not been observed by the writer within the Hanover quadrangle, probably because of the lack of sufficiently good outcrops along the contact between the two units. The mapped geology of the regions north of Hanover suggests that the fault plane is approximately vertical, and that rocks of the westerly block have slid upward an indeterminate amount. The fault is indicated on the map as dying out in the central part of the Hanover quadrangle, largely because of lack of evidence for its existence in the southern part of the area.

The Northey Hill fault, in the extreme southeasterly corner of the map area, has black Orfordville schist of the western block in contact with black Littleton schist of the eastern block. Like the Monroe fault, the Northey Hill is non-observable within the Hanover quadrangle. Its existence, however, must be inferred because of the absence of five formations of Ordovician and Silurian ages which should normally intervene between the Orfordville and Littleton formations. From regional geologic relations it is thought that the rocks west of the Northey Hill fault have slid vertically upward several thousand feet relative to those on the east.

The course of he Connecticut River through the Hanover quadrangle is roughly coincident with the Ammonoosuc fault. Along the west bank of the Connecticut, particularly a few miles north of Norwich, Vermont are several outcrops where the broken-up rock (fault breccia) in the fault plane is well exposed. At these localities the dip of the fault plane is 35 to 45 degrees westerly. Evidence near Littleton, New Hampshire indicates that the rocks in the upper (hanging-wall) block have slid easterly several thousand feet over rocks of the lower (footwall) block of the Ammonoosuc thrust. The amount of displacement in the Hanover area is uncertain, but probably of the order of several thousand feet.

Before leaving the topic of faulting, it should be mentioned that almost all rocks are broken by fractures known as joints. In contrast to faults, joints have no displacements of the blocks on either side of the fracture. There are literally thousands of joints in the rocks of the Hanover area, most of them smooth plane surfaces. The most prominent and consistent jointing is in an east-west direction, approximately perpendicular to the trend of the regional structure. These, and less common joints that trend approximately north-south and dip at 45 degrees (plus or minus) easterly or westerly are due to the same compressive forces which first folded the rocks, and then faulted them. A less common type of jointing, termed sheeting, is weakly developed in the Lebanon granite and is due, indirectly, to forces resulting from the removal of the bedrock (unloading) by erosive processes.

Injection of Dikes

Periods of strong geologic compression are oftentimes preceded and succeeded by intervals of relaxation of stress, or even of tension. At such times cracks, or joints, may develop and may extend tens of miles into the earth's crust. Hot liquid rock (magma) in the depths of the earth discovers these fractures, and quickly makes its way toward the surface, congealing and crystallizing as it penetrates the crust. The resulting tabular bodies of igneous rock are known as dikes. Dikes of two ages and types are represented in the Hanover quadrangle. The older dikes, now metamorphosed to chlorite and hornblende schist, occupied fractures developed subsequent to the folding of the rocks, but prior to the metamorphism of the rocks. These dikes are, locally, extremely abundant and make up what are known as "swarms." Places where such swarms make up a significant proportion of the bedrock are indicated on the geologic map by a red overprint, and on the map legend by the words "metamorphosed diabase." These swarms are largely restricted to the New Hampshire portion of the map area.

Not indicated on the geologic map because of their rarity are some dark, unmetamorphosed trap dikes. Some of these are to be found, for example, on the west slopes of Crafts Hill, in West Lebanon, New Hampshire, or in the area east of Hanover, where they intrude the Lebanon granite. These dikes are mineralogically similar to dikes in northern New Hampshire which are considered to be part of the White Mountain plutonic-volcanic series. This series, in turn, consists of intrusive rocks of several types (among them the well-known Conway granite), has been dated by radioactive methods as approximately 186 million years old, and is thought to have been emplaced toward the close of the Permian period. Mt. Ascutney, a conspicuous landmark 20 miles south of Hanover, is an eroded mass of granite, syenite, and gabbro belonging to the White Mountain series. It is probable that the trap dikes of the Hanover region were injected concurrently with the emplacement of the rocks now forming Mt. Ascutney.

DESTRUCTION OF THE ANCIENT MOUNTAINS

There is no such phenomenon as an indestructible rock, an eternal hill, or an everlasting mountain. Over the eons of geologic time all substances at the earth's surface are destined for destruction. Rocks are weakened and decomposed chemically by the attack of oxygen and the weak acids of the groundwater; they are disintegrated mechanically by the action of running water, waves, frost, glaciers, wind, alternate heating and cooling, and the effects of growing organisms. Over a period of a year, the amount of material eroded from the land and carried to the oceans is truly enormous. It is estimated that, for the United States, the annual transport of materials by streams emptying into the oceans is 513 million tons in mechanical suspension, and 270 million tons in chemical solution. The average annual amount of mechanical erosion is approximately 166 tons per square mile; of chemical erosion, 87 tons per square mile. This implies an average lowering of the land of approximately one foot in 10,000 years. If the present rate of erosion were to be maintained, North America, with an average elevation of 2,400 feet, should be reduced to average mean sea level in a mere 24 million years. Such a gross calculation is obviously erroneous to the extent that it does not consider varying rates of erosion throughout geologic time, or variations in different localities. The geologic record, nevertheless, offers irrefutable proof that at various times in the past much of North America has been so reduced by erosion that the ocean has encroached over most of the continent. There is an endless natural struggle between those forces tending to elevate continents and build mountains, and those processes tending to destroy them.

What have been the effects of erosion in the Hanover region during the last 300 million years? At the western end of cross-section A-A′ (see geologic map) dotted lines have been drawn showing the probable position of the Standing Pond amphibolite, before erosion, across the top of a dome. The elevation of the amphibolite at the center, or top, of the dome is close to 5,000 feet. Approximately 7,500 feet of Gile Mountain beds and 6,000 feet of Orfordville beds once rested on top of the Standing Pond amphibolite. There were, in addition, at least 15,000 or more feet of Upper Ordovician, Silurian, and Devonian rocks overlying the Orfordville formation. Thus the uppermost rocks arching across the dome would have had a minimum elevation of 28,500 feet above sea level — an elevation close to that of Everest (29,141 feet). Because the present elevation at the center of the dome is a mere 1,520 feet, 27,000 feet (more than 5 miles) of bedrock must have been removed from this area by erosive processes. Most of the rocks now exposed at the surface in the Hanover region were, at one time, five miles deep within the earth's crust.

Whether there have been, at times past, peaks of 28,000- to 29,000-foot elevation in the Hanover region is not known with certainty. Study of mountain ranges has shown us that they pass first through a geosynclinal cycle, during which they accumulate sediments in a subsiding trough, and then through a cycle of crumpling and folding of the rocks. Final elevation of these folded rocks into towering ranges takes place gradually and intermittently over a period of several million years. During all of this time erosion is attacking the emerging mountain chain, and the maximum elevation it attains is a compromise between the rate and amount of uplift, and the rate and amount of erosion. In view of our lack of information on rates of uplift and erosion in New England during the past 300 million years, we are, understandably, somewhat uncertain about the topography in that bygone era.

Because some five miles of solid bedrock have been eroded from the Hanover region there is very little relation between the present distribution of hills and valleys and the original structures in the bedrock. Local variations in the erosive resistances of the different rock units, and the locations of the major valleys account for most of the present topography. Thus Griggs Mountain (el. 1,800 feet) in the north-central part of the Hanover quadrangle appears to be the highest peak in the area because it is underlain by hard quartz-mica schists of the Gile Mountain formation, and because it is at some distance from both the White and Connecticut Rivers. The pink granite of the core of the Lebanon granite is chemically more resistant than the outer quartz-diorite shell; it therefore underlies the hills between the villages of Lebanon and Hanover whereas the quartz diorite underlies the valley of the Mascoma River west of Lebanon. The pronounced topographic break between the hills underlain by the Meetinghouse slate and the low-lying adjacent areas underlain by the Post Pond volcanic member of the Orfordville formation is due, again, to the chemical inertness of the slate, and the relatively higher chemical solubility of the Post Pond chlorite schists.

The problem of why the major stream valleys follow their present courses in northern New England, and the question of how long they have maintained their present patterns are imponderables. We know of minor shifts in the courses of these rivers produced as aftermaths of continental glaciation, but we have no way of knowing, to cite only one example, how many millions of years the Connecticut has risen in northern New Hampshire, and has flowed southward along its present course. It seems unlikely that we ever shall.

GLACIATION

It was slightly more than 110 years ago that Louis Agassiz, the great Swiss-born naturalist, commenced the series of observations which soon led him to propound the theory that much of North America had, at one time, been covered by a continental ice sheet. Although Agassiz first recognized and studied the effects of glaciation in the Rhone Valley in Switzerland, the evidence he observed there and in America is familiar to us all — the polished and grooved appearance of fresh exposures of bedrock, the large foreign boulders (erratics) scattered over the countryside, and the unique types and forms of the unconsolidated materials mantling the bedrock.

Geologists believe that the beginning of the recent glacial episode (the Pleistocene period) was approximately 600,000 to 1,000,000 years ago. At intervals during the Pleistocene, great continental ice sheets covered large portions of the northern hemisphere. In North America the ice sheets had maximum probable thicknesses, in the Hudson Bay region, of some 15,000 to 20,000 feet, and extended as far south as Long Island and southern Illinois. Glacial geologists have been able to prove that there were four major cycles of accretion and subsequent wasting of the ice sheets during the Pleistocene, although we have little evidence for any but the last of these cycles (the Wisconsin advance) in New Hampshire. Radiocarbon dating of Wisconsin glacial deposits in the Mid-West proves that some of these were formed as recently as 8,500 years ago.

Bedrock atop Mt. Washington (el. 6,288 feet) has been scraped and scoured by Wisconsin ice, and Mt. Ascutney's summit (el. 3,144 feet), 20 miles south of Hanover, has a liberal sprinkling of erratic boulders deposited by the overriding ice sheet. It is probable that a mile-thickness of the continental ice cap covered the Hanover region as recently as 20,000 years ago.

Effects of glaciation in this area are locally visible on polished and scratched (striated) bedrock outcrops, the scratching or grooving having been made by boulders embedded in the bottom of the southward-moving ice sheet. The major effects, however, are apparent in the bouldery, clayey soil (till) which mantles the bedrock. This material represents soil and rocks scraped up, carried southward, and dropped by the glacier as it overrode New England. Some of the boulders in the till have come from nearby areas to the north, but others originated hundreds of miles away in the region between Hudson Bay and New England.

Exposed along the valleys of the Connecticut and its tributaries at elevations below 660 feet is a second type of unconsolidated material, slightly younger than the till, but also of glacial origin. This is the banded (varved) clay upon which many of the villages of the area are built. As New England was gradually uncovered by the melting Pleistocene ice, the lower reaches of the Connecticut Valley were plugged with glacial debris, and the glacial meltwaters were temporarily dammed. The discovery of the precise locations of the Pleistocene dam (or dams) in the Connecticut Valley has been one of the main research activities of R. J. Lougee for the past thirty years. He has concluded that a major dam existed near East Haddam, Connecticut, with a secondary, younger dam near Turners Falls, Massachusetts. A great lake (Lake Hitchcock) gradually formed in the Connecticut Valley, spreading northward from East Haddam, Connecticut to Lyme, New Hampshire, and flooding the valley to the level, at Hanover, of the 660-foot contour line. The dam in Connecticut was eventually breached, and the lake level abruptly reduced by 90 feet. Subsequently a smaller lake (Lake Upham), its level controlled at Turners Falls, Mass. existed in the Upper Connecticut, extending to within a few miles north of East Burke, Vermont. Some glacial geologists have raised questions as to whether the evidences discovered by Lougee might not be alternatively interpreted as indicating the existence of scattered smaller lakes in the Connecticut Valley rather than one 150-mile long Lake Hitchcock. Regardless of this possibility, there is no doubt that the Connecticut Valley in the Hanover quadrangle was, in Late Pleistocene time, a great lake, and that the lake floor was gradually silted in with meltwater debris.

The silts which were deposited at the bottom of Lake Hitchcock are conspicuously varved (banded), the alternating light and dark layers corresponding to sediment of lesser and greater organic content. According to one interpretation of varved silts spring and early-summer sediments are free of vegetal material, and are therefore light-colored; fall and winter sediments contain the dead carbonaceous matter of the preceding summer, and are therefore dark. A combination of a light and a dark silt layer (a varve) therefore represents a year's accumulation of sediment on the bottom of a glacial lake. Using this premise, and also accepting the idea of a continuous lake (Lake Hitchcock) in the Connecticut Valley, Ernst Antevs has studied and correlated the varves in numerous clay pits between Hartford, Connecticut and St. Johnsbury, Vermont. His conclusion is that Lake Hitchcock had an existence of approximately 4,000 years, and that its successor (Lake Upham) lasted approximately 600 years. Our present best estimate is that these lakes existed in the interval between 17,000 and 11,000 years ago.

There is evidence near Littleton, N. H. of a late-stage Wisconsin ice advance, estimated to have taken place about 9,000 years ago. There is little indication, however, that this advance extended as far southward as Hanover.

Before leaving this abbreviated summary of the glacial geology of the Hanover region, it is appropriate to discuss the origin and occurrence of the economically valuable sand and gravel deposits. These are of two main types. The first is perhaps best exemplified by the large gravel deposit currently mined by the Twin State Gravel Company immediately south of the village of West Lebanon. This may have originated as a delta or outwash deposit where the Mascoma and White Rivers emptied into glacial Lake Hitchcock, discharging their heavy burden of sand and gravel into the quiet waters of the lake. Similarly, many of the tributary streams of the region have deltaic gravel deposits somewhere along their courses, at elevations below 660 feet.

The second type of gravel desposit is far more unusual, but by no means unique in glaciated areas. This is a continuous low ridge of gravel (an esker) roughly paralleling the Connecticut River on the Vermont side, but crossing to New Hampshire for a total distance of four miles in the vicinity of Hanover. Where the ridge has been broken into, as at White River Junction or Hanover, it is evident that it is partly buried by varved clays, and must be older than them. The accepted theory for the origin of eskers, and for the esker of the Hanover quadrangle, is that they represent deposits of sand and gravel laid down by streams flowing under the ice cap. When the ice has finally melted this gravel deposit stands up as a ridge, outlining the previous path of the under-ice stream. If there had been no Lake Hitchcock in the Hanover region, the esker would have stood some 50 to 100 feet above the surrounding topography. Its burial by Lake Hitchcock silts makes its present outline locally obscure.

Since the wasting away of the Pleistocene ice, there has been extensive erosion of the soft glacial deposits. The floor of Lake Hitchcock, for example, is deeply dissected and is represented now only by remnants such as the plain on which the campus of Dartmouth College is situated, and by the numerous similar bench-like terraces of the Connecticut Valley with mean elevations of 500 to 540 feet. In a similar manner, areas covered by the glacial till have been deeply dissected by post-glacial streams.

Another, more subtle, post-glacial event has been a gradual upwarping of the crust of New England. In discussing the deposition of the bedrock of the Hanover region we have pointed out how, under a sedimentary load, the earth's crust progressively sags as the load increases. A mile-thick ice cap certainly constitutes a great load on the earth's crust, and New England as a whole undoubtedly sagged downward under the Pleistocene ice. The amount of the depression at the latitude of Hanover is uncertain, but if the ice were a mile thick (a reasonable estimate) the crust may have been depressed as much as 1,700 feet. As the ice cap melted away the crust of the earth rebounded to something approximating its former position, but the recovery was slow and is still incomplete. R. J. Lougee has accumulated evidence indicating that the total amount of post-glacial upwarp at the latitude of Hanover is at least 700 feet, and possibly much more.

A demonstration of present-day upwarping is not easily made because the rate of rebound of the earth's crust is extremely slow. Data such as Lougee's are based partly upon the measurement of such features as the elevations of the upwarped shorelines of Lake Hitchcock, and the interpretation of these measurements. An indirect visual clue that post-glacial uplift has gone on in the Hanover region is possibly afforded by the terraces so strikingly developed along the Connecticut and several of its tributaries. These record the history of the Connecticut River as it re-excavated its course, which had been choked with glacial sediments. The village of West Lebanon, New Hampshire, for example, is built on a series of six terraces. Terraces such as these are developed when a stream has established an equilibrium between its gradient, its volume of water, and the amount of material it transports. At this stage it changes its major erosional attack from one of down-cutting to one of lateral meandering and erosion.

The terraces of the Hanover region are cut, generally, into varved clay, and therefore post-date Lake Hitchcock. There are several possible explanations for their origin. First, post-glacial streams may become locally entrenched over some bedrock obstruction as they clean out the glacial debris filling their former valleys. This has two consequences; it may result in a waterfall at the obstruction, and it may also allow the upper reaches of the stream, flowing on soft sediment, to develop a flood plain. Gradual downcutting and uncovering of several such bedrock obstructions in the downstream part of a valley may result in the development of several terraces upstream.

A second explanation of terrace development is that it is due to variations in the rate of post-glacial upwarping. A stage of almost no active upwarping may coincide with a stage of stream meandering and the development of a broad flood plain. During active upwarping there should be downcutting by the streams of the region, and the former flood plain would become a terrace. Whether this explanation or the preceding one applies to the terraces of this region is not known with certainty. Should the latter explanation be correct, it implies irregular step-like post-glacial rebound of the Hanover region during the past 11,000 years.

It is very possible that a combination of the two explanations outlined in the preceding paragraphs is the correct answer to the problem of terrace development in the Connecticut Valley during post-Pleistocene time.

ECONOMIC DEPOSITS

The deposits of major current economic importance in the Hanover quadrangle are all of glacial origin, and have been discussed incidentally under the section on "Glaciation." Although no comparative data are available, it is probable that the Densmore Brick Company's operations in Lebanon are of first importance. The plant is situated at the northern edge of the village of Lebanon, and has manufactured brick and tile from varved clay in this locality for a period of more than sixty years. At the present time the company mines varved clay from a new pit a mile and a half west of the village of Lebanon, on the south bank of the Mascoma River. In view of the large resources of clay in this region and the steadily increasing demand for brick, it is safe to predict that this industry should flourish for many years to come.

Another large and actively exploited deposit is the large gravel delta (?) mined by the Twin State Gravel Company on the southern limits of the village of West Lebanon. Since 1926 the pit has produced an estimated 3 million yards of sand and gravel, with a total value of several million dollars. Test boring by the present operators indicates another forty feet of sand and gravel below the level of the present pits, a reserve which should be adequate for another decade. In addition to serving as a source of sand and gravel, the pits are also presently yielding raw material for a road-surfacing company, and a ready-mix concrete plant.

Other large gravel pits in the Hanover quadrangle have been opened on delta deposits along Bragg Brook west of Norwich, Vermont and north of the village of Wilder, Vermont, near the mouth of Dothan Brook. The esker of the Hanover quadrangle is mined a mile and a half north of the village of Hanover, at Hanover, at White River Junction, and a mile north of the southern boundary of the map area, west of the Connecticut River in the township of Windsor, Vermont. This last locality is the site of the plant of the Vermont Concrete Pipe Corporation. In addition to these mines, there are numerous other smaller gravel deposits, generally of deltaic origin, which have been opened up in numerous localities along the tributaries to the Connecticut. Few of these are sufficiently large to be of major economic significance.

Before the granite industry of New England declined because of a variety of economic ills and the competition of Indiana limestone and poured concrete, pink Lebanon granite was quarried at several localities, notably at Quarry Hill a mile and a half north of the village of Lebanon. The granite is of good quality and has been successfully used in a number of local buildings. The Lebanon quarrying industry, however, has been defunct for thirty-five years, and there seems to be no reason for predicting its revival in the foreseeable future.

One of the potential non-metallic deposits of the Hanover quadrangle is kyanite, an aluminum silicate mineral used in the manufacture of refractory porcelains, such as are necessary in spark plugs. Kyanite occurs in many of the schists within the kyanite isograd (see geologic map), but has not been observed by this writer in an abundance sufficient for commercial production. Kyanite in the schists is generally unrecognizable, except by a trained mineralogist. A second variety, however, occurs as long blue bladed crystals in quartz veins penetrating the schists. This type of kyanite is conspicuous, and although it is generally not commercially exploitable, it has attracted some prospecting activity. During the summer of 1951 the United States Bureau of Mines diamond-drilled a prospect on Tigertown Brook, north of the village of West Hartford, Vermont. Total indicated ore reserves proved too low for production. The most promising occurrence of kyanite in this region is in schists on Signal and Hayes Hills, three to four miles northeast of the village of Lebanon, and east of the limits of this map. A brief account of the geology of these deposits has been published by Dr. H. M. Bannerman in

Part IV of New Hampshire Mineral Resources Survey, issued by the New Hampshire Planning and Development Commission in 1941.

Because less than two per cent of the bedrock of the Hanover region is exposed, the remainder being concealed by glacial deposits, it is not unreasonable to hope that the area may contain valuable deposits of metallic minerals, as yet undetected. The best possibility appears to be for copper and, secondly, for lead and zinc. The Vermont copper belt eight to fifteen miles north-northwest of Hanover has been worked intermittently since 1793, and has recently supported a 150-man mine at South Strafford, Vermont. Major metallic minerals in the Vermont mines are chalcopyrite, a golden-yellow copper iron sulfide, and pyrrhotite, a bronze-colored iron sulfide. Several prospect pits have been opened on pyrrhotite-chalcopyrite outcrops of the Hanover quadrangle. Largest of these is on the northeastern slope of Farnum Hill, 2.4 miles S. 30° W. of the village of Lebanon, on property now owned by the Lillipage family. Here, more than seventy years ago, a shaft reputedly 75 feet deep was sunk into the bedrock, and several drifts and trenches were opened up. From the ore now exposed on the mine dumps it is evident that the distribution of copper in the deposit was spotty, and possibly below commercial grade. Because of the extent of the mineralized area, however, the prospect merits further exploration.

Galena, a silvery-colored lead sulfide, and sphalerite, a tan zinc sulfide had been mined in colonial times at Thetford, Vermont, seven miles north of Hanover. Approximately 15 years ago a 45-foot shaft was sunk on a galena-sphalerite vein a half mile east of the village of Lebanon, and a hundred yards south of U. S. Route 4. Like other galena-sphalerite occurrences in the area, this prospect was apparently uneconomic because of the narrowness of the vein and the small amount of exposed ore.

INTERESTING LOCALITIES

Quechee Gulf

One of the tourist attractions of the Hanover quadrangle is Quechee Gulf, a mile-long 160-foot deep gorge cut into the Gile Mountain formation by the Ottauquechee River at Deweys Mills, Vermont. Like the waterfalls and other minor scenic beauties of the region, Quechee Gulf is an indirect result of stream diversion resulting from the Pleistocene glaciation.

Prior to the glacial period the Ottauquechee River made a loop a half mile east of Deweys Mills, and then flowed southward, emptying into the Connecticut near Hartland, Vermont. When the Connecticut was dammed, with the resulting development of Lake Hitchcock, the Ottauquechee Valley was flooded as far west as the village of Taftsville, Vermont, and was gradually clogged with the sand and varved clay washed into the lake by glacial meltwaters. Thus a 160-foot thickness of sediment filled in the pre-glacial valley of the Ottauquechee, and a level floor was developed across the bottom of this estuary of Lake Hitchcock. When Lake Hitchcock's waters suddenly receded, there was no compelling reason for the newborn Ottauquechee to flow in any specific direction across the flat lake floor and the direction it chose was apparently fortuitous. Near the present lower end of Quechee Gulf the Ottauquechee eroded quickly through soft glacial deposits, and became entrenched on the bedrock of the Gile Mountain formation. Subsequently the river has worn itself downward and headward through the schists, following the direction of least resistance (the structural trend of the bedrock), and abrading its channel by rubbing stones and sand along the bottom of the stream. At Deweys Mills the gorge intersects the pre-glacial course of the Ottauquechee. The abrupt widening of the valley above this point is due to the relative ease with which the river has been able to erode the sediment plugging its preglacial channel. If our glacial chronology is correct, the excavation of Quechee Gulf to its present form has been accomplished within a period of some 11,000 years.

Hartford, Vermont

Probably the best locality in the Hanover quadrangle to give one an idea of the complexity of the bedrock structure is on Route 14, along the north bank of the White River, and a mile west of the village of Hartford, Vermont. The excellent exposures here are of the upper portion of the Gile Mountain formation, and consist of alternating layers of black phyllite (originally black mud), and tan quartz-mica schist (originally sand). These beds have been squeezed into a series of tight northward-plunging synclines and anticlines (fig. 6) and have been jointed, and subsequently exhumed by erosion. Several structural geologic phenomena are nicely illustrated in the exposure, such as lineation, axial plane cleavage, bedding cleavage, slip cleavage, micro-faulting, jointing, reverse drag folding, and plastic flowage of the weak phyllite into the noses and troughs of the folds.

Fig. 6. Detail of the highly folded rocks of the Gile Mountain formation a mile west of Hartford, Vt. Light-colored beds are quartz-mica schist; dark beds are phyllite. Veins of quartz intrude the beds, and the cleavage in the formation dips toward the right at an angle of approximately 60 degrees. Pencil is for scale.

The surface of these outcrops is peculiarly irregular and bumpy, particularly near their eastern end, where varved clays rest upon the bedrock. The clue to the origin of these surface irregularities is provided by two six-foot diameter holes in the bedrock, one in the center of the outcrops, and the other at their western end. These, very clearly, are potholes and must have been formed at a time when the White River flowed at a level approximately 30 feet above its present course, at which time these outcrops were at the bottom of the river. This must have been prior to the development of Lake Hitchcock, inasmuch as its varved clays cover up the waterworn bedrock surface.

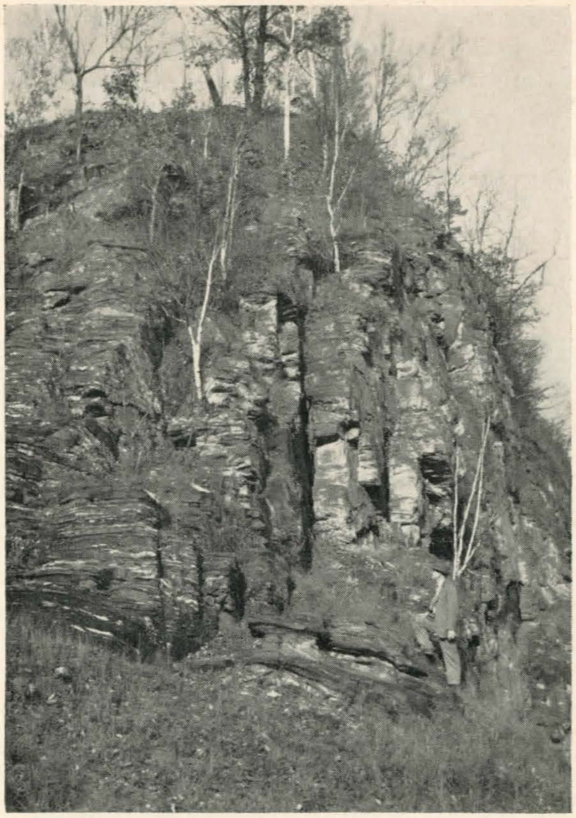

Fig. 7. Jointing in the Waits River formation 1.5 miles N. 55 W. of West Hartford, Vt. Schistosity dips away from the observer. Structure appears simple, but rocks are complexly folded (see Fig. 8).

The Hartford outcrops have been discussed in some detail because they are beautifully illustrative of the geology of the region as a whole. Few other localities show the detail so well preserved in these rocks, but we infer from examination of the minor structures in other outcrops that all the metamorphic rocks of the Hanover quadrangle have a similar structural complexity. The ultimate in rock contortion is visible in a 100-foot cliff of the Waits River formation, 1.5 miles N. 55° W. of the village of West Hartford, Vermont. Here the rocks are not only tightly folded, but the folds have been rotated into a sub-horizontal position and the beds zig-zag across the cliff face in a most complex pattern (figs. 7 and 8).

Blow-Me-Down Brook
Plainfield, New Hampshire

Lavas which are extruded underwater, or which flow from the land into the ocean, assume peculiar ellipsoidal shapes descriptively called pillows. A remarkably preserved outcrop of pillow lava occurs in the bed of Blow-Me-Down brook, 1.2 miles

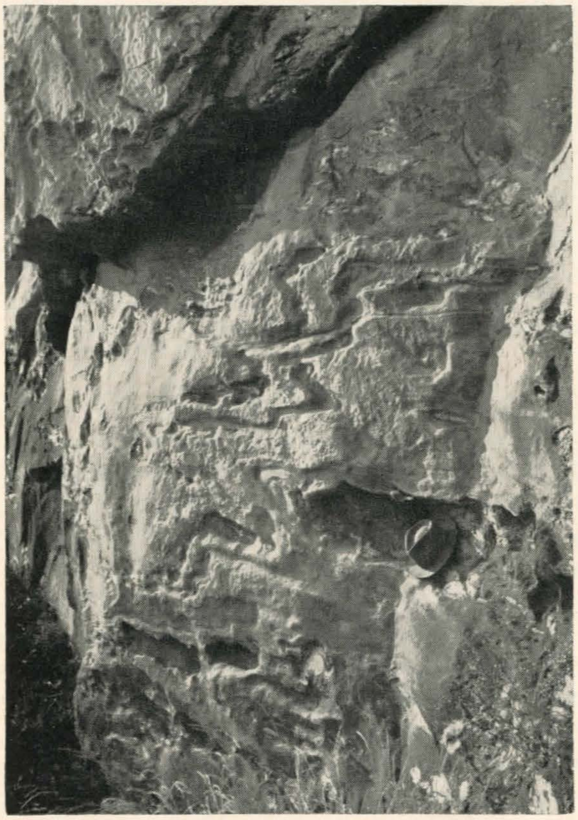

Fig. 8. Detail of the complex fold pattern in the Waits River formation. View is looking toward one of the joint surfaces shown in Fig. 7.

east of Plainfield, where the brook crosses the belt of rocks marked "Oov" on the geologic map. The ancient basaltic pillows at this locality have been tilted on end, metamorphosed to hornblende schist, and eroded by the brook, but their ellipsoidal outlines are beautifully preserved, even to the dark outer rinds (fig. 9). Other less perfectly preserved pillow lava outcrops in the Hanover quadrangle may be seen on a hill 1.3 miles north of the village of Norwich, Vermont, 1.5 miles upstream from the mouth of Beaver Brook in the south-central ninth of the quadrangle, and at several places along Blood Brook from the village of Meriden westward.

Ammonoosuc Thrust Fault

The best exposure of the Ammonoosuc thrust fault in the Hanover quadrangle is at a locality 2.3 miles north of the settlement of Lewiston, Vermont (in the township of Norwich), in the cliffs on the west side of Route 5. Rocks in the lower 40 feet of the cliff consist of dark green hornblende gneiss and interbedded quartzite. The fault zone itself, 30 to 35 feet in thickness, is marked by a band of crushed rock (fault breccia), the bottom surface of which dips westerly at 35 to 40 degrees. The upper 50 feet of outcrop consists of crenulated sericite-chlorite schist which has been shoved easterly several thousand feet over the underlying hornblende gneiss and quartzite.

Other Localities

Some localities in the Hanover quadrangle are well known in the geological literature. The beautifully exposed varved clay bank on Mink Brook south of the village of Hanover and the terraces on Girl Brook north of the town have been shown to generations of Dartmouth students, and have been very carefully studied and described by Antevs, Goldthwait, and Lougee. Occom Ridge and Occom Pond in Hanover (not labelled on the geologic map) are well known as esker and kettle hole respectively. The Bayou, a mile southwest of Hanover near the mouth of Mink Brook has been excellently described by Goldthwait as an abandoned channel of that stream, and the rocking stone in Prexy's garden on the Greensboro Road between Hanover and Lebanon has been illustrated in several of his publications. These features are all related to the glacial geology of the region.

For those interested in mineral collecting there are the prospect pits described in the preceding pages, and other unique localities. On the southwest slopes of Craft's Hill in West Lebanon (0.75 miles S. 15° E. of the summit) a quartz vein cutting through amphibolite ("a" on the geologic map) has, in addition to the quartz, 5-inch long sheaves of actinolite and clinozoisite — an unusual development for both minerals. The Standing Pond

Fig. 9. Hornblende schist in the bed of Blow-Me-Down Brook, 1.2 miles east of the village of Plainfield, N. H. Well-preserved pillow structure indicates that these rocks were formerly submarine lavas.

amphibolite in the southwestern ninth of the quadrangle carries garnet crystals the size of golf balls. Excellent quartz-kyanite specimens have come from Tigertown Brook, in the northwestern part of the region. Some of the granite on Quarry Hill, Lebanon has small cavities in which beautifully terminated quartz and feldspar crystals may be found. Staurolite, in typical cruciform twins, may be collected on the wests lopes of Crafts Hill in West Lebanon.

Bedrock structures exist in profusion. There are, for example, unusual vertically-plunging folds on the south slopes of Farnum Hill, southwest of Lebanon; stretched amygdules in the metamorphosed lavas 2½ miles south of West Lebanon; dike swarms on Black and Prospect Hills north-northeast of Plainfield, New Hampshire; lit-par-lit injection of chlorite schist by granite east of Hartford, Vermont; recumbent (horizontal) folds at Bunker Hill in the northwestern part of the quadrangle and along Hubbard Brook in the southwestern part of the quadrangle; metamorphosed conglomerate at French's Ledge in Meriden; and flow structures (lineation and foliation) in the Lebanon granite. Even the man-made structures of the region pay their respects to the geologic framework of the area. The new Wilder dam sits astride the Connecticut at a seemingly peculiar angle to take advantage of the strong ridge of hornblende schist running beneath it and serving as its foundation.

There are, it is apparent, an endless array of interesting geologic phenomena about us. It seems equally evident that it is impossible to describe them all. If this booklet provides a framework for understanding some of the things we see, and if it in any way heightens the reader's appreciation of the ground beneath him, it has served its purpose.

GLOSSARY

actinolite a mineral occurring in slender green needles; a calcium iron magnesium hydroxy-silicate

amphibolite a rock composed chiefly of the mineral hornblende (q.v.)

anticline an upfold in layered rocks

basalt a black fine-grained lava

brachiopod marine organism, an inch or so in diameter, with two symmetrical shells

biotite brown mica; a potassium magnesium iron aluminum hydroxy-silicate

calcareous an adjective applied to rocks containing calcium carbonate (calcite)

chlorite a green platy mineral; a magnesium iron aluminum hydroxy-silicate

cleavage the tendency of a rock or mineral to split in preferred directions

clinozoisite a gray mineral occurring in sheaves; a calcium aluminum hydroxy-silicate

conglomerate a sedimentary rock containing worn and rounded pebbles of other rocks; a cemented gravel; popularly known as pudding stone

crinoid sea lilies and other members of the phylum **Echinodermata**

cystoid extinct marine organisms, somewhat similar to the sea lilies; phylum **Echinodermata**

diabase a dark rock, generally occurring as dikes; composed chiefly of feldspar and pyroxene

dike a tabular body of now-solidified but once hot liquid rock; cross-cutting

dip the maximum angle between an imaginary horizontal plane and an inclined rock layer; measured in a plane at right angles to the strike; i.e. the inclination of a rock layer

dome a type of anticline with a sub-circular map pattern; beds dip off equally in all directions from the top of the dome

fault a break or fracture along which there is relative movement of the bedrock on either side of the fault plane

feldspar the commonest of all minerals; a pink, white, or gray aluminum silicate of potassium, or sodium and calcium

foliation a parallelism of the platy minerals in a rock; most foliated rocks cleave easily parallel to the plane of foliation

gabbro a dark-colored coarse-grained rock consisting principally of feldspar and pryoxene

garnet a red equidimensional mineral, forming small crystals in the rock; an iron magnesium aluminum silicate

gastropod typified by the snails; a mollusk, typically having a coiled shell

gneiss a banded metamorphic rock

hornblende dark green needle-like mineral; a silicate of complex composition

intrusive a once-molten rock which has penetrated into or between other rock formations

kettle hole a hole or depression in sediments of glacial origin formed where buried ice has gradually melted away

kyanite an aluminum silicate occurring in light-blue bladed crystals

limestone	a sedimentary rock composed of calcium carbonate
lineation	parallelism of elongate minerals or minor directional structures in rocks
magma	the term applied to hot fluid rock; temperatures of magmas approximate 1000°C. (1800°F.)
metamorphism	reconstitution or recrystallization of one rock into a different variety under the influence of temperature, pressure, and shearing stresses
metasomatized	an adjective applied to rocks which have had chemicals added or subtracted as a consequence of complex geologic processes
mica	a common sheet-like mineral; in metamorphic rocks it is the common mineral which makes the rock glisten. Brown mica is biotite; white mica is muscovite or sericite
orogeny	the process of mountain building; this involves folding, and elevation of rocks above sea level
phyllite	a lustrous gray or black rock, intermediate between slate and schist
plutonic	deep-seated; applied to rocks formed at some depth within the earth
pothole	a circular hole drilled into rock by sand or stones eddying in the bottom of a stream
pyroxene	a dark elongate mineral; a calcium iron magnesium silicate; easily confused with hornblende (q.v.)
quartz diorite	a type of rock resembling granite, but containing a higher proportion of dark-colored minerals, and a different type of feldspar
quartzite	a hard metamorphic rock composed of interlocked quartz grains
radiogenic	produced by spontaneous radioactive breakdown
sandstone	a sedimentary rock composed principally of quartz
schist	a metamorphic rock having excellent cleavage
sedimentary	formed by deposition, from water or air, of grains of rock-making material; chemical and organic precipitates are also considered to be sedimentary
sericite	fine-grained white mica
shale	a sedimentary rock made of compacted mud
stratigraphic	pertaining to the science of sedimentary-rock study
staurolite	a red-brown mineral occurring in cross-shaped crystals in metamorphic rocks; an iron aluminum hydroxy-silicate
strike	the direction of trend of a layered rock; technically the strike is the direction of a horizontal line of intersection made by cutting the layered rock with an imaginary horizontal plane
syenite	a rock resembling granite, but lacking quartz and consisting predominantly of feldspar
syncline	a downfold in sedimentary rocks
trap	hard black basalt occurring either as a flow rock (a lava) or as a dike rock

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