Geology and Mineral Resources of the Hudson and Maynard Quadrangles Massachusetts

GEOLOGICAL SURVEY BULLETIN 1038

Prepared in cooperation with the Commonwealth of Massachusetts Department of Public Works

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By WALLACE R. HANSEN

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GEOLOGY AND MINERAL RESOURCES OF THE HUDSON AND MAYNARD QUADRANGLES, MASSACHUSETTS

By Wallace R. Hansen

ABSTRACT

The highest summit in the Hudson and Maynard quadrangles stands only 642 feet above sea level; nevertheless, the area is characterized by many steep slopes and low cliffs. In general, the land surface increases noticeably in height and local relief from east to west.

Pleistocene continental glaciation has strongly modified both the topography and the drainage. Glacial deposits cover broad areas, commonly as a thin veneer but locally as a blanket of substantial thickness. Most of the higher hills in the Maynard quadrangle are drumlins, and more than 80 of these occur in the two quadrangles.

By far the greater part of the area is underlain by metasedimentary rocks of Carboniferous age. These rocks are of diverse composition and metamorphic grade, and nearly everywhere are strongly deformed. Rocks formerly mapped as Worcester phyllite and Brimfield schist are regarded as stratigraphically equivalent but metamorphically different facies of the same formation. In redefining these rocks for this area, the name Worcester formation is proposed, and the terms phyllite facies and mica schist facies are applied. At the base of the phyllite and mica schist facies is a quartzitic facies, the Vaughn Hills, which feathers out to the north and northeast. It is underlain by the Harvard conglomerate lentil.

The gneissic Nashoba formation, youngest of the metasedimentary rocks in the area, is several miles in outcrop breadth; although this great breadth undoubtedly is due in part to multiple folding, the formation is probably at least 5,000 feet thick.

The Nashoba is moderately to strongly feldspathized. Its greater bulk is quartz-biotite gneiss, but amphibolite and quartzite are common, and marble occurs locally. Feldspathization for the most part stopped abruptly at the Worcester and Marlboro contacts, but a smaller center of intensive feldspathization was localized around Bare Hill Pond.

A belt of granitic rocks 2 to 3 miles across in Hudson tapers to a fraction of a mile across northeastward in Concord. These rocks, the Gospel Hill gneiss, appear on earlier maps as Andover granite but are here regarded as a granitized facies of the Nashoba and Marlboro formations.

On the southeast the Gospel Hill gneiss is in contact with the Marlboro formation. This contact, gradational where exposed, throws doubt upon the pre-Cambrian age assignment of the Marlboro and upon the age assignments of igneous rocks that invade the Marlboro. Unless granitization has obscured an unconformity lying somewhere within what is now the Gospel Hill gneiss, the Marlboro here and in its type locality must be Carboniferous.

Late Carboniferous(?) igneous rocks of mappable dimensions occupy a relatively small part of the area but over broad stretches hardly an outcrop does not contain some igneous material. Igneous intrusion was mostly subsequent to the deformation that produced the folding. Small basic dikes probably of Triassic age, observed at a few localities in the Maynard quadrangle, are the youngest rocks exposed.

Structural trends are predominantly northeastward. Major fold axes have not been identified, however, because they are mostly obscured by countless minor folds. In the belt of the Nashoba formation the structure is probably an asymmetrical synclinorium. On its overturned northwest limb is the mica schist facies of the Worcester formation and on its normal southeast limb is the Marlboro formation. Large anticlines containing igneous cores flank the synclinorium on both limbs. Minor folds in the Nashoba formation are oriented parallel to the major structural trends; in the formations flanking the Nashoba, however, cross folds are nearly athwart the major structural trends and, presumably, were produced by a second episode of deformation.

Axial stretching in the belt of the Nashoba is indicated by cross joints, in places very prominent, and by linear structures lying parallel to the fold axes. Stretching is attributed in part at least to arcuation during folding.

Glacial features of the area were formed chiefly by the latest ice sheet that overrode the area. These features include a wide variety of drift deposits, both sorted and unsorted. Deglaciation left a myriad of ice-contact deposits, and chronologic relationships of these indicate that in general the ice withdrew from south to north. In most places a broad, irregular zone of stagnation characterized the margin of the withdrawing ice, but in the southeastern part of the Maynard quadrangle a rather continuous ice front was maintained. Ponding at the ice margin produced temporary marginal lakes. Large ice masses remained within the lake basins, however, and broad stretches of open water probably never existed in either quadrangle. Some deltaic deposits probably almost filled the ice-enclosed openings into which they were deposited.

Mineral resources, developed and undeveloped, include surface and underground water, sand and gravel deposits, till, fine-grained lake-bottom deposits, crushed stone, granite, flagstone, marble, and peat.

INTRODUCTION

The Hudson and Maynard quadrangles comprise an area of about 110 square miles in east central Massachusetts (fig. 1) within Worcester and Middlesex Counties. A new topographic survey of the area by the Geological Survey was completed in 1941, and the maps were published on a scale of 1:31,680, or 2 inches to the mile, and with a contour interval of 10 feet. These topographic maps were used as a base for the geologic mapping, which was done during the field seasons of 1948 and 1949 in cooperation with the Massachusetts Department of Public Works.

Before the present investigation, the area had been examined in whole or in part by several geologists. Emerson (1917) studied the rocks of the Hudson quadrangle during his investigation of broad areas in central and western Massachusetts. Those sections of his report dealing with rocks of the Maynard quadrangle, however, are largely the results of work by Laurence La Forge. Alden (1924)

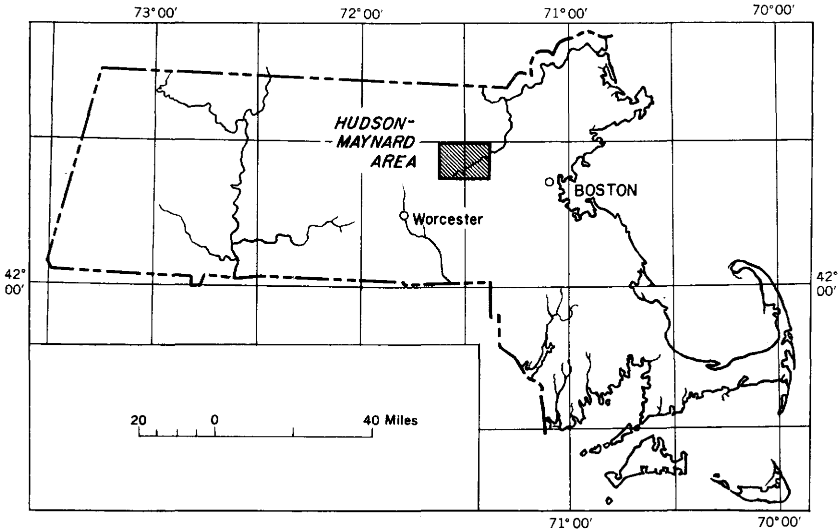

FIGURE 1.—Index map showing location of Hudson and Maynard quadrangles, Massachusetts.

examined the surficial deposits of the Hudson quadrangle during his studies in 1906 and 1907 of the Ware and Quinsigamond 30-minute quadrangles. Goldthwait (1905) examined the deposits of glacial Lake Sudbury. His investigations covered parts of the Maynard quadrangle. Most of glacial Lake Nashua occupied areas that lie beyond the western limits of the Hudson quadrangle; this lake was described in several reports by W. O. Crosby (1899a, 1899b, 1903–04), who gave the lake its name, by Alden (1924), T. C. Brown (1931), and more recently by R. H. Jahns (1953).

The old, now abandoned, lime quarry at Bolton, because of its interesting mineral assemblage and because of the rarity of marble in eastern Massachusetts, has received attention in the literature for more than a century. Other studies of direct or indirect bearing on the geologic problems of the Hudson and Maynard quadrangles are referred to in the text.

For many helpful suggestions offered both in the field and in the office, the writer is indebted to Messrs. L. W. Currier, M. E. Willard, and R. H. Jahns. Many ideas arising from discussions with these geologists have been incorporated into this report.

TOPOGRAPHY

The Hudson and Maynard quadrangles lie in the "bordering slope" of the Worcester plateau (Emerson, 1917, p. 16); to the east of this slope lies a narrow coastal lowland with which the bordering slope merges. Fenneman (1938, p. 370) included the bordering slope in his "Seaboard Lowland," pointing out that "in its larger aspect the relatively low coastal border of New England is merely the sloping margin of the upland." It is not surprising, therefore, that the boundary between these regions is indistinct and somewhat arbitrary.

In general the lowland is typically lower and its surface is more regular than that of the adjoining upland, but in certain areas, particularly those toward the west, the differences are slight. In traveling across the Maynard and Hudson quadrangles from east to west one observes a gradual change from relatively smooth, subdued topographic forms in Concord and Sudbury, characterized by broad valleys and low, rounded hills, to areas of markedly greater relief in Harvard, Bolton, and Berlin, where narrower valleys, steeper slopes, low cliffs, and sharp ridges abound.

About half of the Maynard quadrangle lies below 200 feet altitude, and only the higher hills rise above 300 feet. The highest summit, Flag Hill in Boxborough, is astride the boundary between the Maynard and Hudson quadrangles and stands 466 feet above sea level. The lower reaches of the Assabet River and the wide swamps and meadows along the Sudbury River are below the 120-foot contour. Several large areas and many hills in the Hudson quadrangle exceed 400 feet altitude; most of the quadrangle is above 300 feet and the general altitude rises to the west. The northern of the two Vaughn Hills in Bolton, which stands 637 feet above sea level and rises about 420 feet above the bottom of the Nashua Valley 1 mile to the west, has the greatest local relief in the area. The dominating physiographic feature of the terrain, however, is a long ridge that traverses Harvard and Bolton in the Hudson quadrangle and extends into the Ayer quadrangle on the north and into the Clinton quadrangle on the west. Most of this ridge is above the 500-foot contour; from its crest broad vistas are obtained eastward toward the Boston Basin and westward toward Mount Wachusett and central Massachusetts. Its highest point, an unnamed hill in Bolton, stands 642 feet above sea level and is the highest summit in the Hudson and Maynard area. Bare Hill in Harvard and Wataquadock Hill in Bolton are other prominent features of this ridge.

Unconsolidated deposits, largely of glacial origin, mantle most of the Hudson and Maynard quadrangles and, in fact, cover essentially the entire Maynard quadrangle. Here, and in parts of the Hudson quadrangle as well, bedrock is exposed sparingly and in many places lies deeply buried. Thus, the effects of continental glaciation upon the topography are marked, and postglacial changes due to resumption of normal erosional processes are slight. The great abundance of glacially constructed landforms that remain essentially unmodified attest to the recency of the disappearance of the ice.

Three general, rather distinctive, types of topography that now characterize the landscape are (1) areas of relatively thick till where bedrock outcrops are few, (2) areas of water-deposited drift, and (3) areas where the drift cover is thin or absent and bedrock outcrops are abundant. Areas of thick till commonly exhibit smoothly rounded contours and profiles; there is some tendency for such landforms to be elongated in a general southerly direction, the direction of ice movement. Drumlins, especially, exhibit a decided alinement, but locally other till terranes are hummocky and extremely irregular. Areas of water-deposited drift are characterized by a great variety of landforms that range widely in shape and size. These were constructed during deglaciation and reflect local conditions of ice stagnation and melting. In those areas where the glacial cover is thin or absent the major bedrock structure commonly is reflected in the topography. The northeasterly trend of the steep-dipping rock formations in Harvard, Bolton, and Berlin is evident and shows clearly on the topographic map. The divergence of these trends from those of the till-drumlin topography is striking, particularly where the terranes overlap or are in close proximity, as at the drumlin, hill 382, Stow Road, Harvard, and at the drumlin just north of Murrays Lane, Harvard. Some other hills are composite forms and have thick, lenticular till accumulations on their northward-facing slopes and alined cliffs or ledges on their southeastward slopes. Gospel Hill in Hudson is a good example.

In certain areas joints in the bedrock have influenced the topography. A set of cross joints is prominent in some of the bedrock formations (fig. 15) and has a general northwesterly trend that is reflected by steep slopes and small cliffs. The more conspicuous of these face toward the southwest and have been accentuated by glacial plucking, as at Rattlesnake Hill and Powder House Hill in Bolton, and at several other unnamed hills in the vicinity. At these places the contours turn sharply from a northeasterly alinement parallel to the trend of the formations to a northwesterly alinement parallel to the trend of the joints.

DRAINAGE

GENERAL FEATURES

The principal stream of the Hudson and Maynard quadrangles is the Assabet River, and most of the area lies within its drainage basin. About one-third of the Maynard quadrangle, the southeast portion, lies within the Sudbury River basin. The Assabet and Sudbury Rivers join to form the Concord River a short distance east of the Maynard quadrangle boundary, and the Concord flows northward to join the Merrimack River at Lowell. Bowers Brook and Beaver Brook, in the northern part of the Hudson quadrangle, drains into the Nashua River and into Stony Brook, respectively; these streams also flowing northward, join the Merrimack independently. Thus the drainage of the entire area flows ultimately into the Merrimack.

In late preglacial time most of the minor streams of the area probably flowed in channels that were well adjusted to the underlying bedrock structure. Except locally where the rock structure is essentially homogeneous, as in parts of Sudbury, headward erosion followed principally along the northeastward-trending foliation planes. The markedly linear arrangement of ridges and valleys in Harvard, Bolton, and Berlin, and to a lesser degree in parts of Hudson and Acton (where the till cover is thicker) indicate preglacial trellis drainage in the smaller tributaries even though the present streams follow somewhat haphazardous courses. The larger preglacial streams of the area, however, probably followed courses that mostly ignored the bedrock structure. It seems likely that these streams were consequent upon an old land surface that had been base-leveled during the Cretaceous period and uplifted in the Tertiary period. Alden (1924, p. 15–18 and p. 27–29) and Fenneman (1938, p. 358–366 and p. 372–373) present in some detail the views of various workers, notably W. M. Davis, W. O. Crosby, B. K. Emerson, and Joseph Barrell, who have studied the broad, regional problems regarding the origin and history of this surface.

Glaciation has profoundly affected the drainage of central and eastern Massachusetts, and the deposition of glacial debris probably was a factor of far greater importance in modifying the details of the landscape than was glacial erosion. The combined effects of erosion and deposition have been in a large measure to reduce the relief as well as to rearrange the drainage. Bedrock is buried to depths of 80 feet or more at several places in the Maynard quadrangle, and many valleys in the Hudson quadrangle afford evidence of substantial filling. Accumulations of glacial debris within the valleys not only caused many streams to alter their courses but in some places disrupted the drainage entirely. Even now the drainage is only partly integrated, undrained depressions are numerous, and swamps cover broad areas. Dual drainage, known to exist in many youthful glaciated regions (Cabot, 1946), is exhibited on a small scale by several swamps in the Hudson quadrangle. A swamp just northwest of Stow Country Club, for example, is drained at the opposite ends by two separate streams.

DRAINAGE ADJUSTMENTS

Several significant drainage changes, involving major stream displacements, are suggested in the area. Because these drainage changes are described in detail elsewhere (Hansen, 1953), they are mentioned but briefly here.

The Assabet River east from Gleasondale to its junction with the Sudbury River in the Concord quadrangle probably occupies a postglacial course; a large channel, buried under glacial debris, appears to extend southeastward from Gleasondale, via Boons Pond, White Pond (in Hudson), and Hop Brook, to the Sudbury River south of the Maynard quardangle, perhaps near Heard Pond in Wayland.

Fort Pond Brook, in its course eastward from South Acton, probably occupies a postglacial channel; a buried valley appears to extend southwestward from South Acton, through Lower Village in Stow, toward Boons Pond, where it seems to join the large buried valley mentioned above.

Assabet Brook, in its course eastward from Wheeler Pond in Stow, probably occupies a postglacial channel; a buried valley appears to extend southward from Wheeler Pond to the Assabet River just northwest of Orchard Hill at Gleasondale. From the Boxborough town line to Wheeler Pond, Assabet Brook flows upon a thick fill but seems to follow essentially a preglacial valley.

The valleys of Danforth Brook and Great Brook, in the Hudson quadrangle, appear to have had a complex history involving both Tertiary capture and, subsequently, glacial diversion. Great Brook arises at Bolton Pan Cemetary from the confluence of two streams; the Tertiary drainage of these two streams seems to have been at one time into Danforth Brook to the south. Both streams, however, appear to have been captured by preglacial Great Brook, which eroded headward parallel to the foliation of the underlying bedrock. Mill Brook, the present headwaters of Danforth Brook, seems also to have flowed into Great Brook in preglacial time but was diverted into Danforth Brook by an obstruction of glacial debris at the sites of Little Pond and West Pond.

Another possible buried valley, not well substantiated, appears to extend southward from West Concord, via White Pond (in Concord), to what is now the Sudbury River in the southeast corner of the Maynard quadrangle.

BEDROCK GEOLOGY

The bedrock formations of the Hudson and Maynard quadrangles include a wide variety of metamorphic and igneous rock types. Age and structural relationships of many of these rock types are uncertain, and the viewpoints of various geologists who have studied them are divergent. Many problems will remain unsolved until detailed mapping has progressed widely into adjacent areas.

Rocks that earlier writers have regarded as of pre-Cambrian age are represented here by the Marlboro formation. Devonian(?) rocks are represented by a quartz diorite, regarded as probably a facies of the Dedham granodiorite, and by an associated gabbro-diorite complex. The great bulk of the rocks in this area, however, probably is of Carboniferous age and includes most of the metasedimentary rocks as well as a large portion of the igneous rocks. A few small basic dikes that may be of Triassic age are exposed in the Maynard quadrangle.

PRE-CAMBRIAN(?) MARLBORO FORMATION

The Marlboro formation was named by Emerson (1917, p. 25) for exposures along the north side of Main Street in the town of Marlboro. In the Maynard quadrangle it is exposed in two separate belts of steep-dipping rocks. One belt is along the Maynard-Framingham quadrangle boundary in the southeast corner of the area, and the other, averaging about 3,000 feet in width, extends southwesterly in a broad arc across the Maynard quadrangle, from Concord to the type locality at Marlboro, in the Marlboro quadrangle. This belt doubtless crosses the extreme southeast corner of the Hudson quadrangle but is covered there by glacial deposits. Outcrops in the Maynard quadrangle are abundant in several areas, but over other broad areas the formation is not exposed, and at no place, in fact, is exposure continuous for more than a few tens of yards. Contact relationships, where seen, are much complicated by metamorphism and igneous invasion. In addition, the formation is intricately folded (fig. 2), and the thickness of the formation, therefore, cannot be determined accurately in this area, but it probably exceeds 2,500 feet.

As exposed in the Maynard quadrangle, the Marlboro formation is predominantly a fine-grained medium-gray to dull-olive-gray amphibolite schist which commonly contains considerable quartz, mica, and feldspar, a varying amount of chlorite, and a small percentage of disseminated magnetite. Epidote veinlets are abundant. Locally there are exposed brownish arenaceous beds, intercalated with amphibolite, and containing small amounts of biotite and muscovite, and beds of white or cream-colored quartzite. Just east of Dakin Road, Sudbury, and well within an area of gabbro-diorite outcrops, is a mass (not shown on the map) of the Marlboro formation that contains strongly contorted beds of marble. Here, too, are small roundish inclusions that seem to be quartzite pebbles and may represent a conglomerate lentil.

Judging from its wide distribution, mica schist probably constitutes a significant part of the Marlboro formation, but such rock commonly is not well exposed in the Maynard quadrangle. Beds of coarse reddish-brown muscovite schist containing considerable biotite are exposed near the top of the formation along Old Marlboro Road in Sudbury, near the Concord town line, and just south of the Hudson

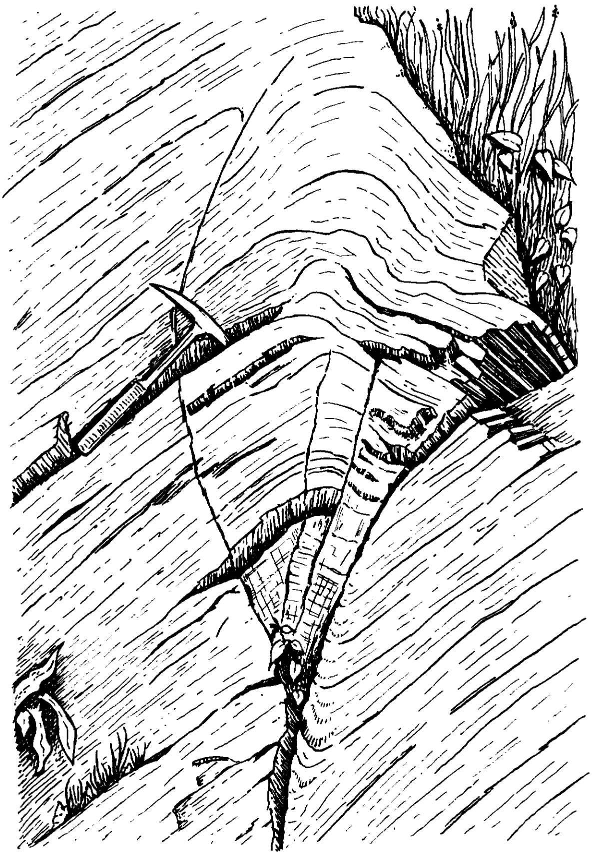

FIGURE 2.—Minor cross fold in the Marlboro formation one-half mile east of Vose Hill, Maynard. The axes of this and similar folds trend nearly normal to the regional strike.

quadrangle; reconnaissance in the latter locality indicates that the mica schists there have a thickness of at least 200 feet and possibly as much as 400 feet. At several other places in the Maynard quadrangle mica schist layers a few feet thick are intercalated with amphibolite.

What apparently is original bedding is well preserved and is parallel to the schistosity in most of the amphibolitic exposures of the Marlboro formation. Bedding in the mica schists, however, is largely obliterated. Coarse-textured dark-greenish-gray amphibolites that show neither bedding nor distinct foliation are exposed at several places, but these grade laterally into well-bedded or well-foliated rocks.

Many exposures of the formation display distinctive secondary structures, some of which are uncommon or lacking in other rocks of the area. Perhaps the most conspicuous of these structures are beadlike or knotlike masses of epidote that are abundant in the amphibolites. These range in longest dimension from a fraction of an inch to more than a foot, and probably once were continuous beds that have

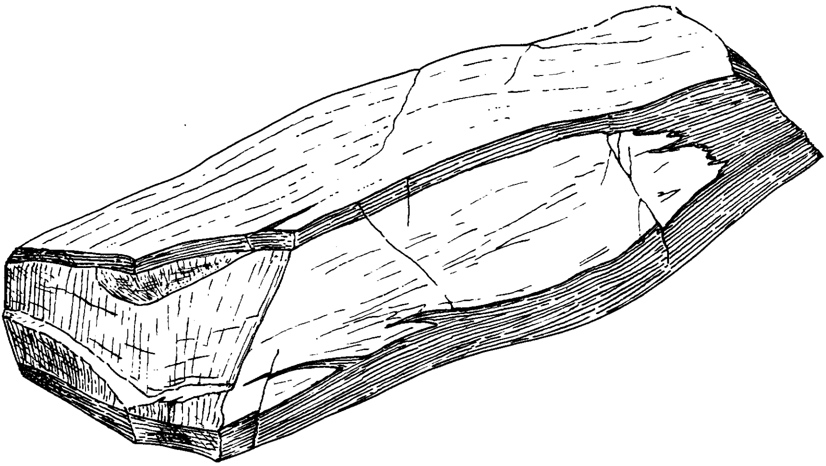

FIGURE 3.—Epidote knot from the Marlboro formation near Vose Pond, Maynard. Note how ragged end on right suggests that knot has been forcibly torn apart. Dark shell is amphibolite schist. Specimen is about 4 inches long. (See also fig. 5.)

been stretched, squeezed out, and sheared off during regional deformation. They grade, in fact, from discrete knots a few inches apart to continuous layers several feet long. (See figs. 3, 4, and 5.) In

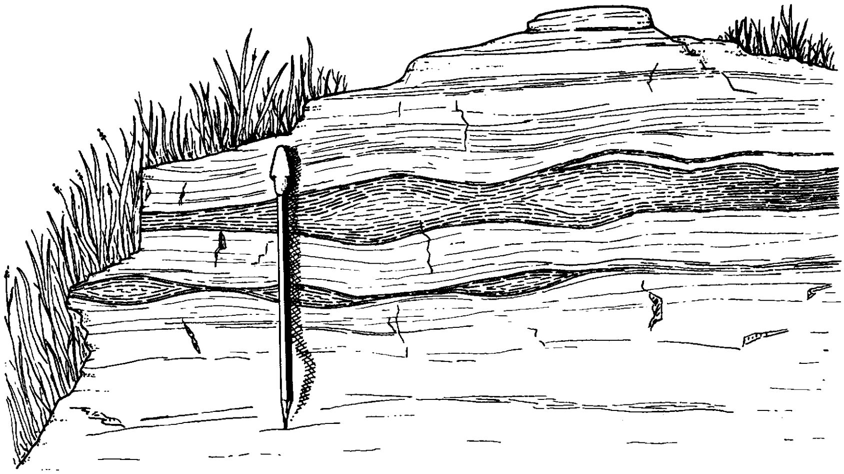

FIGURE 4.—Squeezed epidote layers (dark) in the Marlboro formation near Vose Pond, Maynard. Compare with figures 3 and 5.

places, individual knots that are drawn out and tapered at both ends are joined by thin septa a fraction of an inch wide. The more continuous layers also commonly have pronounced bulges and constric-

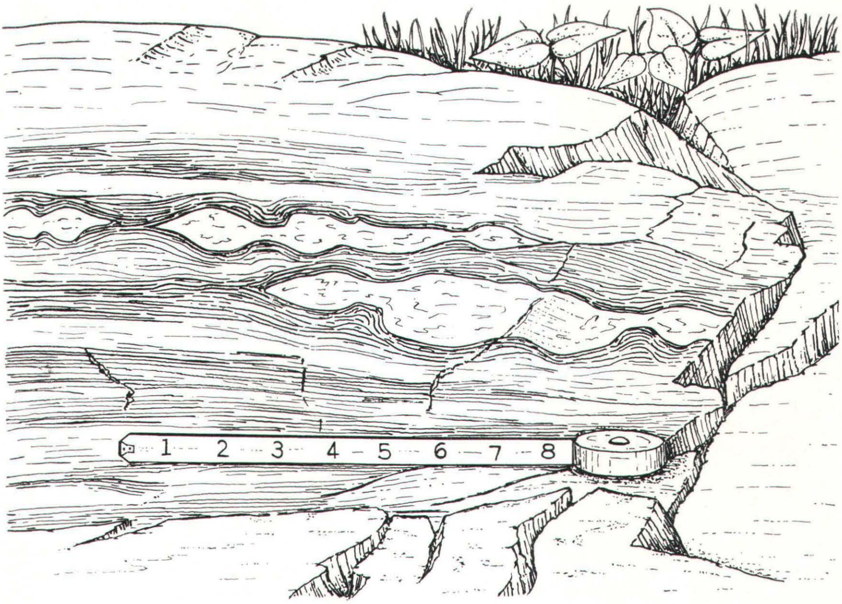

FIGURE 5.—Epidote knots in the Marlboro formation near Vose Pond, Maynard. Dark material is amphibolite schist. (See also fig. 4.)

tions. Completely separated knots commonly are frayed at the ends as though they were torn forcefully apart. Under stress they must have behaved essentially as relatively brittle, competent members, although some measure of plasticity is indicated. Most of them have slightly foliated outer shells that contain hornblende. The less competent surrounding amphibolites have flowed into the areas left by thinning and separation of the epidote beds and now envelop them in blanketlike layers of foliae.

Thin, very elongated lenses of quartz are found in many exposures. These range in thickness from a fraction of an inch to several inches and in length from several inches to several feet. They are present in both the mica schists and in the amphibolites, and they tend to be conformable with the schistosity of these rocks. Most of the lenses occur in fairly well defined zones that commonly are several feet thick and many feet long. Some have been fractured and displaced by minute faults, subsequently healed, and a few seem to have been folded, although they may have been deposited along the foliation planes of already folded rocks. Similar quartz lenses are abundant in the mica schists of the Worcester formation in the Harvard-Bolton area.

Many of the finer grained, hornfelslike amphibolites are characterized by numerous small subhedral metacrysts of microline (fig. 6). Few of these exceed a quarter of an inch across and most of them are

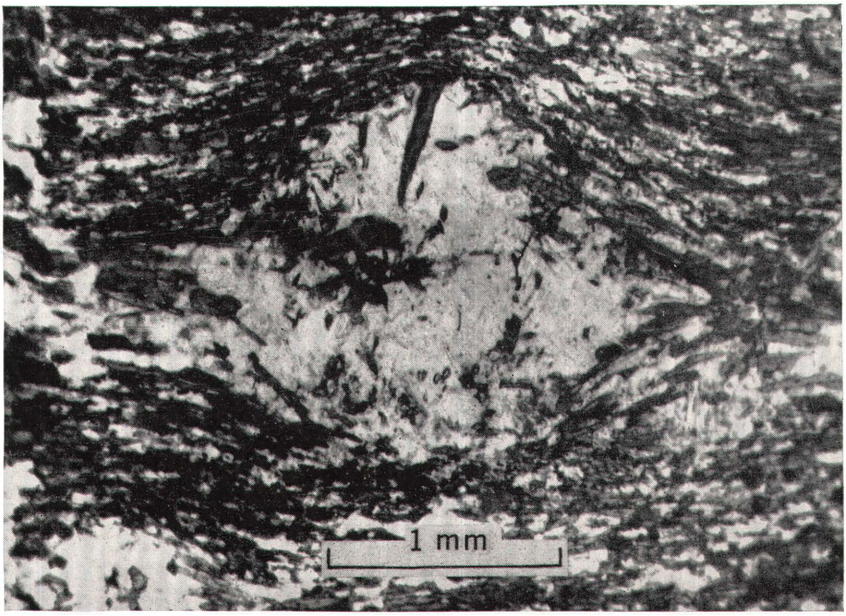

FIGURE 6.—Photomicrograph showing orthoclase metacryst in hornblende schist, Marlboro formation, Sudbury. Contrast with figure 16.

smaller. They impart a pseudoamygdaloidal appearance to some of the denser rocks. Their growth, however, has been subsequent to the development of schistosity in the amphibolite, for the schistosity is partly bent around them, parallel to their edges, and partly truncated by them.

Emerson's assignment (1917, p. 26) of a pre-Cambrian(?) age to the Marlboro formation seems to be based largely upon correlation with similar rocks also believed to be of pre-Cambrian age in the Blackstone valley of Rhode Island. However, no direct tie can be made between the type locality and the Blackstone valley exposures because they are separated by a broad area of pre-Cambrian(?) gneisses and Devonian(?) granites. In the type locality of the Marlboro formation the oldest unit in contact with the Marlboro formation is the Wolfpen tonalite of Devonian(?) age. Because the Wolfpen tonalite is of doubtful age, however, it is of no value in dating the Marlboro formation. Furthermore, Quinn, Ray, and Seymour (1949) have recently abandoned Emerson's use of Marlboro in Rhode Island and have revived the name Blackstone series for the sequence that includes those rocks, as originally used in that area by Shaler, Woodworth, and Foerste (1899, p. 104–109).

If Emerson's correlation of the Marlboro formation with rocks in the Rhode Island area is not valid, little evidence remains to support the hypothesis that the rocks of the type area at Marlboro, Mass., are of pre-Cambrian (?) age. He has tentatively correlated certain rocks of northeastern Massachusetts with the Marlboro, but these "occur for the most part in comparatively small isolated lenses and ovals surrounded by and included in the Paleozoic igneous rocks" (Emerson, 1917, p. 28). He regards them as probably pre-Cambrian "because they are so much more metamorphosed than the Cambrian rocks of the region and appear to have been affected by a deformation to which those rocks were not subjected, and because they are so largely volcanic" (Emerson, 1917, p. 30). In the type area he has mapped Brimfield schist (Carboniferous) overlying Marlboro and stated that "the presence of so much biotite with cordierite and wollastonite indicates metamorphism under great pressure and high temperature, higher than that at which the muscovite schist adjoining on the north was formed, but without mashing or shearing" (Emerson, 1917, p. 25–26). In the Maynard quadrangle, however, such muscovite schists are common in the Marlboro formation and must have been subjected to the same stresses as other rocks in the formation. Moreover, these schists are very similar in lithology and appearance to the mica schist facies of the Worcester formation in the Harvard-Bolton area. The overall difference in appearance between the Marlboro formation and the mica schist of the Harvard-Bolton area, in fact, is due more to differences in relative quantities of various rock types than to lithologic differences. These dissimilarities might easily be ascribed to premetamorphic facies variations within a single formation. Hence, apparent differences of metamorphic grade may be of little significance in dating the age of the Marlboro formation relative to other units in the area.

In the absence of cogent evidence no attempt is made here to revise the status of any part of the Marlboro formation, but the weaknesses of its present correlations should be reviewed and brought into focus. In Sudbury and Concord the Marlboro is invaded by gabbros and diorites that in turn are intruded by a quartz diorite facies of the Dedham granodiorite (Devonian?). Certainly the quartz diorite intrudes these rocks, but some question might be raised as to the validity of its correlation with the Dedham granodiorite and also as to the age of the granodiorite itself. The contact of the Marlboro with younger rocks to the north is not well exposed in the Maynard quadrangle, but in the Marlboro quadrangle to the southwest it is well exposed. Here mica schists of the Marlboro formation are in gradational contact with Gospel Hill gneiss, a highly granitized facies of the Nashoba formation (Carboniferous). In a zone more than 200 feet wide across the strike, mica schists of various thickness and of various degrees of feldspathization alternate conformably with coarse-textured well-foliated granite gneisses. If the quartz diorite in Sudbury is properly correlated with the Dedham granodiorite of eastern Massachusetts, therefore, and if the Dedham granodiorite is actually of Devonian age, or older, an unconformity must once have existed between the Marlboro and the Nashoba formations, and this unconformity must have been obscured by granitization. If, however, the Marlboro and Nashoba formations are conformable—and the only evidence now available suggests that they are—the quartz diorite at Sudbury can hardly be correlated with the Dedham granodiorite unless the Dedham, in turn, is of Carboniferous age or younger. Perhaps the true relationships will be disclosed when detailed mapping has been completed in adjoining quadrangles.

DEVONIAN(?) IGNEOUS ROCKS

Igneous rocks presumably of Devonian age underlie most of Sudbury and parts of adjacent towns in the Maynard quadrangle. These rocks include a quartz diorite, which Emerson (1917, p. 175 and p. 178) regarded as a facies of the Dedham granodiorite, and a previously unmapped complex of gabbros and diorites which are intruded by the quartz diorite, and whose general character and relationships suggest an affinity with the Salem gabbro-diorite of the Boston area.

Although the Dedham granodiorite is exposed over a wider area in eastern Massachusetts than any other formation, opinion as to its age diverges widely. Emerson (1917, p. 172) regarded its age as probably Devonian. La Forge (1932, p. 69), however, believed it to be Ordovician or Silurian, Billings (1929, p. 103) considers it to be pre-Cambrian, and Rhodes and Graves (1931, p. 364) consider it to be probably Devonian. None of these views seems to be supported by positive evidence, and positive evidence is wanting also in the Maynard quadrangle. With reservation, therefore, Emerson's usage is adopted here.

SALEM(?) GABBRO-DIORITE

Salem gabbro-diorite has never been recognized in this area, and direct ties with other areas of known Salem gabbro-diorite apparently do not exist. The assignment here made, therefore, is somewhat questionable, but it is supported by similarities in composition and structural relationships between rocks here called Salem(?) gabbro-diorite and the Salem gabbro-diorite of other areas. Rocks mapped as Salem (?) gabbro-diorite in the Maynard quadrangle are exposed in two irregular strips between outcrops of the Marlboro formation and a central area occupied by a quartz diorite facies of the Dedham granodiorite. These rocks range considerably in texture, composition, and general appearance and may include rocks of more than one lithologic unit, but, owing largely to poor or disconnected exposures, individual relationships are uncertain so that subdivision of them is not feasible. Moreover, considerable textural variations are found even in a single outcrop.

Probably the greater part of the rock is a medium- to coarse-grained hornblende gabbro. Green hornblende, much of it poikilitic, and labradorite are the dominant constituents, magnetite is a prominent accessory mineral, and sulfides are common as minute grains. Some of the rock contains a small amount of microcline. A finer grained facies, containing chiefly hornblende and andesine, is dioritic in composition. In places it is a dense fine-grained almost aphanitic dark rock of ophitic texture and contains abundant magnetite. Generally, because of widely separated exposures, the various rock types cannot be observed in contact with one another. In a few exposures a very coarse grained type crosscuts the others as irregular dikelike masses, but the contacts are so tightly welded and interlocked as to suggest that both rocks solidified at almost the same time. At several places, and in many glacial boulders, such rocks are cut also by dikes of aplite and other light-colored rocks, and in at least one exposure by fine-grained diorite.

Most of the rocks are so greatly altered that many of the feldspar grains can scarcely, if at all, be recognized. Commonly the feldspar is replaced by finely felted sericite, much of the hornblende is partly altered to biotite, and epidote is widely present as veinlets and irregular replacement masses. The sulfides commonly have stained rims of limonite, probably due however to atmospheric weathering. In general, the rocks of this group are closely fractured, and fresh surfaces can be obtained on hand specimens only with some difficulty.

The gabbro-diorites invade the Marlboro formation in a complex and irregular manner. The relationships are best exposed along Dakin Road in North Sudbury, and just west of Water Row Road between Wayland Road and Old Sudbury Road.

At Dakin Road a zone of mixed rocks has a maximum width of about 1,000 feet. Here the intrusion of magmatic material into virtually all available fractures, joints, and openings in the invaded rock has created a complicated network of crosscutting dikes and veins of various sizes, textures, and composition. In places the intrusion has followed the foliation planes of the schist, giving rise to gneissic rocks of the so-called injection type. Sharp contacts exist commonly between the invading and the invaded rocks, but in many places reaction with the wall rocks has caused blurred or gradational boundaries between schist and igneous rock. The invasion, in fact, appears to have been accompanied by extensive soaking of the invaded rocks with magmatic fluids, and in many places the original character of the rock has been largely obliterated by the reaction and recrystallization of the mineral constituents. Thus, biotite gneisses resembling those of the Nashoba formation are common near the outer limits of the mixed zone, but large masses of the Marlboro formation that exhibit little more alteration than a lacelike network of minute veins, nevertheless, lie well within the area of mixed rocks and grade without distinct boundaries into masses of igneouslike, though somewhat foliated, rocks.

Exposures at Water Row Road show much the same conditions as at Dakin Road although the rocks there are less well exposed; there the invasion is so irregular and the replacement is so extensive that for mapping purposes the boundary between the two formations must be arbitrarily drawn. In one exposure about 100 feet long, well-foliated amphibolite grades, through a gradual increase of feldspar accompanied by coarsening of grain size and obliteration of foliation, into a medium-grained rock of dioritic composition—a rock that appears to be igneous but which, as Currier (written communication 1952) points out, satisfies what could be expected of feldspathization of an amphibolite.

QUARTZ DIORITE FACIES OF THE DEDHAM GRANODIORITE

Most of the Dedham granodiorite, as mapped in eastern Massachusetts, is really of granodiorite composition, but several other acid and intermediate varieties are included in the formation. One such variant is the quartz diorite of the Maynard quadrangle. Within this area its outcrops are confined to the town of Sudbury, but, judging from widespread glacial boulders, the formation apparently extends into adjacent towns. As exposed the rock is a medium-grained medium-light-gray faintly foliated quartz diorite composed chiefly of calcic oligoclase and quartz but containing both hornblende and biotite. Some of the plagioclase is zoned and most of it is partly sericitized. The biotite and hornblende are important constitutents and together compose as much as 25 percent of the rock. Orthoclase generally is present in minor amounts and in places is sufficiently abundant to give the rock a pinkish hue. Minor accessory minerals are sphene, apatite, and zircon. Epidote is abundant as veinlets, as encrustations on joint surfaces, and as a secondary mineral replacing hornblende.

Small dikes of pink aplite cut the quartz diorite in many exposures. One-half mile east of Pine Rest, Sudbury, is an unusually large bosslike mass of pinkish-gray to light-orange aplite composed mostly of perthite and quartz with minor amounts of muscovite and biotite. It is crossed by two sets of high-angle joints approximately normal to each other trending roughly northeast and northwest. The latter set is the more prominent. The aplite body seems to cut both the quartz diorite and the gabbro-diorite with steep contacts, although the relationships are not clearly exposed.

Dark sharply angular xenoliths occur in nearly all exposures of quartz-diorite of the Dedham in the Maynard quadrangle, and in countless glacial boulders of the rock. (See fig. 7.) Probably most of these xenoliths have been derived from the adjacent gabbro-diorite. They are sufficiently abundant in most places to form a large portion of the rock and, locally, to constitute plutonic breccias. Most of them are rather small, less than a foot in longest dimension, but some attain considerable size. A spindle-shaped inclusion found in North Sudbury measures 10 by 24 feet. Many of the inclusions are vaguely oriented by a subparallel arrangement of their longer dimensions,

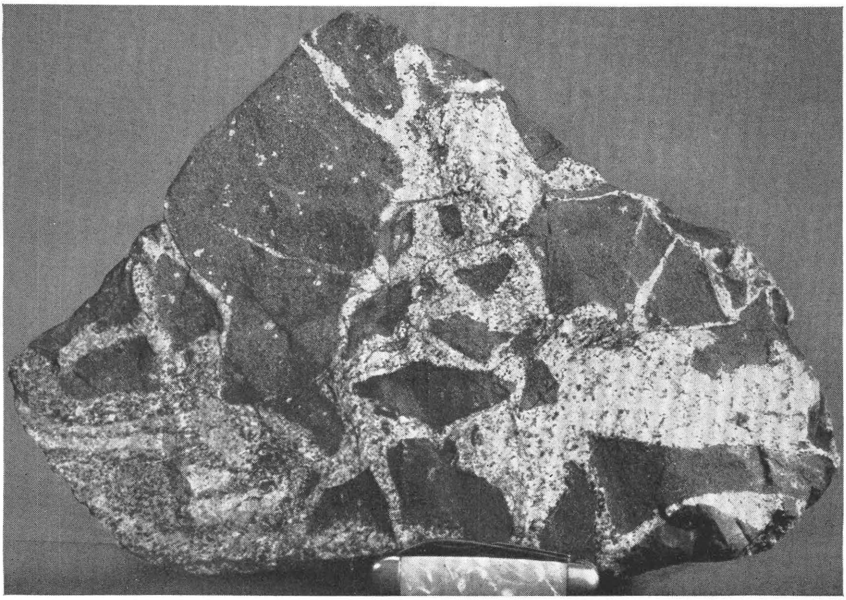

FIGURE 7.—Glacial boulder, from North Sudbury, containing basic xenoliths in a matrix of the quartz.

which in turn tend to parallel the foliation (where discernible) of the quartz diorite. This relationship, which suggests that the foliation is a primary flow structure rather than a secondary structure, is seen better in the numerous boulders than in the less abundant bedrock exposures, which too commonly are covered with lichens. Small apophyses of quartz diorite, moreover, show foliation parallel to their walls, regardless of their orientation with respect to enclosing rocks. In general the xenoliths weather more rapidly than the quartz diorite, so that exposed surfaces of the rock commonly are pitted with saucerlike dark depressions.

Many of the xenoliths have been partly assimilated by the quartz diorite magma. Most of them show biotite selvages at their edges, and biotite partly replaces their original hornblende. Several stages of assimilation may be illustrated by a single exposure, and in advance stages the fragment is hardly more than a shadowlike image in the enclosing rock, its outlines blurred by reaction with the magma.

The ubiquity of the basic xenoliths and their attack by the quartz diorite magma may explain in part the higher basicity of the quartz diorite of this area than of the Dedham granodiorite batholith as a whole.

LATE PALEOZOIC ROCKS

GENERAL FEATURES

Almost the entire Hudson quadrangle and nearly three-quarters of the Maynard quadrangle are underlain by rocks of late Paleozoic age. By far the greater bulk of these consists of Carboniferous metasedimentary rocks of several sorts and of several grades of metamorphism. Late Paleozoic(?) igneous bodies of dimensions mappable on the present scale occupy less than 5 percent of the total area, but over large areas hardly an outcrop exists that does not contain some igneous material in the form of small dikes, intrusive sheets, or irregular masses of granite, aplite, or pegmatite.

The metasedimentary rocks were formed from rocks that apparently were laid down in a continuous uninterrupted sequence of deposition, for they appear to grade from one to another with no stratigraphic breaks. The oldest of these rocks is the Harvard conglomerate lentil of the Worcester formation. It is overlain by the quartzitic Vaughn Hills member (name proposed in this report) of the Worcester formation. The Vaughn Hills is overlain in separate areas by a phyllite facies and a mica schist facies that are considered to be stratigraphically equivalent to each other. The term Brimfield schist was applied by Emerson (1917, p. 18) to the mica schist facies, but, for reasons discussed under the section on the Worcester formation, that designation has been abandoned for this area. Overlying the mica schist facies of the Worcester formation, and more widely distributed than any other unit in the area, is the Nashoba fromation (name proposed in this report), the youngest unit of the group.

Age determination of the Carboniferous metasedimentary rocks rests upon the earlier discovery of Carboniferous fossils in the phyllite facies of Worcester formation. Perry (1885, p. 157) discovered stem fragments of a lepidodendron species in graphitic anthracite at the old Worcester coal mine in the eastern part of Worcester, Mass. Previous to this time the phyllite had been widely regarded as pre-Cambrian, and some geologists, not acknowledging the validity of the fossil, retained this view. Subsequently, however, White (1912, p. 114) not only confirmed the validity and age of Perry's fossil but also discovered better preserved fragments of several varieties of Carboniferous plants in pyritic nodules at the mine.

All the metasedimentary rocks are strongly deformed, and much of their original character has been obliterated by the development of secondary structures. Steep dips, tight folds, and overturning are the rule. For the most part the rocks probably had attained essentially their present attitudes and metamorphic rank before the intrusion of the igneous rocks. It is equally probable, however, that intrusion had begun before deformation had entirely ceased and, furthermore, that widespread, late syntectonic, soaking of the rocks with magmatic fluids preceded actual igneous intrusion. The Nashoba formation particularly was the center of intensive migmatitization, and a broad belt along its southeast margin, the Gospel Hill gneiss, was converted into granite gneiss. Migmatitization died out rapidly, except locally, at the Nashoba-Worcester contact. A high degree of selectivity, effective structural control, or a combination of both factors probably was responsible. Most of the Worcester (mica schist facies) probably was relatively impervious to circulating solutions.

In a smaller but intensive center of migmatitization in the Bare Hill Pond area, parts of the Harvard conglomerate lentil and of the Vaughn Hills member of the Worcester formation have been changed into an igneouslike rock.

The late Paleozoic(?) igneous rocks of the area range in composition from granite to diorite. They occur mostly as very elongate generally concordant bodies that have been intruded essentially parallel to the foliation planes and bedding of the country rocks. Locally, however, they exhibit crosscutting relationships and sharply truncate the invaded rocks. Most extensive in exposed area is the Assabet quartz diorite (name proposed here) which extends southwestward from Concord to Maynard as a long tongue-shaped mass; several smaller bodies of this rock are exposed in parts of Maynard and Stow. More widely distributed, but exposed as much smaller plutons, is a fine-grained moderately foliated granite for which the name Acton granite is proposed. It is most prominent in the town of Acton, but small bodies of it are numerous in Boxborough, Stow, Bolton, and Hudson. Another variety of igneous rock, the Straw Hollow diorite, is exposed in Hudson and extends southward into the Marlboro quadrangle. Still another variety, the Ayer granite, extends southward from the Ayer quadrangle into the town of Harvard northwest of Bare Hill Pond. It is a moderately coarse grained granite that consists of two mappable facies—a porphyritic and a nonporphyritic variety.

CARBONIFEROUS METASEDIMENTARY ROCKS

WORCESTER FORMATION

The name Worcester formation is proposed here to include those rocks of Carboniferous age formerly mapped in this area as Worcester phyllite and Brimfield schist and also a previously unmapped quartzite unit here called the Vaughn Hills member. The Worcester phyllite and Brimfield schist of previous reports dealing with this area are regarded as stratigraphically equivalent metamorphic facies, and the terms "phyllite facies" and "mica schist facies" are suggested for use in this area. This view is shared with the author by R. H. Jahns, L. W. Currier, and M. E. Willard; these geologists have spent much time studying the regional correlations of these units and had largely reached the conclusions drawn here before the author's study was begun. It is further proposed that the term "Brimfield schist" be restricted to those areas where the schist is not known to be equivalent to the Worcester formation. Whether or not the Worcester formation of the Hudson quadrangle and adjoining areas is to be correlated with the Brimfield schist of Emerson's type locality (1917, p. 69) is problematical, for the two areas are separate and the schist is not exposed continuously between them. On the other hand, field evidence supports the correlation of the mica schist facies of this area with the phyllite facies of the Worcester formation.

HARVARD CONGLOMERATE LENTIL

The name Harvard conglomerate was apparently first used by Crosby (1876), who recognized the relationship of this unit to the Worcester formation and regarded the unit as probably a basal conglomerate. Emerson (1917, p. 66) redefined it, applied the name Harvard conglomerate lentil, and selected Pin Hill in the town of Harvard as the type locality. The Harvard conglomerate lentil is exposed discontinuously in the northwestern part of the Hudson quadrangle. The largest area of exposures is on the summit and flanks of the northern of the two Vaughn Hills in Bolton. A second area appears as a narrow belt extending from the type locality southwestward along the northwest side of Bare Hill Pond; it seems to pinch out southward, between Ayer granite and the unnamed gneiss on the west side of Bare Hill Pond. This belt is flanked along its entire length in the Hudson quadrangle by granite on the west and gneiss on the east. A third, poorly exposed belt extends into the Hudson quadrangle from the Ayer quadrangle just west of Prospect Hill road (Jahns, oral communication, 1949); it appears to be truncated on the south by Ayer granite.

The Harvard conglomerate lentil consists of pebbles of several rock types and various sizes in a matrix that is predominantly bluish argillite. The matrix also includes slate, phyllite, chlorite schist, and gritty quartzite. Most of the pebbles are quartzites of various shades of pale green, violet, gray, and blue gray. According to Jahns (oral communication, 1949) these quartzites are lithologically the same as quartzite beds in the Merrimack quartzite of the Lowell area. Other pebbles are composed of slate, phyllite, chlorite schist, and milky quartz. Some of the pebbles exceed 4 inches in length, but most of them are much smaller. The pebbles range from sharply angular to well rounded. Most of them are somewhat tabular, and these commonly lie with their flat surfaces approximately parallel to the bedding planes.

The conglomerate occurs as well-defined generally lenticular beds that range in thickness from a few inches to several feet. The beds are interlayered with, and grade into, coarse-grained quartzites or grits, and into pebble-free beds of slate, phyllite, and chlorite schist that are similar in appearance and lithology to beds of the phyllite facies of the formation. Pebble-free beds are predominantly bluish, but shades of gray, cream, and light olive green are common.

The Harvard lentil, together with the other metasedimentary rocks of the area, has been deformed strongly, and the relatively great width of its outcrop belt at the Vaughn Hills area undoubtedly is due in part to multiple folding. Myriads of folds, which range from minute wrinkles to structures several feet across, are shown by almost every outcrop. These are especially well shown by those outcrops that contain pebble-free material. The conglomerate beds, because of their greater competence, are somewhat less severely deformed and are folded into broader, more open structures, and many of the pebbles in them are only moderately deformed, few of them being greatly elongated. A slaty cleavage parallel to the axes of the minor folds occurs in the pebble-free material but is rare in the conglomerate beds. (See figs. 8, 9.)

Most exposures of the Harvard conglomerate lentil contain abundant quartz veins. Many of these veins predate the deformation of the beds; some, however, are undeformed, cut across the folded structures, and must have been deposited after deformation had ceased. On the northwest side of Bare Hill Pond near the Ayer granite, quartz veins are extremely abundant in the Harvard.

Emerson (1917, p. 66) suggested that the Harvard lentil is a tillite and compared it with the Squantum tillite member of Roxbury conglomerate of the Boston area. He regarded the angular character of many of the pebbles and the argillaceous nature of the matrix to be indicative of tillite. Overall, however, the conglomerate beds seem to be better sorted and better stratified than he suggested, and boulders, which one might expect to find in stony tillite, are conspicuously lack-

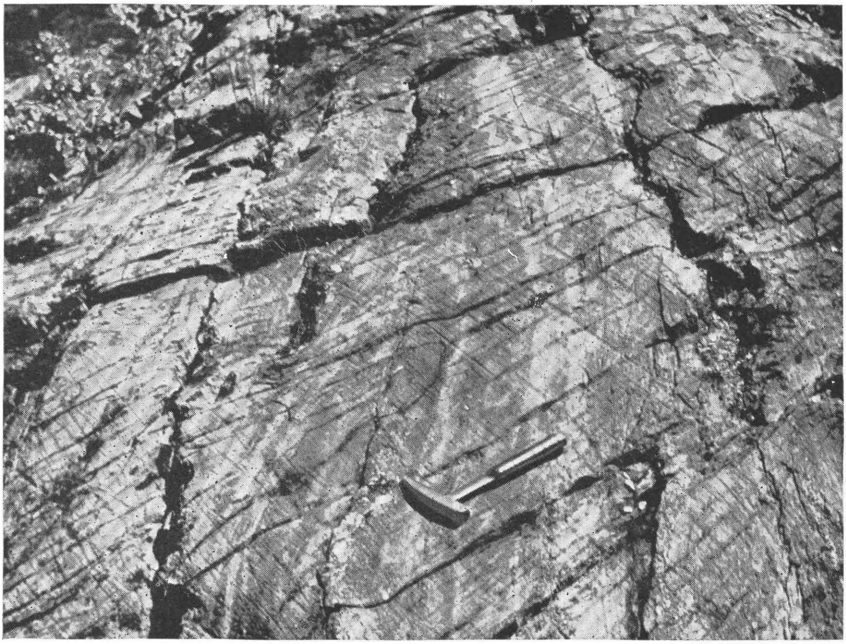

FIGURE 8.—Slaty material in the Harvard conglomerate lentil at north Vaughn Hill, Bolton, Bedding trends from front to rear of picture. Fracture cleavage is parallel to handle of hammer. Glacial striations trend from upper left to lower right corner of picture.

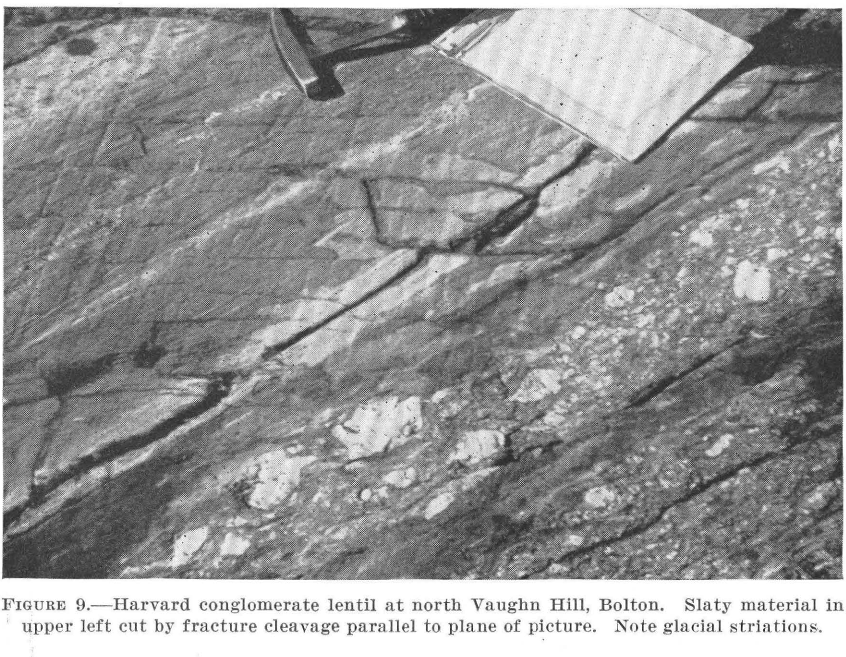

FIGURE 9.—Harvard conglomerate lentil at north Vaughn Hill, Bolton. Slaty material in upper left cut by fracture cleavage parallel to plane of picture. Note glacial striations.

ing. The stratified character of the conglomerates, and their interbedding with and gradation into finely laminated pebble-free beds seem incompatible with ice deposition. These features suggest a water-laid, perhaps littoral origin, rather than a glacial origin. Furthermore, the Harvard is probably a basal conglomerate, as first suggested by Crosby (1876), for if it contains pebbles derived from the Merrimack quartzite, as suggested by Jahns (oral communication, 1949), an erosion interval is indicated after the deposition of the Merrimack quartzite and before the deposition of the Harvard conglomerate lentil.

VAUGHN HILLS MEMBER

The name Vaughn Hills member of Worcester formation is proposed here for those predominantly quartzitic rocks, previously undifferentiated, that lie at the base of the mica schist facies of the Worcester formation in the Harvard and Bolton area and are believed by the writer to lie also at the base of the phyllite facies of the Worcester formation in this area. These rocks also grade laterally into the phyllite facies near the village of Still River.

The Vaughn Hills member is best exposed, and appears to be thickest, on the southern of the two Vaughn Hills (locality from which member was named) in the town of Bolton. From there it extends northeast along the east side of Bare Hill Pond into the Ayer quadrangle, where it becomes increasingly schistose and is distinguished from the mica schist facies only with some difficulty. According to Jahns it thins out to the northeast at least 8 miles from the Vaughn Hills. West and northwest of the Vaughn Hills it grades into the phyllite facies of the Worcester formation and seems to finger out in the vicinity of Still River. Unfortunately this area is thickly mantled with glacial deposits, but, although bedrock exposures are not numerous, the interfingering of quartzitic material with phyllitic material is clearly shown in several outcrops. North of Still River the Vaughn Hills member cannot be distinguished.

On the southern of the two Vaughn Hills the rock is predominantly a very fine grained thinly bedded cream- to flesh-colored quartzite that is interbedded with cream-colored to pale-green phyllitic layers composed predominantly of sericite. Bedding-plane surfaces, freshly exposed, commonly have a pearly luster. Some of the weathered surfaces are mottled rusty brown, owing to oxidation of iron-bearing minerals, especially pyrite. The rock is strongly deformed, displaying countless minor crenulations and, in the phyllitic layers, a prominent axial plane cleavage (figs. 10, 11). Fracture cleavage occurs in some of the quartzite beds but more commonly is lacking.

Northeastward from the Vaughn Hills the proportion of quartzitic material decreases along the strike, and the quartzitic beds are in-

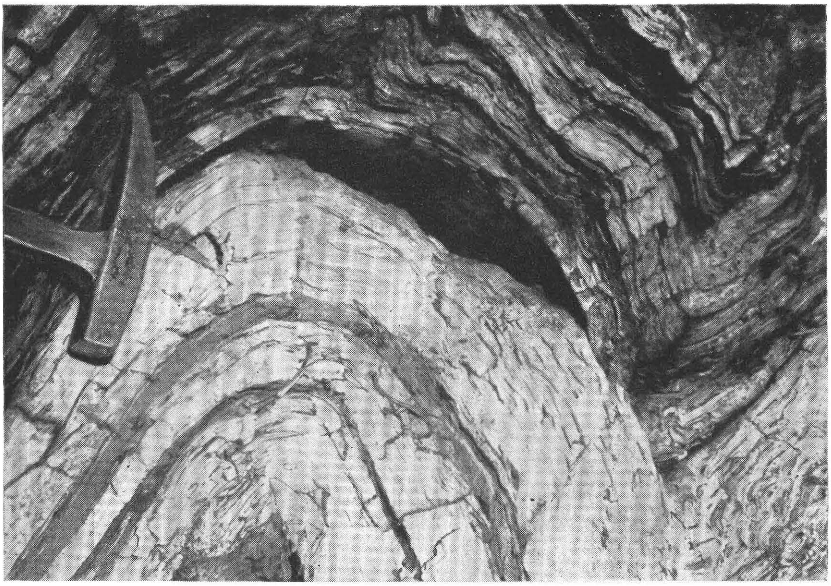

FIGURE 10.—Minor folding in quartzite of the Vaughn Hills member near Vaughn Hill Road, Bolton. Fracture cleavage inconspicuous. Dark patch is shadow cast by overhanging beds; it is not an opening in the rock.

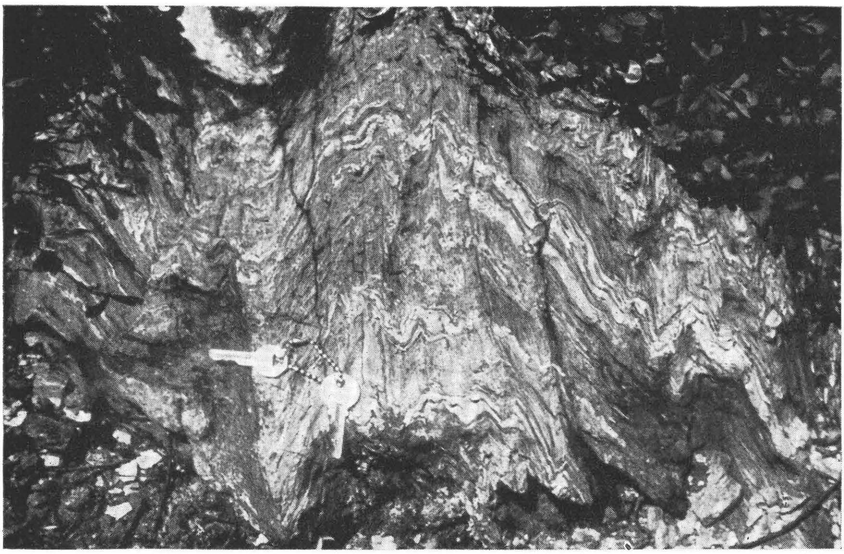

FIGURE 11.—Wrinkling and axial plane cleavage in quartzite of the Vaughn Hills member at south Vaughn Hill.

creasingly thinner and less continuous. Eastward across the strike, and rising stratigraphically in the section, the proportion of quartzitic material similarly decreases as the rock grades into mica schist. Near Green Road in Bolton the gradation southeastward across the strike from the Vaughn Hills member into mica schist is fairly well exposed and is rather abrupt, but east of Bowers Brook and Bare Hill Pond in Harvard, the boundary is less easily defined, owing to a greater cover of ground moraine and to fewer bedrock exposures.

To the west the Vaughn Hills member grades into the phyllite facies of the Worcester formation. Its interlayering with typical phyllite of the Worcester is well displayed just west of Vaughn Hill Road in the Clinton quadrangle. East of Still River Road the boundary between the Vaughn Hills member and the phyllite facies is somewhat arbitrarily drawn, owing again to the widespread mantle of ground moraine and to the sparseness of outcrops.

Dark-gray to dull-greenish-gray chlorite schist occurs at the base of the Vaughn Hills member adjacent to the migmatite on the east side of Bare Hill Pond. This schist is shown separately on the map. It is similar in appearance to pebble-free chloritic layers in the Harvard conglomerate lentil. In part it is well laminated and contains thin calcareous layers that appear to represent original bedding. In other places the bedding has been completely obliterated. This chlorite schist seems to be thickest near the north end of Bare Hill Pond, tapering out both to the northeast and to the southwest. Owing to inadequate exposure its full lateral extent is not known. Other smaller masses of chloritic material, which appear to be minor lenses not more than a few yards wide, crop out irregularly at many places in the Vaughn Hills member and are exposed as far south as Green Road in Bolton.

The contact of the chlorite schist with the migmatite at Bare Hill Pond is comparatively sharp in some places, but in others there is a broad transition zone. Small masses of schist having the same orientation as the main body of schist lie well within the migmatite at many localities. Near the migmatite the schist commonly contains abundant metacrysts of feldspar, and nearly all gradations can be found from chlorite schist free of added feldspar to typical granitic migmatite.

PHYLLITE FACIES

In these quadrangles the phyllite facies of the Worcester formation is limited to a small area surrounding the village of Still River in the northwestern corner of the Hudson quadrangle. It is well exposed in many outcrops north of Still River near the boundary between the Hudson and Ayer quadrangles, but elsewhere it is largely covered by glacial deposits. As exposed in this area the unit is perhaps more properly called a slate or even an argillite than a phyllite, for, although it commonly is tightly folded and possesses a slaty cleavage, it tends to split more readily along its bedding planes than along its cleavage planes. (See fig. 24.) Locally it splits in both directions with approximately equal facility, and loosened fragments have an elongated, prismatic shape.

Its most characteristic color is dull bluish gray, but it ranges through pale rusty brown to yellowish green. Some surfaces have a satiny luster; others are almost pearly where slippage between beds has produced slickensides.

The rock originally was an impure sandy shale. It contains abundant thin laminae of sandy material, and locally, cream-colored quartzite layers similar to those of the Vaughn Hills member of the formation.

Although its contacts are concealed, the phyllite facies appears to grade downward into the Harvard conglomerate and laterally, through an increase in metamorphism, into the mica schist facies.

MICA SCHIST FACIES

In the Hudson quadrangle the mica schist facies of the Worcester formation is exposed in a broad belt that extends southwestward from the Ayer quadrangle diagonally across the Hudson quadrangle through Harvard and Bolton into the Clinton quadrangle near the center of the boundary between the Hudson and Clinton quadrangles. It forms the crest of the long ridge of Bare Hill in Harvard, as well as of Wataquadock Hill, the southwesterly extension of this ridge in Bolton. Exposures are larger and more numerous on the steep southeast slopes of these hills than on the summits or northwest slopes. The minimum thickness of the mica schist facies in Bolton, barring possible structural repetition, is about 2,000 feet; it thickens appreciably toward the northeast in Harvard.

As typically exposed in the Hudson quadrangle the larger part of this facies is a moderately coarse grained muscovite schist that commonly contains abundant quartz and pyrite and minor but, locally, considerable biotite, andalusite, and sillimanite. It weathers rapidly on exposed surfaces, and most of the outcrops are stained deeply by rusty oxidation products of pyrite. Freshly exposed, the rock is commonly light gray and owes its pearly luster to the predominance of muscovite. Most shallow cuts, however, do not extend through the weathered zone.

Toward the west, and hence stratigraphically downward in the section, the mica schist facies grades into the quartzitic Vaughn Hills member. Thin quartzite beds, in fact, are widely distributed throughout the unit. These mostly are of fine grain, are not more than a few inches in thickness, and cannot be traced for more than a few yards.

The metamorphic grade of the mica schist facies increases across the strike from west to east. Near its contact with the Vaughn Hills member the rock is essentially a fine-grained somewhat sandy phyllite that is much deformed and sheared but clearly exhibits its original bedding. The grain size of the rock, due to recrystallization, is progressively coarser toward the east. Near its contact with the Nashoba formation metacrysts of muscovite attain diameters in excess of an eighth of an inch, and the original bedding is largely obscured. Most of the muscovite flakes are parallel to the plane of schistosity, but some are randomly oriented and occur as wafer-shaped crystals whose sides are parallel to the plane of schistosity but whose basal plates in some instances are nearly normal to the plane of schistosity.

Near the middle of the facies is a zone of andalusite-bearing mica schist that extends the entire length of the formation in the Hudson quadrangle. Because of the sparseness of outcrops the width of this zone cannot be accurately measured, but it is at least 600 feet wide in places and probably has very indefinite boundaries. Small metacrysts of andalusite are displayed by most outcrops along Bolton Road south of Slough Road in Harvard; clear, pink crystals in irregular knots as large as 6 inches across occur locally, as in those outcrops just west of the intersection of Harvard Road and Green Road in Bolton. Well-crystallized prisms of chiastolite, somewhat crushed and now largely sericitized, are found in some outcrops.

Southeastward across the strike the andalusite-bearing zone grades into a zone of sillimanite-bearing mica schist that extends to the Nashoba formation boundary. The sillimanite occurs mostly as localized, thin-matted layers of minute needlelike crystals that lie in the plane of schistosity. Sillimanite also is common in parts of the Nashoba formation.

Concordant lenses of hydrothermal quartz are abundant in the mica schist, particularly in the upper part of the unit. These rarely exceed an inch in thickness, but commonly are several inches to several feet in length. The quartz is massive and vitreous; commonly it is rusty brown owing to staining by iron oxides from the weathered schist. Crosscutting veins and irregular masses of quartz also are abundant.

Pegmatite bodies abound in the upper half of the mica schist facies. A few of these are discordant, crosscut the schist at wide angles, and appear to be intrusive. Many, however, are concordant and probably are of metasomatic origin; these commonly possess a moderate foliated structure that is caused by a subparallel arrangement of coarse biotite flakes in wavy wisps. This foliated structure is con-

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formable with the schistosity of the country rock, and, althongh contacts are rarely exposed, foliated pegmatites are seen locally to grade into schist, through a transition zone of so-called injection gneiss. In places long oriented stringerlike inclusions of schist lie well within the pegmatite mass. The foliated structures, the vague or indefinite contacts, and the relict inclusions together suggest a metasomatic origin, and the schistosity of the country rock probably acted in large part as paths of access for the invasion of replacing solutions.

The pegmatites in the mica schist facies of the Worcester formation in the Hudson quadrangle contain few unusual minerals. Microcline, quartz, and mica (chiefly muscovite) are the chief constituents, perthite is common, and garnet is a usual accessory mineral. Some of the pegmatites also contain crystals of black tourmaline as much as half an inch in length, and, more rarely, small prisms of pale-green beryl. Books of muscovite locally exceed 4 inches across, but most of them are smaller.

Several beds of amphibolite schist are exposed near Woodchuck Hill Road in Harvard within the upper third of the mica schist facies. Because they are rarely well exposed, occurring mostly in single outcrops only or in scattered groups of closely spaced outcrops, their extent along the strike is unknown. Some amphibolite bodies, however, appear to be wide—perhaps more than 100 feet—and these bodies probably extend at least several hundred feet along the strike.

Between the mica schist facies and the Nashoba formation is a wide, remarkably continuous transition zone of amphibolitic beds. This zone is traceable northeastward through the Ayer quadrangle (Jahns, oral communication, 1949) and southwestward into the Clinton quadrangle; it may extend still farther, into the Shrewsbury quadrangle, and prove to be identical with part of the Straw Hollow diorite as mapped by Emerson (1917, pl. x). In the Hudson quadrangle this zone has a mean width of about 450 feet and a maximum width of more than 500 feet; it is narrowest in the areas between Nourse Road and Harvard Road in Bolton, where its minimum width is about 200 feet. The rocks of the amphibolitic zone are predominantly quartz-hornblende schist but they range from actinolite, chlorite, and biotite schists to moderately coarse grained gneissic types of dioritic composition composed of approximately equant grains of hornblende as large as one-fourth inch across and with ragged edges, in a matrix of interlocking hornblende, quartz, and andesine. Apatite, magnetite, and sphene are common accessory minerals. Other rocks are of gabbroic composition, are composed mostly of pyroxene, and contain finely disseminated sulfides, probably pyrite.

The amphibolite zone grades into the mica schist facies of the Worcester formation at its base and into the Nashoba formation at its top; it contains interbedded mica schists of the Worcester formation type as well as biotite gneiss of the Nashoba type. In the Hudson quadrangle interbedded mica schists are far more abundant than are biotite gneisses, but in the Ayer quadrangle Jahns (oral communication, 1949) found that gneisses predominate. Probably, therefore, the zone cannot properly be assigned to either formation, but for convenience of presentation they are referred to the Nashoba formation in this report. Moreover, some interbedding of Worcester and Nashoba types extends beyond both the upper and the lower limits of the zone as mapped. Biotite gneiss, for example, is exposed locally near the top of the Worcester mica schist facies below the base of the mapped zone, and mica schist is exposed locally in the Nashoba formation above the top of the zone.

The origin of the amphibolites is not clear. Some workers regard such rocks to be generally of igneous origin, either volcanic or intrusive. Many amphibolites certainly have such an origin, and some of the amphibolites of this zone are igneouslike in appearance. Emerson (1917, p. 219) regarded similar rocks of the Worcester and Shrewsbury area as intrusive, probably differentiates or border variants of the Andover granite, and as "probably owing their character in some way to their relationship to the Brimfield schist." In the Hudson quadrangle, however, the amphibolite zone is remote from any exposed bodies of Andover granite. The nearest large body of intrusive rock is the Ayer granite in Harvard, but this granite and the many small bodies of fine-grained granite in the Nashoba formation are clearly younger than the amphibolites. The amphibolites and the rocks into which they grade antedate the major deformation of the formations, whereas the granites postdate the deformation, or at least were emplaced in its waning stages. Moreover, except that some of the rocks resemble plutonic igneous rocks, clear evidence of an intrusive origin is lacking. Crosscutting relationships have not been observed; on the contrary, the rocks are everywhere concordant, and contacts commonly are completely gradational. By a gradual increase of mica and a decrease of hornblende the rocks grade into mica schist, and by an increase of feldspar and biotite they grade through hornblende gneiss into biotite gneiss. It is difficult to attribute such graduations to simple igneous intrusion. If the rocks were originally of igneous origin, they probably were volcanic and formed first as interbedded basaltic tuffs, perhaps in part as interbedded flows. Any primary volcanic structures that may have existed, if ever present, have not survived metamorphism.

Because of the variations in composition, the structural relations, and the gradational features, it seems more probable that the rocks were derived from impure magnesian limestones, limy sandstones, or limy shales. To be so derived, little material needs to be added to or subtracted from the original rock, and the presence of abundant quartz in such otherwise basic rocks as hornblende schist is readily rationalized. Some additional iron and alumina may be required, and carbonate must be removed, but most of the constituents—the lime, magnesia, and silica—are already available and need only to be combined into new minerals. Such a change, resulting from hydrothermal invasion, is entirely compatible with present concepts of metamorphism of the area (Currier, 1938, p. 168 and 1947, p. 77). Magnesian marbles, some of which are very sandy, occur in the adjacent Nashoba formation; amphibolites that contain abundant primary calcite, and that are clearly derived from limestones (fig. 12), are fairly common, particularly in Boxborough.

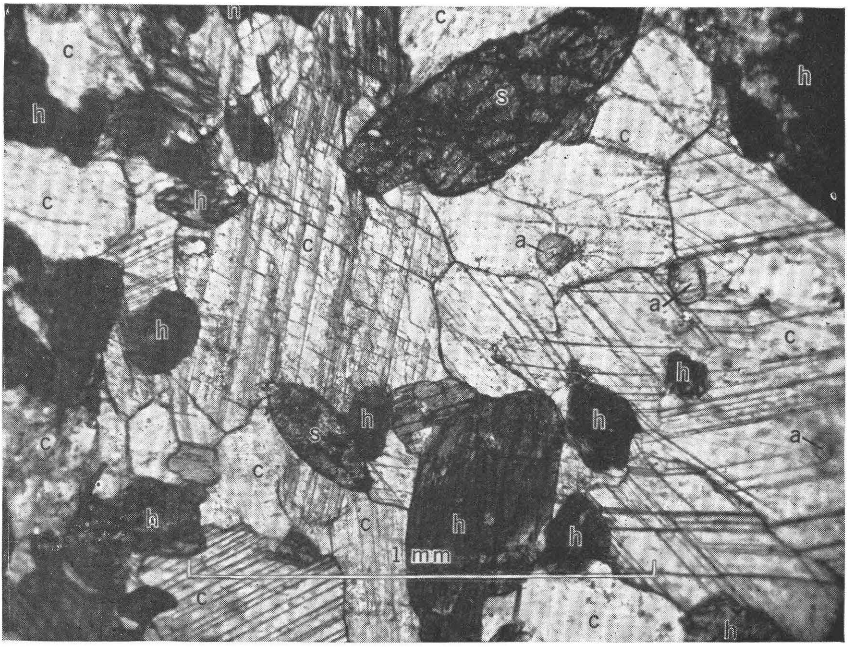

FIGURE 12.—Photomicrograph of hornblende marble, Sherry Road, Boxborough. c, calcite; h, hornblende; s, sphene; a, apatite.

At several places, but best exposed between Nourse and Harvard Roads in Bolton, are beds of light-colored moderately coarse textured very strongly foliated muscovite gneiss. These beds differ markedly in appearance from the gneisses of the Nashoba formation chiefly because of their relatively scant content of biotite and quartz and their relatively high content of feldspar. Albite, microcline, and muscovite (fig. 13) are the principal constituents. Apatite and sillimanite

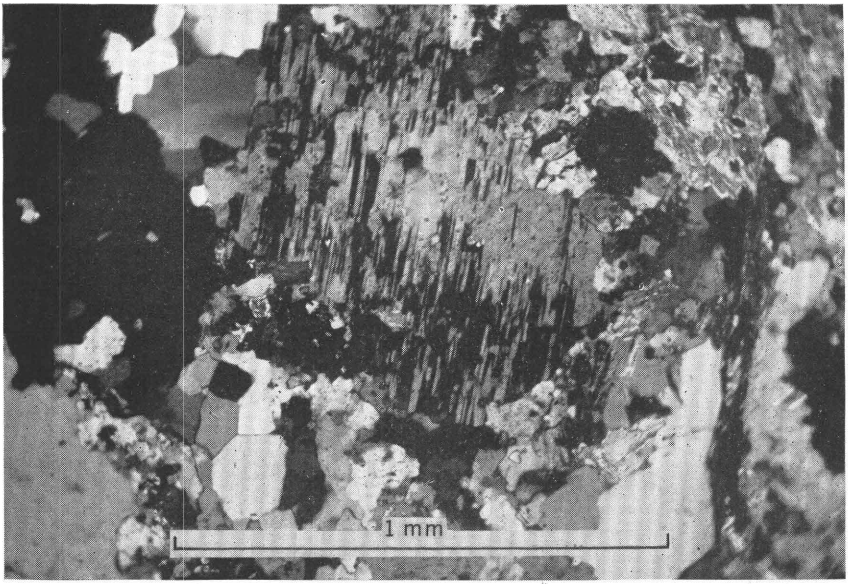

FIGURE 13.—Photomicrograph showing albite porphyroblast tending toward chessboard structure, in quartz mica gneiss near Norse Road, Bolton.

are minor accessory minerals. Ovoid porphyroblasts of microcline are common and attain considerable size, as much as an inch in length. The rocks grade locally into pegmatite and coarse granulite. Probably they originally were muscovite schists and were essentially like other muscovite schists that remain unfeldspathized in the amphibolite zone. Probably also these gneisses have been feldspathized by the same solutions that altered the Nashoba formation to its present character, and that may have converted limestone into amphibolite.

There is much evidence of hydrothermal activity in the amphibolite zone. Pegmatites commonly similar to those in the Brimfield schist are exposed throughout its length. Quartz veins and lenses are also common.

NASHOBA FORMATION

The name Nashoba formation is proposed for a great mass of metamorphic rocks of Carboniferous age that extends northeastward across east-central Massachusetts almost from Connecticut to New Hampshire. The name is proposed because of the occurrence and good exposure of these rocks in the valley of Nashoba Brook in the Maynard and Westford quadrangles. They are probably best exposed in the town of Bolton, and the name Bolton gneiss was originally applied to them by Emerson (1917, p. 81); he abandoned this appropriate name, however, as it had been preoccupied for a different formation elsewhere.

In the Hudson and Maynard quadrangles the Nashoba formation underlies a wider area than all other formations combined. The great width of its outcrop belt undoubtedly is due partly to multiple folding (fig. 22), although the details of its complicated structure have not been fully solved. Its thickness may well exceed 5,000 feet.

The formation is composed chiefly of biotite gneiss but contains also biotite schist, numerous interbedded layers of amphibolite schist, hornblende gneiss, quartzite beds that are largely feldspathized, and a few beds of marble. It also contains abundant masses of pegmatite and veins of quartz. A thick series of rocks on its southeast margin, for which the name the Gospel Hill gneiss is proposed in this report, has been strongly granitized. The Nashoba formation is the youngest metasedimentary rock in the area. It grades downward into the mica schist facies of the Worcester formation through an amphibolitic transition zone already described.

BIOTITE GNEISS

These beds are predominantly hard medium-grained light- to medium-gray paragneiss composed chiefly of quartz, biotite, and sodic plagioclase. Increased proportions of biotite in places make the rock dark gray and more schistose. Magnetite is disseminated widely as minute irregular grains and locally is sufficiently concentrated to strongly deflect the compass needle. Originally the rocks were impure sandstones, probably sandy shales in part; locally, they exhibit well-preserved original bedding. Individual grains of quartz sand as much as a millimeter in diameter, some of them well rounded, may be observed in places with the unaided eye or with a hand lens. These are especially prominent on weathered edges of the rock, where they are etched into relief by decomposition of the micas and feldspars. A pronounced gneissic banding, caused largely by introduced feldspar, parallels and accentuates the bedding. Some feldspar grains are surrounded by myrmekitic intergrowths. Most of the rocks are well foliated, owing chiefly to a preferred orientation of the micas parallel to the bedding. Muscovite is common and locally is conspicuous where it forms thin, shiny laminae of flaky plates as much as a quarter of an inch across. In places, the bedding is obscured completely because of strong folding and shearing that was followed by intensive feldspathization; occasionally preserved are the noses of minor isoclinal folds, a few or several inches across, composed of amphibolite or quartzite beds in a strongly foliated coarse-textured gneiss. Axial planes of the folds are mostly parallel to the foliation of the gneiss, but some have been rotated out of this orientation.

Grains of potash feldspar that formed late in the general feldspathization are prominent constituents of many of the rocks. They occur as thin layers along the bedding planes and as randomly oriented subhedral metacrysts, some an inch long or more, that are sufficiently abundant in places to cause pseudoporphyritic textures. Irregular knots of pink microcline, several inches across, grade into lenses and pods of pegmatite.

Garnet, sillimanite, and apatite are widely distributed, apparently without any broad zonal arrangement. Garnet is most plentiful in the more biotitic layers, commonly as small metacrysts less than a quarter of an inch across, but some crystals are as much as an inch across. Garnet occurs also as continuous beds of massive garnet rock, as at Pine Hill in Bolton where such beds are associated with amphibolite and can be traced for several hundred feet. Sillimanite occurs as minute needlelike crystals in fibrous, salmon pink, or pearly gray mats that lie in the planes of foliation and commonly show a pronounced linear structure caused by alinement of the individual needles. Sillimanite and garnet commonly occur together. (See fig. 14.)

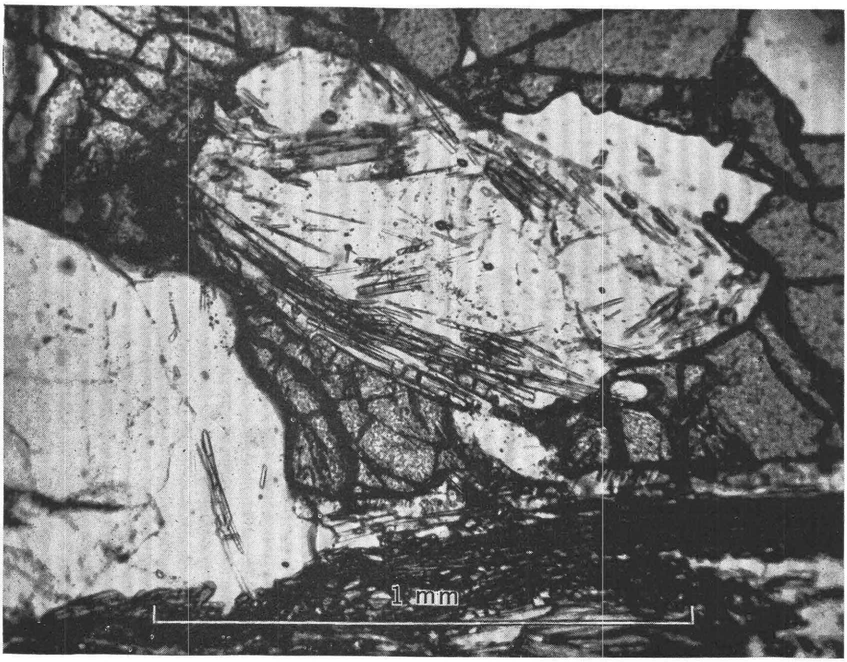

FIGURE 14.—Photomicrograph of sillimanite needles in gneiss from Nashoba formation near Rocky Dundee Road, Berlin. Gray mineral with high relief is garnet. Light mineral is quartz.

The beds of biotite gneiss are usually well jointed. Most prominent is a set of nearly vertical cross joints, although some exposures display low-angle joints and locally, high-angle obliques joints (fig. 15).

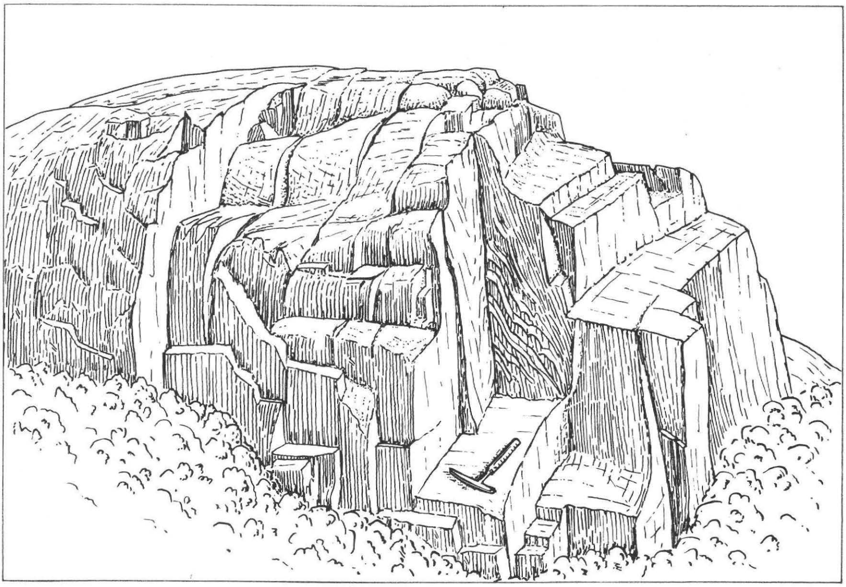

FIGURE 15.—Cross joints exposed in plucked lee end of roche moutonnée near Rocky Dundee Road, Berlin. Foliation planes (shaded) face the observer. Ice moved from left to right.

The rocks tend to break into tabular slabs bounded by foliation planes and joint surfaces. They are drilled with difficulty and tend to shatter on blasting. Owing to great bearing strength they will stand unsupported in vertical cuts. Weathering is confined mostly to minor oxidation on exposed surfaces and along joints.

Because of their gradation into biotite gneiss both along and across the strike, quartzite beds cannot be traced for any great distance in the Nashoba formation, and hence it is not practicable to map them separately. They are well displayed in many places, however, especially in parts of Bolton and Berlin. Well-preserved quartzite beds are uncommon in the Maynard quadrangle where in general the feldspathization is more intense; there they occur chiefly as small, lenticular masses, and in the sheared-off noses of small, plunging folds surrounded by coarse-textured gneiss. Between Rattlesnake Hill and Sugar Road in Bolton, large outcrops have been sharpened by glacial plucking along prominent cross joints; here the rocks are strongly deformed, and myriads of minor folds are exposed on every joint face. Despite moderate feldspathization, details of original bedding are well preserved.

A distinctive, fine-grained blue-gray quartzite is exposed at a few localities in Bolton and Harvard. It contains scattered well-rounded grains of apparently detrital oligoclase (fig. 16) in a matrix of quartz and biotite grains. The biotite, visible only under the microscope,

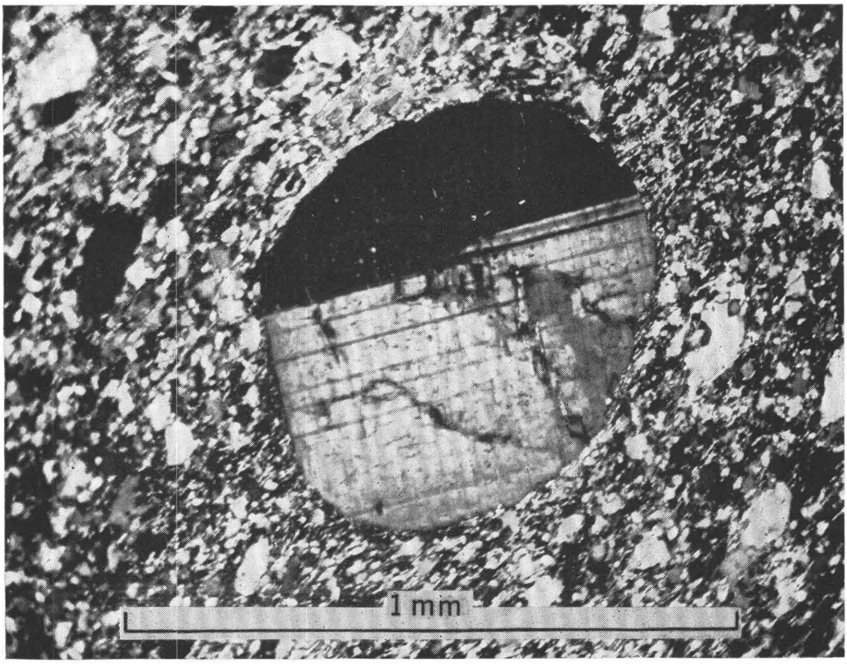

FIGURE 16.—Photomicrograph showing rounded plagioclase grain in fine-grained quartzite from the Nashoba formation, Bolton. Plagioclase grain appears to be relict.

gives the rock its dark color. Calcite and apatite are minor constituents. Although the feldspar grains in this rock appear to be detrital sedimentary grains, the rock grades laterally into rocks that contain introduced feldspar.

AMPHIBOLITE

Most large exposures of the Nashoba formation contain some amphibolite, either as short, discontinuous lenses or as thin, more continuous beds. The greater bulk of the amphibolite, however, occurs in rather well-defined stratigraphic zones in which it is a prominent if not predominant rock type. Individual beds in these zones do not appear to extend very far but seem instead to thin out, mostly in a few tens of yards or less. They range in thickness from a fraction of an inch to several feet, and commonly they are interbedded with biotite gneiss. Contracts are mostly gradational, although in places they are very sharp.

Most extensive of the amphibolite zones in the area mapped is one that crops out from the northeast corner of the Maynard quadrangle to South Acton. This zone includes considerable interbedded biotite gneiss and hornblende gneiss. Its southwestern limit is poorly exposed and may extend farther than is shown on the map—perhaps to Stow but probably not so far as the boundary between the Maynard and Hudson quadrangles. Many smaller bodies of amphibolite are also exposed in Acton and these too may be more extensive than could be shown on the map, because of the widespread cover of glacial deposits.

Strongly schistose, mostly fine grained, varieties predominate, and hornblende is the chief constituent. Most of the hornblende crystals are oriented randomly in the plane of schistosity, but locally a pronounced linear structure is caused by parallelism of their long axes. Quartz and feldspar vary widely in their proportions from place to place. The quartz is mostly detrital, forming in places distinct quartzitic beds, or laminae; the feldspar has been introduced, and through its increase the rock grades into hornblende gneiss. Biotite commonly replaces hornblende as a secondary mineral. Magnetite is very widespread, and apatite is a common accessory mineral. Some of the rocks are actinolitic.

The large amphibolite mass that is well exposed along Sherry Road, in Boxborough, is distinctive in that in many places it contains abundant recrystallized calcite apparently derived from limestone. These calcareous beds are easily identified in the field by pitted surfaces and small saucerlike solution cavities. They bubble vigorously in dilute acid. Some beds grade into impure marble (fig. 12) that contains minute grains of hornblende, zoisite, sphene, apatite, and brown mica. Some of the rocks along Sherry Road are not foliated, but they possess a very pronounced lineation caused less by orientation of the individual grains than by segregation of the grains into streaks. Other beds, more amphibolitic and less calcareous, are well foliated and have equally strong linear structures caused by streaking or mineral alinement, or both, and by wrinkling of the beds into myriads of minute folds. The various linear elements are parallel to the minor fold axes.

Many small masses of amphibolite have igneouslike textures although an igneous origin is not necessarily indicated. Some occur as short, thick lenses, dark greenish gray to almost black, are of dense, diabasic texture, and contain randomly oriented, lath-shaped feldspars. Other amphibolite bodies are tabular; one such body, at the intersection of Great and Delaney Roads on the Bolton-Stow town line, has interlocking poikilitic black hornblende crystals nearly half an inch long and sphene and apatite in subhedral grains. The hornblende crystals are partly replaced by biotite and contain small grains of andesine and diopside, the latter mineral being partly replaced by actinolite. The presence of diopside suggests a derivation from limestone.

Intense regional migmatitization leads to a compositional convergence, so that rocks of diverse origin tend to resemble one another in appearance and composition. The origin of the bulk of the amphibolites in the Nashoba formation, therefore, like the origin of those that border the formation on the west, is largely conjectural. Many are derivatives of limestone, but the possibility that some are of volcanic origin cannot be summarily dismissed. In a thick sequence of rapidly accumulating sandy and argillaceous sediments, limestones or limy shales and limy sandstones might be expected to accumulate and, in the case of the Nashoba formation, did accumulate. All these known calcareous rocks have since completely recrystallized; some were converted to marble and others apparently, and in varying proportions, to amphibolite. For want of clear evidence of igneous origin all amphibolites in the formation might be regarded as derivatives from limestone beds. Some of the amphibolites have textures similar to those of igneous rocks, but descriptions of such textures that have resulted from metamorphism are common in geologic literature. Where rocks of such textures prevail in the Nashoba formation, moreover, field relationships in most instances rule out the possibility of intrusive origin, as pointed out earlier, and the textures, therefore, must be secondary. Volcanic rocks, however, some of probable Carboniferous age, occupy large areas of the Boston basin and parts of the Narragansett basin, as noted by La Forge (1932, p. 29), and it is reasonable to assume that similar rocks might have accumulated farther west.

Many basic and ultrabasic rocks, some igneouslike in composition and texture, seem validly ascribed to a process wherein the basic elements, particularly iron, magnesium, and calcium, are displaced in a "wave" of migmatitization by siliceous, feldspathizing solutions and become concentrated in a peripheral, desilicated zone or "basic front." The concept of the "basic front" has been recognized and described in part by many workers. It has been elaborated by Doris L. Reynolds (1946, p. 394). In the Hudson and Maynard quadrangles, however, the distribution of amphibolitic material is difficult to explain on this basis—why many almost paper-thin layers, as well as larger bodies, should be randomly distributed in a great thickness of otherwise feldspathic gneiss, or what caused fixation of the base elements in these zones instead of in a peripheral zone. Clearly, many of the rocks were basic in character before migmatitization of the area started; in this regard, as Bowen (*in* Gilluly, 1948, p. 88) has pointedly remarked, "Many masses that have been so interpreted were originally of basic character (limestones, basic intrusives) and have been modified by addition of salic material."

Similar questions arise regarding the amphibolite zone that borders the formation to the west, although its fortuitous position between the relatively unfeldspathized Worcester formation and the feldspathized Nashoba formation seems at the outset entirely in line with the basic front concept. Any postulated migration of basic elements to be concentrated in this zone leaves unanswered questions as to why some of these rocks are basic, others are feldspathic, and others (muscovite schists) are apparently neither basified nor feldspathized; why feldspathized rocks (biotite gneisses) occur locally in the Worcester formation (mica schist facies) more remote, presumably, from the source of the migmatitizing emanations than the basic rocks themselves; and why basic material in masses large and small should still remain undisplaced in the generally feldspathized Nashoba formation. It seems more likely that large-scale migration of basic elements has not occurred in the area and that rocks now basic were basic before feldspathization of the area began.

MARBLE BEDS

The marble beds and lenses of the Nashoba formation have been known since colonial time. The best known marbles in eastern Massachusetts occur in the old quarries in Bolton between Rattlesnake Hill and Brockway Corner, just north of Great Brook near the intersection of Main Street and Meadow Road. Further discussion of these deposits is found under "Mineral resources." Marble beds are exposed at several other localities in the Hudson quadrangle; they have not been observed in the Maynard quadrangle, but they are exposed in the Ayer and Westford quadrangles to the north and in the Concord quadrange to the east. In the Hudson quadrangle, except where exposed in the Bolton quarries, they are weathered on the outcrop and are deeply stained by oxidation. Outcrops also tend to be pitted by shallow solution cavities, and the rock is loose and friable owing to removal of the carbonates. Some rocks possess what appears to be original bedding but what may also be a secondary structure caused by flowage.

Marble crops out 1,700 feet due east of the Bolton town hall on hill 423. Exposure is nearly continuous to Main Street, 1,000 feet to the southwest, where the rock is well shown in road cuts; 1,500 feet to the northeast, in a small knob 600 feet west of Sugar Road, marble is also exposed and probably is the same bed. At hill 423 the marble is interbedded with many thin seams of quartzite, mostly less than half an inch in thickness and spaced an inch or two apart. The whole outcrop is stained deep brown, and the quartzites are etched into strong relief by solution of the surrounding marble. Intricate folding on a small scale, due largely to flowage, imparts a striking appearance to the outcrop. Similar marbles are exposed in

Berlin on a small hill just north of Central Street, east of Sawyer Hill Road, and in Harvard a quarter of a mile south of Mead Road.

PEGMATITE

Most of the large exposures of the Nashoba formation contain pegmatite, and in some areas it is the only rock exposed. Pegmatite is particularly abundant in Bolton in a zone that extends from the east slopes of Pine Hill northeastward through Camp Resolute to the east slopes of Rattlesnake Hill. In Harvard, pegmatite is abundant north of Sherry Road, particularly in the hill east of Horse Meadows.

Most of the pegmatite bodies are concordant and foliated. Except for those in the Bolton marble quarries, they contain few unusual minerals. Quartz, microcline, and mica are the principal constituents. Garnet and perthite are common, and graphic intergrowths of quartz and feldspar are locally abundant. Magnetite generally is present in small quantities and in places as natural lodestone.

Some pegmatite bodies exhibit features that suggest a metasomatic origin. At Camp Resolute, for example, biotite gneiss grades without a distinct contact into foliated pegmatite. The transition from gneiss to pegmatite is marked by large, randomly oriented metasomes of microcline, some more than 2 inches long, that increase in size and number as the pegmatite mass is approached until the identity of the gneiss is lost. The pegmatite owes its foliation largely to long wisps and streaks of biotite that are conformable with the foliation of the gneiss and that commonly are bent in a wavy fashion, presumably by the growth of the feldspar. Similar relationships are repeated in many other places.

Two episodes of pegmatitization are indicated. The earlier formed pegmatite seems to be mostly metasomatic and probably formed before regional deformation died out; twin laminae of the feldspars commonly are bent, and in places the crystals are fractured and displaced. The later formed pegmatite is intrusive and largely posttectonic; it cuts across the Nashoba formation and earlier formed pegmatite, as well as across various intrusive rocks, such as the Acton granite that was emplaced after the Nashoba formation was folded and metamorphosed.

GOSPEL HILL GNEISS

The name Gospel Hill gneiss is suggested for a large mass of granitic rocks of Carboniferous age that Emerson (1917, p. 220) mapped as a variant of the Andover granite but that is here regarded as a granitized product of the Nashoba and Marlboro formations.

Not only is the rock unlike the typical Andover granite of Essex County, but it displays abundant evidence of its metasomatic origin. It is particularly well exposed on the rugged southeast slopes of Gospel Hill in Hudson, the locality from which it was named. It extends from the Concord quadrangle southwestward across the Maynard quadrangle, through the southeast corner of the Hudson quadrangle and into the Marlboro quadrangle. In Concord and Sudbury it is separated from the main mass of the Nashoba formation by the wedge-shaped body of Assabet quartz-diorite. The outcrop belt is narrowest in Sudbury where it is less than half a mile across. To the southwest in the Hudson and Marlboro quadrangle it thickens to a width of more than 2½ miles.

The rock is composed chiefly of microcline, albite, quartz, muscovite, and biotite. In some exposures, however, biotite is scant or lacking. Garnet is a prominent accessory mineral, and some crystals are as much as half an inch across. Apatite is widely distributed as minute rods and prisms.

On exposed surfaces the rock is typically pearly gray to almost white. Fresh surfaces tend to be pinkish or flesh colored. It is of generally uneven grain and of medium to coarse texture. Its foliation, commonly moderate, ranges from vague to strong and is due largely to a subparallel arrangement of wavy, somewhat bent, plates of mica.

Many large exposures of the Gospel Hill gneiss exhibit gradations into biotite gneiss of the Nashoba type that apparently represent only moderately feldspathized portions of the original rock. They contain a host of nonigneous relict structures, such as drag folds and what is probably original bedding that is closely parallel with the regional structure. Some patches of this rock, limited to small parts of single outcrops, fade gradually into the granitized rock. Others extend for considerable distances, as in the southeast corner of the Hudson quadrangle where a mappable zone of biotite gneiss, interlayered with the coarser, granitelike muscovite gneiss, extends from Marlboro northeast toward Boons Pond. In like manner, many exposures contain amphibolites similar to those exposed over broad areas of the Nashoba formation. On the southeast slope of Gospel Hill, for example, thick amphibolites that are interlayered with the muscovite granite-gneiss are exposed in almost continuous outcrop for several hundred feet. Moreover, the foliation of these amphibolites not only conforms with that of the adjoining muscovite gneiss and with the broader regional trend, but their linear structures (mainly rodding of hornblende) are in general accordance with those of the biotite gneisses and amphibolites outside the granitized area. Similar relationships are repeated near Forest Avenue in Hudson, and elsewhere. Such masses of rock could be regarded as large tabular xenoliths in a magmatic granite, but this possibility is largely precluded by their remarkable orientation. Even under the most ideal conditions of magmatic intrusion, in which planar structures in tabular xenoliths might appear to remain oriented, linear structures probably would be rotated out of alinement.

The contact of the Gospel Hill gneiss with the main body of the Nashoba formation is not exposed. Judging from the distribution of outcrops, it appears to crosscut the foliation, but it probably is gradational and interfingering over a rather broad area.

Along its southeast marginal belt the Gospel Hill is in contact with the presumably pre-Cambrian Marlboro formatiton. The abrupt change from very feldspathic to relatively nonfeldspathic rocks is remarkable, but the structures of the two formations are conformable, and the contact is gradational. The relationship is well exposed in the northeast corner of the Marlboro quadrangle, (adjacent to Hudson quadrangle on the south). Here, in a zone more than 200 feet across, mica schists of the Marlboro formation are interbedded and conformable with typical granite gneiss of the Gospel Hill. Inasmuch as this contact is completely conformable and gradational, any unconformity that may have existed before granitization must lie somewhere well within what is now the Gospel Hill mass and must have been largely obscured by granitization. The only alternative is that no unconformity ever existed, that the Marlboro is essentially the same age as the Nashoba (perhaps the equivalent of the Worchester) formation and that it is part of the same continuous depositional sequence. Whatever the explanation, granitization has involved some part of the Marlboro formation as well as part of the Nashoba.

Granitization that led to the forming of the Gospel Hill gneiss probably began while deformation was still in progress. Thus, the twin laminae of some of the feldspars are bent and fractured, and very commonly the fractures are filled with veinlets of quartz. The first step toward granitization seems to have been an introduction of albite-oligoclase. Albitization was followed by the addition of microcline, both as metacrysts partly replacing albite (fig. 17) and as small, irregular veinlets. The albite-oligoclase commonly is partly sericitized; the microcline is fresh but fractured. Introduction of silica as quartz brought the rock essentially to its present composition. Quartz occurs as irregular masses and grains—some of which apparently are primary—as secondary veinlets that cross all other minerals, as thin, sliverlike masses in microcline that resemble micrographic intergrowths, and less commonly in minute grains of myrmekite.

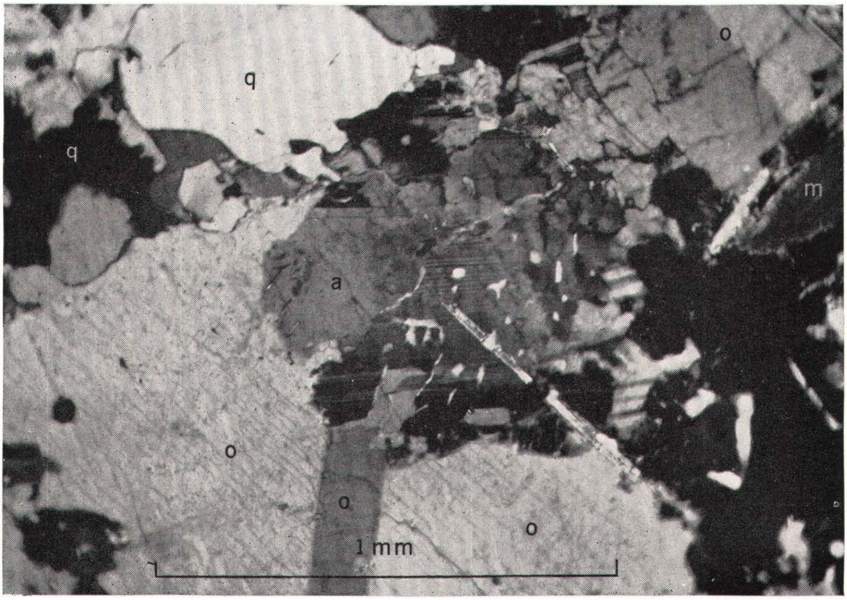

FIGURE 17.—Photomicrograph of Gospel Hill gneiss from Hudson showing orthoclase intergrown with albite. o, orthoclase; a, albite; q, quartz; m, muscovite.

UNNAMED GNEISS AT BARE HILL POND

Extending southwest from the Ayer quadrangle and across the northwest corner of the Hudson quadrangle is a mass of distinctive gneiss. In the Hudson quadrangle it is best exposed on the shores and islands of Bare Hill Pond in Harvard, but it extends southwest into Bolton, and a narrow tongue projects into the Clinton quadrangle. Emerson (1917, pl. 10) mapped it as Ayer granite. Jahns was first to recognize it as a migmatite and suggests (oral communication, 1949) the name Green Eyrie migmatite but has not proposed this name for formal adoption. Its relationship to the Harvard conglomerate lentil and to the Vaughn Hills member of the Worcester formation, from which rocks it is derived, is well displayed in many outcrops, especially along the north and east shores of Bare Hill Pond and along both sides of Vaughn Hill Road in Bolton in the Clinton quadrangle. Probably most of the rock has been derived from the Vaughn Hills member, but a sizable part has been derived from the Harvard lentil, which, in the southwest part of the area, seems to be the principal host rock, for relict inclusions of conglomerate are abundant in that area.

The rock is predominantly medium but uneven grained, moderately foliated, and granitelike in appearance. Most of it is gray or greenish gray, but locally it tends to be pinkish or salmon colored where microcline is a prominent constituent. It is composed chiefly of albite, orthoclase, quartz, chlorite, and locally microcline, and contains minor amounts of biotite, muscovite, apatite, and hornblende.

Much of the quartz probably is relict. It occurs as detrital grains and less commonly as well-preserved quartzite pebbles, and exhibits strain shadows. Secondary quartz veinlets abound. The feldspars occur as irregular masses penetrating quartz, as veinlets, and as thin projections extending from larger grains. Albite and orthoclase occur also as perthitic intergrowths. Small grains of albite, all with the same optical orientation, are enclosed within and surrounded by larger grains of orthoclase. Most of the albite is partly sericitized, whereas the orthoclase commonly is relatively clear. Most of the feldspar grains are fractured, and the twin laminae of the albite, especially in the larger grains, commonly are bent or distorted.

Chlorite is abundant in the host rocks as well as in the gneiss. In the gneiss, where it probably is a relict mineral, it gives the rock its greenish cast. Even small wisps as seen under the microscope commonly exhibit tight crenulations and flow cleavage inherited from the host rocks. (See fig. 18.)

Megascopic relict structures are abundant, chiefly near the borders of the gneiss mass. Most of these are oriented inclusions, in various states of preservation, composed chiefly of quartzitic and chloritic

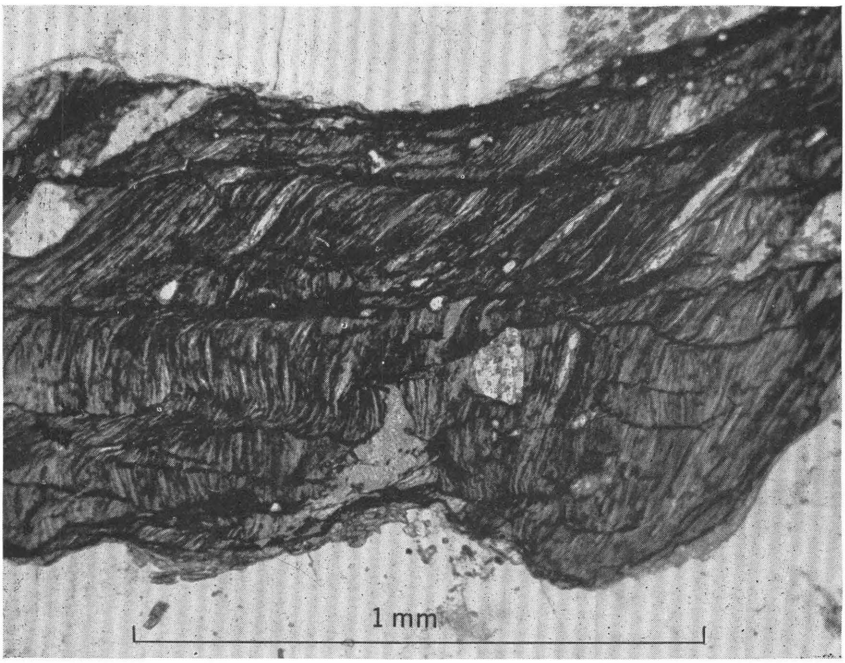

FIGURE 18.—Photomicrograph of migmatite at Bare Hill Bond, Harvard. Fracture cleavage in relict phyllite inclusion. Plain light.

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rocks of the Vaughn Hills member, and less commonly of the Harvard conglomerate lentil. Large oriented masses of chlorite schist, some several feet long and identical in type with beds within the Vaughn Hills member, occur sporadically in the gneiss. In many places, notably just west of Bromfield Academy and along the east shore of Bare Hill Pond, thin beds of dense fine-grained quartzite are almost completely enclosed in migmatitized rock, exhibit well-preserved drag folds, and retain their original orientation. In the southwestern part of the migmatitized area many exposures display masses of party altered conglomerate.

Locally, migmatitization has exercised a high degree of selectivity, for in some localities strongly migmatitized rocks are in sharp contact with practically unaffected rocks. On the small island northwest of Ministers Island in Bare Hill Pond, for example, the well-exposed contact of the gneiss with the Harvard conglomerate lentil is of knife-edge sharpness and is parallel to the bedding. On the east side of the Pond the contact with the Vaughn Hills member is more gradational, but nevertheless is about parallel to the strike of the bedding; slight lithologic differences may have been of importance in limiting migmatitization. Cleavage planes probably served as the chief channelways for invading solutions. To the southwest in Bolton, exposures northwest of the Vaughn Hills show relatively unfeldspathized rocks that can be traced along the strike into migmatite in a distance of a few yards.

The invasion of the rocks by migmatizing solutions, by and large, was posttectonic. Even though distortions in the crystals of introduced feldspar indicate movements in the rocks subsequent to feldspathization, the numerous partly replaced relicts, large and small, all showing approximately the same degree of deformation and the same orientation of secondary structures as in the corresponding rocks of the adjoining unmigmatized areas, indicate that deformation had about reached its present state before migmatitization began.

Evidence that material has been added to the rocks extends beyond the limits of the migmatite proper. Small amounts of metasomatic feldspar are found in otherwise unmodified rocks of the Vaughn Hills member. In the Harvard conglomerate lentil basic material has been added in the form of chloritoid (fig. 19); this mineral appears mostly in chloritic beds and in the conglomeratic beds that have a chloritic groundmass. Euhedral metacrysts, randomly oriented without regard to bedding or cleavage directions, have formed later than the bedding or the cleavage, and a definite correlation, therefore, is indicated between the age of the chloritoid and the age of the migmatitization.

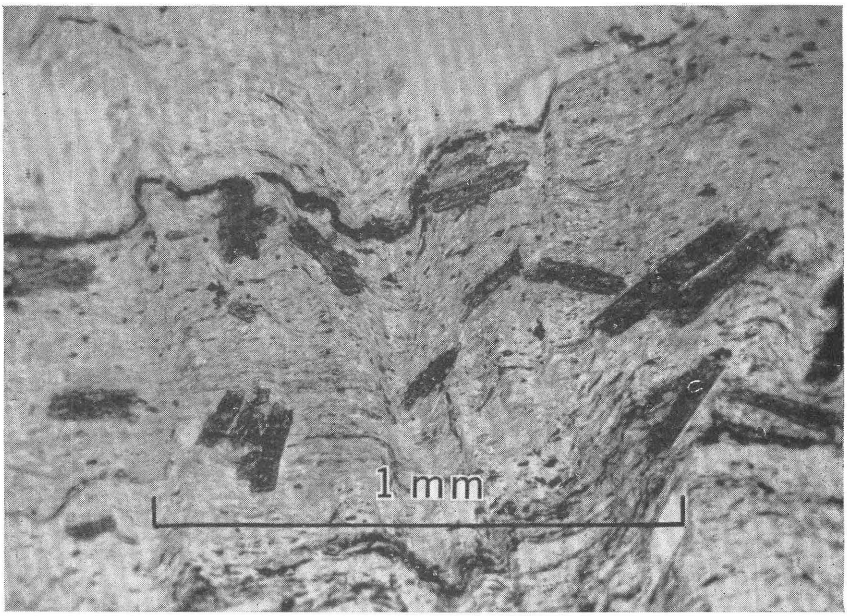

FIGURE 19.—Photomicrograph showing chloritoid laths crossing earlier fracture cleavage in Harvard conglomerate lentil (slaty interbed), north Vaughn Hill, Bolton. Plain light.

IGNEOUS ROCKS OF LATE PALEOZOIC(?) AGE

GENERAL RELATIONSHIPS

Intruded into the Carboniferous metasedimentary rocks of the area are many bodies, large and small, of igneous rock. Their exact age is unknown, and they may be as young as Triassic, but because they appear to have been intruded before the late Paleozoic deformation of the area had completely died out, they are regarded as probably of late Paleozoic age. Little is known, moreover, of their relative ages because all crop out in different areas. All possess certain characteristics in common although they range in composition from diorite to granite. They occur as lenticular and sheetlike masses that with few exceptions have been intruded roughly parallel to the foliation planes or the bedding of the metasedimentary rocks. Locally, however, they exhibit crosscutting relationships and sharply truncate the invaded rocks. Most of them are weakly foliated, but this structure may be scarcely discernible. Most of them, also, are somewhat crushed, owing probably to movement during or after consolidation. Such crushing is largely restricted to microscopic fracturing and bending of crystal grains, and shows most prominently in the twinned feldspars, especially the plagioclases. Quartz, with few exceptions, displays undulatory extinction.

ASSABET QUARTZ-DIORITE

The Assabet quartz-diorite of late Paleozoic age is here named for exposures near the Assabet River in the town of Maynard. Exposures on hill 272 in the northeast corner of Maynard may be considered as the type locality. The Assabet quartz-diorite probably underlies a broader area than all other late Paleozoic igneous rocks in the Hudson and Maynard quadrangles combined. It is well exposed, however, in only three major outcrop areas, although small exposures are fairly numerous and large glacial boulders abound in the intervening covered areas. Well-exposed outcrop areas, in addition to those on hill 272, may be seen near the intersection of Harrington Avenue and Old Marlboro Road in Concord and on both sides of the Boston and Maine Railroad just west of the Concord Turnpike overpass in Concord. Contacts with adjacent rock units are not exposed.

The main tongue-shaped mass of the rock extends from Maynard northeastward into the Concord quadrangle. Smaller separate bodies crop out in Maynard and Stow, and some of these may be more extensive than shown because their limits are masked by glacial deposits. A few small bodies are unmappable on the present scale.

The rock characteristically is medium grained, medium to dark gray, and slightly to moderately foliated. It is composed chiefly, and in order of abundance, of andesine, hornblende, quartz, and biotite, and contains considerable accessory apatite and some sphene and hematite. The foliation of the rock is due largely to a planar orientation of the hornblende, and in a lesser measure of the biotite, some of which is secondary after hornblende. On weathered surfaces the biotite is altered to a bronze red.

Superficially the Assabet resembles the Dedham granodiorite of the Sudbury area. It is distinguished in the field, however, by its much higher proportion of hornblende, and by its low proportion of quartz, which is rarely identifiable megascopically but is very conspicuous in the Dedham granodiorite, especially on weathered surfaces. The feldspar in the Assabet quartz-diorite is somewhat fresher and glassier than that of the Dedham. In addition, xenoliths are very rare in the Assabet quartz-diorite, but they are abundant in the granodiorite of the Dedham of the Sudbury area.

Most exposures of the Assabet quartz-diorite contain pegmatite, and many also contain acid and intermediate aplitic dikes.

STRAW HOLLOW DIORITE

Exposures of the Straw Hollow diorite in the area mapped are confined to the town of Hudson south of the Assabet River. It is exposed in scattered outcrops on both sides of Broad Street and in large and numerous ledges at the southern quadrangle boundary just west of the Marlboro branch of the Boston and Maine Railroad.

Most of the rock as exposed in Hudson is a medium-grained medium-gray diorite composed of andesine, hornblende, biotite, minor amounts of apatite and sulfides, and veinlets of quartz. Some outcrops display a finer grained variety of the rock that has essentially the same mineral composition as the coarser variety. Owing to limited exposures the two varieties are not mapped separately, and their structural relationship is undetermined.

The Straw Hollow diorite commonly exhibits a linear structure, locally very pronounced, that is caused by a combination of rodding and streaking of the minerals, especially hornblende. Only rarely does the rock exhibit planar structures, and these seem to be confined to the borders of the mass. In places the rock is strongly sheared and fractured, as if to suggest deformation and movement within the mass after at least part of it had consolidated.

Contacts of the Straw Hollow diorite are not exposed. Near the south boundary of the Hudson triangle, however, about a quarter of a mile east of Broad Street, the rock may be seen in close proximity with outcrops of Gospel Hill gneiss, and, judging from the apparent lack of any gradation between the two formations, the contact probably is sharp. Moreover, both formations are foliated in that area, and the foliation of the Straw Hollow diorite appears to cut across that of the Gospel Hill gneiss at an angle of about 40°.

AYER GRANITE

The Ayer granite, as described by Emerson (1917, p. 224), includes several acid and intermediate rock types; a granodiorite facies has been described by Jahns (1942, p. 341). The granite is exposed west of Bare Hill Pond in Harvard in a mass that projects south from the type area. As here exposed it is a light- to medium-gray, moderately coarse grained granite, hard and resistant to erosion, forming bold outcrops and occupying relatively high ground. It consists of two mappable facies, one that is nonporphyritic and contains few if any phenocrysts in most exposures and another that is porphyritic and contains abundant orthoclase phenocrysts as much as 3 inches in length, slightly perthitic, and commonly twinned. Except for the presence or lack of phenocrysts the two facies are essentially the same. Moreover, although the boundary separating them is surprisingly sharp, it seems to be completely gradational and does not involve any structural discontinuity.

The Ayer granite in the vicinity of Bare Hill Pond consists chiefly of orthoclase, quartz, and albite, and contains accessory biotite, muscovite, chlorite, and apatite. Much of the albite occurs in crosscutting veinlets and as microperthitic intergrowths. Some form individual clouded grains that penetrate both orthoclase and quartz. Quartz occurs both as grains and as vein fillings; many quartz grains exceed a quarter of an inch (10 mm) in diameter. Most of the larger mineral grains of the rock, including the large orthoclase phenocrysts, are fractured or somewhat distorted, and many of the fractures are filled by veinlets of quartz or of quartz and sericite.

The porphyritic facies of the rock commonly has a rude planar structure caused by a subparallel orientation of its phenocrysts, due probably to viscous flow of the magma before complete solidification, as noted by Emerson (1917, p. 224). The porphyritic facies also contains xenoliths, which in places are abundant, particularly near the border of the mass. These probably have been derived chiefly from the Worcester formation. Some still retain their original slaty character.

The Ayer granite has caused little apparent contact alteration of the adjacent rocks. On the shore of Bare Hill Pond, about 400 yards northwest of Ministers Island, the Ayer granite and the Harvard conglomerate lentil are exposed within a few feet of one another, and except that the Harvard there contains myriads of quartz veins its appearance is not perceptibly different from other exposures more remote from the granite. Similarly, the phyllite facies of the Worcester formation is not of perceptibly higher metamorphic rank as exposed near the granite than it is at relatively great distances from the granite.

ACTON GRANITE

The Acton granite is here named for the town of Acton where it is well exposed. (See fig. 20). In the Hudson and Maynard quadrangles it is the most widespread of the Late Paleozoic igneous rocks, and in total bulk probably is exceeded in this area only by the Assabet quartz diorite. It occurs, however, in relatively small individual plutons, chiefly as intruded sheets or sill-like bodies, and also as crosscutting dikes and irregular masses that range in thickness from a few inches to perhaps several hundred feet and in length from a few yards to more than a mile. Many small bodies are not mappable on the scale of the geologic map (pl. 1). Outcrops are largest and most abundant in Acton but are common in Boxborough, Bolton, Harvard, Hudson, and Stow. All observed exposures lie within the boundaries of the Nashoba formation..

The Acton granite is a hard and fresh fine-grained moderately foliated rock, light gray to light olive gray on fresh surfaces On weathered surfaces it is almost white and has a bleached appearance. The rock is composed chiefly of quartz, orthoclase, microcline, and oligoclase. The ratio of potash feldspars to oligoclase is more than

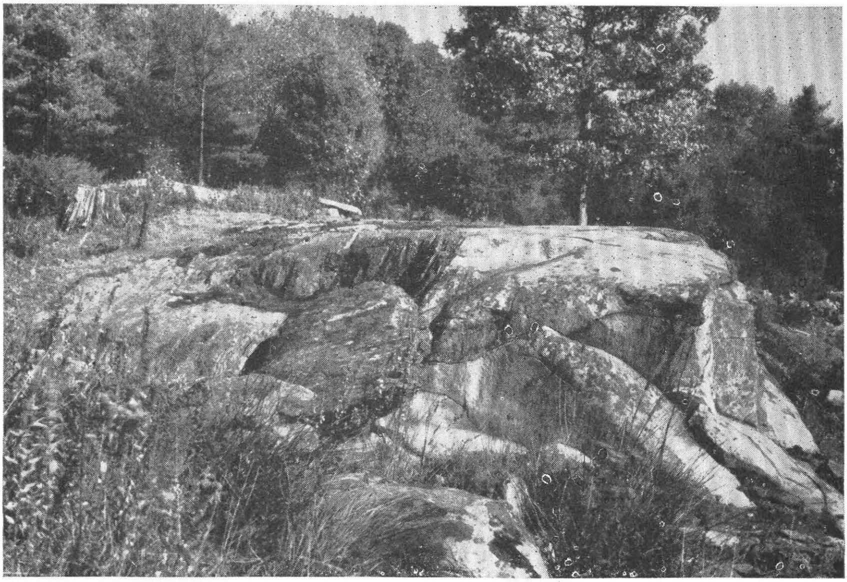

FIGURE 20.—Roche moutonnée near Nashoba Road, Acton. Ice moved from left background to right foreground. Light-colored Acton granite (right) intrudes darker colored Nashoba formation (left).

2 to 1. In large part, the microcline seems to have formed by a transformation of the orthoclase, in the manner described by Laves (1952). Thin sections of many such crystals show untwinned portions and partly or wholly twinned portions; in some crystals the twinned portions form a rim or uneven shell surrounding the untwinned interior. Mica, including both biotite and muscovite, is the chief accessory mineral and gives the rock its foliated structure. Apatite, zircon, garnet, and a little epidote are minor constituents.

Some exposures of the Acton granite show xenoliths of biotite gneiss derived from the Nashoba formation; although some of these xenoliths have been thoroughly impregnated by magmatic material, most of them are still similar to their parent rock. Together with discordant contacts of granite against wall rock, they indicate that the Acton was not emplaced until after the Nashoba formation had attained essentially its present attitude and metamorphic rank, and they point out, with other supporting evidence, the intrusive origin of the granite. Individual granite bodies commonly are concordant, or nearly so; their planar structures tend to parallel their walls, and thus, also tend to parallel the foliation of the country rock, giving an impression of relict bedding. However, crosscutting relationships do occur, and the planar structure of the crosscutting granite commonly truncates the foliation planes of the country rock at angles of several degrees.

(See figs. 21 and 22.) Moreover, although xenoliths in the granite commonly are elongated about parallel to the walls of the granite body, they lack internal orientation—their foliation planes are arranged and truncated at random. (See fig. 21.)

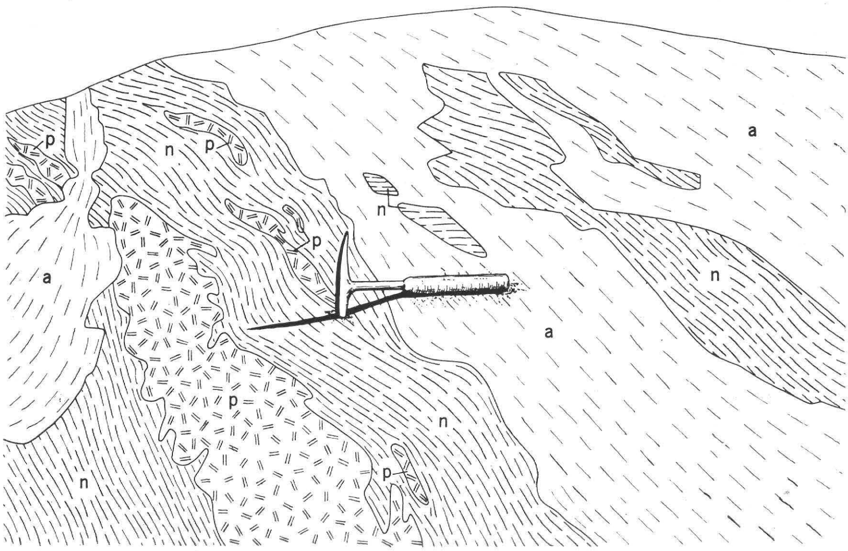

FIGURE 21.—Glaciated ledge near Nashoba Road, Acton, showing crosscutting relationship of Acton granite (a) to Nashoba gneiss (n) and to pegmatite (p). Note elongated gneiss xenoliths oriented with respect to flow lines of granite but randomly arranged with respect to their own foliation.

The Acton granite probably is younger than most of the pegmatites in the area, for where the two rocks are observed together it commonly crosscuts the pegmatite. In a few places, however, mostly small and relatively fine-grained pegmatites can be seen crosscutting the granite.

BASIC DIKES OF PROBABLE TRIASSIC AGE

Small dark-colored dikes have been observed at 4 localities in the Maynard quadrangle. One dike is exposed about 400 feet south of Strawberry Hill Road in Acton, near the Concord town line; another is exposed just south of Annursnack Hill in Concord; 2 are exposed in Sudbury, 1 about 600 feet west of Dakin Road, and 1 about 400 feet west of Water Row Road. None of these dikes could be traced beyond a single outcrop, and neither their trends nor their thicknesses are known. The dike near Dakin Road seems to strike about N. 40° W. and is probably less than 3 feet thick, but its contacts are not well exposed.

The age of the dikes is uncertain, and all may not be of the same age, but because two of them occur within the Nashoba formation, and because all apparently are unaffected by the regional metamorphism, they are tentatively assigned to the Triassic period and are tentatively correlated with the Triassic dikes of the Boston basin.

These dikes are of fine grain, of diabasic texture, and are composed chiefly of augite and a highly altered plagioclase, probably labradorite. A fine, fibrous mineral, probably antigorite, is a pseudomorph after olivine and retains in aggregate the crystal outline of the original olivine. Magnetite is abundant both as an alteration product of olivine and as small flecks disseminated through the rock. Secondary calcite is fairly common.

In all probability, more such dikes occur in the area but are hidden by surficial deposits.

STRUCTURAL GEOLOGY

FOLDS

The stratified rocks of the area have been closely folded. Small minor folds, evident in nearly all outcrops, tend to be asymmetrical and overturned. The outcrop belts of the formations and, in general, the strike of the foliation, have a northeasterly trend throughout most of the area. This trend, however, swings from a more northerly bearing in the southwestern part of the area to a more easterly bearing in the eastern part and even to a southeasterly bearing in the southeast corner of the Maynard quadrangle. Folding, therefore, was accompanied by arcuation, and, as indicated by lineation parallel to the fold axes and by cross joints normal to them, folding was also accompanied by elongation parallel to the fold axes. Indeed, arcuation was probably the cause of elongation. Cloos (1946, p. 36) has pointed out that "in the arcuation of folds, elongation parallel to the fold axes is inescapable."

The dominating structural feature of the area is a broad asymmetrical synclinorium. Its central part is occupied by the Nashoba formation; on its overturned northwest limb is the mica schist facies of the Worcester formation; on its normal but steep-dipping southeast limb is the Marlboro formation. Both limbs are flanked by large anticlines. To the northwest in Harvard the core of a major anticline is occupied by the Ayer granite. To the southeast the Marlboro formation is exposed on both limbs of a large anticline, the core of which is occupied by the quartz diorite facies of the Dedham granodiorite.

Owing to the magnitude of these structures and to the relatively small part of them lying within the Hudson and Maynard quadrangles, their regional relationships are indicated better on Emerson's map (1917, pl. x.) of Massachusetts and Rhode Island, even though the units mapped by him differ in detail from those mapped for this report. Although Emerson (1917, p. 59) mapped the Oakdale and

Merrimack quartzites separately, he nevertheless regarded them as the same formation. He (1917, p. 77) further pointed out that "in pitching folds the Oakdale regularly passes under the Worcester."

MINOR FOLDS

IN THE NASHOBA FORMATION

Superimposed upon the major structural features of the area are countless minor folds (fig. 22) that range in size from minute crenulations to structures many feet across the limbs. Although they are more abundant in some areas than in others, scarcely an outcrop does not display them.

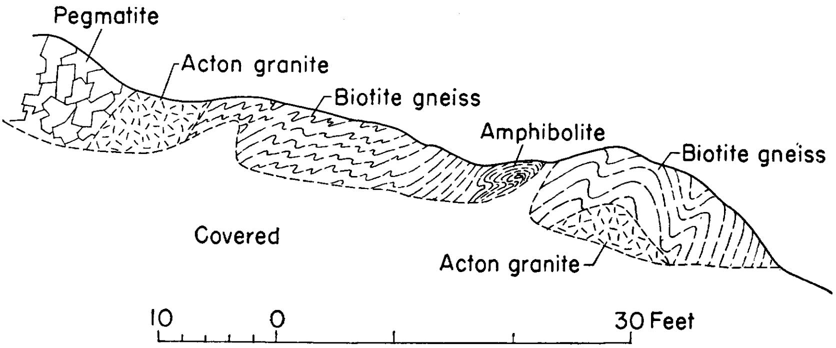

FIGURE 22.—Cross section of exposure near Rattlesnake Hill, Bolton, showing typical minor structures in Nashoba formation. Beds are mostly right side up and dip more gently than usual. Small overturned anticline on right. Note crosscutting relationships of Acton granite.

In the Nashoba formation most minor folds strike parallel to the strike of the major folds. Plunges are generally moderate and may be either northeast or southwest. Most of the minor folds are asymmetrical and overturned; their axial planes dip chiefly northwestward. In some places overturning has rotated the axial planes to a horizontal position. The minor folds of the Nashoba formation may be regarded as drag folds upon the larger folds. Inasmuch, however, as no beds appear to have been sufficiently competent to have withstood crumpling for any great distance, the term "flow folding" as applied by Billings (1942, p. 89) seems more applicable to this particular type of deformation than does drag folding.

Nevertheless, the minor folds appear to bear the same relationship to the larger folds as do true drag folds.

In any area where minor folds are as abundant as they are in the Nashoba formation, no single minor fold or group of minor folds can be expected to reveal much exact information about the positions or attitudes of the major structures; taken in the aggregate, however, they are imporant aids in the solution of major structural problems.

Almost every exposed minor fold along the northwestern third, roughly, of the Nashoba belt is overturned toward the southeast, and almost without exception the overturned limb is the longer limb; in extreme cases, the axial plane is horizontal or nearly so. The beds, therefore, are overturned.

In more southeasterly portions of the Nashoba belt, overturning is less conspicuous. The minor folds of that area are also asymmetrical and their axial planes dip also northwestward, but, if one limb is overturned, it more commonly is the shorter limb, indicating that the beds are right side up.

Moderately large folds are discernible in a few places, and doubtless more could be located if exposures were more continuous and key horizons could be discriminated. At Rattlesnake Hill in Bolton, where exposures are better than average, is a fairly well-displayed syncline. Its width across the limbs is at least half a mile, and it plunges gently northeastward.

Another plunging synclinal fold is suggested by the abrupt southwestward termination in Boxborough of a large amphibolite mass. Tight folding, streaking of mineral grains, and rodding produce strong lineations that plunge steeply northeastward. The bending of the foliation around the suggested synclinal nose, however, is less convincingly displayed than at the Rattlesnake Hill locality, and, although a hypothesis of folding seems to explain the observable relationships better than any other hypothesis, at least one alternate structural interpretation is possible. The southwestward termination of the amphibolite may be due primarily to premetamorphic intertonguing and may have been accentuated subsequently, during regional deformation, by squeezing, flowage, and migration of material toward the northeast. It is possible, too, that the amphibolite mass in Boxborough may correlate with the amphibolitic zone that trends through Acton and Concord into the Westford and Billerica quadrangles, on the other limb of the synclinorium.

IN THE MARLBORO FORMATION

The Marlboro formation exhibits few minor folds that can be correlated definitely with the major structural features of the area. Unlike the minor folds of the Nashoba formation, which tend to strike parallel to the major features and to the general elongation of the formation, and which are best viewed in the field in vertical exposures normal to the regional strike, most minor folds in the Marlboro formation tend to be oblique or nearly normal to the trend of the formation, and are best viewed in the field in vertical exposures parallel to to the formational strike. (See fig. 23.) The smallest of these cross folds are minute wrinkles similar to incipient slip cleavages. They

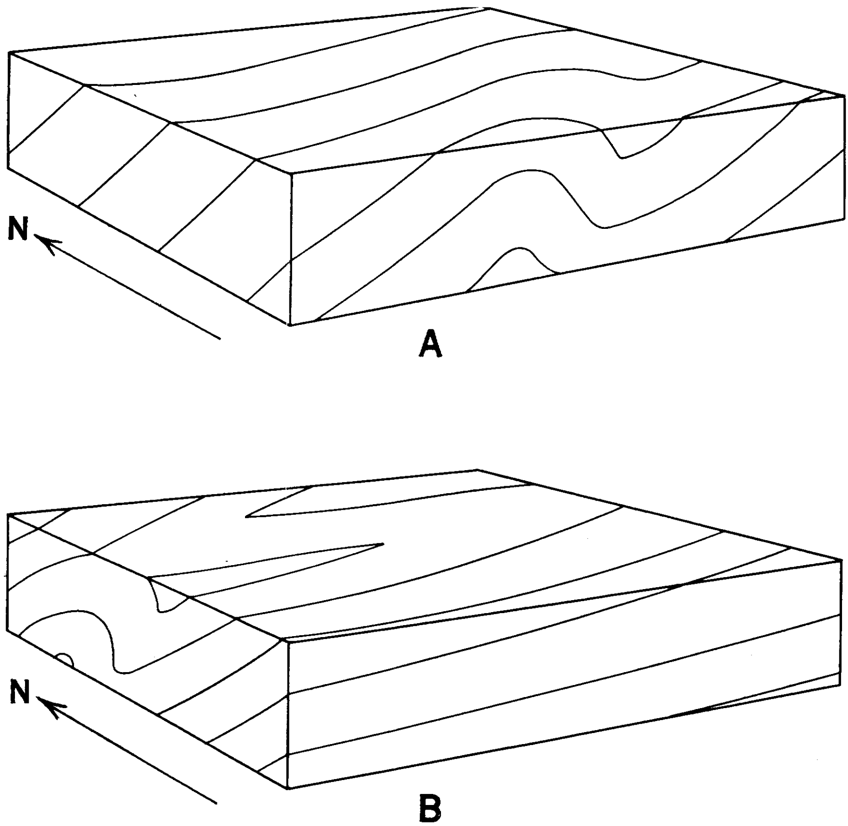

FIGURE 23.—Diagrams illustrating the relationships of minor folds in the Marlboro formation (*A*) and in Nashoba formation (*B*) to regional strike. Minor fold axes are oblique or nearly normal to the strike in the Marlboro and are parallel to the strike in the Nashoba.

are superimposed upon larger structures (fig. 2) that may be fully displayed in a single outcrop, and these in turn are superimposed upon still larger structures indicated by broad undulations in the strike pattern. All plunge north to northwest down the dip of the formation. They are asymmetrical and their axial planes dip westward or southwestward. Many are fractured and displaced along or near to their axial planes by small thrust faults.

IN THE WORCESTER FORMATION

These features are best displayed in the Vaughn Hills area where exposures are excellent, though discontinuous. Folds in this area are very intricate. (See figs. 10, 11.) The minor folds do not seem to be related to the major structural features but appear to possess an independent alinement oblique to the formation trends—in this respect they are analogous to the cross folds of the Marlboro formation. Most of them plunge west or southwest and their axial planes dip north or northwest. Within a single outcrop, however, the direction of plunge may infrequently change 180 degrees, although the axial plane directions are quite persistent.

In places a prominent fracture cleavage parallels the axial planes; incipient fracture cleavages in several other directions from place to place are produced by small, differently oriented wrinkles. Some exposures display two distinct cleavages in addition to bedding.

In places, bedding in slaty rocks has been completely obliterated because material has been squeezed from the limbs of the folds and has migrated toward the fold axes, so that the only discernible structure in the slate is a flow cleavage parallel to the axial plane of the fold. Such cleavage is generally confined to slate and phyllite beds, but even in quartzite beds the crests and troughs of the folds are characterized by thickening, and the limbs by thinning.

GENERAL SIGNIFICANCE OF MINOR FOLDS

Most minor folds of the Nashoba formation are clearly related to the larger scale features of the area and must be products of the same disturbance. Their overturned attitude, moreover, suggests that the deforming stresses came from a northwesterly direction. In the Marlboro and Worcester formations, however, much minor folding appears to be unrelated genetically to the major structures and therefore appears to be related to a second episode of disturbance.

Many exposures in the Nashoba formation show that the bulk of major and minor folding preceded feldspathization. Many of these rocks are now so highly granitized that they would be expected to behave under stress more like granite than like stratified rocks. It seems unlikely that the intricate pattern of folding exhibited by these rocks could be duplicated in a rock possessing the present physical properties of much of the Nashoba formation. A moderate second episode of disturbance might have little notable effect upon the Nashoba formation, whereas the less competent adjoining formations would yield readily to repeated deforming stresses.

More regional studies, involving areas beyond those mapped for this report, would be required before conclusions could be drawn regarding the possible directions from which stresses might have come to produce the structural features attributed to a second period of deformation. The orientation of minor fold axes in the formations flanking the Nashoba formation in the mapped area suggests that the Nashoba, relatively, may have moved northeastward as an essentially rigid, competent unit, crumpling and dragging the adjoining incompetent formations into a series of obliquely oriented minor cross folds superposed upon the prevailing and earlier formed northeastward-trending structure. The minor folds are influenced in the bearing and plunge of their axes by the dip of the larger features. In the Marlboro they plunge predominantly north to the northwest, in the Worcester formation predominantly west to south. Because the rocks are steeply tilted, no other plunges could result from the postulated relative movement suggested above.

LINEAR STRUCTURES

Most linear structures in the metasedimentary rocks are parallel to the axes of the minor folds and lie in the planes of foliation, schistosity, or bedding. Wrinkling—actually minor folding on a minute scale—is probably the commonest form. Mineral streaking, caused by trains of mineral grains (particularly of mica flakes) is fairly common in the Nashoba formation and generally is associated with wrinkling. Rodding, or alinement of lath-shaped and needle-like minerals, is prevalent in amphibolite, especially in the large amphibolite mass in Boxborough where it is associated with streaking and wrinkling. Streaking and rodding parallel to the fold axes, together with cross jointing (evidently caused by tension) normal to the fold axes suggest that elongation parallel to the fold axes accompanied folding.

Where lineation has been observed in the igneous rocks, as in the Straw Hollow diorite, it is chiefly in the form of rodding, but it also occurs as streaks. Foliation may or may not be discernible.

Intersection of bedding and cleavage forms lineations that are parallel to the axes of minor folds in the Worcester formation. Where cleavage is incipient, the lineation is in the form of minute crenulations.

FRACTURE CLEAVAGE

Fracture cleavage is confined to relatively low grade metamorphic rocks west of the belt of the Nashoba formation. It is especially prominent in the Harvard conglomerate lentil and in the phyllite facies of the Worcester formation, less prominent perhaps in the Vaughn Hills member and in the mica schist facies. Cleavage of this sort is commonly accompanied by some mechanical reorientation of mineral grains in and along the fracture plane, but bedding commonly remains as a distinct and important direction of rock parting.

Much of the fracture cleavage is due to rupture along the thinned limbs of minute wrinkles and is akin, therefore, to the shear cleavage or slip cleavage of Billings (1942, p. 217) and of White (1949, p. 591). Some cleavage, however, is nothing but very closely spaced jointing. (See fig. 24).

In the Nashoba formation true fracture cleavage has not been observed. However, incipient fracture-cleavage planes are formed where incompetent biotitic layers are tightly crenulated between rela-

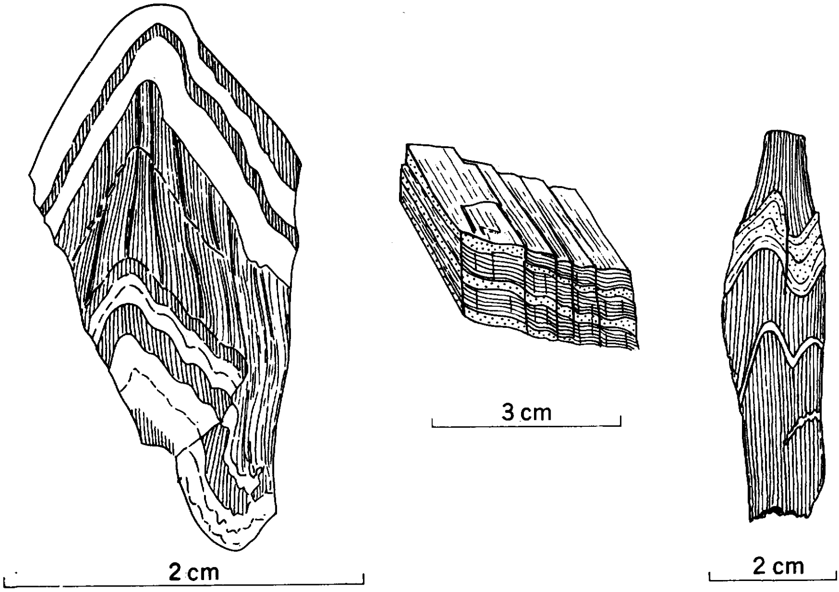

FIGURE 24.—Slaty cleavage displayed by phyllite specimens of Worcester formation from Harvard. Light-colored beds are quartzite. Cleavage in center specimen is essentially closely spaced jointing. Note tendency of cleavage to form inverted fan structure in specimen at left.

tively competent quartzose layers. Very similar structural features occur in micaceous layers in the Marlboro formation.

FOLIATION IN PARAGNEISS

Foliation in paragneiss, particularly in the Nashoba formation, is regarded as mimetic. Wherever observed in conjunction with bedding, or with mineralogic layering that probably reflects bedding, it coincides with these structures. Secondary growth of platy minerals probably has been influenced in its orientation by preestablished directions of crystal orientation. Thus, during sedimentation, detrital mineral grains of platy habit, such as micas and clay minerals, tend to become oriented parallel to the bedding planes by gravitative settling during deposition and by compaction of the sediment during lithification. Secondary growth then may proceed on already oriented crystal lattices. If the foliation of the paragneiss were an axial plane cleavage, crosscutting relationships between bedding and foliation should somewhere be seen. In the noses of all observed folds, foliation is folded and is parallel to bedding.

SCHISTOSITY IN THE MICA SCHIST FACIES OF THE WORCESTER FORMATION

The origin of schistosity in the mica schist facies of the Worcester formation is not entirely clear, but it appears to be a flow cleavage.

It is best displayed by relatively high grade schists in the upper part of the unit. In most such exposures bedding cannot be discerned. In some exposures, however, the noses of small folds can be seen, and in these the schistosity is parallel to the axial planes; in other places, apparently the limbs of isoclinal folds, schistosity is parallel to relatively competent quartzite layers.

JOINTS AND THEIR STRUCTURAL SIGNIFICANCE

Joints are especially conspicuous in the Nashoba formation where many of the bold outcrops owe their clifflike form to glacial plucking along favorably oriented joint planes.

Most joints of the area are of a single vertical or nearly vertical set. These are cross joints, mostly normal to the strike of the foliation but in places slightly oblique; the general trend of the cross joints, therefore, is northwest.

Most of those that are not vertical dip steeply southwestward. Broad variations in the strike of the foliation are reflected by corresponding variations in the cross-joint pattern; minor variations generally are not reflected by the joints. The broad curvature in trend of the foliation across the area is concave toward the southeast; it is reflected throughout the area by a fanlike arrangement of the cross joints converging toward the southeast.

Cross joints have been observed in all stratified formations of the area, as well as in the Acton granite, the Assabet quartz diorite, and early pegmatite bodies. They are more abundant in the Nashoba formation than elsewhere and are best formed and most closely spaced in the northwest half, roughly, of the Nashoba outcrop belt. (See fig. 15.) In small bodies of Acton granite, in which the wall rocks are exposed, cross joints can be observed transecting both the granite and the wall rocks. Similar relationships are shown by many pegmatite bodies, especially by concordant ones. On the other hand, some cross joints are filled by pegmatite.

Both low-angle joints and high-angle oblique joints have been observed in the Nashoba formation. However, such joints are uncommon, they do not seem to form a consistent pattern, and they have not been referred to any set or system.

The cross joints in the Hudson and Maynard quadrangles are regarded as tensional features. They seem to reflect relatively late adjustments made by rocks behaving essentially as rigid, brittle solids. Thus cross jointing is more conspicuous in the brittle rocks of the Nashoba formation than in the relatively incompetent formations that flank the Nashoba.

The greater preponderance of cross joints over any others strongly suggests that folding was accompanied by tensional elongation parallel to the fold axes. This suggestion, moreover, gains support from the presence of streaking and rodding parallel to the fold axes. Folding in the Hudson-Maynard area was accompanied by arcuation concave toward the southeast; arcuation is especially pronounced in the curved patterns of the Marlboro outcrop belts, but it is also indicated in the rest of the area by a gradual swing of the foliation trend and by the fanlike arrangement of the cross joints. It may have been a chief cause of axial elongation in the area and consequently of the formation of cross joints.

FAULTS

Small faults having displacements of a few inches to a few feet are rather common; faults of mappable dimensions on the present scale, however, have not been observed in the Maynard quadrangle, and only four are mapped in the Hudson quadrangle. Very likely many others exist, but owing to the paucity of traceable horizons they have not been identified.

What may be a very large fault offsets the mica schist facies of the Worcester formation, the amphibolite at its top, and a part of the Nashoba formation in the prominent gap occupied by Main Street just northwest of Bolton center. This gap very likely owes its existence to the presence of the fault. The fault trace is concealed, but the fault can be fairly well located by bedrock exposures. The total displacement is unknown, but the horizontal offset is about 1,000 feet. Unless there has been a strong horizontal component of movement, the total displacement must be very large because the rocks in this vicinity stand nearly on edge.

Two other faults, both in the town of Harvard, are identified by offsets in the same amphibolite zone. These faults are less accurately located than the large one in Bolton because outcrops in their vicinities are less abundant.

A probable fault is mapped in the low saddle between the Vaughn Hills in Bolton. This saddle separates a large mass of Harvard conglomerate lentil from quartzite of the Vaughn Hills member, both relatively resistant rock types. As indicated by the relatively steep plunges of the minor folds in this area, however, the conglomerate may possibly plunge under the quartzite without a fault contact.

QUATERNARY DEPOSITS

GENERAL RELATIONSHIPS

Most of the unconsolidated materials that today mantle the bedrock surface of the Hudson and Maynard quadrangles owe their presence to continental glaciers which overrode New England and other parts of North America during the Pleistocene epoch. Only thin and rela-

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tively minor deposits, chiefly alluvium and windblown sand, have accumulated since the ice withdrew, and much of the windblown sand probably accumulated during the withdrawal stage.

The glacial deposits of the area, that is, those deposits laid down either directly by glacial ice or by melt water that issued from the ice, range widely in thickness and character from one locality to another. Collectively called drift, they are separated into two main categories, that is, unsorted drift or till and sorted or stratified drift. Further subdivision is made on a morphologic basis and has proved a convenient means of discriminating and mapping the various types of deposits in the area. (See pl. 2.)

TILL

Although the till in the area contains pockets or lenses of stratified sediment that are not separately mappable, and may otherwise show some evidence of local reworking by melt water, it is chiefly an ice-laid deposit that has accumulated either by direct accretion to the subglacial floor from active, overloaded basal ice, or by gradual accumulation, through wastage or ablation, of stagnating, debris-laden ice. It is essentially, therefore, a heterogenous mixture of unsorted rock fragments of all sizes that range from clay-size particles to great boulders many feet in diameter. One such boulder near Mill Road in Bolton is 18 feet long and 12 feet wide. It is partly buried but is 12 feet high above the ground surface and probably weighs more than 250 tons. A fragment nearly as large has been broken off and lies nearby. Several other boulders that may be even larger lie in other parts of the area; one in Stow and one in Boxborough are indicated on the topographic map by closed contours.

Most rock fragments in the till, including those of minute size, are sharply angular, but some have been polished and faceted by glacial abrasion. Because much of the till has been derived locally, it reflects to a remarkable extent the lithologic composition of the underlying bedrock, or of bedrock formations nearby. Thus, in Still River most of the rock fragments in the till are slates and phyllites, in Stow they are gneisses, and in a large part of Sudbury they are granitic types. Along and to the lee of a given belt of bedrock, boulders of that rock commonly abound in the till, and the distribution of such boulders is of material aid in the delimitation of bedrock units in areas of few outcrops. Most of the larger fragments lie within the boundaries of the formations from which they have been derived, and most of them seem to have traveled not more than 2 or 3 miles. Some, however, have traveled farther and a few probably many miles farther. A specimen of phyllite of the Worcester found on Orchard Hill in Gleasondale must have been carried at least

7 miles, and many large boulders of Ayer granite, conspicuous and easily recognized, have been carried comparable distances.

In the Hudson and Maynard area as elsewhere in Massachusetts and New England, two distinctive types of till have long been discriminated (Currier, 1941, p. 1895). Exposures displaying both types have not been seen in the Maynard quadrangle and they are few and poor in the Hudson, but in many nearby exposures it is clearly shown that one, the so-called younger till, overlies the other, the so-called older till. The younger till is light gray to light bluish gray where freshly exposed. It has a yellowish- or brownish-weathered zone that commonly extends to a depth of 1 to 3 feet. Below this the till is fresh and unaltered. Characteristically it is loose, incoherent, and relatively pervious, and slacks quickly on drying. Its texture is relatively coarse, and it contains many boulders.

The so-called older till is light brown to yellowish brown and dusky yellow. This coloration apparently is a result of deep oxidation. The weathered zone of the older till, as here observed in the upper parts of exposures, is essentially similar to that of the younger till. The older till is somewhat finer and certainly less bouldery than the younger till. Also it possesses a prominent cleavage or fissility that lies essentially parallel to the ground surface. It is compact, tough, coherent, and relatively impervious. On drying it indurates to a hard, almost concretelike mass. It is more difficult to excavate than the younger till, therefore, and has earned the local name of hardpan, but it is easily worked with power shovels.

The younger till probably has a broader surface distribution than the older till but probably is less in total volume. In many areas, the older till is exposed at the surface, and in such places the surface tends to be smoother and more even than younger till areas and therefore exhibits subdued relief features.

Two explanations have been offered to account for the dissimilarities of the two tills. One view holds that a considerable time interval elapsed between their deposition, that the older till was deposited by an ice sheet that advanced and withdrew from the area before a later ice sheet (or a readvance) deposited the younger till. The other view holds that both tills are accumulations from a single ice sheet, that one till is a basal accumulation and the other is an englacial or superglacial accumulation. Both views have many adherents, and until unequivocal evidence is discovered, such as a buried soil or an interglacial deposit, agreement on the problem probably will not be reached. The writer strongly favors the views that the two tills are deposits of separate and distinct ice sheets.

Till deposits in the Hudson and Maynard quadrangles have been divided into two mappable morphologic forms, ground moraine and drumlins.

GROUND MORAINE

Ground moraine has a broader surficial distribution than any other unconsolidated formation in the area, and presumably it underlies many of the stratified drift deposits. Because it is a relatively thin accumulation it rarely exerts much control upon the topography but reflects in a general way the configuration of the underlying buried bedrock surface. In places, it is thick enough to possess its own distinctive topographic expression, and in such places it is characterized mostly by gentle, undulatory relief. Locally, however, it is very hummocky and irregular, as in a tract near the south boundary of the Hudson quadrangle on the Worcester-Middlesex county line. Here the ground moraine is composed of younger till, contains no exposed bedrock, but strongly resembles the knobby terrane so commonly found in end moraines.

At a few localities in the Maynard quadrangle ground moraine composed of the older till has been observed overlying glacial gravels. Best exposed of these is a gravel pit in Maynard on the south side of Great Road (State Route 117) just east of its intersection with the old Boston and Maine Railroad grade. In this pit yellowish-brown till 4 to 6 feet thick overlies mixed gravel and sand 20 feet thick or more. The correlation of the gravel and sand is uncertain. They may have been deposited by a glacier older than the one that deposited the overlying till or by the same glacier advancing over its own outwash. Their immediate significance lies in the fact that they certainly are as old as the till and may be older, a relationship seldom described in central New England where most of the gravels overlie stratigraphically both the younger till and the older till and are ascribed to the glaciation that produced the younger till.

DRUMLINS AND THEIR RELATION TO STRIATIONS ON BEDROCK

Most of the higher hills in the Maynard quadrangle and many of the most imposing ones in the Hudson quadrangle are drumlins (fig. 25). More than eighty of these exist in the area mapped, and their smooth, graceful contours contribute much to the charm and natural beauty of the landscape. Judging from test holes and from natural exposures, the drumlins of the area are composed chiefly of the older till but commonly are veneered for the most part with the younger till. They are mostly oval or elongate in plan. Some, such as Round Hill in Sudbury, are nearly circular. On the average they are relatively shorter and relatively broader than those of such classic drumlin areas as the Boston basin; Clyde, N. Y.; and Watertown, Wis.

In the Hudson and Maynard area no obvious relationship exists between the positions of the drumlins and irregularities in the bedrock surface. Drumlins occur to the lee, to the stoss, on the flanks, and

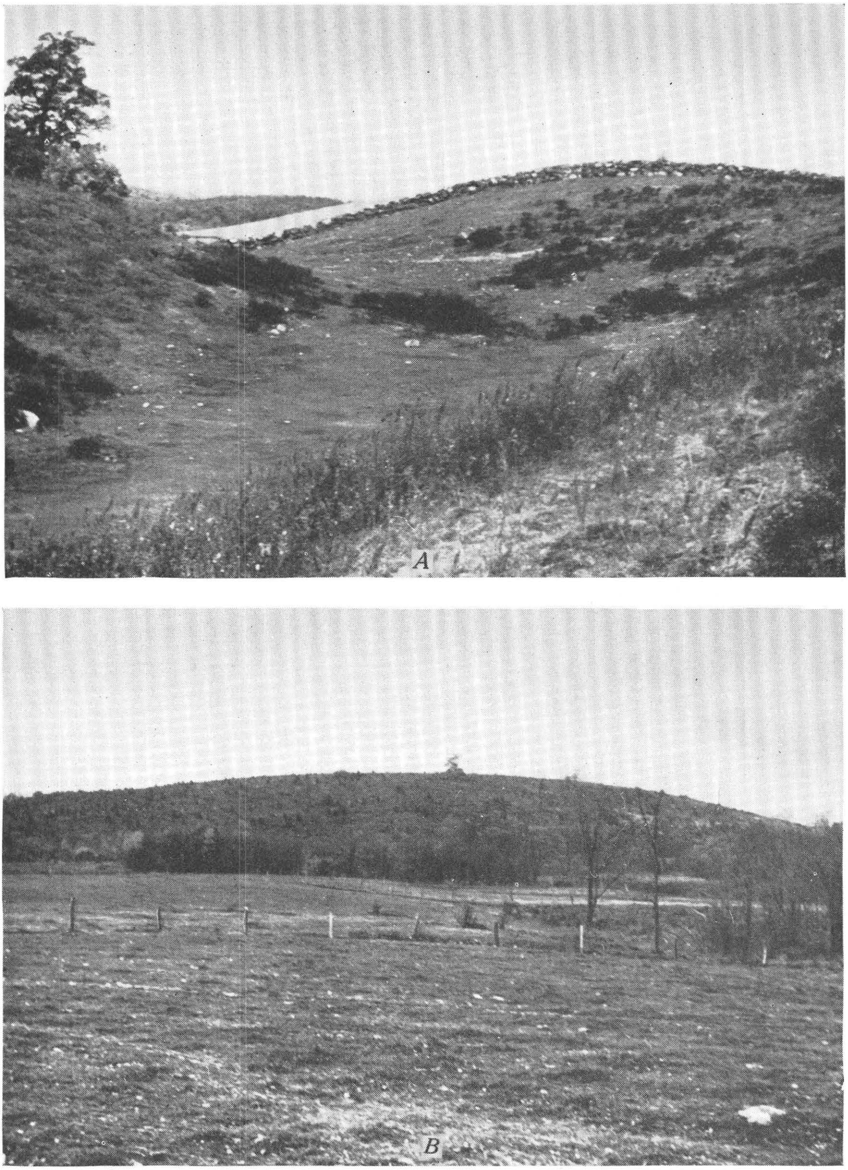

FIGURE 25.—Drumlins in the Hudson quadrangle. *A*, Scoured melt-water channel in crest of Orchard Hill, Gleasondale. Windblown sand in botton of channel. View toward northwest. *B*, Spindle Hill, Stow, viewed from near Gleasondale Road. Ice moved from right to left.

on top of bedrock hills. They are found in valleys, on broad plains, and in hilly uplands. They occur singly or as composites—partly joined clusters of two or more. Summer Hill in Maynard is the highest summit in a cluster of at least six drumlins.

Available evidence indicates that bedrock cores are not integral parts of drumlins and are not essential to drumlin construction. Not only is bedrock unexposed on any drumlin in the area, but a well drilled near the summit of Boon Hill, a drumlin in Stow, penetrated 120 feet of till before reaching bedrock. Boon Hill stands hardly more than 100 feet above the surrounding areas. In Hudson a well was drilled to a depth of more than 80 feet on the flank of a drumlin southeast of Gospel Hill without reaching bedrock. Such evidence rarely is available because drumlins are so seldom drilled for water, and records are seldom kept of those which are drilled. Corroborative evidence is found in other areas. In the Boston basin, for example, where many drumlins are partly dissected by wave action, none display bedrock cores. The drumlin Governors Island in Boston harbor, moreover, was excavated to a platform a few yards above sea level, in order to make way for the enlarged Logan airport, without exposing a core of bedrock.

Most interesting of all drumlins in the area is Orchard Hill near Gleasondale. Viewed from its base, Orchard Hill betrays nothing unusual in its form, but extending for about three-fifths of its length, parallel to and just west of its axis, is a remarkable scoured melt-water channel (fig. 25, *A*). First described by Barton (1895, p. 8) and later noted by Alden (1924, p. 55), the channel is 27 feet deep at its deepest point. Its gradient is toward the south except in a short segment at the north end where it has been reversed by postglacial erosion. Its sides remain steep and sharply outlined. In the bottom of the channel is a mixture of sand, silt, and pebbles that appears to be partly windblown material and partly colluvium. If a concentration of boulders originally covered the bottom of the channel, as seems probable, it has been buried beneath this mixture. Any boulders that may have remained exposed, moreover, probably have been added to nearby stone fences, for the hillsides and the channel itself are cleared for cultivation and pasturage.

Both Barton and Alden recognized the channel as the product of scour by late glacial melt water. Both believed that at the time of its formation the front of the retreating ice stood at the north end of Orchard Hill, and water draining off the ice scoured the channel. This view, however, must be modified somewhat to fit the conditions as we now see them. The concept of a continuous, slowly withdrawing ice front in this area no longer appears valid, and it seems probable that Orchard Hill was not only buried under ice at the time the channel was cut but that the ice margin lay far to the south. Instead of a continuous ice front the glacier margin at this time was probably a broad, highly irregular zone of stagnation. Melt water pouring off the wasting ice eroded to the bed of the glacier, and there, encountering Orchard Hill, cut the channel now preserved. Meanwhile a small esker was constructed at the lower end of the channel, perhaps of material eroded from the channel. Inasmuch as this esker could only have been formed against supporting ice walls, the channel must have been incised through ice into the till of Orchard Hill, for otherwise a fan instead of an esker would have been constructed. One might argue that at this time the top of Orchard Hill could have been exposed although surrounded by ice to the level of the top of the esker. If this were true, however, melt water, seeking the lowest available escapeway, would have flowed between the exposed part of the hill and the adjacent ice instead of over the top of the hill, and the scoured channel would now follow essentially a contour instead of the crest of the hill.

In Maynard just south of Tuttle Hill is another channeled drumlin probably no less remarkable than Orchard Hill. Because of heavy underbrush and timber, however, the channel is less well displayed. Unlike the Orchard Hill channel, it crosses the drumlin almost diagonally, and from a saddle in the crest of the drumlin it grades downward on both sides. The bottom of the channel is extremely bouldery, although it is choked with windblown sand on the southeast side of the hill.

Although it is not well understood why drumlins abound in certain areas and are lacking in others, and although many questions remain regarding their origin, it is generally agreed that they are subglacial accumulations formed beneath and molded by moving ice. Because their shape offers least resistance to the overriding ice, their long axes accord in a general way with the direction of ice movement as indicated by striations and scorings on exposed bedrock surfaces. (See fig. 26.) There is, however, a notably wider variation in the alinement of drumlin axes than of the observed striations on bedrock. The axis of Annursnack Hill, three-fourth miles north of the Concord Reformatory, for example, bears about S. 50° E. whereas striae in the same vicinity bear from S. 4° E. to S. 11° E.; the axis of Wright Hill in West Acton bears about S. 40° E. whereas nearby striae bear from S. 4° E. to S. 8° E.; and the axis of hill 321, just south of Tuttle Hill, Maynard, bears S. 10° W. whereas the nearest observed striation bears S. 3° E.

The striations now found on exposed ledges probably represent a relatively short and late interval in the life of the ice sheet that produced them, whereas the period of drumlin construction must have continued over a relatively great span of time. Thus, a striation is formed in the short time required by the ice to move a part of its basal load, its cutting tools, across a given ledge, but drumlin construction requires enough time for the accumulation and shaping of a great mass of debris by overriding ice. Stated differently, formation of striae requires passage over a given ledge of an amount of ice approximately equal in length to the length of the striation, but a drumlin must require the passage of ice equal to many times the length of the drumlin. It is altogether probable, therefore, that the drumlins of the area, during their construction, were affected by, and responded

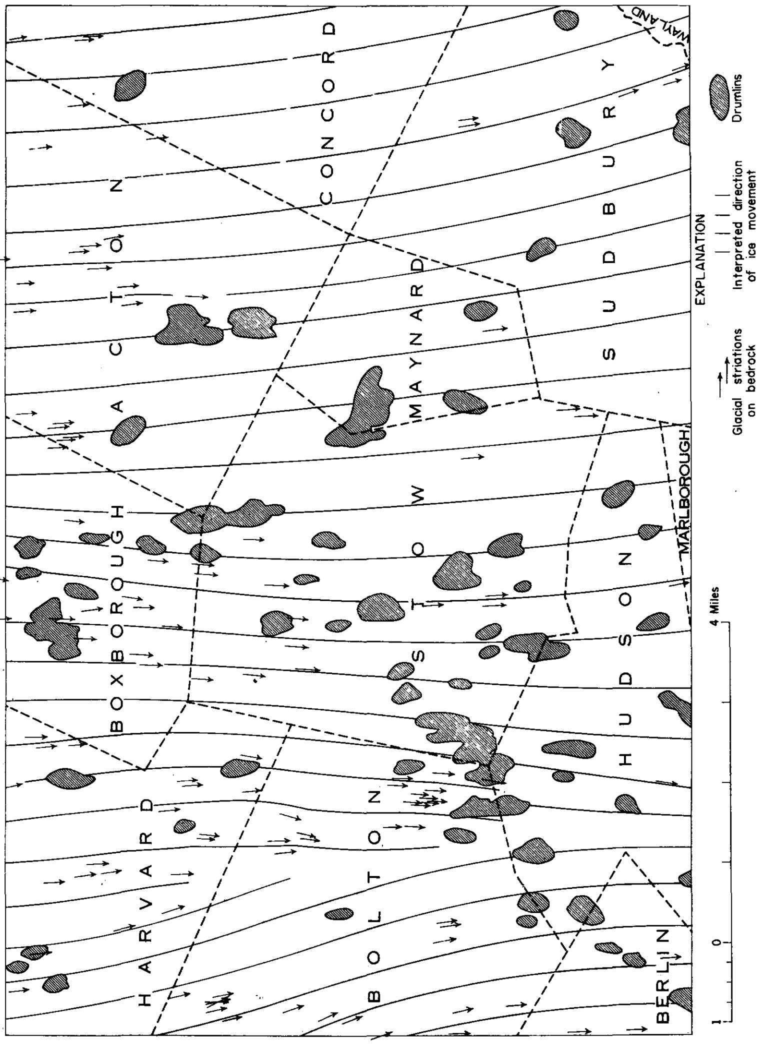

FIGURE 26.—Diagram showing directions of latest ice movement in Hudson and Maynard quadrangles as indicated by glacial striations on bedrock. Arrows represent striations; closed lines represent drumlins.

to, many factors—perhaps recurrent changes in direction and velocity of ice movement and perhaps variations, as to both time and place, in the basal load carried by the ice—factors that little if at all affected final orientation of striations because striations represent only the flow direction of the latest ice to abrade the outcrop. Such effects and responses might have taken the form or part remolding of already constructed drumlins, perhaps of complete remolding of some, and of different orientations in drumlins of slightly different age. No such response would be indicated by the striations on exposed bedrock surfaces, for any shift in ice flow would quickly obliterate most if not all previously formed marks.

Deep scorings might withstand considerable shifting of flow, but most striae in the Hudson-Maynard area are shallow superficial scratches. At only one locality in the area, at Vaughn Hills, have striae of more than one orientation in one place been observed, and there is no reason to believe that all these are not essentially contemporaneous. The weaker and more obscure directions, having departures of 10 degrees from the prevailing direction, probably represent slightly earlier flow adjustments. It is also possible, of course, in our present knowledge, that the drumlins were formed by one or more earlier advances of the ice, even by more than one ice sheet, and that they reflect in a complex manner the results of ice flow of a very long period of time.

STRATIFIED DRIFT

Deposits of sorted or stratified drift, those deposits reworked by glacial melt water, are placed in two main categories in the area mapped; these are ice-contact deposits and proglacial deposits. By far the greater bulk fall into the first category.

Ice-contact deposits, as the name implies, accumulate in contact with the ice, that is, upon, against, or beneath wasting ice masses. Complete melting of the ice leaves a characteristic surface, which, though commonly slumped or deformed, represents the surface of ice contact. Wasting ice, therefore, plays a preeminent part in the configuration and accumulation of these deposits. The proglacial deposits, on the other hand, accumulated beyond the ice margin and in most respects resemble normal waterlaid sediments.

In the Hudson-Maynard area stratified drift is of several distinctive morphologic forms, each indicative of a particular mode of origin and of a particular relationship to the wasting ice. Gradations from one form to another in shape, size, and composition are numerous and are expectable in the light of the respective origins of the various forms.

KAMES AND KAMEFIELDS

Kames are mounds or hillocks of poorly to well-sorted drift, diverse in size, shape, and composition. Where closely spaced, they are collectively called kamefields and as such are characterized by unusually hummocky terrain.

Most kames of the area are completely enclosed by abrupt ice-contact slopes. Some kames have considerable relief, as much as 70 feet, although 35 feet or less is a more common height. Many are connected with kame terraces or to headward parts of kame deltas and are clearly related to them genetically. Other kames grade into eskers or crevasse fillings, and still others are isolated, apparently independent of any other ice-contact features.

Most of the kames consist of sediments that have been reworked only moderately by melt water and transported only short distances from their source in the ice. Thus, most of the stones are subangular to subrounded, and some retain glacially polished and striated surfaces that would have been destroyed by percussion and abrasion during long transit. Such sediments consequently have been but slightly sorted and have a range of grain size almost as great as that of the till from which they were derived. Fine sand, cobbles, and boulders may occur together in one deposit, although medium gravel is commonly the dominant constituent and some deposits are nearly all sand.[1] Some kames are so bouldery that, without adequate exposures, they are easily mistaken for hummocky ground moraine.

As in most torrential deposits, stratification ranges from poor to good. In most instances it has been deformed by settling, slumping, and sliding that accompanied wasting of the adjacent supporting ice. Hardly an actively worked pit in the area, where kame deposits have been exploited, does not exhibit these collapse features. Bedding may be highly contorted and tilted far beyond its normal angle of repose. In a large kame near Laws Brook road in Acton, crossbedded and ripple-marked beds of sand had been tilted, pushed, and crenulated into tight, accordionlike folds.

ICE-CHANNEL FILLINGS

The term ice-channel fillings as here used is an inclusive, morphological designation for both eskers and crevasse fillings. This general term is applied to these features because they possess many common attributes and cannot in every instance be distinguished. Well-formed ice-channel fillings occur in every town in the area. They are long, narrow, commonly steep-sided ridges of stratified drift that have been deposited in subglacial tunnels or in ice-walled channels open to the sky. Well known to local farmers as sources of gravel, they are locally called "whale backs."

Ice-channel fillings of the Hudson and Maynard quadrangles vary considerably in shape, dimensions, composition, and mode of origin. Most of them are sinuous in plan, but some are nearly straight. Most have sharp, uneven crests (fig. 27), but some have relatively broad,

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[1] In describing grain size of sedimentary materials, this report follows the nomenclature adopted by the National Research Council (1947). It should be borne in mind, however, that grain sizes herein described are approximate values obtained from field observation.

FIGURE 27.—Esker near Flag Hill Road, Boxborough. Coarse poorly sorted gravel is vaguely stratified. Light-colored layers are sand. Note sharp crest.

flat tops. Many are bifurcated into branches, some of which rejoin. Most of them are segmented; some segments are less than 200 yards long, but others extend three-quarters of a mile without a break. A segment half a mile long, however, is longer than average.

The ice-channel fillings range in height from a few feet to 40 feet or more, and most of them lie at low levels in swampy ground in the bottoms and sides of valleys, although a few cross uplands of ground moraine. Commonly they merge with kames, kame terraces, or kame deltas.

Most of the ice-channel fillings are composed of coarse and poorly sorted sediments, which fact suggests overloading, torrential flow, and rapid fluctuations in the volume of discharge of the melt-water streams that deposited them. Coarse gravel, therefore, is a prominent and expectable constituent, but the range of grain size is wide. Some, moreover, are composed chiefly of sand, and one near the Assabet River in Concord contains a section 6 feet thick of varved silts and clays (fig. 28).

Stones in the coarser textured deposits tend to be subrounded. Cobbles, and less commonly boulders, are strewn along the crests. Stratification generally is fair to good, but mostly it is somewhat deformed, especially along the flanks of the ridges where collapse has been severest. Beds are characteristically lenticular, and cross-bedding is common.

FIGURE 28.—Laminated silts exposed in a crevasse filling beside the Assabet River in Concord, near the Acton town line. Thin, dark layers are clay.

Most of the ice-channel fillings in the area have been deposited by turbulent, fast-flowing streams, for only such streams could have deposited the coarse and heterogeneous type of material commonly found in such deposits. Whether most of them have been deposited in open-walled channels or in subglacial tunnels, however, is not known, for conclusive evidence is rarely available. Some probably are true tunnel eskers, for they evidently were deposited by streams that flowed uphill under the force of hydrostatic pressure. Such an esker was formed near Flag Hill, on the Acton-Boxborough town line. In a horizontal distance of about 1,600 feet the base of this esker rises southward 15 to 20 feet, and its crest rises about 50 feet. At the time this esker was visited well-formed crossbedding was exposed in a gravel pit near its center, and the forsetting in these beds dipped southward, indicating that the aggrading melt-water stream flowed southward and uphill, a condition possible only under hydrostatic pressure in a confined tunnel. At its south end this esker grades into kames that seem to have formed at the tunnel mouth but in openings within the ice.

Other ice-channel fillings almost as certainly were deposited in open-walled channels, and illustrative among these is one in Bolton west of Rattlesnake Hill. This feature extends about half a mile from Sugar Road to Burnam Road. Its comparatively even and broad crest, which resembles a railroad embankment, accords in height and gradient with nearby kame terraces that skirt the valley sides, suggesting that both kame terraces and ice-channel filling were constructed at the same time and were graded to the same temporary local base level. Such conditions, of course, do not preclude the possibility that the ice-channel filling still may have accumulated in an ice tunnel, given a sufficiently large tunnel and unobstructed flow of its contained stream. It seems very unlikely, however, that a tunnel, broad enough and high enough to accommodate at grade the stream that deposited the filling, could have remained roofed over in the advanced stage of deglaciation that must have prevailed at the time kame terrace material was accumulating nearby. As indicated by the configuration of the terrace margins, only a thin, narrow, and elongate mass of stagnant ice lay in the valley at this time, and it would seem that collapse of the tunnel roof almost certainly would have accompanied the rapid wastage caused by melting from above as well as melting and erosion by the flowing stream within. The channel need not even have originated as a tunnel but may have formed by entrenchment of melt-water drainage flowing over the surface of the ice. Such drainage need not flow over the surface for a long time but may quickly entrench itself. On the edge of the Greenland icecap near Kjoge Bay, the author has seen melt-water rivulets entrench themselves, in a few days, 10 to 30 feet or more into crevasse-like channels in the stagnant ice of the marginal area.

Of special interest because of its fine texture, which is indicative of slow sedimentation under slack water conditions, is an ice-channel filling in West Acton between the Assabet River and Main Street, three-quarters of a mile southwest of the intersection of Main Street and Harrington Avenue. In this deposit, exposed at road level, is a 6-foot section of varved silts. These silts grade upward into mixed sand and gravel 4 to 6 feet thick and downward into fine sand; remarkable collapse features are displayed on the flanks of the deposit. Inasmuch as 12 pairs of varves are exposed in this section, 12 years is regarded as the minimum length of time required for the accumulation of the deposit.

Certain other short but coarse-textured ice-channel fillings probably are transitional forms closely related to kames. Several of these lie just north of the large kame delta west of Nine Acre Corner in the southern part of Concord. They are closely associated with, and grade into, coarse-textured kames that constitute part of the kame delta's upstream ice contact. These features appear to have been deposited by vigorous streams pouring torrents of debris-laden water into crevasselike openings adjacent to the ice contact of the delta.

KAME TERRACES

Kame terraces were formed by melt-water streams that deposited their loads between wasting ice masses and adjacent ice-free uplands or valley walls. They acquired their terracelike form following complete dissipation of the ice.

Kame terraces range widely in shape, dimensions, and composition. In general they have broad, relatively flat cross profiles which break away sharply at the ice-contact slope. Locally, however, the terrace surface, instead of being flat, slopes irregularly from the upland margin to the valley floor, a condition especially common to some of the smaller, somewhat isolated kame terraces that lie as rather formless sloping masses against higher ground. In many places the terrace tops are pitted by dimplelike closed depressions or kettles formed by melting of buried or partly buried residual ice blocks. In some places the terrace tops are crossed by shallow channels scoured by eroding melt-water streams.

Irregular ice-contact slopes, marked by many projections and reentrants, characterize most of the kame terraces. These are mostly abrupt and steep, but some are rather broad and gentle. Along them the bedding tends to be slumped and deformed by collapse. Here, too, kamefields may grade into the terrace.

Variations in composition from place to place and from terrace to terrace are wide. Certain of the smaller deposits are composed of poorly sorted, heterogeneous mixtures of sand, gravel, and cobbles. Others are chiefly sand. Most of them, however, are composed mainly of gravels that are well stratified, fairly well sorted, and fairly well rounded.

Crossbedding is prominent in most kame terraces. In places certain kame terraces exhibit deltaic bedding that suggests local ponding of the melt water and a depositional environment transitional between that of normal kame terraces and kame deltas.

Because kame terraces were partly confined by ice during their formation, they may bear only general relationship to the present-day drainage of the area. Most of them, it is true, lie in or along the present major drainageways, for the ice remained there longest, but in some instances at least, the melt-water drainage flowed opposite the direction of the present drainage. Along lower Heathen Meadow Brook, for example, kame terraces are graded southward, but the brook now flows sluggishly northward.

Some of the terraces, as well as associated kames and other features, are graded to bedrock-defended cols or low points along the divides. These served as temporary drainage base levels only until downwasting of the valley ice uncovered lower escapeways for the melt water. Thus new drainage profiles were established as old ones were abandoned. Some terraces, however, bear no apparent relationship to any such cols, and may have been graded to temporary ice lips. Still others were graded to ephemeral proglacial lakes.

Stream erosion seems to have modified parts of certain kame terraces before complete disappearance of the adjacent ice. Thus, the broad levels at West Concord (altitude about 150 feet) appear to have been somewhat more extensive at one time than at present, and in places they may even have extended completely across the valley from wall to wall. Between Harrington Avenue and Main Street the Assabet River, flowing in a shallow trench, now bisects the levels roughly into north and south counterparts. The terrace margins facing this trench probably are not ice contact; more likely they are due to later entrenchment of the river. It is unlikely that a wasting ice block could have assumed the very elongated, narrow, and arcuate shape required by this trench; instead it probably would have separated into smaller blocks, and these would have produced a chain of kettles instead of one long trench. Just upstream and downstream from here, however, the valley bottom widens into what are probably ice block areas. Moreover, terrace margins in these areas are clearly ice contact, for they are associated with kettles, hummocks, irregular projections and re-entrants, and even with ice-channel fillings whose bases lie at river level. These forms must have been protected by enclosing ice to have escaped destruction by the entrenching river. Downstream from Harrington Avenue, in the vicinity of the New York, New Haven and Hartford Railroad bridge, the river swings north in a broad curve. Here the terrace margins display no ice-contact features, but on the contrary seem to be incised; the flattish, convex left bank of the stream appears to be a slip-off slope, and the steep, concave right bank, on which the stream impinges, appears to be an undercut slope.

While terrace construction was still in progress, however, and the depositing stream was flowing at the present terrace summit level (altitude about 155 feet), the waters must have been confined and held to this level by large ice masses. A few hundred feet south of Harrington Avenue is a large ice-block swamp that drains eastward into Dugan Brook. This swamp lies about 10 feet above present river level, and about 20 feet below the 155-foot terrace level. Dugan Brook flows at about the same altitude as the Assabet River. If the swamp and the drainage basin of Dugan Brook had not been occupied by ice at the time of terrace construction, they would have been filled with sediment, and if ice had not remained there until the Assabet had entrenched itself below the swamp level, the river would have flowed into the swamp through the low divide at Harrington Avenue, it would have occupied the valley of Dugan Brook, and it might have remained there to the present time, for its gradient would have been steeper than the present bed, and its course to a junction with the Sudbury River would have been greatly shortened. Moreover, the eskers and kames that cross the lower course of Dugan Brook probably would have been largely destroyed by any stream significantly larger than the present brook. It seems likely, therefore, that the course of the Assabet, essentially as it is today, was determined before glacial ice completely disappeared from the immediate area.

KAME PLAINS

Associated with other ice-contact deposits of the area are kame plains. These are flat-topped, steep-sided hillocks composed of sand and gravel and enclosed by ice-contact slopes. In outline some are fairly regular, but others are very irregular. They range in height from a few feet to 30 feet or more and in breadth from a few hundred feet to half a mile or more. Having been deposited by aggradating melt-water streams, they possess characteristics of both kames and kame terraces. Unlike kamefields, which are hummocky, kame plains possess relatively flat tops but may be pitted by kettles. Many of them lie adjacent to kame terraces, separated commonly by a narrow trench or a swampy moat.

Large cuts in the sides of kame plains characteristically reveal well-stratified and fairly well sorted sediments. Probably sand is the chief constituent, but variations in material from place to place, even in a single deposit, are wide. The size range is from coarse gravel to silt. Bedding is mostly horizontal or nearly so, and the finer sediments commonly display cross lamination.

Kame plains can be seen in most towns of the area. Good examples occur along Assabet Brook in Stow (Brookside Cemetery is on top of one), Bolton, and Harvard; Pratts Mill Road in Sudbury crosses a large kame plain near the south boundary of the Maynard quadrangle.

OUTWASH PLAINS

In the southwest part of the Maynard quadrangle, and extending into the Hudson quadrangle, broad plains of sand and gravel were constructed by melt waters during the withdrawal of the ice. Although these waters were confined on the southwest by a till-mantled bedrock highland in Marlboro and on the east by a line of till or bedrock hills and ice blocks in Sudbury, they spread out more broadly than did melt water in any other part of the area, flowing over and around isolated ice blocks and around isolated hills of till and bedrock to form broad, fanlike structures. Because many buried ice blocks were left behind the retreating ice front, and remained unmelted until after deposition of outwash had ceased, the plains are pitted by numerous small kettles, many of which contain swamps, and by a few large ones, some of which contain ponds. Largely because of the many stranded ice blocks, the plains possess some of the attributes of kame terraces, although the waters that constructed them were essentially proglacial. Locally, in fact, the outwash plains grade into true kame terraces, as in the area southwest of Boons Pond in Hudson. On the other hand, they also bear some resemblance to the subaerial parts of deltas and, indeed, when detailed mapping has been accomplished in the Framingham quadrangle to the south, may ultimately prove to be graded to a water plane of extinct glacial Lake Sudbury.

Although the ice front seems to have been essentially continuous at the time that the outwash plains were being constructed, it should be emphasized that much thinning and ice-block separation at the ice front is indicated by the many swamps, ponds, and kettles that dot the surface of the plains.

A pause in the back-melting of the ice front during construction of the outwash plains is indicated by an irregular line of ice-contact slopes in Sudbury. These extend northeast from Hudson Road, south of Bottomless Pond, along the south shore of Willis Pond to Willis Hill. From these ice contacts a broad, sloping plain, having its main apex at Willis Pond, was constructed southward. Apparently ice that remained in the Willis Pond area protected these ice-contact slopes from destruction by melt water when the ice front withdrew to the north. Burial of such ice under debris swept down from the glacier might well have retarded melting until the main ice mass had melted back well to the north. Thus, the Willis Pond-Bottomless Pond area, and the intervening swamp is regarded as a sort of fosse.

East of Willis Hill the frontal zone appears to have disintegrated into a mass of wasting ice blocks, just as it later did farther north in the kame terrace areas. Much of the Sudbury basin, moreover, became flooded by ice-marginal lakes, as described below.

On the north the outwash plains are bounded by a line of very irregular, northward-facing ice-contact slopes similar to those near Willis Pond, but more extensive. These ice-contact slopes extend from a point near the intersection of Old Marlboro Road and Powder Mill Road in Sudbury, west into Maynard, thence southwest along the south side of the Assabet River to Boon Hill, and southwest to Gospel Hill in Hudson—a total distance of about 6 miles. They are interrupted locally by hills of till or bedrock but are continuous around the margins of kames and small kame terraces that grade into the outwash plains. Southward from these ice-contact slopes the plains were constructed by waters that flowed off the ice, much as alluvial fans are built against a mountain front.

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A rather wide range of grain size characterizes the sediments of the outwash plains. In general the texture grades from coarser near the ice-contact slopes to progressively finer farther south, although exceptions are many. The chief constituent of the deposits near the ice-contact slopes, and of most of the related kames and kame terraces, is medium gravel, but southward this grades into mostly sand and fine gravel. The deposits are also most heterogeneous near the ice contacts where, locally, lenses of coarse gravel and even of fine sand are interbedded with medium gravels.

Most cuts in outwash plains display well-developed stratification. Crossbedding is fairly common in the finer sediments as well as in the coarser ones, and collapse structures have been observed in exposures near ice-contact slopes.

EXTINCT GLACIAL LAKES AND THEIR DEPOSITS

As the ice margin withdrew northward in eastern Massachusetts the upper reaches of many northward flowing streams became cleared of ice while their downstream portions remained blocked, and broad areas thus were flooded with water. In parts of the Hudson and Maynard quadrangles are deposits that have been attributed to three such glacial lakes—Lake Sudbury, Lake Assabet, and Lake Nashua.

Deposits of glacial Lake Sudbury, described by Goldthwait (1905, p. 298), cover part of the Maynard quadrangle as well as larger areas to the east and south, chiefly in the Sudbury River basin. Deposits of glacial Lake Assabet, described by Alden (1924, p. 74), cover areas mainly to the south of the Hudson quadrangle in the Assabet River basin, but embayments of this lake covered parts of Hudson and Berlin in the Hudson quadrangle. Deposits of glacial Lake Nashua, first described by Crosby (1899b, p. 106) and later by Alden (1924, p. 60), by Brown (1931, p. 475), and by Jahns (1953), cover parts of several quadrangles in the Nashua River basin of central Massachusetts; in the northwest part of the Hudson quadrangle, deposits assigned to glacial Lake Nashua by Alden (1924, pl. 6) are here regarded as kame terraces. Relatively small parts of any of these three extinct lakes lay within the Hudson or Maynard quadrangles; fuller discussions of these lakes than can be made here, therefore, may be found in the reports cited above.

GLACIAL LAKE SUDBURY

Melt water that swept directly off the ice constructed large kame deltas into the standing water of glacial Lake Sudbury in the east-central part of the Maynard quadrangle. The term "kame delta," as defined by Richmond (1952) and as used in this report, refers to those lacustrine deltas that were built against glacier ice by loaded streams that flowed off the ice. Such deltas, therefore, possess ice-contact slopes along their proximal sides; most of them, also, are pitted with kettles and contain ice-rafted boulders.

In addition to kame deltas, lake-bottom deposits underlie rather broad tracts. These deposits consist chiefly of fine sands and varved silts which in colonial time were used for making bricks. Lake-bottom sediments have been identified in test holes and ditches along both sides of Cold Brook in Sudbury and Concord, near Concord Road in Sudbury, and near Lincoln Road in Sudbury. Thus it is evident that standing water in the Sudbury basin was fairly extensive.

Other indications suggest, however, that at least as far as the Maynard quadrangle portion of Lake Sudbury is concerned, the lake basin was not occupied by one broad body of open water but was choked with many large masses of wasting ice, and as such probably appeared as several relatively small, connected lakes, separated largely by ice blocks.

The broad swamps in that portion of the Sudbury basin drained by Cold Brook, Pantry Brook, and Bridge Brook are bounded, at least partly, by steep banks that range in height from a few feet to 10 feet or more. The individual swamps, therefore, are separated by intervening, somewhat higher areas composed of lake-bottom deposits, and the steep banks that separate them are probably ice-contact slopes constructed subaqueously against blocks of grounded ice. These banks are doubtless constructional forms, because most of them could not conceivably have been cut by laterally swinging streams. Moreover, they are forms that could not have been constructed by sedimentation in a lake free of grounded ice blocks, for such sedimentation tends to even out irregularities rather than to produce them.

If open water had flooded the whole Sudbury basin to the altitude indicated by the kame delta tops in that area, a large lake would have existed. Strong wave action could have been expected in such a lake, especially because of the probable severity of the periglacial climate, which must have been attended by strong and probably frequent winds, as indicated by widespread aeolian deposits. Under such circumstances prominent benches should have been cut into the soft and easily worked glacial deposits that mantle the basin, particularly at such exposed sites as Round Hill. Search has been fruitless for such features, except a possible shingled slope of sand-covered till just west of the kame delta at Haynes Road in North Sudbury. If most of the lake surface were broken by large and abundant grounded residual ice blocks, however, strong wave action would be unlikely, even during gales, and such strandline features might be weak or even wanting.

Although wind and wave action may prevent freezing on the surfaces of large water bodies when the air temperature falls below 32° F., even freezing may promote rather than retard the formation of shore features. After ice has formed on a lake, or any other confined body of water, further lowering of the temperature causes shrinkage that produces tension cracks. New ice forms in these cracks; any subsequent rise in temperature then causes expansion of the whole ice mass, and the force of the expansion is directed against the shore. Temperature fluctuations, therefore, promote a sort of ratchet action by the shore ice capable of moving large quantities of bottom material, even boulders, from the offshore area to positions above the water line. Harding (*in* Meinzer, 1942, p. 229) has pointed out that "such shore crowding exerts sufficient force to affect structures along the shore * * * and to push lake-bed materials shoreward, forming ridges or bars above the water line." The wider the water body, of course, the greater is the total expansion of the ice, the greater will be the movement of the shore ice, and the greater will be its effects upon the shore. In lakelets the total expansion is not large, and its effects may be negligible.

Floating bergs, if abundant, could have effectively dampened wave propagation and thus retarded shore erosion, but calving, by which bergs are discharged from glaciers, operates most effectively in actively moving glaciers that are discharging into deep water. Gravity is essential in the process, and the ice either must break and fall from the glacier front under its own weight (hence the ice front must be steep), or it must break from below and be carried to the surface by its own buoyancy. Some floating berg ice might have entered Lake Sudbury, but the quantity probably was small. Not only was the ice that dammed the lake on the north stagnant and very thinned at its edges, and the water relatively shallow, but kame deltas then being actively constructed outward from the ice front would have impeded calving.

The kame deltas also afford evidence that large blocks of ice remained in the lake basin. Where delta growth was unhindered, digitate frontal slopes were formed, as exemplified by the excellent delta at Haynes Road in North Sudbury and by parts of several other deltas. But the many irregularities in both the tops and flanks of most of the deltas were caused by ice blocks. White Pond, in the delta near Nine Acre Corner in Concord, for example, is the site of a former large ice block, as is the deep box canyonlike re-entrant just to the southeast.

That ice masses remained in the lake basin not only throughout the life of the lake but also after it was drained is indicated in the West Concord area. Most of West Concord stands on a kame terrace whose summit level is about 155 feet in altitude. This terrace and other nearby terraces, kames, and ice-channel fillings of the same general altitude, stand well below the level of the delta tops and hence of the old lake surface, and must have been deposited by running water after the lake was drained.

Although it seems evident that much of Lake Sudbury was crowded with large masses of grounded ice, the problem remains as to how the lake was held on the south. This problem involves areas beyond those mapped, but because of its bearing locally it should be reviewed here.

The confluence of the Assabet and the Sudbury forms the Concord River, which flows northeastward. If a dam 40 feet high were now built across the Concord at Billerica, and if all drainage were blocked down the Shawsheen River to the east, water would be backed as far west as Maynard on the Assabet River and as far south as Framingham on the Sudbury River, and would submerge Bedford, Concord, Wayland, and Saxonville. Regardless of the height of the dam, however, the surface of this lake could not rise much above an altitude of 140 feet, which is about the altitude of the lowest point in the divide between the Sudbury and Charles Rivers. This is about 50 feet lower than the pool level of glacial Lake Sudbury, as indicated by the tops of the kame deltas in the Maynard quadrangle. To gain closure for the lake basin, at such an altitude (190 to 195 feet) several gaps in the divide between the Sudbury and Charles Rivers must be closed. Damming may have been accomplished by blocking with ice all gaps lower than the indicated lake surface, or by relative uplift of the divide to the required altitude. Goldthwait (1905, p. 298) favored the latter conclusion, namely, that present altitude discrepancies between the height of delta tops and outlets to the south are due to postglacial differential uplift, the area to the north having risen higher than the area to the south. He estimated the required tilt to be about 7 feet per mile in a direction due south. On this basis he postulated several successive outlets and several successive water stands. The deltas in the Maynard quadrangle he assigned to his "Cherry Brook stage."

So far as the Maynard quadrangle is concerned, the area involved is too small to draw any safe conclusions regarding tilt. Although the kame deltas in this area are distributed north and south over a distance of about 4 miles, they all stand, with one exception, at about the same height. If postglacial tilt has occurred, it is not readily apparent in this area. On the other hand, kame terraces near Bridge Brook Swamp in Sudbury stand somewhat lower (170–180 feet) than the deltas to the north. Inasmuch as these kame terraces were constructed in the Sudbury basin probably before the deltas, and hence when Lake Sudbury should have been in existence, their seemingly anomalous height is probably best explained by the tilt hypothesis. Bedding in the kame terrace at Lincoln Road, just north of Bridge

Brook, moreover, is partly deltaic, suggesting that this kame terrace was built partly into standing water. It is also conceivable that these kame terraces were deposited on grounded ice, and that their present altitude discrepancies are due to a combination of postglacial tilt and lowering of the deposits by melting of such buried grounded ice.

GLACIAL LAKE ASSABET

In the Hudson quadrangle the deposits associated with glacial Lake Assabet are all of ice-contact origin, and they indicate by their configuration that very little open water ever existed in the Hudson quadrangle portion of the lake basin. If any broad stretches of open water existed, all of them were south of the Hudson quadrangle boundary. Many of the deposits in the Hudson area are not lacustrine in the strictest sense, and many deposits attributed by Alden (1924, p. 74 and pl. VI) to "glacial Lake Assabet and other temporary glacial lakes," moreover, now appear to be fluviatile ice-contact deposits.

In Berlin near the Hudson town line, Gates Pond Road runs along the top of a small kame delta that marks the highest stand of Lake Assabet in this area, at an altitude of about 315 feet. On the north this kame delta is backed by steep ice-contact slopes. To the northwest it grades into a kame terrace. The southern or frontal slope is foreset and digitate, indicating that open water stood to the south. This deposit, however, may have formed in what was hardly more than a water-filled hole in the ice, for no lake-bottom deposits have been identified in the area, and lower level fluviatile deposits, laid down at a later time south of the kame delta, are ice contact at least in part.

Some kames, kame terraces, and ice-channel fillings in the vicinity, attain approximately the same altitude as the kame delta just described and appear, therefore, to be graded to the same water plane. (See pl. 3.) If this is true, openings in and around the remaining valley ice must have been sufficiently connected at this stage to have enabled standing water to attain a common level at the several sites of deposition, and thus to constitute a common base level to which those deposits were graded.

A lower or intermediate stand of the water is indicated by kames and kame terraces in the vicinity of Hudson at an altitude of about 280 feet. (See pl. 3.) At the time of this water stand the lake basin apparently was still being drained by an outlet well south of the Hudson quadrangle boundary. In the Hudson quadrangle, however, ice blocks remained in the lake basin until after the lake was completely drained.

The lowest and last stand of the water began when the gap south of Gospel Hill was opened and admitted drainage into the Fort Meadow Brook valley. This water stand is indicated in Hudson by the broad kame terraces that stand at an altitude of about 250 feet.

Probably it is approximately contemporaneous with, or at least overlaps, the episode of kame-terrace construction just east of Gospel Hill and the related outwash-plain construction farther east in the Maynard quadrangle. The relatively great size of the outwash plains as compared with the smaller deposits of the 250-foot stage suggests that construction of the outwash plains lasted correspondingly longer. If the ice had not been cleared from the highland areas in the southeast corner of the Hudson quadrangle to approximately the position indicated by the ice-contact slopes east of Chestnut Street and north of Main Street in the Fort Meadow Brook area, the gap south of Gospel Hill could not have functioned as an outlet even if it had been cleared of ice. It would merely have contained an embayment. On the other hand, if the ice had been cleared from the Chestnut Street-Main Street area before it was cleared from the Gospel Hill area, and at the same time had been cleared from either of the gaps north or south of Orchard Hill, the gap south of Gospel Hill could not have functioned as an outlet because the Orchard Hill gaps are lower. Clearing of either of the Orchard Hill gaps drained what remained of Lake Assabet and gave rise to the present Assabet River, flowing in the entire drainage basin above that point. However, ice still remained in the Hudson area at this time, and the earliest deposits of the newly formed Assabet River were ice-contact deposits.

Probably the gap north of Orchard Hill was cleared before the gap south of it. Otherwise, the Assabet River would have flowed through the south gap and probably would have remained there. No evidence of scour is found in the south gap; it is bottomed with sand and contains swamps, and is all but closed by constructional landforms. The north gap, on the other hand, is clearly scoured below the 200-foot contour. Gleasondale, in fact, was known for many years as "Rockbottom" because of the bouldery bed of the Assabet River in this gap.

GLACIAL LAKE NASHUA

Glacial Lake Nashua has been described and discussed in several reports by Crosby, Alden, Brown, and Jahns. Centering in the vicinity of Clinton, just west of Berlin and Bolton, this lake at one time probably covered parts of several quadrangles.

Although a small area in the northwest corner of the Hudson quadrangle lies within the Nashua Valley and below the levels of certain of its glacial lake stages, the field evidence here suggests that this area was not flooded by waters of the lake but was largely covered by ice during the existence of the lake.

On the high till-covered slopes west of the village of Still River and also northwest of the Vaughn Hills are several large deposits of sand and fine gravel. None of these however, appear to be lake shore deposits. The southernmost and highest, just northwest of the

Vaughn Hills in Bolton, is a small extension of a large and well-formed kame terrace that stretches southwestward to the town of Clinton. The extreme irregularity of the frontal slopes of this broad terrace and its uneven and pitted surface leave little doubt that it was formed under ice-contact conditions and that a large mass of ice, therefore, lay in the Nashua Valley to the west at the time of its formation.

To the north, near the village of Still River, other deposits stand at lower heights. These, too, seem to be kame terraces rather than beach deposits. They are localized, as if deposited in small re-entrants in the ice, and their valleyward slopes are very irregular, whereas beach deposits should be less localized and should present relatively smooth valleyward slopes.

In several published reports T. C. Brown, has taken issue with the ideas of Crosby and Alden regarding Lake Nashua. Rather than a single, large body of open water as envisaged by Crosby (1899b) and Alden (1924), Brown (1931, p. 475) believes that relatively narrow marginal lakelets surrounded large masses of ice that occupied the central part of the Nashua Valley throughout the life of the lake, and that the shore features built into the water are essentially kame terraces. The views of Brown seem to be entirely correct for the Hudson quadrangle, which contains but a very small part of the Nashua basin. In the Ayer and Shirley quadrangles, however, fairly large bodies of open water are indicated by varved lake-bottom deposits, according to Jahns (1953).

UNDIFFERENTIATED SAND AND GRAVEL

Many ice blocks remained after the general ice front had retreated. Areas once occupied by such ice blocks commonly are veneered by sand, gravel, or silt, or mixtures of all three. Much of this material probably came from the melted ice blocks themselves, but part was carried in by winds, and part almost certainly is colluvial wash. In general it has been found impractical to attempt genetic separation of such deposits on a map of the scale here used, so that all have been mapped together. Because of its small area and patchy distribution alluvium in the Hudson quadrangle has not been mapped separately from these deposits, although locally small flood plains are well formed along the Assabet River in Hudson; alluvium has been mapped separately with satisfactory results in the Maynard quadrangle. It has been impractical to attempt mapping lake-bottom sediments separately in the Lake Sudbury area because of their general concealment beneath veneers of sand.

VALLEY TRAINS AND OUTWASH TERRACES

The youngest glacial outwash deposits in the area are valley trains and outwash terraces. They are composed chiefly of fine gravel, sand, and silt. Morphologically these resemble normal alluvium more than any other glaciofluvial deposits.

As mappable features valley trains and outwash terraces are confined in this area to the lower Assabet valley and its tributaries. Here they were deposited after glacial ice had all but disappeared from the immediate vicinity. The overloaded melt-water streams that deposited them probably rose in relatively distant valley areas still occupied by wasting ice. Kettles are the only ice-contact features, and they are uncommon.

The low outwash terraces along the Assabet River, Nashoba Brook, and lower Fort Pond Brook are essentially remnants of valley trains that once extended as fills across the valley bottoms. Terracing has been produced by entrenchment of these streams.

In an area where both downcutting and aggradation are now evidently slight, several factors may have acted alone or jointly to cause entrenchment. At the time of valley-train construction the Assabet River and its tributaries were loaded with glacial sediment. Very likely, the clearing of the streams, following disappearance of the ice, enabled them to revert from an aggrading to a degrading regimen. If postglacial tilt has occurred in this area, one net result has been a gradual flattening of the gradients of the northward flowing streams since the ice was first removed. At present, a further tilt toward the south of a few inches per mile would cause ponding of both the Sudbury and the Concord Rivers. It is readily apparent, therefore, that if postglacial tilt has indeed occurred, the gradients of the Sudbury, Assabet, and Concord Rivers must have been steeper immediately following removal of the ice from the area than they are at present, and, other things being equal, these streams and their tributaries would have been better able to entrench themselves then than they are now. Even now, the Assabet, with a gradient of about 7 feet per mile between Hudson and West Concord, is probably capable of scouring its bed, at least during the high water of the spring runoff. Much of its length, of course, is now ponded behind small dams at several mill sites, and in these places cutting is no longer effective.

Terracing has not occurred in the valley train at West Acton. Upper Fort Pond Brook and the valley train there are graded to a bedrock threshold at South Acton where Fort Pond Brook turns eastward. This threshold has largely checked entrenchment of the brook and terracing of the valley train above South Acton.

AEOLIAN DEPOSITS

Over broad areas in both the Hudson and Maynard quadrangles, periglacial winds deposited a thin, loesslike veneer of silt and fine sand. These aeolian deposits range generally from a few inches to probably 4 or 5 feet in thickness. Their distribution is very patchy, and they are without mappable boundaries. Somewhat thicker deposits accumulated locally as small dunes, but none of these dunes is now active.

Most of the windblown deposits exhibit no stratification, although a deposit observed in Maynard displays delicate crossbedding. Probably because of their loose texture and high permeability, most of them are oxidized throughout. Their color, therefore, is characteristically grayish orange to light brown.

Most windblown deposits on prominent hills are noticeably thicker on the southeast slopes than elsewhere. In places they are lacking from the northwest slopes, as at Round Hill in Sudbury, which fact suggests that the stronger winds blew from the northwest, perhaps as gravity winds flowing off the retreating ice sheet.

POSTGLACIAL DEPOSITS

ALLUVIUM

Since glacial time narrow flood plains have formed along the Assabet River, along lower Fort Pond Brook as far up as Parker Street, and along lower Nashoba Brook. In times of heavy precipitation, or after heavy winters, these flood plains are still occupied. During mapping of the area, a very high flood stage was observed in the spring of 1948, but in the spring of 1949 the streams did not overflow their channels.

The Sudbury River has no flood plain, strictly speaking, in the Maynard quadrangle. Ordinarily its broad flanking meadows are under water most of the time. Even at highest water the river has little current, however, and probably the only significant deposits now accumulating are organic.

Thin layers of alluvium have accumulated in some of the smaller valleys of the area. The material consists chiefly of reworked glacial sand and silt, and commonly contains organic material and some colluvium.

SWAMPS

Swamp accumulations throughout the area consist of sand, silt, and interbedded peat and other organic material. Some peat deposits in the area have been exploited on a small scale for top dressing on lawns and gardens. Some of the swamp deposits probably attain considerable thickness; others are bottomed at shallow depth with till, and commonly display scattered boulders at the ground surface. Many small ponds and pools, by gradual encroachment of vegetation upon their shores and bottoms, are slowly being converted to swamps. It is possible, of course, that much of the material in some of the thicker swamp deposits is not strictly of postglacial origin but accumulated periglacially.

GEOLOGIC HISTORY

PRE-CARBONIFEROUS

The earliest events recorded in the Hudson-Maynard area occurred, presumably, during the deposition of the Marlboro formation, for it is generally regarded as pre-Cambrian. This assignment, however, is certainly not unequivocal, and what evidence is available in this area does not preclude, but rather supports, the possibility that the Marlboro formation mapped here and in its type locality may even be as young as Carboniferous. Its interstratified relationship with the Gospel Hill gneiss, which in part is undoubtedly a granitized facies of the Carboniferous Nashoba formation, indicates either uninterrupted deposition or obliteration by granitization of an unconformity once existing somewhere within the borders of what is now the Gospel Hill gneiss, at least in the area where the Gospel Hill-Marlboro contact is exposed.

Because of the uncertain age of the Marlboro formation, uncertainty also obscures the chronology of events relating not only to it but to several other formations in the area as well, particularly the intrusive rocks that invade the Marlboro. These intrusive rocks are presumed to be of Devonian age, but such an age obviously is impossible if the Marlboro formation ultimately proves to be no older than Carboniferous.

The Marlboro formation was deposited as a thick series of sediments of several types. Most of the rocks, or a large portion of them, are hornblendic, and may, therefore, have been volcanic. They may also, however, be derivatives of calcareous sedimentary rocks. Arenaceous deposits are now represented by quartzite beds, and originally shaly rocks have been converted to mica schist.

Before the igneous invasion, the Marlboro formation had attained essentially its present degree of deformation and grade of metamorphism. Gabbro-diorite intrusion was followed by the intrusion of less basic quartz diorite. Solidification of this magma was accompanied by shrinkage and fracturing, and aplite was injected into many of the fractures. Finally, widespread epidotization extended along joints and fractures beyond the limits of the quartz diorite mass into the gabbro-diorite and the metasedimentary rocks of the Marlboro formation.

CARBONIFEROUS PERIODS

The Carboniferous rocks lying north of the belt of the Marlboro formation can be traced into fossiliferous rocks in the Worcester area. Thus, the Worcester formation, extending from the fossil locality through Harvard was laid down in a continuous depositional sequence that involved almost all the metasedimentary rocks in the Hudson quadrangle and, if not the Marlboro formation, all others in the Maynard quadrangle.

The earliest episode recorded by these rocks is the deposition of the Harvard conglomerate lentil under littoral conditions. The base upon which this formation lies is not exposed. A gradual change toward deeper water conditions followed, accompanied first by the accumulation of sands that later became the Vaughn Hills member and then by the accumulation of the somewhat finer grained sediments that are now represented by the phyllite and mica schist facies of the Worcester formation. The Vaughn Hills member, however, appears to grade through a change of facies directly into pelitic rocks both toward the north and toward the west. Toward the top of the mica schist facies are amphibolite beds, but whether these represent a change to limy sedimentation or the intercalation of volcanic material, is not clear. The contact of the mica schist with the Nashoba formation is marked by a fairly thick and very continuous zone of amphibolitic material, and more amphibolite beds, some of these undoubtedly derivatives from limestones, are distributed throughout the Nashoba formation.

The Nashoba formation itself represents a very thick accumulation of mostly arenaceous sediments deposited for the most part in shallow water. Here and there it tends to be more schistose, and at infrequent intervals limestone beds were deposited.

The end of deposition of the Nashoba sediments marked, apparently, the close of sedimentation in the area for a long period of time and the beginning of mountain-forming movements that folded and otherwise deformed the rocks of the area to such an extent that, with accompanying metamorphism, many of the original features were completely obliterated, and the mode of origin of some of the rocks became doubtful.

The stresses responsible for the bulk of the folding, as it is now displayed, appear to have come from a northwesterly direction, for nearly all the minor folds are asymmetrical with axial planes that dip steeply northwestward.

Feldspathization of the Nashoba formation closely followed the deformation; indeed, as shown by the bending, fracturing, and microfaulting of some of the feldspar grains, it probably began before deformation had ceased. As with many granitelike rocks that possess relict bedding and other evidence of a sedimentary origin, however, it seems clear that the greater bulk of the deformation preceded feldspathization. Certainly with their present physical properties such rocks would have behaved differently under stress and could not have been thrown into tight minor folds.

If a second period of deformation followed, or if, in continuing, the deformation entered a second phase of redirected stresses, this probably postdated the general feldspathization. The cross folding in the rocks that flank the Nashoba may be a product of such a disturbance. Cross folding antedated the feldspathization that led to the formation of the gneiss at Bare Hill Pond, however, because oriented relicts of these folds are found within and on the borders of the migmatized mass.

INTRUSION OF THE LATE PALEOZOIC(?) IGNEOUS ROCKS

Igneous intrusion began after folding and migmatization had nearly ceased. There seems to be no evidence in this area that the igneous rocks were folded along with the metasedimentary rocks. Pegmatitization began fairly early in the epoch of deformation, but many of the earlier pegmatites are probably of metasomatic origin. Inclusions of country rock in many of the igneous bodies indicate that the country rock was essentially in its present state when it was invaded. Little is yet known of the order of instrusion of the several igneous bodies, because all of them crop out in separate areas. Certain late pegmatite veins crosscut most of the other igneous rocks and, except for the few later basic dikes in the Maynard quadrangle, are the youngest igneous rocks in the area.

JOINTING AND FAULTING

Jointing in the area may have been almost fully developed by Triassic time, for some of the joints contain dikes of probable Triassic age. High-angle faulting which produced the displacements in Bolton and Harvard, and probably much of the small-scale faulting observed elsewhere, may also have occurred in Triassic time. Faulting and jointing are the latest expressions of general structural deformation in the area.

PENEPLANATION AND RE-ELEVATION

The geologic history subsequent to general deformation and earlier than the Pleistocene glaciation must be pieced together largely by inference. Uplift of the region by folding of the rocks exposed the area immediately to a long period of erosion. By Late Jurassic or Early Cretaceous time, the land surface had been reduced to a peneplain (Alden, 1924, p. 15 and p. 27). Submergence of at least part of this erosion surface followed in eastern Massachusetts, for Miocene strata are now exposed in Scituate (Currier, personal communication, 1952), and Cretaceous strata are exposed on Martha's

Vineyard (La Forge, 1932, p. 76). It is not know, however, whether or not Cretaceous rocks ever covered any of the Hudson or Maynard area. If they did, all remnants have been removed. At any rate, renewed uplift ultimately followed peneplanation. The first streams to flow off the re-elevated surface were consequent and largely ignored the structure of the underlying bedrock, but, as dissection progressed, the tributary streams in large part adjusted themselves to the bedrock structure and developed a trellis drainage pattern in the areas of folded rocks.

By late Pliocene time rather complete dissection of the peneplain surface had been attained. The general land surface over which the glaciers were later to advance was both higher and of greater local relief than now (La Forge, 1932, p. 78). Some of the preglacial valleys in the Hudson-Maynard area became filled with drift to depths of 80 feet or more. Subsidence of the land surface since dissection is indicated in coastal areas where the mouths of the major valleys have been drowned. In the bottoms of many of these drowned valleys, bedrock is many feet below sea level.

PLEISTOCENE PERIOD

Continental glaciers occupied the area probably several times during the Pleistocene period. Nevertheless, deposits of more than one glacial advance cannot positively be identified. In the Midwestern States and in parts of the northern Great Plains at least four glacial advances and withdrawals have been established; multiple glaciation also is indicated on Cape Cod and Long Island. The two lithologically dissimilar tills recognized in the Hudson and Maynard quadrangles probably are products of different glacial stages or substages, but conclusive evidence that they are, has not been found. At any rate, most of the glacial features now displayed in the area are clearly products of the latest ice sheet that occupied the area. Judging from the slight postglacial dissection of landforms and from the immaturity of the postglacial soil profile, this ice sheet was of late Wisconsin age. Little is known of the Pleistocene period there before that time.

Although the direction of ice movement may have varied during the existence of the ice sheet, the ice flowed across the Hudson and Maynard quadrangles with little regard for the underlying topography. The largest hills deflected it little if at all.

At the time of its greatest magnitude, the ice sheet over the area must have been hundreds, possibly thousands of feet thick; it covered the highest hills in central Massachusetts. Not only was the ice, with rock fragments firmly frozen in its bed, capable of scouring and polishing the surfaces of outcrops (fig. 8), but it also was able to pluck large masses of rock directly from the outcrops and transport them southward. In this manner the south- and southeast-facing slopes of many hills were oversteepened into clifflike forms, and, locally, large depressions were excavated into bedrock. Picturesque Bare Hill Pond in Harvard is due in part to glacial plucking in the bed of preglacial Bowers Brook; several smaller but still relatively large bedrock basins, due undoubtedly to plucking, lie high on the rocky hill between Murrays Lane in Harvard and Codman Hill Road in Boxborough. The largest of these is about 800 feet long. Horse Meadows, about a mile farther north, is of similar origin.

Erosion, however, was not the only obvious effect attributable to the moving ice. A veneer of unsorted drift, generally thin but locally very thick, was deposited blanketlike over broad tracts of the landscape. The smoothly rounded contours and the gently flowing lines of this terrain indicate that it is a product of deposition by moving ice.

DEGLACIATION

Deglaciation finally began when total wastage at the ice margin, and over the surface of the ice, exceeded the increment of new snow. Perhaps temporary withdrawals, pauses, and re-advances preceded the general recession. Once the recession was well under way in this area, however, surges of renewed forward motion—if they occurred—probably were unable to reach the ice margin. By this time the margin had been reduced to a broad zone of wasting and stagnant ice, highly irregular in outline and thickness, and hardly capable either of flowing itself or of transmitting the force of any flowing ice to the north. Brown (1933, p. 149) described evidence of a late re-advance in the Nashua Valley to the west. His evidence rests largely upon the occurrence of till masses overlying glacial gravels and upon what he regarded as ice-shove features. Exposures of till on gravel occur in the Maynard area, and other occurrences there are indicated by subsurface data, but these do not in themselves prove a re-advance—they indicate only that the gravel was deposited before the overlying till.

In general the outwash chronology of the area indicates a progressive uncovering of the land from south to north. Nevertheless, the zone of stagnation was very broad (Currier, 1941, p. 1895) and at one time must have extended nearly the length of the Hudson quadrangle, for ice-contact features in the vicinity of Hudson and Gleasondale are correlated with similar features as far north as Boxborough. Downwasting in the marginal area, therefore, was as important a factor in promoting deglaciation as was actual withdrawal of the ice front. In effect, the ice front ceased to exist, because the ice first disappeared from the upland areas of the frontal zone while it yet remained in the valleys, and many stagnant blocks became completely separated from the main ice mass. Discharging melt water deposited its load chiefly in and along the lowland areas, therefore, where the ice still lay, and the variety of ice-contact forms that results are numerous and are intricate in form.

For the most part the various melt-water deposits can be correlated chronologically by their relative altitudes at points at mutual abuttal. In such instances the deposit that stands the higher is generally the older, although the generalization does not necessarily apply to those deposits—certain kames and eskers, for example—that have been deposited in ice-enclosed openings and hence may not have been brought up to grade. Graded deposits of a single depositional sequence [2] attain accordance of summit level; such sequences commonly display longitudinal surface gradients that rise perceptibly in the direction of the melt-water source. There is, moreover, a general tendency toward size grading, from coarser to finer, downstream—especially in the longer sequences.

Because ice lay in the valley bottoms at the time of sequence deposition, the present drainageways do not necessarily coincide with those followed by the melt water. Low points in the divides between drainageways served as temporary base levels for some sequences at times when present drainageways were still blocked by ice. Downwasting and melting back of the general frontal zone uncovered new and lower escapeways from time to time, thus causing abandonment of old drainageways or partial regrading of a sequence to a new base level.

Although the chronological succession of deposits in a single trunk valley can generally be determined with reasonable assurance, difficulties often arise when correlations are carried up the tributaries or from one valley to another. In some such instances, two sequences in different valleys may easily be correlated relative to a third common to both valleys but not to each other. Moreover, the direction of runoff, controlled partly by ice barriers, was in places so balanced that slight back melting diverted the drainage despite only slight lowering of the aggradation surface. This condition apparently prevailed in the Maynard quadrangle when outwash-plain deposition was interrupted by back melting and the melt water was diverted eastward along the Assabet valley to glacial Lake Sudbury.

CHRONOLOGY OF THE OUTWASH OF THE HUDSON QUADRANGLE

All but a few relatively small melt-water deposits in the Hudson quadrangle can be dated relative to the extensive sequences of ice-contact features that extend down Assabet Brook, across the low divide between Assabet Brook and the Assabet River (via Stow Coun-

[2] The term "sequence" as used in this report designates collectively all fluvioglacial features deposited contemporaneously and graded to a common base level. In this general sense, the term was introduced by Jahns (1953).

try Club), and along most of the length of the Assabet River. At the time this sequence was deposited, downwasting had cleared ice from a large part of the area, leaving blocks in the valleys. Melt-water runoff by this time, therefore, was fairly well integrated into one broad, graded sequence.

The earliest event in the chronology of the outwash of the Hudson quadrangle was the deposition of small terraces and related features at Gates Pond in Berlin, which grade southward into the Marlboro quadrangle. (See pl. 3.) Deposition stopped here when northward shrinkage of the ice opened a lower drainageway to the east. Accompanied by a drop in level of about 10 feet, drainage now fed the small kame delta built east of the intersection of Marlboro Road and Gates Pond Road at the highest level of glacial Lake Assabet. Sequences then appear to have developed concurrently, or nearly so, in both the Hudson area and in the Berlin-Bolton area.

In the Hudson area, grade was controlled by the water stands of glacial Lake Assabet, and, although the deposits of this area are chiefly ice contact, they nevertheless are graded to horizontal water planes of that lake. Evidently the ice to the north of the main lake basin contained enough interconnected and continuous openings to permit attainment of a common water level with the main lake basin.

Three water planes of glacial Lake Assabet are apparent in the Hudson area. The highest at an altitude of about 310 feet and an intermediate at about 280 feet were controlled, apparently, by outlets south of the Hudson quadrangle boundary. Ice prevented overflow to the north. The lowest water plane, at about 250 feet, was controlled by a bedrock gap just south of Gospel Hill. Lake Assabet fell to the 250-foot level when this gap was cleared of ice, and a torrent of water overflowed into Fort Meadow Brook. At about the same time, the kames, kame terraces, and ice-channel fillings east of Gospel Hill, the outwash plains south and east of Boons Pond, and the kames, kame terraces, and ice-channel fillings east of Birch Hill in Stow were all being constructed.

When the gap north of Orchard Hill at Gleasondale was finally opened, Lake Assabet was drained. Probably construction also stopped on the outwash plains and related features of the area between Boons Pond and Gospel Hill, for the ice could hardly have been effectively cleared from the gap at Orchard Hill without also withdrawing from the ice-contact slopes that lie to the southeast. At any rate, withdrawal of the ice from these areas opened the way for deposition of the broad terrace system and related features along Assabet Brook and below the level of the lowest Lake Assabet water stand along the Assabet River. Drainage continued to follow the course indicated by these landforms until the ice withdrew sufficiently from Assabet

Brook below Spindle Hill to permit a diversion of Assabet Brook drainage to essentially its present course. A lower set of kame terraces was then constructed along Assabet Brook, probably partly by reworking of the higher terraces, before the glacial ice completely disappeared.

Along upper Heathen Meadow Brook small sequences developed at about the same time as those along Assabet Brook. Features along Taylor Street in Stow were graded to a gap just north of Marble Hill. (This small sequence is not shown on plate 3 because it cannot be correlated directly with any other deposits.) Features at the head of Heathen Meadow Brook and Guggins Brook in Boxborough were graded to a bedrock threshold across Heathen Meadow Brook just east of Boxboro Road in Stow. Deposition by melt water graded to this threshold stopped when the ice was cleared from the area just south of and parallel to Guggins Brook, opening a lower drainageway eastward into Acton in the Maynard quadrangle. Thus, a lower sequence formed along Guggins Brook graded eastward and southward, via West Acton, into Stow where it abuts against the slightly older upper sequence of Assabet Brook. By the time that Guggins Brook was completely cleared of ice, deglaciation of the area was nearly complete, and any ice that may have remained in the area probably exerted little if any influence on the disposition of the drainage.

Meanwhile, however, another group of drainage sequences was forming independently in Bolton and Berlin. Small uncorrelated terraces were constructed west and south of Fryville, graded to a col crossing Frye Road just west of Hog Swamp, and a small uncorrelated terrace also was constructed along Central Street at South Bolton, graded to a col at the north end of Sawyer Hill. Both of these small sequences were abandoned when the clearing of Hog Brook east of Hog Swamp left them standing high and dry. The col just southwest of the intersection of Sawyer Hill Road and Central Street may have served temporarily as an outlet before the Hog Brook outlet was cleared.

Deposits graded to the Hog Brook outlet extend northward into Bolton nearly 2½ miles and include ice-contact features of many sorts. Probably at the time these deposits were formed, Pine Hill, Wataquadock Hill, and Powder House Hill, all in Bolton, were completely freed of ice, and drainage to the Hog Brook outlet was derived largely from melting valley ice. When the ice was cleared from the vicinity of Danforth Brook, the Hog Brook outlet ceased to function and melt-water drainage was instead diverted down Danforth Brook. An ice barrier between Long Hill and Rattlesnake Hill, now marked by steep ice-contact slopes northeast of West Pond, prevented drainage from escaping down Great Brook. When the ice withdrew from the north end of Long Hill, however, the drainageway of Great Brook was opened and the Danforth Brook outlet ceased to function. Melt-water diverted down Great Brook first built the short terraces west and southwest of Brockway Corner when the ice still impinged against the base of Long Hill just west of the Bolton-Stow town line. Further withdrawal of the ice brought the grade of Great Brook to that of the broad terraces along Assabet Brook.

Fluvioglacial features in the northwest corner of the quadrangle are not correlated with those of other areas because of the lack of any direct ties between deposits. Wider mapping may eventually reveal some connections outside the area mapped so far. The oldest features—high kames and kame terraces—seem to be isolated. Lower, and probably younger, features are several disconnected sand and gravel deposits, apparently kame terraces, that seem to be graded to water stands of glacial Lake Nashua to the west. Probably these features were deposited in ice-enclosed openings interconnected with the water of Lake Nashua, through fractures or other channelways in the ice, so that the water in these openings attained a common level. Evidence of any extensive body of water seems to be wanting in the Hudson quadrangle.

CHRONOLOGY OF THE OUTWASH OF THE MAYNARD QUADRANGLE

Several ties exist between the melt-water sequences of the Maynard quadrangle and those of the Hudson, and events recorded in the two areas during deglaciation can be fairly well correlated.

In the southern part of the Maynard quadrangle back melting seems to have been interrupted by several pauses of sufficient duration to have permitted accumulation of extensive ice-contact deposits along a stationary and almost continuous ice front. The withdrawal of the ice from this area, therefore, was in sharp contrast with that from the Hudson quadrangle and from the northern part of the Maynard quadrangle, for in those places a broad, very irregular stagnation zone of wasting ice several miles wide remained in the valleys long after the uplands had become cleared. The Assabet River roughly marks the position in the Maynard quadrangle where the ice front ceased to withdraw as a unit.

The oldest sequential deposits of the Maynard quadrangle are those kame terraces, kame plains, and ice-channel fillings in Sudbury that extend from Lincoln Road southwestward past St. Elizabeth Chapel to the south boundary of the quadrangle near the intersection of Peak-ham Road and Pratts Mill Road. These deposits are bounded for the most part by ice-contact slopes on the north and west, and by a till-covered bedrock upland on the east and south. At the time of their accumulation, ice probably filled the broad lowlands along the

Sudbury River in Wayland and vicinity, for this area lies below them and should otherwise have been filled with drift. A few isolated kames in the same general area stand higher than these deposits and probably are older than the kame terraces.

The second important episode was the withdrawal of the ice front to the Willis Pond-Willis Hill area, together with the southward construction of outwash plains and associated features from that vicinity. Large masses of detached ice remained in the valley of Hop Brook and in other nearby areas marked by swamps. Probably the meadows along the Sudbury River and the swamps along Pantry Brook also were still occupied by ice, although flooding of some of this area by the waters of glacial Lake Sudbury may have already taken place.

A further withdrawal placed the ice front at the south bank of the Assabet River in Stow and at a position several hundred yards north of Great Road in most of Maynard and Sudbury. From this front, outwash-plain construction was resumed after it had been interrupted by the withdrawal of the front from the Willis Pond Area. This sequence is the earliest to which deposits of both the Hudson and Maynard quadrangles can be correlated. Its deposits include those kame terraces and related features in the Hudson quadrangle between Gospel Hill and Boons Pond.

Many detached ice masses stood south of the main ice front. Ice still remained as far south as Hop Brook, and it occupied the sites of Boons Pond, White Pond (Hudson), Puffer Pond, and Willis Pond, as well as many swamps and smaller kettles. Ice remained in these places until after outwash-plain construction had ceased.

By this time open water probably stood in North Sudbury, and deposition of the kame delta at Haynes Road probably was under way. Large ice blocks, however, probably remained in those areas now occupied by swamps.

Although the ice yet remained against the south bank of the Assabet River in Stow, it appears to have withdrawn from contact with the head of the outwash plain north of Great Road in Maynard and Sudbury and from the kame delta at Haynes Road. It paused in its withdrawal long enough for melt water to construct the large kame delta at Nine Acre Corner and the associated kame terraces west of the delta.

Still another withdrawal, of about half a mile, was again followed by a pause, at which time three more kame deltas were constructed along, roughly, an east-west line marking the position of the ice front. Abandonment of these kame deltas was caused by an almost complete disintegration of the ice front. It ceased to withdraw as a unit, and large blocks of ice became detached from the main ice mass.

From this time, downwasting supplanted frontal retreat as the chief process of deglaciation in the area. Succeeding kame deltas were subsequently abandoned not by a further withdrawal of the ice, but by the draining of Lake Sudbury through a newly opened outlet somewhere to the east, beyond the limits of the quadrangle, and all later sequences were confined to the valleys, where stagnant masses of valley ice lay between ice-free uplands. Subglacial topography may have been of considerable importance in changing the mode of deglaciation. The southern part of the quadrangle is flatter than the country to the north; hence, wasting ice to the south was less subject to detachment during downwasting than was ice to the north, and a more continuous ice front was maintained.

Following the draining of Lake Sudbury, the Assabet River assumed essentially its present course. Ice still lay in the valley, however, and the first deposits there were kame terraces. For a short time the Assabet at West Concord flowed through the gap now occupied by the Boston and Maine Railroad just east of the intersection of Main Street and Baker Avenue. This gap was abandoned when the area to the north, in the vicinity of the Concord Reformatory, was cleared of ice.

For a time ice blocked the lower course of Nashoba Brook, and drainage probably spilled through the gap at Pope Road, one-half mile northeast of East Acton. Well-formed kame terraces and related features along Nashoba Brook are graded to this gap. When Nashoba Brook was cleared of ice in East Acton, the Pope Road gap was abandoned.

After ice had nearly disappeared from the Assabet valley and its tributaries, the grades of most melt-water streams were lowered. Valley trains were constructed a few feet above present stream level, and subsequently were terraced by stream entrenchment. Meanwhile, however, sequence drainage was still in progress along lower Heathen Meadow Brook and along Guggins Brook near West Acton. Deposits of this sequence appear to be graded to gaps connected to Assabet Brook at Ministers Pond and at Lower Village in Stow. The gap at Lower Village, crossing Great Road, is a well-preserved scoured channel. This sequence was abandoned when the gap at South Acton was cleared of ice, opening the way for the present course of Fort Pond Brook and almost completing the deglaciation of the area.

POSTGLACIAL CHANGES

Since glacial time small flood plains have formed along segments of the Assabet River, lower Fort Pond Brook, and lower Nashoba Brook. Thin deposits of alluvium floor some of the smaller valleys, and probably considerable material, partly organic, has accumulated in most of the swamps and ponds. Certainly, most of the peat deposits are of postglacial origin. By and large, however, postglacial changes in the topography have been slight, and many features remain essentially as the ice left them. Soil has begun to form on most of the glacial deposits, but it is neither thick nor mature. Slight weathering stains the surfaces of most outcrops of bedrock, but some retain the polish produced by the overriding glacier. Many of the best preserved striae and polished surfaces occur on outcrops that have been protected by a cover of glacial deposits only recently stripped off.

Fort Pond Brook, Heathen Meadow Brook, Danforth Brook, and Hog Brook all cross bedrock ledges at many points along their courses, and all have cut down appreciably into these points. Postglacial downcutting in bedrock at Danforth Falls, near the Bolton-Hudson town line, probably exceeds 10 feet. Comparable downcutting by Fort Pond Brook is indicated at South Acton, and by Heathen Meadow Brook below Boxboro Road. Although the Assabet River crosses bedrock ledges at Maynard, it does not appear to have eroded them appreciably.

Perhaps the greatest changes have been made by man himself. Small dams constructed along many of the streams for power and other uses have altered sedimentation and runoff, and of course have inundated previously dry land. Artificial ponds have been created in many places, and the levels of natural ponds have been raised. Many swamps have been drained to reclaim the land for agriculture. Even the clearing of boulders from the fields has altered the appearance of the landscape. The effects of the deforestation that culminated near the turn of the century probably did little to alter the operation of geologic processes. Second-growth vegetation now covering much of the area probably is thicker and less penetrable in many places than the primeval forests that confronted the earliest settlers.

MINERAL RESOURCES

WATER

In a broad sense, water may be regarded as a mineral resource; as such, it is the greatest single mineral resource of the area. Surface water is used for household, industrial, and recreational purposes. Industry is concentrated chiefly along the Assabet River, the power potential of which is largely responsible for the greater growth of Maynard and Hudson than of other towns in the area. Fort Pond Brook also provides waterpower below South Acton, where several factories are located. Most other streams of the area have insufficient volume or gradient to provide usable power.

Of the natural and artificial ponds in the area, Bare Hill Pond in Harvard, Boons Pond in Stow and Hudson, Willis Pond in Sudbury, West Pond and Little Pond in Bolton, and White Pond in Concord are the chief recreational attractions. Facilities for swimming, fishing, and boating are provided at most of these ponds, although some are not open to the public. By fuller use of underground water sources, which should be plentiful, other local ponds now reserved for water supply could probably be converted to recreation. Large reservoirs of subsurface water undoubtedly exist in the thicker glacial sediments, especially those that occupy buried stream channels. West Acton obtains its water from glacial gravels, and other communities could do the same. In general, glacial gravels provide the largest and most reliable sources of underground water. Many wells, however, provide modest water supplies from till; some, moreover, obtain water from fractures in the bedrock. Probably large and reliable supplies, however, can be taken only from the sand and gravel deposits.

The depth of water table varies greatly from place to place. It also varies considerably from season to season and, sometimes, from year to year. In the autumn of 1949, when mapping was in progress, much land normally swampy was dry to depths of several feet below the surface. Normally, water is near the surface in the bottom lands, and abundant supplies often can be obtained from shallow wells. Recharge may be slow in till or silt areas. In upland areas the water table is, in general, deeper and the supply shorter. Some drumlins, and perhaps most of them, are dry nearly to their bases. Water supplies from bedrock areas depend mostly upon fortuitously spaced water-bearing fractures.

CONSTRUCTION MATERIALS

SAND AND GRAVEL DEPOSITS

Except for water, deposits of sand and gravel probably have the greatest actual and potential value of any mineral resources in the area. Moreover, their value is likely to increase, not only as old sources of material become exhausted, but also as the population of the area continues to grow. In the Boston area the marked postwar suburban expansion is being felt in towns as far from Boston as Harvard and Stow, and continued growth of such places is accompanied by an unending demand for construction materials.

Aided by the geologic map and explanation, one generally can gain some idea of the composition and volume of a deposit. A direct relationship commonly exists between composition and form of the deposit, as pointed out in the section of this report on Pleistocene deposits, but, because of local variations in composition, careful sampling may be required for more specific information about any given deposit.

Special attention should be given to deposits to be used for concrete aggregate. Most of the gravels of the area, after washing, should provide a good bond with cementing material. Schistose or slaty pebbles, however, generally are weak or unsound, and because of their tabular shapes may promote uneven mixing, stratification, and planes of structural weakness in concrete if present in appreciable quantities. Pebbles that are coated seldom provide a good bond; in this area, any coating present is likely to be iron oxide, and this may further cause unsightly brownish or yellowish stains on concrete structures.

TILL

Till, obtained from ground moraine or drumlins, is useful for back fill. The more compact tills are quite impervious to water and afford excellent, cheap, and readily available material for earthfill dams. Till areas, moreover, make good, watertight reservoir sites. Many farmers in the area have constructed small reservoirs, and these, in areas not reached by water mains, afford diverse benefits in addition to providing valuable insurance aginst fire hazard and drought.

LAKE-BOTTOM DEPOSITS

In colonial time according to local residents, brick clay was obtained in the Concord area from bottom sediments of extinct Lake Sudbury. At the time of mapping, none of these deposits was being utilized. Most of them are overlain by sand deposits several feet thick and most lie below or partly below the water table; such factors might discourage exploitation. The deposits examined seemed too silty for use in ceramics, but some may be suited to such industrial uses as fillers or filters.

CRUSHED STONE

Crushed stone is not produced in the Hudson and Maynard quadrangles, but rocks of the Marlboro formation are successfully used for this purpose in nearby areas, and probably could be so used in the Maynard quadrangle. Crushed and graded material obtained from parts of the Marlboro formation is comparable to the trap rock found in other areas.

MARBLE

The best known marbles in eastern Massachusetts occur in the old quarries in Bolton. These are especially noteworthy not only for their early records of production but also for their interesting assemblages of minerals. The quarries are located between Rattlesnake Hill and Brockway Corner, just north of Great Brook near the intersection of Main Street and Meadow Road. A few small prospects have been found on Rattlesnake Hill.

Records kept by the town of Bolton indicate that quarrying may have begun as early as 1736. At that time, and for many years to follow, the marble was calcined at the quarry, and the old kiln, built by General John Whitcomb, still remains on the site. The lime was used widely for plaster by the early settlers in the vicinity, and many of the old houses in which it was used still retain the original plaster on their walls. Production eventually ceased, and for many years the quarries lay idle. In 1937 the larger, more northerly, quarry was reopened and for 2 or 3 years produced agricultural lime; at present, however, all quarries are inactive, the larger one has filled partly with water, and the two smaller ones are overgrown with brush and small trees.

All three quarries seem to be in the same thick marble bed, although the rock is exposed nowhere beyond the limits of the quarry walls. The marble is magnesian, medium to coarse textured, and pearly gray on fresh surfaces. It has been completely recrystallized, and bedding, if originally present, has been obliterated. The several varieties of associated minerals, notably scapolite, probably owe their formation to the invasion of the limestone by pegmatitic solutions. Pegmatites abound in the neighboring gneisses, but only those that invade the limestone are characterized by unusual minerals. These minerals have been described in some detail by Palache and Pinger (1923, p. 153) and include scapolite, boltonite (a variety of forsterite), microcline, andesine, diopside, actinolite, apatite, zircon, allanite, garnet, chondrodite, brown mica, sphene, spinel, rutile, graphite and magnetite, and the sulfides pyrite, pyrrhotite, chalcopyrite, and arsenopyrite.

Earlier workers (Emerson, 1917, p. 84; Palache and Pinger, 1923, p. 153) described a zonal arrangement of the minerals that no longer can easily be seen owing to slumping of the quarry walls, part filling of the quarries with water, and the overgrowth of vegetation. The conformable contact of the limestone with the biotite gneiss, however, is still well shown. In the larger quarry a lenticular layer of very coarse pink scapolite rock as much as 16 feet thick is in contact with the gneiss on the southeast quarry wall, and great bladed crystals, some nearly 6 feet long, are exposed on the wall. Large boulders composed of well-formed scapolite prisms in a matrix of smoky quartz lie in the pit, but the rock is not seen in place. Between the scapolite zone and the limestone is a layer of greenish diopside rock that also contains actinolite and sphene. Diopside occurs also in the limestone as replacement veins. The diopside rock grades into boltonite-rich marble, poorly exposed; this in turn grades into mica-rich marble and finally into pure coarse-textured gray marble.

In 1939, when the marble was being actively quarried and the zonal arrangement was well displayed, G. M. Richmond (unpublished report, 1939) examined the deposit and noted the following general relationships: Next to the gneiss is a scapolite zone that contains chiefly scapolite, quartz, apatite, and sphene. This zone grades into a diopside zone that contains diopside, actinolite, tremolite, apatite, and sphene. A boltonite zone follows containing boltonite, chondrodite, serpentine, and spinel; this zone grades into marble containing phlogopite, allanite, graphite, and garnet. Richmond believes the pegmatite invasion was of two main stages. The first solutions that were introduced, he believes, precipitated quartz-lean biotite-andesine pegmatite and produced diopside, boltonite, and chondrodite by reaction with the marble. Actinolite and tremolite were deposited shortly after diopside. Chlorine later was introduced and through reaction with the andesine produced scapolite. Probably at this time sphene and apatite also formed. Finally, as the solutions weakened and the newly formed contact zones could no longer be penetrated, silica was deposited as vein quartz.

COMMERCIAL GRANITE

The Acton granite has been quarried on a small scale for building and ornamental stone. Many barns and old houses in the area have slabs of it in their foundations. Even large boulders of the rock have been split and trimmed for use. Dressed, it takes a high polish and is a very attractive stone, but, because of the small size of individual granite bodies in the area, it probably never will be used extensively. The demand for granite, moreover, is met at present by large quarry operations in other parts of Massachusetts and New England.

FLAGSTONE

Much of the Nashoba formation is well suited to use as flagstone. Where not contorted by tight folding it splits readily into tabular slabs that are easily trimmed to desired shape and size. Enormous quantities of good material occur in undeveloped woodland areas.

PEAT

Peat has never been utilized extensively in the area, but its potential value should not be overlooked. Most swamp areas contain some peat, and in places it is thick. A few deposits in the Maynard quadrangle have been used locally for top dressing on lawns and gardens. In general, swamps having scattered boulders at the surface are likely to contain little or no peat, for in such swamps ground moraine is commonly near the surface. Swamps that contain large trees also are generally shallow bottomed and hence are unlikely places for thick peat deposits. Broad grassy marshes probably offer best possibilities for thick accumulations of peat.

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