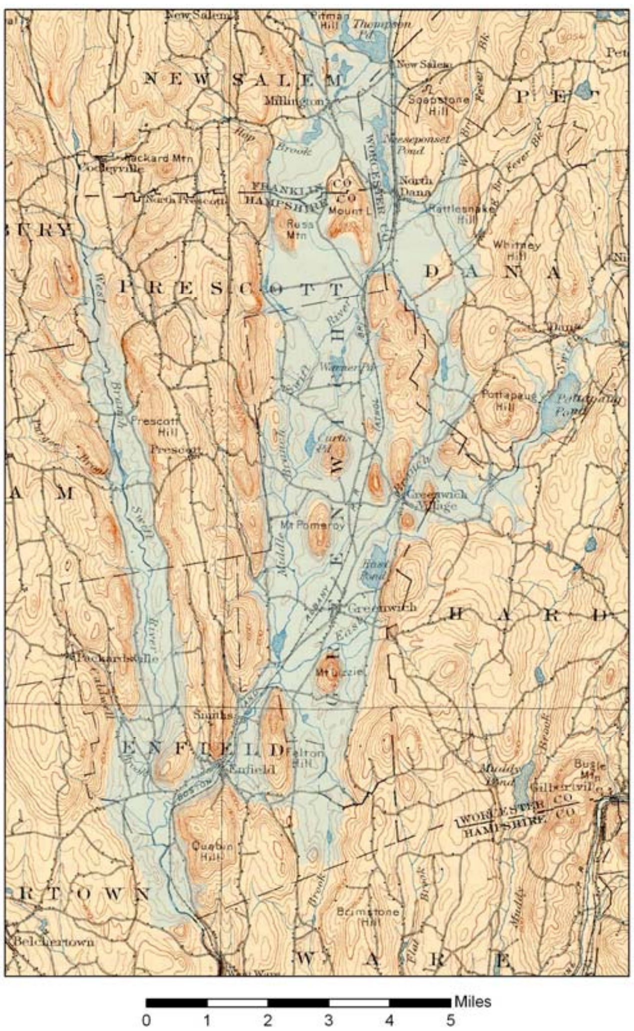
Prepared in cooperation with the Commonwealth of Massachusetts
Massachusetts Geological Survey and Office of Geographic Information (MassGIS),
Information Technology Division

Surficial Geologic Map of the Mount Grace-Ashburnham-Monson-Webster 24-Quadrangle Area in Central Massachusetts

Compiled by Janet R. Stone



Open-File Report 2006–1260–I

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Cover figure: Quabbin Reservoir serves as water supply for the city of Boston, and is shown here (in blue) superimposed on part of the 1908 Ware 30-minute topographic quadrangle map. Constructed between 1933 and 1939 by impounding three branches of the Swift River with two dams, the reservoir inundated significant areas of four towns—Dana, Enfield, Greenwich, and Prescott, and parts of several others. Wide areas of glacial meltwater deposits now lie below water level in the valley; the surfaces of these deposits rise to the north by about 5 feet per mile (mostly due to tilting caused by glacial rebound) and emerge above water level in the northern part of the reservoir. Lower photograph shows bedrock, locally mantled by till, sloping toward the water's edge in the southern part of the reservoir near the former site of Greenwich Village; stratified deposits are completely submerged. Upper photograph shows islands of glacial stratified deposits at the north end of the reservoir, viewed from the overlook at New Salem. Photographs by J.R. Stone and M.L. DiGiacomo-Cohen, U.S. Geological Survey.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

Surficial Geologic Map of the Mount Grace-Ashburnham-Monson-Webster 24-Quadrangle Area in Central Massachusetts

Compiled by Janet R. Stone

Introduction

The surficial geologic map layer shows the distribution of nonlithified earth materials at land surface in an area of 24 7.5-minute quadrangles (1,238 mi^2 total) in central Massachusetts (fig. 1). Across Massachusetts, these materials range from a few feet to more than 500 ft in thickness. They overlie bedrock, which crops out in upland hills and as resistant ledges in valley areas. The geologic map differentiates surficial materials of Quaternary age on the basis of their lithologic characteristics (such as grain size and sedimentary structures), constructional geomorphic features, stratigraphic relationships, and age. Surficial materials also are known in engineering classifications as unconsolidated soils, which include coarse-grained soils, fine-grained soils, and organic fine-grained soils. Surficial materials underlie and are the parent materials of modern pedogenic soils, which have developed in them at the land surface. Surficial earth materials significantly affect human use of the land, and an accurate description of their distribution is particularly important for assessing water resources, construction-aggregate resources, and earth-surface hazards, and for making land-use decisions.

The mapped distribution of surficial materials that lie between the land surface and the bedrock surface is based on detailed geologic mapping of 7.5-minute topographic quadrangles, produced as part of an earlier (1938–1982) cooperative statewide mapping program between the U.S. Geological Survey (USGS) and the Massachusetts Department of Public Works (now Massachusetts Department of Transportation) (Page, 1967; Stone, 1982). Each published geologic map presents a detailed description of local geologic map units, the genesis of the deposits, and age correlations among units. Previously unpublished field compilation maps exist on paper or mylar sheets and these have been digitally rendered for the present map compilation. Regional summaries based on the Massachusetts surficial geologic mapping studies discuss the ages of multiple glaciations, the nature of glaciofluvial, glaciolacustrine, and glaciomarine deposits, and the processes of ice advance and retreat across Massachusetts (Koteff and Pessl, 1981; papers in Larson and Stone, 1982; Oldale and Barlow, 1986; Stone and Borns, 1986; Warren and Stone, 1986).

This compilation of surficial geologic materials is an interim product that defines the areas of exposed bedrock and the boundaries between glacial till, glacial stratified deposits, and overlying postglacial deposits. This work is part of a comprehensive study to produce a statewide digital map of the surficial geology at a 1:24,000-scale level of accuracy. This surficial geologic map layer covering 24 quadrangles revises previous digital surficial geologic maps (Stone and others, 1993; MassGIS, 1999) that were compiled on base maps at regional scales of 1:125,000 and 1:250,000. The purpose of this study is to provide fundamental geologic data for the evaluation of natural resources, hazards, and land information within the Commonwealth of Massachusetts.

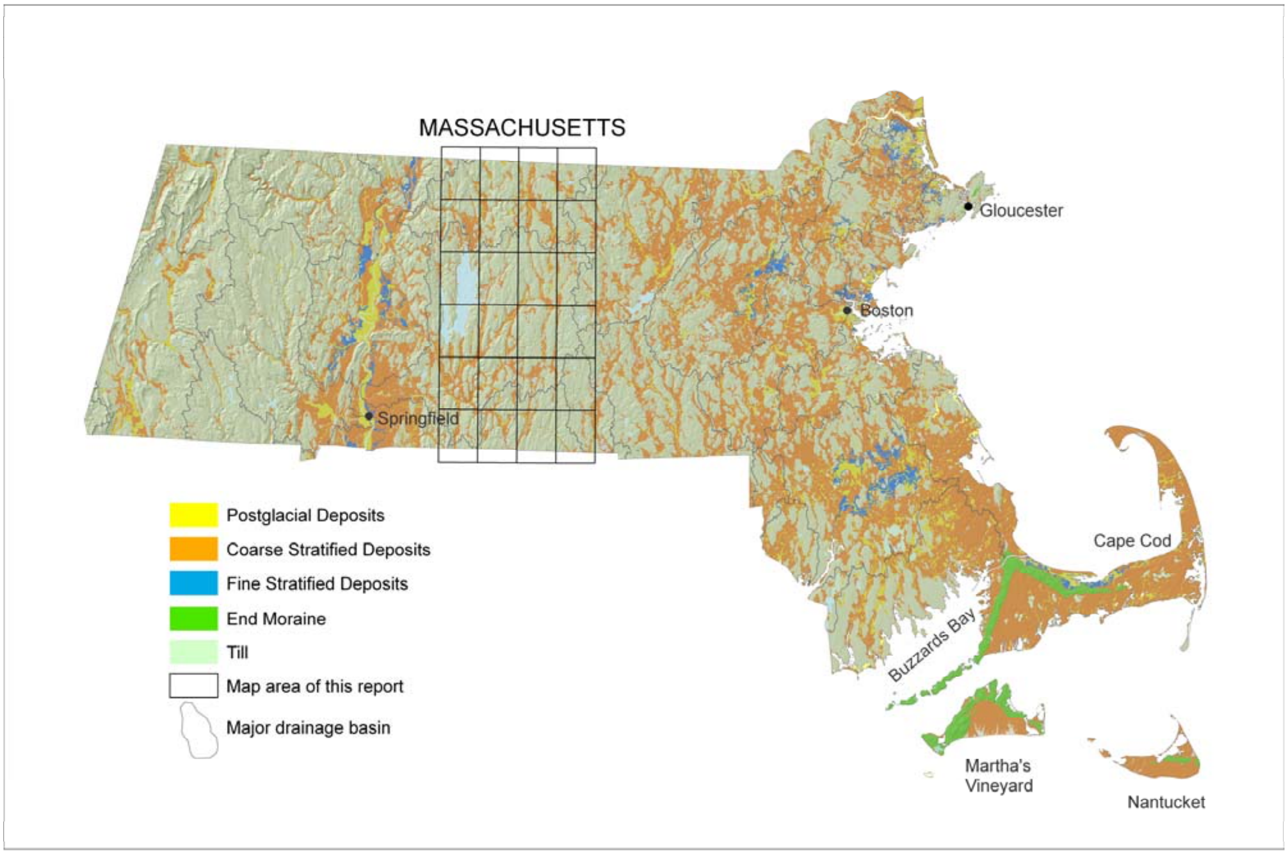


Figure 1. General distribution of glacial and postglacial deposits in Massachusetts (Stone and others, 1993; MassGIS, 1999) and 1:24,000-scale quadrangles covered by this report.

Surficial Materials in Massachusetts

Most of the surficial materials in Massachusetts are deposits of the last two continental ice sheets that covered all of New England in the latter part of the Pleistocene ice age (Schafer and Hartshorn, 1965; Oldale and others, 1982; Stone and Borns, 1986). The glacial deposits are divided into two broad categories, ***glacial till*** and ***glacial stratified deposits***. Till, the most widespread glacial deposit, was laid down directly by glacier ice. Glacial stratified deposits are concentrated in valleys and lowland areas and were laid down by glacial meltwater in streams, lakes, and the sea in front of the retreating ice margin during the last deglaciation. Postglacial sediments, primarily floodplain alluvium and swamp deposits, make up a lesser proportion of the unconsolidated materials.

Glacial till deposits consist of nonsorted, generally nonstratified mixtures of mineral and rock particles ranging in grain size from clay to large boulders. The matrix of most tills is composed dominantly of fine sand and silt. Boulders, within and on the surface of tills, range from sparse to abundant. Some tills contain lenses of sorted sand and gravel, and less commonly, masses of laminated fine-grained sediments. The color and lithologic characteristics of till deposits vary across Massachusetts but generally reflect the composition of the local underlying and northerly adjacent bedrock, from which the till was derived. Till blankets the bedrock surface in variable thickness, ranging from a few inches to more than 200 ft, and commonly underlies stratified meltwater deposits. Tills deposited during the last two glaciations occur in superposition within Massachusetts (Koteff, 1966; Newton, 1978; Weddle and others, 1989). The upper till was deposited during the last (late Wisconsinan) glaciation; it is the most extensive till and commonly is observed in surface exposures, especially in areas where till thickness is less than 10 to 15 ft (thin-till unit on the map). The lower till ("old" till) was deposited during an earlier glaciation (probably Illinoian). The lower till has a more limited distribution; it is principally a subsurface deposit that constitutes the bulk of material in drumlins and other hills, where till thickness is greater than 15 ft. The distribution of lower till is shown primarily by the thick-till unit on the map. The lower till generally is overlain by a thin mantle of upper till in these areas. In all exposures showing the superposed two tills, the base of the upper till truncates the weathered surface of the lower till. The lower part of the upper till commonly displays a zone of shearing, dislocation, and brecciation in which clasts of lower till were mixed and incorporated into the upper till during the last glaciation.

End moraine deposits are composed predominantly of bouldery ablation till but also locally may include sorted sediments. These deposits were laid down by glacial-melting processes along active ice margins during retreat of the last (late Wisconsinan) ice sheet. Extensive end moraines on Nantucket and Martha's Vineyard (fig. 1) are related to the terminal position of the late-Wisconsinan ice sheet, and the end moraines on Cape Cod are associated with recessional positions of the last ice sheet. Less extensive end moraines occur locally elsewhere in southeastern Massachusetts, in the Boston area, and in the Gloucester-Rockport area of northeastern Massachusetts.

Glacial stratified deposits consist of layers of well-sorted to poorly sorted gravel, sand, silt, and clay laid down by flowing meltwater in glacial streams, lakes, and marine embayments that occupied the valleys and lowlands of Massachusetts during retreat of the last ice sheet. Textural variations within the meltwater deposits occur both areally and vertically because meltwater-flow regimes were different in glaciofluvial (stream), glaciodeltaic (where a stream entered a lake or the sea), glaciolacustrine (lake bottom), and glaciomarine (marine bottom) depositional environments. Grain-size variations also resulted from meltwater deposition in positions either proximal to, or distal from, the retreating glacier margin, which was the principal sediment source. A common depositional setting contained a proximal, ice-marginal meltwater stream in which horizontally bedded glaciofluvial gravel and (or) sand and gravel were laid down; farther down valley, the stream entered a glacial lake where glaciodeltaic sediments were deposited, consisting of horizontally layered sand and gravel delta-topset beds overlying inclined layers of sand in delta-foreset beds. Farther out in the glacial lake, very fine sand, silt, and clay settled out on the lake bottom in flat-lying, thinly bedded glaciolacustrine layers. Thick sequences having these textural variations commonly are present in the vertical section of meltwater deposits across the State (Stone, J.R., and others, 1992). Most of the meltwater sediments in Massachusetts were deposited in or graded to large and small glacial lakes. These large and small lakes formed in north-sloping valleys and basins where they were dammed by the ice margin (ice-dammed lakes) and in south-sloping valleys and basins where they were dammed by slightly earlier deltaic sediments (sediment-dammed lakes). The largest glacial lake in Massachusetts was an extensive sediment-dammed lake (glacial Lake Hitchcock), which occupied the Connecticut Valley lowland at altitudes below 365 ft during the retreat of the last ice sheet. Lake Hitchcock was dammed behind a mass of earlier deltaic sediments in the Cromwell-Rocky Hill area of central Connecticut, and the lake lengthened northward into northern Vermont and New Hampshire as the ice sheet retreated.

Detailed geologic maps can show meltwater sedimentary units within each glacial lake or valley outwash system (Jahns, 1941, 1953; Koteff, 1966). These units, known as *morphosequences* (Koteff, 1974; Koteff and Pessl, 1981), are the smallest mappable stratigraphic units depictable on detailed geologic maps. Morphosequences are bodies of stratified meltwater sediments that are contained in a continuum of landforms, grading from ice-contact forms (eskers, kames) to non-ice-contact forms (flat valley terraces, delta plains) that were deposited simultaneously at and beyond the margin of the ice sheet, and were graded to a specific base level. Each morphosequence consists of a proximal part (head) deposited within or near the ice margin and a distal part deposited farther away from the ice margin. Both grain size and ice-melt collapse deformation of beds decrease from the proximal to the distal part of each morphosequence. The head of each morphosequence is either ice marginal (ice contact) or near ice marginal. The surface altitude of fluvial sediments in each morphosequence was controlled by a specific base level, either a glacial-lake or marine water plane or a valley knickpoint. Few morphosequences extend distally more than 6 miles, and most are less than a mile in length. In any one basin, individual morphosequences were deposited sequentially as the ice margin retreated systematically northward. Consequently, in many places the distal, finer-grained facies of a younger morphosequence stratigraphically overlies the proximal, coarse-grained facies of a preceding morphosequence.

Figure 2 shows an example of the variability of sediment types in the subsurface of glacial stratified deposits. The figure shows schematically the relationship between coarse-grained deltaic deposits (sand and gravel and sand) and extensive fine-grained lake (or marine) deposits (fine sand, silt, and clay) in the subsurface. Such coarse- and fine-grained units are common in most of the valleys and lowlands of Massachusetts (Langer, 1979; Stone and others, 1979; Stone, J.R., and others, 1992; Stone and others, 2005). On these interim maps, coarse-grained and fine-grained textural variations within glacial stratified deposits are shown only where they occur at land surface. Subsurface textural variations are not shown.

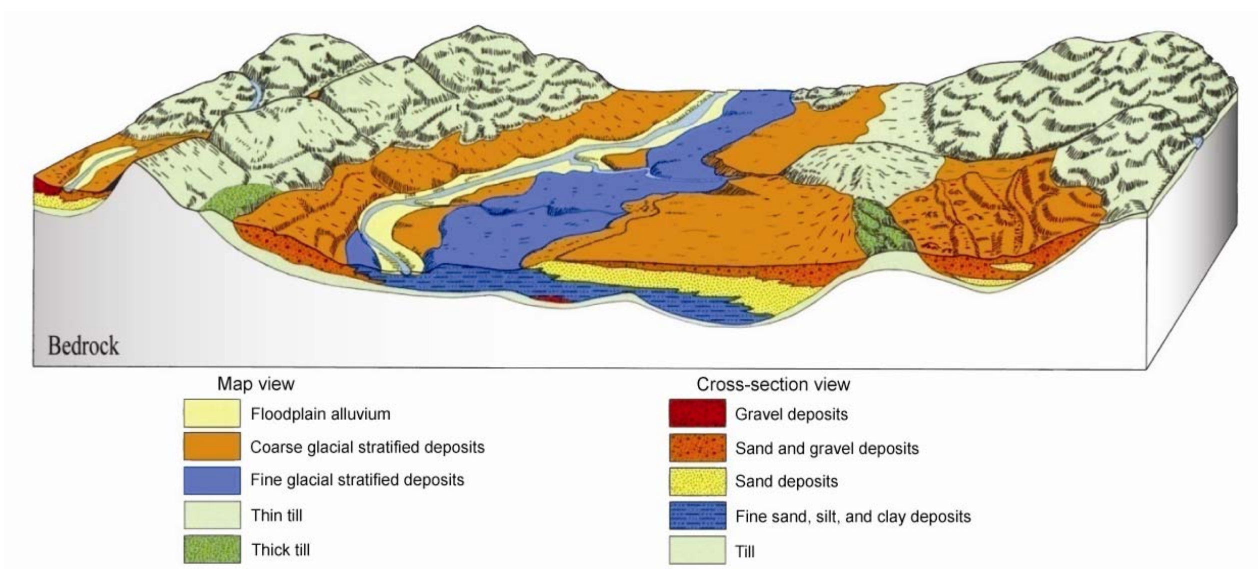


Figure 2. Block diagram illustrating the typical areal and vertical distribution of glacial and postglacial deposits overlying bedrock (modified from Stone, J.R., and others, 1992).

The areal distribution of till and stratified deposits is related to the physiography of the State (fig. 1). The thickness of these materials varies considerably within these regions because of such factors as the high relief of the bedrock surface, changing environments of deposition during deglaciation, and various effects of postglacial erosion and removal of glacial sediments. In highland areas, notably in the western and central regions, till is the major surficial material, and is present as a discontinuous mantle of variable thickness over the bedrock surface. Till is thickest in drumlins (reportedly as much as 230 ft thick) and on the northwest slopes of most bedrock hills. Glacial meltwater deposits that average 50 ft in thickness (Stone and others, 1993) overlie the till in small upland valleys and north-sloping basins between bedrock hills. Glacial stratified deposits are the predominant surficial materials in the Connecticut River valley, the northeastern and southeastern lowlands, and on Cape Cod and the islands. These deposits generally overlie till; however, well logs indicate that in some places till is not present and the stratified deposits lie directly on bedrock. On Cape Cod and the islands, in the southeastern lowland, and in parts of the Connecticut River valley, these deposits completely cover the till-draped bedrock surface.

Postglacial deposits locally overlie the glacial deposits throughout the State. Alluvium underlies the floodplains of most streams and rivers. Swamps occur in low-lying, poorly drained areas in upland and lowland settings, but swamp deposits are shown only where they are estimated to be at least 3 ft thick. Salt-marsh and estuarine deposits are present mainly along the tidal portions of streams and rivers entering the offshore areas. Beach and dune deposits occur along the shoreline.

Description of Map Units

Postglacial Deposits

Artificial fill—Earth materials and manmade materials that have been artificially emplaced, primarily in highway and railroad embankments and in dams; may also include landfills, urban-development areas, and filled coastal wetlands

Floodplain alluvium—Sand, gravel, silt, and some organic material, stratified and well sorted to poorly sorted, beneath the floodplains of modern streams. The texture of alluvium commonly varies over short distances both laterally and vertically, and generally is similar to the texture of adjacent glacial deposits. Along smaller streams, alluvium is commonly less than 5 ft thick. The most extensive deposits of alluvium in the map area are along the Millers, Swift, Ware, and Quaboag Rivers. Alluvium typically overlies thicker glacial stratified deposits

Alluvial-fan deposits—Generally coarse gravel and sand deposits on steep slopes where high-gradient streams entered lower gradient valleys. Some alluvial fans in this area were graded to lowering levels of glacial lakes. Some fans continue to form today

Swamp deposits—Organic muck and peat that contain minor amounts of sand, silt, and clay, stratified and poorly sorted, in kettle depressions or poorly drained areas. Swamp deposits are shown only where they are estimated to be at least 3 ft thick. Most swamp deposits are less than 10 ft thick. Swamp deposits overlie glacial deposits or bedrock. They locally overlie glacial till even where they occur within thin glacial meltwater deposits

Glacial Stratified Deposits

Sorted and stratified sediments composed of gravel, sand, silt, and clay (as defined in particle-size diagram, fig. 3) deposited in layers by glacial meltwater. These sediments occur as four basic textural units—gravel deposits, sand and gravel deposits, sand deposits, and fine deposits. On this interim surficial geologic map layer, gravel, sand and gravel, and sand deposits are not differentiated and are shown as *Coarse Deposits* where they occur at land surface. *Fine Deposits* also are shown where they occur at land surface. Textural changes occur both areally and vertically (fig. 2); however, subsurface textural variations are not shown on this interim map.

PARTICLE DIAMETER											
	10	2.5	.16	.08	.04	.02	.01	.005	.0025	.00015	inches
	256	64	4	2	1	.5	.25	.125	.063	.004	mm
Boulders	Cobbles	Pebbles	Granules	Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay	
GRAVEL PARTICLES				SAND PARTICLES				FINE PARTICLES			

Figure 3. Grain-size classification used in this report, modified from Wentworth (1922).

Coarse deposits include *Gravel deposits* composed of at least 50 percent gravel-size clasts; cobbles and boulders predominate; minor amounts of sand occur within gravel beds, and sand comprises few separate layers. Gravel layers generally are poorly sorted, and bedding commonly is distorted and faulted due to postdepositional collapse related to melting of ice. *Sand and gravel deposits* occur as mixtures of gravel and sand within individual layers and as layers of sand alternating with layers of gravel. Sand and gravel layers generally range from 25 to 50 percent gravel particles and from 50 to 75 percent sand particles. Layers are well to poorly sorted; bedding may be distorted and faulted due to postdepositional collapse. *Sand deposits* are composed mainly of very coarse to fine sand, commonly in well-sorted layers. Coarser layers may contain up to 25 percent gravel particles, generally granules and pebbles; finer layers may contain some very fine sand, silt, and clay

Fine deposits include very fine sand, silt, and clay that occur as well-sorted, thin layers of alternating silt and clay (varves), or as thicker layers of very fine sand and silt. Very fine sand commonly occurs at the surface and grades downward into rhythmically bedded silt and clay varves

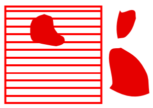
Glacial Till Deposits

End moraine deposits—Composed predominantly of boulders and ablation-facies sandy upper till; lenses of stratified sand and gravel occur locally within the till. Surface boulders on end moraine deposits are generally more numerous than on adjacent till surfaces; dense concentrations of boulders are present in some places. Deposits occur as freestanding hummocky landforms, commonly in ridges. Only two small end moraine deposits are present in this compilation area, in the village of Hardwick in the Ware quadrangle

Thin till—Nonsorted, nonstratified matrix of sand, some silt, and little clay containing scattered pebble, cobble, and boulder clasts; large surface boulders are common; mapped where till is generally less than 10 to 15 ft thick including areas of shallow bedrock. Predominantly consists of upper till of the last glaciation; loose to moderately compact, generally sandy, commonly stony. Two facies are present in some places: a looser, coarser grained ablation facies, melted out from supraglacial position; and an underlying more compact, finer grained lodgement facies deposited subglacially. In general, both ablation and lodgement facies of upper till derived from fine-grained bedrock are finer grained, more compact, less stony and have fewer surface boulders than upper till derived from coarse-grained crystalline rocks. Across Massachusetts, fine-grained bedrock sources include the red Mesozoic sedimentary rocks of the Connecticut River lowland, marble in the western river valleys, and fine-grained schists in upland areas

Thick till—Nonsorted, nonstratified matrix of sand, some silt, and little clay containing scattered pebbles, cobbles, and boulders in the shallow subsurface; at greater depths consists of compact, nonsorted matrix of silt, very fine sand, and some clay containing scattered small gravel clasts. Mapped in areas where till is greater than 10 to 15 ft thick, chiefly in drumlin landforms in which till thickness commonly exceeds 100 ft (maximum recorded thickness is 230 ft). Although upper till is the surface deposit, the lower till constitutes the bulk of the material in these areas. Lower till is moderately to very compact and is commonly finer grained and less stony than upper till. An oxidized zone, the lower part of a soil profile formed during a period of interglacial weathering, is generally present in the upper part of the lower till. This zone commonly shows closely spaced joints that are stained with iron and manganese oxides

Bedrock Areas



Bedrock outcrops and areas of abundant outcrop or shallow bedrock—Solid color shows extent of individual bedrock outcrops; horizontal-line pattern indicates areas of shallow bedrock ***or*** areas where small outcrops are too numerous to map individually; in areas of shallow bedrock, surficial materials are less than 5 to 10 ft thick. These units are not mapped consistently among all quadrangles; see Appendix for level of bedrock outcrop mapping in each quadrangle

Map Compilation

This compilation is the eighth in a series of interim products and shows surficial geology in an area of 24 7.5-minute quadrangles in central Massachusetts. The quadrangles are Mount Grace, Royalston, Winchendon, Ashburnham, Orange, Athol, Templeton, Gardner, Quabbin Reservoir, Petersham, Barre, Wachusett Mountain, Winsor Dam, Ware, North Brookfield, Paxton, Palmer, Warren, East Brookfield, Leicester, Monson, Wales, Southbridge, and Webster (fig. 4; fig. 5, area I). Figure 5 shows all of the compilation areas for surficial geology in Massachusetts. The surficial geologic maps produced to date are areas A–G and area I.

The surficial geologic map layer was compiled in several steps:

1) Paper copies of the published surficial geologic maps for 9 quadrangles were scanned and georeferenced by MassGIS;
2) The Office of the Massachusetts State Geologist (now the Massachusetts Geological Survey) vectorized the georeferenced images in order to digitally retain the original linework of the published maps (Mabee and others, 2004);
3) Digital geologic map units were compiled and grouped into basic units in three shapefile layers: *Postglacial deposits* including artificial fill, floodplain alluvium, alluvial-fan deposits, and swamp deposits; *glacial stratified deposits* including coarse-grained and fine-grained deposits; and *glacial till and bedrock* including thin till, thick till (drumlins), outcrops and areas of shallow bedrock. The distribution of glacial stratified deposits beneath adjacent overlying postglacial deposits and water bodies was inferred by the compilers;
4) The same basic units as those listed in step 3 above were compiled and digitized for 15 unpublished quadrangles from scanned field maps by USGS personnel;
5) The 24 individual quadrangle maps were joined and edge-matched in order to form a seamless digital geologic map layer. Discrepancies along quadrangle boundaries were resolved, and thick-till areas and shallow bedrock areas were added by the compilers in quadrangles where these units had not been previously mapped.

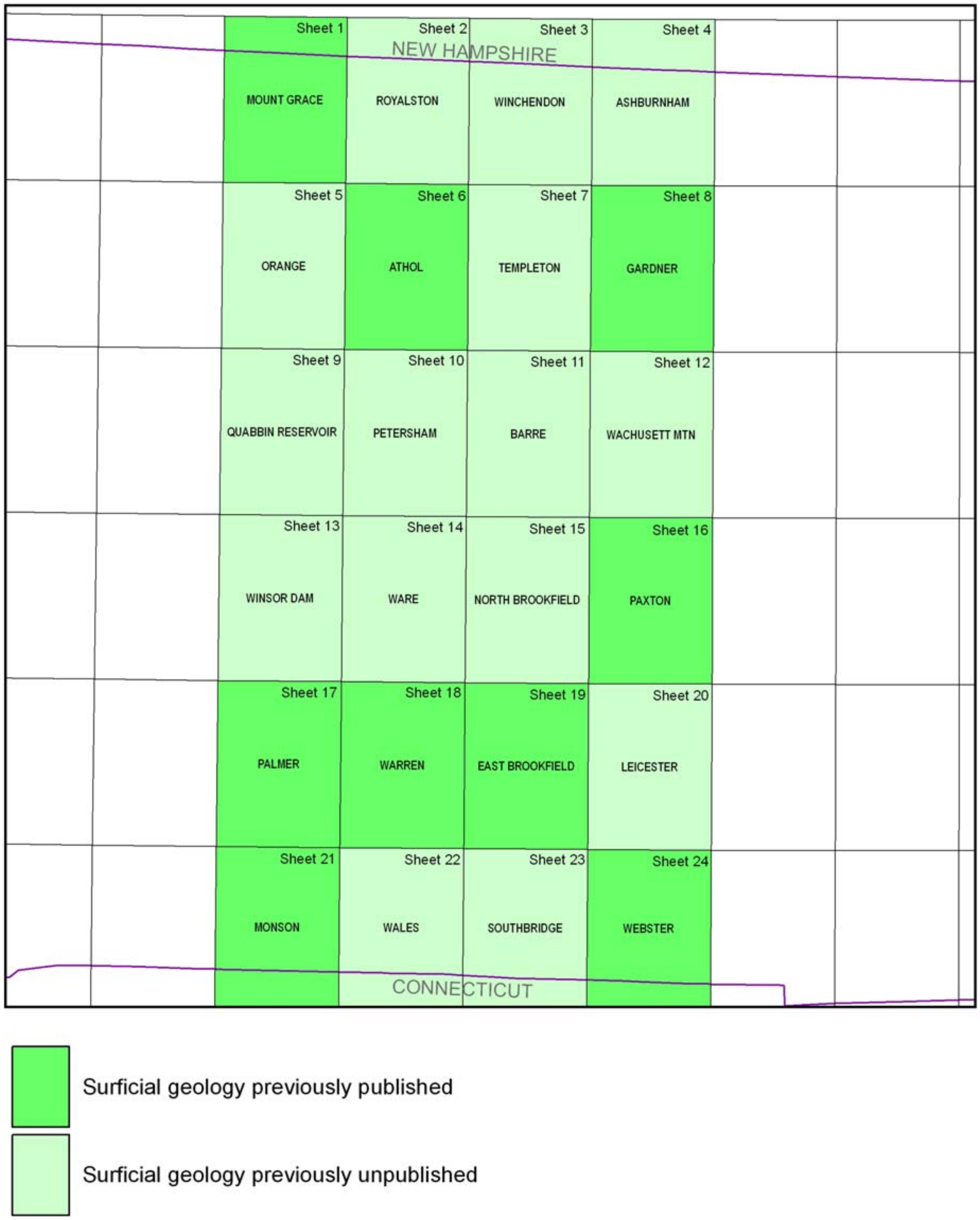


Figure 4. The 24 USGS 7.5-minute, 1:24,000-scale quadrangles in this compilation. Sheet numbers refer to Adobe PDF map files of individual quadrangles.

All geologic mapping was completed at 1:24,000 scale (several quadrangles were previously published at 1:31,680 scale). The 1:24,000-scale, 10-ft contour interval topographic base maps (1954–1972 editions) used for this mapping effort are included as part of the digital data package in the *24k_basemaps* folder. The GIS folder included with this report contains three ArcGIS shapefiles, which show the distribution of geologic units that cover the entire map area, and are intended for use at quadrangle scale. The shapefiles can be clipped by quadrangle or by town boundary. Unlike the units in conventional geologic maps, the digitally defined map units are arranged in layers according to superposition. The shapefile for till and bedrock is the bottom layer, which is overlain by the succeeding stratified deposits shapefile layer; these materials are shown everywhere they occur, including beneath postglacial deposits such as swamp deposits, and also beneath water bodies. The shapefile for postglacial deposits should be placed on top because these materials overlie the other two layers. Instructions for using the digital files are included in the README file and metadata.

In addition to the seamless digital layers that cover the entire compilation area, Adobe PDF map files of the surficial geology layers shown with 1:24,000-scale topographic base map images have been generated for each quadrangle (see Sheets 1–24, indexed on figure 4).

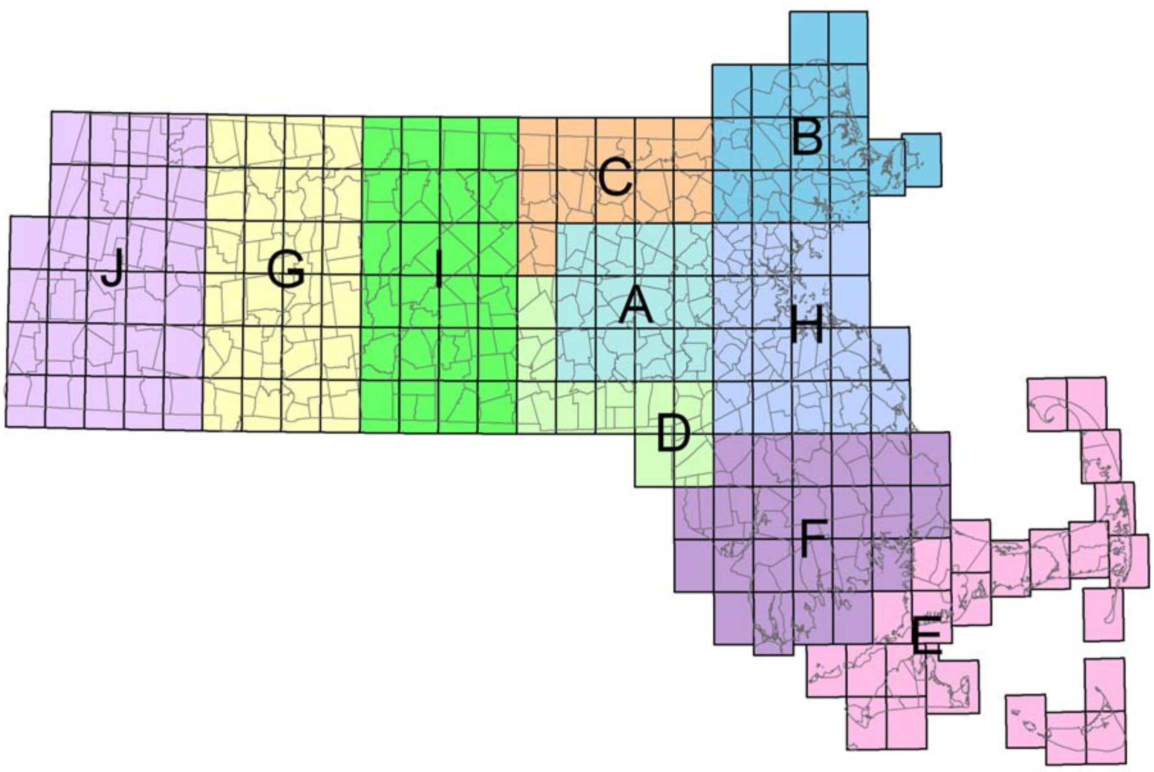


Figure 5. Compilation areas in Massachusetts. Letters represent sections of Open-File Report 2006–1260. Sections published to date are available online at http://pubs.usgs.gov/of/2006/1260/.

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Appendix

Sources of Data by 7.5-Minute Quadrangle

Mount Grace Quadrangle

Map units were reproduced from Hadley (1949). Glacial Stratified Deposits include units Qk and Qe of Hadley (1949), which are predominantly coarse-grained glaciofluvial and glaciodeltaic sediments graded to small glacial lakes in the valleys of the West Branch Tully River, Mirey Brook-Mountain Brook, Darling Brook, and Hodge Brook. Thick-till areas were delineated based on topographic analysis. The shallow bedrock unit represents areas of abundant outcrop. Some postglacial units were mapped using 2005 orthophoto images.

Royalston Quadrangle

Stone, J.R., 1975, unpublished field map; Larsen, F.D., 1980, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained glaciofluvial and glaciodeltaic sediments graded to small glacial lakes in the valleys of the East Branch Tully River, Lawrence Brook, Beaver Brook, and Millers River. Few bedrock outcrops were mapped in the field in this quadrangle; some outcrops in the northwestern part of the map area were mapped from the position of structure symbols shown by Springston (1990, pl. 2). Some outcrops were mapped where visible on 2005 orthophoto images, and shallow-bedrock areas were delineated using topographic analysis. Additional outcrops and shallow-bedrock areas are most likely present, particularly in areas of thin till that have steep slopes and (or) irregular topography. Some postglacial units were mapped using 2005 orthophoto images.

Winchendon Quadrangle

Stone, J.R., 1979, unpublished field map. Glacial Stratified Deposits include coarse- and fine-grained sediments graded to glacial lakes in the Otter River and Millers River valleys. The shallow-bedrock unit represents areas of small scattered bedrock outcrops. Additional bedrock outcrops and shallow-bedrock areas are most likely present, particularly in areas of thin till that have steep slopes and irregular topography.

Ashburnham Quadrangle

Stone, B.D., 1978 unpublished field map. Glacial Stratified Deposits are predominantly coarse-grained glaciofluvial and glaciodeltaic sediments in the Phillips Brook valley and in headwater valleys of the Millers River. Bedrock outcrops and shallow-bedrock areas in the eastern part of the quadrangle were reproduced from Peterson (1984, pl. 3). Some outcrops were mapped where visible on 2005 orthophoto images, and shallow-bedrock areas were delineated using topographic analysis. Additional outcrops and shallow-bedrock areas are most likely present, particularly in areas of thin till that have steep slopes and (or) irregular topography. Some postglacial units were mapped using 2005 orthophoto images.

Orange Quadrangle

Stone, J.R., 1976, unpublished field map; Larsen, F.D., 1980, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained glaciofluvial and glaciodeltaic sediments graded to glacial lakes in the valleys of the Millers River and tributaries, Middle Branch Swift River, and Whetstone Brook. Distribution of bedrock outcrops and shallow-bedrock areas is from Robinson (2008). Some postglacial units were mapped using 2005 orthophoto images.

Athol Quadrangle

Map units were modified from Eschman (1966). Glacial Stratified Deposits include predominantly coarse-grained glaciofluvial and glaciodeltaic sediments in the Millers River and tributary valleys, and in the valleys of the East Branch Swift River, Riceville Brook, and Beaver Brook. The shallow-bedrock unit is defined as “areas of numerous small scattered exposures or where bedrock is very near the surface and controls the topography” (Eschman, 1966). Thick-till areas were mapped based on topographic analysis and on well and test-hole data. Some postglacial units were mapped using 2005 orthophoto images.

Templeton Quadrangle

Stone, J.R., 1979, unpublished field map. Glacial Stratified Deposits include coarse- and fine-grained sediments graded to ice-dammed glacial lakes in the valleys of the Otter River and tributaries and sediment-dammed glacial lakes in the Burnshirt River-Trout Brook valley. The shallow-bedrock unit represents areas of small scattered bedrock outcrops and where bedrock is interpreted to be within 10 ft of land surface.

Gardner Quadrangle

Map units were reproduced from Stone (1978). Glacial Stratified Deposits include predominantly coarse-grained glaciofluvial and glaciodeltaic sediments graded to small glacial lakes in the valleys of the Whitman River and Mahoney Brook and their tributaries. The shallow-bedrock unit is defined as “areas where surficial deposits are generally less than 3 meters thick, and may contain numerous small bedrock outcrops.”

Quabbin Reservoir Quadrangle

Stone, J.R., 1975, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained sediments graded to a series of glacial lakes in the East, Middle, and West Branch Swift River valleys; today these deposits lie mostly underwater beneath Quabbin Reservoir. Bedrock outcrops were not mapped in the field. Those shown on the map are visible on 2005 orthophoto images. The distribution of shallow-bedrock areas was interpreted by topographic analysis. Additional bedrock outcrops and shallow-bedrock areas are present, particularly in areas of thin till that have steep slopes and (or) irregular topography. Some postglacial units were mapped using 2005 orthophoto images.

Petersham Quadrangle

Stone, J.R., 1976, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained sediments graded to glacial lakes in the East Branch Swift River valley. Bedrock outcrops were not mapped in the field. Those shown on the map are visible on 2005 orthophoto images. The distribution of shallow-bedrock areas was interpreted by topographic analysis. Additional bedrock outcrops and shallow-bedrock areas are present, particularly in areas of thin till that have steep slopes and (or) irregular topography. Some postglacial units were mapped using 2005 orthophoto images.

Barre Quadrangle

Larsen, F.D., 1982, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained sediments graded to glacial lakes in the Ware River valley and its tributary valleys. Bedrock outcrop areas are from Tucker (1977). The shallow-bedrock unit represents areas of closely spaced outcrops.

Wachusett Mountain Quadrangle

Stone, B.D., 1982, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained sediments graded to glacial lakes in the valleys of the East Branch Ware River and tributaries, West Branch Ware River, and Wachusett Brook. Bedrock outcrop areas are from Tucker (1977). The shallow-bedrock unit represents areas of closely spaced outcrops.

Winsor Dam Quadrangle

Stone, J.R., 1976, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained sediments graded to glacial lakes in the Swift River, Beaver Brook, Flat Brook, and Muddy Brook valleys. Bedrock outcrops were not mapped in the field. Those shown on the map are visible on 2005 orthophoto images. The distribution of shallow-bedrock areas was interpreted by topographic analysis. Additional bedrock outcrops and shallow-bedrock areas are present, particularly in areas of thin till that have steep slopes and (or) irregular topography. Some postglacial units were mapped using 2005 orthophoto images.

Ware Quadrangle

Map units were modified from Mulholland (1975). Glacial Stratified Deposits include predominantly coarse-grained glaciofluvial and glaciodeltaic sediments in the valleys of the Ware River, Muddy Brook, Mill Brook and tributaries, and Winimusset Brook. Fine-grained deposits occur in the subsurface in the Winimusset Brook valley (Stone, B.D., and others, 1992). Some bedrock outcrop areas are from Field (1976). The shallow-bedrock unit represents areas of closely spaced outcrops. Thick-till areas were mapped based on topographic analysis and on well and test-hole data. Some postglacial units were mapped using 2005 orthophoto images.

North Brookfield Quadrangle

Larsen, F.D., 1982, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained deposits graded to sediment-dammed glacial lakes in the Ware River, Sevenmile River, and Fivemile River valleys and ice-dammed glacial lakes in the north-draining Bell Brook and Burrow Brook valleys. Most bedrock outcrops were not mapped in the field. Those shown on the map are visible on 2005 orthophoto images. Additional bedrock outcrops and shallow-bedrock areas are present, particularly in areas of thin till that have steep slopes and (or) irregular topography. Some postglacial units were mapped using 2005 orthophoto images.

Paxton Quadrangle

Stone, B.D., 1982, unpublished field map, western part of quadrangle. Map units in the eastern part of the quadrangle were reproduced from Stone (1980). Glacial Stratified Deposits include coarse-grained sediments graded to glacial lakes in the Sevenmile River, Turkey Hill Brook, and Asnebumskit Brook valleys. The shallow-bedrock unit in the eastern part of the quadrangle is defined as “areas where surficial deposits are generally less than 3 m thick, locally containing numerous bedrock outcrops.” Some bedrock outcrops were taken from Walsh (2002). Thick-till areas were mapped based on topographic analysis and on the position of drumlin axes shown on the map of Stone (1980). Some postglacial units were mapped using 2005 orthophoto images.

Palmer Quadrangle

Map units were reproduced from Peper (1978). Glacial Stratified Deposits include coarse-grained, glaciofluvial and glaciodeltaic sediments graded to glacial lakes in the valleys of the Swift River, Ware River, and Quaboag River and their tributaries. The shallow-bedrock unit is defined as “areas of abundant outcrop and thin surficial cover.” Thick-till areas were mapped based on topographic analysis and on the position of drumlin axes shown on the map of Peper (1978).

Warren Quadrangle

Map units were reproduced from Pomeroy (1977). Glacial Stratified Deposits include coarse-grained glaciofluvial and glaciodeltaic sediments graded to glacial lakes in the Quaboag River valley and its tributary valleys. The shallow-bedrock unit is defined as “closely spaced outcrops where surficial deposits are thin.” Thick-till areas were mapped based on topographic analysis and on the position of drumlin axes shown on the map of Pomeroy (1977).

East Brookfield Quadrangle

Map units were reproduced from Pomeroy (1975). Glacial Stratified Deposits include coarse-grained glaciofluvial and glaciodeltaic sediments graded to glacial lakes in the Quaboag River valley and its tributary valleys. The shallow-bedrock unit is defined as “closely spaced outcrops where surficial deposits are thin.” Thick-till areas were mapped based on topographic analysis and on the position of drumlin axes shown on the map of Pomeroy (1975).

Leicester Quadrangle

Stone, B.D., 1982, unpublished field map. Glacial Stratified Deposits include predominantly coarse-grained sediments graded to glacial lakes in the French River and Cranberry River valleys. Bedrock outcrops were not mapped in the field. Those shown on the map are visible on 2005 orthophoto images. A few outcrops were located from structure symbols shown on the map of Barosh and Johnson (1976). The distribution of shallow-bedrock areas was interpreted by topographic analysis. Additional bedrock outcrops and shallow-bedrock areas are present, particularly in areas of thin till that have steep slopes and (or) irregular topography. Some postglacial units were mapped using 2005 orthophoto images.

Monson Quadrangle

Map units were reproduced from Peper (1977). Glacial Stratified Deposits include coarse-grained predominantly glaciodeltaic sediments laid down in an ice-dammed glacial lake in the valleys of the north-draining Chicopee Brook, Twelvemile Brook, Vinica Brook, Conant Brook, and Foskett Mill Stream. The shallow-bedrock unit is defined as “areas of abundant outcrop and thin drift.” Thick-till areas were mapped based on topographic analysis and on the position of drumlin axes shown on the map of Peper (1977).

Wales Quadrangle

Stone, J.R., 1975, unpublished field map. Glacial Stratified Deposits include coarse-grained glaciofluvial and glaciodeltaic sediments graded to small glacial lakes in the Quinebaug River valley and its tributary valleys. Bedrock outcrops and shallow-bedrock areas were reproduced from Seiders (1976), where the shallow-bedrock unit is defined as “areas of thin till and abundant outcrop.” Thick-till areas were mapped based on topographic analysis. Some postglacial units were mapped using 2005 orthophoto images.

Southbridge Quadrangle

Map units were modified from Moore (1978). Glacial Stratified Deposits include coarse-grained glaciofluvial and glaciodeltaic sediments graded to small glacial lakes in the Quinebaug River valley and its tributary valleys. Bedrock outcrops were reproduced from Moore (1978), and many areas of abundant small outcrops were included in the shallow-bedrock unit. Thick-till areas were mapped based on topographic analysis and on well and test-hole data. Some postglacial units were mapped using 2005 orthophoto images.

Webster Quadrangle

Map units were modified from Barosh (1973). Glacial Stratified Deposits include coarse-grained glaciofluvial and glaciodeltaic sediments graded to glacial lakes in the Quinebaug and French River valleys and their tributary valleys. Bedrock outcrops and areas of shallow bedrock are from Barosh (2009) where the shallow-bedrock unit is defined as “areas of abundant outcrops and areas where bedrock lies within 3 m of the surface.” Thick-till areas were modified from the Qt_3 unit and from the position of drumlin axes, both shown on the map of Barosh (1973). Some postglacial units were mapped using 2005 orthophoto images.