DEPARTMENT OF INTERIOR
UNITED STATES GEOLOGICAL SURVEY

GEOLOGIC INTERPRETATION OF AN AEROMAGNETIC MAP OF SOUTHERN NEW ENGLAND

By David S. Harwood and Isidore Zietz

Prepared in cooperation with
THE COMMONWEALTH OF MASSACHUSETTS
DEPARTMENT OF PUBLIC WORKS
THE STATE OF CONNECTICUT GEOLOGICAL AND
NATURAL HISTORY SURVEY
THE STATE OF NEW HAMPSHIRE
DEPARTMENT OF RESOURCES AND
ECONOMIC DEVELOPMENT

GEOPHYSICAL INVESTIGATIONS MAP
Published by the U.S. Geological Survey 1977
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INTRODUCTION

The aeromagnetic map of southern New England includes all of Massachusetts, Connecticut and Rhode Island, adjoining areas of New York, Vermont and New Hampshire, a small part of northeastern New Jersey, and areas over the Atlantic Ocean and Long Island Sound. It shows the total intensity of the earth's field contoured at intervals of 50 and 100 gammas relative to an arbitrary datum. The main magnetic field of the earth has been removed by the method of Fabiano and Peddie (1969); this main field is commonly referred to as the International Geomagnetic Reference Field (IGRF). Each color on the map represents 100 gammas with the lower magnetic intensities represented by the violet end of the color spectrum and grading to the higher intensities shown by the red end of the spectrum. The magnetic data covering Connecticut, Massachusetts and Rhode Island were compiled from maps published at a scale of 1:62,500 and a contour interval of 20 gammas.

The flight spacing and elevation vary somewhat from area to area (see index map showing sources of data). In general, the flight elevation is very close to 500 feet above the ground. The flight spacing is ½ mile on east-west lines for all of Connecticut, Massachusetts and Rhode Island. Except for a small area in New Hampshire the flight spacing is everywhere 1 mile or less over the land areas, and Long Island Sound. Over the ocean the flight spacing is about 5 miles.

The slight elevation changes and variable line spacing produce such minor discrepancies that contours and character of the map are not affected at this scale.

The relative intensities of the magnetic anomalies are accentuated by color which also distinguishes the short from the long wavelength anomalies.

Most of the data for this map were obtained through cooperative programs of the U. S. Geological Survey with the Massachusetts Department of Public Works and with the Connecticut Geological and Natural History Survey. Part of the data for New Hampshire was also obtained through a State Cooperative program with the Department of Resources and Economic Development.

REGIONAL GEOLOGIC SETTING

The area of this report spans the Appalachian geologic province and includes a wide variety of lithologic units. In their regional context these lithologic units define major tectonic belts which where derived, in part at least, from their depositional framework. Some of these major litho-tectonic zones are clearly shown by their magnetic patterns. The regional geologic setting briefly outlined here serves as an introduction to the following section in which the magnetic anomalies are related to specific lithologic units or groups of units. More detailed accounts of the regional geology are given by Zen, White, Hadley, and Thompson, (1968), Rodgers (1970), Bird and Dewey (1970) and Zen (1972).

West of the Hudson River, unmetamorphosed and weakly deformed rocks of the Appalachian foreland are present in the Catskill Plateau and Hudson Lowlands. Only the northeastern-most part of the Catskill Plateau is included in the study area. Cambrian and Ordovician quartzite, carbonate rocks, and shale comprise the Hudson Lowlands section and lap unconformably onto Precambrian gneisses in the Adirondack Mountains to the north. None of the foreland rocks have recognizable magnetic patterns of their own and the broad anomalies west of the Hudson River are related to buried Precambrian rocks.

Cambrian and Ordovician rocks of the foreland are separated from their lithologic and stratigraphic correlatives to the east by a narrow zone of low-angle, east-over-west thrusts along the Hudson River. This tectonic break is the southern extension of a zone of thrust faults known as Logan's Line and marks, in a general way, the western limit of intense multiple Paleozoic deformation in this part of the Appalachian belt. East of this zone of thrusts, Middle Ordovician black shale and graywacke rest unconformably on the carbonate and quartzite sequence. This unconformity marks the beginning of tectonic activity associated with the Taconic orogeny. Deformation and metamorphic grade in the carbonate and quartzite sequence and in the overlying black shale and graywacke increase to the southeast.

Within the carbonate and quartzite terrain east of Logan's Line, there are extensive tracts of allochthonous rocks, largely slate and graywacke, equivalent in age to the underlying miogeosynclinal rocks. These detached rocks of the Taconic allochthon moved westward, first as gravity slides then followed by hard-rock thrust slices, from their site of deposition which was located probably over the Precambrian massifs east of the miogeosynclinal sequence of carbonate and quartzite rocks. Deformation is intense in the rock of the Taconic allochthon and the degree of metamorphism increases to the southeast. Sharp, local magnetic anomalies associated with the allochthonous rocks appear in the biotite zone or lower part of the garnet zone (see Mt. Everett, southwestern Mass., aeromagnetic map); in areas of lower metamorphic grade there are no local anomalies associated with the allochthonous rocks.

East of the miogeosynclinal sequence there are isolated patches of Precambrian rocks exposed in the Green Mountains, and the Berkshire, Housatonic, New Milford and Hudson Highlands (See fig. 1). These Precambrian rocks form part of the core of a major anticlinorium extending the length of the Appalachian belt from the Blue Ridge Mountains in the south to the Long Range in Newfoundland. The western front of the Precambrian rocks is marked by strong westward overturning in the Green Mountains and profound westward thrusting in the Berkshire Highlands and probably in the Housatonic Highlands as well.

Slate, graywacke, and volcanic rocks ranging in age from Cambrian to Devonian flank the chain of Précambrian "massifs" on the east. The Cambrian and Ordovician section, which contains most of the volcanic rocks as well as scattered serpentinite bodies, is clearly marked by belts of sharp linear magnetic anomalies in western Massachusetts. Highly magnetic Ordovician volcanic rocks also show up prominently in the cores of several structural domes near the eastern side of the Hartland-Rowe belt, (fig. 2). Silurian and Devonian rocks in this eugeosynclinal sequence form the trough of the Connecticut Valley - Gaspé synclinorium (fig. 2) and display broad, low amplitude magnetic anomalies.

On the east flank of the Connecticut Valley - Gaspé synclinorium, pre-Silurian eugeosynclinal rocks, here largely of Ordovician age, are exposed again in the Bronson Hill anticlinorium. A belt of gneiss domes, cored by Ordovician volcanic rocks and pre-Silurian intrusive rocks extends along the Bronson Hill anticlinorium. These domes postdate large scale, westward directed recumbent folds in the anticlinorium.

A large expanse of pelitic schist and impure quartzite of possible Silurian and Devonian age lies east of the Bronson Hill anticlinorium and forms the trough of the Merrimack synclinorium. Although the lithologic sequence here is not identical to the Silurian and Devonian sequence in the trough of the Connecticut Valley - Gaspé synclinorium these two broad expanses of Silurian and Devonian rocks have similar patterns of low-amplitude magnetic anomalies. Tectonic transport in the Merrimack synclinorium is directed to the east and involves eastward-directed recumbent folds and thrust movement on the Honey Hill - Lake Char fault system.

Pre-Silurian rocks are again exposed in a narrow belt on the east limb of the Merrimack synclinorium. Here, high grade schist, gneiss, and volcanic rocks of Ordovician and older ages are associated with a belt of sharp linear magnetic anomalies similar to those associated with the Bronson Hill anticlinorium and the east flank of the Berkshire anticlinorium. Rocks in all three of these belts are probably equivalent, at least in part, but this has not been clearly established as yet because the eastern belt (Putnam and Marlboro belts, (fig. 2)) is complicated by extensive faulting and, unlike the other two belts, cannot be traced into low grade, fossiliferous rocks. The relationship between rocks in the Putnum and Marlboro belts to the extensive tracts of felsic intrusive rocks in southeastern Connecticut, Massachusetts and western Rhode Island is also uncertain.

The major tectonic framework of southern New England, outlined briefly above, was largely set in its present spatial arrangement by Devonian time. To this framework were later added several basins of Pennsylvanian sediments in Rhode Island and eastern Massachusetts and the major half-graben of Triassic arkosic sediments and basaltic flows in central Connecticut and Massachusetts.

GEOLOGIC INTERPRETATION

In much of southern New England there is good correlation between the aeromagnetic patterns and the distribution of major lithologic belts. It is apparent, however, that some magnetic anomalies are not related to the surface rocks, that some magnetic patterns change significantly along the strike of the lithologic belts, and that similar rocks types in adjacent areas show remarkably different magnetic patterns. These apparent inconsistencies between the magnetic and lithologic patterns are at first disconcerting but they represent one of the major contributions of this regional aeromagnetic study and neither the magnetics nor the geology should be dismissed out of hand.

The magnetic patterns on the aeromagnetic map are best suited for regional analysis and comparison within the area of southern New England and between this area and other parts of the Appalachians. Specific anomalies associated with relatively small lithologic units, such as small plutons, are best analyzed at 1:24,000 or larger scales where the 20 gamma contour interval shows the magnetic gradients with greater detail and accuracy. In recent years there have been some excellent analyses and geologic interpretations of specific anomalies in New England; some within the area of this aeromagnetic map (see Griscom and Bromery, 1968, for examples and references).

The following geologic interpretation is organized according to geographic and lithologic belts and generally proceeds from west to east across the area of southern New England. Location of the specific belts is shown on figure 2.

SOUTHEASTERN NEW YORK

There are two major belts of positive magnetic anomalies in southeastern New York that extend northeastward into westernmost New England. Harwood and Zietz (1974) have recently related these belts of anomalies to buried masses of probable Precambrian rocks and have referred to the northern belt as the Albany-Bennington anomaly and to the southern belt as the Beacon-Copake anomaly.

Albany-Bennington anomaly.—West of the Hudson River the source of the Albany-Bennington anomaly lies below unmetamorphosed, flat-lying to gently west and south dipping sedimentary rocks of Devonian to Ordovician age (Hamilton Group to Trenton Group; see Fisher et al., 1971). Between the Hudson River and Bennington, Vermont, the source is covered by Cambrian to Ordovician slate and graywacke that make up several slices of the Taconic allochthon as well as autochthonous slate and carbonate rocks of the same age which underlie the allochthon (see Zen, 1967; 1972).

From the Hudson River to the Vermont state line the magnetic anomaly, and presumably the source, trends about N. 65° E. and lies at depths ranging from about 7,000 feet south of Albany to more than 10,000 feet near the Vermont line. In southwestern Vermont the magnetic source appears to be offset by the high angle fault mapped by MacFadyen (1956) south of Bennington. East of this fault the anomaly trends about N. 30° E. at depths ranging from about 4,000 feet at the south to no more than 700 feet east of Bennington. Harwood and Zietz concluded that this major anomaly marked a mass of Precambrian rocks similar to those exposed in the Adirondack Mountains to the northwest but that these rocks differed magnetically and probably lithologically from the Precambrian rocks exposed in the Green Mountains.

Beacon-Copake anomaly.—The belt of positive anomalies that trends about N. 30° E. between Beacon, New York, and Copake, New York, is very similar in amplitude and lateral persistence to anomalies associated with Precambrian rocks exposed to the southwest in the Reading Prong (see Henderson et al., 1966). The source of the Beacon-Copake anomaly lies below the same Paleozoic rock units that cover the source of the Albany-Bennington anomaly. The cover rocks are mostly in the chlorite zone of regional metamorphism to the west and in the biotite, garnet, staurolite, and sillimanite zones to the east (see Balk, 1936; Thompson and Norton, 1968).

From the amplitude, asymmetrical shape, and persistence of the Beacon-Copake anomaly, Harwood and Zietz (1974) concluded the source was probably a slice of Precambrian rocks similar to those to the southwest in the Reading Prong (see fig. 1) and bounded on the northwest by a major thrust fault. Depths to the western part of the magnetic rocks range from about 4,000 feet near Beacon, N. Y. to about 1,500 feet south of Stissing Mountain. The upper surface of the magnetic rocks apparently dips to the southeast so that the depth of burial increases in that direction.

The northern end of the Beacon-Copake anomaly near the Massachusetts-Connecticut-New York corner is overprinted by small, high amplitude, steep gradient local anomalies produced by magnetite-rich, garnet and staurolite schist of the allochthonous Everett Formation (Zen, 1967; Zen and Hartshorn, 1966). These local anomalies around Mount Everett reflect the presence of magnetite in pelitic rocks in the Taconic allochthon due to increased metamorphic grade. Apparently above the biotite isograd, hematite in the red slate of the Taconic sequence reacts with ferromagnesian silicates, such as chlorite, to produce magnetite as discussed by Thompson and Norton (1968, p. 322, eq. 5).

SOUTHWESTERN NEW ENGLAND

For the purpose of this discussion the eastern boundary of southwestern New England is taken as the western boundary of the Triassic basin in Massachusetts and Connecticut and as the Connecticut River north of the Triassic basin. The region is divided into the carbonate-quartzite belt on the west, the areas of Precambrian rocks, the Manhattan-Waramaug-Canaan Mountain belt (shown as M-W-C belt on fig. 2) and the Hartland-Rowe belt in the central part, and the Connecticut Valley - Gaspé synlinorium and Wepawaug syncline on the east. These divisions are shown on figure 2.

Carbonate-quartzite terrain.—The carbonate-quartzite terrain in southwestern Vermont, westernmost Massachusetts and Connecticut and adjacent New York produces a featureless, generally low magnetic pattern in all grades of regional metamorphism. The rocks are quartz-feldspar metasandstone, quartzite, limestone and dolostone, and sulfidic, carbonaceous black slate or schist. Magnetite is virtually absent from all of these rocks.

The easternmost exposure of the carbonate-quartzite belt is an arcuate belt in western Connecticut that extends from Danbury, Conn. northeastward to the Mount Prospect mafic complex (aeromagnetic map). This belt is marked by a pronounced, trough-like magnetic low. Presumably carbonate rocks and quartzite underlie the Paleozoic rocks west of this narrow belt and they may lie beneath thrust slices of Precambrian rocks in the Housatonic Highlands and southern Berkshire Highlands as well.

Precambrian terranes.—A variety of metasedimentary and metaigneous gneisses of Precambrian age are exposed in the Green Mountains, the Berkshire, Housatonic, New Milford, and Hudson Highlands and the Manhattan Prong south of the Hudson Highlands. Although there are local high magnetic anomalies scattered in these Precambrian terrains, their overall magnetic patterns are surprisingly low compared to the pattern of Precambrian rocks of the Reading Prong (see Henderson et al., 1966) and the Adirondack Mountains exclusive of the large anorthosite complex. The explanation for this difference in overall magnetic pattern is not known, but Harwood and Zietz (1974) suggested that the Precambrian rocks with low magnetic patterns may represent 1) a different sequence of Precambrian rocks, or 2) the same Precambrian rocks metamorphosed to a lower grade during Precambrian time than the magnetite-rich pyroxene-granulites to the west, or 3) the western sequence of Precambrian rocks in which the magnetite has been destroyed by Paleozoic metamorphism. Either of the first two explanations seems more reasonable than the third because the Paleozoic metamorphism appears to have little effect on the magnetic pattern of Precambrian rocks in the various areas.

The positive anomaly at the south end of the Green Mountains is apparently related to the mass of magnetic rocks that produces the Albany-Bennington anomaly. Harwood and Zietz (1974) suggested the bulk of Precambrian rocks in the Green Mountains may be thrust westward over these highly magnetic rocks.

In the Berkshire Highlands the local positive anomaly that trends southeastward from Lee, Mass. past Otis, Mass. is produced by abundant lenses of magnetite developed along a major fault zone mapped by N. M. Ratcliffe (personal commun., 1972). This local anomaly is superposed on a broader northeast-trending positive anomaly that trends across the trace of three major thrust fault slices along the western front of the Berkshire Highlands (see Ratcliffe, 1969; Ratcliffe and Harwood, 1971). This northeast-trending anomaly and a smaller northeast-trending anomaly south of Beartown Mountain appear to be local highs on a broad magnetic high that underlies the carbonate terrain of southwestern Massachusetts and adjacent Connecticut.

Harwood and Zietz (1974) concluded there were Precambrian rocks in at least three different structural levels; the Beacon-Copake mass being the lowest overstepped by an intermediate layer that produces the broad high under the carbonate terrain which, in turn, is tectonically overlain by Precambrian rocks exposed in the Berkshire Highlands.

The pronounced north-northeast-trending positive anomalies in the southeastern part of the Berkshire Highlands coincide with a zone in which various Precambrian gneisses have been intruded and injected by pink and gray granite. The granite occurs as small northeast-trending pods and plutons and, more abundantly, as swarms of thin dikes and sills. Large knots and segregations of magnetite are abundant in the pink granite.

The Housatonic Highlands apparently contain Precambrian gneisses similar to those in the Berkshire Highlands (see Gates, 1961). The structure and stratigraphy of these Precambrian rocks are not known in detail but Balk (1936) shows evidence for westward directed thrusting along at least part of the western front of the Housatonic Highlands. The low featureless magnetic pattern found over most of the western half of the Housatonic Highlands may reflect a relatively thin section of the gneiss complex resting structurally above the Paleozoic carbonate and quartzite terrain.

Precambrian rocks of the Hudson Highlands between Danbury, Conn. and the Hudson River are a collection of metasedimentary gneisses, including graphitic calc-silicate rocks and marble, metavolcanic rocks, and granitic gneisses (Clarke, 1958, Prucha and others, 1968). Rocks in this complex are similar to those of the Berkshire Highlands (Harwood, 1971; Ratcliffe, 1969; Ratcliffe and Harwood, unpub. data) as well as to Precambrian rocks in the Manhattan Prong (Hall, 1968; Prucha and others, 1968). The magnetic pattern of the Precambrian rocks in both the Hudson Highlands and the Manhattan Prong is generally low with scattered, local high anomalies commonly associated with masses of granitic gneiss and, to a lesser extent, with metavolcanic rocks. In the Hudson Highlands there is no apparent relationship between the magnetic pattern and the grade of Paleozoic metamorphism which ranges from sillimanite grade on the east to chlorite grade just east of the Ramapo fault.

Manhattan-Waramaug-Canaan Mountain belt.—Interlayered feldspathic quartzite, garnet-sillimanite schist, and scattered amphibolite have been mapped as units B and C of the Manhattan Formation as used by Hall (1968) in the southwest, the Waramaug Formation of Gates (1961) in the central part, and Canaan Mountain Schist of Rogers and others (1959) in the northern part of this belt. This collection of clastic and volcanic rocks is separated from Precambrian rocks in the Manhattan Prong by a thin but persistent layer of carbonate rocks, the Inwood Limestone, not shown separately on the aeromagnetic map. Although the rock types are strikingly similar, the relative proportions of the various lithologies and their position with respect to adjacent Precambrian rocks and Paleozoic carbonate rocks changes throughout the belt (see Rodgers and others, 1956, p. 10-11). This has led to doubts as to the correlation and age of the rocks in this belt. The low magnetic pattern of the Waramaug in the central part of the belt contrasts sharply with the varied but generally higher magnetic pattern of the Canaan Mountain rocks to the north and the Manhattan Schist to the south. Garnet-sillimanite schist on Canaan Mountain and in parts of the Manhattan Schist contain abundant, fine-grained, disseminated magnetite suggesting that the protolith was hematite-rich red shale or siltstone. The rocks on Canaan Mountain are lithologically similar to the rocks in the Taconic allochthon near Mount Everett and June Mountain; all have comparably high magnetic patterns. Harwood (unpub. data) has concluded that the rocks of Canaan Mountain are part of the Taconic allochthon rather than part of the Waramaug-Hoosac sequence. Hall (1968, p. 128) also tentatively correlated his units B and C of the Manhattan (not shown separately on the aeromagnetic map) with rocks in the Taconic allochthon.

Hartland-Rowe belt.—In western Massachusetts the Cambrian to Middle Ordovician rocks of the Hartland-Rowe belt (fig. 2) contain a distinctive pattern of north-trending magnetic lows and highs. On the west side of this belt, adjacent to the Berkshire Highlands, there is a low magnetic pattern that follows the distribution of an albite schist and feldspathic quartzite mapped as the Hoosac Formation by Hatch, Schnabel, and Norton (1968). This pattern is succeeded eastward by a pronounced linear belt of sharp positive anomalies that follow a unit of magnetite-rich schist and metavolcanic rocks mapped as the Rowe Schist. The low magnetic pattern east of the magnetite schist corresponds to the outcrop belt of feldspathic granulite and pelitic schist mapped as the Moretown Formation and the magnetic high along the eastern margin of the Hartland-Rowe belt marks the position of a belt of metavolcanic rocks mapped as the Hawlay Formation (Hatch, 1967). Small bodies of serpentinized ultramafic rocks occur in this part of the Hartland-Rowe belt generally in or near the area of the Rowe Schist. Pronounced high-amplitude magnetic anomalies are associated with the serpentinized ultramafic rocks in western Massachusetts.

The four part, low-high-low-high, magnetic pattern in the Hartland-Rowe belt persists southward from the Vermont state line to the vicinity of Blandford, Mass. At Blandford the Hartland-Rowe belt is offset eastward and the distinctive magnetic high of the Rowe is lost leaving a broad magnetic low on the west associated with the Hoosac and a complex pattern on the east over the Moretown and Hawley Formations (Hatch and Stanley, 1974). South of the Connecticut state line, the magnetic pattern characteristic of this belt in Massachusetts becomes progressively "washed out" and is totally obliterated in the area between the Waterbury dome (fig. 2) and the Hodges Mafic Complex of Gates and Christensen (1965). The sharp local anomalies found in Massachusetts appear again in the area of the Mine Hill Granite but they terminate abruptly to the southwest although similar metasedimentary rocks persist as patches in a predominantly granitic terrain.

The loss of magnetic character in this belt south of Blandford reflects a regional change so widespread and pervasive that it does not appear to be wholly related to the loss of specific magnetic units along known or possible faults in the area. It seems more reasonable, instead, to consider the replacement of magnetite-rich units by magnetite-poor ones through changes in lithologic or metamorphic facies, or both. For example, the Hawley Formation is composed primarily of magnetite-bearing metavolcanic rocks in the core and west of the Shelburne Falls dome (fig. 2), but according to Hatch (1967) the metavolcanic rocks interfinger with magnetite-poor, graphitic metasedimentary rocks to the north and south. From the Blandford area south, the Hawley Formation is largely graphitic pelitic rocks and the only significant concentrations of metavolcanic rocks within the Hawley appear in the cores of the Granville, Collinsville, and Bristol domes. Thus, in this case, the high magnetic anomalies reflect largely the metavolcanic facies of the Hawley Formation.

The linear belt of positive anomalies associated with the Rowe Schist in western Massachusetts is not readily apparent to the south in adjacent Connecticut. West of the Collinsville dome, Stanley (1964) mapped a magnetite-rich, coarse kyanite schist which he correlated with the Rowe Schist. The reason this magnetite-rich unit produces such an insignificant magnetic anomaly compared to the Rowe to the north is unknown but the answer may lie in the diverse orientation of the magnetite which Stanley (1964, p. 41) reports is predominantly included in randomly oriented kyanite porphyroblasts on gently dipping foliation surfaces. The magnetic vectors of these diversely oriented magnetic grains may, in effect, integrate to a low total magnetic intensity.

Connecticut Valley - Gaspé synclinorium.—The broad low magnetic pattern east of the Hartland-Rowe belt and west of the Triassic rocks in Massachusetts is associated with carbonaceous schist, quartzite, and carbonate-bearing granulite mapped as the Silurian and Devonian Goshen and Waits River Formations (Hatch, Schnabel and Norton, 1968). These rocks are intruded by granitic and, to a lesser extent, by mafic plutons. These Silurian and Devonian rocks, like most of those elsewhere in New England, show typically weak magnetic patterns.

The low magnetic pattern around the western sides of the Granville, Collinsville, and Bristol domes is also produced, in part, by carbonaceous schist which Hatch and Stanley (1974) correlate with the Goshen Formation. South of the Waterbury dome the lowest magnetic patterns overlie areas of carbonaceous and calcareous schist and phyllite of the Wepawaug Schist which Hatch and Stanley (1974) correlate with the Silurian and Devonian rocks to the north. The very low magnetic pattern extending southwestward from the Milford area into Long Island Sound probably marks an area of Silurian and Devonian rocks similar to the Wepawaug Schist.

The circular magnetic highs in the Connecticut Valley - Gaspé synclinorium are produced by pre-Silurian metavolcanic rocks in the cores of the Shelburne Falls, Granville, and Woronoco domes.

Triassic rocks of the Connecticut Basin.—Triassic rocks of the Connecticut Basin are largely reddish brown, maroon, gray and black shale, arkose and conglomerate that contain three major sheets of basaltic volcanic rocks and several smaller basalt intrusions in the southern part of the basin. The entire eastern border of the Triassic rocks is a high angle fault and the western border south of the Woronoco dome is also a fault. North of the Woronoco dome the western border of the Triassic rocks has been mapped as an unconformity.

The generally low magnetic pattern of the Triassic rocks is typical of a thick collection of hematite-bearing sedimentary rocks. The very weak magnetic pattern over the basaltic rocks, on the other hand, appears to be anomalously low particularly when compared to the magnetic expression of the Palisades Sill on the west side of the Hudson River in the southwesternmost part of the aeromagnetic map. All of the basaltic rocks in the Triassic basins southwest of this study area have significantly higher magnetic patterns than those in the Connecticut Basin (see Henderson and others, 1966; Zietz, unpub. data).

The low amplitude, low and high anomalies associated with the western edges of the flows in the Connecticut Basin indicate that the magnetic vector in these flows is nearly horizontal, whereas the pattern over the Palisades Sill and flows in the Newark Basin and those basins further south (see fig. 1) indicate a more steeply inclined magnetic vector. Paleomagnetic studies in the Connecticut Basin by deBoer (1967) indicated that the thermo-remanent directions of magnetism become more steeply inclined to the north (from +12° to +42°) from the oldest to youngest basalt flow. Opdyke (1961) and Beck (1965), working on Triassic rocks in New Jersey and Pennsylvania, respectively, found a more consistent northerly inclination of +23° to 28° Down-faulting along the northwest and north sides of the Newark and Gettysburg Basins appears to have increased the inclination of the thermo-remanent magnetic vector thus producing the relatively high aeromagnetic pattern over the basaltic flows. Faulting along the east side of the nearly north-trending Connecticut Basin had little effect on the orientation of the magnetic vector. Thus, it appears that the different magnetic patterns over the various Triassic basins reflect the effects of basin orientation and fault movement on the thermo-remanent magnetic vector.

The eastern border fault and the western boundary of the Triassic rocks appear to converge south of New Haven, Conn. suggesting that the Triassic rocks do not extend far into Long Island Sound. This strengthens the probability that the low magnetic pattern southwest of New Haven is produced by Silurian and Devonian rocks.

SOUTHEASTERN NEW ENGLAND

The area east of the Triassic rocks in the Connecticut Basin is referred to collectively in this report as southeastern New England. For discussion it has been divided into the Bronson Hill anticlinorium, the Merrimack synclinorium, the Marlboro belt, the Putnam belt, the New London-Sterling-Milford belt, the Carboniferous basins, the Cape Cod area, and the Cape Ann-Salem belt: all shown on Fig. 2.

Bronson Hill anticlinorium.—East of the Triassic rocks in central Massachusetts and Connecticut a belt of gneiss domes form the southern part of the Bronson Hill anticlinorium (Billings, 1956; Thompson and others, 1968). Thompson and others (1968) report the cores of these domes are composed of massive granite and quartz diorite gneiss of probable intrusive origin, layered felsic and mafic gneisses of probable volcanic origin, some metasedimentary rocks, and massive amphibolite interpreted in some areas to be premetamorphic mafic dikes. The overlying strata are a variety of gneisses, amphibolites, pelitic schists, quartzite, and calc-silicate rocks.

The magnetic pattern of the rocks outside of the domes is generally low and featureless in central Massachusetts and adjacent Vermont and New Hampshire except locally south of the Keene dome (fig. 2) and around the Warwick dome (fig. 2) where the Ammonoosuc Volcanics apparently produce small positive anomalies. About the same thickness of Ammonoosuc Volcanics occurs around the Vernon dome (fig. 2) and on the west flank of the Keene dome, but there the volcanic rocks do not produce significant local anomalies. The reason for this is unknown.

Core rocks of the various domes have remarkably different magnetic patterns. Rocks of intrusive igneous origin and obvious metasedimentary origin have low magnetic patterns whereas layered feldspathic gneisses and amphibolite of volcanic origin have a higher, more varied magnetic pattern. For example, the weakly magnetic core rocks of the Vernon, Warwick, and Glastonbury domes are largely biotite-quartz-feldspar gneiss of the Oliverian Plutonic Series of Billings (1956). In the core of the weakly magnetic Pelham dome, Robinson (1963, 1967) has mapped quartzite, quartzose gneiss and calc-silicate rock and abundant granitic gneiss but only minor amounts of layered metavolcanic rocks. The highly magnetic rocks in the main body of the Monson Gneiss, the "Tulley" body of the Monson Gneiss (fig. 2) and much of the Keene dome, on the other hand, contain layered feldspathic gneiss and amphibolite and lesser amounts of intrusive feldspathic gneiss.

The lower magnetic pattern on the southeast side of the core of the Keene dome may be caused by a relatively thin sequence of core rocks that have an inverted magnetic vector relative to the core rocks to the west and north. Thompson and others (1968, fig. 15-16, section DD′) show the southeast part of the Keene dome as an overturned flap of gneiss underlain by the younger rocks. The weakly magnetic Devonian rocks exposed east of the Keene dome may be present in significant amounts beneath the overturned southeastern part of the Keene dome.

The sharp linear anomalies associated with the main body of Monson Gneiss trace southward east of the Glastonbury dome but in central Connecticut they become less intense, scattered positive anomalies. In the Killingworth dome (fig. 2) east of New Haven, rocks shown as Monson Gneiss by Dixon and Lundgren (1968) have a much lower magnetic pattern than the Monson in central Massachusetts. The explanation for this change in magnetic pattern along the trace of the Monson Gneiss is not known. Most of the Monson in this belt is in the sillimanite zone of regional metamorphism so a loss of magnetite due to a metamorphic change seems unlikely. There may be, however, a change in the relative proportion of felsic and mafic gneiss in the Monson which may account for the change in magnetic pattern. On the other hand, the lower magnetic pattern in the Killingworth dome could be related to the generally shallow dip of the Monson Gneiss in this area.

Merrimack synclinorium.—East of the belt of gneiss domes which comprise the Bronson Hill anticlinorium there is a broad belt of generally low magnetic patterns associated with the southern part of the Merrimack synclinorium (fig. 2). This broad belt is bounded on the east in Massachusetts by the Clinton-Newbury fault (see Skehan, 1968) and by the Lake Char fault in eastern Connecticut. The southern end of the belt is marked, in part, by the Honey Hill fault (fig. 2).

Where detailed mapping is available, primarily in eastern Connecticut (see Dixon and Lundgren, 1968; Pease and Peper, 1968; Snyder, 1964; Lundgren, 1962), it is known that the belt contains a variety of feldspar-quartz-mica schist and granofels, calc-silicate rocks, and sulfidic sillimanite-garnet schist. Amphibolite layers are present locally and granitic intrusives, ranging from pegmatites to large plutons, are common. In New Hampshire the western part of the belt contains weakly magnetic pelitic schist and granofels of the Littleton Formation (Billings, 1956).

None of the rocks in the Merrimack synclinorium have a particularly distinctive magnetic pattern except the sulfidic schists north and west of the Eastford Fault. There, pyrrhotite-bearing rocks in the sillimanite-K-feldspar zone of regional metamorphism produce a series of narrow, low amplitude, northeast-trending anomalies giving a magnetic "texture" that is somewhat more detailed than that in the rest of the belt.

Marlboro belt.—The belt of northeast-trending sharp linear anomalies between the Clinton-Newbury fault and the Bloody Bluff fault in eastern Massachusetts coincides in part with the Nashoba and Marlboro Formations (Hansen, 1956). The highest anomalies are associated with magnetite-rich biotite-quartz-plagioclase gneiss (see Hansen, 1956, p. 32-33) of the Nashoba Formation. The gneiss is associated with sillimanite schist, amphibolite, calc-silicate rock, marble, and scattered granitic intrusives. The Marlboro Formation, southeast of the Nashoba, consists of the same rock types but the primary lithology is massive to well-bedded amphibolite.

The distinctive linear anomalies associated with the Nashoba give way northeastward to a zone of lower amplitude, locally northwest-trending small anomalies related to large intrusive masses of porphyritic granite gneiss (Andover Granite of Emerson, 1917; see also Skehan, 1968). Near the coast north of Cape Ann this belt contains mafic plutons mapped as the Salem Gabbro-Diorite complex by Emerson, (1917) which have a significantly lower magnetic pattern than the Salem Gabbro-Diorite complex south of the Bloody Bluff fault. The reason for this apparently anomalous low magnetic pattern is unknown unless, of course, the two areas mapped as Salem Gabbro-Diorite contain significantly different rocks.

Dixon (1964) reports the Nashoba and Marlboro Formations trace southwestward and are apparently correlative with rocks of the Putnam Group in eastern Connecticut.

The distinctive magnetic pattern of the Marlboro belt, however, appears to be cut out for a distance of about 0.5 mile between the Clinton-Newbury fault and the Bloody Bluff fault just north of the Connecticut state line but then the pattern reappears on strike to the south in the Putnam belt.

Putnam belt.—In eastern Connecticut there is a belt of north-northeast-trending anomalies, shown as the Putnam belt on figure 2. This belt is bounded on the east by the Lake Char fault and on the south by part of the Honey Hill fault. Rocks in the western part of this belt are predominantly pelitic schist, calc-silicate rock, biotite-muscovite-schist and sillimanite gneiss assigned to the Tatnic Hill Formation by Dixon (1964). The Tatnic Hill is underlain on the east by well-layered hornblende schist and gneiss, amphibolite, biotite-quartz-plagioclase gneiss and minor calc-sillicate rock of the Quinebaug Formation. Collectively the Tatnic Hill and Quinebaug Formations make up the Putnam Group (Dixon, 1964).

The biotite-muscovite schist and calc-silicate rock of the Tatnic Hill Formation along the western part of this belt have a generally low magnetic pattern that cannot be used, at this scale, to distinguish these rocks from the adjacent rocks of the Merrimack synclinorium to the west. The pelitic schist units of the Tatnic Hill and Quinebaug Formations, on the other hand, generally produce high amplitude, steep gradient anomalies. The metavolcanic rocks of the Quinebaug Formation produce a magnetic pattern that is significantly lower than the pelitic schists.

The Preston Gabbro (fig. 2), which produces the high magnetic pattern in the southeastern part of this belt, has been discussed by Griscom and Bromery (1968, p. 425-426). They conclude from magnetic and gravity data that the Preston Gabbro is a west-dipping, nearly circular basin-shaped pluton about 4,000 to 6,000 feet thick; a configuration in good agreement with the interpretation of Sclar (1958, p. 122).

New London-Sterling-Milford belt.—The area south of the Honey Hill fault and east of the Lake Char fault extending eastward to the Narragansett basin and north to the Bloody Bluff fault is underlain by quartz-rich metasedimentary rocks, metavolcanic rocks, and large expanses of various felsic gneisses. The metasedimentary and metavolcanic rocks are quartzite, biotite-quartz schist, and hornblende schist included in the Plainfield Formation (Goldsmith, 1966), the Blackstone Series (Quinn, 1971), and the Westboro Quartzite (Emerson, 1917). The felsic gneisses include a variety of apparently comagmaticrock types, referred to as the Sterling Plutonic Group in Connecticut by Goldsmith (1966) and the Milford Granite and at least parts of the Dedham Granodiorite of Emerson (1917) in Massachusetts and Rhode Island. The area underlain by felsic gneiss also includes the more mafic Ponaganset Gneiss (Quinn, 1971) and the Northbridge Granite Gneiss of Emerson (1917). South of the Honey Hill fault there are areas underlain by rocks of the Ivoryton Group (Lundgren, 1962); a group of metamorphosed volcanic rocks that includes the Monson Gneiss.

The magnetic pattern of the same rock unit varies considerably within relatively small parts of this belt. For example, rocks of the Plainfield Formation and Sterling Plutonic Group are the dominant rocks in both the Lyme dome (fig. 2) and the Seldon Neck fold (fig. 2) but the magnetic pattern is significantly higher over the northeast-trending, steeply-dipping rocks in the Lyme dome than it is over the east-trending moderately north-dipping rocks of the Seldon Neck fold immediately to the north. This relationship would suggest that orientation of the rock units controlled the magnetic pattern, in part at least, but the east-trending Sterling and Plainfield units south of the Preston Gabbro have nearly as high a pattern as those in the Lyme dome. Thus, there does not appear to be an obvious correlation between magnetic patterns and structural trends or metamorphic grades in this area. Perhaps the different magnetic patterns reflect, in part, different proportions of the Sterling and Plainfield lithologies with the higher magnetic patterns associated with greater amounts of the Plainfield Formation; the lower part of which contains 1 to 2 percent magnetite (Lundgren, 1962). The reason why the magnetic patterns of the Sterling and Plainfield are so much higher in the New London area than they are east of the Lake Char fault, where they contain comparable amounts of magnetite, is unknown.

The bullseye shaped magnetic high in western Rhode Island is situated over an extensive area of Sterling Plutonic Group rocks (see Quinn, 1971). The trend of the foliation and the orientation of minor rock units in this area conform fairly well with the trend of the magnetic contours particularly on the north and west sides of the anomaly. Lineations plunge about 25 degrees north or northwest in the area suggesting the structure of surface rocks is a broad northward plunging foliation dome. The amplitude of the "bulls-eye" anomaly is comparable to but lower than the amplitudes of anomalies over parts of the Sterling Plutonic Group south of the Honey Hill fault. The gradients of the "bullseye" anomaly, on the other hand, are much lower and wider than those south of the Honey Hill fault. These low gradients suggest that the surface rocks are not causing the anomaly. This anomaly may reflect a large mass of gabbro at depth similar to the smaller mass of gabbro exposed at the surface to the northwest. The exposed gabbro appears to extend to the north down the direction of regional plunge. The generally low gravity anomalies (see Kane and others, 1972) in the area of the bullseye shaped magnetic anomaly, on the other hand, argue against a buried mass of gabbro and suggest that buried magnetic granitic rocks, perhaps like those exposed on Cape Ann, may be causing this magnetic anomaly.

Rocks of the Sterling Plutonic Group extend northward into eastern Massachusetts southeast of the Marlboro belt where they are apparently continuous with at least part of the Milford Granite of Emerson (1917). The Milford Granite, like the Sterling rocks in western Rhode Island produces a broad, low, generally featureless magnetic pattern that is accentuated by scattered local positive anomalies. These local anomalies probably reflect compositional variations in the Milford Granite but little detailed geologic mapping is available in the area so specific correlation is difficult at this time.

Much of southeastern Massachusetts and eastern Rhode Island, south of the Boston Basin and east of the Norfolk and Narragansett basins, is underlain by a collection of felsic igneous rocks mapped as the Dedham Granodiorite and associated rocks by Emerson (1917). Little modern bedrock mapping is available in this area and the best account of the various rock types, which range from hornblende and biotite granites through syenite to gabbro and diabase, is given by Emerson (1917, p. 172). Because of the lack of geologic data it is impossible at this time to correlate the northeast- to north-trending magnetic anomalies southeast of the Narragansett basin with specific lithologic units.

Carboniferous basins.—There are five basins in eastern Massachusetts and Rhode Island that contain predominantly clastic nonmarine sedimentary rocks and lesser amounts of felsic volcanic rocks of Pennsylvanian age. The sedimentary rocks are largely maroon to gray conglomerate, sandstone, shale, and argillite that are generally of arkosic or graywacke composition. Minor amounts of limestone, meta-anthracite and basalt occur locally (see Quinn, 1971). For the most part, the Pennsylvanian rocks are well indurated but not metamorphosed except in the southern part of the Narragansett basin where they have been progressively metamorphosed to quartz-mica schist and pelitic schists by the Narragansett Pier Granite (Quinn, 1971).

The Pennsylvanian rocks have little, if any, magnetic expression and the basins generally show broad, featureless, low magnetic patterns. The magnetic patterns of the pre-Pennsylvanian rocks show through the cover rocks as broad low amplitude anomalies near Bristol, R. I. in the Narragansett basin and as varied anomalies in the central part of the Norfolk basin and the western part of the Boston basin.

Cape Cod area.—Cape Cod in southeastern Massachusetts is covered with thick glacial deposits and the only bedrock data comes from a few deep wells and geophysical investigations (Oldale and Tuttle, 1964). There are two distinct trends in the magnetic patterns in the Cape Cod area; one about N. 70° E., and the other about N. 10° E. Griscom and Bromery (1968, p. 433-434) show detailed aeromagnetic and gravity data for the area east of the major N. 10° E. belt of anomalies and suggest that the pronounced N. 70° E. trending magnetic high is produced by a north-dipping tabular sheet of mafic igneous rock. Northeast of this magnetic high Griscom and Bromery (1968, fig. 32) show the location of two deep wells that penetrate granitic gneiss. South of the anomaly they locate a well that penetrates micaceous phyllitic schist (see Koteff and Cotton, 1962).

The belt of magnetic anomalies that trends N. 10° E. has a major gravity high associated with it. Griscom and Bromery (1968, p. 434) interpret the source of this anomaly to be mafic plutonic rocks similar to those in the Cape Ann area in northeastern Massachusetts and in the Bays-of-Maine Complex of Chapman (1962). The pronounced magnetic anomaly south of Nantucket Island also may be associated with a mafic pluton.

Cape Ann-Salem area.—The Cape Ann-Salem area in northeastern Massachusetts is underlain largely by intrusive igneous rocks ranging from gabbro and granite and syenite (see Toulmin, 1964; Warren and McKinstry, 1924). The Salem Gabbro-Diorite extends north-northwestward from the vicinity of Salem, Mass. and is apparently responsible for the extremely high magnetic pattern in that area. Toulmin (1964, p. A11) reports abundant magnetite as inclusions in augite. The magnetic anomalies associated with the Salem Gabbro-Diorite extend beyond the mapped boundaries of that body and suggest that much of the area of the Cape Ann Granite northeast of Salem is underlain by gabbro-diorite.

CORRELATIONS AND CONCLUSIONS

Because of the numerous exceptions pointed out in this report, it is hazardous to make inflexible correlations between all the magnetic patterns and their associated lithologic belts but some general points are noteworthy.

1. Silurian and Devonian metasedimentary rocks in the Connecticut Valley-Gaspé synclinorium, the Wepawaug syncline, and the Merrimack synclinorium have a generally low magnetic pattern in all grades of metamorphism. This correlation is supported by the magnetic data for Vermont and New Hampshire (Zietz, unpub. data) and northwestern Maine (Boucot, Allingham, and Griscom, 1964) where there are much larger tracts of Silurian and Devonian rocks.

2. Felsic intrusive rocks have extremely varied magnetic patterns. Post-metamorphic and, to some extent, syn-metamorphic felsic intrusives have low magnetic patterns. Premetamorphic felsic intrusives, notably some Precambrian granitic gneisses, and post-metamorphic felsic intrusives, such as the Narragansett Pier Granite, have a somewhat higher magnetic pattern.

3. The magnetic pattern of mafic and ultramafic rocks in southwestern New England may be related to metamorphic grade. For example, the ultramafic rocks in the Hartland-Rowe belt extending from the East Dover body (fig. 2) in Vermont to the vicinity of Blandford, Mass. show high magnetic patterns from the garnet to sillimanite zones. South of Blandford, mafic and ultramafic rocks in the Hodges and Mount Prospect complexes, those east of Danbury, Conn., and the Peach Lake and Croton Falls ultramafic bodies (fig. 2) show distinctly lower magnetic patterns within the sillimanite zone. The Cortland Complex, which is located west of the Paleozoic sillimanite isograd, has a high magnetic pattern similar to that north of Blandford. The magnetic-metamorphic correlation may also apply to mafic volcanic rocks in the Hartland-Rowe belt and explain, in part, the "washed-out" magnetic pattern in this belt in western Connecticut.

In eastern Massachusetts and Connecticut there does not appear to be a good correlation between magnetic patterns of mafic plutons and metamorphic grade. The mafic pluton at Salem, Mass. is located south of the sillimanite isograd and has a very high magnetic pattern, but the mafic pluton west of Salem is also south of the sillimanite isograd and has a much lower magnetic pattern. Both the Lebanon Gabbro and the Preston Gabbro (fig. 2) are in high metamorphic grades, both are apparently fairly shallow basin-shaped bodies yet the magnetic pattern of the Preston Gabbro is extremely high and the Lebanon Gabbro has virtually no magnetic expression.

4. The Precambrian rocks in western New England and the Hudson Highlands and Manhattan Prong (fig. 2) are

very similar in their generally low magnetic patterns that contain scattered, local high anomalies. These patterns are quite different from the persistent, high anomalies over the Reading Prong, the Beacon-Copake anomaly, the Albany-Bennington anomaly and the Adirondack Mountains (exclusive of the anorthosite masses). The reason for the different magnetic expression over the Precambrian rocks is not known but may be related to primary lithologic differences, to differences in Precambrian metamorphism, or possibly to differences in Paleozoic metamorphism.

5. There is a striking difference between the magnetic pattern of the Triassic rocks in the Connecticut basin and those to the south. The pattern over the basalt flows in the Connecticut basin is one to be expected if the magnetic vector is subhorizontal. The magnetic patterns of the Triassic rocks appear to reflect significant differences in the present inclination of the thermo-remanent magnetic vector which is controlled by the orientation of the Triassic basin and the movement of the Triassic rocks along their boundary faults. The north-dipping remanent magnetic vector of the Triassic rocks south of the Hudson River was steepened by down-faulting along the north and northwest sides of those basins whereas it was relatively unaffected by faulting along the east and west (partially) sides of the Connecticut basin.

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Figure 1—Index map showing location of study area in relation to Grenville-type Precambrian rocks (ruled pattern) and Triassic rocks (stippled). Precambrian masses are:

1. Adirondack Mountains
2. Green Mountains
3. Berkshire Highlands
4. Housatonic Highlands
5. Hudson Highlands
6. Manhattan Prong
7. Reading Prong
8. New Milford Highlands

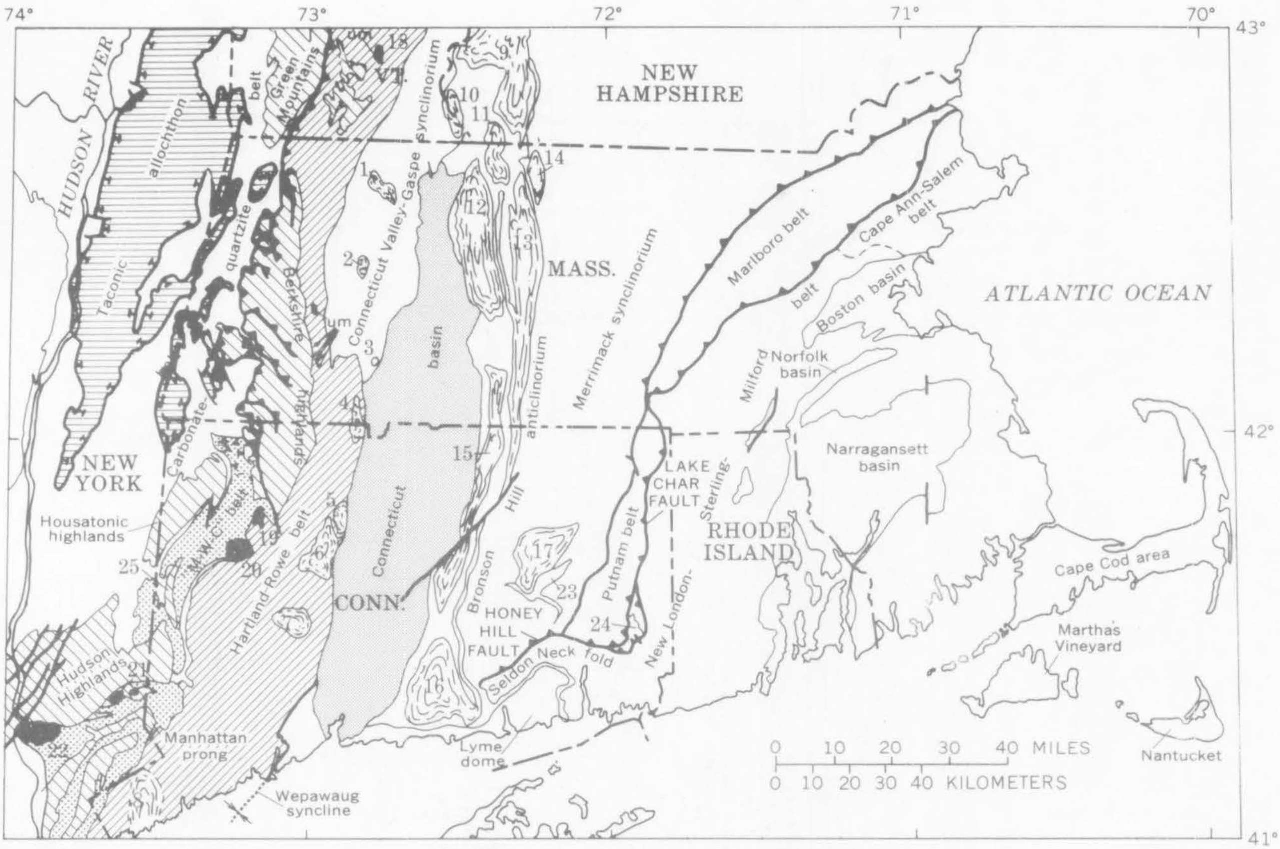

Figure 2—Generalized geologic map of southern New England showing major geologic belts and major structural features discussed in this report. Features identified by number are:

1. Shelburne Falls dome
2. Goshen dome
3. Woronoco dome
4. Granville dome
5. Collinsville dome
6. Bristol dome
7. Waterbury dome
8. "Stamford dome"(?)
9. Keene dome
10. Vernon dome
11. Warwick dome
12. Pelham dome
13. Main body of Monson Gneiss
14. "Tulley" body of Monson Gneiss
15. Glastonbury dome
16. Killingworth dome (Haddam dome)
17. Willimantic dome
18. East Dover ultramafic body
19. Hodges mafic complex of Gates and Christensen (1965)
20. Mount Prospect complex of Cameron (1951)
21. Peach Lake and Croton Falls ultramafic bodies
22. Cortlandt complex
23. Lebanon Gabbro
24. Preston Gabbro
25. New Milford gneiss complex

EXPLANATION