Regional Geologic Setting for the Boston Area

Much has been learned over the last generation to fuel a broader understanding of the geologic structure and development of Southern New England.

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The understanding of the geologic development of southern New England has changed greatly over the past fifty years. Earlier, it was thought that the geology of the area developed primarily due to some great Devonian Acadian Orogeny followed by a lesser Permian Alleghanian Orogeny. Features ascribed to these events are found to have occurred much earlier and the revealed plate collision records additional complex events. The ancient edge of North America (Laurentia), formed in the Middle Proterozoic, and its younger offshore basin, collided with and was underthrust in the Late Proterozoic by the volcanic terrain of ancient northwest Africa (Gondwana). This collision changed most of this northwest edge of Gondwana into batholithic granite and squeezed out much of the intervening sea (see Figure 1-2). The subsequent rapid rise of this batholith and the formation of the Boston Basin were followed by a rising sea from the east that spread onto the land in the Cambrian. Further underthrusting at the end of the Ordovician closed any remaining gap between Gondwana and Laurentia and caused volcanism. Most of the resulting fused landmass (Pangea) then rose to form land or shallow coastal waters in the Early Silurian. The terrestrial setting continued the rest of the Paleozoic with extensional faulting and volcanism over most of the region. In the Mesozoic, the land began to fracture and slip into the developing Atlantic Ocean to the east.

A Piece of Africa

The principal geologic events of the Boston Basin are the great Late Proterozoic Pan-African Orogeny, a lesser Taconic Orogeny toward the end of the Ordovician, and the Mesozoic Orogeny that has dwindled down to today's activity. A series of smaller events occurred during Silurian-Devonian time, of which the Middle Devonian Acadian Orogeny was probably the largest, and was followed by a Pennsylvanian event and weak Permian activity in the south. The main orogenic episodes appear to have started in the east and moved westward first as the orogen was compressed inward toward the core of North America and then as the land collapsed into the Atlantic. Many events, rather than being distinct orogenic episodes, appear to be times of relatively greater deformation during more or less continuous activity.

The shallow sea that filled the Boston Basin and spread onto eastern North America in the Cambrian was matched by one that lapped onto the west side of the land in the Berkshire Hills that created a barrier to the early marine life forms as discovered in a series of brilliant studies by Charles Walcott (1891a & 1891b) at the end of the nineteenth century. He discovered that the Early Cambrian fossils in the Berkshire Hills and those around Boston are different. This fossil divide then was found to extend not only through eastern North America and Canada, but in northwestern Europe as well. This finding posed a question on possible connections across the North Atlantic Basin and laid the grounds for the discovery of the ancient plate collision by J.T. Wilson in 1966. Wilson's revelation was followed by studies by the Boston office of the United States Geological Survey (USGS) that produced perhaps the most detailed description of any collision zone.

Much later in the Mesozoic, Pangea began to breakup about 235 million years ago and gradually widened into today's Atlantic Ocean, leaving a piece of the ancient northwestern African coast and the site of Boston behind. As a result, the geology around Boston is very similar to parts of Morocco, but greatly different from central Massachusetts and Connecticut. The movement caused the broken edge of the continent to sag down and become buried offshore while superimposing new sets of extensional faults across the region. The fissure east of Boston became the Mid-Atlantic Ridge and both sides of it began a slow separation, which is still continuing, with new rock filling in from sub-sea intrusion. From the fragments of Pangea emerged the modern crustal plates of North and South America, Africa, Europe and other areas. The continental break occurred just east of the old collision zone and left fragments of Gondwana on the west side of the growing North Atlantic Ocean. The only exposed fragment in the United States forms southeastern New England. Other less complete pieces lie along coastal maritime Canada, and the rest are deeply buried along the Mid-Atlantic coast and underlie the carbonate deposits of central Florida.

The understanding of this opening of the Atlantic Ocean and continental drift was not an instant breakthrough, but occurred over a period of three hundred years of collecting evidence. The way the continents fit together across the Atlantic Basin was first described by Abraham Ortelius in 1596 (who suggested that the Americas were torn from Europe and Africa), and were followed by more detailed description, such as Federico Sacco in 1895 and Frank B. Taylor in 1910. Between 1908 and 1912, Alfred L. Wegener assembled extensive evidence showing the previous connection of the continents. It was not, however, until after World War II when the magnetic pattern of the rock filling the ocean basin was mapped that most American geologists accepted this theory. The magnetic pattern displays the progressive addition of new crust at the Mid-Atlantic Ridge as well as the mechanics of separation. The close correlation of the geology and magnetic pattern in southern New England shown in the early 1970s illustrates how the oceanic features come ashore. The initial phase of the stretching formed down-dropped blocks that resulted in extensive basin-and-range mountains, now mostly drowned off the coasts of New England and Morocco (see Figure 1-2). The early faults mostly trend northeast and some appear to modify the southern Boston Basin. These faults were soon followed by more extensive north-south faults across the basin and a final set of regional northwest-trending faults, which account for most of the earthquakes in the region. During this time, the edge of the continent sagged into the growing Atlantic as the sea again flooded the Boston Basin and rivers carved into the rock as they flowed into the nascent harbor. Thus, the foundation of Boston was formed in the closing and separation of continental plates. However, much was still to come since glaciers modified the basin over the last million years. The sea fell and rose with the forming

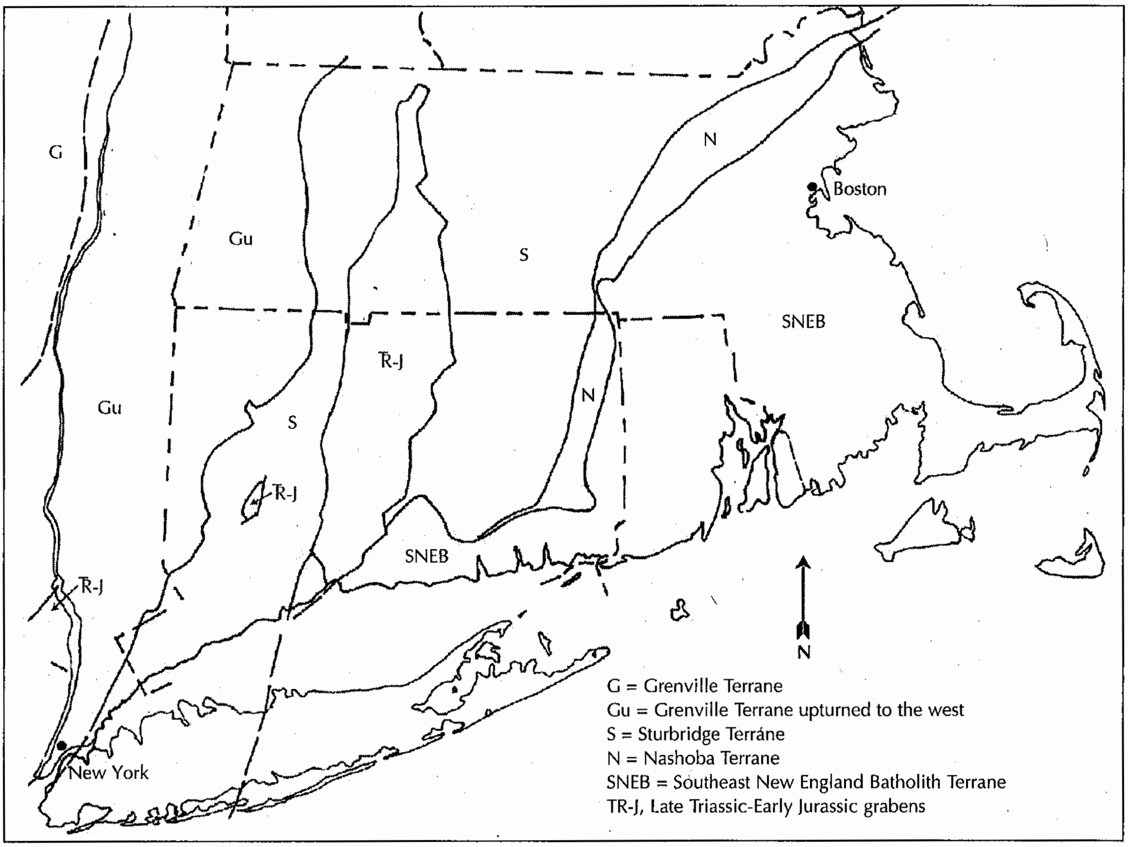


FIGURE 2-1. Geologic terranes and major Triassic-Jurassic grabens of southern New England.

and melting of ice as glaciers advanced and retreated across the environs of Boston, leaving a confused infilling mixture of different types of terrestrial and marine deposits, which makes for one of the most complex geologic areas in the country.

The collision of the Gondwana and Laurentia continents also resulted in four principal geologic provinces between the Hudson River and the Atlantic Ocean and set the character of the geology of southern New England (see Figure 2-1). These provinces, or *terranes*, constitute the basement and consist chiefly of deformed moderately to highly metamorphosed strata and generally foliated granitic rock. They have been identified as:

- the Grenville Terrane, which lies along the New England-New York border and forms the southern extension of the Green Mountains where they devolve into the Berkshire Hills and the Taconic Range;
- the Sturbridge Terrane to the east, which consists of the lower rolling land, split by the Connecticut River valley, and forms most of Connecticut and central Massachusetts;
- the Nashoba Terrane, which forms some higher ridges in a zone that trends north along easternmost Connecticut and northeast across eastern Massachusetts; and,
- the Southeast New England Batholith Terrane, which forms the hilly region farther east that slopes to the sea across southeastern Connecticut, Rhode Island and eastern Massachusetts, and contains several very low basins.

The Boston Basin, filled with the latest Proterozoic strata, is the earliest of these fault-bounded basins (see Figures 1-2 & 2-1). Each terrane consists primarily of a basement of one group of ancient rock with a local cover of deposited early Paleozoic strata, down-dropped blocks of younger strata, later plutons and local exposures of the over-ridden rock.

These structural terranes provide an unrivaled exposed cross-section of Appalachian structure seen nowhere else in North America. The exposure is largely due to a later regional northerly tilt, which raised into view the deep structural zones along the Connecticut and Rhode Island coasts while relatively lowering northern New England. The terranes were compressed by underthrusting from the east on several occasions during the continental plate collision and their principal structural contacts dip to the west.

The landform of the terranes reflects the crustal movement, the relative ease and length of time of bedrock erosion, and glacial processes. Southern New England, despite the low relief, is fortunate in that the geology is generally well expressed in the topography because repeated glaciations have cleaned away soil and weathered rock and etched out the fault zones. The relative hardness of general metamorphic rock types is reflected in different terrane heights, but specific formational differences forming the smaller ridges and valleys commonly are very subtle, except around Sturbridge, Massachusetts, where they stand out remarkably well. The expression of the etched faults is discernable unless covered by thick glacial till or outwash and lake deposits. In fact, the thickness of the glacial material can be estimated by the degree it masks the bedrock features (Barosh, 1978a). The glacial features have excellent expression and also commonly reflect those of the underlying bedrock. The north- and northwest-trends of the youngest fault sets are particularly noticeable in stream and river courses across the entire region (Hobbs, 1904a & 1904b); most notably is the latter set, which controls the locations of many of the roads of the pre-expressway era. All types of remote sensing are effective in distinguishing them, which is especially significant since these faults are very important in engineering, environmental and water resource investigations.

Geologic History

The eastern side of ancient North America, Laurentia, was convulsed 1,200 to 900 million years ago in the Middle Proterozoic to form the belt of metamorphic rock and granite of the Grenville Province that underlies most of New York and the western edge of New England. Stretching into Canada, the belt also extends to the south at depth under the western side of the Appalachian Mountains and is exposed only locally along the spine of the mountains. Uplift and erosion created a mountainous continental margin through western New England from these rocks by 800 million years ago in the Late Proterozoic and the debris was carried eastward to form a large coastal plain and offshore basin in the sea (Barosh, 1979a). This ancient ocean, which is known as Iapetus (after the father of Atlas), separated the western continent from ancient Gondwana to the east. The basin may have developed similar to the present Atlantic Coastal Plain and offshore continental platform, although the source region for sediment was moderately unstable with some volcanic activity. "Dirty" sand with volcanic debris, tuff, silt and limy, aluminous and sulfidic mud were deposited southeastward, usually by turbidity currents, forming the very thick strata of the Sturbridge sequence, remnants of which now constitute much of Connecticut and central Massachusetts.

The future site of Boston then lay at the east side of the Iapetus Ocean in a volcano-studded region along the coast of the larger continent now called Gondwana, which is now northwest Africa (see Figure 2-2). The region was undergoing considerable volcanic activity, with sand and more heterogeneous volcanic rock being deposited. Clean sand was laid down near shore between influxes of fine volcanic material and eventually overwhelmed by an irregular mixture of mafic lava flows, including some pillow basalt, basaltic and rhyolitic tuff and some calcareous mud. These deposits now form the Westboro Formation (quartzite, schist and amphibolites), Middlesex Fells Volcanic Series and Burlington Formation sequence north and west of Boston and the partially equivalent Blackstone Series in Rhode Island. A deeper marine basin that lay offshore, perhaps around volcanic islands, was filling with a thick sequence of volcaniclastic sedi-

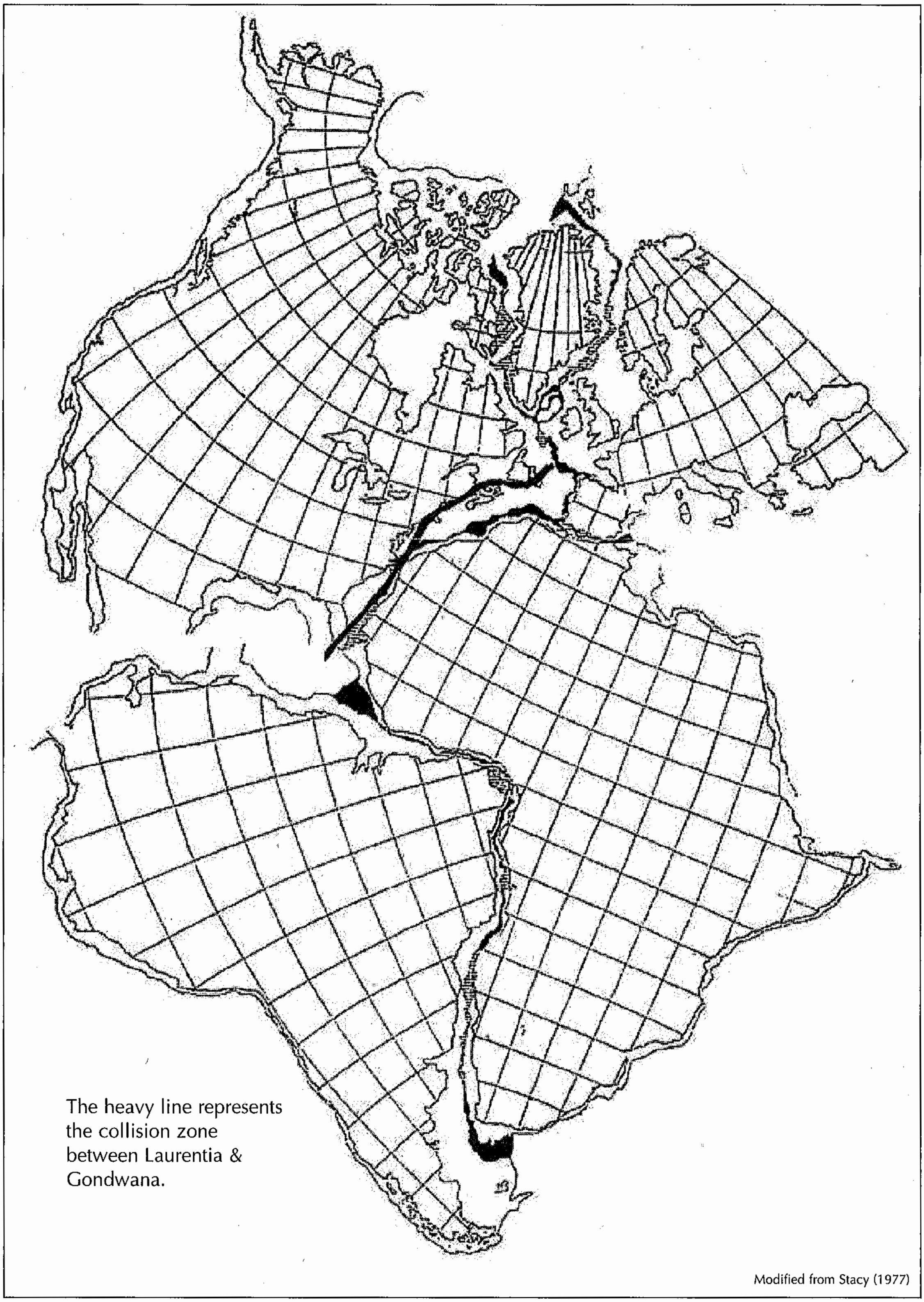


FIGURE 2-2. Western part of Pangea.

ments carried in from the southeast. These sediments were dirty sands with much andesitic debris, interlayered with tuff, tuffaceous silt and mud, aluminous mud, limy mud, thin calcareous material and mafic (dark, low-silica rock such as basalt and andesite) flows. Much of the sediment was carried by turbidity flows and laid down as graded beds that shaped the Nashoba and adjacent formations west of Boston.

The Gondwana plate moved relatively westward to squeeze the Iapetus Ocean. The western edge of its plate boundary collided against the deep marine basin offshore of Laurentia and slid under it during the Late Proterozoic. The collision zone now passes west of Boston and is roughly bracketed by Route 128 and Interstate 495 (see Figure 1-3). This collision triggered the Pan-African Orogeny (a period of deformation and mountain building) referred to as the Cadomian Orogeny in southwestern Europe (Barosh, 1976c & 1998). The collision tore the outer volcaniclastic basin apart in the ensuing subduction zone, and left only remnants of the strata as thrust sheets in the Nashoba Terrane. By 650 million years ago, the Sturbridge strata of the Laurentian plate, against which the collision broke, was sliced into thrust sheets as it began to be underthrusted by Gondwana and compressed from the east, but remained more intact. The lower units of the Sturbridge sequence, however, were progressively cut out to the west by the underthrusting. Further movement drove the collision zone downward beneath an oceanic trench and much of the rock in the lowered eastern Gondwana plate was converted into a granitic batholith between 630 and 620 million years ago. As the granitic batholith formed and plunged beneath the collision zone, its margin and the bordering rock folded against the underside of the zone and the folds became more compressed and broken downward. Elongated granitic bodies formed along some of the early thrusts in the overlying Sturbridge strata and a considerable amount of pegmatitic material formed throughout the strata as they were being metamorphosed and faulted.

When this movement slowed nearly to a halt by 600 million years ago, the future southeastern New England still lay relatively off to the east of its present position. The thickened granitic crust formed during the collision then rose rapidly and dramatically to form a high alpine mountain range across all of southeastern New England. Relaxation of the compression of the plate collision had allowed the thick, relatively buoyant crust to rise and the rapid uplift was accompanied by deep erosion that uncovered the batholith. Tension during the rise resulted in down-dropped extensional fault blocks that formed a basin-and-range topography that spread into coastal New Brunswick and across the then-adjacent Gondwana region, now Morocco (see Figures 2-2 & 2-3). One east-west zone of faults, which passed along what would become Framingham, Blue Hills and the South Shore, dropped the rock down to the north and initiated the Boston Basin by 595 million years ago when the first volcanic debris began to accumulate within the basin (Kaye, 1982a; Kaye & Zartman, 1980). The initial terrestrial and near-shore rhyolite and andesite flow and ash were spewed from volcanoes that were triggered by the faulting and rose up the fault zone bordering the south side of the basin. The debris intermixed with, and then was succeeded by, boulder fans shed northward from the adjacent highlands. The boulder deposit and sand graded north, downslope into mud and silt, which quietly accumulated in marine waters that invaded from the east as the area began to subside. Earthquakes during deposition caused occasional basinward slumping and sliding of the sediments. These basin deposits formed the present intertonguing Mattapan Volcanic Complex, Roxbury Conglomerate and Cambridge Argillite. At that point, if any of the Iapetus Ocean remained west of the range, it was very shallow and restricted from the uplift. The eastern edge of the Grenville Terrane of Laurentia also was elevated and undergoing mild erosion to act as a barrier separating any remaining Iapetus Ocean from a shallow inland sea farther to the west. This western terrane still lay at a considerable distance from the Boston Basin.

The following Early Cambrian to Middle Ordovician was a time of general subsidence, with advancing seas from the east and west.

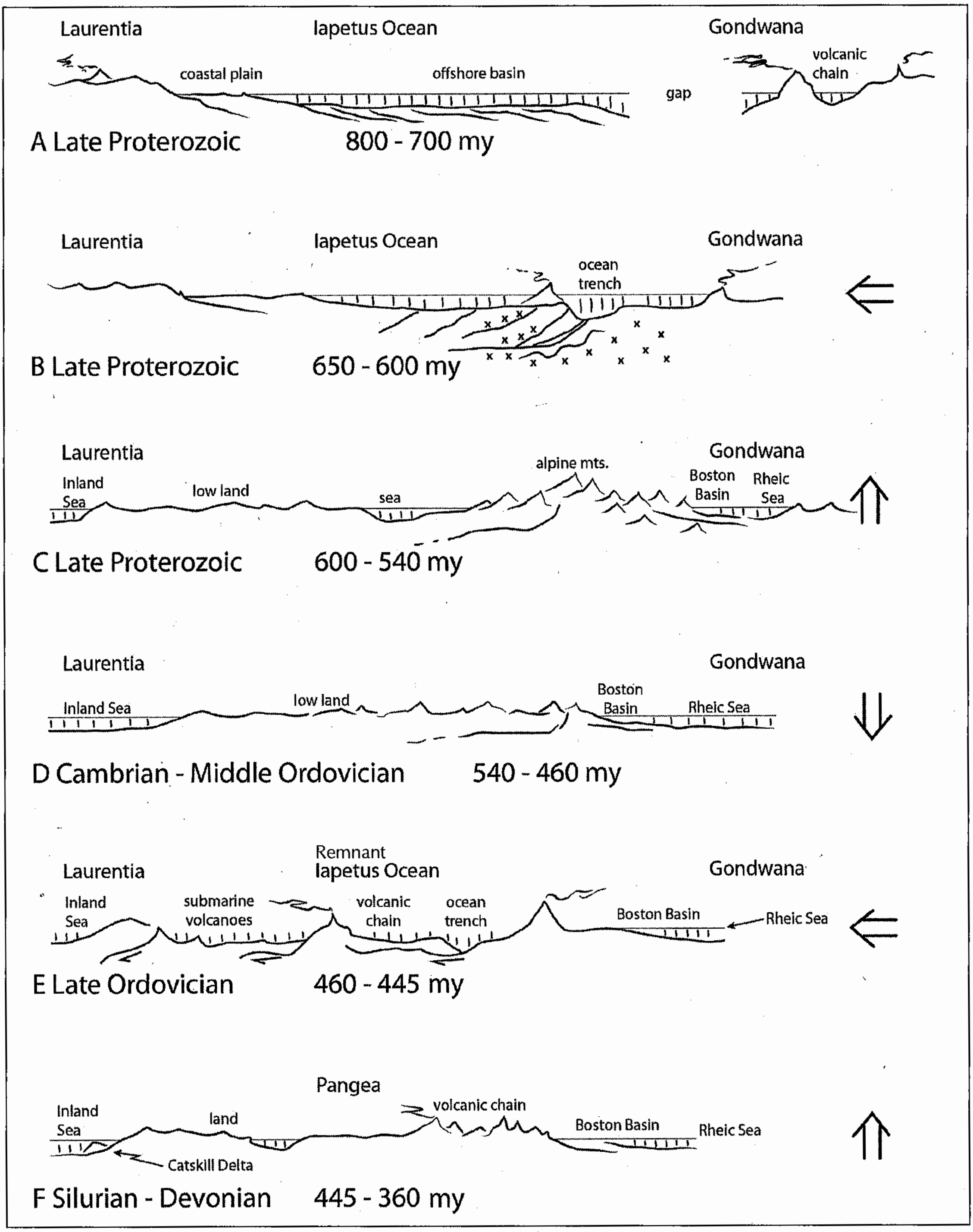


FIGURE 2-3. Paleo-geography of southern New England.

However, the intervening region gradually became mobile again as collision commenced once more. The subsidence farther east near Boston became more general and the Rheic Sea, which spread over Gondwana to the east, rose to overtop the fault bluff of the Boston Basin and spread over the countryside while the first hard-shell marine life emerged during the Cambrian period (the Cambrian explosion) about 545 million years ago. Silt, mud and calcareous mud accumulated in the Boston Basin during Early and Middle Cambrian apparently without a break from the earlier deposition in the Boston Basin and spilled out over the bordering batholithic rock in the advancing shallow waters.

Sand and carbonate mud also were deposited in another shallow inland sea bordering the western side of New England as it extended eastward onto the Grenville rock (Walcott, 1891b; Pumpelly *et al.*, 1894). The two seas on either side of what is now New England formed over sags in the continental plates and, unlike the Iapetus Ocean, which would have been underlain by a true oceanic basaltic crust that would have mostly disappeared during the earlier collision. Thick clean sands accumulated in the advancing Rheic Sea to the east in the Early Ordovician, while mud and carbonate material covered the Cambrian in the far west. The area of the previous remnant of the Iapetus Ocean buckled downward and deepened to become a sea again during the Ordovician 490 to 443 million years ago as the Iapetus Ocean re-formed over a region that included most of Connecticut and central Massachusetts. The ocean then narrowed as the sides once more moved toward one another to cause underthrusting along its western edge and to cause the formation of an oceanic trench along the reactivated collision zone with the Gondwana plate (see Figures 2-1 & 2-3). Submarine volcanism occurred along the western edge that is well recorded in Québec, but only marked by remnant feeder dikes in Massachusetts. The Middle Ordovician Bronson Hill ridge rose across the middle of the Sturbridge Terrane and probably supported a volcanic chain that extended northeastward into Maine (Moench, 1980). The granitic ridge separated a basin to the west that received marine mud and basic submarine volcanic material of an ophiolite suite (an assemblage of basic, magnesium-rich igneous rock and basalt) and the trench along the collision zone, which began filling from the west with turbidic silt and mud deposits over what may be Cambrian age basaltic debris.

Other long northeast-trending faults apparently cut across the Boston Basin and guided new outpourings of volcanic rock, causing volcanoes, with underlying granite, to form in the Blue Hills south of the Boston Basin and to the north at Cape Ann, thus completing the basic geologic framework of Boston. Meanwhile, in the west underthrusting had raised the edge of the old continent, including the Taconic chain of mountains along western New England. The term *Taconic Orogeny* has been applied to this time of collision and deformation, which caused the uplift of mountains across the Berkshire region.

Increased compression and underthrusting during the Middle and Late Ordovician caused the widespread deformation and intrusion of the Taconic Orogeny. Generally small scattered granitic bodies intruded in the west while larger ones formed in the reactivated collision zone, and others developed beneath volcanic complexes to the east where the land once more rose. The Salem Gabbro-Diorite intruded as a large basaltic complex north of Boston and extended southwest along the edge of the collision zone as a series of small basaltic cones. Also a series of mafic dikes and small plutons invaded the Boston Basin to mark the beginning of this activity. Large andesitic and rhyolitic volcanoes formed in Cape Ann and the Blue Hills in the batholithic region on either side of the Boston Basin. The Lynn Rhyolite north of Boston was accompanied by the Cape Ann Granite, which overlapped in time and area with the episode of Salem activity and continued later (Dennen, 1981). To the south, the ash-flow tuffs in the Blue Hills erupted from a volcano whose conduit is represented by the Quincy Granite (455 million years ago). Other small bodies of Quincy, which extend southwest into Rhode Island (Quinn, 1971), may represent feeders to small volcanic cones. The large Spencer volcanic complex farther south may date from this time, too. The Boston Basin strata were very slightly metamorphosed by this activity and the mafic dikes were altered to greenstone. The renewed collision, which brought on the Taconic Orogeny, also affected the Nashoba Terrane west of Boston, with extensive intrusion by the Andover Granite in Late Ordovician. Reactivated thrusting in the Sturbridge Terrane caused parts of the Sturbridge strata to be repeated by faults, which also trapped the overlying Ordovician trench deposits in the Nashua and Haverhill troughs (Peck, 1976; Smith & Barosh, 1981). The metamorphism accompanying the orogeny was generally moderate in the Sturbridge and Nashoba terranes — being distinctly less than the earlier collision and deformation — and did not produce the ubiquitous pegmatite lenses that commonly occur under intense shearing and metamorphism. The western side of the Sturbridge Terrane underthrust the edge of the Grenville Terrane to jack it up to send some of the Cambrian-Ordovician onlap deposits sliding off to the west toward the Hudson River.

The direction of tectonic movement then changed to northwest over southeast during the Taconic Orogeny. The thrusts in the collision zone overrode the folded edge of the batholith in southeastern Massachusetts and while the North Boundary Fault of the Boston Basin broke and moved to the southeast, some folding occurred within the basin. By the end of the Ordovician, thrusting had ended in the collision zone and any gap between it and the Ordovician turbidite deposits to the west was closed, thus allowing the Andover Granite to cross-cut the Nashoba sequence and extend into those to the west (LaForge, 1932; Barosh, 2000). The Iapetus Ocean was nearly eliminated in southern New England, but lingered as a narrow strait to the north at the close of the period owing to the greater compression in the south that gave New England its characteristic V-shape. This final push at the end of the Ordovician, some 450 million years ago, ended the collision between Laurentia and Gondwana in New England. At that point uplift again returned to the region, marking a change in the geologic regime. Southern New England became part of the supercontinent Pangea, formed of an amalgam of the ancient Americas, Africa, Eurasia and other continental masses (see Figures 1-2, 2-2 & 2-3).

After this period of collision ended, the land was again buoyed upwards because of the thickened crust of land that formed most of southern New England. This uplift caused extensional faulting to create small rifts and a volcanic chain was built across the region. A chiefly terrestrial volcanic chain, which had occasional incursions from the sea, formed along eastern New England and overlapped the closed collision zone from the eastern Sturbridge Terrane to the batholithic complex (Gates, 1969; Shride, 1976; Bell *et al.*, 1993). The well preserved fossiliferous sections in the coastal volcanic belt of eastern Maine show that the activity began in the Early Silurian and continued through the Devonian (from 444 to 359 million years ago) while normal faulting was occurring (Gates & Moench, 1981). The Late Silurian-Early Devonian Newbury Volcanic Complex in northeastern Massachusetts (Shride, 1976) may have been down-dropped by such general faulting or it may have been dropped as a basin under tension that was related to right-lateral movement along the Clinton-Newbury Fault Zone. Volcanoes supplying the Newbury Volcanic Complex produced a mixture of both basaltic to rhyolitic tuff, flows and breccia that interfingered with tongues of sediment ranging from red mud to boulders and an occasional thin near-shore limestone bed. Circular- to irregular-shaped nonfoliated granitic and mafic plutons intruded farther south and served as volcanic conduits during this time. A Devonian granite pluton occurs in Worcester and a Silurian mafic one in southeastern Connecticut (Dixon & Femlee, 1986). In Rhode Island, Devonian alkalic rock constitutes the East Greenwich Group (Hermes *et al.*, 1981b) and the Spencer Hill volcanic rocks appear to be co-magmatic with the nearby Devonian-aged Cowesett Granite (Quinn, 1971). The large circular Middle Devonian granite bodies in Maine are ascribed to an Acadian Orogeny at this time, but this minor orogeny seems to be the only more active occurrence during a wider period of instability from Early Silurian (Gates & Moench, 1981) to at least Late Devonian (Schluger, 1973) and may extend to the Mississippian, as in New Brunswick. The coastal volcanic belt in Maine was flanked on either side by a sea, but only limited marine waters remained to the west and in the south, where some Devonian carbonate was deposited in the northern Connecticut River valley of Massachusetts. Southern New England was elevated during the Silurian and Devonian and it sent an immense amount of eroded debris westward to build the Catskill delta westward out into the inland sea in New York. Southern New England had reached roughly its present extent by that time, about 345 million years ago. All of New England appears to have been uplifted to land by the Mississippian, to judge by the redbed land deposits in New Brunswick. The record is blank in southern New England, which may have been eroding until the Pennsylvanian (318 to 299 million years ago), when extensional faulting formed the Narragansett, Norfolk and smaller basins. Rivers and streams deposited into these basins a wide variety of valley fill, river and back-swamp deposits, some of which formed peat bogs that later became coal (Shaler *et al.*, 1899). These basins were apparently part of a broad lowland that extended northeastward into the Bay of Fundy within a broader basin-and-range setting. Bordering fault scarps apparently aided the development of fans of pebbles to boulders, while erosion of the uplands stripped away the Paleozoic strata (layered sedimentary lithology) in southeastern New England. These fan deposits extended well into the sand and shale of the basin, at times creating intertonguing deposits in addition to coarse gravels carried by rivers. Faulting in the Norfolk Basin south of Boston may have been aided by right-lateral moment along the Clinton-Newbury Fault Zone (Barosh, 1983a & 1995). However, the Pennsylvanian strata on the west side of the fault zone in Worcester, Massachusetts, suggest that any offset was limited.

Only local deformation, intrusion and metamorphism affected the southern edge of New England during the Permian "Alleghanian" Orogeny (Zartman *et al.*, 1965; Quinn, 1971). During this time, the Pennsylvanian strata in southwestern Narragansett Basin were mildly deformed and metamorphosed in a tectonic episode, which culminated in the intrusion of the Narragansett Pier and Westerly granites (Quinn, 1971; Burkes, 1981; Hermes *et al.*, 198la), whose dates range from Permian to Middle Triassic in age (see Figure 2-4). The activity may have begun with uplift that first produced some slumping in the Narragansett Basin strata and then intensified to produce some compressional deformation about the mouth of Narragansett Bay. The metamorphism of the Pennsylvanian strata is highest adjacent to the granite and rapidly drops off toward the north side of the basin, demonstrating that it was essentially contact metamorphism. A regional bedrock heating event, which was probably contemporaneous with the intrusion, dated at 240 million years ago (Middle Triassic), extended to New Hampshire (Zartman *et al.*, 1965). Pink pegmatite dikes, associated with the Narragansett Pier granite, also extend beyond it to New Hampshire. The nonfoliated post-tectonic granite in southwest Rhode Island was emplaced in a relatively passive manner that did not disturb the earlier structure of the rock and indicates that compression had ended before the intrusion (Hermes *et al.*, 1981a). A late phase of the granite intrusion produced the Westerly Granite that forms a system of east-west, south-dipping dikes along the Rhode Island and eastern Connecticut coasts (Feininger, in Quinn & Moore, 1968). The extensional fractures controlling the dikes cut across the older structure and appear to be a precursor to the formation of the south coast of New England by the Cretaceous (145 million years ago). The fractures might be related to the raising of southern New England that created a regional northward tilt. This tilt probably occurred near the beginning of the Late Triassic (if the age of 240 million years is correct), and is responsible for the northward plunging structures, northward decrease in effects of different metamorphic events, uplift of the Narragansett Pier Granite and progressively younger strata to the north. There is no sign of an Alleghanian Orogeny north of the Narragansett Basin and the nearly undeformed Permian redbeds in Prince Edward Island indicate that this time was quiet in the north. The relatively mild deformation of the orogeny at the southern edge of New England may be the northernmost part of the uplift of the Appalachian Mountain spine to the southwest that caused the great gravity thrusts to slide westward and fold across much of Pennsylvania where the orogeny was named. The rapid uplift and erosion of southern New England during the Early and Middle Triassic was followed by extensional faulting during the Late Triassic and Early Jurassic (235 to about 190 million years ago) that inaugurated

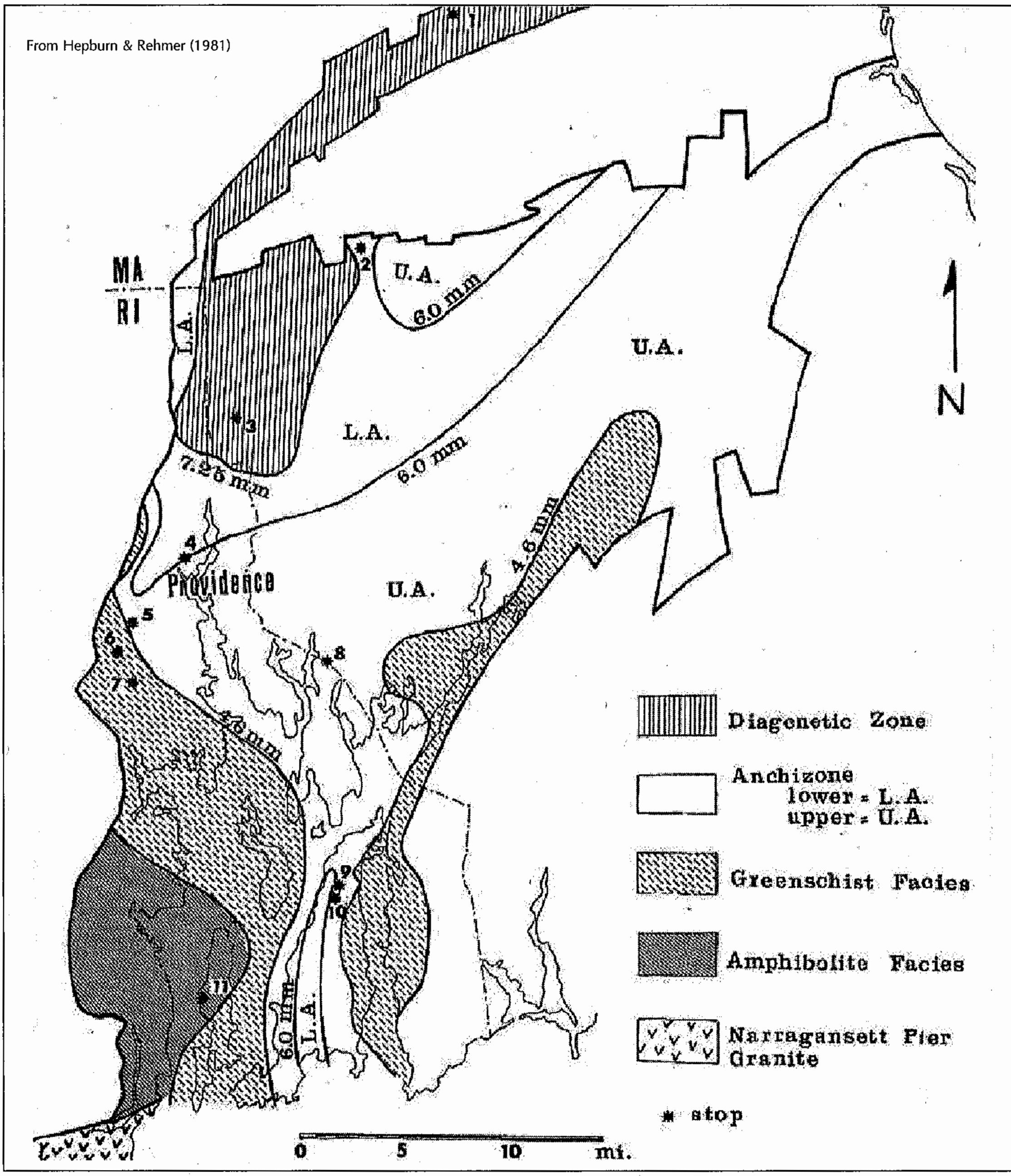


FIGURE 2-4. Metamorphic effects in the Pennsylvanian Narragansett Basin strata extending out from the Narragansett Pier Granite of Permian to Triassic age. The metamorphic grade decreases upward in divisions shown to none in the Diagenetic Zone.

major rifting and the formation of the North Atlantic Basin. The center of rifting occurred east of the earlier plate collision zone and left southeast New England attached to North America. A smoothed upland plain that had developed across southern New England in the early Mesozoic was broken by normal faulting into a generally northeast-trending basin-and-range topography across the region (see Figures 1-2 & 2-5) and continental clastic red sediment and basalt accumulated in the basins (Hubert *et al.*, 1978; Kaye, 1983a). Most of the valleys formed by the basins presently lay off-shore to the east (Ballard & Uchupi, 1975) and diminish in number toward the northwest. Many normal faults were formed by reactivation of earlier ones, including thrust faults, one of which controlled the aberrant northerly trend of the Hartford Graben (Barosh, 1976c). There may have been minor left-lateral movement along faults (Ballard & Uchupi, 1975) when the geologic constraints are taken into consideration, but no large-scale offset is evidenced, although such was hypothesized by Kent and Opdyke (1978) from paleomagnetic data.

A pulse of extensional activity at the beginning of the Jurassic (200 million years ago) produced widespread basalt flows and numerous diabase dikes along faults along the Atlantic Seaboard. In New England, the few local lamprophyre dikes (composed chiefly of biotite, hornblende and pyroxene) present may be of similar age (Ross, 1981). A volcanic conduit lay against the southeast boundary of the Hartford Graben in the southern Connecticut River Valley (where extensive lava flowed northward) and now stands out as ridges in the valley. A line of very large diabase dikes called the Higganum Dike also extends from the conduit northeastward across Connecticut and central Massachusetts to the New Hampshire border. Some of the larger dikes may have reached the surface to form basaltic volcanic cones. Many smaller northeast-trending diabase dikes invaded eastern Massachusetts west of Boston. Numerous northeast-trending faults offset the basalt flows in the Hartford Graben by further movement in the Jurassic.

As the Atlantic Basin widened, the fault blocks subsided and evaporite deposits formed in the eastern basins (Grow, 1981), now offshore, from saline lakes and restricted seas in the Middle Jurassic (see Figure 2-5). Continued opening of the Atlantic during the remainder of the Jurassic and Cretaceous caused further lowering, and most of the southern and eastern fault-block valleys were submerged below a growing ocean that spread to form the coastline of New England. A thick apron of clastic sediment from rising and eroding Appalachian uplands to the northwest was deposited on this newly formed continental edge and covered the earlier fault basins. The sediment continued to build the Atlantic Coastal Plain in the Tertiary, although this process was interrupted briefly by regional uplift that caused a low sea stand and erosion in the Oligocene at 34 to 23 million years ago (Weed *et al.*, 1974; Valentine, 1981; Kaye, 1983b). This very wide coastal plain was similar in extent to that of the modern Mid-Atlantic coast, before later shrinking due to glacial erosion and sea-level rise.

The widening of the North Atlantic Basin created new sets of faults, which extended across the earlier structural trends on land, in the Late Jurassic or Cretaceous (see Figure 2-6). These faults formed in the Late Mesozoic as adjustments to movement of a widening ocean basin. The western side of the East Coast of America had rotated relatively clockwise with respect to Africa as the basin grew, causing the earlier Triassic rifts to shift to a northeastern alignment and out of the line of the north-south compression that had formed them. New northerly trending rifts then took their place (Barosh, 1986c). New valley systems formed, at least on land, in graben systems along the northerly trending faults. The north-trending Narragansett Bay Graben, which formed across the southwest Narragansett Basin (McMaster *et al.*, 1980), formed a south draining valley system, as well as the smaller Assawompset Graben to the east that is north of, and possibly including, New Bedford (Koteff, 1964a). Some reactivation probably occurred along some faults in the older north-trending Hartford Graben as well. The numerous large north-south diabase dikes in and south of the Boston Basin apparently are associated with the faults that formed then. The Medford Dike was an early one of this set. A buried north-trending basic pluton at the western edge of Cape Cod is also probably a larger member of this set (Barosh *et al.*, 1977b).

Transverse adjustments, called transform fracture zones, also took place as the Atlantic Basin formed. These trend about east-west near the Mid-Atlantic Ridge but swing to the northwest near the East Coast, because of the rotation mentioned previously (see Figures 2-6 & 2-7). They extended onto land to form ubiquitous, generally small northwest-trend-

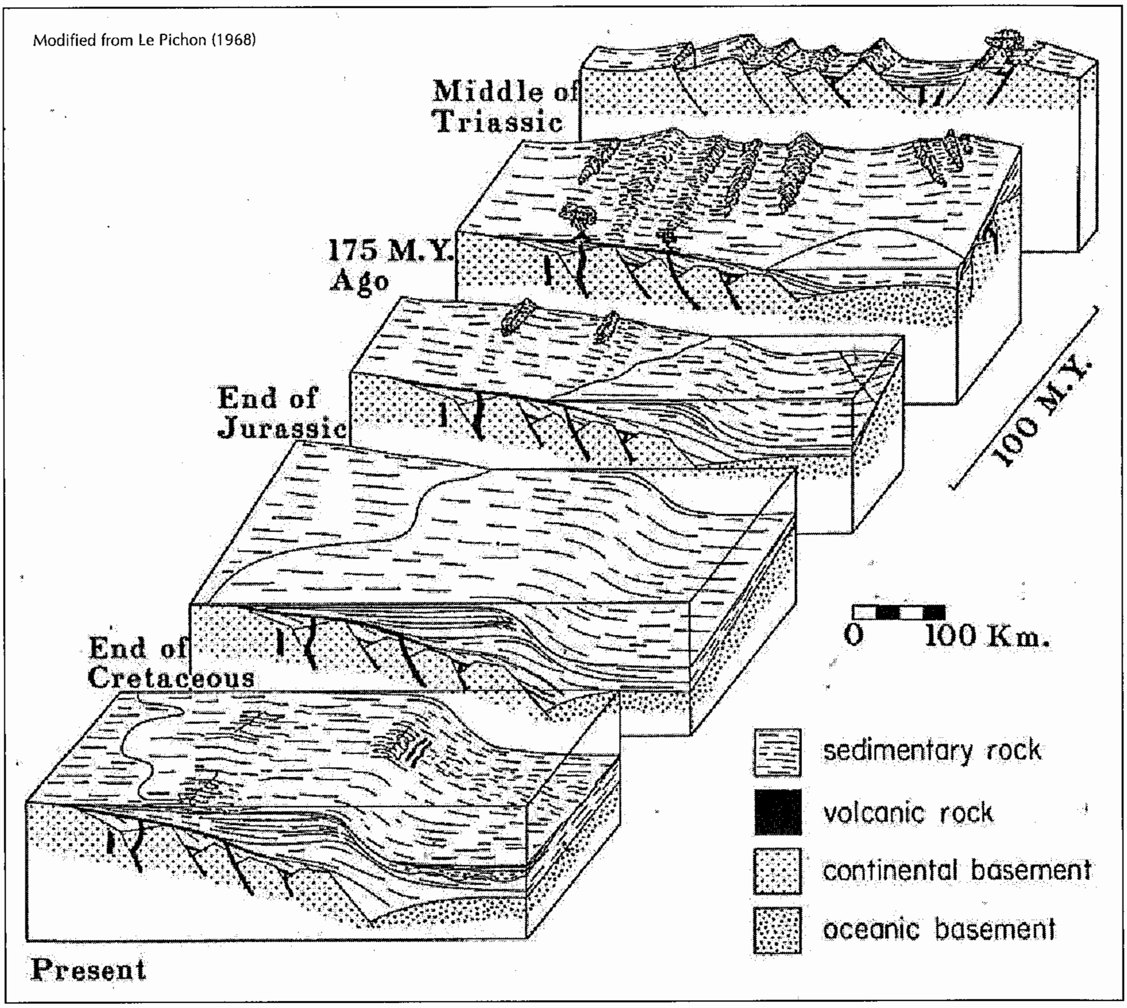


FIGURE 2-5. Formation and development of the Atlantic continental margin.

ing faults across all of New England, but in places they form prominent zones of faults. The northwest-trending faults appear to have been mainly contemporaneous with the northerly ones, but many continued to be active later than the northerly ones and some still are active (Barosh, 2006b). A zone of such faults, which crosses New England to pass near the southern New Hampshire-Maine border and extend southeast offshore, controlled a volcanic chain in the Jurassic and Cretaceous (Barosh, 1992). This chain passed east of Cape Ann and apparently connected in some irregular fashion with the drowned Cretaceous volcanoes of the chain of New England Seamounts, which extended southeastward 1,100 kilometers (682 miles) from Georges Bank (see Figure 2-8). These volcanoes are now deeply submerged due to further subsidence of the sea floor.

The activity slowed, but still continued into the Tertiary, and some regional crustal movements took place. Some of the northwest-tending faults along the New Hampshire-Maine border are continued active and cut volcanoes in the chain (Freedman, 1950; Barosh, 1992). Other north- and northwest-trending faults cut the Cretaceous and Tertiary deposits just offshore to the south (McMaster *et al.*, 1980; Hutchinson & Grow, 1982). The coastal plain deposits along the Atlantic Coast were affected by areas of local subsidence, which appear connected with the propagation of the transform fracture zones. These northwest-trending faults

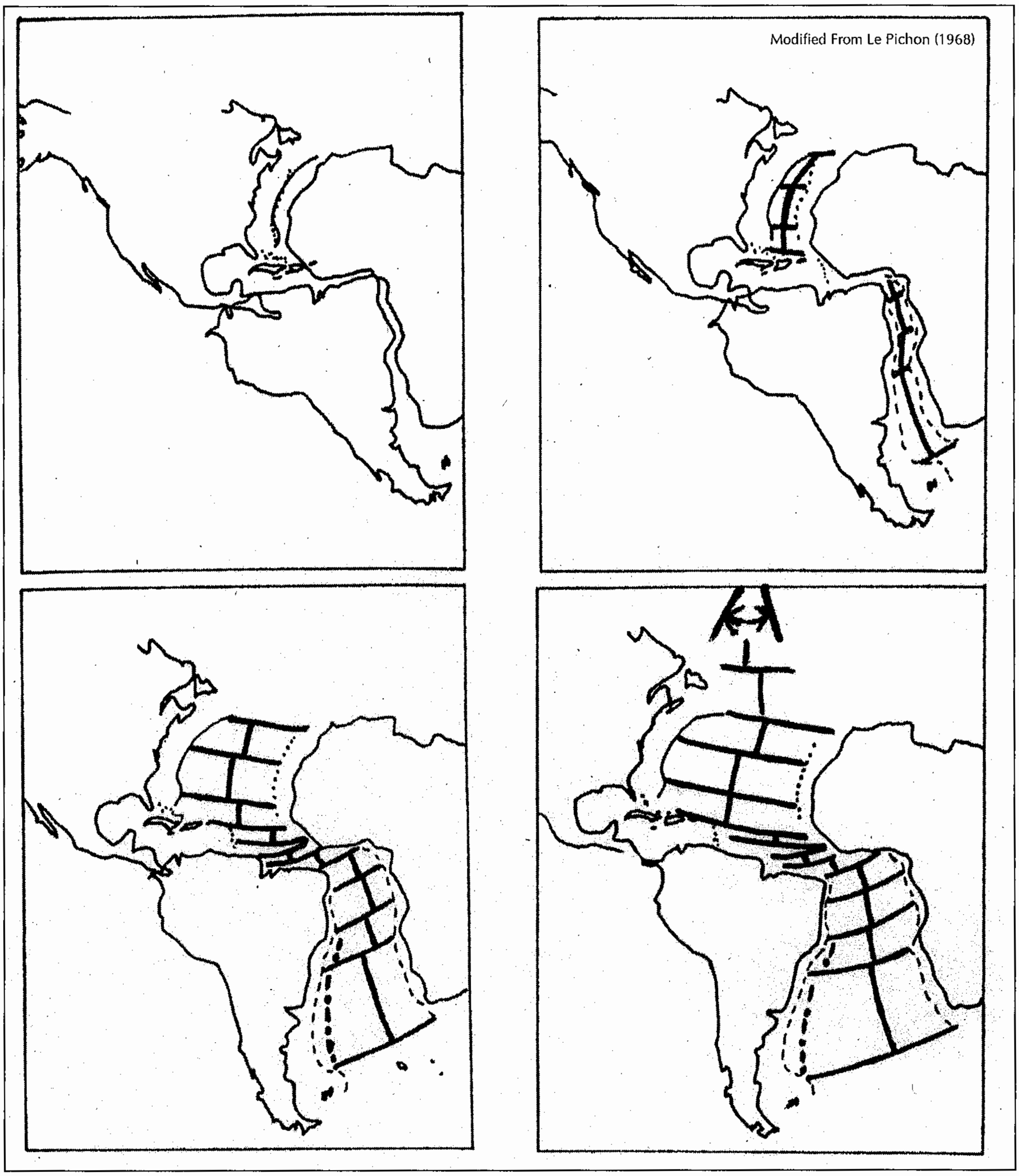


FIGURE 2-6. Progressive Mesozoic opening of the Atlantic Basin showing the Mid-Atlantic Ridge and a few transform zones. The angle at the top of the last frame indicates the lesser opening in the North Atlantic that causes the opposite shores of the North Atlantic to rotate away from one another.

also seem to control an area of submergence centered on the New Hampshire coast (Smith, 1982) and another near New York. In addition, the entire East Coast began a slow downward tilt to the north and a rise to the south again in the Late Cretaceous that caused the coastal plain to emerge south of New York City and to submerge to the north (Barosh, 1986c).

Several periods of glaciation affected the region during the Pleistocene, 2 million to

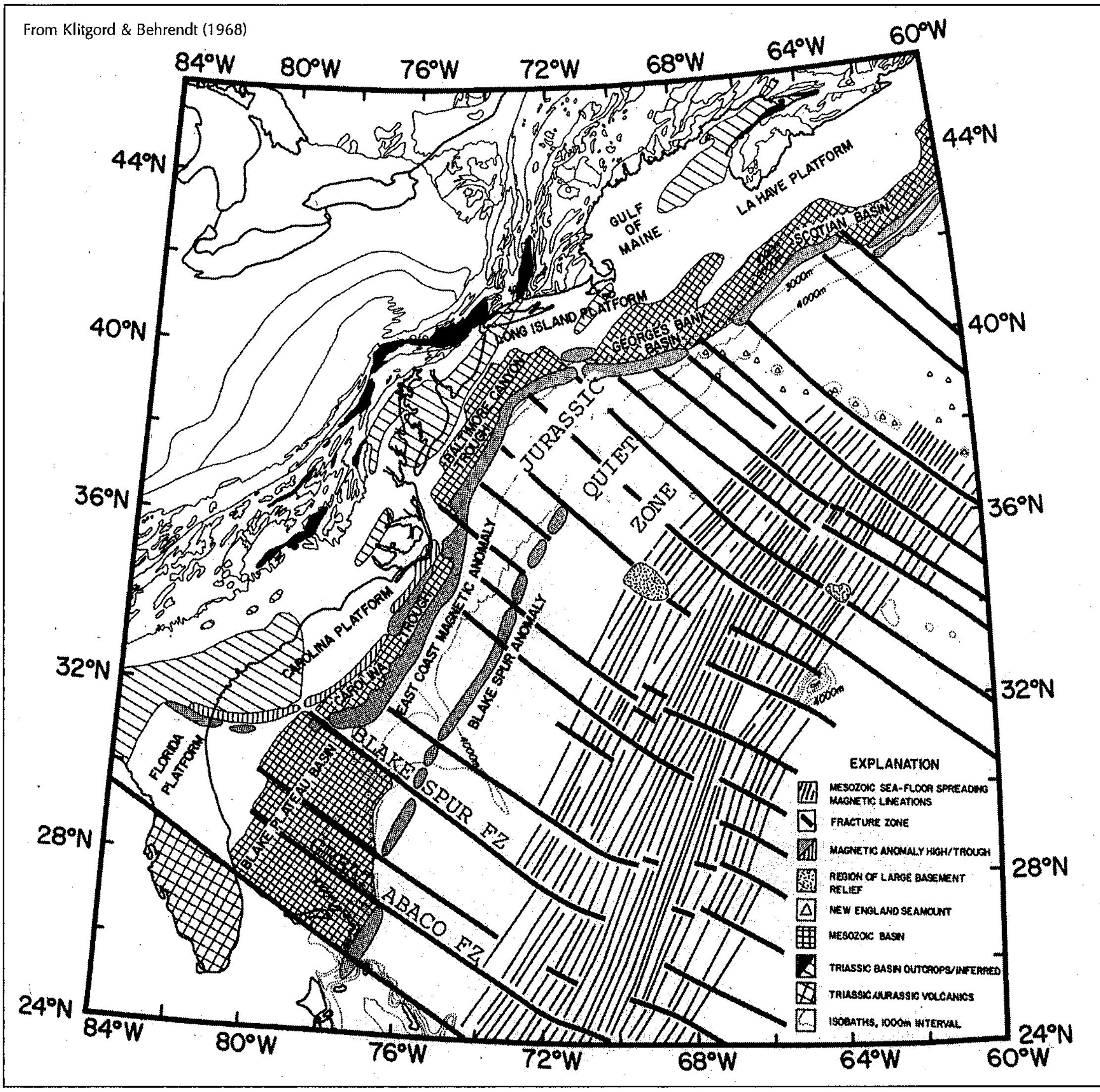


FIGURE 2-7. Western North Atlantic Basin showing major transform fracture zones impinging on the East Coast of North America.

11,000 years ago, but the only clear record of retreat is at the end of the late Wisconsin. At least three Wisconsin glaciations left a very complex array of deposits in the Boston Basin where the sea level varied greatly due to worldwide decline to form glaciers, depression from the ice load, rebound from removal of the load and general sea-level rise from melting. The last rebound of the crust began soon after the ice started its final retreat 13,500 years ago (Larsen, 1987) and caused a regional downtilt to the south of about 90 centimeters per kilometer (57 inches per mile). This tilt and the post-glacial rise in sea level combined to deeply submerge the Late Pleistocene New England shoreline offshore to the south of Boston (Schlee & Pratt, 1970; USGS, 1976; O'Hara & Oldale, 1980), whereas north of a point on the south side of Boston the old shoreline is exposed and progressively rises to the north.

Tectonic activity continues in the region as shown by many local areas of earthquakes from some active north- and northwest-trending faults. The most prominent system and most active of the northwest-trending zones of

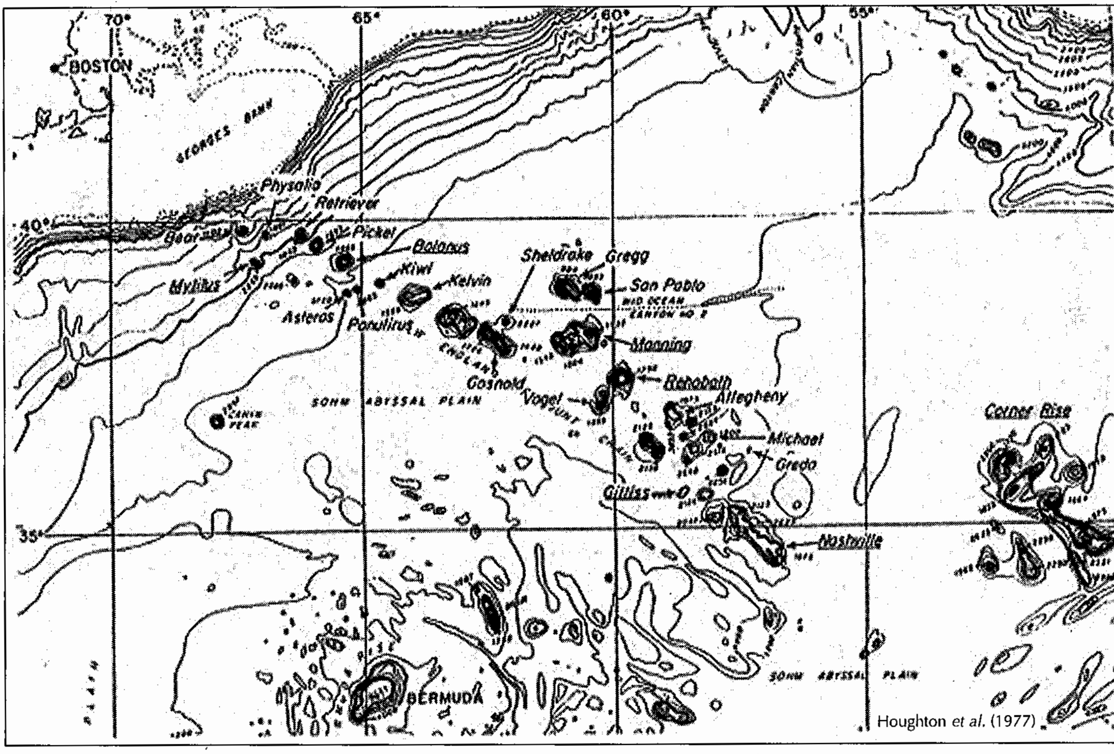


FIGURE 2-8. New England seamount chain extending southeast of Boston to east of Bermuda shown on a bathymetric chart.

faults crosses New Hampshire and passes along the north side of Cape Ann and out to sea just east of Boston (Barosh, 1986a, 1986b & 1986c). These earthquakes appear to result from local crustal subsidence in the bays and river valleys related to continued movement in the North Atlantic Basin. The glacial rebound is long over in New England and its effect on tectonic activity is long passed. The regional tilt to the north is again operating and adding to the shoreline changes from sea-level rise.

Proterozoic & Paleozoic Geology

Grenville Terrane. The Grenville Terrane (see Figure 2-1) is underlain by a wide band of deformed rock along the eastern side of Laurentia that was metamorphosed and intruded in the Middle Proterozoic about 1,200 to 900 million years ago. The restricted portion of the Grenville Terrane described here is its eastern edge where the rock turns up to form the west side of the Appalachian Chain of New England (see Figure 2-9). This portion of the terrane covers the area where the southern Green Mountains divide into the Berkshire Hills and the Taconic Range and the extension into the Hudson Highlands and Manhattan. The region underlain by Grenville is overlapped by a transgressive sequence of Cambro-Ordovician strata and is seen as local exposures, such as the granite on Mount Hoosac in northwestern Massachusetts. There, the younger strata arch over the crest of the granite in a north-plunging fold and extend down its eastern side (Pumpelly *et al.*, 1894). The arch is pierced by the 8-kilometer (5-mile) long Hoosac railroad tunnel, which exemplifies an early achievement in engineering geology, and one that has held up well (see Figure 2-10). Highly metamorphosed schist and gneiss, of apparent Late Proterozoic age, wedges in over the east flank of the Grenville rock in southern Massachusetts and expands to the southwest into New York. There, it includes the New York City Group, which also includes the Manhattan Schist and Inwood Marble units.

The later Cambro-Ordovician strata are deformed in broad north-plunging folds, with

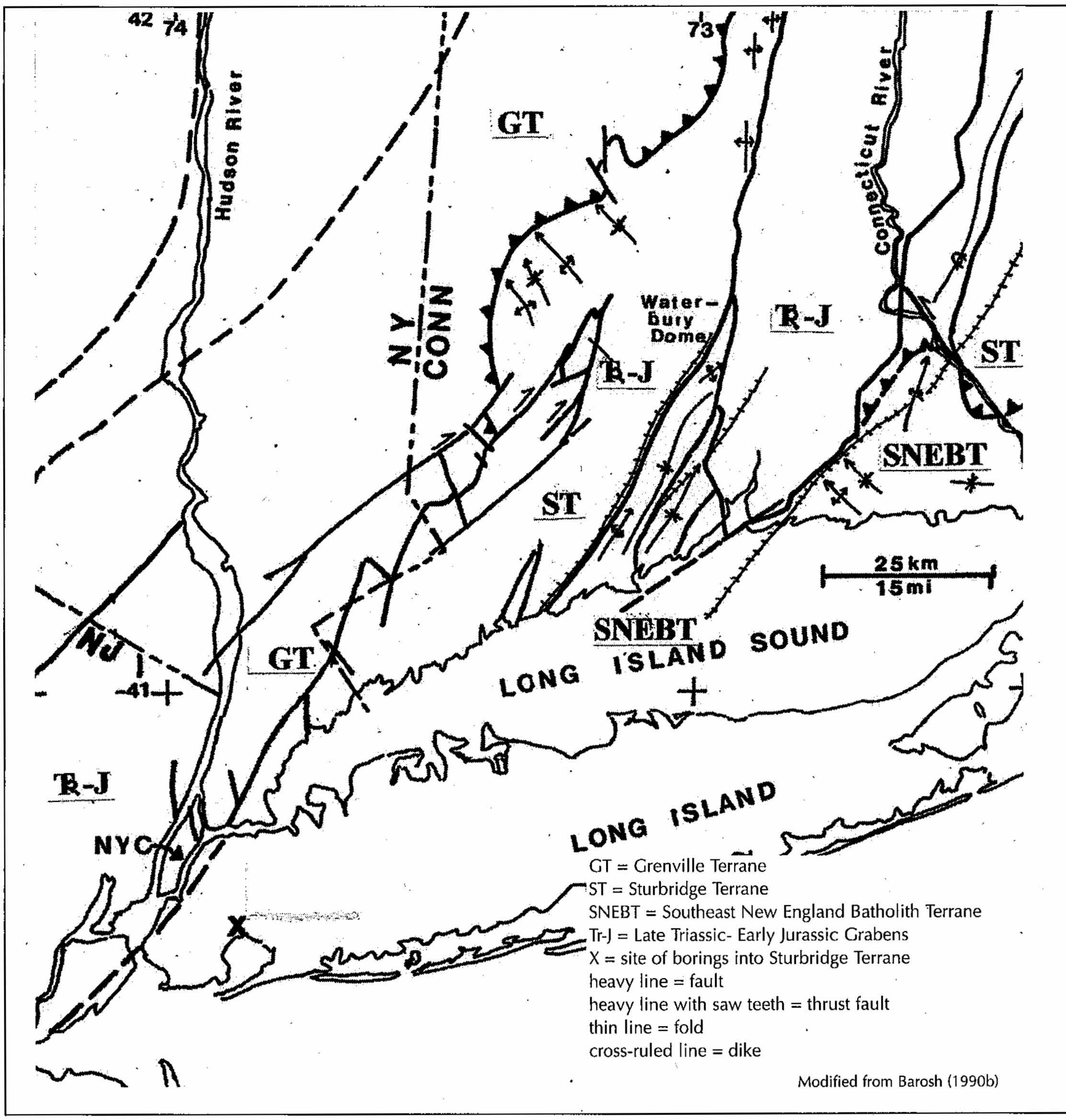
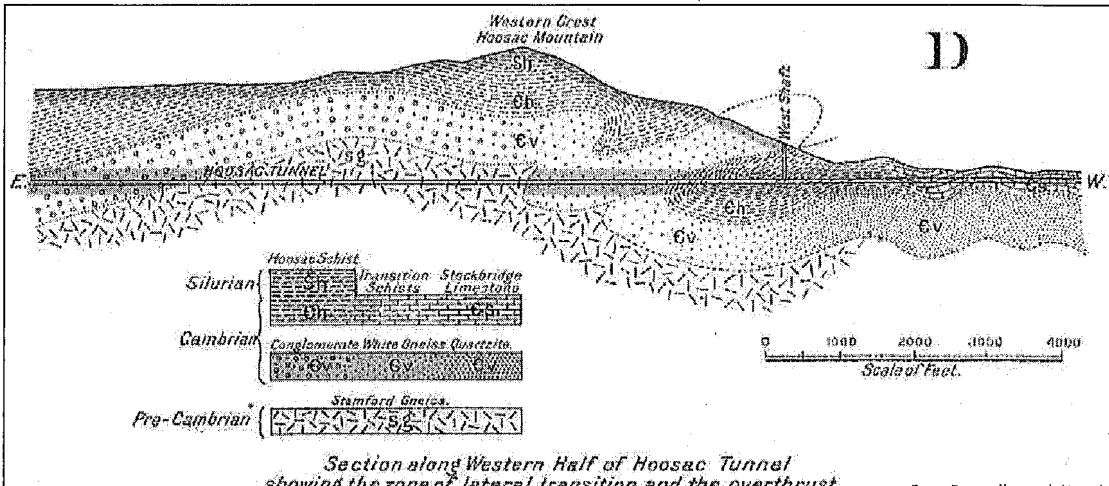


FIGURE 2-9. Map of southwestern Connecticut and adjacent New York showing geologic terranes and selected geologic structures.

smaller local compressed zones that show some overturning to the west. The general structure is relatively simple, but, "[s]mall structures, in contrast to the simple large structures are remarkably complex. Small tight folds may be observed at many outcrops, and boudinage [squeezed into string-of-sausage-shapes] is common. These small structures seem to be rather unsystematic fold axes [that] plunge in different directions" (Quinn, 1967). This result is due to movement in incompetent strata, whereas the enclosing competent layers remain planar (Balk, 1932). Some of these small-scale internal folds have been interpreted to represent very complex regional refolded structures with the different local axial trends representing different periods of folding (Ratcliffe & Harwood, 1975; Stanley, 1975; Zen *et al.*, 1983; Hepburn, 1975). This interpretation, however, conflicts with the attitudes and stratigraphy of the strata (Hobbs, 1904b; Schnabel, 1976; Gates & Martin, 1976), and the geophysical data (Bell



From Pumpelly *et al.* (1894)

FIGURE 2-10. Geologic section of the Hoosac Tunnel, view south.

& Schnabel, 1972; Barosh *et al.*, 1977b), in addition to being geometrically incompatible and apparently structurally impossible. The known folding appears related to westward-sliding gravity-thrust sheets and slides along the western flank of the mountains toward the Hudson River valley. The Taconic thrust faults are the most notable.

The Grenville Terrane is bounded on the east by a west-dipping thrust zone, sometimes referred to as Cameron's Line (Clarke, 1958; Gates & Bradley, 1952; Gates & Martin, 1976) after a student who recognized it (see Figure 2-11). The moderate west dip of the fault gradually steepens northward across Connecticut into Massachusetts where it is mapped as the Barkhamsted Fault (Schnabel, 1976). The zone swings to the southwest in southwest Connecticut, into a broad right-lateral, northwest-dipping fault zone, which continues southwestward down the East River. This swing is well shown by offsets of geophysical and geologic features (Clarke, 1958; Prucha *et al.*, 1968; Barosh, 1976a; Barosh & Pease, 1976; Tillman, 1981). The Grenville Terrane has been thrust eastward along these faults over the adjoining Sturbridge Terrane (Clarke, 1958) and not the reverse as has been sometimes assumed in northern Massachusetts (Karabinos *et al.*, 1998) where the evidence is lacking.

Sturbridge Terrane. The Sturbridge Terrane (see Figure 2-1) is characterized by a very thick west-dipping section of gneiss, schist and granulite laced with pegmatite and intruded by tabular bodies of foliated granite, which form the Late Proterozoic Sturbridge Province or sequence (Barosh, 1998). These rocks are divided in half by the Upper Triassic-Lower Jurassic strata of the Hartford Graben, which contains the Connecticut River Valley (see Figures 2-1 & 2-9). Moderately metamorphosed lower Paleozoic strata cover the section west of the graben in Massachusetts and occur as down-dropped fault troughs in east-central Massachusetts. Slightly foliated to nonfoliated Paleozoic plutons of mostly Ordovician age are scattered about. The terrane forms a large sheet-like body underthrust by the terranes to the east, which show through locally as windows, such as the Waterbury and Willimantic domes in western and eastern Connecticut, respectively (Pease, 1982 & 1989) and the Pelham Dome in central Massachusetts (see Figures 2-9, 2-12, 2-13 & 2-14). The Sturbridge Terrane is cut into thrust slices with west over east movement. The lower, flatter slices pinch out northward at the Massachusetts border, where the terrane forms a series of west-dipping thrusts (see Figure 2-15). Northeast of Worcester, Massachusetts, and in southeastern New Hampshire, the thrust slices are repeated on the east by steeper thrust faults (see Figure 2-16).

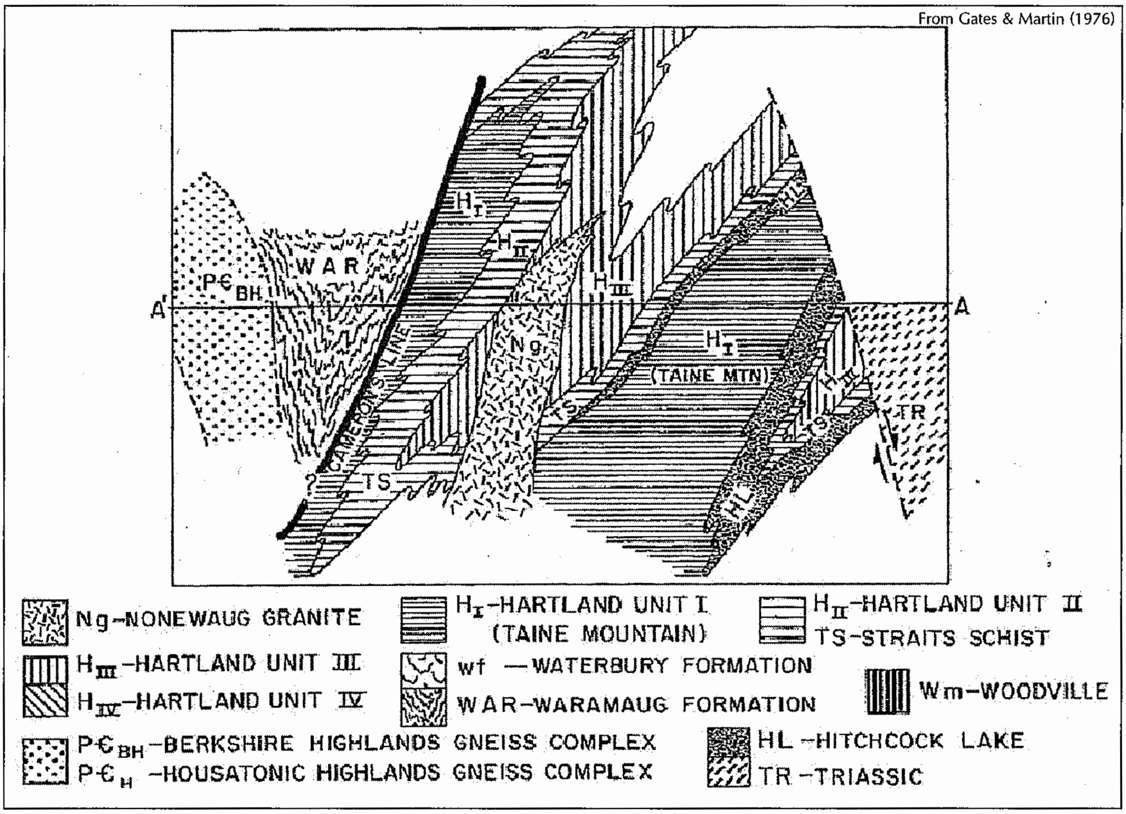


FIGURE 2-11. Section showing west-dipping thrust zone along Cameron's Line, which separates the Grenville Terrane on the west from the Sturbridge Terrane on the east; view north.

The Proterozoic units were broadly defined a century ago (Perry & Emerson, 1903; Emerson, 1917), subdivided in west-central Connecticut (Gates & Martin, 1976) and painstakingly described, measured and redefined in the northeastern Connecticut-Massachusetts border region, and correlated to the northeast into Maine (Pease, 1972 & 1989; Peper *et al.*, 1975; Peper & Pease, 1976; Peck, 1976; Barosh *et al.*, 1977a; Barosh & Pease, 1981; Pease & Barosh, 1981; Barosh & Moore, 1988). These are the only modern studies of these high-grade strata and may be the only such detailed studies following the Stratigraphic Code in the entire Appalachian System. The original strata consist of a turbidic sequence of moderate to gentle west to northwest-dipping and northwest-topping siltstone, graywacke and shale that built offshore of the east coast of Grenville rock. They have generally undergone high-grade regional metamorphism, which produced abundant pegmatitic lenses. The units are, from base upwards, the Oakdale Formation, Paxton Group and Brimfield Group, which are characterized by metasiltstone, metagraywacke, and mixed metagraywacke and schist, respectively. The Oakdale Formation contains a few muscovite schist lenses (the Scotland Schist Member) that may be locally thick. The schist in the Brimfield Group is commonly garnetiferous and contains significant pyrrhotite (a magnetic variety of pyrite) in some units. The section totals 22.5 kilometers (14 miles) in thickness with no top exposed and the base of the Oakdale Formation ends against the collision zone to the southeast. The strata are usually moderately to well-bedded in thin to medium beds that are commonly graded. The lower units are seen to become finer and contain more carbonate to the southeast in New Hampshire and contain some detrital zircons of Grenville age.

These units have been followed from their terminus in east-central Connecticut northeastward across southern New Hampshire into

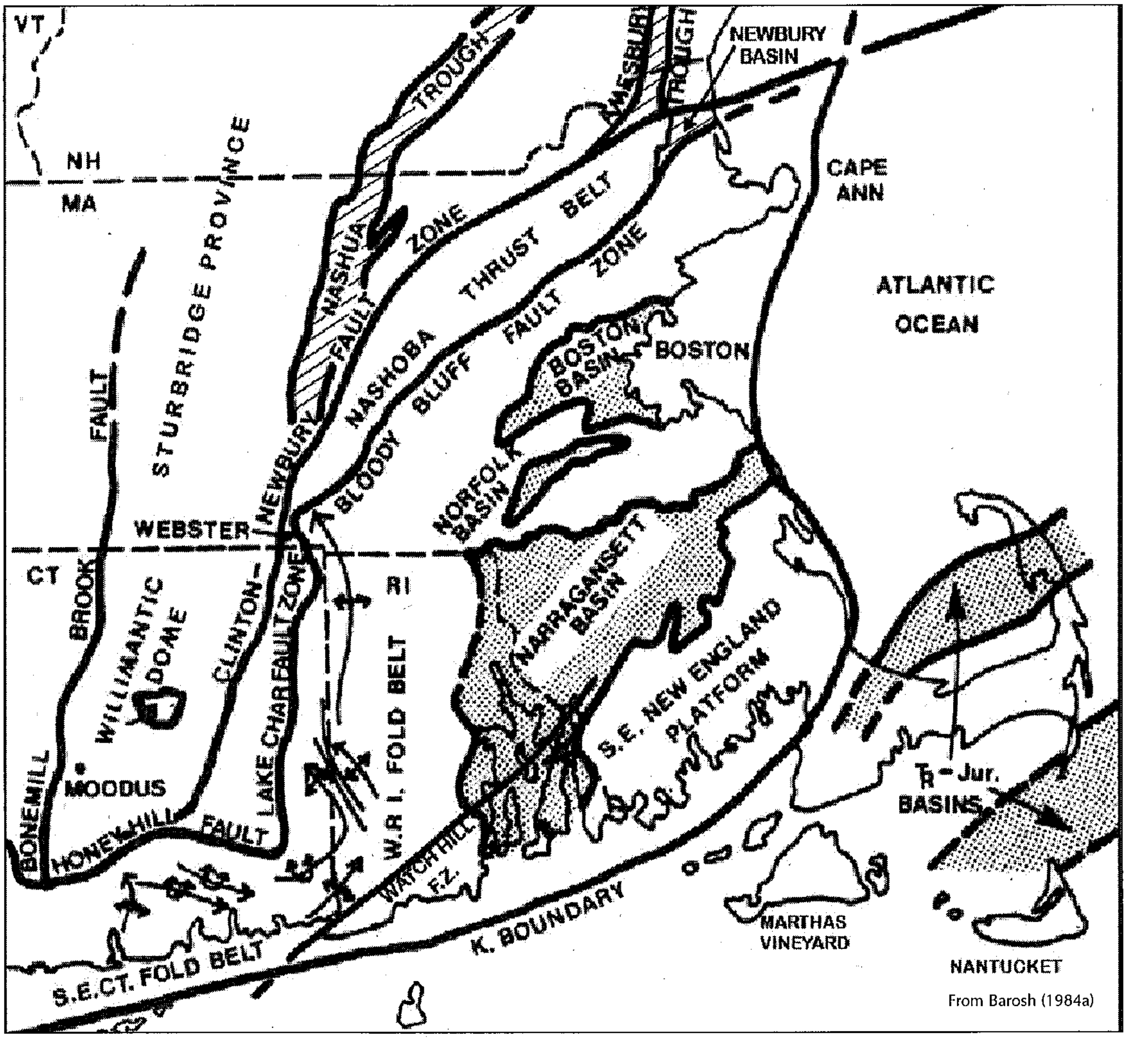


FIGURE 2-12. Map of southeastern New England showing the collision zone, which is marked by the Nashoba Thrust Belt, between ancient North America (Laurentia) on the northwest and ancient Africa (Gondwana) on the southeast, along with major tectonic provinces and structures.

coastal Maine nearly to New Brunswick before becoming completely covered (Barosh & Moore, 1988; Barosh *et al.*, 1977a; Pease, 1989). Parts of the sequence are repeated three times by faulting in northeastern Massachusetts and the different fault slices farther northeast were given different stratigraphic names since the faults were not recognized. In New Hampshire, for example, the Paxton and Oakdale strata along the coast are called the Rye and Kittery formations, respectively, and are grouped as the Berwick Formation to the northwest. The metagraywacke and schist sequence on the west side of the Hartford Graben in Connecticut is referred to as the Hartland Group, but it is essentially the same as the Brimfield Group to the east and apparently a repeat of it. The Hartland Group has been studied and divided into several west-dipping units (Gates & Martin, 1976), some of which have been followed by deep drilling southwestward along strike to beneath western Long Island (Barosh, 1990b). Pegmatitic lenses and "sweat outs" are common throughout the sequence and locally form a high percentage of the rock. A series of elongated tabular foliated granitic bodies are present, especially near the eastern margin where they appear to have formed in place from rock along early thrust faults. These bodies are mainly quartz monzonite in composition, with slight to strong flow foliation, reflecting the degree of movement along the intruded zone as the granite formed. Most of the granitic rock is either a coarsely porphyritic "Ayer" type or a medium-grained muscovite-bearing "Chelmsford" or "Fitchburg" type. These were thought to represent two granitic units, but where mapped in detail are found to consist of several repeated pulses of similar granite (Gore, 1976; Barosh, 1977a; Barosh *et al.*, 1977a).

The Late Proterozoic age of these strata is well demonstrated by the dating of detrital zircons, cross-cutting granite and overlying strata. The much less deformed, moderately metamorphosed Cambro-Ordovician deposits in the Nashua and Amesbury troughs unconformably overlie these highly deformed strata in northeastern Massachusetts (Peck, 1976; Barosh, 1998). These Paleozoic deposits, in turn, are intruded by the Late Ordovician Andover Granite (LaForge, 1932) and the Bare Hill Granite, which appears to be of the same age (Barosh & Alvord, in press). To the north, along the Maine coast, much of the sequence is buried by an unmetamorphosed Silurian-Devonian redbed-volcanic sequence (Gates, 1969; Gates & Moench, 1981). The Paxton and Oakdale contain detrital zircons of Middle Proterozoic age — 1,188 and 1,237 million years ago — as mentioned (Aleinikoff *et al.*, 1979; Barosh & Moore, 1988; Pease, 1989) and are intruded by the Late Proterozoic Massabesic Gneiss, which is a foliated granite, of Late Proterozoic age in southeast New Hampshire. The Massabesic intrudes the country rock (Sriramadas, 1966) along the Brimfield and Paxton contact (Barosh *et al.*, 1977a; Barosh & Pease, 1981; Smith & Barosh, 1982) and most of the "gneiss" represents the migmatitic (or mixed) border zones with these units with foliated granitic rock. It has been dated as Late Proterozoic, approximately 650 million years ago (Besancon *et al.*, 1977; Aleinikoff *et al.*, 1979; Lyons *et al.*, 1982) and 625 million years ago (Dorais *et al.*, 2001). Several dated Ordovician granitic plutons cut the metamorphosed strata and small Silurian and Devonian ones are probably present as well, both east and west of the Hartford Graben (Pease & Barosh, 1981; Barosh & Moore, 1988; Pease, 1989). Diorite bodies, of probable Ordovician age, are aligned in one zone that extends northeast from near Lowell, Massachusetts. Another line of small basic to ultrabasic intrusions, near the west edge of the terrane, apparently served as feeders to a submarine volcanic and ophiolite suite, such as that preserved along strike to the north in Québec (Castonguay *et al.*, 2001). The Sturbridge strata and foliated granite also can be indirectly dated as Proterozoic by correlation with other proven Proterozoic rock. There is only one period producing high-grade metamorphic strata accompanied by well-foliated syntectonic granite, along with matching structure in the Sturbridge, Nashoba and Southeast New England Batholith terranes and it must have occurred at the same time in each. This period is dated as pre-Latest Proterozoic by fossil and radiometric ages in the Boston Basin.

Cambro-Ordovician strata are caught in fault troughs where the Paxton Group and Oakdale Formation are repeated twice by thrust faults in northeastern Massachusetts. A third repetition just off the New Hampshire coast is seen in the Isles of Shoals where pendants of the Paxton Group are present in the granite forming the islands. Both the Nashua Trough, which extends from near the Connecticut line northward along the Nashua River Valley into New Hampshire, and the Amesbury Trough to the east end to the south against the Clinton-Newbury Fault Zone (Barosh, 1974 & 2005; Smith & Barosh, 1981 & 1982), which forms the boundary with the Nashoba Terrane, end to the south (see Figures 2-1, 2-12 & 2-16). The south end of the Nashua Trough has been dragged into slivers by right-lateral movement of the fault, the largest of which forms the ridge beneath Holy Cross College in Worcester.

The Nashua Trough contains a thick sequence of rock consisting of thin-bedded quartzite, fine-grained sandstone, siltstone and mudstone that are only moderately metamorphosed and not laced by pegmatite. Peck (1976) describes these strata of the trough as

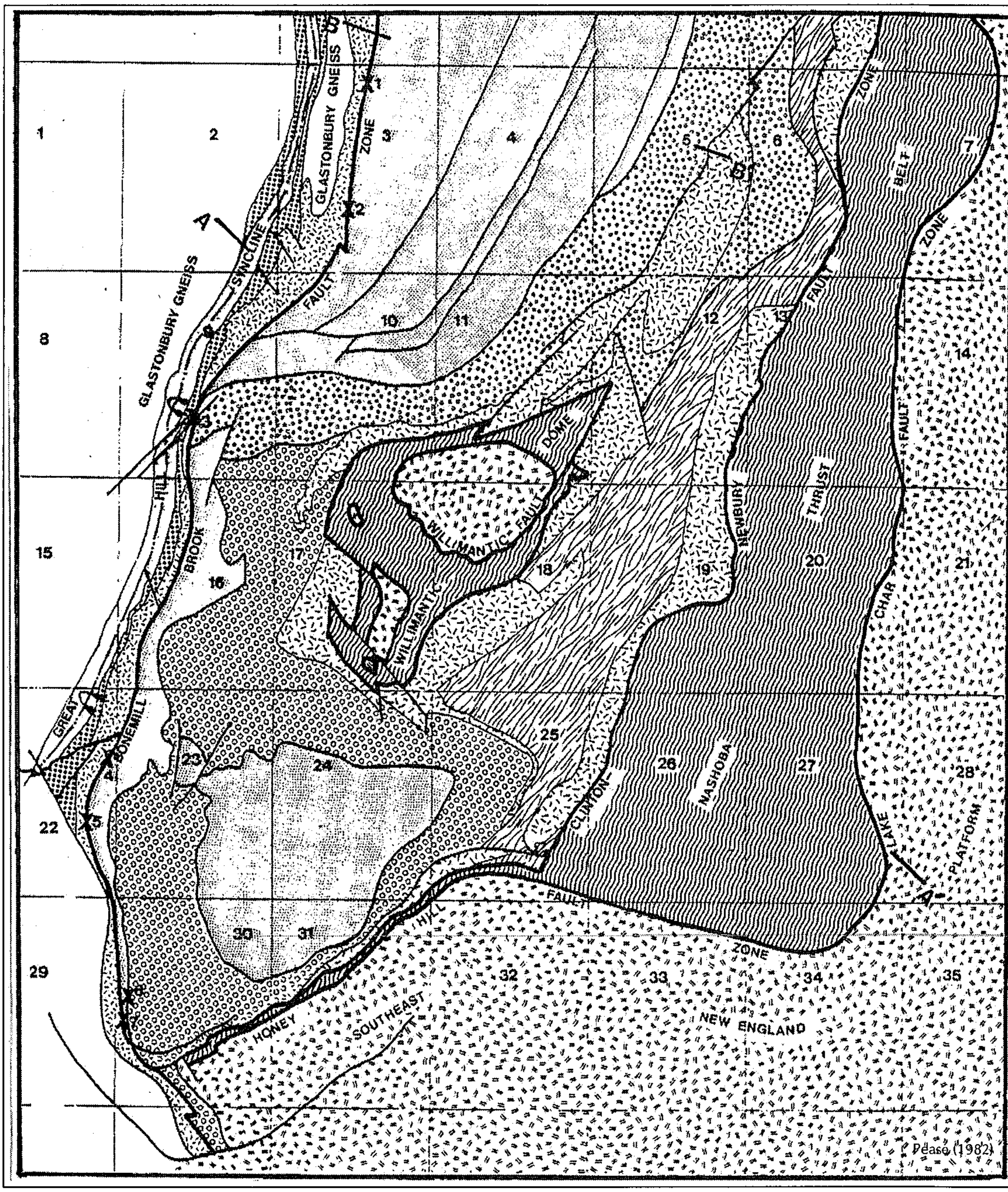
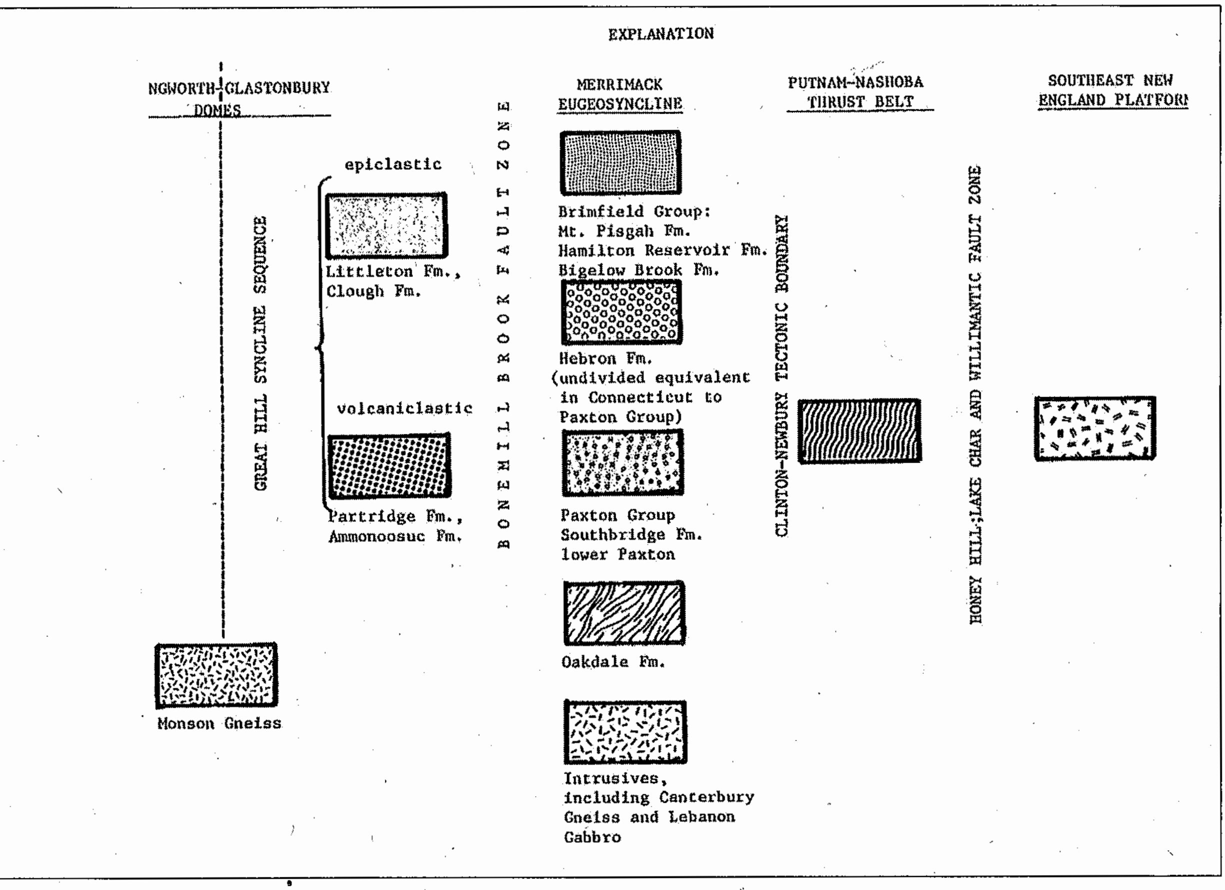


FIGURE 2-13. Map of eastern Connecticut and adjacent areas showing structure of the eastern Sturbridge Terrane and its relations with the Nashoba and the Southeast New England Batholith terranes. Sections A-A′ and B-B′ are shown in Figures 2-14 and 2-15, respectively.

Units 1 to 4 (Smith & Barosh, 1981). The exposed base is white quartzite, which is overlain by well-bedded, thin-bedded and graded-bedded dark-gray siltstone to mudstone. Some medium-bedded sandstone with staurolite occurs in the upper part. These deposits are formed on a submarine slope, distant from their source, by turbidity currents and, in some cases, slumps. The Eliot Formation of southern Maine (Katz, 1918; Hussey, 1962) correlates with Unit 2 of the sequence (Peck, 1976). Unit 2 has interbedded siltstone and



mudstone that is commonly highly folded apparently due to contrasting rock strength in slipping while soft and the folds do not extend into the adjacent strata. Similar mudstone with intervals containing pebbles of siltstone and quartzite is known as the Harvard Conglomerate, which seems to fit between Units 1 and 2 and represents a slump deposit. This conglomerate is a pendant within the apparently Late Ordovician Bare Hill Pond Granite in Harvard, Massachusetts (Barosh & Alvord, in press). Another adjacent unit in Clinton, Massachusetts, consists of altered dark-gray basaltic ash (Peck, 1975).

Similar strata occur in local fault troughs along strike across the New Hampshire and Maine coastal region and into New Brunswick (Ludman, 1991; Fyffe *et al.*, 1991). The large Fredericton Trough on the Maine-New Brunswick border contains a near identical section as the Nashua Trough, with a basaltic formation below, as that at Clinton (Barosh, 1999b). Some strata in Maine and those in the Fredericton Trough are fossiliferous and show the volcanic base to be Cambrian and the turbidic sequence to be Ordovician in age. No fossils have been found in place in the Massachusetts section, although trilobite fragments were seen in float (Peck, 1976), but the close lithologic correlation shows them to be the same age (Barosh, 1999b). Although these pre-Silurian strata cannot be correlated across the Sturbridge-Nashoba Terrane boundary, Silurian-Devonian strata can (Gates, 1969; Barosh *et al.*, 1977a). Some small blocks of younger Paleozoic rock are present and others may exist. A small fault block of slightly metamorphosed Devonian limestone occurs at the north end of the Hartford Graben in Massachusetts (Hitchcock, 1871).

The Sturbridge strata structurally overlie parts of both the Nashoba and Southeast New England Batholith terranes (see Figures 2-13 & 2-14) that are exposed in windows locally (Pease, 1982 & 1989). The Willimantic Dome in eastern Connecticut displays a thin slice of the

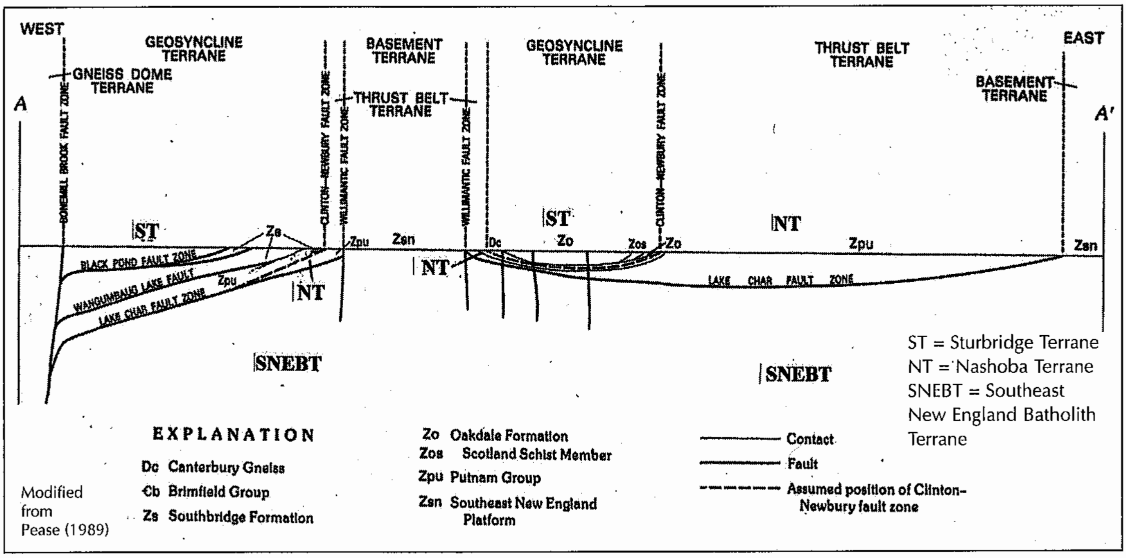


FIGURE 2-14. Section through eastern Connecticut showing structural relations of different terranes. Location is shown as A-A′ on Figure 2-13.

Nashoba rock over that of the Southeast New England Batholith (Pease, 1989). The linear Bronson Hill uplift, to the east of the Connecticut River Valley, also shows rock of the Southeast New England Batholith along with probable Ordovician granite and strata. The assignment of the highly deformed metamorphosed strata exposed in the underlying Waterbury dome of southwestern Connecticut is not yet clear.

The structure of the region was thought to represent several complexly folded anticlinoria (arches) or synclinoria (swales) that ran the length of New England by Billings (1956). These features were interpreted without support from field data. No stratigraphic or structural relations indicated that there were such features. The part across eastern Connecticut, east-central Massachusetts and southeastern New Hampshire is referred to as the Merrimack Synclinorium between the Rockingham Anticlinorium to the east and the Bronson Hill Anticlinorium on the west (Billings, 1956). Smaller hypothetical folds within these large

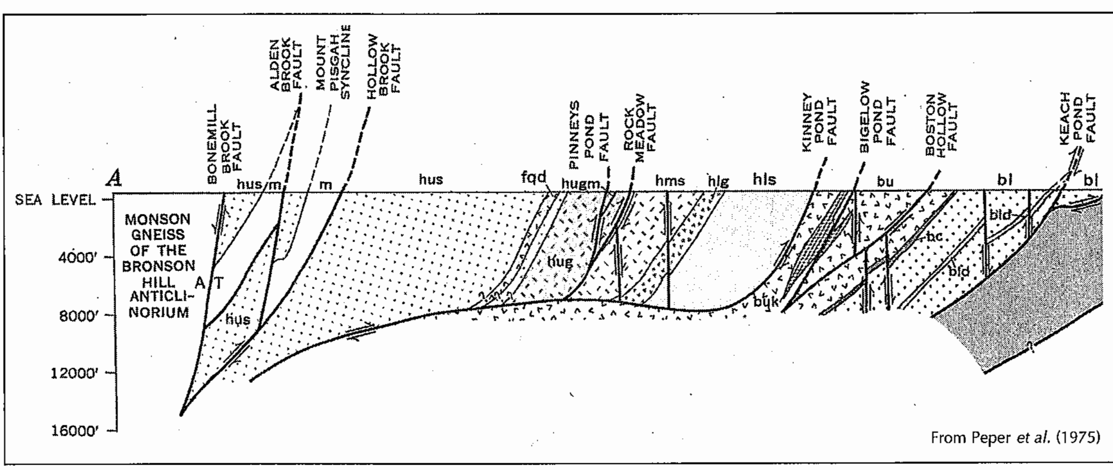


FIGURE 2-15. Section through the Brimfield area along the Massachusetts-Connecticut border. Detail of westernmost edge of Figure 2-7. Location is shown as B-B′ on Figure 2-13.

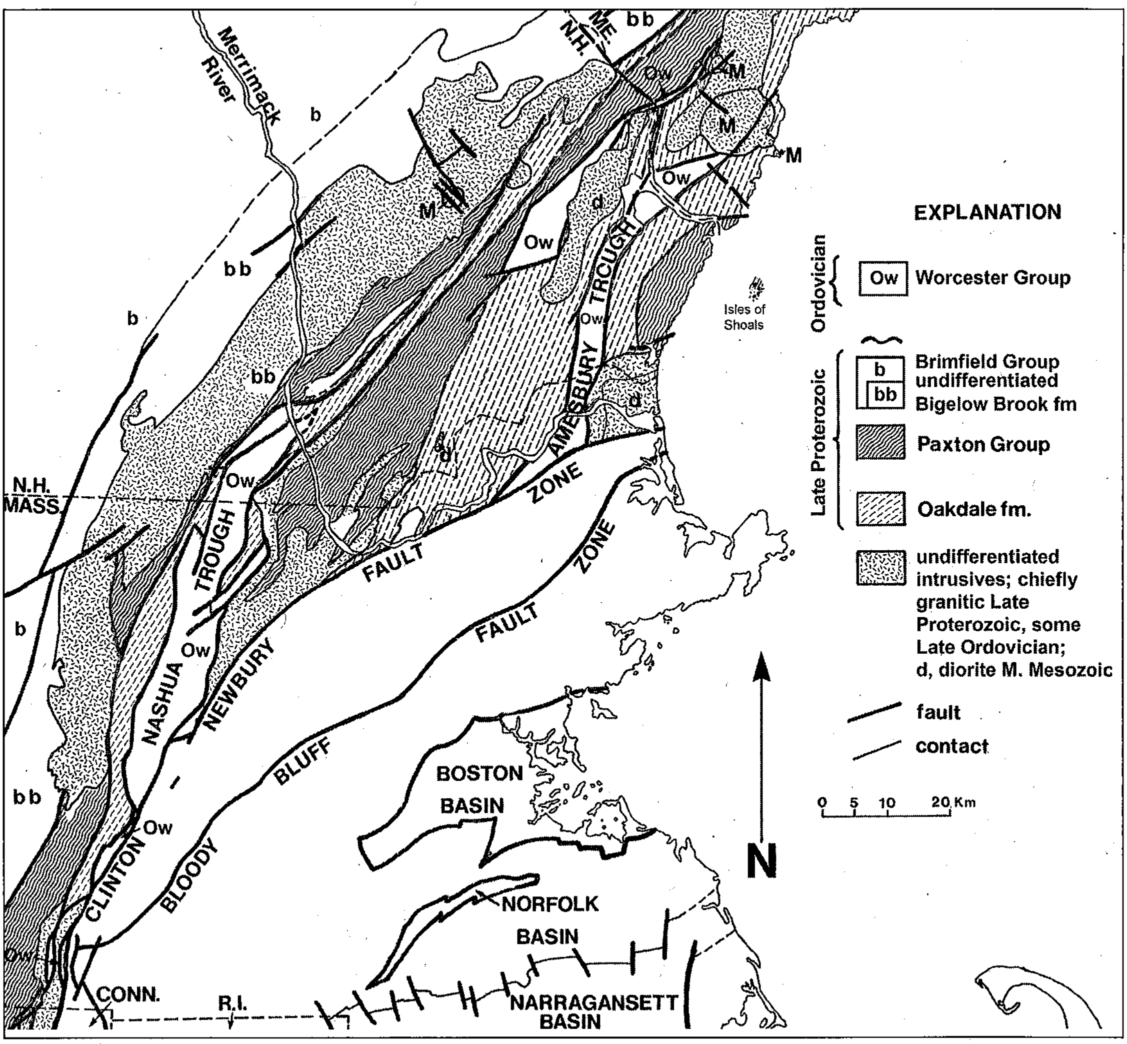


FIGURE 2-16. Map of northeastern Massachusetts to southern Maine showing the geology of part of the Sturbridge Terrane.

structures then were drawn by Robinson (1963), Thompson *et al.* (1968), Dixon and Lundgren (1968), Robinson and Hall (1980) and Zen (1983). However, more information became available from detailed mapping of stratigraphy along the Connecticut-Massachusetts border (Pease, 1972 & 1989; Peper *et al.*, 1975; Pomeroy, 1975; Moore, 1976; Pease & Barosh, 1981; Barosh, 1974 & 2005; Barosh & Moore, 1988). In addition, more information from mapping the bedrock in the Wachusett water diversion tunnel across the region to the north (Callaghan, 1931) also became available. All this information demonstrated that such hypothetical folds were not supported by field evidence. Few folds are observed in the region, except for drag folds along thrust faults (such as the large one along the west edge of the Nashua Trough). The Sturbridge Terrane is a large slab that underthrusts the Grenville Terrane to the west and is itself underthrust by the terranes to the east, which are seen to underlie it along its eastern and southern borders and in windows. Both the Oakdale and the Paxton are cut out to the west against the basal thrust zone. Internally, the slab essentially consists of west- to northwest-dipping strata sliced by a series of early approximately bedding-plane thrust faults, which are offset by various later smaller

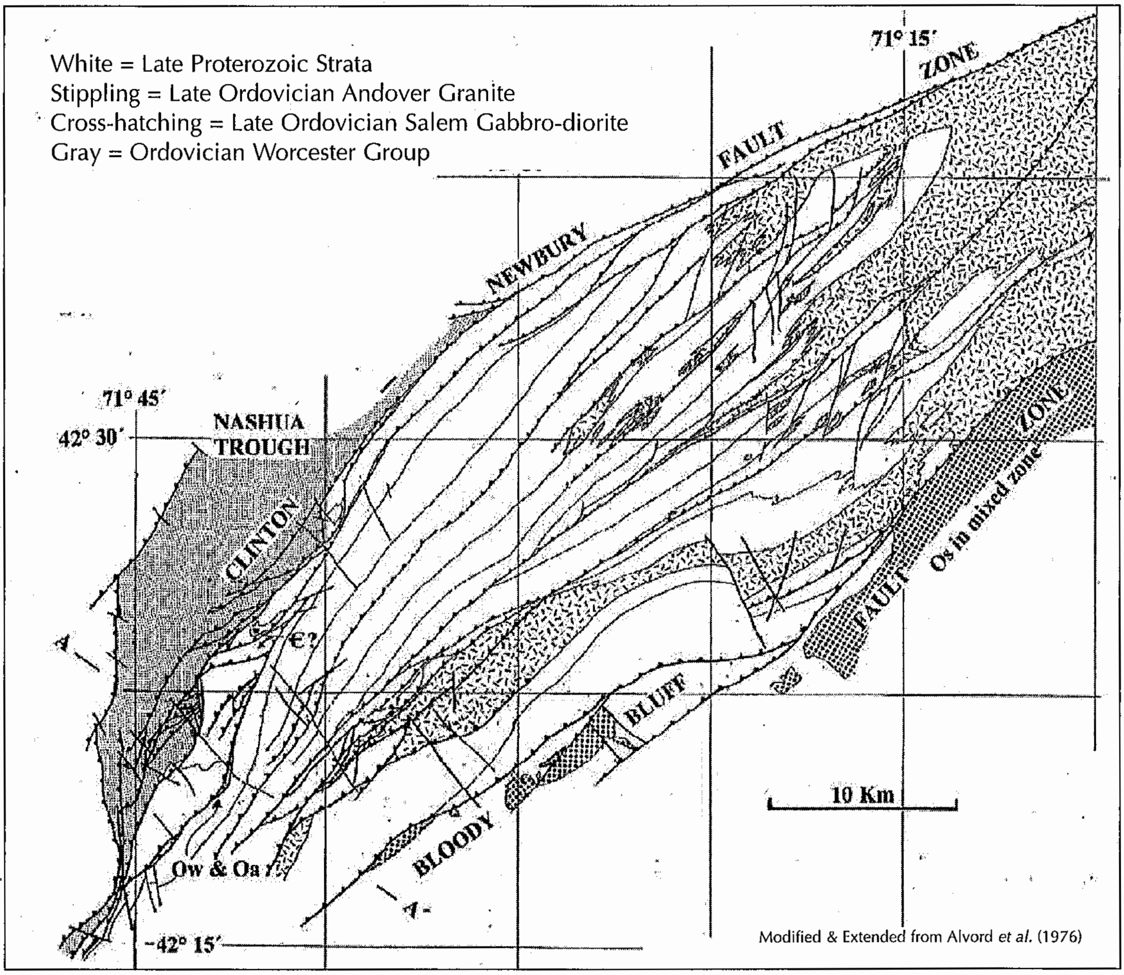


FIGURE 2-17. Structural map of the Nashoba Thrust Belt northwest of Boston, Massachusetts. Section A-A′ is shown in Figure 2-18.

faults. The eastern part, between the Nashoba Terrane and the Bonemill Brook fault, which borders the Bronson Hill uplift, has complex overlapping thrust sheets near its southern edge in Connecticut (Pease, 1989). These thrust faults decrease in both number and offset northward into central Massachusetts, where a few very gentle folds are present (Callaghan, 1931) between more widely spaced thrust faults. In other words, the rocks are more squeezed and deformed to the south nearer the base of the terrane. Reactivation of some thrust faults in eastern Massachusetts caused the repetition of the Oakdale and Paxton (see Figures 2-12 & 2-16) and caught younger, less metamorphosed rock between steeply west-dipping faults in the Nashua and Amesbury Troughs (Smith & Barosh, 1981 & 1982). The offset along the thrust faults is west-over-east, with a right-lateral strike-slip component. One example of this configuration is the northeast-trending Eastford Fault in northeast Connecticut, which has 4 kilometers (2.5 miles) of right-lateral offset and bends northward to end as a thrust in the Webster area (Barosh, 1974 & 2009).

Nashoba Terrane. The Nashoba Terrane forms a plate collision zone of closely spaced west-dipping thrust faults (Bell & Alvord, 1974), called the Nashoba Thrust Belt, which separates the Southeast New England Batholith Terrane from the Sturbridge Terrane in eastern Massachusetts and Connecticut (see Figures 2-12, 2-17 & 2-18). The rock and struc-

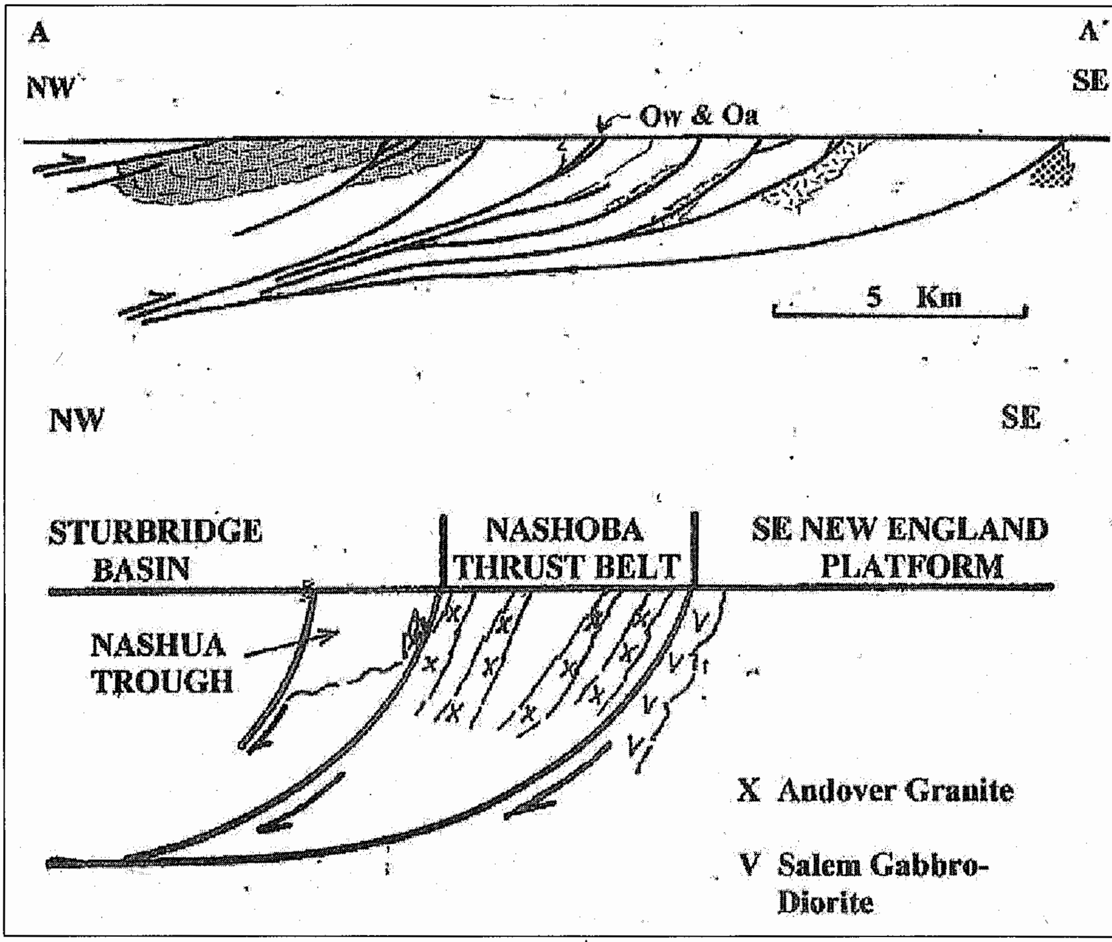


FIGURE 2-18. Section through the Nashoba Thrust Belt; location marked in Figure 2-17. Upper section shows actual scaled section with fault slice of Ow (Ordovician Worcester Group) and Oa (Andover Granite). Lower section is sketch showing structural relations.

ture of the adjacent terranes terminate against it. No stratigraphic correlation has been possible between the pre-Silurian strata of these fault bounded terranes (Barosh *et al.*, 1977a), and the early rock composing them apparently formed at considerable distances from one another. These fault slices are particularly prominent in the aeromagnetic data (Bell, 1972; Alvord *et al.*, 1976; Barosh, 1972; Barosh *et al.*, 1974 & 1977b).

The terrane contains a high-grade metamorphic volcaniclastic sequence over 18 kilometers (11 miles) thick where it was measured and described northwest of Boston (Bell & Alvord, 1976; Alvord, 1975). The moderately to well-bedded, mostly thin-bedded sequence consists mainly of varying proportions of light-gray gneiss, schist, amphibolitic gneiss, amphibolite and marble lenses with a sillimanite-muscovite schist at the top. These strata were formed from sand that was derived from andesitic and basaltic debris, silt and both aluminous and limey mud. The units, from the base upwards are: Marlboro Formation, Shawsheen Gneiss, Fish Brook Gneiss, Nashoba Formation and the Tadmuck Brook Schist. The Marlboro and Nashoba formations extend into Connecticut where they were named the Quinebaug and Tatnic Hill, respectively (Dixon, 1964; Barosh, 2005 & 2009). The Fish Brook Gneiss gave a date of 730 million years ago (Zartman & Marvin, 1987). Strata of the Nashoba Terrane are invaded by several types of intrusive rock.

Moderately foliated Assabet Quartz Diorite, of apparent Late Proterozoic age, forms elongate bodies paralleling the structure in Massachusetts and are apparently controlled by the thrust faults. The abundant slight to nonfoliated Andover Granite has a Late Ordovician best date of 460 million years ago (Zartman, 1976). The granite has intruded along the thrust faults and other structures, but also cuts across the structure in Massachusetts and very locally extends into Ordovician strata of the Sturbridge Terrane (LaForge, 1932). The Andover Granite occupies much of the northeastern part of the terrane and fingers out to the southwest. A large foliated granite body known as the Canterbury Gneiss formed along the Clinton-Newbury Fault Zone in Connecticut and obliterated the mylonite from its early movement (Pease, 1989).

A few later small, nonfoliated, generally circular plutons invaded the terrane in the Silurian and Devonian periods. The Silurian Preston Gabbro crosses the structure in southeastern Connecticut (Dixon & Felmlee, 1986), a smaller circular one of perhaps the same age is in Concord, Massachusetts (Barosh, 1979c), and the Millstone Granite, which is dated as Devonian, is at Worcester. Some Devonian ages are reported from the Canterbury Gneiss that appears to be much older, but could include younger intrusions. The Silurian and Devonian plutons may have served as feeders to volcanic deposits such as the Newbury Volcanic Complex (described below) and accompanied a period of mild regional metamorphism suggested by Pease (1989) or local contact metamorphism that extended from the Early Silurian to the Early Devonian in Connecticut. Pink pegmatite dikes of apparent Permian or Middle Triassic age also occur locally.

A fault block containing the unmetamorphosed Late Silurian-Early Devonian Newbury Volcanic Complex is dropped into the terrane in northeastern coastal Massachusetts (see Figures 2-12 & 2-19). It aggregates more than 4,400 meters (14,432 feet) of interbedded basaltic, andesite and rhyolitic flows and ash, red mudstone and siltstone, and gray calcareous mudstone (Shride, 1976). Enclosed fossils indicate a specific correlation to one unit in the coastal volcanic sequences of northeastern Maine and others are temporal equivalents. These fauna are of Baltic-British affinity rather than Appalachian (Gates, 1969; Shride, 1976). The Maine strata overlie the Sturbridge Terrane. These two sections and a small patch of the Newbury on the nearby Southeast New England Batholith Terrane (Bell *et al.*, 1977, 1993; Dennen, 1981) demonstrate that the Siluro-Devonian volcanic sequence overlaps all three terranes. The Maine strata extend down to the Early Silurian (Gates & Moench, 1981). A sliver of smashed and slickensided Pennsylvanian strata occurs at the west side of the thrust zone adjacent to the Clinton-Newbury Fault Zone in Worcester, Massachusetts. This mildly metamorphosed Pennsylvanian carbonaceous siltstone constitutes the so-called "Worcester Coal Mine" (Perry, 1885; Kemp, 1887; Grew, 1973) and correlates with identical strata at Cranston, Rhode Island, at the west side of the Narragansett Basin farther east (Emerson, 1907). Apparently it is a remnant of more widespread Pennsylvanian strata over the region.

The thrust belt is bounded on the northwest by the Clinton-Newbury Fault Zone, which is the largest fault known on the East Coast, and on the southeast by the Bloody Bluff Fault Zone that joins the Lake Char Fault in northeastern Connecticut (Cupples, 1961; Dixon, 1974; Barosh, 1984b, 1996a & 2005) and the Honey Hill Fault in southeastern Connecticut (see Figure 2-19). The regional northerly structural tilt brings such a cross-section into view and demonstrates that the thrusts flatten and merge downward. The faults are near vertical in northeastern Massachusetts, and then shallow to a 20-degree west dip at the Connecticut border and flatten out in southeastern Connecticut, where the thrust faults in the zone merge into the basal Honey Hill Fault above the Southeast New England Batholith Terrane (Pease, 1989). The basal thrust also is exposed in the Sturbridge Terrane in a window that forms the Willimantic Dome where it is called the Willimantic Fault Zone (see Figures 2-13 & 2-14). The thrust belt is squeezed more and drastically thinned by thrust faults to the southwest across Massachusetts. This condition results in the lower formations being progressively reduced from its 26 kilometer (16

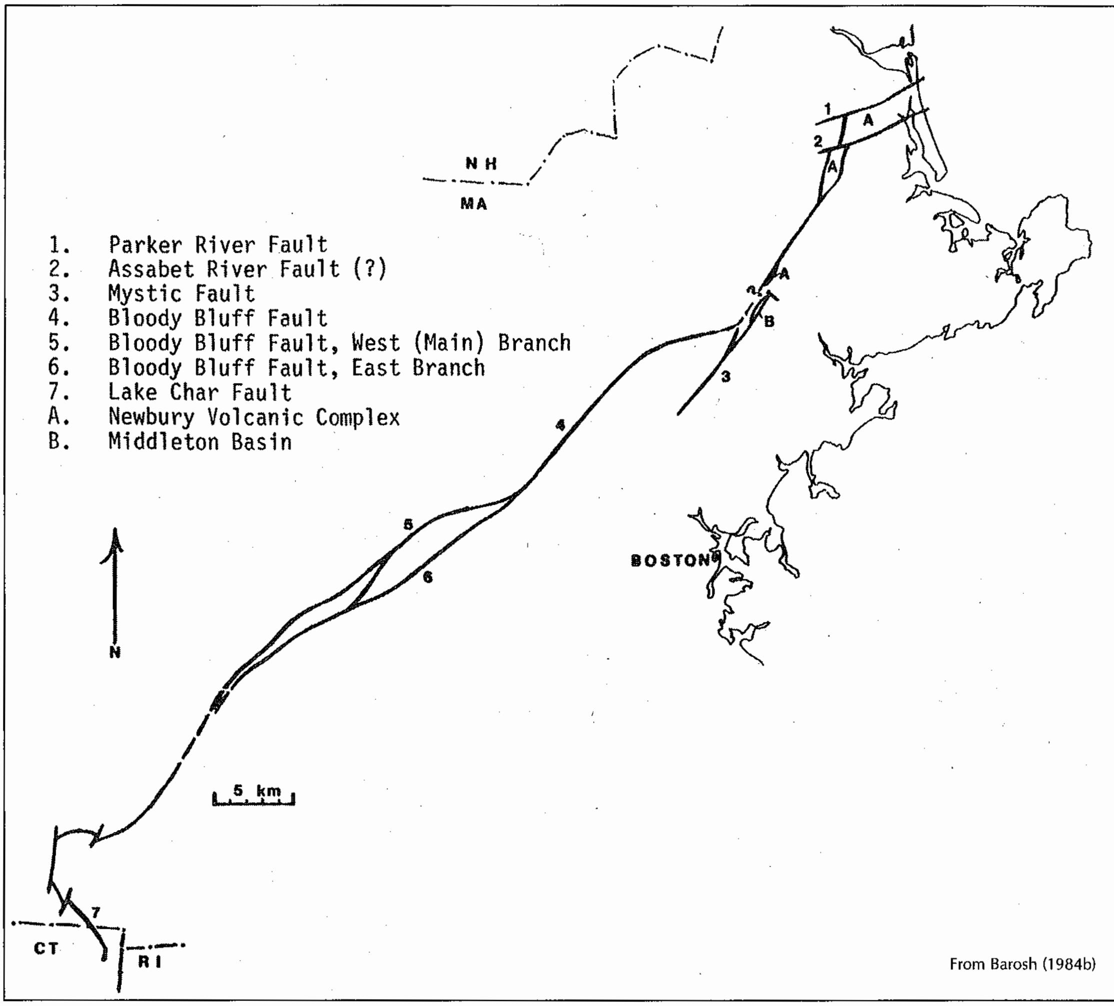


FIGURE 2-19. Map of eastern Massachusetts showing the Bloody Bluff Fault system.

mile) width northwest of Boston to only about 100 meters (328 feet) wide near the Connecticut border (Barosh, 1974, 2005 & 2009). The Tadmuck Brook Schist, at the top, is gradually cut away by the Clinton-Newbury Fault Zone until it pinches out just north of Connecticut (Barosh, 2005 & 2009). Farther south in Connecticut, the zone widens again and a partial section re-emerges. This section thins again against the basal thrust, as can be seen (see Figure 2-14) along the Honey Hill Fault Zone and in the Willimantic Dome (Pease, 1989). The observed displacement across the thrust belt along the Honey Hill Fault Zone measures about 150 kilometers (93 miles) and this displacement is probably only a fraction of the total. However, the direction and type of movement have changed with time. The early movement along the thrust faults is west over east, but later it shifted to northwest over southeast as the collision zone closed at the end of the Ordovician. A right-lateral strike-slip component appears to have increased with time as adjacent extensional features formed in the Mid-Paleozoic and then ceased near its end.

Southeast New England Batholith Terrane. The Southeast New England Batholith Terrane is one of the most variable, complicated and geologically interesting regions in the eastern United States (see Figure 2-1). The terrane consists of remnants of an ancient volcanic pile that had been invaded by a Late Proterozoic batholithic complex, which was later the site of

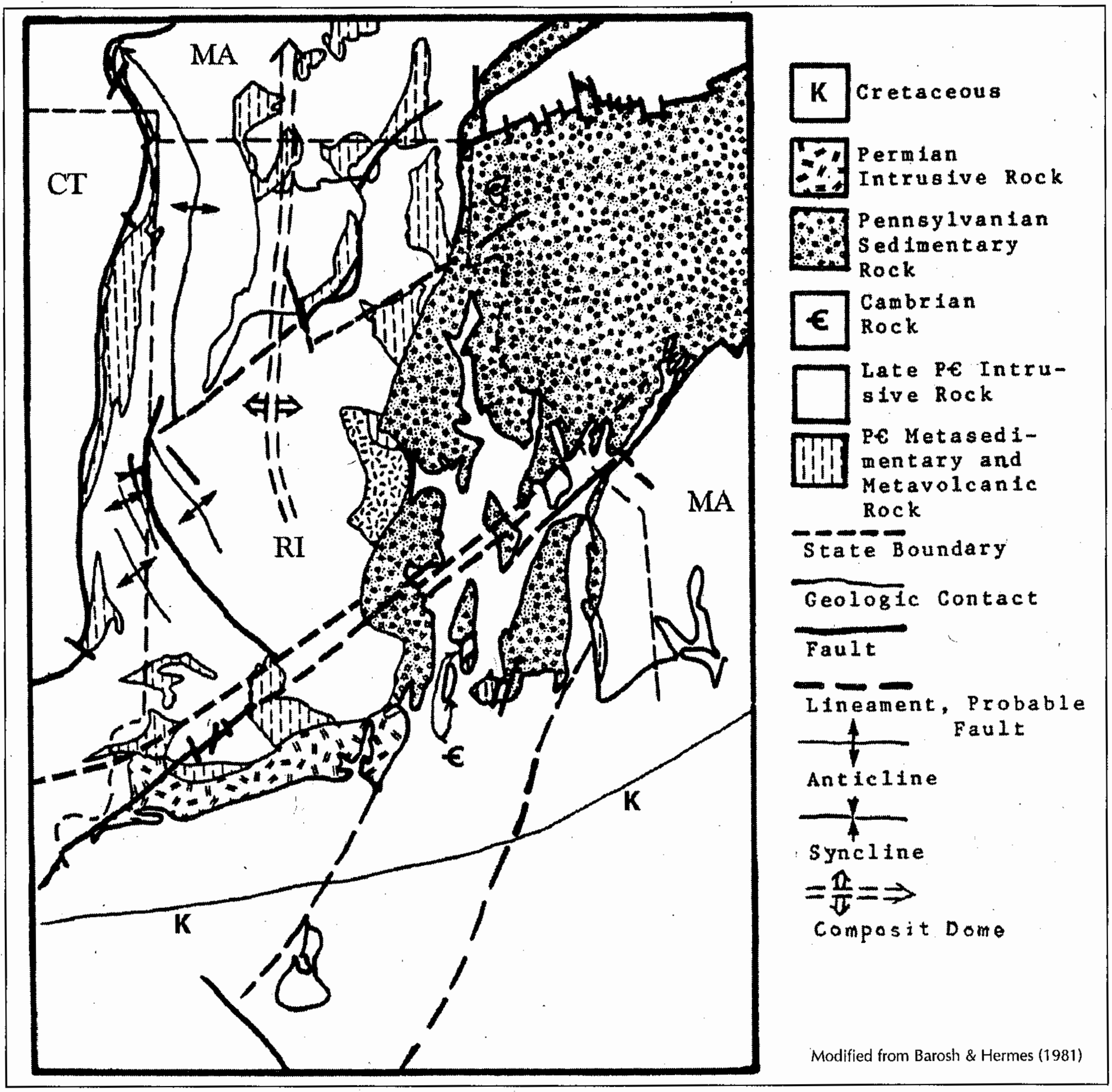


FIGURE 2-20. Sketch map of Rhode Island and vicinity showing major structural features.

volcanic centers and intrusions of different ages, and partially covered by sediment of a wide variety of ages. The sediment occurs chiefly in fault basins that include the latest Proterozoic Boston Basin, the Pennsylvanian Narragansett, Norfolk, North Scituate and Woonsocket basins, and various Mesozoic basins (see Figure 2-12). Remnants of Cambro-Ordovician overlap deposits and minor Siluro-Devonian redbeds, which may lie in another basin, also are present. Rock of this general age and type occurs in the Avalon Peninsula in Newfoundland as well, and the Southeast New England Batholith has been grouped with the Avalona Peninsula by some as the "Avalon Zone" or as a remnant of an ancient continent called "Avalonia." However, the granite and its relations are similar to Pan-African granite and this term is more explicit and can be used where a larger context is needed.

The volcanic pile is represented by moderate- to high-grade meta-sedimentary and meta-volcanic strata, which remain as xenoliths, large pendants and as a border of the batholithic complex. The border zone is chiefly developed around a semi-domal structure (see Figure 2-20) centered over western Rhode Island (Barosh & Hermes, 1981). The zone is narrow along southeastern and eastern Connecticut where it is cut off to the west by the Lake Char-Honey Hill fault zones, but it widens and spreads out across northeastern Massachusetts north of the Boston Basin. These strata grade upward from an intruded base of quartzite and interbedded quartz schist into a thick sequence of mafic volcanic rock. The quartzitic basal portion is mapped as the Plainfield Formation, Westboro Formation or lower Blackstone Series in Connecticut, Massachusetts and Rhode Island, respectively (Bell & Alvord, 1976; Barosh, 2005). This near-shore, laminated, thin-bedded light-gray to tan quartzitic unit is succeeded by a dark to light-gray metamorphosed sequence of amygdaloidal (filled almond-shaped vesicles) and massive mafic and minor felsic flows, pillow lavas, mafic pyroclastic deposits and ash-fall tuffs that form the Middlesex Fells Volcanic Complex in Massachusetts and, in Rhode Island, the upper Blackstone Series, which also contains a marble unit (Shaler *et al.*, 1899; Bell & Alvord, 1976; Quinn, 1971; Dennen, 1981). These strata are overlain northwest of Boston by an additional northwest-dipping sequence that wedges in southeast of the Bloody Bluff Fault Zone. It consists of an unnamed fine-grained volcaniclastic unit, the Greenleaf Mountain Formation of mostly amphibolite, and the Burlington Formation of impure quartzite, gneiss and amphibolite with some capping metaconglomerate (Bell & Alvord, 1976). The top is truncated by the Bloody Bluff Fault. The aggregate thickness of the total section (Bell & Alvord, 1976) northwest of Boston is 3,325 meters (11,000 feet), and at least 4,600 meters (15,000 feet) to perhaps more than 6,100 meters (20,000 feet) is preserved in Rhode Island (Quinn, 1971).

The Late Proterozoic batholithic complex that characterizes this region ranges from quartz-rich alaskite to diorite or gabbro (Quinn, 1971; Hermes *et al.*, 1981b). Light-colored granodiorite and quartz monzonite are the most common. The gabbro and diorite formed early and are present chiefly east of Milford where they show up as xenoliths and large pendants in the granitic rock (Crosby, 1904). They were locally mislabeled by Chute (1966 & 1969) south of Boston as the younger Salem Diorite. The granitic rock consists of a number of large bodies. The Northbridge Granite and Dedham Granodiorite form the extensive large bodies near Boston and several others are widespread in Rhode Island and adjacent Massachusetts and Connecticut (Quinn, 1971; Barosh *et al.*, 1977a; Barosh, 2005). These bodies may have a confusing number of names. The Northbridge, for example, was called provisionally the Ponaganset Gneiss in Rhode Island by Quinn (1971) and mistakenly the Milford Granite west of the Boston Basin by Emerson (1917). The granites tend to become finer grained toward their borders and may have locally preserved aplitic border zones, which have been described as separate plutons in places. The Dedham has undergone alteration of the original light-gray rock in most places, and consequently has developed a pinkish to salmon cast or pink and green mottling. Flow foliation and lineation increase toward the borders. Moderate to very strong flow foliation is found adjacent to the Nashoba Terrane, especially in Connecticut and Rhode Island, but to the east most granite is nonfoliated and can be fresh looking. The foliation is syntectonic, being the result of deformation while the granites formed and serves to demonstrate their close ages.

The granites are known to be pre-Cambrian from the overlying Cambrian strata and are older than the latest Proterozoic fill of the Boston Basin. Rock of the batholithic complex yield ages that generally range from 600 to 620 million years ago (Zartman & Naylor, 1984; Galloway 1973; Smith 1978; Hermes *et al.*, 1981b), but older ages occur and the ages are most likely between 620 and 630 million years ago (Zartman, 1976). However, experience has shown that dating these granites can prove difficult, as was the case of granites west of Boston that when dated (Thompson *et al.*, 1996) actually produced results nearly opposite the known sequence.

The batholith is overlain by scattered remnants of a transgressive overlap assemblage of lower Paleozoic strata described by Walcott (1891a & 1891b). Much of these remnants of Lower to Upper Cambrian strata of mostly argillite and siltstone are preserved at several locations around the Boston Basin. Also, altered shale and limestone with a thin basal quartzite occur over the granite near the northeast corner of Rhode Island (Shaler *et al.*, 1899). Additional shale with interbeds of siltstone, now metamorphosed to argillite or schist due to nearby Permian granite, is present at Jamestown, Rhode Island, in southwestern Narragansett Bay, where fossils were found by Trem Smith (Skehan *et al.*, 1977). A thick, white quartzite bearing Ordovician inarticulate brachiopods had formerly covered the Cambrian, but was almost all stripped off during Pennsylvanian time and now forms clasts in conglomerate of that age or reworked into Pleistocene and Holocene deposits.

The Cambrian strata also overlap the easterly trending fault trough forming the Boston Basin (see Figure 2-12). The basin contains a thick, barely altered, very Late Proterozoic section with a volcanic unit resting over the batholithic granite at the base and overlain by conglomerate that passes upward through an interfingering sequence into thin-bedded argillite, which contains minor quartzite and tuff beds near the top. The volcanic and conglomeratic rock is mostly terrestrial and the argillite marine in origin.

Late Ordovician (461 to 444 million years ago) alkalic granite plutons and a variety of associated rhyolitic flows and tuff mark a volcanic chain, extended north-northeastward across the region from Rhode Island to at least Cape Ann, north of Boston (see Figure 2-21). Another line of basic plutons extends northeast along the southeast side of the Bloody Bluff Fault Zone from west of Boston to Cape Ann, forming a lesser chain of basaltic cones (see Figure 2-17). The intrusive rock is not metamorphosed, only has flow foliation locally at its borders and tends to form circular bodies of several phases. The largest center is about Cape Ann, formed of Cape Ann Granite, which consists of several phases of quartz monzonite, and the approximately contemporaneous and highly-variable Salem Gabbro-Diorite (Toulmin, 1964; Bell & Dennen, 1972; Dennen, 1976, 1981, 1991a, 1991b & 1992). The several bodies of Salem Gabbro-Diorite that lie along the east side of the Bloody Bluff Fault Zone to the west of Boston display none of the intense flow foliation and shearing near the fault that is present in the older batholithic rocks (Barosh, 1977a, 1977b & 1984b). The associated volcanic rock comprises the Lynn Rhyolite, formerly called the Lynn Volcanic Complex or Series (Dennen, 1981 & 1991a), found around Lynn and Marblehead on the south side of Cape Ann (Warren, 1913; Dennen, 1981 & 1991a). The Lynn complex is composed of a wide variety of flow, ash-flow, tuff and agglomerate of intermediate to sialic composition, but chiefly rhyolite. The Lynn Volcanic Complex rests unconformably (Clapp, 1921) on the batholithic rock and has an estimated thickness of 600 meters (2,000 feet). Similar rhyolitic ash-flow tuff and flows are preserved around the Quincy Granite at another volcanic complex in the Blue Hills, which border the south side of the Boston Basin (Chute, 1969; Sayer, 1974; Kaktins, 1976; Naylor, 1981; Kaye, 1982a). These formations are described with the Boston Basin rock. Some siliceous pyroclastic tuff, which occurs to the southwest in Medfield (Volckmann, 1977) may be part of it or possibly correlate with the latest Proterozoic Boston Basin volcanic fill. An additional volcanic center to the southwest forms the circular Rattlesnake pluton that is composed of different intrusive phases, but has lost its cover of volcanic rock (Lyons & Krueger, 1976).

Similar small granite plutons occur in northeastern Rhode Island, and the East Greenwich Group forms a much larger complex in west-central Rhode Island (Quinn *et al.*, 1949; Quinn & More, 1968; Quinn, 1971). The group consists of rhyolitic flows, tuff and breccia around a center of Cowesett Granite and related granite. These granites contain only a minor amount of riebeckite, but are otherwise similar to the riebeckite-bearing Cape Ann and Quincy granites. The Cape Ann Granite dates at 450 (±25) million years ago, which is the Middle-Late Ordovician boundary, and the Quincy Granite has a similar 430-457 million years ago age, which places them in the Late Ordovician (Zartman, in USGS, 1967; Zartman & Marvin, 1971; Dennen, 1991a). These findings are consistent with their relations with fossil-bearing stratigraphic units. The Cowesett Granite, and associated volcanic rock in Rhode Island, have been dated as Devonian by Hermes *et al.* (1981b);

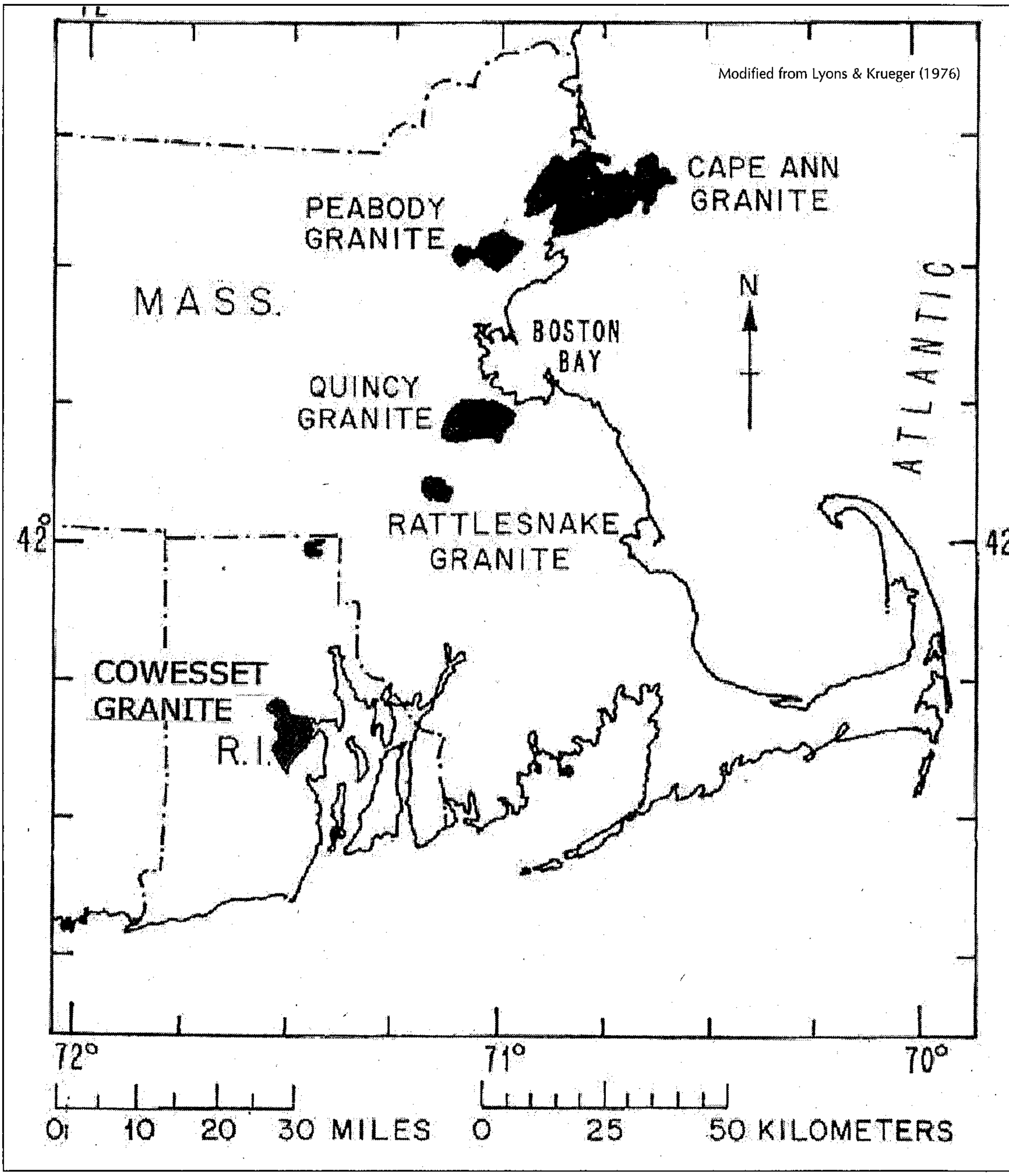


FIGURE 2-21. Areal distribution of Late Ordovician alkalic granite in southeastern New England.

however, they also dated the nearby Scituate Granite as Devonian. This foliated granite is clearly part of the Late Proterozoic batholith, so the dating or sampling is in error. Other batholithic granite in southwestern Rhode Island that was previously dated as Devonian (Moore, 1959) is found to consist of a mixture of Late Proterozoic and Permian rock (Hermes *et al.*, 1981a).

The unmetamorphosed Late Silurian-Early Devonian (423 to 416 million years ago) volcanic-redbed sequence, present in the Newbury Basin in the Nashoba Terrane, also is represented in this terrane by the small remnant mentioned in northern Massachusetts (Bell *et al.*, 1977 & 1993) that Dennen (1981) thought was a fault basin. Volcanic rock in the Norfolk Basin, south of Boston, has been dated as Devonian (Maria & Hermes, 2001). However, these rhyolite and basalt flows are interbedded with terrestrial red mudstone, siltstone, sandstone and conglomerate of the Wamsutta Formation, which is part of the fossiliferous Pennsylvanian sequence (Knox, 1944; Lyons *et al.*, 1976). Until stratigraphic studies separate this rock from the Pennsylvanian strata, the Devonian dating remains very doubtful. In any case, the Wamsutta is an early fill in the Norfolk Basin.

The fault-bounded Norfolk and Narragansett basins south of the Boston, along with the smaller North Scituate and Woonsocket basins to the west of them (see Figure 2-22), are filled with a thick succession of terrestrial conglomerate, sandstone, shale and some coal of Pennsylvanian age (Shaler *et al.*, 1899; Quinn & Oliver, 1962; Oleksyshyn, 1976; Lyons, 1978; Lyons *et al.*, 1976). The sequence has been described as a basal Pondville Conglomerate (Bellingham Conglomerate in the western basins), overlying redbeds of the Wamsutta Formation, followed by the Rhode Island Formation of generally gray shale and sandstone with some coal and great lenses of a higher Purgatory Conglomerate, and topped by the Dighton Conglomerate. The Pondville consists of interfingering lenses of conglomerate and sandstone. And at least some of the higher conglomerate is fault repetition, indicating a much more detailed study of the structure and stratigraphy is needed. The total thickness is estimated (Shaler *et al.*, 1899) to be about 3,660 meters (12,000 feet), but the evidence for this estimate is weak (Quinn, 1971).

The conglomerate was shed into the basin from the rising borders to interfinger with the finer deposits formed along southwest-flowing rivers and backwaters in a valley system similar to and contemporaneous with ones in basins in Maritime Canada (Ballard & Uchupi, 1975; Oleksyshyn, 1976; Lyons *et al.*, 1976, Towe, 1959). The Canadian basins lie along the same trend to the northeast and there may be considerable intervening offshore basins. The basin fill in Canada began earlier in the Pennsylvanian (Lyons *et al.*, 1976) and has similar underlying Mississippian deposits. This evidence suggests that southeastern New England was either higher or eroding in the Mississippian or that the deposits are buried below the Pennsylvanian strata. The Narragansett deposits had far more extensive distribution in the past, and extend westward into the Sturbridge Terrane where the Worcester exposure lies.

The southwestern shore of Rhode Island, adjacent Connecticut and eastern Long Island are underlain by the nonfoliated Narragansett Pier Granite and by its late dike phase, the Westerly Granite and pegmatite dikes (Quinn, 1971). Late pink pegmatite dikes, identical to the late-stage pegmatite associated with this granite, are found scattered northward across the region into New Hampshire (Barosh, 1984a; Hermes *et al.*, 1981a) and westward to beneath western Long Island (Barosh, 1991). Southern Rhode Island has suffered more erosion than to the north and shows the irregular roof of the granite to dip gently to the north. These granites intrude Pennsylvanian strata and are generally considered Permian in age, yet yield a variety of radiometric dates that range from Early Permian to Late Triassic (Quinn, 1971). Note is made that K/Ar radiometric dates can be restarted by high temperatures. No related volcanic rock is known.

The Carboniferous strata (see Figure 2-4) are metamorphosed to upper amphibolite facies in the southwestern part of the basin adjacent to the Permian Narragansett Pier Granite (Shaler *et al.*, 1899; Quinn, 1971; Hermes *et al.*, 1981a; Hepburn & Rehmer, 1981). The grade of metamorphism decreases to the north away from the granite (Shaler *et al.*, 1899; Quinn, 1971) and represents a complex contact metamorphism during which two separate thermal events may have occurred (Hepburn & Rehmer, 1981). All of Rhode Island and eastern Massachusetts were heated enough to reset K/Ar dates to about 240 million years ago, which is Middle Triassic (Zartman *et al.*, 1970; Day *et al.*, 1980; Dallmeyer, 1981), far beyond where the rock is noticeably altered. The metamorphism and intrusion are undoubtedly part of the same event with the high temperature just preceding the granite.

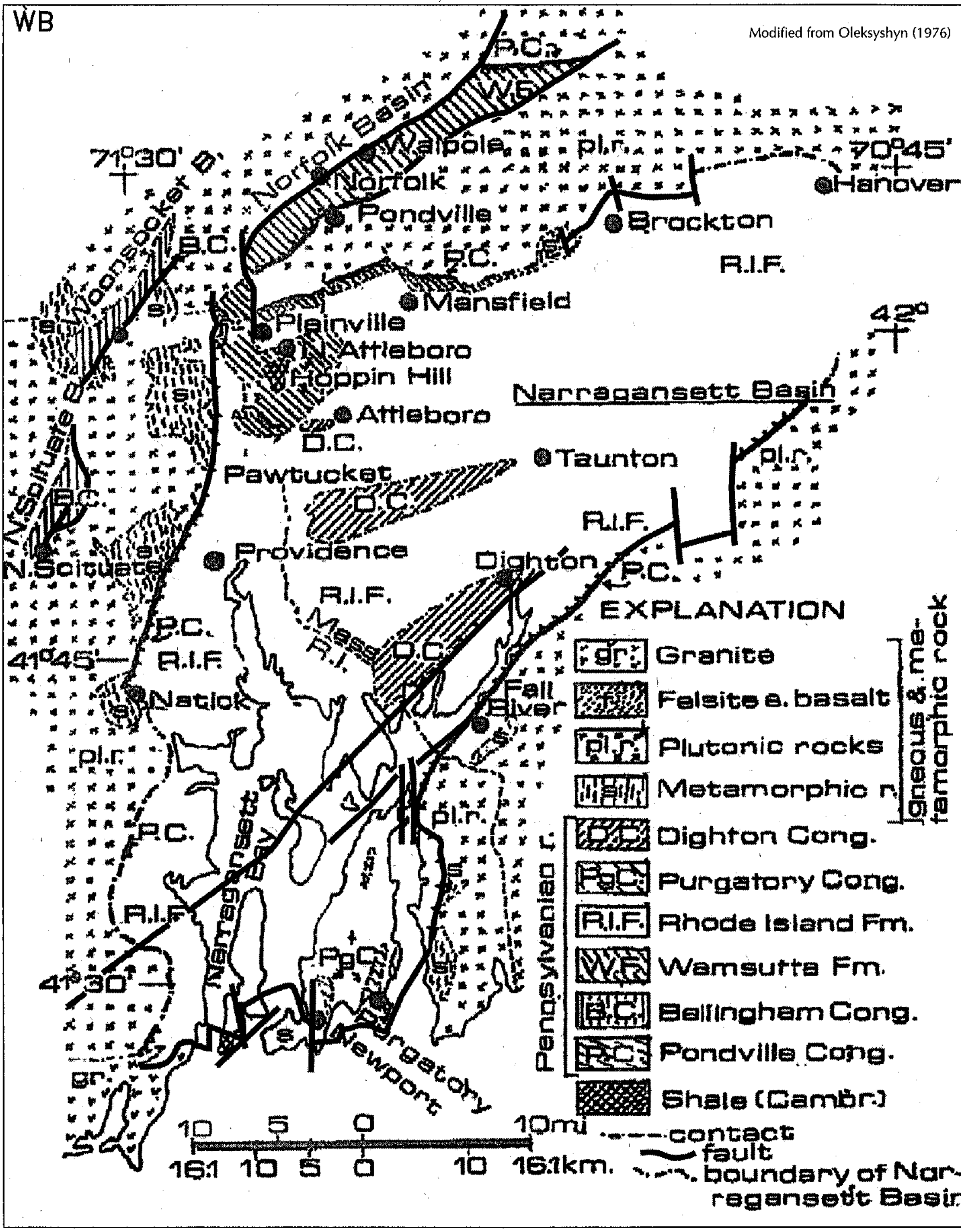


FIGURE 2-22. Map showing basins of Pennsylvanian terrestrial strata in Rhode Island and adjacent Massachusetts.

Some complexities are probably mainly due to irregularities along the shallow northward-dipping surface of the granite.

The structure of the area is varied and complex. The Southeast New England Batholith is syntectonically folded along its northwest side

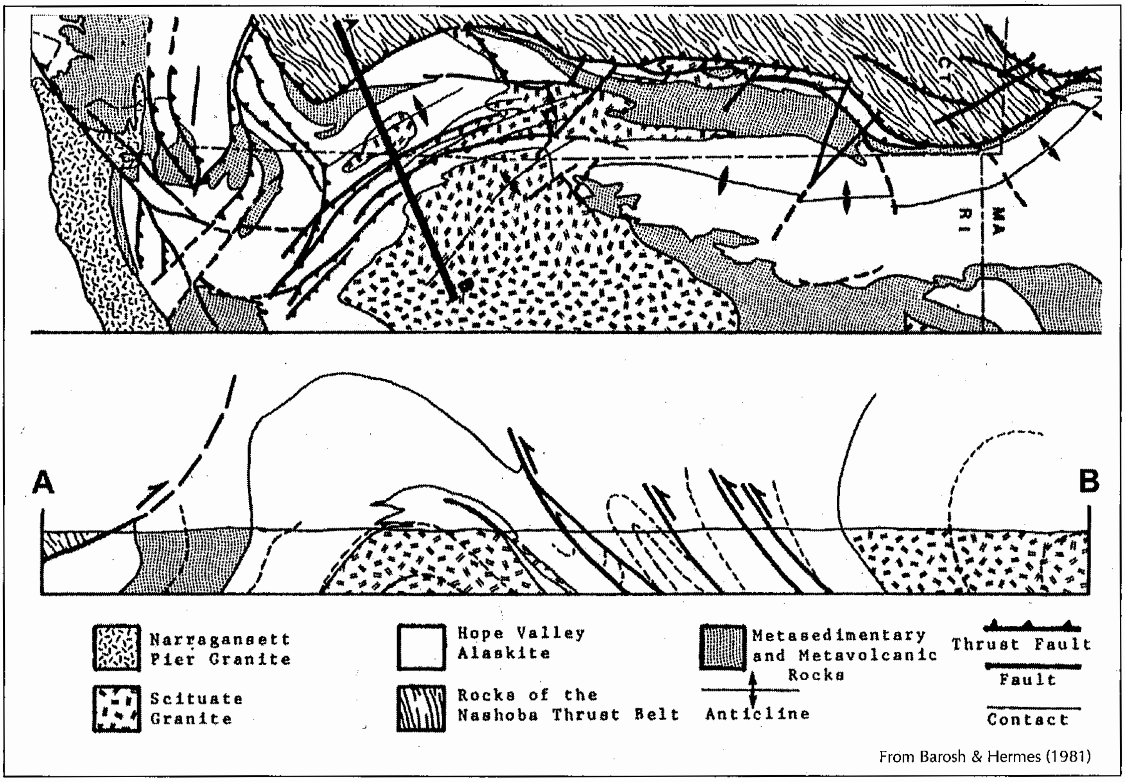


FIGURE 2-23. Sketch map and section of the West Rhode Island Fold Belt.

against the Nashoba Thrust Belt in Rhode Island and Connecticut (see Figures 2-12, 2-20, 2-21, 2-22 & 2-23) and the rock is strongly foliated, sheared and folded adjacent to the Bloody Bluff-Lake Char-Honey Hill Fault System (Feininger, 1965; Barosh *et al.*, 1977a; Barosh & Hermes, 1981; Barosh, 2005 & 2009; Smith & Barosh, 1983). A series of north-trending, north-plunging syntectonic folds, designated the West Rhode Island Fold Belt (Barosh 1972 & 1976b; Barosh & Hermes, 1981; Hermes *et al.*, 1981a), lie along the Connecticut-Rhode Island border (see Figures 2-23 & 2-24). These folds are broad and open in the north, but become progressively more compressed to the south where they are overturned and broken by thrust faults, which tend to cut out the synclines (Feininger, 1965; Barosh, 1972). One of these faults that was mapped by Barosh *et al.* (1974 & 1977b; Barosh & Hermes, 1981) was proposed to be a plate boundary called the "Hope Valley shear zone" (O'Hara & Gromet, 1985), but all the mapping shows it to have the same rock on either side and the fault dies out to the north at the southern edge of Massachusetts (Barosh, 2005) and terminates southward against a fault in southwestern Rhode Island. The western part of the fold belt swings southwest and west approximately parallel to the Honey Hill Fault Zone in southeastern Connecticut where the folds are all overturned and dip to the northwest. The eastern part swings to the southeast across southwestern Rhode Island where the folds are overturned and dip to the northeast. Both the northwest- and northeast-dipping overturned folds and associated thrust faults merge northward and apparently formed at the same time. The folds are described by both the flow foliation in the granite and the bedding of the invaded metasediment (Feininger, 1965; Barosh, 1972 & 2005), demonstrating both rocks deformed together against the underside of the thrust belt as the granite formed in the Late Proterozoic. The folds broke with further compression in the latest Proterozoic and Ordovician. The degree of metamorphism and deformation increases to the south where the

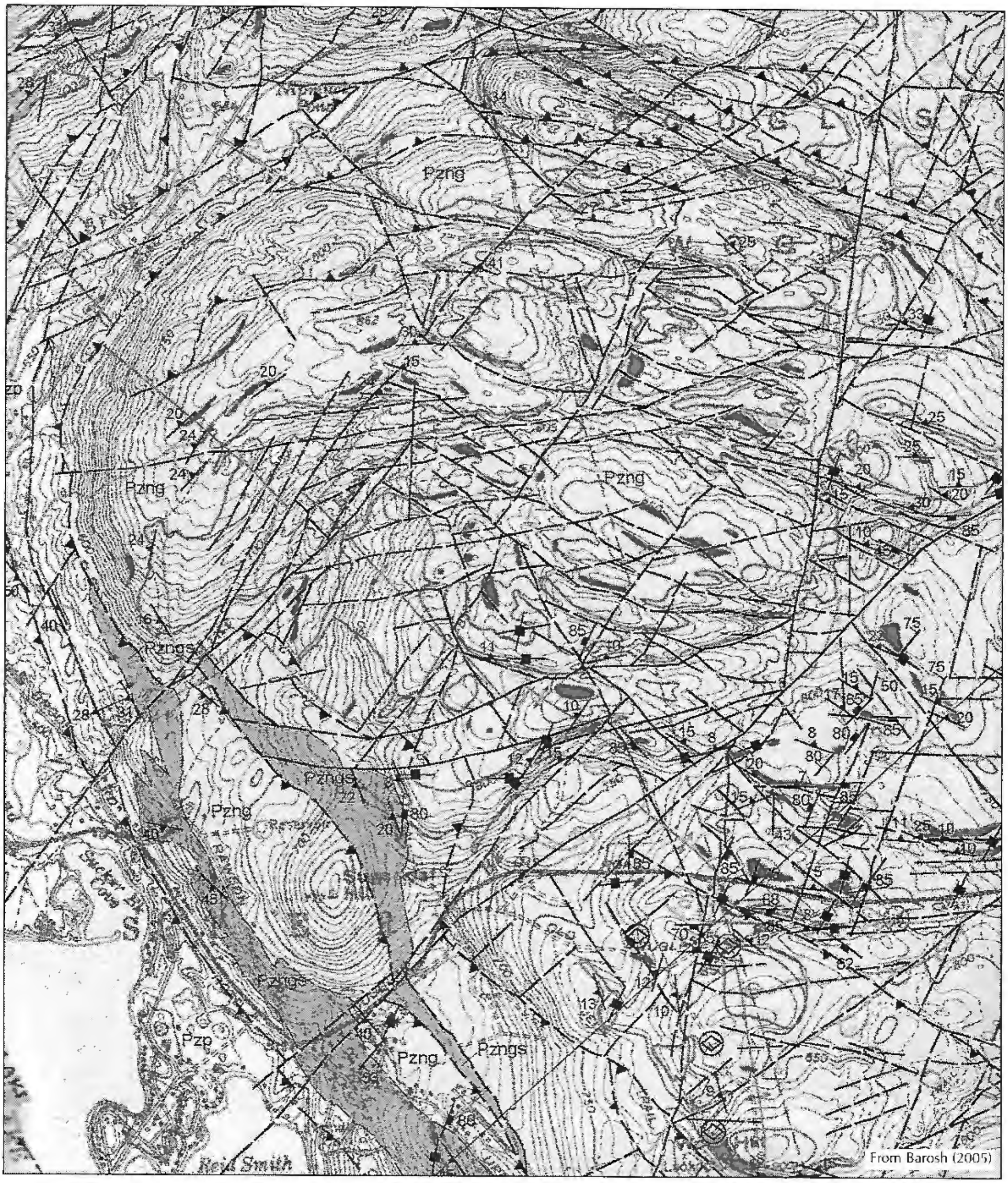


FIGURE 2-24. Anticlinal nose at the north end of the West Rhode Island Fold Belt consisting of highly faulted Late pre-Cambrian Northbridge Granite and intruded metamorphic strata, southern Massachusetts just north of the northwest corner of Rhode Island.

rock was originally deeper. The gentle north plunge of the lineation in the granite that formed parallel to the fold axes also shows the present north tilt of the structure. The West Rhode Island Fold Belt ends to the north just inside Massachusetts, where the Nashoba Thrust Belt changes direction from the north to the northeast (see Figures 2-1 & 2-12). This shift is apparently due to later overlap of the folds northward by relative southeast move-

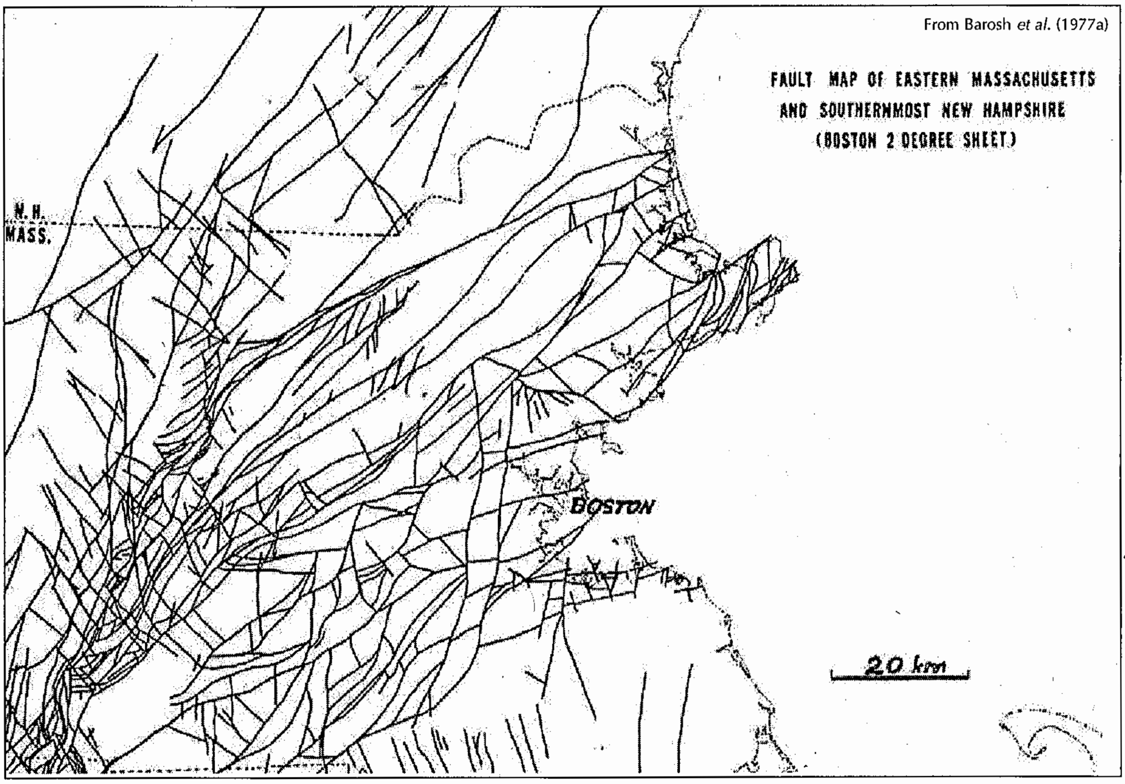


FIGURE 2-25. Map of eastern Massachusetts and southern New Hampshire showing mapped faults.

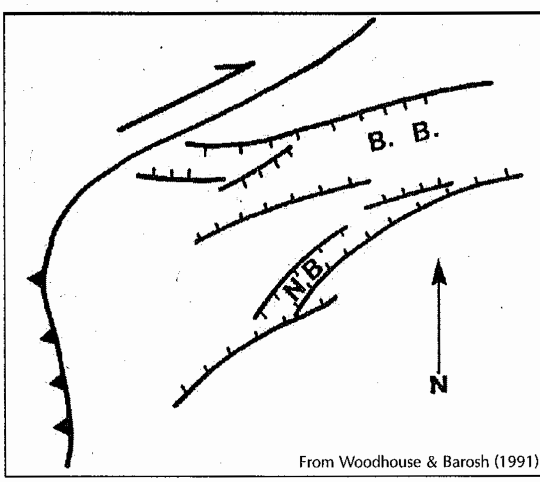


FIGURE 2-26. Sketch map showing structural relations of the Boston (B.B.) and Norfolk (N.B.) basins with the eastern edge of the Nashoba Thrust Belt.

ment along the Bloody Bluff Fault Zone during the Ordovician. Farther north, the batholithic complex is foliated and sheared adjacent to the thrust belt rather than folded, and less deformed in general.

Several northeast-trending fault zones are indicated to cross the Rhode Island Dome by coinciding topographic, aeromagnetic and gravity lineaments (Barosh, 1972 & 1986a; Schwab & Frohlich, 1979). The distribution pattern, attitudes and magnetic characteristics of the Blackstone Series where crossed by these fault zones suggest each has a few kilometers of right-lateral offset and the southernmost one, the Queen River fault, extends from southeastern Connecticut and cuts off the domal structure to the south (see Figure 2-20). The aggregate number of these and later faults results in the Proterozoic basement being extremely faulted. At least seven fault sets are seen to cut well exposed rock (see Figure 2-24) near the northwest corner of Rhode Island into small blocks (Barosh, 2005) similar to the mosaic of faults cutting the Nashoba Terrane to the north (Bell & Alvord, 1976) and where there is structural control in the Boston Basin and good exposures on the surface (Crosby, 1880; LaForge, 1932; Kaye, 1980a; Ross & Bailey, 2001) and in tunnels (Barosh & Woodhouse, 1990; Stone & Webster, 1995).

Several east-northeast- to northeast-trending fault basins are dropped into the eastern portion of the terrane and more are indicated offshore (Ballard & Uchupi, 1975). They may be part of an early fault system that reactivated at different times. The controlling faults end to the west (Barosh, 1977a) against the Bloody Bluff-Lake Char fault zones (see Figure 2-25). Their orientation may have been controlled by right-lateral movement (Barosh, 1984a) along the Nashoba Terrane (see Figure 2-26) or by the earlier east-west oriented collision. Extension across such faults apparently controlled the early volcanism in the Boston Basin and also may have possibly controlled the later nearby Late Ordovician granite plutons.

Faults of the northeast-trending Norfolk Basin to the south merge with those along the southeastern side of the Boston Basin and could be reactivated ones (Barosh, 1995). The Norfolk and the North Scituate, Woonsocket and Narragansett basins all appear to have their greatest offset along their southeast sides. The northeast side of the Narragansett Basin is a faulted depositional contact. Some of the faults in the basin have Mesozoic movement and the degree to which they represent reactivation of original basin faults is unknown. The northern part of the Narragansett Basin exhibits (Shaler *et al.*, 1899) a few broad east-northeast-trending bands of strata interpreted as large open folds (see Figure 2-22), but gravity profiles (Sherman, 1978) and evidence of faults (Barosh, 2006b & 2006c) indicates some if not all are fault blocks. Small isoclinal to recumbent north-northeast-trending folds, some of which are overturned, occur locally in the southern part of the basin. These folds have been interpreted by some workers to represent multiple episodes of regional deformation (Burkes, 1981). However, the folding appears to be highly irregular, local and not to affect the adjacent older rock. Also, the style of the regional Permian-Triassic Narragansett Pier Granite intrusion into these rocks does not indicate any regional compression (Hermes *et al.*, 1981a). Furthermore, the rock in the basin exhibits considerably soft sediment deformation and there is evidence for a great deal of sliding along the coal seams in this area (Rabin, 1981). Most folds can thus be accounted for by internal movement in gliding along the coal seams. However, the deformation shown by the stretched clasts in the conglomerate and some broad folds at the southwestern edge of the Narragansett Basin is compressional. The strike of the stretched pebbles and small faults around southern Middletown, Rhode Island, trends northerly and they show west over east movement, as do a few small thrust faults to the east. These structures pre-date the Narragansett Pier Granite.

Mesozoic & Cenozoic Geology

A new system of structures and basins developed across the terranes as the North Atlantic Basin was initiated about 235 million years ago and developed later in the Mesozoic as Pangea broke up. These structures transcended the terrane divisions discussed above and the region behaved as a single unit. Normal faults, graben basins and dikes, largely controlled by earlier faults, formed in the Late Triassic-Early Jurassic under the initial extension and under north-south compression. Then fresh systems of faults and basins developed as the new edge of the present North American continent formed and sagged downwards. The changes reflect the early faults rotating out of the line of the active stress system as the Atlantic widened and were replaced by new more compatible structures (see Figure 2-27). Some of the zones of these later faults are the landward extensions of structural adjustments within the North Atlantic that control a late Mesozoic volcanic chain and present-day earthquakes. Southeastern New England presents the best expression of these post-Paleozoic features on the East Coast.

Many Late Triassic-Early Jurassic terrestrial basins are present onshore and offshore as part of a northeast-trending system connecting those of the Mid-Atlantic (Ballard & Uchupi, 1975; Kaye, 1983a) with the Fundy Basin of Nova Scotia (see Figures 2-12 & 2-28). Most of the onshore basins are small north-

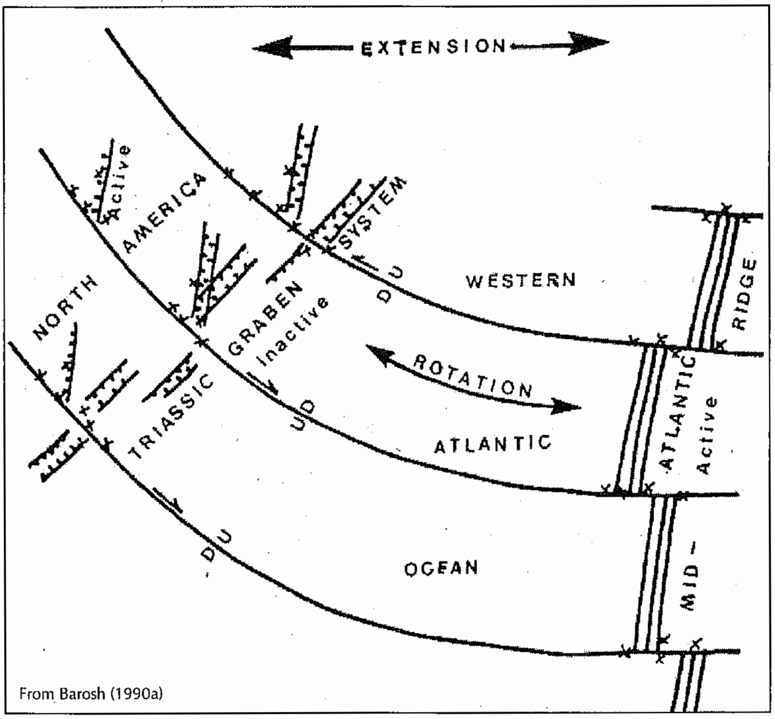


FIGURE 2-27. Diagrammatic sketch showing relations of the Triassic grabens with the plate boundary at the Atlantic Ridge and the later Jurassic and younger grabens that developed due to rotation of the North American Plate. X marks the location of an earthquake.

east-trending ones (see Figure 2-29). The large north-trending Hartford Graben is a prominent exception, due to control by an older fault along the west side of the Bronson Hill uplift, although the great majority of the numerous small faults within the graben trend to the northeast. The displacement in the Hartford Graben is mainly along its eastern side and is essentially a half graben as are some of the others. The other basins are controlled by older faults as well, such as the small Middleton Basin northwest of Boston where red conglomerate, sandstone and siltstone form a fault sliver within the Bloody Bluff Fault Zone (Kaye, 1983a; Barosh, 1984b) northwest of Boston (see Figure 2-29). Other such small basins probably lie undiscovered. The fill of the Hartford Graben, as in the others, consists of chiefly red to chocolate brown mudstone, siltstone, sandstone and minor pebble conglomerate. A volcanic vent against the southeast side of the graben fed three composite basalt flows that mark the basal Jurassic part of the section. These basalts flowed generally eastward (Gray, 1982) toward the active border fault. Graben basins of Late Triassic to Early Jurassic red clastic rock and basalt lie offshore buried beneath the thick glacial outwash sands and gravels of Cape Cod and coastal plain deposits (Ballard & Uchupi, 1975) and have been reached by drill (Folger *et al.*, 1978) on Nantucket Island (see Figures 2-12 & 2-30). Similar grabens lay farther offshore to the north and northeast. These basins were contiguous with a similar cluster of basins off Morocco (see Figure 1-2). Pollen and spores date the Hartford Graben deposits from early Late Triassic to at least middle Early Jurassic, approximately 227 to 195 million years ago, although the Fundy Basin to the northeast may have begun in the latest Middle Triassic (Traverse, 1987).

Other northeast-trending normal faults in the region and earlier thrust faults, which reactivated as normal faults, are apparently also of this age. One of these zones, the Watch Hill Fault Zone that extends from eastern Long Island to Cape Cod Bay, has been mapped in detail (see Figure 2-23) through southwestern Rhode Island (Moore, 1967; Smith & Barosh, 1981; Frohlich, 1981; Hermes, *et al.*, 1981a). Red sandstone float has been found near the Watch Hill Fault Zone on Long Island and it can be dated to early Mesozoic as it cuts Permian or Triassic granite and is offset by many later Mesozoic or younger faults. The fault continues as a zone of *en echelon* segments northeastward across Narragansett Bay, through Fall River, Massachusetts, and along the southeast side of the Narragansett Basin. The bay changes both

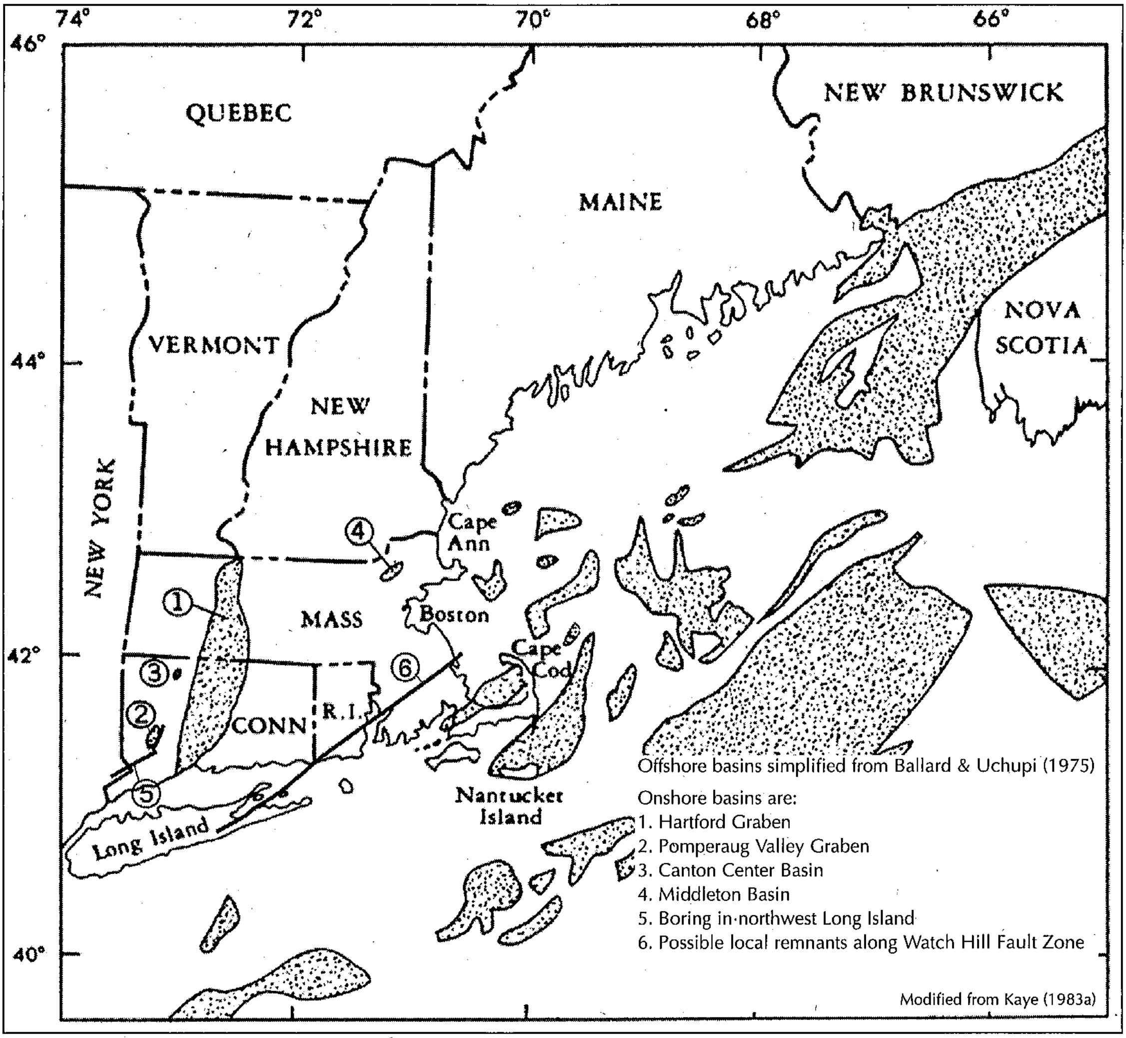


FIGURE 2-28. Map of New England showing locations of basins containing the Upper Triassic-Lower Jurassic Newark Group (stippled) and Watch Hill Fault Zone.

shape and trend where it is crossed by the fault (see Figure 2-22), which is expressed by a zone of geophysically defined faults (Collins & McMaster, 1978). A horst of Proterozoic granite, within the Pennsylvanian strata, lies between the overlapping ends of two en echelon segments (Barosh, 2006a & 2006b) in Bristol, Rhode Island (see Figure 2-30). The Pennsylvanian Dighton Conglomerate in the basin is repeated by the Watch Hill Fault Zone (see Figure 2-22).

Additional northeast-trending faults that cut the Pennsylvanian strata of the Narragansett and Norfolk basins appear to have Mesozoic movement as well. The northeast-trending faults indicated by the aeromagnetic trends in the largely covered region southeast of the Narragansett Basin (Barosh *et al.*, 1977b) also may have moved then. A fault cutting the northwestern side of the Norfolk Basin continues northeastward into Boston Harbor. This fault and the Watch Hill Fault to the south bracket the Pennsylvanian strata and appear to be the southwestern counterpart of the Fundian Basin to the northeast (see Figures 2-22 & 2-28).

A new set of north-trending normal faults and grabens developed across the region in the mid-Mesozoic and cut the earlier northeast-trending faults, but lack onshore deposits. Several of the grabens form a zone

(see color version on page 450)

FIGURE 2-29. Fault slice of Late Triassic redbeds, the Middleton Basin, in the Bloody Bluff Fault Zone, bordering dark Late Proterozoic volcanic rock mined in the SanVal Quarry, Middleton.

from Lake Champlain to Lake George. The Narragansett Bay Graben (Collins & McMaster, 1978; McMaster *et al.*, 1980), shown in Figure 2-31, and the Assawompset Graben to the east (Koteff, 1964a) formed onshore in southeastern New England and the north-trending Hartford Graben may have reactivated. Some of these extension faults have very wide silicified zones, such as those along the Thames River in Connecticut (Goldsmith, 1985), Diamond Hill at the northwest side of the Narragansett Basin and the east side of Bristol, Rhode Island (Quinn, 1971), besides numerous small en echelon zones, with staggered alignment, within Narragansett Bay. The islands and channels in Narragansett Bay reflect the horst and graben system well. A clear example is the Sakonnet Channel of eastern Narragansett Bay where drilling shows a submerged down-dropped block of Pennsylvanian strata within Proterozoic granite (see Figure 2-32), which is exposed onshore (Upson & Spencer, 1964; Barosh, 2006c).

Both of these fault trends control dike emplacement across the region. Small Mesozoic diabase dikes are ubiquitous in the region and lamprophyre dikes are found locally. Generally, they are poorly exposed, but the large ones are well expressed by their magnetic properties (Snyder, 1970) and are commonly seen in tunnels (Crosby, 1904). A long northeast-trending dike system, the Higganum Dike, contains diabase up to 30 meters (100 feet) thick and extends from the southeast side of the Hartford Graben northeastward to New Hampshire. It has been dated to 200 million years ago and is similar in age to the flows in the graben. The Higganum Dike apparently follows a deep structure, but there is little evidence that it follows any significant surface fault zone. Numerous small northeast-trending diabase dikes are found across eastern Connecticut and central Massachusetts, but farther eastward northerly trends are the most common. A large mafic intrusion of possible Mesozoic age with a northward elongation is interpreted from gravity and magnetic data to underlie the western side of Cape Cod, and magnetic highs indicate that there are many other large north-trending dikes onshore, as well as offshore of southeastern Massachusetts (Barosh, 1976a; Barosh *et al.*, 1977b). These include the diabase encountered by deep drilling on Nantucket (Folger *et al.*, 1978). These fresh diabase dikes are seen in tunnels around Boston where they follow north-trending faults and may suffer from later fault offset (Crosby, 1904; Kaye, 1982b; Barosh & Woodhouse, 1990). Several diabase dike sets of various trends occur in central New England northwest of Boston (McHone, 1978, & 1984; McHone & Butler, 1984).

High-angle northwest-trending faults developed both about the same time and later than the north-trending ones and these two sets are the youngest ones found in New England (Barosh, 1986c & 1992). Numerous small faults of these two sets occur throughout the region. Many appear to cut the Higganum Dike (Sawyer & Carroll, 1979), more offset the Watch Hill Fault Zone (Frohlich, 1980 & 1981;

FIGURE 2-30. Map of Mount Hope Bay in northeastern Narragansett Bay showing Mesozoic faults, including northeast-trending segments of the Watch Hill Fault Zone and other north- and northwest-trending faults.

Barosh, 2006b) and some apparent Jurassic structures northwest of Boston (Kaye, 1984a). A few scattered east-west Mesozoic faults also are present in the region, but these may be slightly older.

Nonfoliated circular granitic plutons and associated volcanic rock form remnants of a northwesterly trending volcanic chain that developed along eastern New Hampshire and in southwest Maine during the Jurassic and Early Cretaceous (Eby, 1987). A few related felsic dikes occur in northeastern Massachusetts and the southernmost volcanic neck of this chain may lie just offshore of Cape Ann (Boston Edison Company, 1976a; Barosh, 1992). These plutons occur at intersections of the northwest and north-trending faults (see Figure 2-33), interpreted from aerial photographs, in southern Maine and New Hampshire (Barosh, 1986f & 1992) and are cut by them as well (Freedman, 1950). This volcanic chain apparently is related to the plutons forming the New England Seamounts farther offshore to the southeast (see Figure 2-8).

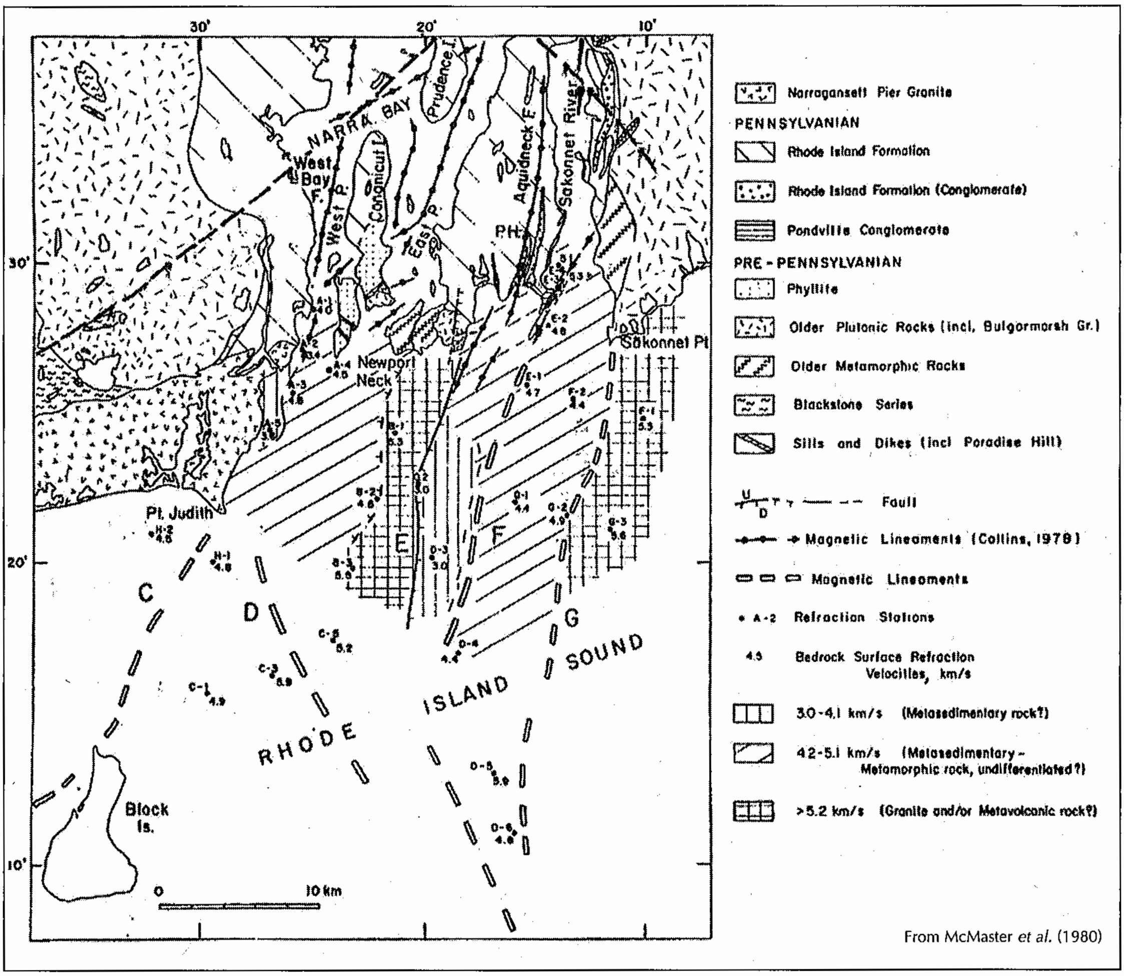


FIGURE 2-31. Geologic map of southern Narragansett Bay and adjacent offshore area.

When the Late Triassic grabens subsided to the east as the Atlantic Basin grew, they first received saline deposits and then were overtopped by a seaward thickening wedge of late Mesozoic and Tertiary deposits, which lie just offshore and are part of the submerged northeast extension of the Atlantic Coastal Plain (see Figure 2-34). A nearly continuous sequence from Middle Jurassic to upper Tertiary is present offshore (see Figure 2-35), but where it laps onto the coast it is interrupted by many unconformities due to many fluctuations of the shoreline (Gibson *et al.*, 1968; Jansa *et al.*, 1979; Valentine, 1981; Grow, 1981), which creates an irregular partial sequence at the inner edge. The inner edge of the strata turns eastward in Raritan Bay at New York City to run beneath northern Long Island under thick glacial deposits. The Upper Cretaceous deposits lie just offshore of Rhode Island where their inner margin forms a northward-facing *cuesta* (O'Hara, 1980). This inner contact swings northward across western Cape Cod beneath a cover of glacial outwash and continues to north of Cape Ann, where the deposits become thin and patchy off New Hampshire (Weed *et al.*, 1974). Cretaceous clays and sands are exposed at a few places on Block Island where they may be in place, and Cretaceous and Tertiary deposits are exposed at Martha's Vineyard to the east where they have been thrust up by glacial action (Kaye, 1964a & 1964b). Small areas of Eocene and Miocene sand and silt occur onshore near the coast in the vicinity of Marshfield, south of Boston. These areas remain the only Tertiary outcrops known on the mainland; those near

Scituate correlate with the Gardiner's Clay in New York (Kaye, 1983b).

These changes in direction of the inner contact of the coastal plain deposits are at least partially structural. Broad transverse arches and swales across the Coastal Plain have long been recognized south of New England by the relative thickening and thinning of the deposits along strike and changes in the coastline. The swales cause the coast to be embayed and the embayments at Raritan Bay and the New Hampshire coast also show evidence suggesting that there is relatively more local down-warping (Barosh, 1986b). Also, the outward curve across Cape Cod may be enhanced by arching. The boundaries between the arches and embayments are aligned with northwest-trending fracture zones offshore and differential movement appears to be taking place across their landward extensions, which tend to be earthquake prone (Barosh, 1986c & 1990a). These northwest-trending fracture zones are referred to as transform fracture zones in the North Atlantic Basin and are due to spatial adjustments as the ocean basin widens.

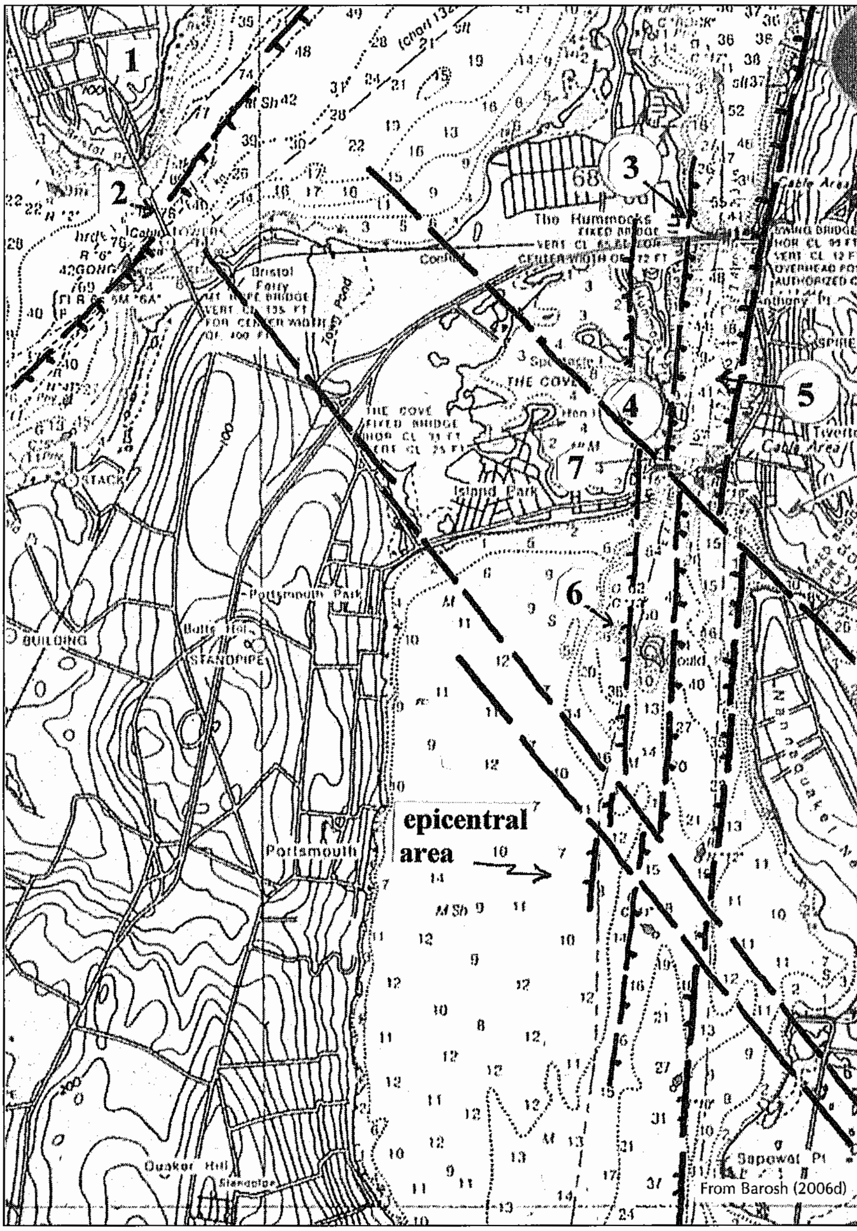


FIGURE 2-32. Map of the Sakonnet River, eastern Narragansett Bay, showing the epicentral area of the 2001 Sakonnet earthquake, the north-trending Sakonnet Graben and the northwest-trending Four-Corners Fault Zone, which is indicated to be active.

The Cretaceous strata are cut by a north- to northwest-trending fault, the New Shoreham Fault, offshore south of Rhode Island (McMaster, 1971) and faults of similar trends onshore (Hermes *et al.*, 1981a) and in lower Narragansett Bay (McMaster *et al.*, 1980) are probably related (see Figures 2-20 & 2-31). The

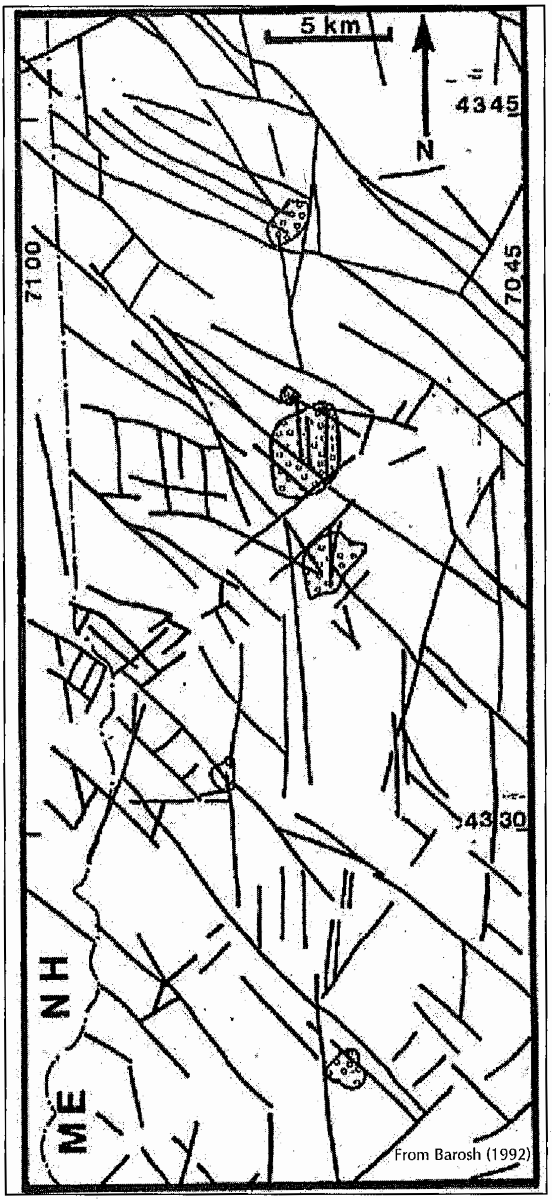


FIGURE 2-33. Map of the New Hampshire-central-west Maine border showing topographical lineaments, which result from at least small Mesozoic faults, and Mesozoic plutons.

New York Bight Fault, farther west, south of western Long Island, cuts Tertiary deposits (Hutchinson & Grow, 1982). Some of the high-angle faults that cut the Tertiary deposits at Marshfield and on Martha's Vineyard appear tectonic in origin and are not due solely to glacial action (Kaye, 1983c).

Repeated Pleistocene glaciations smoothed the general landscape while etching out the fault-controlled valleys and leaving behind a complex cover of till, glaciofluvial and glacio-lacustrine deposits. However, these deposits were eroded by each subsequent glaciation and the record is generally restricted to those of the last event. The last Wisconsin ice sheet covered the entire region and extended off-shore to the east. Extensive outwash plains and moraines developed across Cape Cod and nearby islands near its southern terminus (see Figure 2-36). The southernmost stand resulted in a thick outwash laid down across the edge of the Coastal Plain deposits of Long Island and the islands to the east while the shoreline was farther off to the south (see Figures 2-37 & 2-38). An ice front melted back in stages and a stand in Cape Cod Bay deposited outwash deposits of several hundred feet thick on outer Cape Cod and a significant thickness over southeastern Massachusetts as well. A further retreat to coastal Connecticut-Rhode Island left a depression in Long Island Sound that filled to form a great freshwater lake that drained to the east. Thereafter, as the ice melted back, a complex and often bewildering variety of till, drumlin, esker, outwash, delta and lake clay, sand and gravel deposits were laid down. Each pause in the ice front as it melted and retreated northward resulted in sequences of many types of outwash, delta and lake deposits forming in the shallow valleys (see Figure 2-39) while marine clays were deposited along the shore. Usually the deposits are thin, although they are quite variable in thickness onshore. Little geologic change other than man's activities and the filling of many low-land areas by lake and swamp material has affected the area since the retreat of the ice. This situation makes for highly variable ground conditions that may change over short distances and be full of surprises. For example, occasional readvances might re-shape a variety of deposits into drumlins, such as the large drumlin of outwash sand at Walpole, Massachusetts, and the mixed deposits of the Beacon Hill drumlin in Boston. (These very complex glacial deposits due to the interplay of glacial events and sea-level

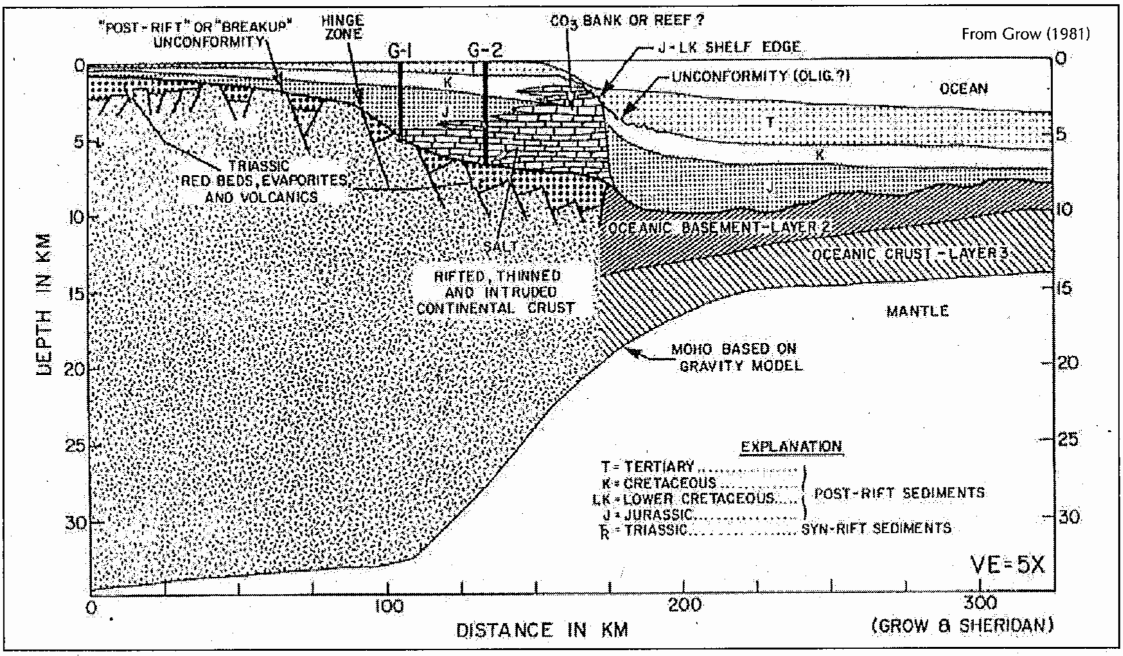


FIGURE 2-34. Composite geologic section across the southwest end of Georges Bank offshore of southeastern New England.

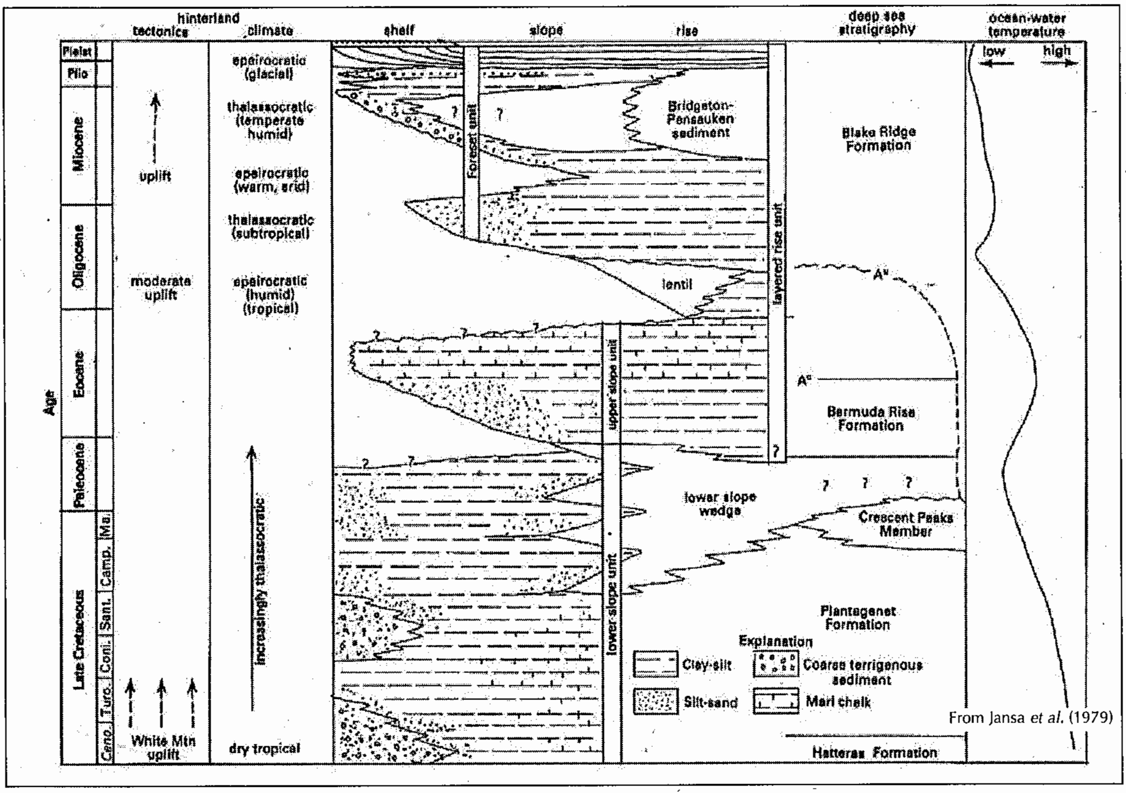


FIGURE 2-35. Schematic stratigraphic relations of Cretaceous and Tertiary strata offshore of New England and the Boston Coastal Plain Margin.

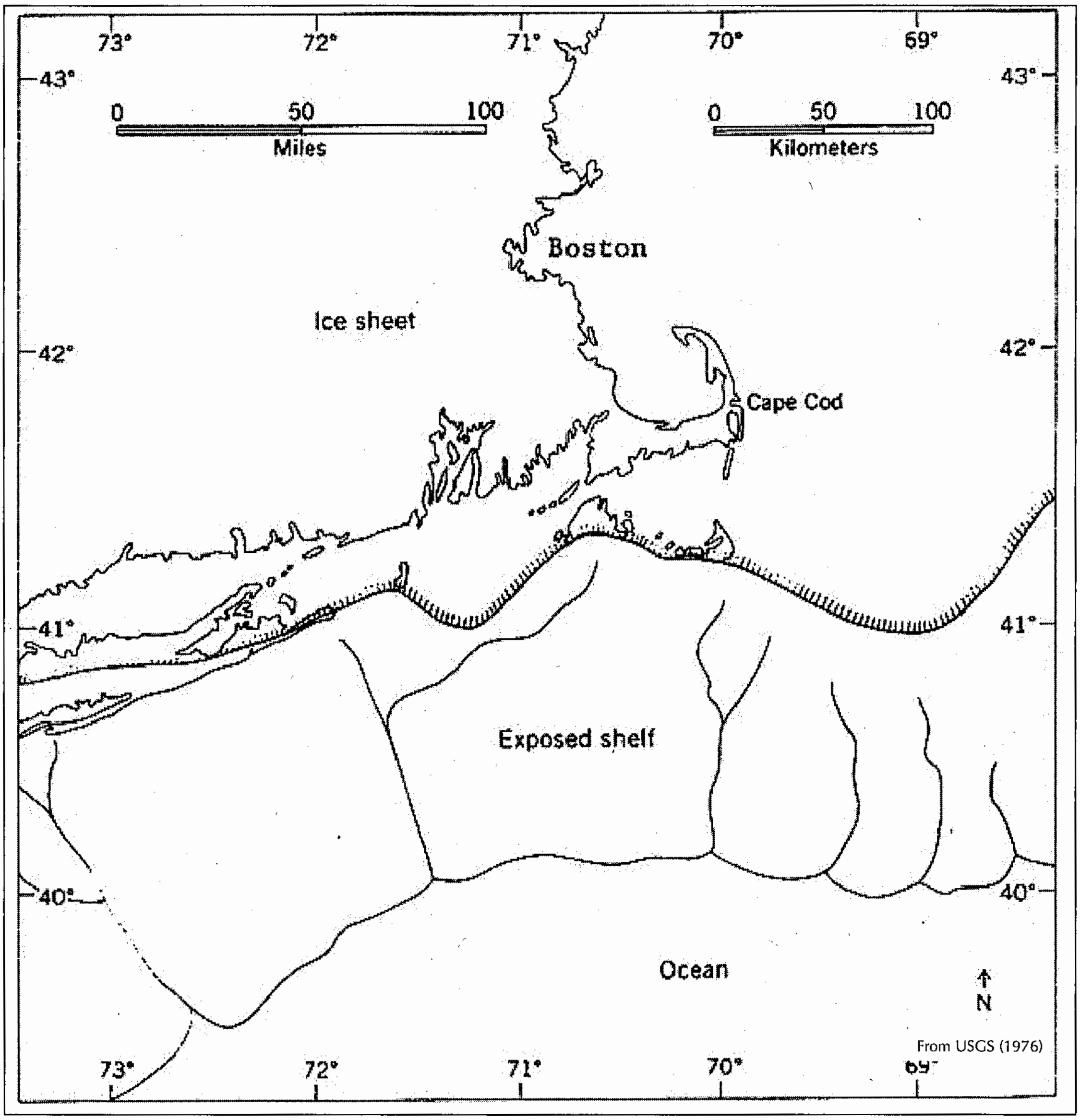


FIGURE 2-36. Map of southeastern New England showing the maximum southward extension of the glacial ice, outwash deposits and shoreline between 18,000 and 25,000 years ago.

changes in the coastal region are described in a section on the Boston Basin.)

Neotectonic Movement & Seismicity

The tectonic activity initiated in the Mesozoic continues to operate, albeit at a lesser magnitude than in the past, and the East Coast is affected by neotectonic movement causing earthquakes. The common labeling of the region as the "passive" edge of the continent in contrast to the Pacific side is a misnomer because it remains tectonically active. This movement is related to the continued opening of the North Atlantic Basin along the Mid-Atlantic Ridge and clearly seen where it is exposed in Iceland. The crust is spreading at an average rate of about 2.5 centimeters (1 inch) per year along the ridge (Kiou & Tilling, 1996) where much of the movement is extensional (Kristansson, 1974), but some lateral, as well as vertical, movement occurs along the oceanic fracture zones, which are transverse

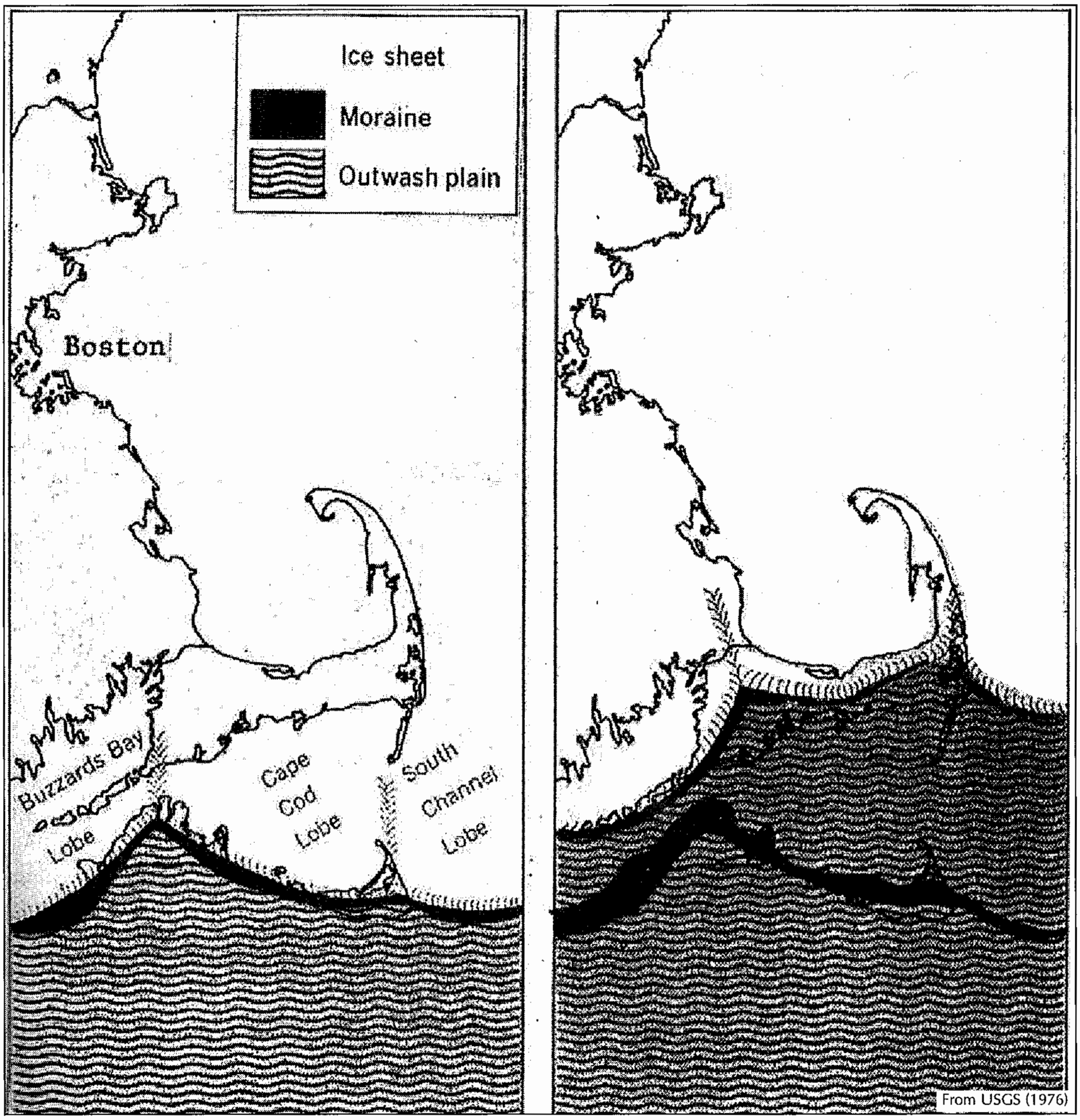


FIGURE 2-37. Map of southeastern Massachusetts showing the last glacial retreat and the moraines formed on Martha's Vineyard, Nantucket and Cape Cod.

structural zones, along which adjustments are made in response to the spreading (see Figure 2-7). The landward response to this movement in New England is activity along many of the northwest-trending zones of faults, although thus far only rare specific active faults are identified (Barosh, 2006b & 2006c).

The current crustal movement in New England is a composite of several causes that need be sorted out, and single measurements or approaches provide scant information. The recognized causes are (see Figure 2-40): regional tilt, transverse arching and subsidence, sagging of the continental edge, and fault offset (Barosh, 1989 & 1991). However, glacial rebound is over in this region. Unraveling these different causes is further confused by sea-level rise from the melting of ice and thermal expansion, residual strain release, and freezing and thawing.

The most obvious recent changes in eastern Massachusetts are due to the general rise in

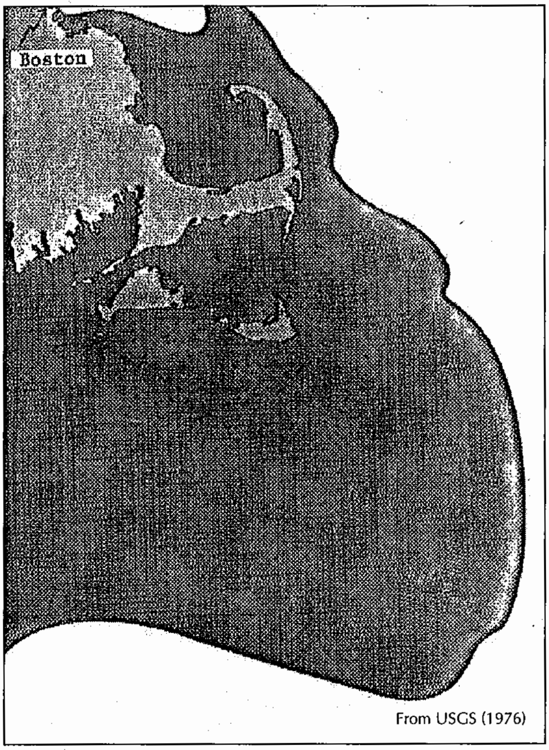


FIGURE 2-38. Map of southeastern Massachusetts showing positions of the shoreline at the end of the Pleistocene and at the present.

sea level and post-glacial isostatic rebound (see Figure 2-41). The rise in sea level has long been noted from its effects on the shoreline and early man-made structures (Sears, 1894 & 1895). Tree stumps are exposed at low tide along the New Hampshire coast and barrier beaches at Duxbury and Castle Neck, south and north of Boston, respectively, where the sea has moved inland, crossing over estuary deposits. Calculating the rate of the general sea-level rise is compromised where data are obtained from deposits that may have been compressed and give too high an estimate or when neotectonic movement is ignored. The world-wide rise in sea level as measured by satellite since 1993 is 3 millimters (0.1 inch) per year, or 30 centimeters (1 foot) per century (Carpenter, 2008). Deviations from this rate are due to the other factors listed above. Recent predictions of an increased 1 to 1.5 meter (3 to 5 foot) rise over the next century have yet to show up in any measurements.

Crustal rebound from the melting of the glacial ice mass and the springing back of the compressed rock has caused uplift and a tilting to the south across New England and adjacent Canada. The tilt, which results from more ice having been to the north and a greater compression there, forms a slope of roughly 1 meter rise for every kilometer northwards (4 feet per mile) as measured from glacial lake shorelines. The uplift caused the relative sea level to fall 83 meters (272 feet) in 2,500 years, from a high stand of nearly 33 meters (108 feet) above present mean sea level about 14,500 years ago to a low of –50 meters (–164 feet) at 12,000 years in northeastern Massachusetts (Oldale *et al.*, 1993). The rising ocean from glacial melting and the southward tilt of the land are in equilibrium just south of Boston, where the Late Pleistocene and the present sea level match (see Figure 2-38). The old shore is deeply submerged to the south and fishermen occasionally snag tree stumps on the bottom. Just recently, cypress tree fragments were recovered from borings for proposed wind turbines south of Cape Cod. The Pleistocene shoreline steadily rises north of Boston to about 250 meters (820 feet) near the St. Lawrence River. This rebound appears to have ended long ago near Boston and is estimated to have terminated about 11,500 years ago along the Maine coast (Stuiver & Borns, 1975; Stuiver *et al.*, 1978), although it may still be occurring farther north in Canada. Since then, the rise in ocean level has dominated the shift in the shoreline.

A seaward tilt of the edge of the continent began by about the Middle Jurassic (176 million years ago) as it sagged into the opening North Atlantic Basin and the subsequent weight of the resulting Coastal Plain deposits (which had been eroded from the land to the west) and advancing ocean water exacerbated the movement. The Coastal Plain deposits tilted seaward with the movement and the New England Seamounts were deeply depressed. These seamounts were volcanoes at the surface near the continental border southeast of New England during the Eocene, and now lie as much as 1,830 meters (6,000 feet) beneath sea level (O'Leary, 1984), which demonstrates the subsidence since the early Tertiary. The

Atlantic is still indicated to be widening and sediment continues to be carried offshore, so some degree of oceanward tilt should still be occurring.

An additional regional northerly tilt also has affected the Coastal Plain deposits along the entire East Coast. This tilt results in their uplift in the southeast United States and their plunging northward beneath the sea in New York. The tilt began in the Cretaceous and the increase in elevation with the age of the deposits at the southern end of the Appalachian Mountains records its progress. The tilt raises the coral and shell platform of Florida and then lowers New England to provide its famed rocky shores. The amount of subsidence is difficult to measure in New England due to the disturbance of the submerged Coastal Plain by glaciers, but it appears reflected in the greater rate of present sea-level rise recorded in the Canadian Maritimes than in southern New England.

The previously mentioned transverse embayments along the inner Atlantic coastline mark areas where subsidence has been more active. By Late Cretaceous time, the axes of these basins became oriented to the northwest and their positions appeared to be controlled by underlying northwest-trending fracture zones aligned with the major oceanic fracture zones (Barosh, 1981a, 1981b, 1986d & 1990a). The embayments are continuing to subside and have seismicity associated with them. This activity is less obvious in the embayed coast of New Hampshire and south-

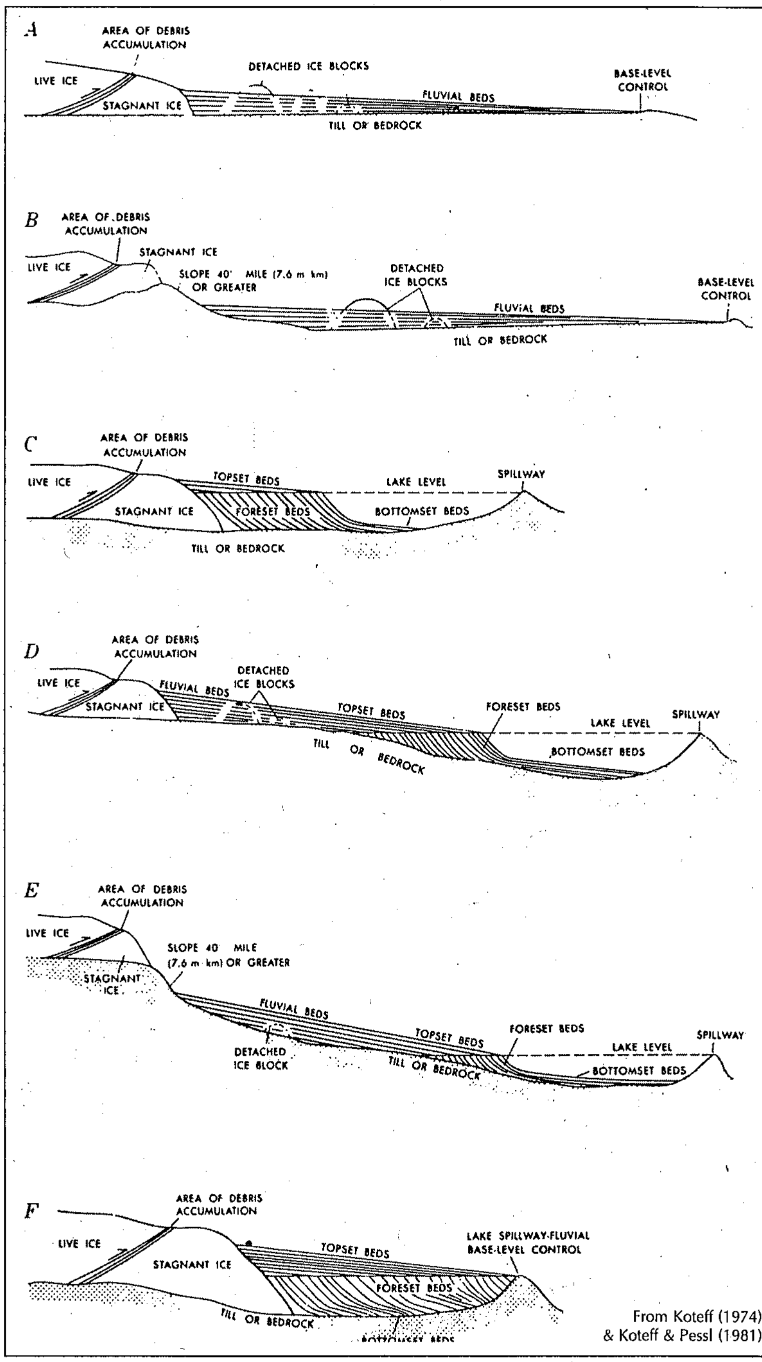


FIGURE 2-39. Diagrammatic profiles of typical sequences of glacial lakes and their deposits present in the valleys of southeastern New England that were deposited near the ice front.

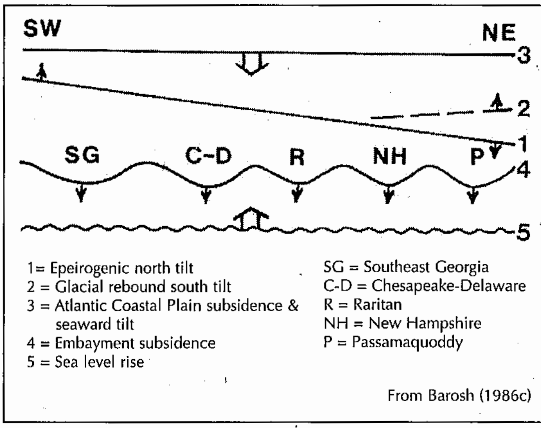


FIGURE 2-40. Schematic diagram showing present-day relative crustal movements and sea-level change along the East Coast of the United States. Arrows represent the relative direction of movement.

ern Maine, north of Cape Ann, than to the south, but it was subsiding 3,400 to 3,250 years ago (Harrison & Lyon, 1963) and the present subsidence is indicated to be perhaps one-third to two-thirds of a meter (1 to 2 feet) per century (Tyler & Ladd, 1981; Smith, 1982). This broad embayment, which contains thin remnants of Cretaceous and Tertiary sediments just offshore (Weed *et al.*, 1974), encompasses the Cape Ann seismic area and the sites of the 1727 and 1755 earthquakes.

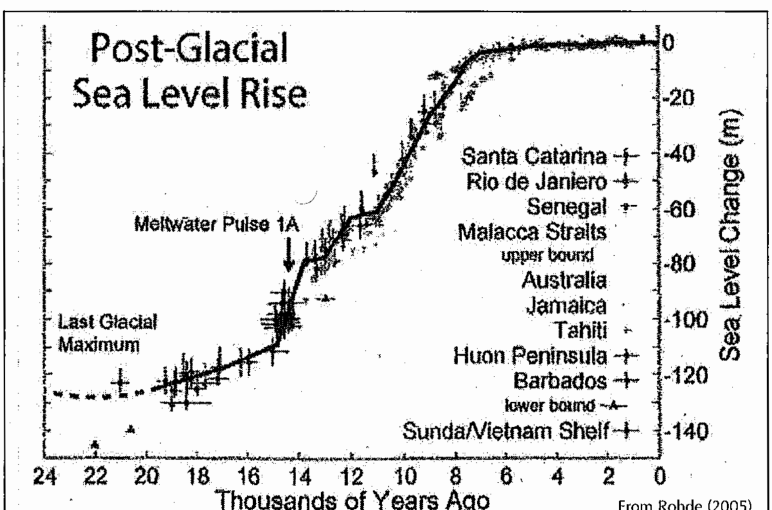


FIGURE 2-41. Global sea-level rise associated with the melting of ice after the last glacial advance.

The glacial rebound is finished and the general northerly and seaward tilts along the East Coast apparently are too slow to cause noticeable seismic activity and too broad to cause concentrations of activity. Thus, it is the subsidence in the northwest-trending embayments and in a few lesser associated north-trending grabens, such as Narragansett Bay and Lake Champlain, that correlate with the seismicity. This finding matches the one that post-Early Jurassic northwest- and north-trending faults form the youngest fault sets across New England.

Seismicity. New England is a region of moderate seismicity, experiencing an earthquake every few days, although most are very small (see Figure 2-42). This rate of activity is at least an order of magnitude less than that for Southern California (Devane & Holt, 1967). The distribution of activity, however, is highly variable within the region. Some areas are quite active, whereas others are nearly aseismic. Northeastern Massachusetts is one of the relatively more active areas and the Boston area has been damaged by earthquakes in 1638, 1669, 1727 and 1755. The greatest earthquake recorded for New England occurred northeast of Boston, offshore of Cape Ann, in 1755. This event had a probable epicentral intensity of VIII on the Modified Mercalli (MM) scale. Its description by Winthrop in 1757 was the first earthquake depicted in a modern straightforward manner without a strong religious bias of "God's just punishment of we all-too-mortal sinners."

The recording of earthquakes began early and these records provide the basis in revealing their cause. Roger Williams's mention of three strong earthquakes felt by the Indians in the ninety years prior to 1643 in southern New England may rank as the first short catalog that was followed by more extensive ones before 1900 (Brigham, 1871; Lancaster, 1873), along with short

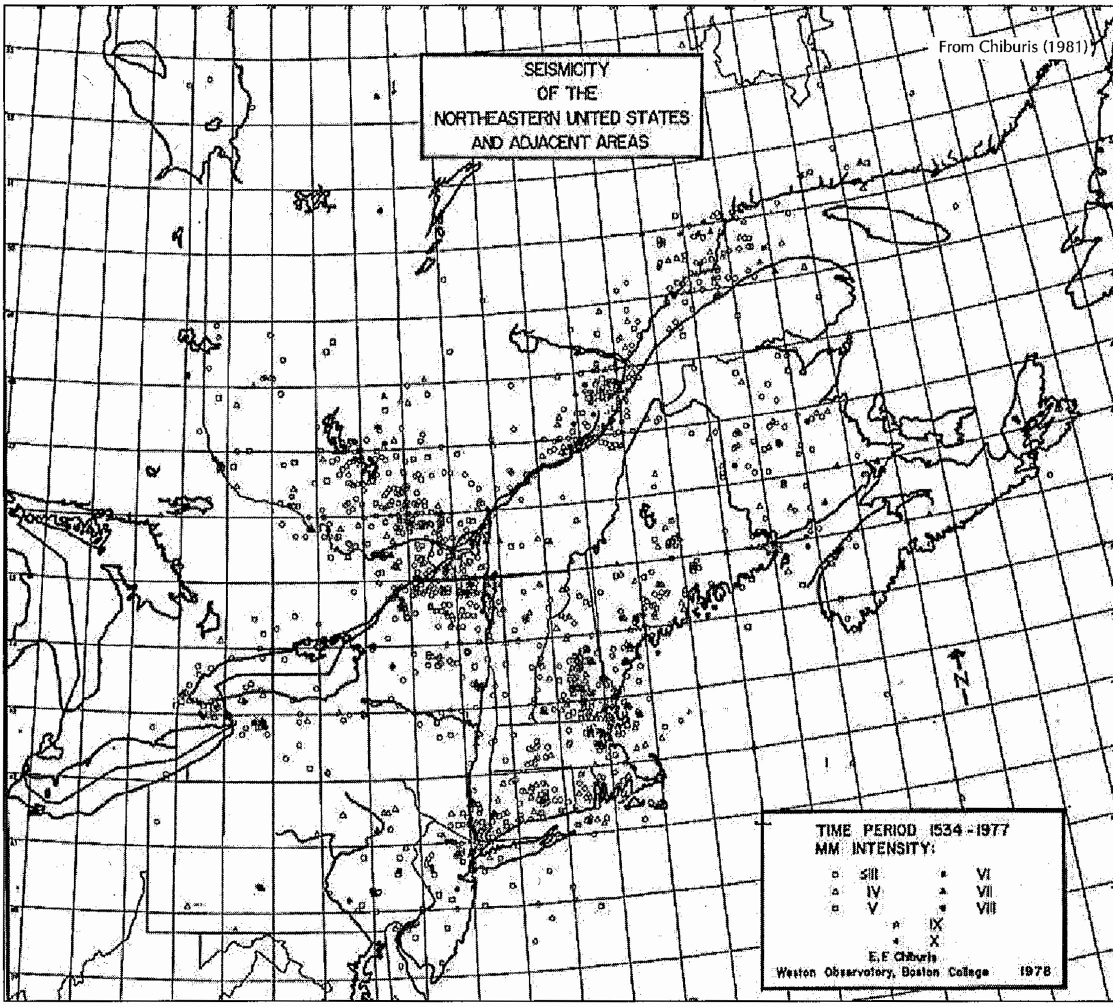


FIGURE 2-42. Map showing the seismicity of the northeastern United States and adjacent Canada from 1534 to 1977.

studies of a few individual earthquakes. De Montessus de Ballore (1898, 1906) assembled epicentral maps of the United States that Hobbs (1907) used to demonstrate the structural relations of earthquakes in the northeastern United States. This study was followed by the start of routine reporting of earthquakes of the region by the U.S. Coast and Geodetic Survey, the initiation of a seismograph network, more detailed descriptions of earthquakes and their effects, and a much better description of the distribution of earthquakes in the New England regions and adjacent Canada (Heck & Epply, 1958; Brooks, 1959; Smith 1962, 1966a & 1966b). Boston was placed in an unwarranted high hazard category (Heck, 1938) due to an error that placed the 1755 earthquake within metropolitan Boston (Devane & Holt, 1967). A study of many of the historic earthquakes of southern New England to improve intensity assignments and epicentral locations, as well as to assemble isoseismal maps, was a major contribution in the investigations for the Pilgrim Nuclear Power Plant site at Plymouth, Massachusetts, and the nuclear plant site at Seabrook, New Hampshire (Boston Edison Company, 1976a, 1976b & 1976c; PSNH, 1980). The Northeastern U.S. Seismic Network of the Weston Observatory, the Masscuhsetts Institute of Technology and the Lamont-Doherty Laboratory began a much needed expansion in the

1970s to improve the accuracy of epicentral locations for the detection of nuclear blasts and nuclear power plant safety. A vastly improved epicentral map and earthquake catalog up to 1980 was then produced for the Nuclear Regulatory Commission for the Northeast (Nottis, 1983). A new epicentral map added locations to 1998 (Wheeler *et al.*, 2000), but in magnitude values rather than in the more useful intensity values and at too small a map scale to be helpful. Recent epicenters are posted now on the Internet by the Weston Observatory and the USGS.

All of these records show well the locations of the larger earthquakes and point out the seismic source zones in the region, but the distribution of the small earthquakes can be misleading. Funding cuts have reduced the number of seismic stations in the Northeast and the unequal distribution of stations is reflected in the unequal distribution of the numbers of small earthquakes recorded. Many such events are recorded in the environs of New York City by a cluster of stations, whereas the single station in the region around Rhode Island misses many and makes determining accurate locations difficult. For example, a recent Rhode Island earthquake was mislocated (Barosh, 2006b) by 16 kilometers (10 miles).

Regional Distribution of Seismicity. The earthquake record for New England is the longest and most complete in the United States and displays several features. During the past four hundred years, earthquakes have been concentrated in certain areas, whereas other areas have remained very quiet. The instrumental record from the expanded seismic network shows the same pattern as the earlier felt events (Barosh, 1979b). The rate of activity within the more active areas may change from time to time (Shakal & Toksoz, 1977), but the areas have not. Thus, the record indicates that significant earthquakes occur in just certain areas and not just anywhere. Many of the scattered earthquakes outside these areas are shown to be spurious (Nottis, 1983) or frostquakes (Barosh & Smith, 1979 & 1982; Barosh, 1999b). The general active zones of the eastern United States were broadly outlined by Hadley and Devine (1974) by contouring the numbers of earthquakes per unit area (see Figure 2-43). The areas of relatively higher seismicity were next delineated in more detail (see Figure 2-43) by arbitrarily defining areas of MM intensity V and above (Barosh 1979b, 1981b, 1982c & 1982d). These areas were confirmed by Chiburis (1981) in a more statistical manner (see Figure 2-44) and reconfirmed by Ebel (1984) using only the post-1978 earthquakes. The general areas of relatively high activity appear well defined on detailed maps and as earthquakes become better located, the size of these source zones tends to diminish, but not always. These clusters of epicenters identify the major source areas in the region.

The seismically active area of greatest concern to Boston and the surrounding urban area is that centered near Cape Ann, to the north and northeast of the city. Other nearby active areas are located in Narragansett Bay and adjacent southeastern Massachusetts, around Moodus in south-central Connecticut and along the Merrimack River valley and central part of New Hampshire. The more distant La Malbaie area on the St. Lawrence River, northeast of the city of Québec, is by far the most active area in the broader region and the site of the largest earthquakes (Smith, 1962; Chiburis, 1981; Nottis, 1983), which have caused damage in the Boston area (see Figure 2-44).

The earthquakes tend to be very shallow and, as a consequence, produce noises. Most of those whose depths have been determined are less than 10 kilometers (6 miles) and many are of only a few kilometers. A suggestion that the larger, more destructive earthquakes were much deeper (Acharya, 1980a & 1980b) has not proven to be so (Stevens, 1981). The shallow nature of the seismicity and the generally moderately to steeply dipping geologic structure indicates that the seismicity should be closely related to the surface geology, which is indicated by its relation to geomorphic features, which are structurally controlled. Most of the earthquakes in the northeastern United States and adjacent Canada are concentrated (see Figures 2-43 & 2-44) in bays, river estuaries and along a few north- and northwest-trending river valleys. The great majority occur in lowlands, below 300 meters (984 feet) altitude, with some upland activity taking

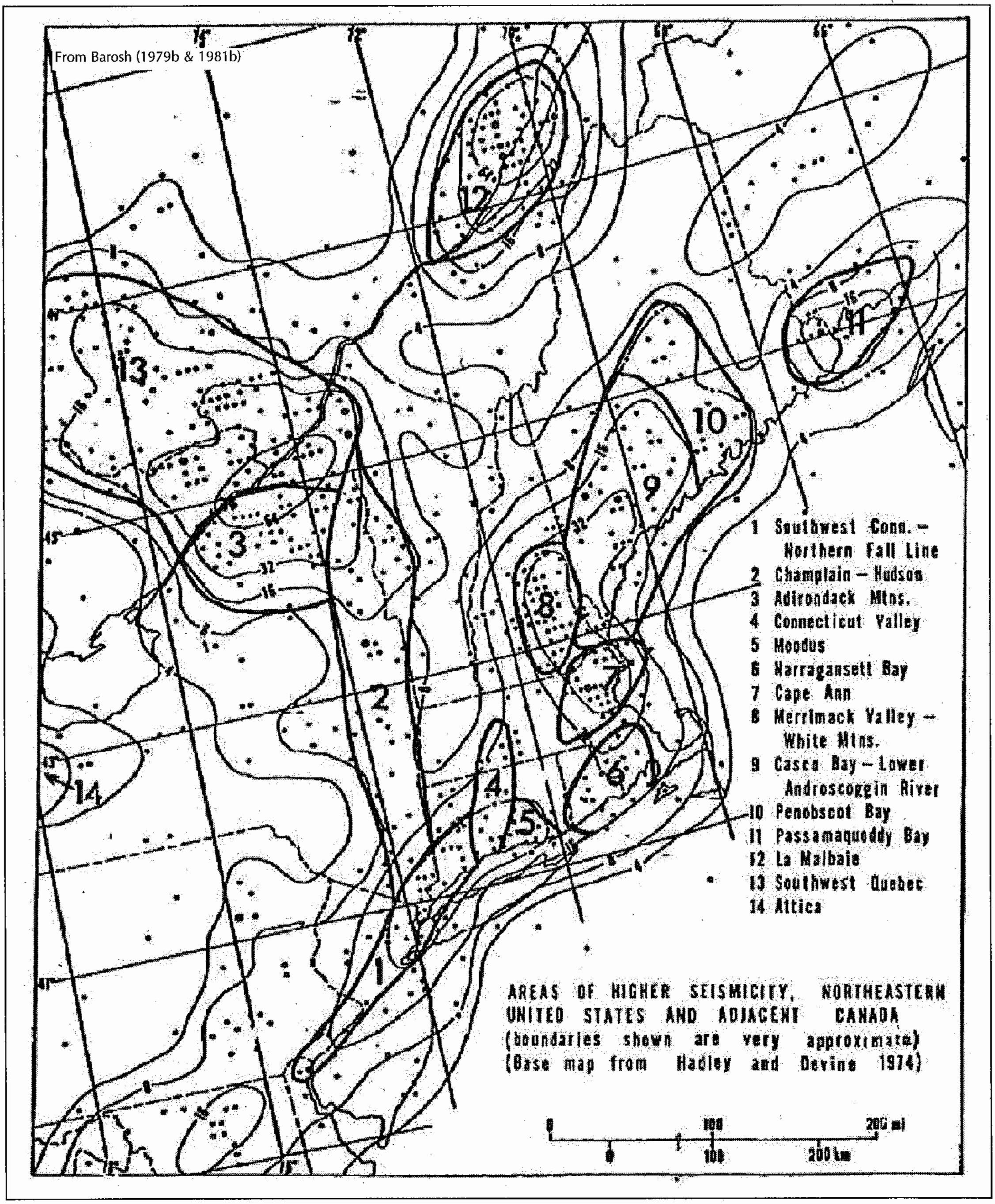
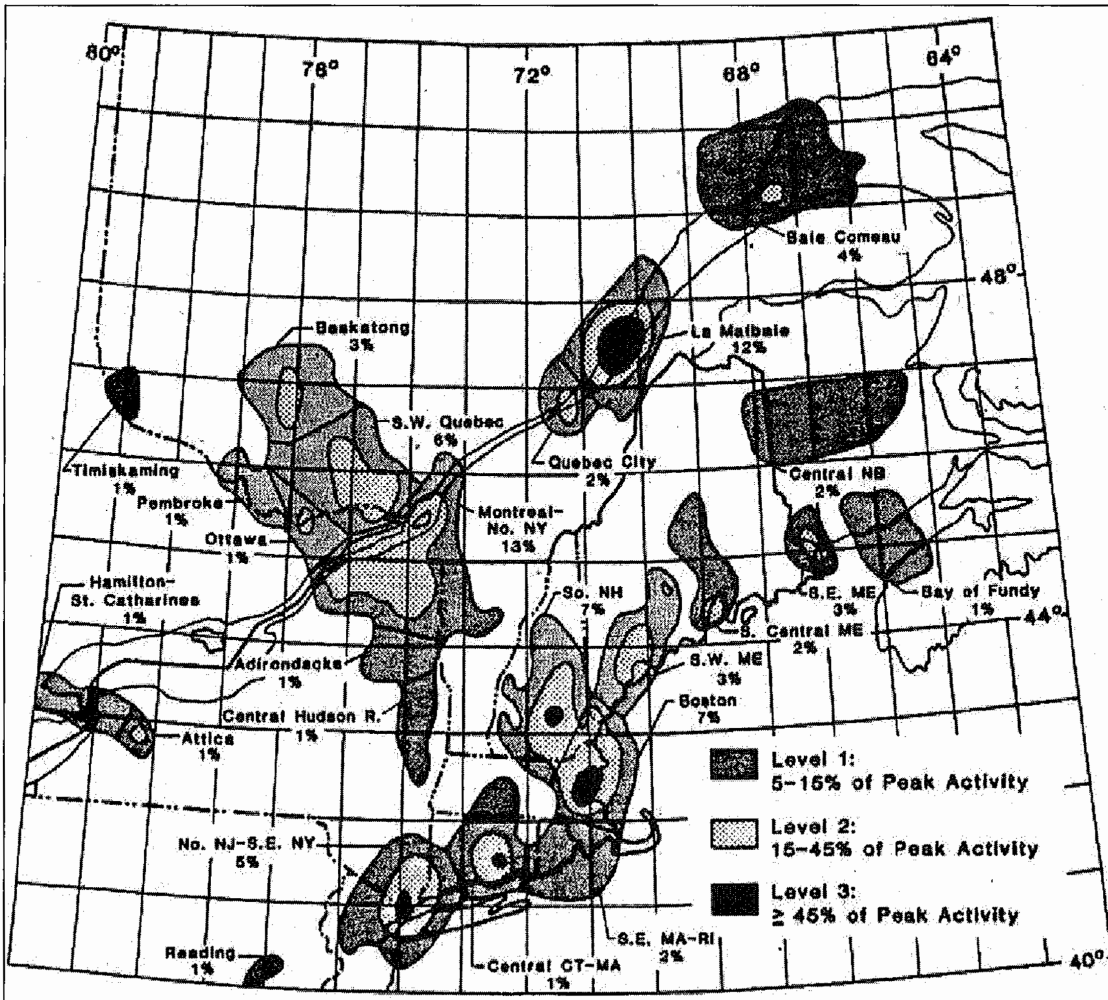


FIGURE 2-43. Map of the northeastern United States and adjacent Canada showing areas of relatively higher seismicity.

place in the Adirondack Mountains, the southern edge of the White Mountains and central New Brunswick (Barosh, 1979b).

Cause of Seismicity. "Earthquakes, the effects of God's wrath" (Burt, 1755) was preached widely across New England following the earthquakes of 1727 and 1755, but the later event also spawned a more rational evaluation (Winthrop, 1755) and other specific causes have been argued since. Several dif-



From Chiburis (1981)

FIGURE 2-44. Map of the northeastern United States and adjacent Canada showing subregions of seismicity between 1534 and 1977 contoured at three levels of relative activity and their percentage of the overall activity.

ferent causes have been proposed for earthquakes in New England and elsewhere in the eastern United States. Earthquakes have been ascribed to volcanism, glacial rebound (Leet & Linehan, 1942), rebound from a meteorite impact, granitic plutons (Collins, 1927; Billings, 1956), basic plutons (Kane, 1977; Long & Champion, 1977; Simmons, 1977; Leblanc *et al.*, 1982), reactivation of ancient deep thrust faults (Behrendt *et al.*, 1981; Seeber & Armbruster, 1981), reactivation of Triassic rifts (Page *et al.*, 1968; Ratcliffe, 1971 & 1980; Sykes *et al.*, 2008), Post-Cretaceous reverse faulting (Wentworth & Mergner-Keefer, 1980), northeast-southwest oriented compression (Zoback & Zoback, 1980), pure random occurrences with present earthquake clusters being aftershocks (presentation by Devine, 1982; Ebel, 2008), a hypothetical Boston-Ottawa seismic zone (Hobbs, 1907; Sbar & Sykes, 1973) and intersections of major structural zones (Hobbs, 1907; Barosh, 1986d & 1990a). All of these studies fail the test of adequately matching the distribution of seismicity, except for the last. Several of these proposed causes were an attempt to provide a non-fault explanation (the folding theory as discussed above in the section on the Sturbridge Terrane) prior to the knowledge of the extensive faulting in the region (Bell, 1967; Barosh, 1976d & 2005; Barosh *et al.*, 1977a). Others attribute all seismicity to one simple type of structure without adequate consideration for the complex interrelations of geologic structure and tectonic movements. The pattern of seismicity shows no relation to post-glacial rebound, which is long over; the activity extends across the area of rebound into the southern states and there is no evidence that such movement is continuing. The Boston-Ottawa seismic zone was proposed as a broad northwest-trending zone with seismic activity passing through Boston and Ottawa, Ontario. This proposed zone provides only a partial explanation since the proposed zone crosses both seismically quiet and active areas and its relation with seismicity is complex. However, in almost all these causes, the critical geologic structures have not been shown on published geologic maps and seismologists have, therefore, had to theorize at possibilities.

The major earthquakes of southeastern New England were located offshore and none of the smaller onshore ones have had any known surface faulting associated with them. The region is known to be intensely faulted, but most of these faults are quite ancient and active faults are difficult to prove. The suggested relation with northeast-trending Triassic faults, such as the Ramapo Fault of New Jersey and New York, arose from their being considered the youngest in the region. The Ramapo is still considered active in a recent evaluation of the seismicity of the New York City area (Sykes *et al.*, 2008), but it is offset by younger faults, and studies for the nearby Indian Point Nuclear Power Plant nearly thirty years ago demonstrated that this fault was inactive (Dames & Moore, 1977). Post-Early Jurassic faults are found to be very common where looked for in and near southern Rhode Island (Frohlich, 1981; Barosh, 1999a). However, these and the earlier fault evaluations were not included in a recent summary by Wheeler (2006).

Very small post-Pleistocene offsets of bedrock surfaces have been found across the region (Woodworth, 1907; Adams, 1981). However, a number of factors make it difficult to show that most small offsets are tectonic in origin: the documentation of ground cracking accompanied by shaking, which may reach MM intensity V, due to deep freezing of the ground in the region (Barosh & Smith, 1979 & 1982; Barosh, 1999c); offsets from residual-strain release from unloading; and, possible freeze-thaw fissures and collapse in glacial deposits. Confusion also can result if unreliable focal-plane solutions are used in the region.

The high residual strain in the pre-Silurian rock of the region from the plate collision may cause rocks to move when they are uncovered and surface rocks to buckle into "pop ups." This phenomenon has been directly observed or measured in quarries and road cuts. The movement takes place along old fractures and is commonly mistaken for, and reported as, recent fault offset. Studies on regional stress for earthquake hazard evaluation using borehole measurements (Zoback & Zoback, 1980) made this mistake and report ancient strain release as the present-day tectonic stress (Barosh, 1986c). However, the fact that the rock in the region holds this high residual strain probably affects its response to present tectonic stress and is a factor why eastern earthquakes are different from western ones.

The neotectonic movements causing most earthquakes in the eastern United States are related mainly to subsidence and this appears to be the case in southern New England. Here, the events are related to northwest- and north-trending faults; the youngest sets found in the region (see Figure 2-45). In a broad sense, this movement is most closely related to the transverse arches and embayments of the coast. Within these areas in the region, most earthquakes happen at fault intersections along the northwest-trending faults as indicated in 1907 by Hobbs (Barosh, 1990a). A zone of northwest-trending faults across New Hampshire, which is part of the Ottawa-Boston zone, extends offshore east of Boston through the New Hampshire embayment and epicentral area of the 1755 Cape Ann Earthquake, which had a probable MM intensity of VIII and an estimated body wave (m_b) magnitude of 5.8; the largest one recorded for the northeastern United States.

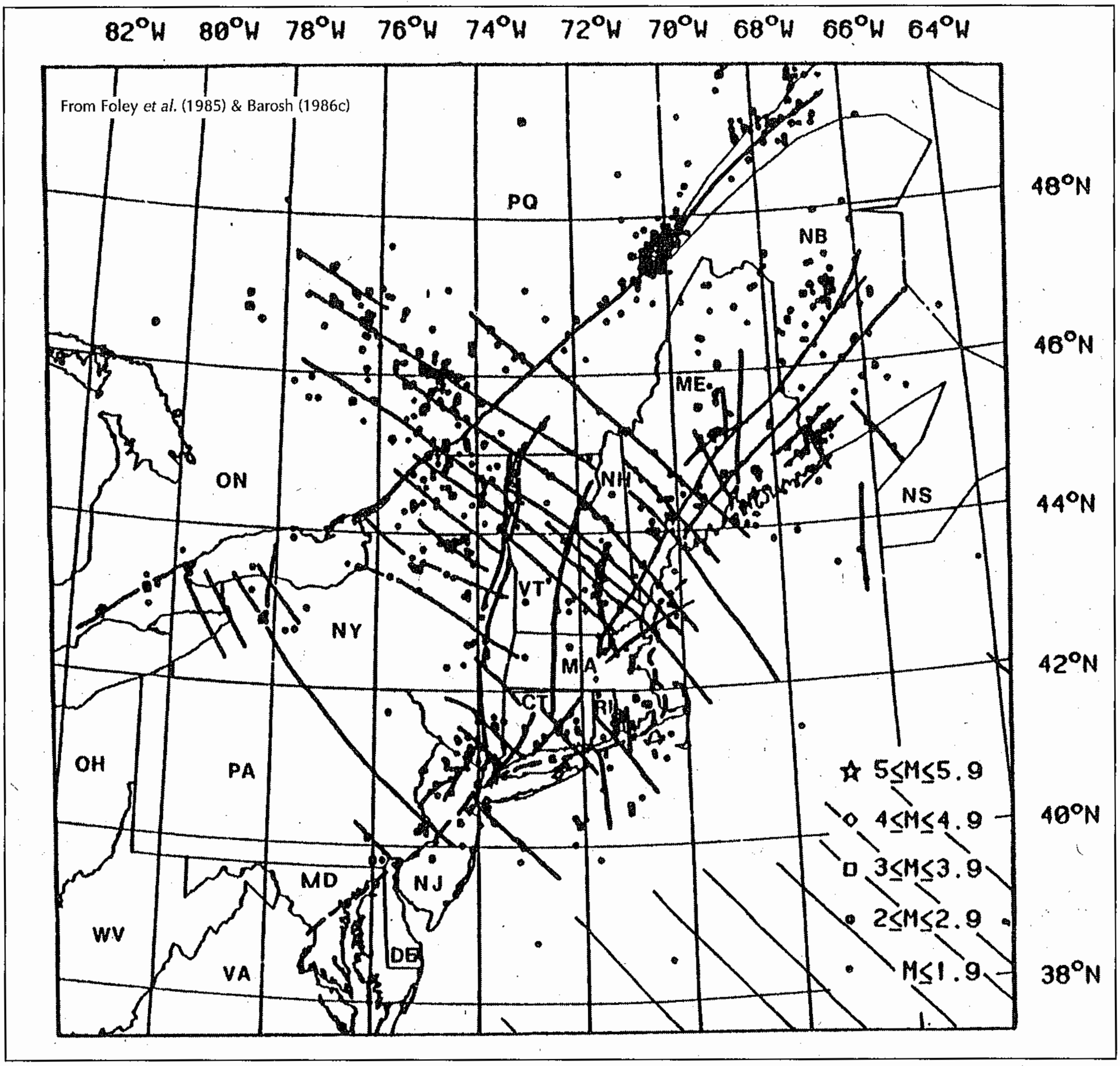


FIGURE 2-45. Map of New England and adjacent areas showing earthquake epicenters for the period October 1975 to March 1984, generalized fault and probable fault zones spatially related to earthquakes (solid lines), and border of the coastal plain deposits (dashed line).

This coastal embayment appears controlled by a system of northwest-trending fault zones. A broad largely unmapped northwest-trending system forms a broad zone, the Winnipesaukee-Winooski Lineament zone, that extends from the northeast side of the Adirondack Mountains, along the Winooski and other rivers of central Vermont, across the Winnipesaukee Lake area of New Hampshire and continues out to sea northeast of Cape Ann (Barosh, 1976a, 1982b, 1986b & 1986c). Hobbs (1904) apparently recognized some of the topographic lineaments along this zone. It consists of some mapped faults and topographic, bathymetric, LANDSAT and geophysical lineaments, that indicate many more (see Figures 2-33 & 2-45). Several individual fractures within the zone are shown to have post-Cretaceous movement (Freedman, 1950; Barosh, 1992) and some have alignments of epicenters along them (Barosh, 1986b, 1986c & 1986e). The zone passes through the most active seismic area in New Hampshire, the site of the 1940 Ossipee earthquakes, and the active area off Cape Ann. However, the zone does not appear active along its entire length and does not constitute a simple "Boston-Ottawa seismic zone" as described by Sbar and Sykes (1973). The seismic activity in New Hampshire may be due to intersections with north-trending faults along the Merrimack River valley and there also may be a controlling intersection off Cape Ann. Cape Ann itself is cut by many post-Ordovician northeast-trending faults (Dennen, 1981) and the Nashoba Thrust Belt, the largest Paleozoic structural zone known in New England, passes out to sea north of this cape (see Figure 2-12). These structures are very old, and although parts of the thrust belt were reactivated during the Mesozoic, the major fault in the belt, the Clinton-Newbury, is cut by both north- and northwest-trending faults. The Nashoba Thrust Belt itself shows no indication that it is an active structure, but it might aid strain buildup where crossed by the younger faults. The only other known seismicity close to it is near Moodus, Connecticut, where it also is crossed by a zone of northwest-trending faults.

A zone of northwest-trending lineaments, defined by both bathymetry and sediment distribution, is present off Cape Ann along the projection of the Winnipesaukee-Winooski Lineament Zone. The most prominent of these lineaments passes between the east end of Cape Ann and the southwest end of Jeffrey's Ledge, a submerged ledge that lies to the northeast; it may well represent the fault zone that caused the 1755 earthquake. The peripheral earthquakes may be caused by local adjustments on various faults due to the subsidence. These relations are similar to those found elsewhere along the Atlantic Coast (Barosh, 1986d & 1990a).

The apparent structural and tectonic controls of earthquakes in New England can explain the irregular distribution of activity as shown by the history of seismicity in the region. These relations do not suggest any new areas of potential activity. The concept of "seismic gaps," quiet areas that may be building up strain between seismically active ones and therefore constitute sites for future large earthquakes, does not apply to New England. This concept applies only to gaps within a single active zone, not to gaps between separate active zones or ones controlled by structural intersections. Nor can fault length be used to indicate the size of a potential earthquake, where only some segments of a fault are active.

The great majority of earthquakes are too small to cause post-Pleistocene fault offset and the epicenters of the larger ones usually are along submerged faults (Barosh, 1986c). These occurrences make the recognition of specific active faults in the region difficult, especially since relatively few faults are mapped. The greatest problem in recognizing such faults remains the lack of fault investigations and tight epicentral control. A great number of post-Early Jurassic faults are present and topographic expression across some of them suggest offset, as in seismic surveys of normal faults in Lake Champlain and Lake George. A few faults are now sufficiently related to earthquakes and their effects to be considered active. These faults include a northwest-trending one in southwestern Pennsylvania (Alexandrowicz & Cole, 1991) and one in the Sakonnet River channel in Narragansett Bay (Barosh, 2006c). The latter occurred near a submerged fault intersection along a northwest-trending fault (see Figure 2-32), which is expressed on the bedrock surface and bottom bathymetry and aligned with an isoseismal pattern (Barosh, 2006b). The seismicity in New England is found related to movement along post-Early Jurassic north-trending extensional faults and northwest-trending ones, most notably at fault intersections, with the driving force being the continuing opening of the North Atlantic Basin.