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Structural Geology of the Moodus Seismic area, south-central Connecticut

by

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INTRODUCTION

The area around Moodus, Connecticut (fig. 1) is one of the most continuously seismically active places in the northeastern United States. Indian legends from pre-colonial times noted the area for its earthquakes. The name Moodus is derived from the Indian name Morehemoodus meaning "place of noises" (Chapman, 1840).

The earthquakes are very shallow, and are accompanied by "noises": rumbling and booming sounds (Ebel and others, 1982) created when the high frequency vibrations of the ground couple with the atmosphere. Earthquakes of less than magnitude 1 have been felt and ones as small as magnitude 0 have been heard (Ebel and others, 1982). The area, thus, has a class of earthquakes that are heard but not felt! The Indian medicine men attributed these noises to the voice of mother earth.

The largest known earthquake in the Moodus area occurred on May 16, 1791, and was felt across all of southern New England. This earthquake had an intensity of about VII, causing slight damage in the Moodus area (Boston Edison Company, 1976). Activity had been low in recent times, up to about 3 years ago. Since then earthquake swarms, numbering a few hundred events each, have occurred in September, 1980, September-October, 1981 and June, 1982 (fig. 2).

An analysis of the earthquake activity at Moodus is of interest as a source of information concerning the cause of seismicity in the region and for evaluation of the seismic hazard at the nearby Connecticut Yankee nuclear power plant. Several investigations in and around the Moodus area have been conducted in the past six years under the auspices of the New England Seismotectonic Study, funded by the U.S. Nuclear Regulatory Commission and in cooperation with the Connecticut Geological and Natural History Survey. These studies include compilation of all available geologic data, five seasons of detailed geologic mapping in and around the Moodus area, a detailed gravity survey of south-central Connecticut, mapping and fracture analysis of the Higganum dike, analysis of Landsat, topographic and aeromagnetic lineaments in the region, mapping of the Pleistocene terraces along the Connecticut River, investigations of recent rock movements, a near-shore magnetic survey in Long Island Sound and the installation of a five station seismic array in the Moodus area. These studies have added greatly to our knowledge of the geology and seismicity of the area. The general distribution of lithologies had been delineated by Lundgren (1963, 1979) Lundgren and Ashmead (1971) and Eaton and Rosenfold (1972), but the structural geology of the Moodus area as it is presently known bears little resemblance to what it was thought to have been six years ago. The bedrock geology of the region is very complex, and much more needs to be done to fully understand it, but detailed studies of

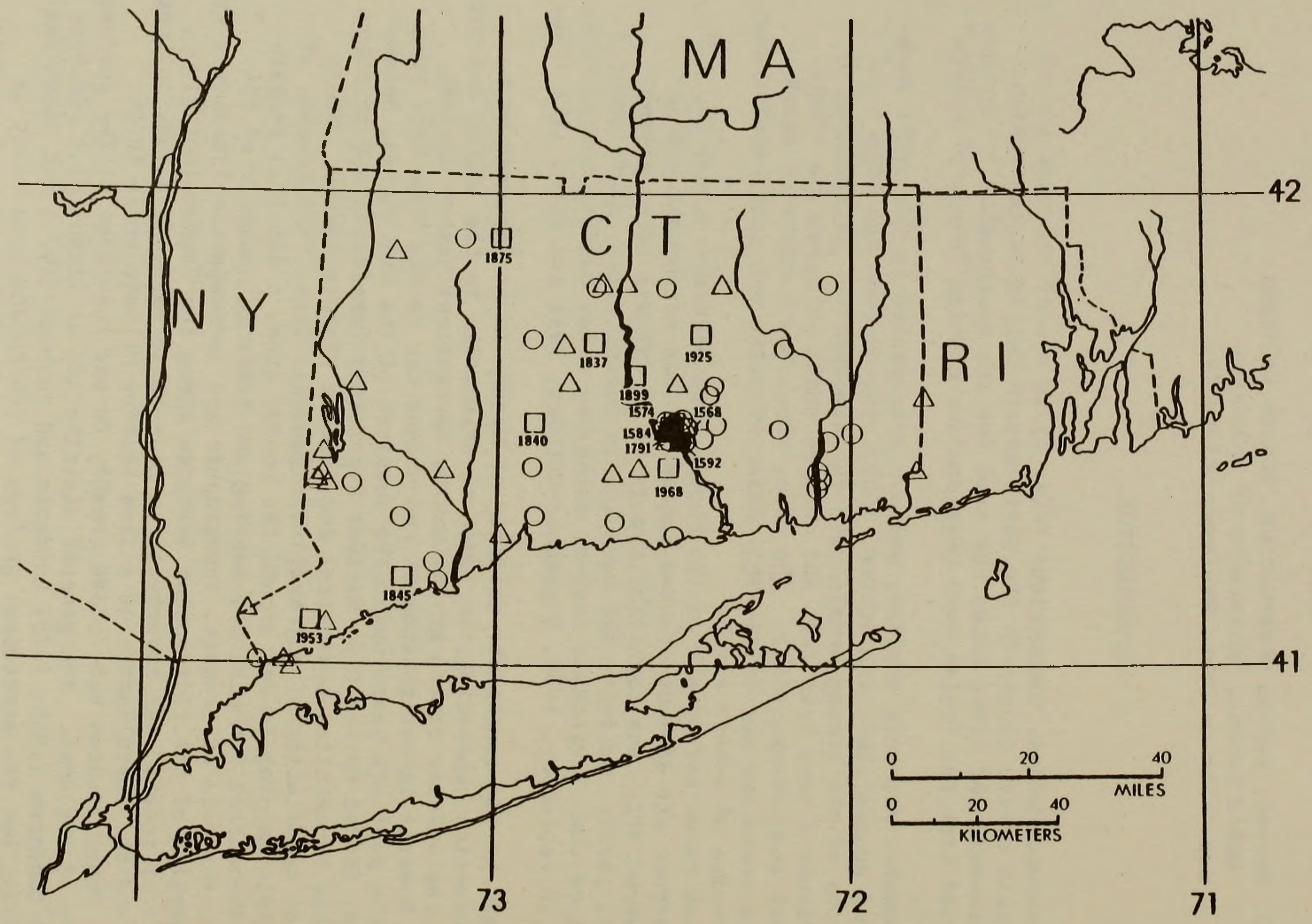


Fig. 1. Historical seismicity of Connecticut. The symbols show the maximum modified Mercalli intensity for the events: ○ = III, △ = IV, □ = V, ● = VI, and ■ = VII . Moodus is located in the area of the concentration of seismicity on the map. The figure is from Chiburis (1981).

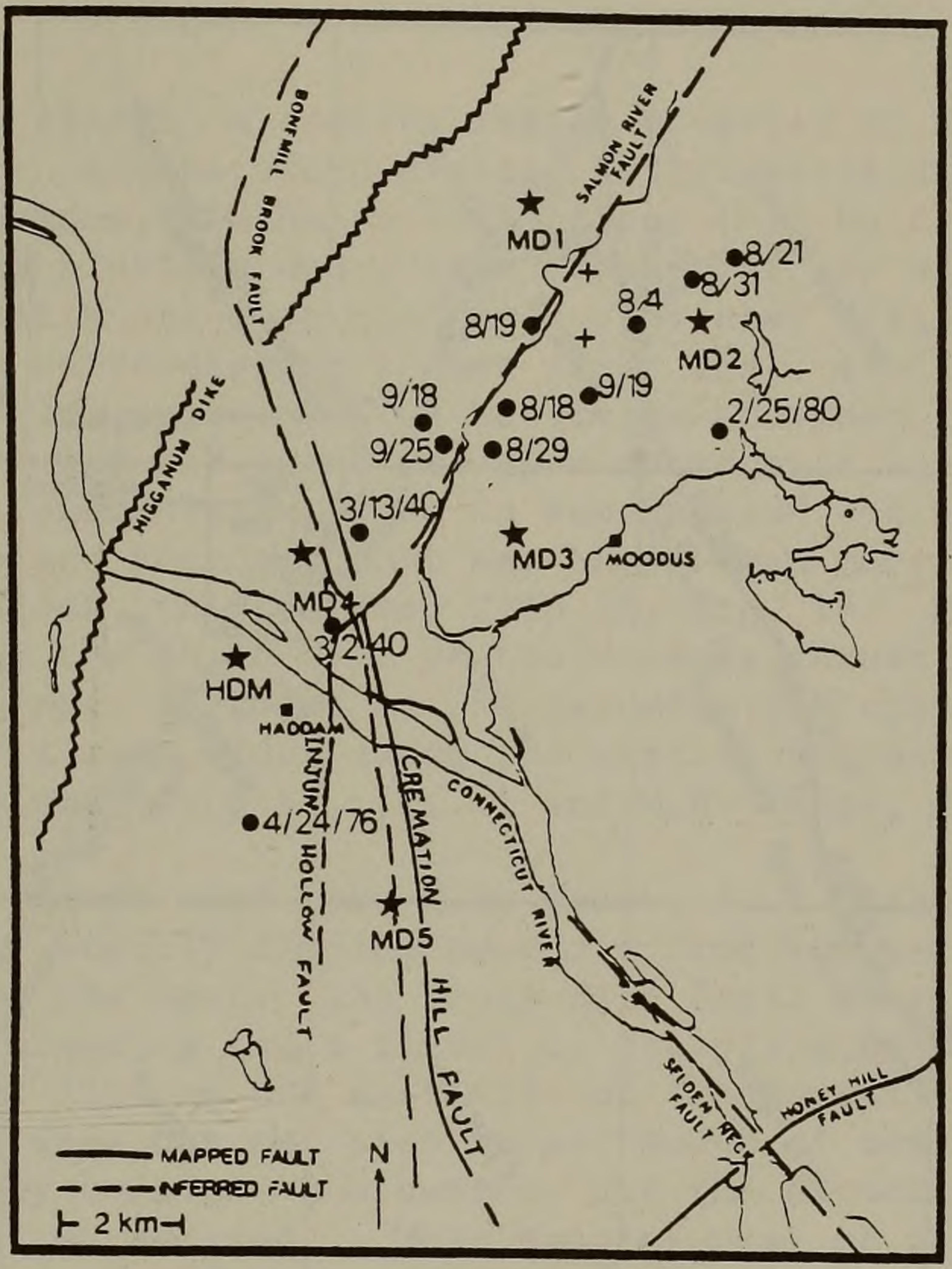


Fig. 2. Map of recent seismicity and tectonics of the Moodus area. The dates of the locations of events from the 1981 swarm are shown, as well as dates and locations from previously located events. Locations of the Moodus network stations are shown as stars, and sites of the two temporary stations which were installed after the August 4 event are shown as crosses. Modified from Ebel and others, 1982.

of the Moodus area (fig. 3) and to the south provide a start in revealing the structure (London, in prep. and Wintsch, in prep. and this volume).

The purpose of this guide is to describe what is presently known about the structural setting of the area of the Moodus earthquakes and to show examples of the variety of deformational structures found there. These structures present a wide range of age of formation and deformational features from very ductile to very brittle. This report borrows heavily from many others involved in these investigations: M.H. Pease, Jr., Brian Koch, J.F. Kick, R.P. Wintsch, J.S. Sawyer, S.E. Carroll, S.S. Quarrier, E.F. Chiburis, J.E. Ebel, Vladimir Vudler, Michael Celata, and Ralph Aoki. It is also indebted heavily to M. H. Pease, Jr., P.V. Smith and P. Lagace for their editing and drafting expertise and to Ralph Aoki, Dorothy M. Sheehan, Joy O'Malley, and Patricia Tassia for manuscript preparation.

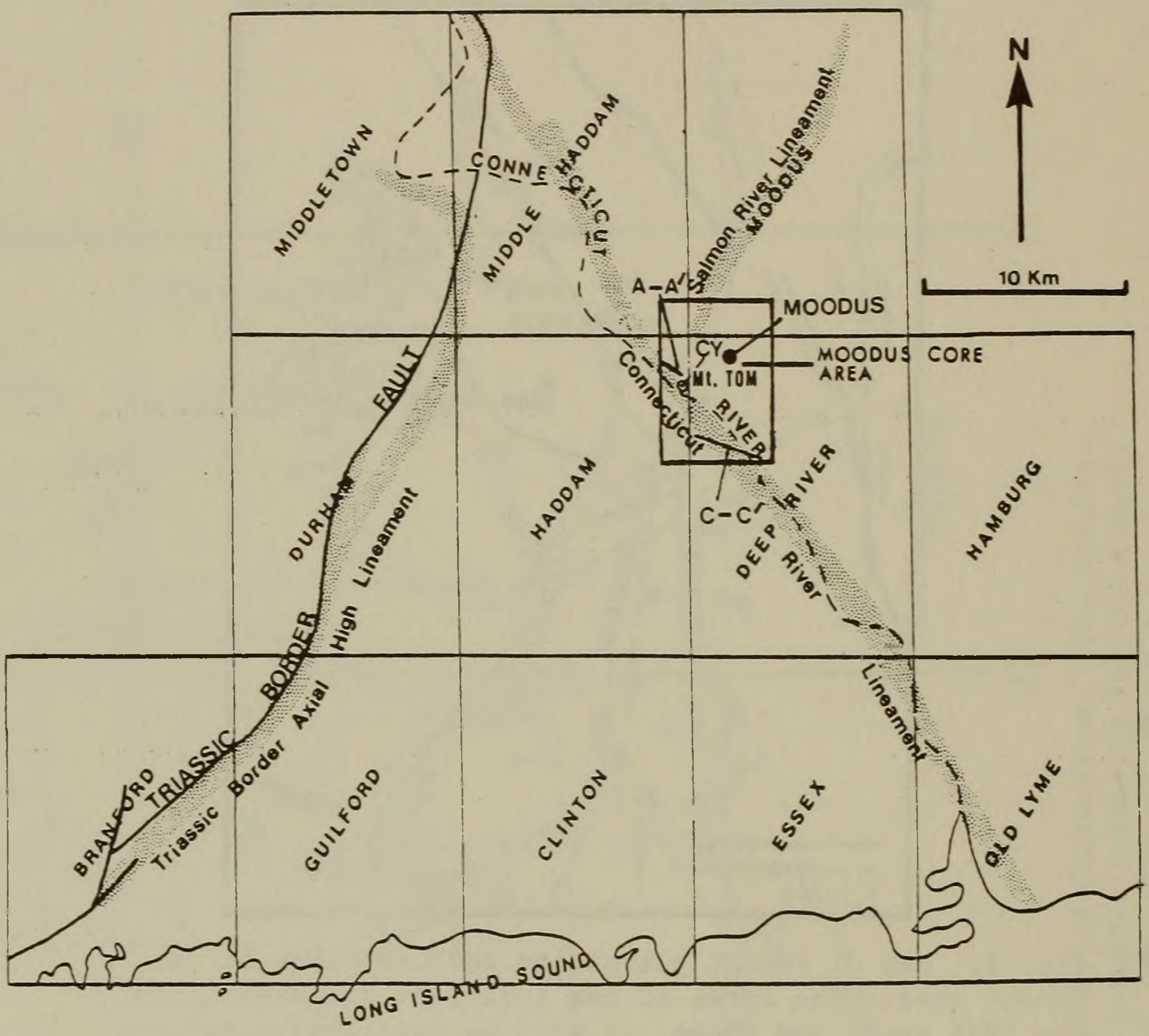


Figure 3. Index map of the Moodus area, south-central Connecticut, showing 7.5-minute quadrangles, selected gravity lineaments, and position of cross sections. Explanation: CY, Connecticut Yankee Nuclear Power Plant; stippling gravity lineament; A-A′ and C-C′, cross sections.

REGIONAL STRUCTURAL SETTING

The Moodus area lies in a complex region composed of six distinct structural provinces: the Hartford graben, Killingworth dome, Glastonbury dome, Merrimack province, Southeast Connecticut fold belt portion of the Southeast New England platform and a thin remnant of the Nashoba thrust belt (fig. 4). Major fault zones separate these provinces (fig. 4). The Honey Hill fault zone is a north-dipping thrust fault that, along with a sliver of the Nashoba thrust belt, separates the Merrimack province from the Southeast Connecticut fold belt and has local relative north over south movement. It is part of the largest fault system known in New England and probably represents an Early Paleozoic plate boundary that may have begun movement as early as Late Precambrian (Barosh, this volume, Trip P6, fig. 1). Most of the length of the fault bounding the north side of the Nashoba thrust sliver along the Honey Hill fault has been intruded by the Devonian Canterbury Gneiss. The Nashoba thrust belt is much wider along the eastern boundary of Connecticut (see Barosh, this volume, Trip P6, fig. 1 and M.H. Pease, Jr., this volume, Trip P2, fig. 1).

The Bonemill Brook fault zone (see M.H. Pease, Jr., this volume, Trip P2) is a northerly-trending, steeply dipping zone dividing the Merrimack province from the provinces to the west. The Honey Hill fault zone is cut off on the west by a northerly-trending fault sliver of steeply dipping deformed rock about 800 m wide that lies on the east side of the Bonemill Brook Fault. The Bonemill Brook fault zone has not been mapped south of the Falls River fault zone (fig. 4); it may continue southwards, but the structure is extremely complex and is as yet unresolved. What happens west of this zone to the Honey Hill and the underlying rocks of the southeast Connecticut fold belt is as yet unknown. However, the kinds of structures at the southern end of the Killingworth dome area are very similar to the kinds of structures south of the Honey Hill and a continuation of the fault may lie in this area.

A broad northwest-trending zone of structural dislocation divides the Glastonbury and Killingworth domes. This zone extends northwestward from the Moodus area mainly along the northeast side of the Connecticut river. Major structural features on either side of this zone terminate against it. This zone is herein named the Middle Haddam fault zone and is described in greater detail in the section on pre-Mesozoic structures.

A normal, extensional, border fault along the east side of the Hartford graben separates the graben from the domes to the east. This fault appears to be a composite fault zone; northeast-trending segments of the fault appear to extend into the Killingworth dome. A strong linear gravity high follows the border fault (Kick, 1982) (fig. 3). It is highest where the thick lava flows in the graben abut the border and may represent a basaltic intrusion that came up the fault and fed the flows.

The provinces exhibit different structural styles and contain separate stratigraphic sequences and, except for continuation of the Monson Gneiss across the boundary between the Killingworth and Glastanbury domes, correlation between provinces must be mainly conjectural.

The structure of the area has previously been considered to consist of long, narrow, sinuous folds with neglible faulting other than along the Honey Hill fault zone (Lundgren, 1963) (fig. 5). The immediate area of Moodus is shown to be formed of two regional folds: the Chester syncline and the Monson

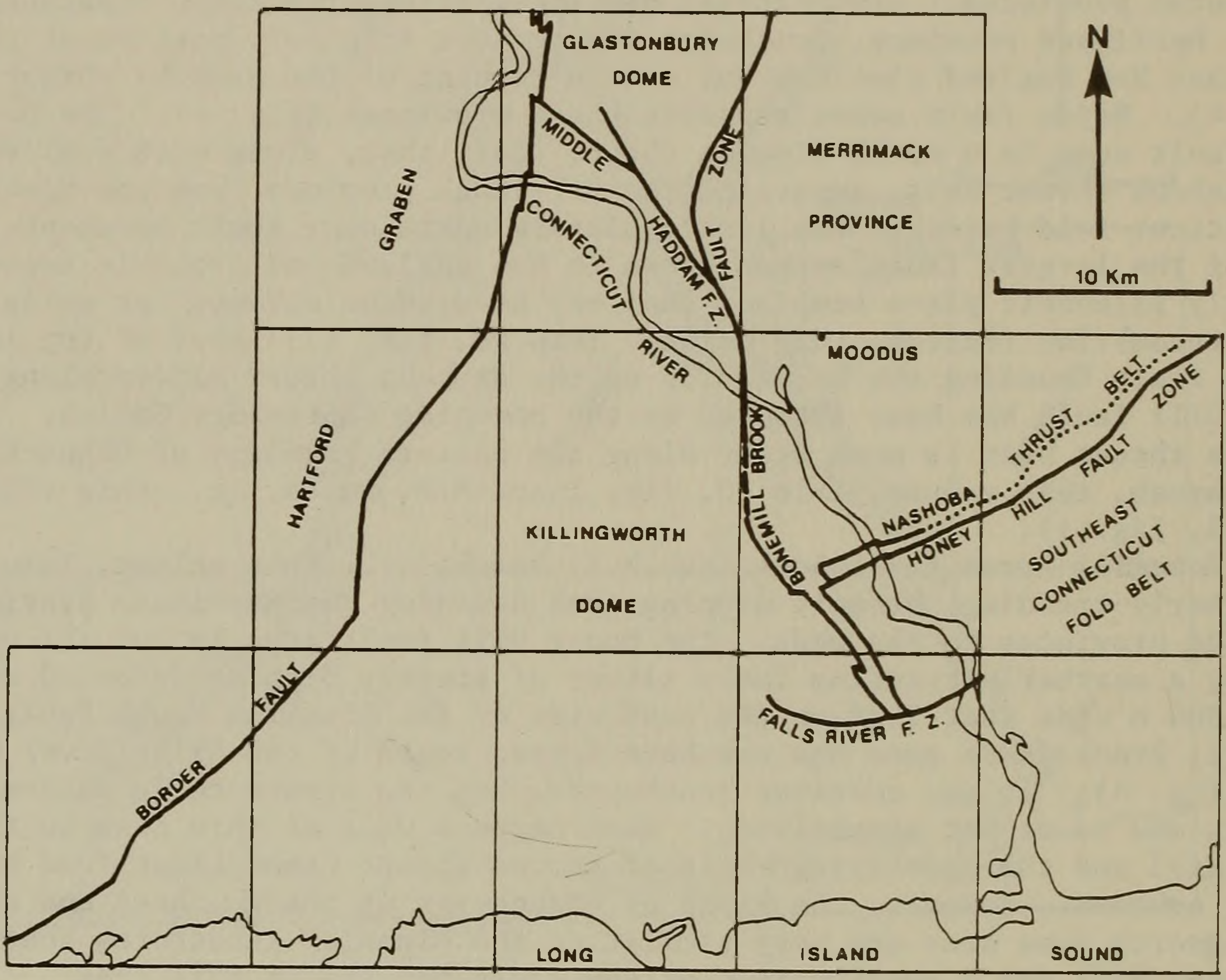


Fig. 4 Map showing structural provinces and their border faults in the region around Moodus, south-central Connecticut.

anticline. Together they form part of the northeast flank of the Killingworth dome. A thin band of rock of the Hebron Formation was depicted as continuing south from the Merrimack province and eastward as the core of the Chester syncline. This very complex syncline was thought to tie together the Killingworth dome, the Merrimack province, and the Southeast Connecticut fold belt in a very large, complicated, recumbent fold relationship (Dixon and Lundgren, 1968) (fig. 5).

Detailed mapping of the structure and stratigraphy in the Hebron Formation has found no supporting evidence for the Chester syncline. Instead, the position of the trace of the axial plane of the syncline was found to be along the moderately to steeply dipping west limb of a broad anticline, whose northwest-trending axis lies east of the center of Moodus (fig. 6). Rocks of the Hebron Formation do continue a few kilometers south of the Honey Hill fault zone as a narrow, fault-bounded band, but they end abruptly against the west-trending Falls River fault (R.P. Wintsch, this volume). The geologic structure as presently interpreted is shown in figure 6.

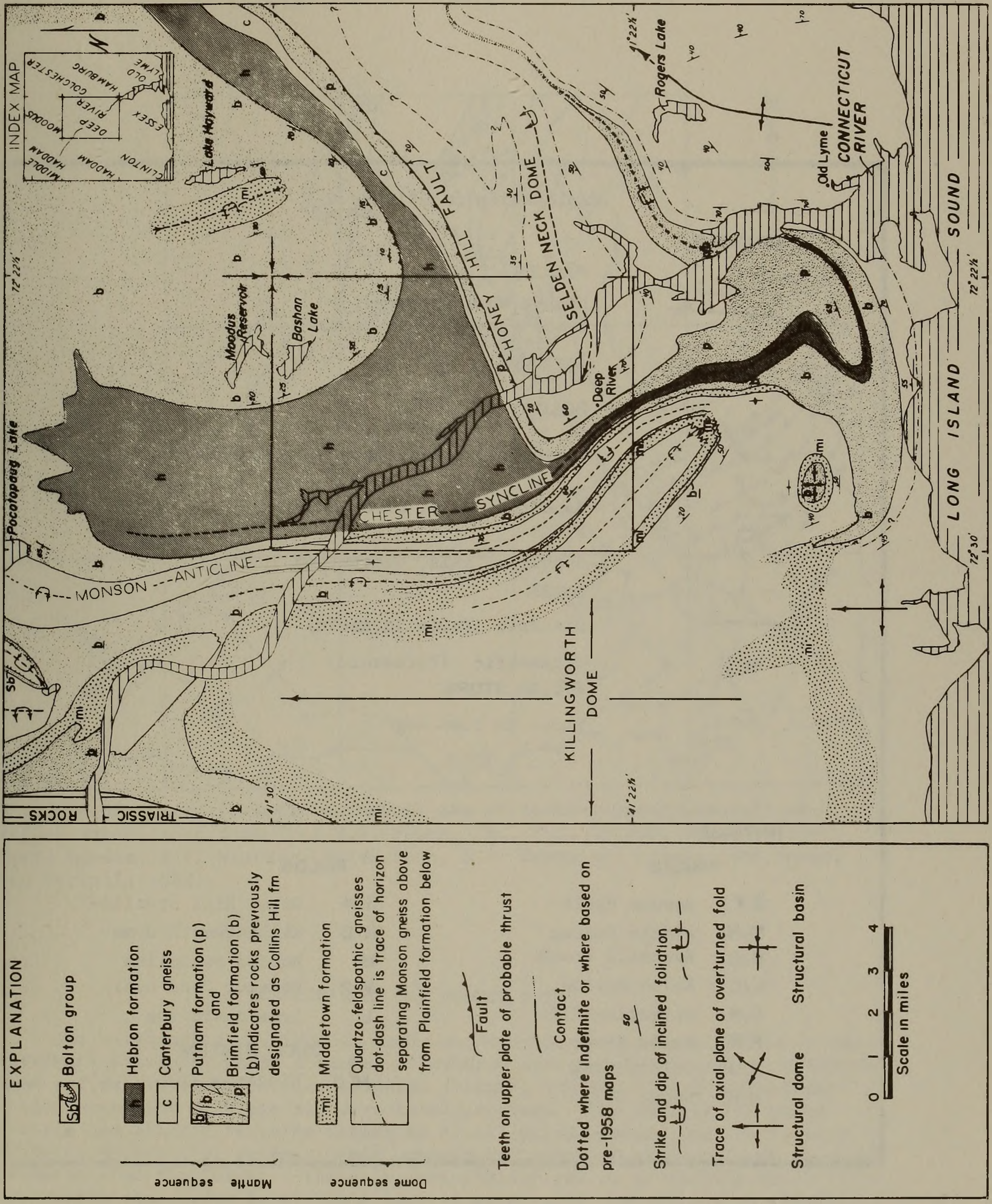
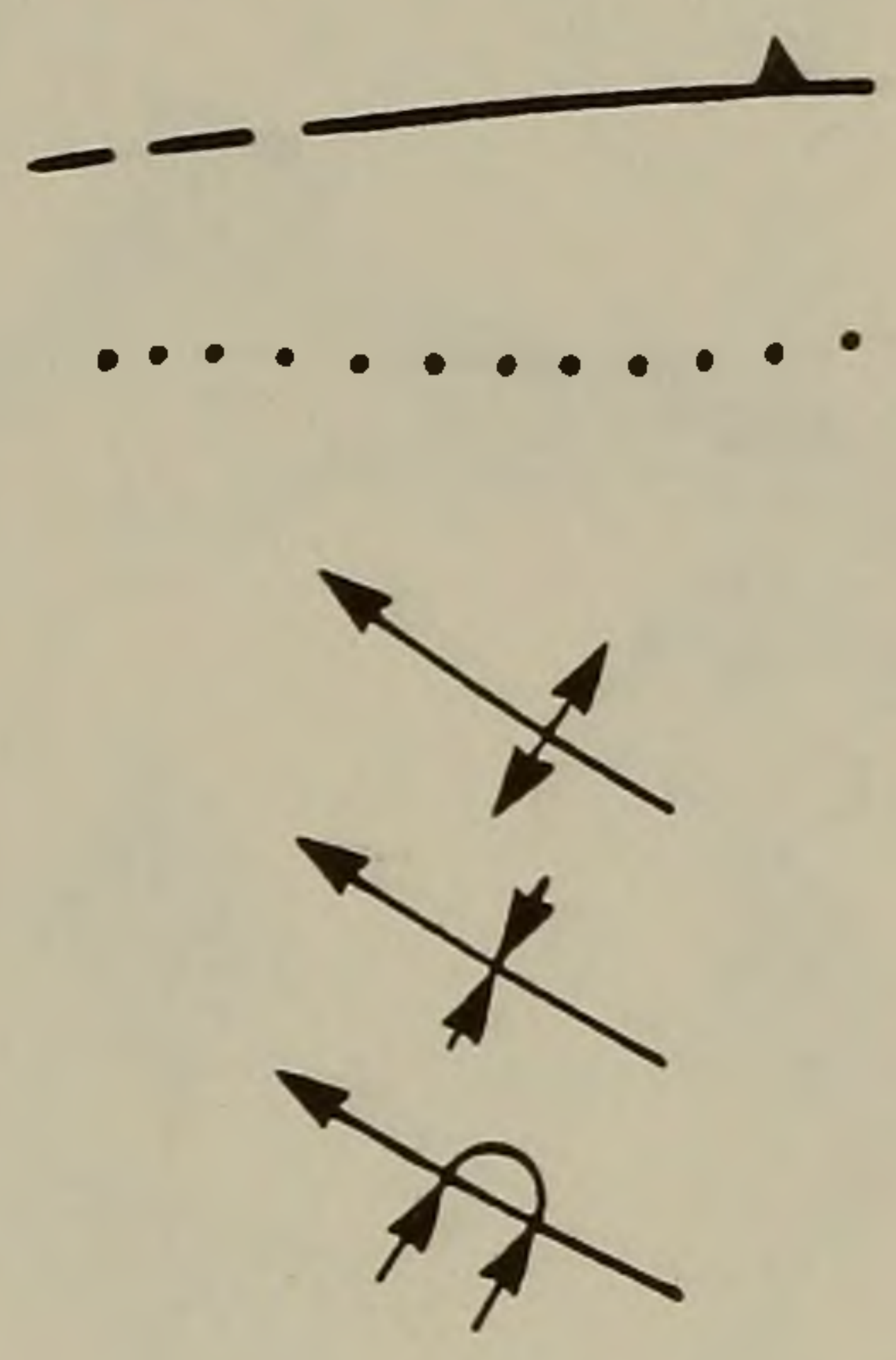


Figure 5. Generalized geologic map of south-central Connecticut showing the regional geology interpreted as a series of folds (Lundgren, 1963).

Explanation for figure 6.

SYMBOLS



FAULTS

Dashed when inferred, teeth where thrust fault

Intruded

FOLDS

Anticlinal axis, arrow showing plunge

Synclinal axis, arrow showing plunge

Synclinal axis, overturned

DIKES

—	Diabasic (Early Jurassic)
●	Ultramafic (Paleozoic)

FIELD STOPS

X 2	Stops in road log

INITIALS

FAULTS

B.F.	Border fault
M.H.	Middle Haddam
B.B.	Bonemill Brook
I. H.	Injun Hollow
C.H.	Cremation Hill
F. R.	Falls River
S.N.	Seldon Neck
H.H.	Honey Hill

FOLDS

G H	Great Hill syncline
K D	Killingworth dome
M	Moodus anticline
V P	Vincent Pond basin
L	Lyme anticline

DIKE SYSTEM

H.D.	Higganum dike

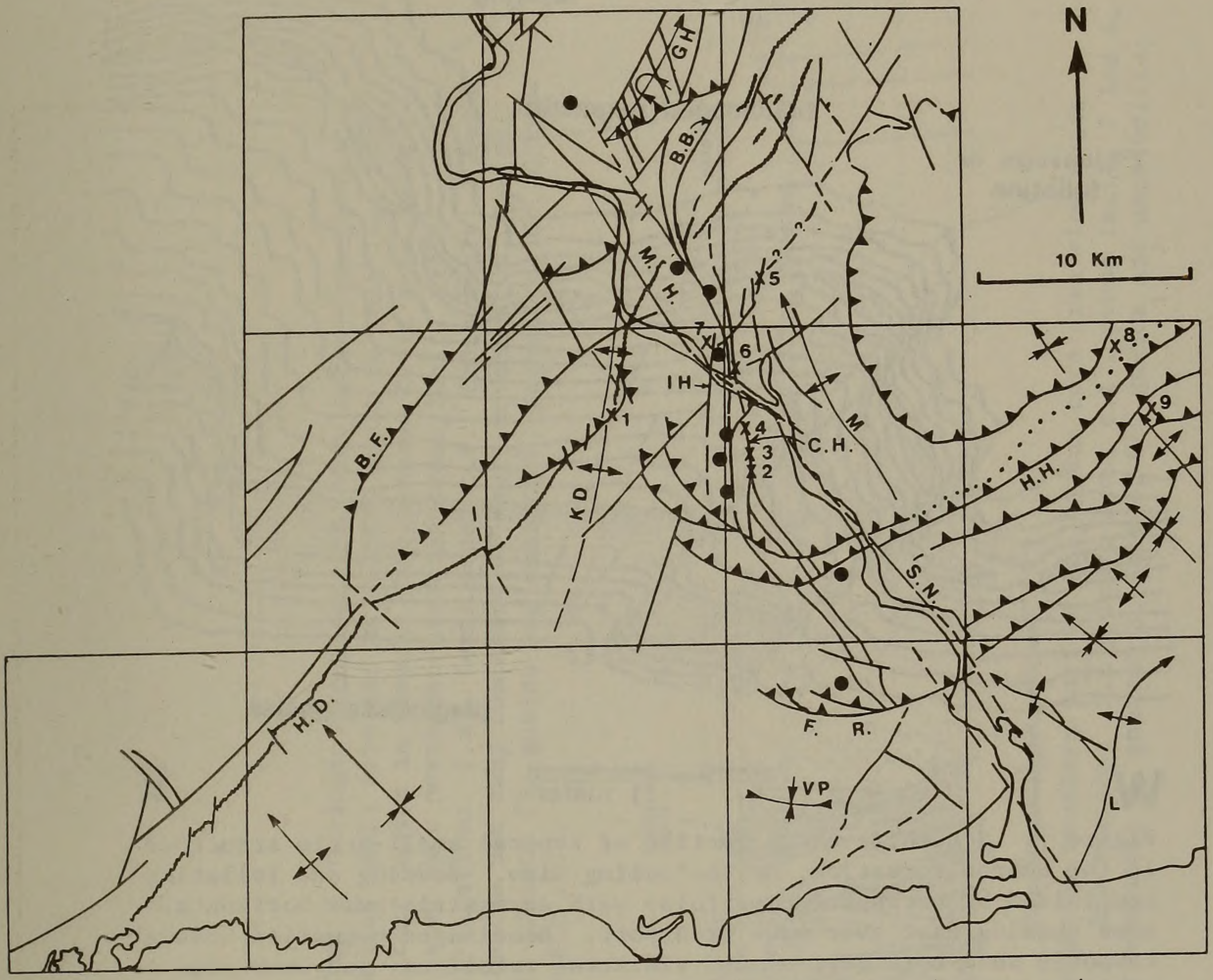


Fig. 6 Generalized geologic structure map of south-central Connecticut (after unpublished data from M.H. Pease, Jr., P.J. Barosh, Jelle de Boer, David London, R.P. Wintsch, Brian Koch, R.J. Fahey and others, and Sawyer and Carroll, 1982).

STRUCTURE OF THE MOODUS AREA

The earthquakes near Moodus occur mainly near the western border of the Merrimack province, where a number of diverse structural features of different ages and deformational styles converge (Barosh, 1981a). The deformational styles vary with both age and structural province. The ductile and mixed ductile and brittle features appear to be all pre-Mesozoic, and the brittle features Mesozoic or younger; this appears to reflect a greater depth of formation for the former. These characteristics are of great help in separating structures by probable age. Considerable information is available on the relative ages of pre-Mesozoic structures but little is definitely known about their absolute ages.

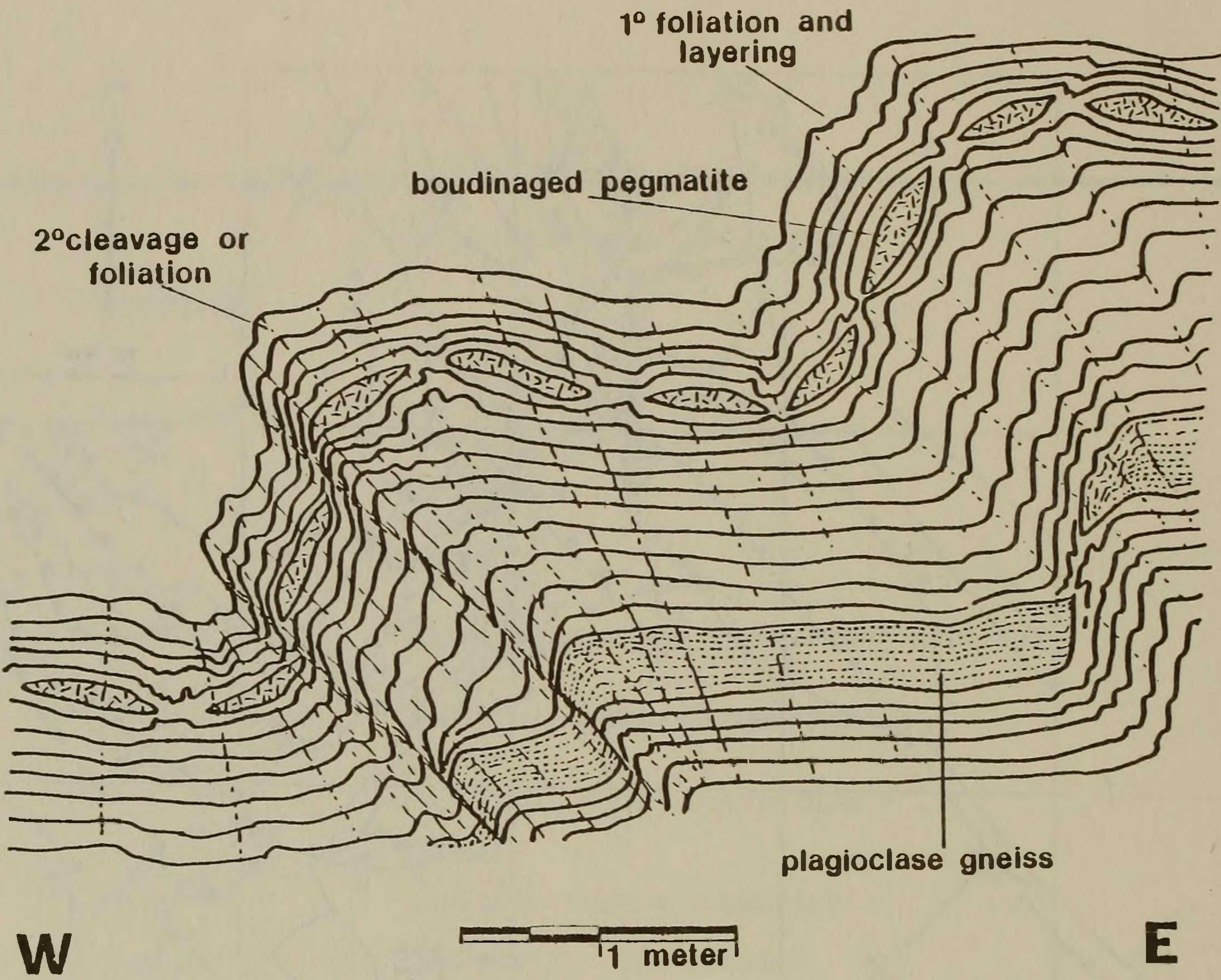


Figure 7. Schematic cross section of typical small-scale structure in the Hebron formation, north-looking view. Bedding and foliation are folded by north-trending folds with asymmetric near horizontal axes showing east over west transport. Boudinaged pegmatite bodies commonly show both dextral and sinistral rotations, and many pegmatites are doubly boudinaged, forming quilted or pancake patterns. (London, in prep.).

PRE-MESOZOIC STRUCTURES

The broad northwest-trending and gently plunging axis of the Moodus anticline deforms rock of the Hebron Formation and passes east of the town center (fig. 6). Much of its northeastern limb is covered by very gently dipping rock of the Brimfield Group that apparently has been thrust slightly over it. Its southwest limb gradually steepens to moderate to vertical dips to the west where it meets and is cut off by the Cremation Hill fault zone (STOPS 2, 3, 4 and 6) (fig. 8). The Hebron Formation is highly deformed adjacent to the fault and is intruded by many irregular pegmatite bodies (fig. 7) (STOP 2). The pegmatites formed during deformation, probably not as an anatectic melt, but under near melt conditions (London, 1982). Elsewhere, the

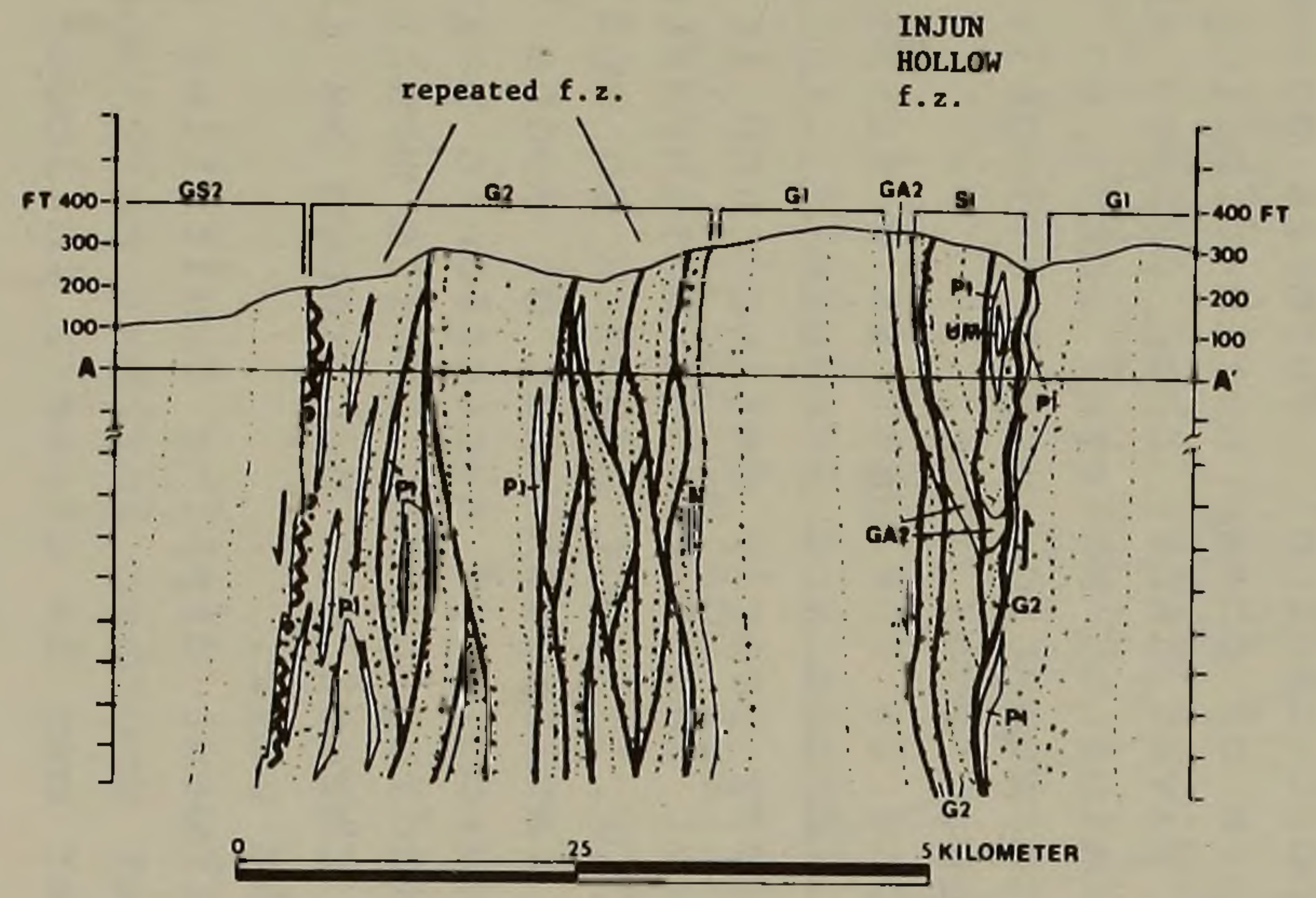


Fig. 9 Geologic cross section, view north through Injun Hollow fault zone and an unnamed fault to west (see fig. 3) (after London in prep.). The unnamed fault zone is repeated by a northeast-striking cross fault. Explanation: f.z., fault zone; c.f., cross fault; T and A, towards and away component of fault movement; G, gneiss; S, schist; GS, gneiss and schist; P, pegmatite; UM, ultramafic rock.

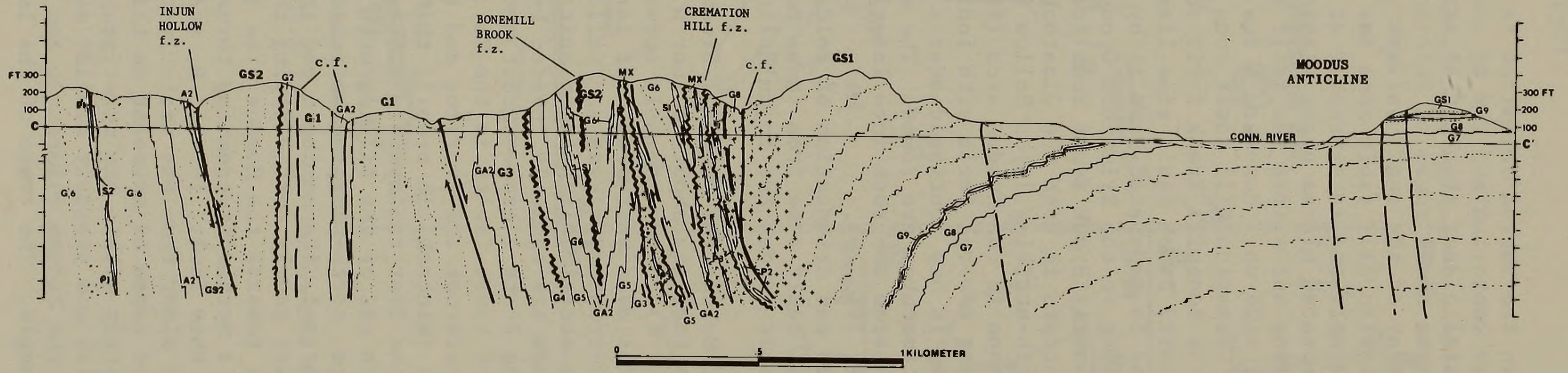


Fig. 8 Geologic cross section through the southern part of the Moodus core area view north (see fig. 3) (after London in prep.) Explanation: f.z., fault zone; c.f., cross fault; T and A, towards and away component of fault movement; G, gneiss; S, schist; GA, gneiss and amphibolite; P, pegmatite; MX, migmatitic zone.

bedding within the Hebron Formation is generally undeformed, except for local zones that are contorted and cut by small reverse faults (fig. 8). The faults are mostly axial planar shears that strike north and display east over west transport. These small zones of deformation lie in and appear to control the location of many of the small valleys and gullies in the area.

The Cremation Hill fault zone has been feldspathized under conditions approaching a melt and is expressed at the surface as a zone of migmatites. Sheared and rotated blocks occur within this foliated migmatitic zone. Structures along and within the fault zone indicate right-lateral movement with the east side up. However, a few local exceptions are present (figs. 6 and 8). The Cremation Hill fault zone may be part of the same general zone of movement as the Bonemill Brook fault zone.

The Bonemill Brook fault zone lies to the west of the Cremation Hill fault zone and is separated from it by slivers of gneiss and schist that appear to belong to the Brimfield Group (M.H. Pease, Jr., this volume, Trip P2). The Bonemill Brook fault zone forms the eastern boundary of the Monson Gneiss that occurs in both the Glastonbury and Killingworth domes.

The north-striking Injun Hollow fault zone lies west of the Bonemill Brook fault zone in the Moodus area (figs. 6, 8 and 9) (STOP 7). It is a steeply dipping reverse fault with indications of left-lateral movement. Movement along it has continued over a long period and both early ductile and late brittle features are found. The movement along it and some of the other faults has sheared the rock into interleaved fault-bounded lenses with little coherent order (fig. 9).

The style and orientation of folds and foliation are different within the Cremation Hill fault zone from those to the east and west (fig. 10). The foliation trends across the Injun Hollow fault zone are also different (fig. 10).

South of Moodus the Bonemill Brook fault zone is cut by several small thrust faults that dip about 45° north and have north over south relative movement (fig. 6). They commonly curve from a westerly to a northwest trend as they are followed westward. The larger ones make curving valleys crossing the northerly-trending ridges and valleys that reflect differential erosion of the northerly striking lithologic units. These thrust faults and fractures related to them are commonly invaded by post-tectonic Permian pegmatite. Roadcuts along Route 9 expose great numbers of these north-dipping pegmatites. The largest of these faults is the Falls River fault that passes through the towns of Centerbrook and Ivoryton and terminates several units on the north-side (fig. 6) (Wintsch, in prep.); this termination was previously considered the nose of the Ivoryton synform (Lundgren, 1964) (fig. 5).

The north end of the Killingworth dome to the west is a fairly well defined, large, north-plunging anticline (Eaton and Rosenfeld, 1972, Lundgren, 1979); in contrast, its southern end is very poorly defined and it may not be a dome. A very gently north-dipping thrust fault trends northeastward across the anticline towards the Moodus area (STOP 1), but appears to end against or merge with a a northwest-trending thrust fault just east of Route 9. The very low angle of this fault, 10°-25° N, and associated syntectonic pegmatite suggest it is older than the westerly-trending thrust faults mentioned above. The amount and sense of movement on this thrust are not known as its observed trace is entirely within one stratigraphic unit.

A parallel and probably similar northwest-dipping fault lies to the northwest in the Haddam quadrangle and yet another farther northwest in the Durham quadrangle. The trace of the later one is closely followed locally be

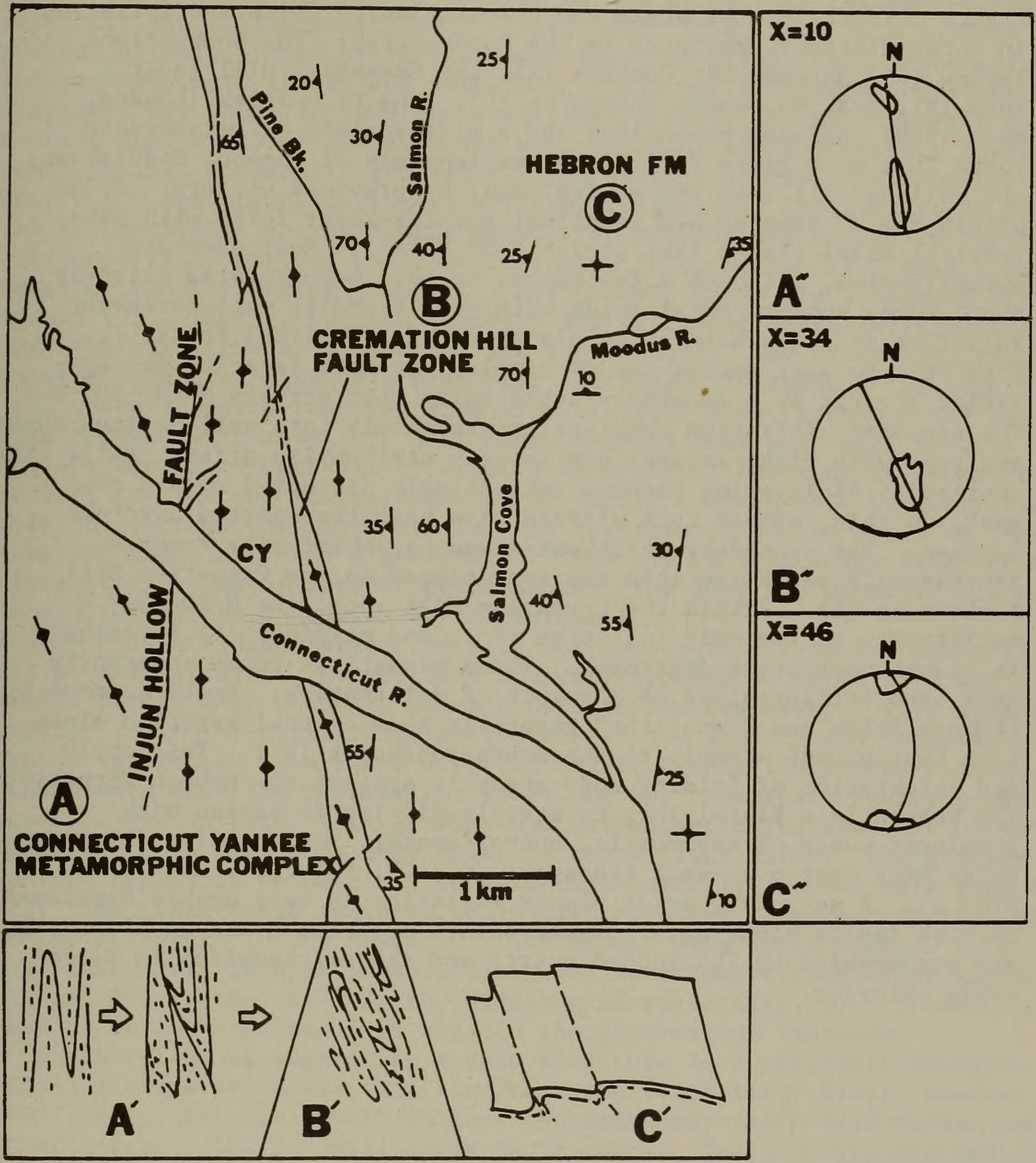


Figure 10. Foliation and small-scale folds in the Moodus area.

Figure 10. Foliation and small-scale folds in the Moodus area. This figure illustrates the style and orientation of folds and foliation in three distinct provinces in the Moodus area: the Connecticut Yankee (CY) Metamorphic Complex (A), the Cremation Hill fault zone (B), and the Hebron Formation (C). The CY complex (London, ms., 1982) includes pegmatites and a wide variety of metamorphic rocks that were given formational assignments of Monson, Middletown, and Collins Hill (and its equivalents) by previous workers. Folds within the CY complex are isoclinal passive-shear folds with subvertical axial planes that strike N 5° W (A"). Most axes are subhorizontal, although a few appear to have been rotated slightly about broad subhorizontal folds with axes trending east-northeast. Foliation is everywhere axial planar to the isoclinal folds. From west to east across the CY complex, primary layering and foliation are cut by a secondary schistosity that strikes N 20°-30° W. The secondary foliation develops progressively into well-defined shear surfaces with right-lateral and largely strike-slip offset. (A'). The continuity of layering becomes increasingly disrupted toward the east, as thin, smooth rock slivers have been transported over one another. The secondary northwest-trending schistosity becomes increasingly pervasive into the zone mapped as the Cremation Hill fault zone (B). Within the Cremation Hill zone, the N 20°-30° W schistosity is the only foliation (B'), and original (?) layering is almost completely destroyed. These migmatitic rocks apparently have been feldspathized as a result of deformation. Small asymmetric flexure folds and "xenoliths" generally show dextral rotation along axes that plunge steeply to the south-southeast (B"). This style and orientation of folding ends abruptly against the Hebron Formation. The Hebron is a flat-lying, to steeply-dipping formation with prominent zones of asymmetric, subhorizontal, N-S-trending flexure folds with east-over-west transport (C', C"; figures 7 and 9, and STOP 2). A secondary axial planar foliation is very weakly developed; reverse faults along axial planar shears are common and usually are accompanied by (b) rodded quartz and (a) slickensides in retrograde chlorite.

the Mesozoic border fault of the Hartford graben (fig. 6).

A steep 3-milligal gravity gradient forms a prominent northwest- trending linear feature along the northeast side of the Connecticut River between the Glastonbury and Killingworth domes (Kick, 1982) (fig. 3). This appears to represent a fault. Most of the geologic contacts within this lineament also trend northwestward (Eaton and Rosenfeld, 1972) and structures on either side end against it; these include the anticlinal nose of the Killingworth dome and the Great Hill syncline and adjacent west flank of the Glastonbury dome. The Maromas Gneiss, a granitic intrusion, lies largely within this zone of discordance and has strong northwest striking foliation. The Maromas is identical in appearance to the Middle Ordovician Glastonbury Gneiss to the north and is apparently part of the same intrusion (M.H. Pease, Jr., oral commun.). Strong northwest-trending joint sets are present where the lineament was examined (J.S. Sawyer, written commun.) and prominent northwest-trending topographic and LANDSAT lineaments lie in the zone. The Great Hill syncline ends at a lake that lies on a prominent northwest lineament. The combination of all these features requires some kind of fault zone, herein named the Middle Haddam fault zone. It is a broad complex zone that will require detailed mapping to unravel. The north boundary of the zone is shown on figure 4. The actual faults depicted on figure 6 along this boundary and within the zone to the south are largely interpreted on the basis of topography and local attitude discordance. They may be relatively late and minor features in this major zone of discordance. The zone may be quite old and may have controlled the intrusion of the Maromas.

The Middle Haddam fault zone does not appear to offset the Bonemill Brook fault at the surface. The northern boundary appears to merge with the Bonemill Brook fault where it makes a bend to the southeast. This area of "merging" is in the seismically active area. The gravity and topographic features apparently associated with the Middle Haddam fault zone continue southeastward down the Connecticut River and may represent faulting not exposed at the surface. Both gravity and aeromagnetic features are offset left-laterally across this zone down the Connecticut River. The gravity anomalies appear to be offset 5 to 6 km left-laterally across this zone (Kick, 1982). The topographic features could have resulted from reactivation of a basement structure in the Mesozoic. The Selden Neck fault appears to be a small, late, left-lateral feature down the lower Connecticut River and a small fault may lie in the river in the Haddam quadrangle (fig. 6). These, however, appear to be much too small to explain the geophysical features.

Another feature suggesting a deep structure is a northwest-trending belt of small ultramafic bodies that lies near the Connecticut River (Sawyer, 1979) (STOP 7) (fig. 6). This belt follows approximately the Middle Haddam and the southern part of the Bonemill Brook fault zones. These bodies may indicate the former presence of deep fractures along these zones. An understanding of the Middle Haddam fault zone must wait on additional field work.

MESOZOIC AND YOUNGER STRUCTURES

The northeast-trending, west-dipping to vertical Early Jurassic Higganum diabase dike zone (STOP 1) is the most prominent known Mesozoic feature passing through the Moodus area. This zone of dikes extends from Long Island Sound to near Portland, Maine and apparently represents a deep fracture zone in the crust, although it does not necessarily follow a fault zone at the surface. The dike locally follows the surface trace of an early thrust fault

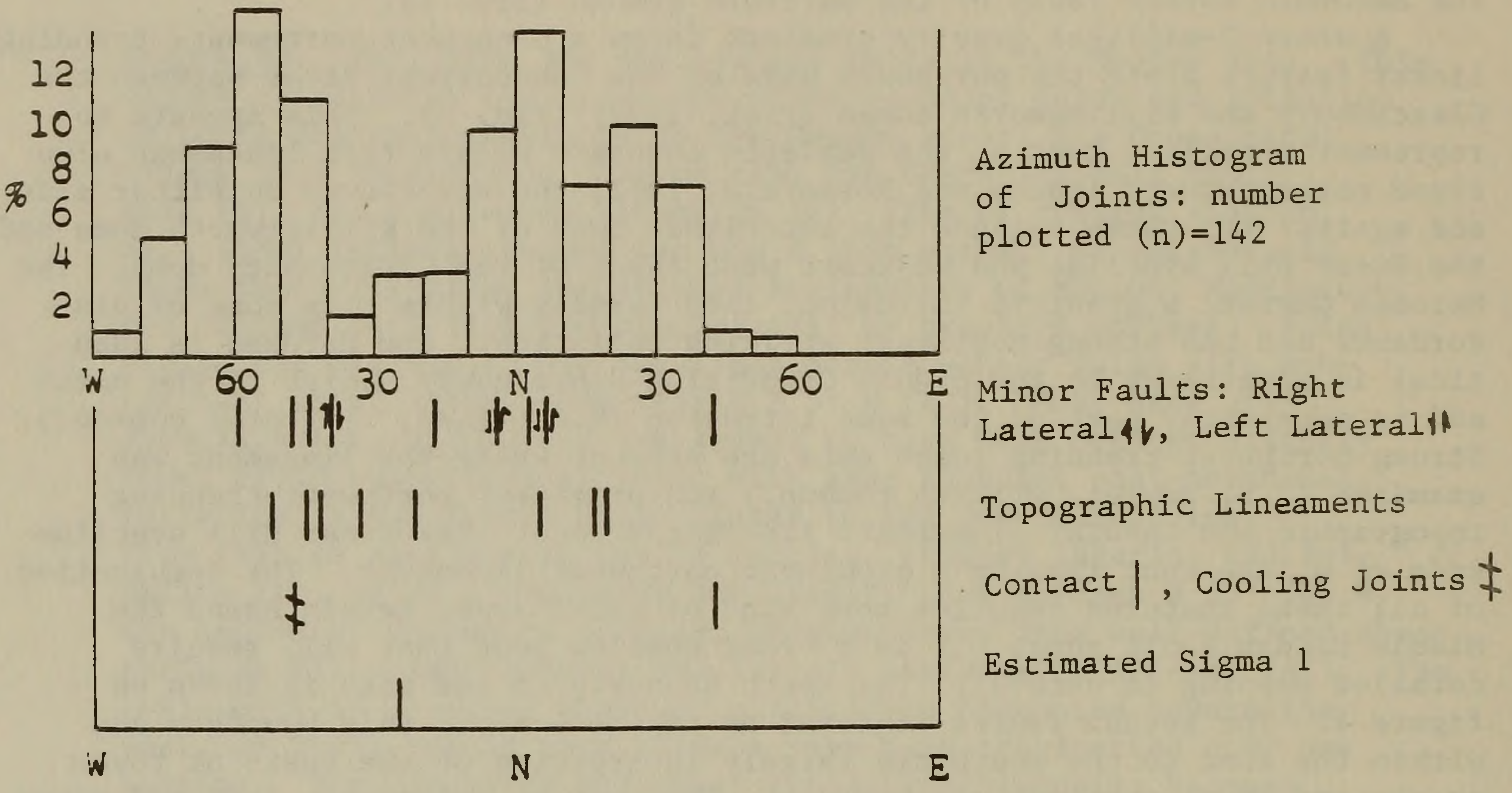


Figure 11. Typical azimuth histogram of joints for a segment of the Higganum dike near the village of Higganum, CT. (Sawyer and Carroll, 1982)

west of Moodus (STOP 1) (fig. 6). The local northwest dip of the normally vertical dike may be due to some deflection of the dike by the thrust zone. The dike is cut by small faults that have northerly and northwesterly trends. Fractures in the dike near Higganum, Connecticut may have been produced by a subhorizontal axis of compression oriented approximately north-northwest--south-southeast (Sawyer and Carroll, 1982) (fig. 11).

Abundant small northeast-,northwest-,and north-trending faults, that may be Mesozoic in age, cut rocks of the Moodus area (fig. 6). The northwest-trending faults appear to be the youngest. These faults are exposed at places in roadcuts and other fresh excavations in bedrock and have steeply dipping fractures and shear zones with slickensides, breccia and gouge (STOPS 1 and 9); these zones are easily eroded and are rarely exposed in natural outcrop. Many of the topographic and LANDSAT lineaments in the region have the same trends as these small faults and may be controlled by them.

The northwest-trending Connecticut River forms the most prominent lineament in the area. The Selden Neck fault, which has an apparent 0.7 km left-lateral offset and is well expressed topographically, may extend northwest up the river to near the mouth of the Salmon River (fig. 6). Projection of mapped contacts from opposite sides of the Connecticut River where it flows east in the Middle Haddam quadrangle indicates that a fault with right-lateral offset of about 200 m lies beneath the river.

The northeast-trending Salmon River forms another very prominent lineament that may be fault controlled. It crosses the nose of the Moodus anticline and appears to be controlled by small faults in the northeast (R. J. Fahey, written commun.) and southeast corners of the

Moodus quadrangle, but its center has yet to be mapped in detail (STOP 5). A gravity low forms a lineament along the river (Kick, 1982) that is not explained by lithologic differences at the surface (fig. 3). The river also has several north-and northwest-trending jogs along its course that follow topographic lineaments extending across it.

No recent offsets have been identified in the Moodus area, but mapping is still incomplete. Recent displacement of bedrock, however, is known to have taken place along Route 11, east of Moodus, where drill hole scars are offset across small thrust faults in roadcuts (Block and others, 1979) (STOP 8). The movement is up, north side over the south. The greatest offset occurs in the exposures that are cut on both sides between the roadways; little is seen in the outer cuts. This movement is similar to that reported from quarries and other highway construction in the region and is apparently from a release of residual strain due to changes in pressure caused by removal of the rock. It is not possible to determine when this strain was imposed on these rocks because the direction of recent movement in the road cuts is approximately the same as the apparent direction of earlier movements dating possibly as far back as the Precambrian.

MOODUS EARTHQUAKES

The Moodus noises have been ascribed to the anger of Indian gods due to the arrival of English ones, subterraenean explosions, a mysterious substance in the neighborhood and glacial rebound (Chapman, 1840). None of these explanations appears adequate. Studies in New England indicate that earthquakes are almost certainly caused by movement on faults generated by tectonic strain (Barosh, 1981b). The number of structures converging at Moodus does make it an unusual area and show it has a long history of tectonic events. Recent movement probably has occurred on structures along the Salmon River because earthquake activity has taken place mainly along the south side of the river (fig. 2), near topographic lineaments extending from jogs in the channel (Barosh and Pease, 1981). The earlier earthquakes are too poorly located to permit associating them with any specific structure. The larger of the many small seismic events presently occuring along the Salmon river might well be generated by some combination of movements on brittle faults along and transverse to the river. Such movements might change the local stress conditions, resulting in movement on old structures due to residual strain release, such as happened along Route 11 (STOP 8), and initiation of a swarm of tiny earthquakes.

FAULT CHARACTERISTICS

The structure of the region developed in several episodes over a long period of time, from Late Precambrian to post-Jurassic. The earthquakes at Moodus apparently indicate continued deformation to the present. The relative timing of deformation is inferred from features indicative of the relative depth (deep, intermediate or shallow) at the time of deformation, with the shallow (brittle) deformation presumed the youngest. The older structures are believed to have developed under much greater pressures and temperatures than the younger ones. Consequently, the structures, especially the faults, vary widely in their characteristics, from deep ductile to shallow brittle features. This variation in fault characteristics and the presence of both compressional and extensional features provide a wide, albeit sometimes confusing, variety of structures to be seen in the region, but is useful in sorting out relative ages.

The deepest deformation is characterized by the development of a strongly mylonitic texture in gneiss, by the growth of feldspar porphyroblasts and quartz-feldspar rods, by migmatization, and by folding to which the alignment of primary minerals is axial planar. Somewhat shallower deformation is characterized by folding of foliation and layering, accompanied by the development of a mineral lineation normal to the direction of movement.

Deformation at intermediate depth is characterized by retrograde metamorphism along structures that appear to have been produced under conditions of low metamorphic grade (zeolite to greenschist facies). The various types of retrograde deformation structures including quartz rods and veins, K-feldspar plus chlorite alteration zones, massive mylonite recrystallized to chlorite and chloritized slickensides are most abundant near shear or fault zones. In the Moodus area, these deformation features are concentrated in broad fault bands, some of which, such as the Injun Hollow fault zone (STOP 7), are up to 200 meters wide. Slickensides in chlorite are by far the most common of these features; such slickensides can be found in most rock types, and they occur in most excavations into bedrock.

Deformation at shallow depths is manifested as tectonic jointing and slickensiding without accompanying retrograde metamorphism, the development of sheared zones of crushed or granulated rock and, with more intense shearing, the production of silty or clayey gouge. Joints are by far the most common of these features in the Moodus area, although not all of them have been produced by tectonic deformation. Slickensides without attendant retrograde alteration are present, but rare. Zones of crushed or finely milled rocks are seldom exposed in natural outcrop, as these zones are very easily eroded and become stream drainages or topographic troughs.

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ROAD LOG

MAPS. 7.5-minute quadrangle maps covered in this road log are the Middle Haddam (STOP 1), Deep River (STOPS 2, 3, 4, 5 and 7), Moodus (STOP 6), Haddam (STOP 8) and Hamburg (STOPS 8 and 9). The STOPS are shown on figure 6.

MILEAGE

0 Start at interchange Rts. 9 and 81; exit 9, Higganum, on Rt. 9 (marked as exit 8 on topo. map).
Park at southwest side of interchange on Rt. 81 at bottom of entrance ramp to Rt. 9 south (To reach the start from the University of Connecticut at Storrs, travel west on Rt. 44A and Rt. 84 to Hartford and thence south on Rt. 91 to Rt. 9. Allow nearly an hour).

STOP 1, Paleozoic thrust fault cutting the Killingworth dome, Mesozoic (?) high-angle reverse fault and Early Jurassic Higganum diabase dike.

This complex of outcrops was chosen primarily for its array of tectonic features which originated under varied conditions of rock strength. The metamorphic rocks provide excellent examples of ductile flow folding and thrust faulting, whereas the diabase dike is laced with cooling joints and fractures resulting from brittle deformation. Three areas of outcrop in this interchange provide details of these different deformation styles.

Area 1 - Outcrops along the southeast side of Rt. 81 northeast of Rt. 9.

The metamorphic units belong to the relatively broad contact zone between the Haddam Gneiss and Middletown Formation. They consist predominantly of felsic gneiss and amphibolite of volcanic origin. Sillimanite occurs as the highest metamorphic index mineral. The meta-volcanics contain northeast-trending flow folds with subhorizontal axes. The axes of the folds show a large variation in trend, as much as 45°, and suggest either decollement movement, or the effects of subsequent shearing along thrust faults. The direction of tectonic transport appears to be predominantly to the southeast, but evidence for the opposite sense of tectonic transport can be found as well. Axial plane cleavage which has developed locally suggests transport to the northwest.

Amphibolitic units clearly outline many of the folds. The folds are intersected and offset along low angle thrust planes, which contain pegmatites which are deformed by boudinage or shearing or both. These pegmatites occur throughout the Killingworth dome along north-dipping low-angle thrust faults and high-angle reverse faults. They appear to have been injected during deformation and are therefore considered syntectonic. The "concordant" syntectonic pegmatites are cut and intersected by younger "discordant" post-tectonic pegmatites determined to be Permian in age by radiometric and paleomagnetic studies. A detailed study of cross-cutting relations and petrology of the pegmatites in this region shows a continuum, suggesting a common age. However, the earlier pegmatites are known to be pre-Permian elsewhere in eastern Connecticut. The earliest syntectonic "pegmatites" are sodic and composed of oligoclase, quartz, and mica. Their emplacement was followed by foliated adamellites, white adamellites and pink trondhjemites, respectively. The post-tectonic sequence starts with pink adamellites, followed by red granites, and "exotic" trondhjemites. The syntectonic pegmatites are generally more sodic, and more radioactive; the post-tectonic pegmatites are more potassic and may contain minerals with relatively volatile elements, such as beryl, tourmaline, apatite and fluorite.

Area 2 - Roadcuts along entrance ramp to Rt. 9 south.

Facing northeast, the outcrop can be seen to contain a series of small nappes, thrust sheets. Northeast-trending flow folds are intersected and offset along a low-angle thrust fault, separating different blocks. In this specific outcrop the direction of thrust motion is difficult to determine. Thrusting could be interpreted to have been either northward or southward. Elsewhere in the dome, however, it is clearly southward. Boudins of sheared pegmatite occur locally along the thrust planes. At both ends of the outcrop the thrust zone is cut by steeply-dipping north- and east-northeast-striking faults. Motion along the north-striking faults appears to have been primarily strike-slip with a slight reverse, up-dip component. The well exposed fracture on the southeast end is a reverse fault with an offset of about 3 m. It is characterized by a wide zone of brecciation, containing narrow, mylonitic slivers. The fault was intruded by a basalt dike. The latter is weathered and no paleomagnetic age determination could be made. However, emplacement of this dikelet is undoubtedly related to that of the nearby Early Jurassic Higganum dike. The fault, which existed in the Jurassic, but is younger than the Permian or older thrust faults which it intersects, is most probably of Early Triassic age. The degree of brecciation suggests a relatively shallow depth of deformation.

Area 3 - Roadcuts along the exit ramp from Rt. 9 south.

Exposed here is part of the Higganum dike, a major tectonic feature which extends northeastward from Long Island Sound to southern Maine. At this locality the dike dips approximately 45° NW, and probably intruded a thrust zone. Magnetic profiles show, however, that it becomes subvertical with depth. Its width varies from 50 to 165m. The quartz tholeiitic dike was emplaced during the Early Jurassic, about 175 m.y. ago. Its emplacement postdates vulcanism in the Connecticut valley. The dike forms part of a regional dike system which extends throughout the Appalachians and is believed to have been emplaced along older faults during shearing with predominant left-lateral rotation.

The dike is characterized by large cooling joints, with excellent plumose patterns, which outline the massive columns; it is intersected by tectonic joints and faults with slickensided surfaces. The dominant fault set here is subvertical and trends northwest. Conjugate sets occur elsewhere. A detailed study of several hundred faults in the dike at 32 locations indicates that the "young" faults developed in response to subhorizontal compressive stress aligned north-northwest--south-southeast (Sawyer and Carroll, 1982). In summary, the following tectonic features can be observed at this interchange.

1. Northeast-trending flow folds, possibly of Acadian age, with subhorizontal axes. The direction of tectonic transport of these folds is predominantly to the southeast in the Killingworth dome, but local evidence has been found for reverse tectonic transport.

2. East-trending, north-dipping, low-angle thrust faults and reverse faults. Pegmatites were intruded and deformed during shearing along these fractures. The youngest (post-tectonic) pegmatites are Permian.

3. A northeast-trending diabase dike which was emplaced along a subvertical zone of shearing and extension during the Early Jurassic. A small dikelet, probably of similar age, that intruded an east-northeast-trending reverse fault. This fault may be of Early Triassic age and perhaps indicates that some compressional movement continued into the Mesozoic. By this time, however, rock units were significantly more brittle.

4. Northwest-trending, high-angle shear faults, with significant strike-slip components, intersect the Jurassic diabase. The principal compressive stress was oriented north-northwest--south-southeast.

Return to car, enter entrance to Rt. 9 south.

5.0 Turn right off Rt. 9 onto exit 7, East-Haddam--Moodus, and cross over Rt. 9 on Rt. 82.

5.8 Pass roadcut on left, that exposes the Bonemill Brook fault zone. Monson Gneiss to west separated from rusty schist of the Brimfield Group on east (see M. H. Pease, Jr., this volume, STOP 7).

6.8 Pass Cremation Hill fault at culvert.

7.1 Stop on shoulder on right next to large roadcut.

STOP 2, Cremation Hill fault zone and deformed Hebron Formation.

This exposure of the fault zone shows well the deformation of the Hebron and the concentration of pegmatite along the fault (fig. 7). The contorted rocks of the Hebron in the roadcut are part of the western flank of the large Moodus anticline (fig. 9). The Hebron Formation consists of thin-to medium-bedded medium-gray fine- to coarse-grained schistose granulite with thin light greenish-gray bands and lenses containing calc-silicate minerals. The foliation is parallel to the bedding. Note the large and small scale asymmetric folds with nearly horizontal north-trending axes (fig. 7). These and other small scale structures within the fault zone suggest that the vertical component of movement along the fault is east side up. The well-bedded schistose granulite rock of the Hebron is generally much less disturbed than is seen here. Abundant pegmatite occurs as wispy lenses to large bodies. Some is boudined and foliated and appears to be syntectonic. Pegmatite commonly forms in the Hebron along shears, small thrust faults and as lenses in folds where it is deformed. These commonly form in irregular shapes that are not necessarily due to later folding. The contorted bedding and pegmatite here is the result of deformation along the Cremation Hill fault.

Walk back, southwest, towards road sign Rt. 9 north and south, to culvert. Notice the increasing amount of deformation and of pegmatite. Some slickensided late fault surfaces can be seen cutting the massive pegmatite; mostly near vertical and trending N 20°-30° E. Strongly foliated migmatite with schist folia at culvert represents Cremation Hill fault. The steeply plunging fold axes of xenoliths in the pegmatite in the fault zone contrast with the near horizonal axes in the Hebron to the east (fig. 10) and indicate lateral movement along the fault. Other good exposures lie on the other side of the highway, just west of a circular asphalted area a short distance off the road. Low exposures of schist are present along the side of the highway slightly farther west of these. This rusty sillimanite schist probably belongs to the upper part of the Brimfield Group (M. H. Pease, Jr. this volume) indicating that the lower part is missing along the fault.

Return to car and proceed east.

7.9 Turn right, south, onto Rt. 9A, Middlesex Turnpike.

8.3 Turn right onto New Old Chester road.

8.35 Turn right again onto Old Old Chester road.
under Rt. 82.

9.2 Park beyond low overpass, Rt. 82. Walk along previous continuation of road for about 200 m to Roaring Brook.

STOP 3 - Cremation Hill fault zone.

This stop will also examine the nature of the contact between rock of the Hebron formation and that to the west. Along Roaring Brook, the Hebron again consists of layered schistose granulite composed of quartz, diopside, phlogopite and plagioclase and also in places carbonate and scapolite. The beds strike north-northwest and dip 20°-30° WSW. As at the previous stop, the Hebron here is folded about sub-horizontal, north-trending axes with asymmetric east-over-west transport. Broad low-amplitude, symmetrical folds that plunge shallowly to the west-southwest also occur. At the small exposure in Roaring Brook, the Hebron ends abruptly against a migmatitic gneiss that strikes N 20° W and dips vertically. The migmatite contains sheared slivers of Hebron that are deformed plastically, a ductile deformation quite unlike that seen elsewhere in the Hebron section. Just to the west are migmatitic muscovite-and K-feldspar-rich gneisses and schists that do not appear to be part of the Hebron section. This contact at Roaring Brook is the eastern exposure of a broad zone of ductile faulting termed the Cremation Hill fault zone (London, in prep.).

Return to car and retrace route to Rt. 9A.

10.5 Turn left onto Rt. 9A.

11.2 Pass Tylerville and junction Rt. 82 east to Moodus.

13.1 Turn left onto Old Turnpike road off Rt. 9A at fork in road.

13.13 Turn left, south, onto Old Ely road.

13.7 Park at powerline crossing. Walk to trail beneath powerline on west side of road.

STOP 4, Cremation Hill fault zone.

The trail uphill exposes the bedded diopside-phlogopite-bearing schistose granulite of the Hebron Formation in which scapolite is abundant. The beds dip about 30° to the west-southwest. The fault contact between the Hebron and rocks to the west is not exposed here, but outcrops in the woods to the north consist of unzoned, quartz-poor pegmatite that contains xenoliths of the Hebron and migmatitic stringers that may be assimilated Hebron granulite. At the crest of the hill, the power line cut exposes a thin band of migmatite and feldspathic blastomylonite that strikes approximately N 10° W through the Moodus area. This zone of migmatite is interpreted as the broad Cremation Hill ductile fault zone on the basis of (1) discordance to regional strike of the other rock types, (2) small-scale folds and mineral lineations in rocks within and surrounding the zone, and (3) the occurrence of deformed xenoliths of rocks that are present on both sides of the zone (London, 1982). The progressive feldspathization of aluminous schist exposed here suggests that the feldspathization of this rock is not the direct result of an anatectic melt. The schist west of the migmatitic zone consists of an apparent prograde assemblage of quartz, muscovite, sillimanite, albite, biotite, garnet, graphite, tourmaline, and some iron sulfide. With increasing migmatization, the graphite disappears, iron sulfides are oxidized to a pervasive hematite stain, and sillimanite is replaced by coarse, pseudomorphic patches of muscovite as the migmatitic zone is approached from the west. The disappearance of sillimanite does not appear to be the result of cordierite-producing reaction between sillimanite and garnet or biotite. Progressive development of K-feldspar porphyroblasts consumes muscovite and quartz. The resultant rock near the fault contact with the Hebron consists of 65-85% coarse-grained K-feldspar, 5-25% plagioclase, 5% fine-grained, 1-3 mm, shreds of relict biotite and garnet, and 5% coarse-grained euhedral muscovite that cuts the foliation. This late-stage muscovite may have been produced as the feldspathized rock attempted to maintain equilibrium with increasingly acidic fluids. Quartz is rare or absent in many of these feldspathized "pegmatitic" samples. This thin band of migmatite was mapped as Brimfield Schist in the Deep River area (Lundgren, 1963). A suggested stratigraphic correlation of this band of rocks with the Tatnic Hill Formation in the southeast Connecticut fold belt constituted much of the argument for a major recumbent synform, the Chester syncline of Dixon and Lundgren (1968). The mineralogy and fabric of the feldspathized rock and feldspathic migmatite, however, appear to be primarily the result of deformation and metamorphism, perhaps metasomatism, and are not directly related to any primary depositional characteristics of the rock. Several different rock types are involved in the feldspathization, and each original rock type produces a distinctive feldspathic rock.

The Cremation Hill fault zone may form an eastern branch of the Bonemill Brook fault zone that has been extended southward through this area (see M.H. Pease, Jr., this volume). The Cremation Hill fault zone itself has been followed north approximately 3 km into the Middle Haddam quadrangle, where the migmatitic gneiss and schist were included within the Schist of East Hampton by Eaton and Rosenfeld (1972). Delineation of the Cremation Hill zone beyond the southern half of the Middle Haddam quadrangle will require detailed field studies.

Two consequences of this recent study, therefore, are (1) that the thin band of migmatite and feldsphathic rock is not necessarily correlative with schist of the Brimfield Group or any other time-stratigraphic unit, and (2) that the migmatite delineates the trace of a ductile fault zone that separates rocks of the Hebron Formation from those to the west. Both of these interpretations contradict the supporting evidence for the Chester syncline in this area.

Return to car and go back to Rt. 9A.

14.3 Turn right onto Rt. 9A.

16.2 Turn left at Tylerville onto Rt. 82 east, to Moodus.

16.8 Bridge over Connecticut River, Hebron exposed on left, north side of east end of bridge.

17.1 Turn left onto Rt. 149, to Moodus.

18.0 Hebron Formation exposed on right for the next mile. Note the nearly undeformed bedding.

19.8 Turn left onto Johnsonville Road.

20.1 Pass Mt. Tom 0.5 mi. to left, west, one of the traditional locations for the Moodus noises. Cave Hill, 1.2 mi. ahead is the other.

20.4 Turn left onto Rt. 151, Moodus road, at stop sign.

21.3 Pass Cave Hill on right.

21.7 Turn right before bridge.

21.9 Turn left onto dirt road, proceed 0.1 mile and park above Salmon River.

STOP 5, Structural control of the Salmon River.

The Salmon River forms one of the most pronounced topographic lineaments in the area and the earthquakes of 1980, 81 and 82 occurred in a zone that extended from near here northeastward mainly along the southern side of the river. The area is not mapped in detail. No large fault has yet been found along the river, but at least small ones follow it southwest of here. The bedding of the Hebron Formation and small faults parallel the sides of the river in the bluff below the parking area and on the west side of the dam to the north. Exposures of Hebron in the river bed show some deformation. A brief reconnaissance to the northeast found a joint set parallel to the local trend of the river at each exposure seen along the river. These observations indicate that the river is structurally controlled whether or not recent faults are found. Examine the rocks in the area and

note the pegmatite in the bank on the northwest side of the dam. This coarse non-foliated pegmatite belongs to the set of Permian pegmatites that cut the region. The pegmatite cutting the Hebron at STOP 2 appears much older.
Return to highway.

22.3 Turn right,north, on Rt.151 and cross over the Salmon River.

22.7 Veer left on Rt. 151.

24.9 Turn left at sign - "Connecticut Valley Energy".

25.9 Turn left at fork, just beyond fire station on left onto Upper road.

26.8 Pass School House Hill Road on right.

27.2 Turn left at fork.

28.1 Pass electrical substation building on left and pass through gate. Hebron Formation on right.

28.5 Park at left at top of decline after passing under power lines.

Walk down hill along road about 100m to first old stone wall on left. Turn right, west-northwest, and go into the brush towards Connecticut Yankee nuclear power plant. Cross over slight knob of Hebron Formation adjacent to road. Walk down slope to concrete box under powerline and up rocky spur just beyond.

STOP 6, Cremation Hill fault zone.

The spur is composed of migmatite along the fault zone; a mixture of schist and some blocks of Hebron in pegmatitic material. Note the discontinuities in flow fabric and rotated folded blocks along this fault zone filled by feldspathized material. This, together with the previous STOPS 2, 3 and 4 helps to demonstrate that the Cremation Hill fault zone is a continuous mappable structure exhibiting deep-seated ductile deformation along its length.

Return to car, turn around and drive back towards fork near fire station.

31.1 Veer left at fork in road onto Middle Haddam Road.

32.5 Veer left at fork onto Injun Hollow Road.

34.0 Park at right on wide shoulder used for turning around; The Connecticut Yankee power plant is just out of sight down the road. Walk back 50 m to beyond small culvert under road and enter woods to east, uphill side. Proceed north angling uphill into Injun Hollow. Please use caution when climbing around the old quarries and steep slopes.

STOP 7, Injun Hollow fault zone, brittle faults and ultramafic intrusion.

This stop offers examples of most of the rock types exposed in the Moodus area and exposes the Injun Hollow fault zone that displays both Paleozoic ductile features and Mesozoic (?) brittle ones and other relatively young brittle faults. The trip begins in typical exposures of the Monson Gneiss. Proceeding northeastward and uphill into the hollow, the Monson Gneiss ends abruptly against pegmatite, followed by a 50-meter-wide interval of schist, gneiss, and amphibolite. At the crest of the hollow, and mainly within the schist, is a small near vertical lens of ultramafic rock, striking N 10° W, that appears to originally have been pyroxenite (the lens is just north of the upper end of the steep stream gulley that leads to the road culvert). The pyroxenite is now partially replaced by relatively fine-grained, acicular hornblende that cuts across grain boundaries and is lineated and foliated parallel to the regional trend in this area. The only exposed contact of the ultramafic body is with K-feldspar-rich pegmatite; apparent reaction between these two rocks has produced coarse-grained biotite at their contact. To the south in the Deep River area, all similar ultramafics occur in amphibolite and gneiss on the east flank of the Monson Gneiss; the ultramafic at Injun Hollow is the first such body to appear on the west side of the Monson (Sawyer, 1979).

The interval of schist, gneiss and amphibolite is bordered to the west, in the quarries, by a prominently lineated and foliated gneiss that may be a recrystallized phase of the Monson. This appears to be part of the west flank of the near vertical Injun Hollow fault zone, that strikes about N 10° E along the east side of the hollow. Quartz and plagioclase are conspicuously lineated; biotite and hornblende are segregated into thin (1-2 mm) folia that are continuous over several square meters of quarried outcrop surface. It is the presence of these folia that facilitated the quarrying of this rock into rectangular slabs. Continuing to the northeast, the Monson is succeeded again by orthoamphibole-bearing gneiss and schist and by aluminous schist, although the sequence of layering is different from that seen below.

Pegmatite and quartz veins are abundant in these exposures. The pegmatite is muscovite-and tourmaline-rich, displays sharp contacts with the host rock, has relatively thin border zones, and consists principally of quartz-K-feldspar block pegmatite with centrally located quartz cores. It is distinctly different from pegmatitic rock in the Cremation Hill fault zone (STOPS 2,3,4 and 6) and in the Hebron Formation (STOP 2).

Rock in the Injun Hollow area appears to have suffered shearing deformation over a long period. This is shown by a continuum of subparallel mineral lineations produced from conditions of high metamorphic grade (upper amphibolite facies, presumably deep-seated and "old") to low metamorphic grade (lower greenschist facies, and relatively shallow and "young"). In the border phase of the Monson Gneiss the segregation of biotite and hornblende into thin but continuous folia also indicates relatively high pressure and temperature that did not produce a cataclastic texture. At some intermediate pressure and temperature, shearing deformation produced planes of rodded quartz with cataclastic feldspar in the mylonitic gneiss. All of this deformation predates the intrusion of the pegmatites and thus is older than 261±4 m. y. before the present (Brookins, 1970). Younger, Mesozoic (?) and shallower shearing deformation produced slickensides in fine-grained chlorite, and chlorite and K-feldspar bleached, oxidized (?) zones adjacent to shears. In the quarries, these shear surfaces can be seen to follow pre-existing planar structures. In one quarry exposure, a slickensided surface covers about 20 square meters of outcrop surface along foliation trending N 20° W before the shear surface veers off abruptly N 30° E along a pegmatite contact. Closely spaced fractures also are localized in planar swarms, but their relation to the "chlorite grade" deformation is not clear.

Throughout the entire episode of faulting, the sense of offset appears to have been left-lateral with west-side-up and largely strike-slip. The amount of offset is difficult to estimate, because most of the deformation is subparallel to layering and foliation; however, the strike of layering and foliation is north in rocks east of the fault zone, but N 20° W in rocks west of the fault. Angular discordance in the fault zone can be seen along the east side of Injun Hollow. The fault zone continues south of the Connecticut River, where it occurs mostly in aluminous schists and is not well exposed; however, the same angular discordance of strike, north versus N 20° W, exists in rocks flanking the fault zone. The Injun Hollow fault zone disappears under glacial drift just north of the stop area, and it has not been recognized in the Middle Haddam and Moodus quadrangles. It appears to cut north-northeastward across the Monson Gneiss and may reappear in rock east of the Monson.

The exposures at Injun Hollow reflect the complex interleaving and the discontinuity of rock units that is characteristic of the Bronson Hill sequence in this region. In this immediate area, there is no consistent lithologic variation across strike that would indicate a repetition of lithologic units by folding as has been suggested by Dixon and Lundgren (1968) and others. Individual rock units in the interval mapped as Middletown Formation and Collins Hill Formation (Eaton and Rosenfeld, 1972, Lundgren, 1979) rarely extend for more than a few tens of meters along strike. The chaotic variation of rock types seen here may be due in part to primary deposition in an unstable tectonic environment; however, it appears to result largely from the subsequent deep-seated ductile deformation that has transported thin, smooth, fault-bounded slivers of rock over one another.

Three subvertical brittle fracture zones trending N 30° E, north, and N 20° W intersect in the area of Injun Hollow, one of the few places in the Moodus area where such a fracture intersection occurs. The relative timing of fractures is not clear here, although the northwest-trending fractures cut all others elsewhere to the east and southeast.

Return to car and turn around.

Return to Rt. 151, Moodus Road.

36.7 Turn right onto Rt 151 and follow it south through Moodus.

44.2 Turn left, east, onto Mount Parnassus Road, 50 m south of intersection of Rt. 151 with Rt. 82.

52.0 Veer right onto Salem Road.

53.0 Turn right onto Mill Lane Road.

54.0 Turn left onto Witch Meadow Road.

54.5 Turn right onto Rt. 11 south.

55.8 Park at large roadcut in southbound lane. Use caution when walking along roadway.

STOP 8- Fault reactivation due to highway construction.

The Hebron Formation, which consists predominantly of calc-silicate-bearing schistose granulite, is tilted slightly north, and contains flow folds with approximately horizontal axes and northward tectonic transport and many boudinaged sodic "pegmatites". The outcrop is intersected by a series of north-northwest-dipping shear planes which mainly follow bedding contacts. The best exposed thrust zone occurs on the south end of the outcrop in the divider strip. It is characterized by a 30 cm shear zone, which is leached. In a zone about 4m above and below this shear zone occur slickensided mylonitic thrust planes along which the vertical drill hole scars from highway construction have been offset updip (Block and others, 1979). Thrust planes generally trend N 55°±20° E and dip 15° ± 10° NNW: a conjugate set of antithetic shears occurs with a trend of N 45°-55° E.

P7-31

Construction of this segment of Route 11, from Colchester to Route 82, Salem, began in 1970. Shortly after construction, it was noticed that a number of drill hole scars in the freshly exposed outcrop were offset. Displacement was southward up shallow north-dipping foliation and thrust planes and generally amounted to a few cm. It initially appeared to be a blasting phenomena, but this possibility was discounted for most offsets when blast patterns and volume of displaced rock were analyzed. In addition it was found that the direction and amount of slip did not vary significantly over a distance of almost 10 miles, whereas the road bends from north to northwest. The following data characterized the drill hole scar offsets:

a. Displacements are invariably updip on planes inclined from 5° to 30°.

b. Displacement occurs either parallel or at slight angles to the road bed. The mean direction is S 32° ± 5° E.

c. Displacement varies between 0.5 and 6.0 cm with a mean value of 2.6 cm.

Shortly after blasting it was decided to monitor 5 sets of drill holes for possible future motion. Measurements were made every 6 months over a period of 10 years. Of these five holes, three showed significant creep in subsequent years, one had little motion, and one none.

Most interesting is the behaviour of one of the sets of drill holes in the Brimfield Schist further north. Initial offset of the drill holes amounted to 19.2 cm. Over a period of 9 years this offset increased to 43.6 cm. No discernible motion has occurred along the slip plane in the last few years, 1980 to 82. Thus, offset caused by creep amounted to more than 50% of the total. Creep rate averaged about 27 mm/yr. The movement shows a direct relation to roadcut excavation. More offset occurs on outcrops in the divider strip, that have been cut on both sides and thus are freer to move than on the outer exposures. A survey did not find any offset of water wells in the area subsequent to the highway construction, as would be expected if the creep rate operated away from the road (J.S. Sawyer, written commun.).

The shear planes along which the motion occurred are characterized by well developed slickensides which provide evidence for an earlier phase of deformation. Earlier thrusting was directed S 54° E. The recent motion is S 32° E, suggesting that the direction of strain release may have rotated some 20° in clockwise fashion. The Early Jurassic Higganum dike has been deformed by stress that appears to have been oriented S 27° E - N 27° W. This coincidence in the direction and types of strain release suggests that the strain may have been imposed as early as the Early Jurassic. It is possible, however, that these stresses already existed at the time of emplacement of the dike and are of Permian origin or older. The direction of movement on the nearby Honey Hill fault zone, that originated at least in the early Paleozoic, is to the south-southeast and the principal direction of transport in the syntectonically deformed Late Precambrian granites, south of the Honey Hill fault, is also to the south-southeast. The movement appears to represent strain released due to the rock adjusting to new conditions of confining pressure caused by highway construction and is not due to recent stress. Whether or not the strain was imposed recently or during the Mesozoic, Paleozoic or even Precambrian cannot be determined. Many similar rock movements have been noticed earlier in quarries and more recently in other highway cuts.

The importance of these movements to the seismicity at Moodus is that the larger amount of offset that occurred during construction probably produced a few small low magnitude earthquakes. "Noises" were heard during times when no blasting occurred and one or two water wells within about 50 m of the road were effected. No instrumentally recorded seismicity is known to be associated with these, but the seismograph network at that time would have been too sparse to record it. Movements of this amplitude along old structures might well be producing the swarms of small shallow aftershock earthquakes occuring along the Salmon River.

Continue south on Rt. 11.

56.4 Pass over Honey Hill fault zone.

57.2 Park to left on divider strip beyond barrier at the end of the highway.

STOP 9, Thrust and normal faults.

The gneiss here consists of a sequence of light-gray biotite-poor and dark-gray biotite-rich varieties that is near the boundary of the Monson and Mamacoke Formations (Lundgren and Ashmead, 1966) of Precambrian age. The roadcuts are intersected by a series of low-angle thrust faults and some small folds. Thrust planes move upward in the section to the south, suggesting southeast motion. In several places one can see northeast-trending, north dipping normal faults which connect thrusts at different levels and contain quartz-albite veins. Significant drag along these faults indicates a degree of ductility in the rock which cannot be seen along younger fractures. These faults may be caused by backward sliding of the rockmass in the late stages of thrusting.

Thrust and associated normal faults are intersected by dense sets of conjugate joints and normal faults. The majority trend northeast and dip 55° ± 10° SE. The antithetic normal faults have similar trends but dip more steeply northward indicating monoclinic symmetry. The best conjugate set can be seen in the outcrop of the divider strip. Here a normal fault shows 1.7m of offset of a mafic gneiss and a conjugate normal fault south of it offsets the same unit in opposite sense about 1m. These faults and associated joints formed pathways for hydrothermal solutions, which left epidote, chlorite, quartz and hematite. Paleomagnetic analysis of the red stained feldspar in 2.5 cm wide zones on either side of the joints, provided Early Triassic paleopoles.

The following tectonic events can be recognized in STOPS 8 and 9.

1. Development of northeast-trending flow folds of Acadian(?) age with subhorizontal axes indicating northward transport.

2. Emplacement of sodic "pegmatite" parallel to the bedding and along low-angle, north-dipping thrust planes. The pegmatite was subsequently sheared and boudinaged. North-dipping normal faults connect the thrust faults. They contain quartz-albite veins and may have formed in the late stages of pegmatite formation. Significant drag in both the hanging and foot blocks indicates a certain degree of ductility of the rock.

3. Reactivation of north-dipping low-angle faults by southeast thrusting; a motion perhaps opposite to that in the earlier deformation stage. Movement resulted in the development of mylonitic (slickensided) and sheared-brecciated zones. At the time of southeast thrusting the rocks appear to have been mostly brittle.

4. Development of a conjugate set of northeast-trending normal faults and joints. Southeast-dipping faults and joints predominate. Hydrothermal solutions followed these fractures and left a chemical remanent magnetization of Early Triassic age.

5. Continued release of strain and continued motion along the thrusts, whether abruptly (possibly causing very low magnitude earthquakes) or by creep.

END OF FIELD TRIP.
(To return to Storrs, CT, follow Rt. 11 north to Colchester, Rt. 85 north to Hebron, Rts. 66 and 84 northeast to Rt. 195 and thence north to Storrs.)