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CHARACTERISTICS AND REGIONAL SIGNIFICANCE OF THE CREMATION HILL DUCTILE FAULT ZONE AT THE BRONSON HILL-MERRIMACK BOUNDARY, SOUTH-CENTRAL CONNECTICUT

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ABSTRACT. The newly identified Cremation Hill ductile fault zone lies at the boundary between the Bronson Hill and Merrimack terranes in south-central Connecticut. Deformation and concomitant high-grade metamorphism in the Cremation Hill fault zone have produced a distinctive blastomylonitic rock composed of nebulitic migmatite, augenoid schist, and gneissic to massive syenitic pegmatite. Pressure-temperature paths for the Cremation Hill fault rocks and adjacent non-migmatitic metapelites were identical; mineral equilibria record retrograde paths from a peak at approx 685°C, 7.1 kb to 560°C, 5.2 kb. Migmatization and feldspar porphyroblasis may be explained partly by anatexis and alkali metasomatism due to locally higher aH_2O in the Cremation Hill fault zone than in surrounding non-migmatitic schists, where aH_2O was ≤ 0.5 during peak metamorphism. Previous stratigraphic correlations of this fault rock (a lithodemic unit) with the Brimfield Schist (a lithostratigraphic unit) are not valid. The Cremation Hill fault apparently represents the southward extension of the Bonemill Brook fault in northern Connecticut; this single ductile fault system may constitute a structural boundary between Bronson Hill and Merrimack terranes in eastern Connecticut.

INTRODUCTION

Improved geological understanding of the crystalline rocks in eastern Connecticut is essential to understanding the Appalachian orogen in New England (Zartman and Naylor, 1984). From quadrangle mapping conducted mostly between 1955–1965, Dixon and Lundgren (1968) synthesized the first model for the geology of eastern Connecticut, and their interpretations have had a profound impact on subsequent maps and models for the tectonic evolution of the region (Rodgers, 1970). The model of Dixon and Lundgren (1968) is predicated on two important inferences: (1) that depositional conformity exists between most (non-intrusive) formations, and (2) that all metamorphic rock bodies are lithostratigraphic. The correlation of similar but widely separated rock types constrained Dixon and Lundgren (1968) to a unique interpretation of the regional structure: a system of rooted nappes and regional folds that provided the continuity dictated largely by inferred stratigraphic correlations (see Dixon and Lundgren, 1968).

Subsequent work in the region has led to a significant departure from the model of Dixon and Lundgren (1968). An important aspect of recent work is the recognition of numerous ductile fault systems that

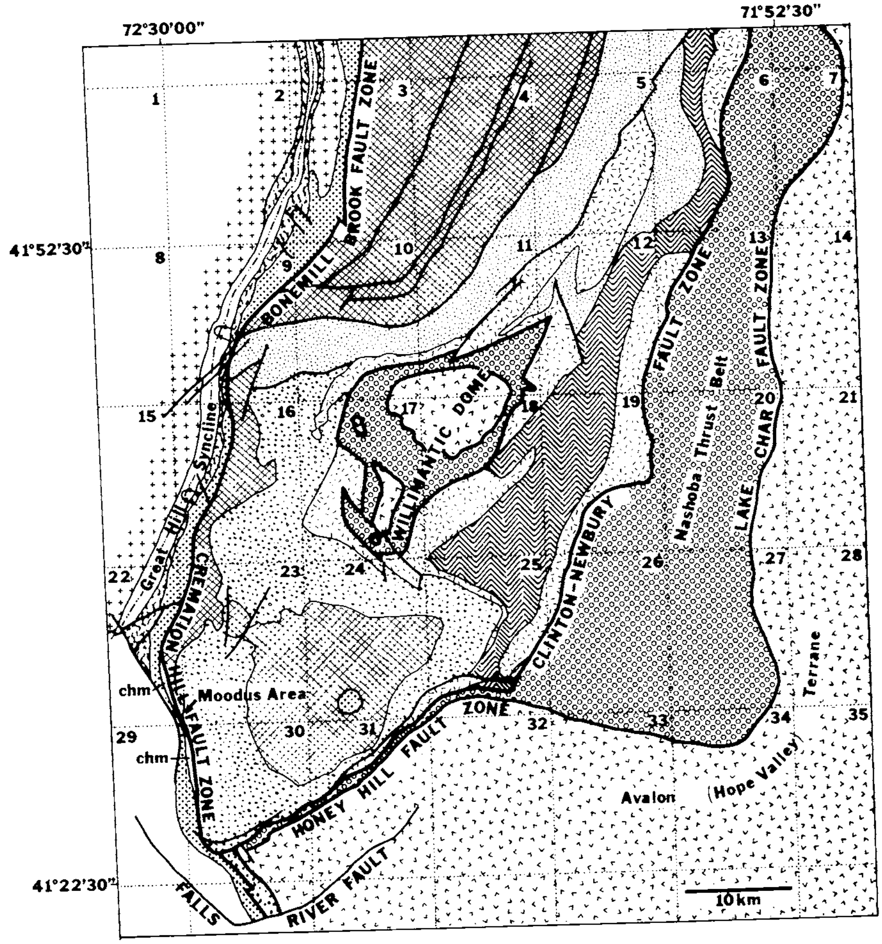

Fig. 1. Generalized geological map of eastern Connecticut from Pease (1982). The map and some labels (Hope Valley terrane: O'Hara and Gromet, 1985) are modified slightly; most map relations, unit labels, and stratigraphy are as depicted by Pease (1982). Note that Pease's interpretation differs substantially from previous maps by Rodgers (1985) and Dixon and Lundgren (1968), and the reader is referred to these latter two works for alternative views. The numbered 7.5' quadrangles are: (1) Broad Brook, (2) Ellington, (3) Stafford Springs, (4) Westford, (5) Eastford, (6) Putnam, (7) Thompson, (8) Manchester, (9) Rockville, (10) South Coventry, (11) Spring Hill, (12) Hampton, (13) Danielson, (14) East Killingly, (15) Glastonbury, (16) Marlborough, (17) Columbia, (18) Willimantic, (19) Scotland, (20) Plainfield, (21) Oneco, (22) Middle Haddam, (23) Moodus, (24) Colchester, (25) Fitchville, (26) Norwich, (27) Jewett City, (28) Voluntown, (29) Haddam, (30) Deep River, (31) Hamburg, (32) Montville, (33) Uncasville, (34) Old Mystic, and (35) Ashaway. The Moodus map area (fig. 2) lies near the intersections of the Haddam (29), Middle Haddam (22), Moodus (23), and Deep River (30) quadrangles. Also shown is the distribution of migmatitic rocks (*chm*) in the Cremation Hill fault zone.

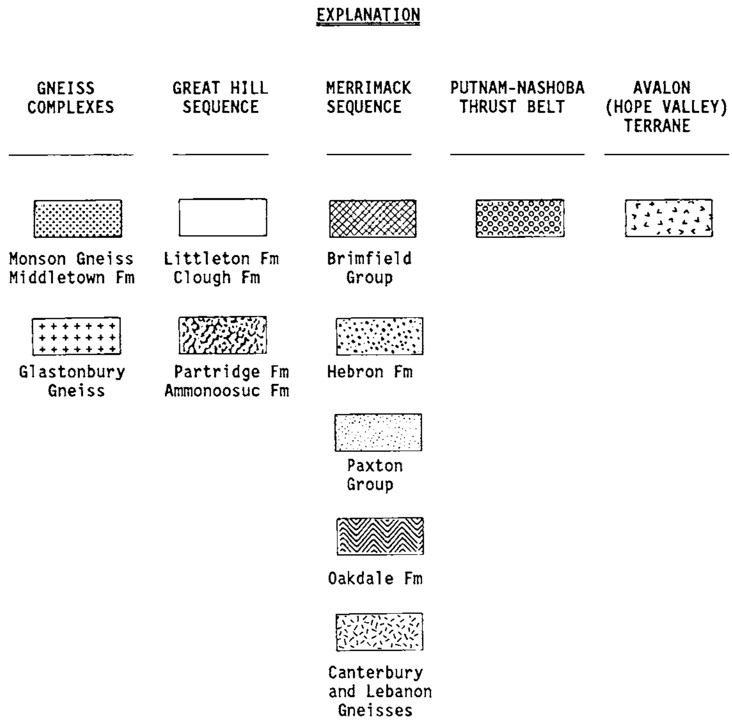

Fig. 1. (continued)

occur both within and between formations (Peper, Pease, and Seiders, 1975; Pease, 1982; Wintsch, 1979) (fig. 1). The discontinuities introduced by ductile fault boundaries place in question much of the inferred stratigraphic continuity that was the foundation of the Dixon and Lundgren model. As a result, the regional structure of eastern Connecticut is no longer limited to the unique solution required by the previous stratigraphic correlations, and numerous alternative hypotheses now exist. The recently compiled bedrock geological map of Connecticut (Rodgers, 1985) depicts several of these ductile fault zones, including the Cremation Hill and Bonemill Brook faults discussed here, but a unified revision of the geology of eastern Connecticut has not yet been presented.

In many instances, the ductile fault zones of eastern Connecticut are difficult to recognize. Most such fault zones were active during high-grade regional metamorphism; hence, foliated, coarse-grained fault rocks dominate, and rocks in and around the fault zones attained similar metamorphic grades. In addition, layering and foliation of the juxtaposed rock units generally parallel the fault traces, and the fault zones themselves may be broad (several hundred meters wide) and diffuse. The identification of ductile fault zones is especially difficult where they traverse relatively incompetent schistose rocks because ductile strain is transmitted pervasively throughout the rock bodies.

This paper presents evidence for a newly recognized ductile fault zone in south-central Connecticut, the Cremation Hill fault zone. Unlike some other ductile fault zones in eastern Connecticut, for example the Honey Hill (Lundgren and Ebblin, 1972) and Willimantic (Wintsch, 1979) faults that are developed mostly in gneissic rocks, the Cremation Hill fault lies entirely within mica-rich schists. Hence, its field characteristics are quite different from the other, better-known fault zones noted above. In addition, the recognition of the Cremation Hill fault zone poses new challenges to the geological model of Dixon and Lundgren (1968) and represents an important component of a revision of the structure and stratigraphy of eastern Connecticut.

GEOLOGY OF THE MOODUS AREA

The Cremation Hill fault zone has been identified through recent detailed mapping in a 60 km^2 area that includes portions of the Haddam, Middle Haddam, Moodus, and Deep River 7.5′ quadrangles (London, 1984, 1988) (fig. 2). In the geological model of Dixon and Lundgren (1968), this region, termed the Moodus area, encompasses the west-to-east transition from mafic to felsic gneisses and amphibolites (Monson and Middletown formations) and aluminous schists (Collins Hill Formation) of the Bronson Hill terrane to aluminous schists (Brimfield Group) and calc-silicate-rich rocks (Hebron Formation) of the Merrimack terrane (see also Zen, 1983; Zartman and Naylor, 1984). In the Deep River and Moodus quadrangles, Lundgren (1961; Lundgren, Ashmead, and Snyder, 1971) correlated a thin band of augenoid, nebulitic, schistose migmatite (labelled *chm* in fig. 1 and stippled area in fig. 2) with the Brimfield Schist (now Brimfield Group: Peper Pease, and Snyder, 1975). Eaton and Rosenfeld (1971) named the migmatitic schist as Schist of East Hampton. Their correlation with Brimfield or Collins Hill was more tentative, because of obvious textural and mineralogical differences between the migmatitic schist and the non-migmatitic metapelites elsewhere in the region. The Moodus area also contains the axial traces of two proposed regional folds, the Monson anticline and the Chester syncline, which are key elements of the Dixon and Lundgren tectonic model. In the Moodus area, the axial traces of both proposed folds strike north-south with vertical axial planes. Dixon and Lundgren (1968) and more recently Rosenfeld and Eaton (1985) have proposed that both folds are overturned to the east, with the eastward-opening Chester syncline overlain by the recumbent anticlinal Monson nappe (Rosenfeld and Eaton, 1985).

In the Moodus area, the mapping by London (1988) has delineated (at a scale of 1:12,000) a greater diversity and complexity of rock types than was previously recognized. The lithologic continuity of units along and across strike has been shown to be far more variable and chaotic than was previously indicated. While some of this complexity may stem

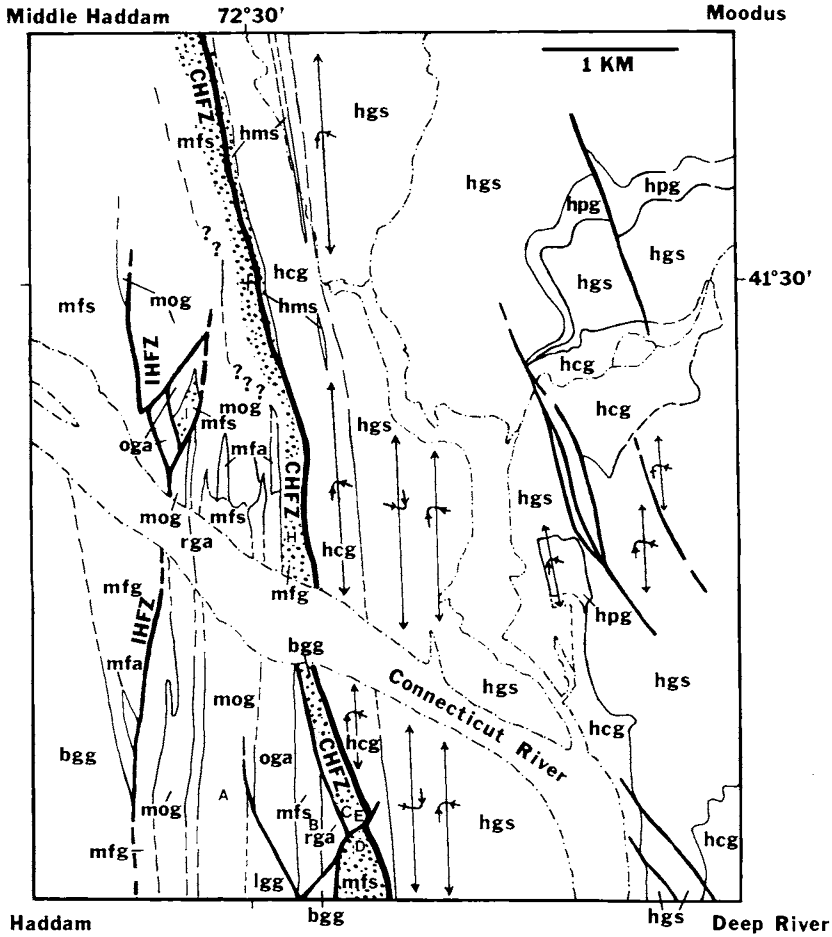

Fig. 2. Simplified geological map of the Moodus area. The Cremation Hill fault zone (CHFZ) marks the boundary between Bronson Hill rocks (west) and Hebron Formation (east); stippled areas denote migmatitic and blastomylonitic fault rocks. Several other ductile faults are shown, including the Injun Hollow fault zone (IHFZ). Map units represent lithodemic descriptions in which no stratigraphic relations are expressed or implied; hence, the sequence in which units are described below has no stratigraphic connotations. In the report of London (1988), rocks in the Bronson Hill interval are grouped as a metamorphic complex in order to avoid any structural implications that would be inferred from ambiguous stratigraphic correlations:

Bronson Hill: *mog* (hornblende-biotite plagioclase gneiss, = Monson Gneiss), *lgg* (leucocratic plagioclase gneiss), *rga* (thinly interlayered hornblende amphibolite—plagioclase gneiss), *mfa* (massive feldspathic amphibolite), *oga* (orthoamphibole-bearing chlorite schist, plagioclase gneiss, and muscovite-sillimanite schist), *bgg* (biotite-garnet-sillimanite gneiss), *mfg* (muscovite-biotite-garnet-sillimanite feldspathic gneiss), *mfs* (muscovite-biotite-garnet-sillimanite schist).

Hebron Formation: *hcg* (diopside-quartz-phlogopite-scapolite-calcite granofels and gneiss), *hgs* (biotite-rich gneiss and feldspathic schist), *hpg* (granitic gneiss), and *hms* (muscovite-quartz schist).

Capital letters denote locations referred to in the text and in figure 3. See London (1988) for additional lithologic descriptions.

from the environment in which the protoliths of the metamorphic rocks were deposited, much of the stratigraphic disruption results from transposition during regional ductile deformation at high metamorphic grade.

THE CREMATION HILL FAULT ZONE

Field characteristics.—The surface expression of the Cremation Hill fault is defined by a thin band of texturally complex, coarse-grained (4–15 mm) feldspathic migmatite and augenoid schist (strippled area in fig. 2), which is distinct from the fine-grained (1–3 mm), non-migmatitic metapelites that typify the Collins Hill Formation (or equivalents?) in this region (fig. 3). The compositions of feldspar augen in the migmatitic schists reflect the compositions of the protoliths: plagioclase predominates in migmatite and feldspathic schist derived from aluminous gneisses (unit *bgg* in fig. 2), and orthoclase is prevalent in the derivatives of muscovite-rich aluminous schists (unit *mfs* in fig. 2). Orthoclase is present within the Cremation Hill migmatites only where sillimanite has been completely replaced by coarse-grained, foliated muscovite, and orthoclase porphyroblasts show no petrographic evidence of replacement or resorption by muscovite. Two generations of muscovite are texturally distinct: (1) an earlier, coarse-grained, foliated muscovite that has partially replaced sillimanite and biotite, and (2) a later generation of randomly oriented muscovite that crosscuts and largely obliterates the foliation. Graphite and iron sulfides in the aluminous protoliths may have been oxidized during migmatization and feldspar growth (see, also, Wintsch, 1981). Graphite is absent in the migmatitic rocks, and the conversion of iron sulfides to oxides has imparted a rusty color to orthoclase porphyroblasts.

Competent biotite gneisses intercalated with the protoliths of the migmatites and augenoid schists show little evidence of change in internal fabric and mineral assemblage. Rotated relic fragments of fine-grained biotite gneiss (the more gneissic layers of unit *bgg*) occur sporadically throughout the coarse-grained migmatitic schists (figs. 3C, F). The Cremation Hill fault zone is further distinguished by characteristic structural fabrics, as discussed below.

Relations to regional structure—Discordance of small-scale structures (folds, mineral lineations, and foliation) provides much of the basic evidence for the Cremation Hill fault (fig. 4). In gneisses and amphibolites of the Bronson Hill terrane, east-west compression produced highly attenuated, passive-slip isoclinal folds with subhorizontal, north-south axes and vertical axial planes (type $F1_C$, fig. 4A). Mineral lineations related to this folding are absent.

In the Hebron Formation, asymmetric, westward-vergent, flexure-slip folds with horizontal, north-south axes and east-dipping (40°–50°E) axial planar surfaces predominate (type $F2_H$, fig. 4D). With the possible exception of one complex outcrop near the interchange between Connecticut Routes 9 and 82 (geographic coordinates 41°25′20″N, 72°29′30″W), the $F2_H$ folds in the Hebron do not penetrate the Bronson Hill rocks across the Cremation Hill fault. A prominent lineation of biotite parallels the direction of vergence. Type $F2_H$ folds occur sporadically throughout the flat-lying Hebron Formation, but they become increasingly abundant toward the western margin of the exposed interval. Note that the westward-vergent $F2_H$ folds deform earlier isoclinal folds that possess subhorizontal axial planes and variable axial strike ($F1_H$, fig. 4C). These $F1_H$ folds, which record the earliest deformation in the Hebron, commonly appear as partial intrafolial folds truncated by axial-plane shear surfaces (equivalent to the prevalent metamorphic foliation in the Hebron Formation; see London, 1988).

In the narrow band of migmatite and augenoid schist (mapped as Brimfield Schist by Lundgren, 1961, and Lundgren, Ashmead, and Snyder, 1971) and massive syenitic pegmatite (labelled *psf* in fig. 5) that separates these two structural zones, small-scale dextral folds plunge steeply (50°–60°) to the southeast with subvertical axial planar surfaces that strike N20°–30°W (type $F2_C$, figs. 4B and 5). A lineation of quartz, feldspars, and micas parallels the axes of these folds. At several localities, type $F2_C$ folds clearly deform the earlier, isoclinal folds that are characteristic of the gneissic Bronson Hill rocks. In addition, the $F1_C$ folds of Bronson Hill gneisses show progressive rotation into parallelism with the $F2_C$ folds toward the migmatitic band (rotated $F1_C$ folds are designated as $F1'_C$ in fig. 4A and 5). Attenuation and right-lateral shearing (development of schistosity $S2_C$, figs. 3B, D, and 5) along the axial planar surfaces have largely obliterated evidence of the $F2_C$ folding. Right-lateral transposition along the cross-cutting, northwest-striking foliation produced by $S2_C$ shearing becomes increasingly pervasive in the thin band of feldspathic augenoid schist and migmatite, where it is the dominant foliation. Within the migmatitic schists, the pervasive system of $S2_C$ shear surfaces cuts rock units into thin, ellipsoidal fault blocks of eccentricity = 0.1 and lower, to the point where the boundaries between transposed rock slivers become unrecognizable (fig. 3D). In summary, (1) isoclinal passive-slip folds ($F1_C$) with subhorizontal north-south axes and vertical axial planes are confined to the Bronson Hill terrane, (2) westward-vergent asymmetric, flexure-slip folds ($F2_H$) with horizontal north-south axes and east-dipping axial planes exist only in the Hebron Formation, (3) there is no clear field evidence that either of these fold sets has been superimposed on the other, and (4) these two major fold sets are separated by a narrow zone of steeply plunging, dextral folds ($F2_C$) and N20°W-striking axial planar shear surfaces ($S2_C$) in the migmatitic band. This thin band of feldspathic augenoid schist, migmatite, and syenitic pegmatite with pervasive $S2_C$ foliation and $F2_C$ folding delineates the Cremation Hill fault zone.

The eastward transition from non-migmatitic aluminous gneisses and schists (units *bgg* and *mfs*, fig. 2) of the Bronson Hill terrane to the feldspathic migmatite is gradational. The contact between migmatite and unzoned syenitic pegmatite of the Cremation Hill fault zone and

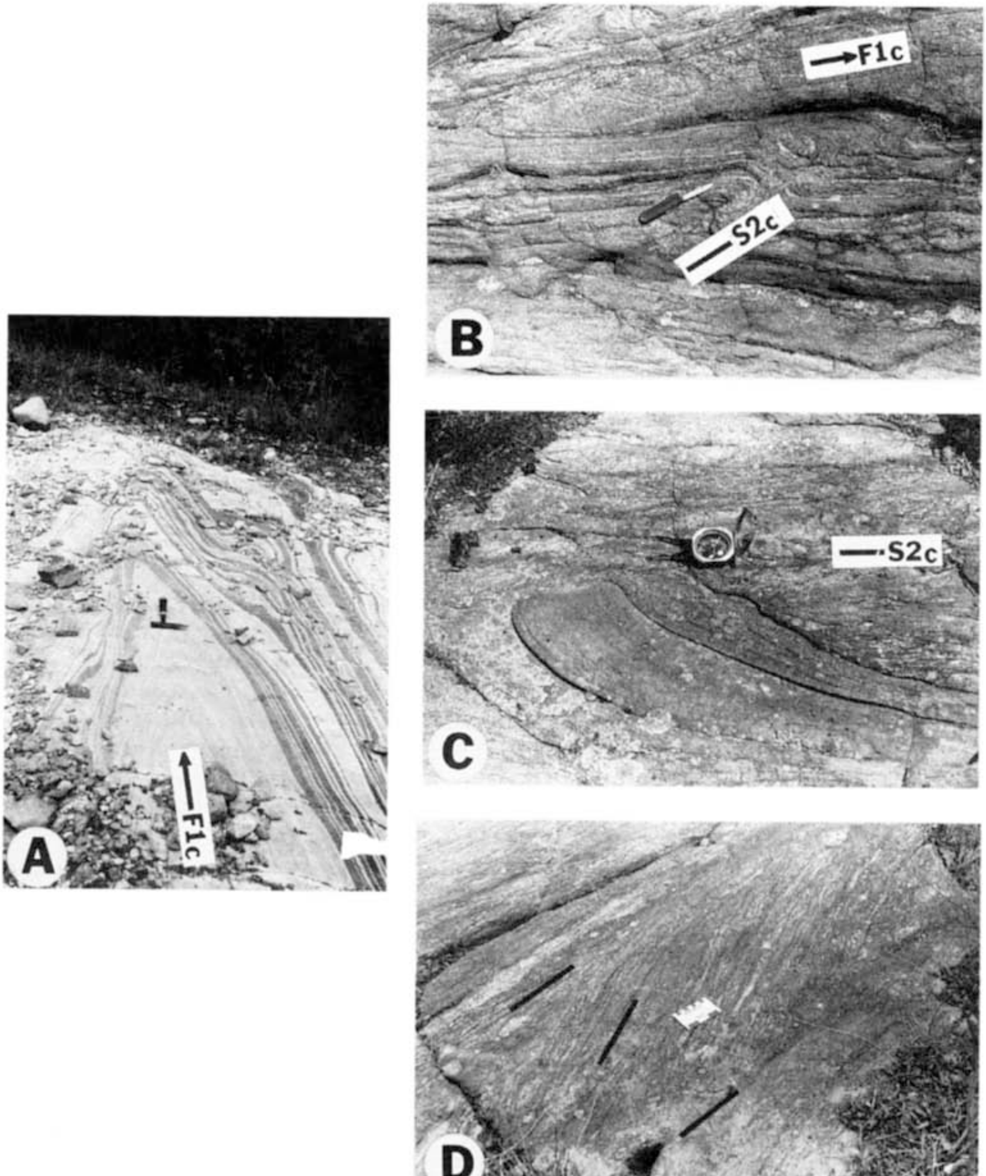

Fig. 3. Mineralogical and textural characteristics of rocks in the Moodus area; locations of photographs are keyed to the Moodus map (fig. 2) by letter designations. (A) Subhorizontal (N10°) isoclinal folds ($F1_C$, fig. 4) in ribboned amphibolite plus gneiss (*rga*). (B) Development of incipient $S2_C$ shear foliation (N30°W) cutting isoclinally folded ($F1_C$) garnetiferous gneiss *bgg*; the knife is 10 cm in length. (C) A folded layer within *bgg* that has been truncated along an $S2_C$ shear surface. Notice that the surrounding schists show incipient migmatization and foliation parallel to $S2_C$ (N10°W). (D) Shear fabrics in slightly migmatitic muscovite schist (*mfs*); note the angular discordance of layering and foliation between adjacent shear-bounded fault blocks (shear zones and vertical foliation highlighted in black lines).

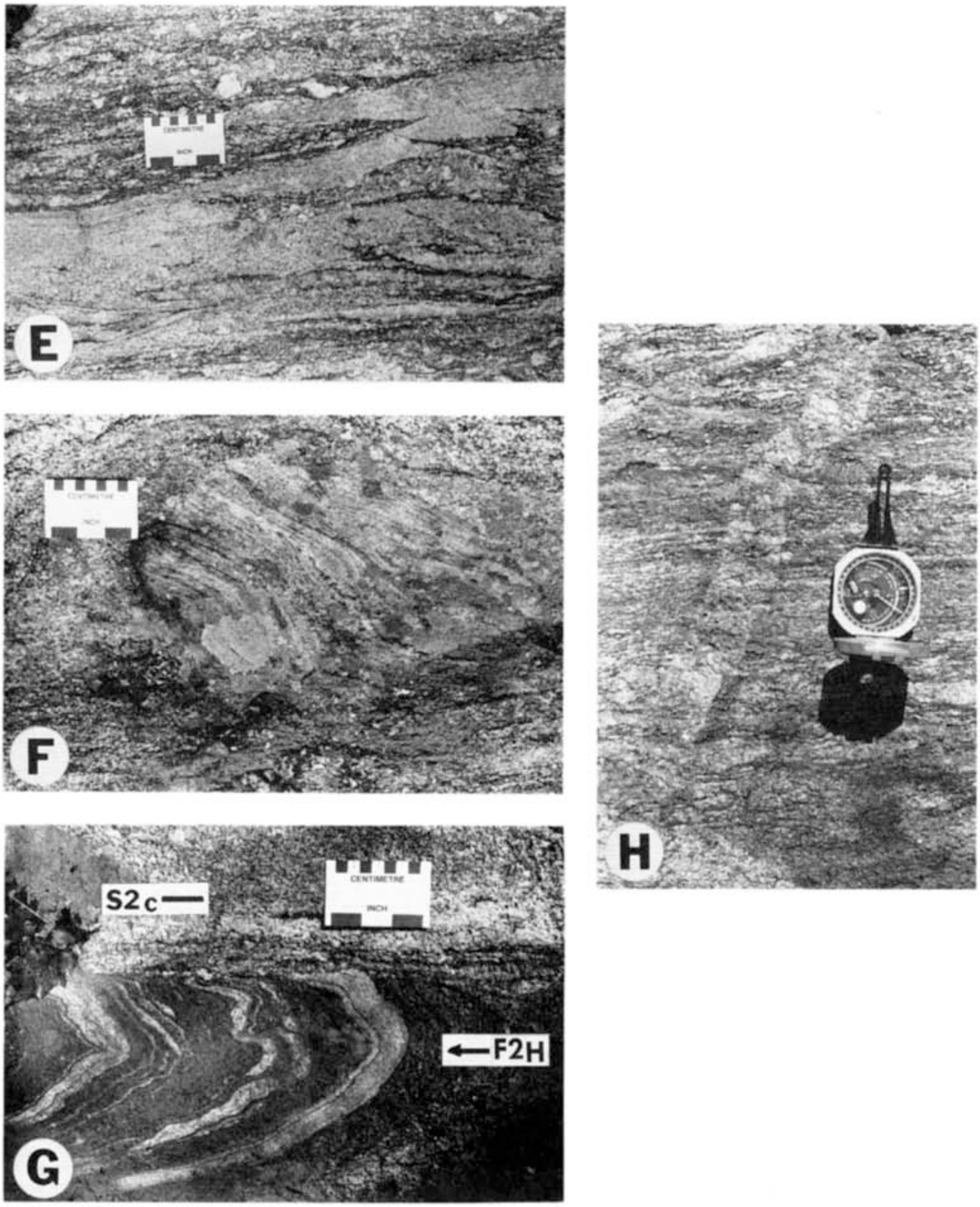

Fig. 3. (continued)

(E) Pervasive migmatization and feldspar porphyroblasis in *mfs* in the Cremation Hill fault zone; although some biotite selvages are apparent, the general character of the migmatite is nebulitic. Such migmatites grade eastward into gneissoid to pegmatitic syenite (labelled *psf* in fig. 5) containing wisps of relic biotite folia and garnet. (F) Rotated relic of biotite gneiss (*bgg*) in migmatitic blastomylonite. (G) Truncation of folded Hebron unit (calc-silicate gneiss *hcg*) against feldspathic blastomylonite at the eastern edge of the Cremation Hill fault zone, location 41°26′30″N, 72°29′00″W south of the Moodus map area; the fold pictured in (G) is half of a warped, doubly plunging synform consisting of an $F2_H$ fold (S15°) that has been folded about a minor, low-amplitude east-west fold axis ($F4_H$ of London, 1987). These subhorizontal folds in the Hebron lie against vertically foliated feldspathic migmatite (= gneissoid to pegmatitic syenite). (H) Penetrative $S2_C$ foliation and dextral offset of a small, zoned pegmatite.

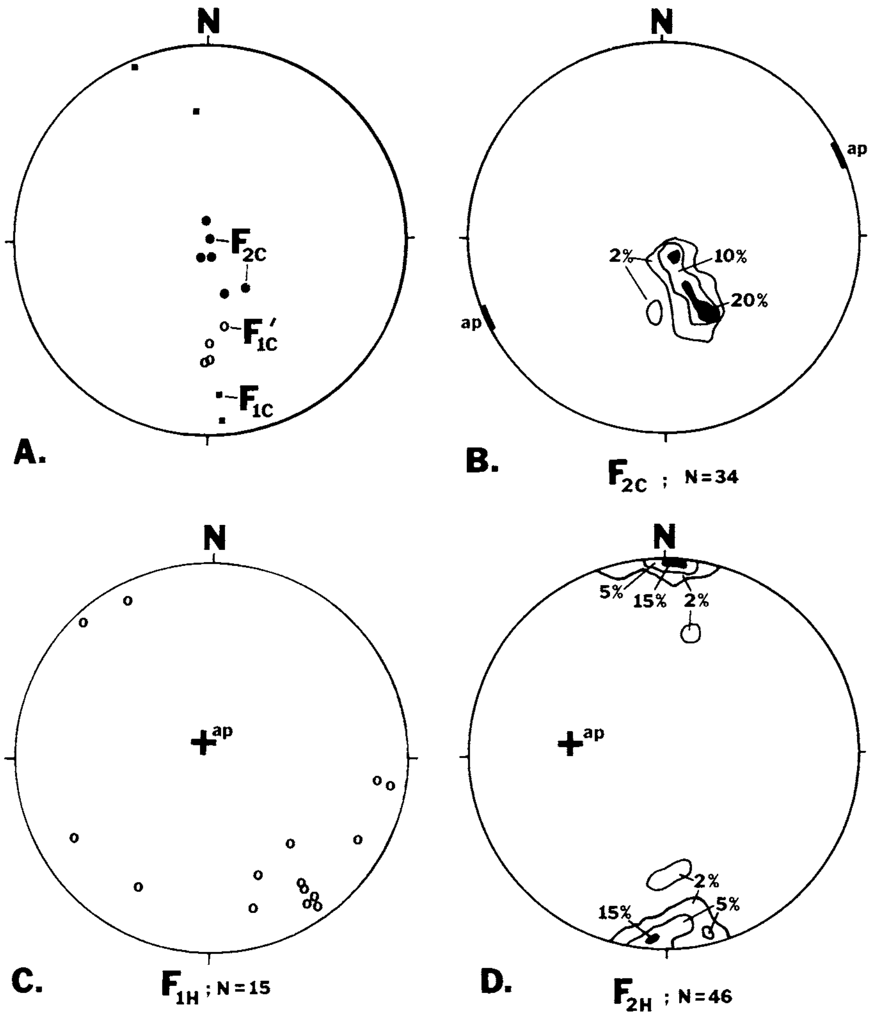

Fig. 4. Lower-hemisphere Schmidt net projections of small-scale fold axes and poles to axial planes. Contours delineate the percentage of total measurements per 1 percent of circular net area. (A) Isoclinal folds with vertical axial planes in non-migmatitic Bronson Hill rocks. Approaching the Cremation Hill fault zone from the west, isoclinal $F1_C$ folds rotate progressively into parallelism ($F1'_C$) with $F2_C$ folds (see fig. 5). (B) Dextral $F2_C$ folds with vertical axial planes in the Cremation Hill fault zone. (C) Isoclinal intrafolial folds in the Hebron ($F1_H$). (D) Westward-vergent asymmetric $F2_H$ folds in the Hebron Formation, the most prevalent folds in the Hebron at small and large scales. Additional symbols are: AP = projection of poles to axial planar surfaces; N = number of outcrops where folds were measured (multiple measurements at most outcrops).

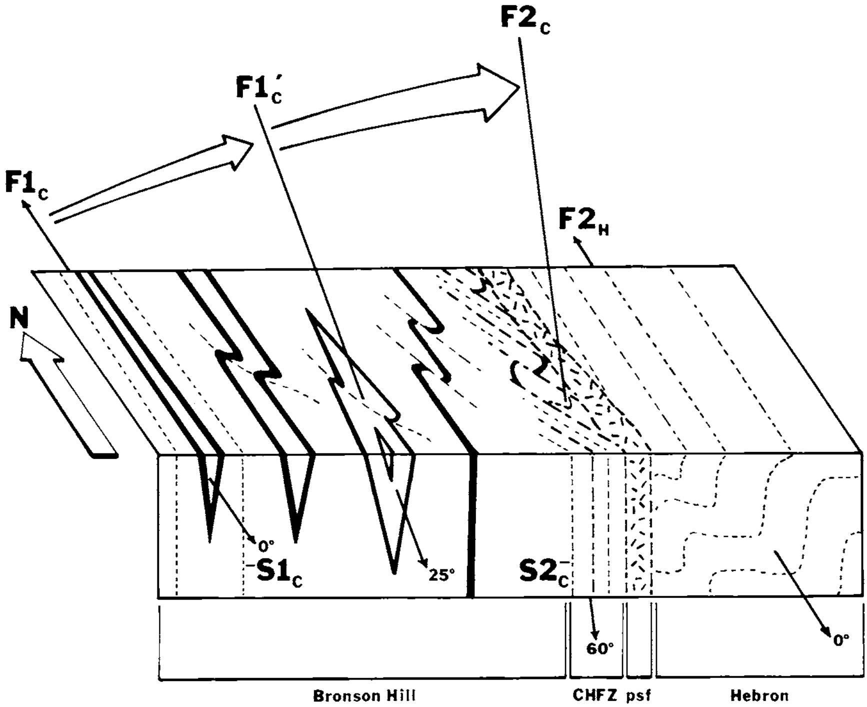

Fig. 5. Schematic structural cross section through the southern portion of the Moodus area, illustrating the relationships between the principal fold and shear-schistosity sets in the Bronson Hill and Hebron rocks, as well as the band of migmatites and syenitic pegmatites (*psf*) that delineates the eastern edge of the Cremation Hill fault zone (CHFZ); this schematic section lies approximately along a ray southeast from point A (fig. 2) eastward into the Hebron Formation.

calc-silicate-rich gneisses and granofels of the Hebron (unit *hcg*, fig. 2), however, is sharp and locally discordant. The $S2_C$ foliation and $F2_C$ folds that are prevalent in the migmatitic schists and syenitic pegmatite in the Cremation Hill fault zone end abruptly at the contact with Hebron gneisses and granofels and are not overprinted on any of the Hebron gneisses. Moreover, the westward-vergent, horizontal folds ($F2_H$) in the gneissic rocks and granofels of the Hebron rarely show any rotation into parallelism with the $F2_C$ folding direction, even at the contact with the Cremation Hill fault (fig. 3G). The nature of this contact is different, however, in the northern portion of the Moodus area, where sulfidic muscovite schists (unit *hms*, fig. 2) that are intercalated with distinctively Hebron gneisses (unit *hcg*) develop migmatitic and augenoid fabrics along the Cremation Hill fault boundary. In this area and northward into the Middle Haddam quadrangle, the Cremation Hill fault zone leaves the contact with Hebron calc-silicate gneisses (unit *hcg*) and veers northwestward across the "Schist of East Hampton" (Eaton and Rosenfeld, 1972): hence, the Cremation Hill fault in the Moodus and Middle Haddam quadrangles is bounded on both sides by muscovite-rich schists (designated as units *mfs* and *hms* on fig. 2). The significance of this relationship is discussed further in following sections.

The structural discordance in and around the fault zone also is evident at a regional scale. The north-south grain of the Bronson Hill rocks and of the Hebron Formation is cut by the N20°–30°W trend of the Cremation Hill fault zone (figs. 2 and 5). Oscillatory variations in the dip of Hebron rocks along the Cremation Hill fault indicate that the fault truncates the $F2_H$ folds and hence was active subsequent to $F2_H$ folding.

In the Deep River area, Lundgren (1963) mapped the migmatitic rocks and augenoid schists in the Cremation Hill fault as Brimfield Schist, whereas he grouped non-migmatitic schists with the Monson and Middletown formations. Subsequently in the adjacent Haddam quadrangle, Lundgren (1979) separated a small body of coarse-grained, feldspathic schist (mapped as Schist of East Hampton) from the muscovite-rich units of the Collins Hill Formation. This small body of feldspathic schist (labelled *mfs* at location I, fig. 2), which is texturally and mineralogically similar to the migmatitic rocks in the Cremation Hill fault zone, also lies at the center of another ductile fault, the Injun Hollow fault zone (London, 1984, 1988); mineral lineations and small-scale asymmetrical folds indicate left-lateral, largely strike-slip motion along the Injun Hollow fault (London, 1988). Other schist lenses, especially those that border or occur within gneissic units such as the Monson Gneiss, possess the same fabrics. The widespread distribution of migmatitic schist, and especially the prevalence of $S2_C$ schistosity and $F2_C$ folds in these schists, demonstrate the regional nature of ductile deformation in the Bronson Hill terrane: the ductile deformation that generated $S2_C$ schistosity and $F2_C$ folds was regional in extent, but strain was localized in schistose rocks. The more competent gneisses experienced little macroscopic deformation except along their contacts with schist lenses (see fig. 5 of London, 1988).

Relations to regional metamorphism.—The principal protoliths of the Cremation Hill fault rocks were fine-grained (1–3 mm), non-migmatitic aluminous gneiss (*bgg* in fig. 2) and interlayered muscovite-rich schist (*mfs* in fig. 2), both of which contain the assemblage quartz–plagioclase–biotite–muscovite–sillimanite–garnet; neither orthoclase nor staurolite is present in either *bgg* or *mfs,* and evidence of anatexis (migmatization) is absent (except possibly in the Cremation Hill fault rocks).

Pressure-temperature conditions for metamorphism of the non-migmatitic protoliths were calculated by garnet-biotite thermometry using the regular solution model of Indares and Martignole (1985, eq 18) coupled with eq (1c) of Ghent (1976). Core-to-rim temperature variations were calculated on the assumption that the composition of biotite is relatively unchanged by retrograde re-equilibration with garnet; in all samples chosen for geothermometry, the modal proportion of biotite:garnet is high (>25:1), and the composition of biotite is uniform throughout a given sample. The spessartine component of all garnets is negligible (>0.01 cations Mn pfu), but the mole fraction of grossular component is 0.04 and is homogeneously distributed throughout individual grains. The Fe/Mg zonation within garnets, which are slightly flattened, is spherically concentric about the core. Biotite contains an average of 1.80 cations Al (total) pfu (11-oxygen basis, corrected for F = 0) and 0.15 cations Ti pfu. Plagioclase compositions are near An_{23} with negligible variation or zonation.

At aH_2O = 0.5, a small *P-T* region (bounded by reaction curves 2, 4′, 5′, and 6′) between approx 5.4 to 7.3 kb and 620° to 675°C satisfies the requirements imposed by the prograde mineral assemblage and non-anatectic fabric of the protoliths (fig. 6). From this region, an initial

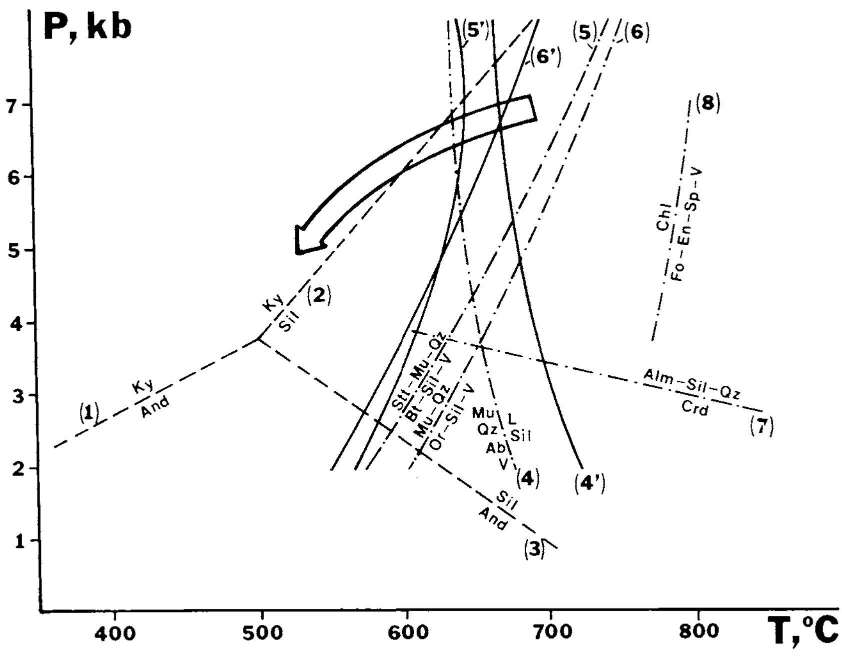

Fig. 6. Petrogenetic grid showing the metamorphic path (arrow) of migmatitic Cremation Hill fault rocks and adjacent non-migmatitic metapelites in the Bronson Hill sequence in relation to pertinent univariant reactions. Dash-dot lines and unprimed numerals denote equilibria at aH_2O = 1 and PH_2O = Ptotal; solid lines and primed numerals are for the same reactions at aH_2O = 0.5. Phase abbreviations are: And = andalusite; Ky = kyanite; Sil = sillimanite; Qz = quartz; Mus = muscovite (non-celadonitic); Or = orthoclase; Ab = albite; Bt = Fe-biotite; Stt = Fe-staurolite; Alm = almandine garnet; Crd = Fe-cordierite; Chl = Mg-chlorite; Fo = forsterite; En = enstatite; Sp = spinel; L = granitic liquid; V = H_2O. The reaction curves are derived from these sources: (1), (2), and (3) Holdaway (1971); (4) Piwinskii (1968) and (4′) Kerrick (1972); (5) Hoschek (1969) and (5′) Novak and Holdaway (1981); (6) and (6′) Kerrick (1972); (7) Thompson (1982); (8) Chernosky (1974).

mean pressure of 6.4 kb was used in the solution of the garnet-biotite equation of Indares and Martignole (1985). The preliminary data yield calculated temperatures (fig. 7) of 653° to 698°C (garnet cores) that increase slightly outward from cores and then fall off sharply toward rims (534°–582°C at the rims along the long axes of flattened garnet grains). The regular solution model of Indares and Martignole (1985) was chosen because of the high siderophyllite component in the biotites, but the calculated values (fig. 7) are only slightly lower than results using the Ferry-Spear (1978) geothermometer.

The garnet-biotite geothermometer of Indares and Martignole (1985) is relatively insensitive to pressure. Changes in pressure of 1.0 kb yield differences of only ±5°C; therefore, the mean temperatures calculated from garnet core (678°C) and rim (558°C) compositions (fig. 7) were used with eq (1c) of Ghent (1976) to estimate changes in pressure during garnet growth. The resultant pressures range from 7.1 kb at 678°C to 5.2 kb at 558°C; thus garnets in the non-migmatitic protoliths

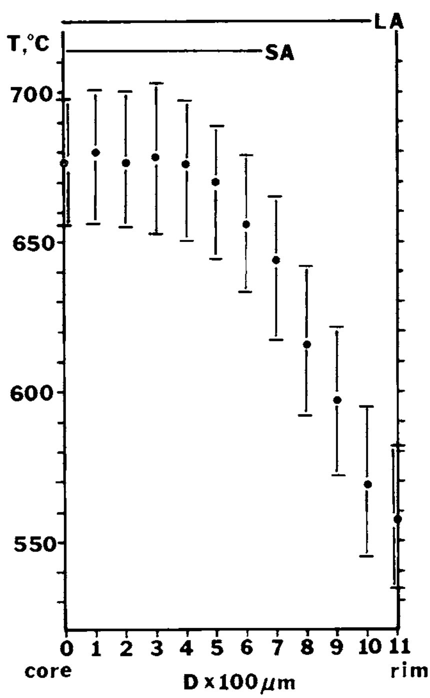

Fig. 7. Temperature profiles (from eq 18 of Indares and Martignole, 1985, at 6.4 kb) along the long axes (LA) and short axes (SA) of zoned, non-equidimensional garnets in the Cremation Hill fault rocks (two samples, two garnets each) and the adjacent non-migmatitic protoliths *bgg* and *mfs* (four samples, two garnets each). Dots are mean values, bars indicate range. Temperature profiles from garnets in non-migmatitic *bgg* and *mfs* are identical to (overlap completely with) data from the migmatitic fault rocks.

bgg and *mfs* record a path of retrograde conditions shown by the arrow in figure 6. The asymmetrical shape and Fe-Mg zoning within garnets, coupled with petrographic fabric, indicate that (1) retrograde growth was syntectonic, and (2) ductile deformation (development of foliation in micas and feldspars around rotated non-equidimensional garnets) continued after garnet growth (below about 550°C).

Feasible solutions of the *P-T* region for apparent peak metamorphic conditions require displacement of reactions 4, 5, and 6 (fig. 6) by reduction of aH_2O to ≤ 0.5. Additional evidence of low aH_2O comes from a small body of ultramafic rock (location I, fig. 2), which contains the assemblage olivine (Fo_{80})–bronzite (En_{75})–spinel (hercynite)–Mg chlorite. At temperatures near 650°C, this assemblage could only be stable at $aH_2O \ll 1$ (see fig. 6 and Tracy, Robinson, and Wolf, 1984). The absence of carbonate- or calc-silicate-rich rocks in the Bronson Hill interval and the general paucity of graphite indicate that the partial pressures of volatile carbonaceous components (CO_2 or CH_4) probably were not high. The available data, therefore, point to fluid-absent peak metamorphic conditions in which the fugacity of H_2O was $\leq$ approx 3000 bars.

Pressure-temperature profiles for zoned garnets within the Cremation Hill fault rocks are indistinguishable from those of the adjacent nonmigmatitic protoliths (figs. 6 and 7). Migmatization in the Cremation Hill fault zone, therefore, apparently was not the result of temperatures higher than in adjacent non-migmatitic schists. Alternative explanations for migmatization may include: (1) anatexis due to locally higher aH_2O in the Cremation Hill fault zone; (2) metasomatic introduction of alkalis as a result of dehydration reactions beneath the present level of exposure; and (3) feldspathization stemming from grain-size reduction or strain solution (Wintsch and Dunning, 1985), or combinations of these possibilities.

Calc-silicate gneisses and granofels of the Hebron Formation (unit *hcg*, fig. 2) contain the assemblage diopside (Di_{61-69})–plagioclase (An_{64-65})–scapolite (Me_{83-84})–calcite (Cc_{99}) At 5000 bars, plagioclase + calcite react to mizzonite (Me_{83}) at approx 625°C and in the presence of fluids with $XCO_2 > 0.15$ (Aitken, 1983, and personal commun., 1985). Note that Rosenfeld and Eaton (1985) delineate a second sillimanite isograd (orthoclase–sillimanite–quartz) in aluminous schists (Brimfield or *hms*) along the eastern boundary of the Cremation Hill fault zone in the Middle Haddam and Moodus quadrangles. Although the schists that reportedly contain this assemblage were not included in this study, very low aH_2O promoted by decarbonation reactions in the underlying Hebron gneisses would displace reaction 6 (fig. 6) to lower *T*, into the *P-T* region of peak metamorphism in the Bronson Hill interval and Cremation Hill fault rocks. In the Hebron unit *hcg* along the Cremation Hill fault, however, coarse-grained clinozoisite (Ps_{31}) and ferroan tremolite (Tr_{66-69}) are locally abundant with diopside and plagioclase; though diminished in modal abundance, scapolite and calcite persist.

The Cremation Hill fault zone may have been a region of comparatively high aH_2O, that is, higher than in rocks on either side of the fault. This interpretation is consistent with an origin for migmatization that includes (1) limited bulk anatexis by a shift in the reaction muscovite–quartz–plagioclase–H_2O = L to lower T with increasing aH_2O (fig. 6), and (2) metasomatic introduction of alkalis (manifested as growth of isolated feldspar porphyroblasts, and syntectonic replacement of sillimanite by muscovite at high metamorphic grade). Higher aH_2O would also contribute to the oxidation of graphite and Fe^{2+} in the Cremation Hill fault rocks. In the Hebron rocks (unit *hcg*) adjacent to the Cremation Hill fault (within several tens of meters), comparatively high aH_2O is indicated by the abundance of clinozoisite and ferro-tremolite and paucity of scapolite and calcite (Storre, Johannes, and Nitsch, 1982). Some degree of H_2O infiltration from Cremation Hill fault rocks to Hebron calc-silicate units is implied.

REGIONAL EXTENT OF THE CREMATION HILL FAULT

The Cremation Hill fault can be traced through the Middle Haddam, Moodus, and Deep River quadrangles by the distinctive migmatite and augenoid feldspathic schist, the anastomosing system of shear-bounded blocks, the prevalence of $S2_C$ schistosity and $F2_C$ folding, and an abundance of postectonic retrograde muscovite. These characteristics serve to distinguish the feldspathic schists and migmatite in the Cremation Hill fault from other muscovite-rich schists and schistose gneisses that occur in the intervals of Bronson Hill and Hebron rocks in this area.

The Cremation Hill fault extends south into the Deep River quadrangle along a contact between the Hebron Formation and the Monson and Middletown formations. The aluminous gneisses and schists that are part of the Bronson Hill terrane (units *bgg* and *mfs*) pinch out to the south along this fault contact, but thin slivers of aluminous schist persist along the fault zone well into the Deep River quadrangle. These schists, which were originally mapped as Brimfield Schist by Lundgren (1963) and Dixon and Lundgren (1968), are now regarded by Wintsch (personal commun., 1986) as products of syntectonic metasomatism in the Cremation Hill fault zone (indicated by Wintsch, 1985, as the Bonemill Brook fault). Wintsch (1985) observed that the Cremation Hill fault is cut to the south by the Falls River thrust fault in the Essex quadrangle (fig. 1), but the Cremation Hill fault apparently continues south of the Falls River fault (Wintsch, 1985). Stratigraphic and structural relations south of the Falls River fault are still enigmatic, but Webster and Wintsch (1987) have demonstrated that at least some gneisses previously mapped as part of the Bronson Hill terrane in the Killingworth dome may be components of the Avalon terrane (fig. 1).

To the north, the Cremation Hill fault enters the the southeast corner of the Middle Haddam quadrangle along the contact with

Hebron gneisses. Where the contact between aluminous schist (unit *hms*) and Hebron gneisses (unit *hcg*) turns to the northeast into the Moodus quadrangle and becomes conformable (north of geographic coordinates 41°32′30″N, 72°30′10″W), the Cremation Hill fault leaves this contact and veers N 20° W to merge with the Bonemill Brook fault (Pease, 1982) along the eastern boundary of the Monson Gneiss (figs. 1 and 2).

The Cremation Hill and Bonemill Brook fault zones are similar in that both are steeply dipping ductile fault systems that now manifest right-lateral, largely strike-slip relative motions. In the Cremation Hill fault zone, this direction of material transport is inferred to have been subperpendicular to the axes of $F2_C$ folds and mineral lineations; right-lateral strike-slip motion is also indicated by the transposition of distinct layers and by the sense of rotation in relic fragments of gneisses (competent layers of unit *bgg*) in the migmatites and augenoid schists in the Cremation Hill fault zone (fig. 3). From this study, the Cremation Hill and Bonemill Brook faults appear to represent a single ductile fault system that extends from Massachusetts at least to the Falls River fault in the Essex quadrangle of southern Connecticut.

Pease (1982), however, regarded the Cremation Hill fault as an eastern splay off of the Bonemill Brook fault. Pease's proposal was based on the fact that in northern Connecticut, the Bonemill Brook fault separates aluminous gneisses and schists of the Brimfield Group from plagioclase gneisses and amphibolites of the Bronson Hill terrane, whereas southward in the Moodus area, aluminous schists and gneisses similar to those of the Brimfield group lie west of the Cremation Hill fault zone (non-migmatitic intervals of units *mfs* and *bgg* in fig. 2). In the Moodus area, Pease (1982) suggested that the Bonemill Brook fault zone must lie between the Monson Gneiss and aluminous schists to the east (between *mog* and its eastern contact with *mfs*, fig. 2). Detailed mapping by London (1988), however, has demonstrated that the migmatization and ductile deformation that characterize the Cremation Hill-Bonemill Brook fault systems are absent at this contact. West of the Cremation Hill fault zone, the schist lenses and slivers of units *mfs*, *mfg*, and *bgg* generally possess metamorphic fabrics and structures common only in the Bronson Hill terrane and do not contain the $F2_H$ folds that occur only in the Hebron Formation. In addition to structural conformity, the eastward transition from Monson and Middletown gneisses (units *mog* and *oga*) to aluminous gneisses and schists (*bgg* and *mfs*) is gradational. Non-migmatitic schists to the west of the Cremation Hill fault, therefore, appear to be part of the Bronson Hill terrane (except possibly at the important and complex outcrops near the interchange between Connecticut Routes 9 and 82, as noted above). The other schist body (unit *hms*, fig. 2), which lies east of the Cremation Hill fault in the Middle Haddam and Moodus quadrangles, is conformable with the distinctive Hebron calc-silicate rocks (*hcg*) and contains $F2_H$ folds, which are restricted to the Merrimack terrane.

REGIONAL SIGNIFICANCE OF THE CREMATION HILL-BONEMILL BROOK FAULT SYSTEM

The identification of the Cremation Hill fault zone, and its continuity with the Bonemill Brook fault of Pease (1982), constitutes an important component of the regional structural geology of eastern Connecticut (fig. 1). The Cremation Hill-Bonemill Brook fault system is the westernmost of the known major ductile faults. Correlation of these two fault zones, however, raises new questions about regional stratigraphic and structural relations. The earliest periods of activity along these faults are still in doubt. Peper, Pease, and Seiders (1975) initially suggested that the Bonemill Brook fault is a westward-dipping reverse fault—the root zone of a series of thrust wedges with east-southeast transport—that represents a lower Paleozoic boundary between Bronson Hill and Merrimack terranes (see also Rodgers, 1981). Pease's (1982) subsequent observation of right-lateral strike-slip motion does not necessarily contradict this interpretation, as this may reflect later activity on the Bonemill Brook fault, as discussed in the following section.

Assessment of the regional significance of the Cremation Hill and Bonemill Brook faults requires consideration of two additional points. One crucial question noted above is whether or not the two bodies of muscovite schist (units *mfs* and *hms* in fig. 2) separated by the Cremation Hill fault are stratigraphically equivalent (both part of the Merrimack stratigraphy), or if the Cremation Hill fault separates and juxtaposes stratigraphically different schists that appear similar because of comparable bulk compositions and metamorphic grade. In the first case, the Cremation Hill fault would represent a zone of tectonic thinning and telescoping within a single stratigraphic schist unit, and the fundamental significance of the Bonemill Brook fault as a terrane boundary would be in doubt. If the schist bodies *mfs* and *hms* are not stratigraphically correlative, then the Cremation Hill-Bonemill Brook fault system *could* constitute a tectonic boundary between Bronson Hill and Merrimack terranes, and as such it would make the Merrimack terrane largely, if not entirely allochthonous in Connecticut (Pease, 1982; Rodgers, 1985). The answer to this question, which lies in the "Schist of East Hampton" in the Middle Haddam quadrangle, may be difficult to resolve. The observations of this study (London, 1988), including lithologic breaks, total structural discordance, truncation of distinctive pegmatite fields, and possible differences in metamorphic grade and bulk compositions of adjacent aluminous schists (*mfs* and *hms*), suggest at least that the Cremation Hill fault has been the locus of significant offset.

A second vital issue pertains to a body of orthoamphibole-bearing gneiss, believed to be an outlier of Middletown Formation, that overlies Brimfield schist in the Colchester quadrangle (Lundgren, Ashmead, and Snyder, 1971) (fig. 1). Pervasive ductile deformation at this gneiss-schist contact raises the possibility that the Middletown gneisses have been structurally emplaced above the Brimfield schists, as along a westward-dipping thrust surface similar to those mapped by Pease and others in northern Connecticut.

TECTONIC EVOLUTION

In the Moodus area, the earliest ductile deformation in the Hebron rocks is represented by the highly attenuated isoclinal $F1_H$ folds. Fold event $F1_C$ records the earliest ductile deformation in the Bronson Hill terrane. The temporal relations of $F1_H$ and $F1_C$ are not clear. Although these folds are similar in style, their axial planes are subperpendicular to one another (fig. 3); moreover, $F1_H$ folds are clearly cut by and attenuated along the high-grade foliation in the Hebron Formation, whereas early foliation of the Bronson Hill rocks appears to have been synchronous with $F1_C$ folding. Fold events $F1_C$ and $F2_H$ could have been contemporaneous, as both events reflect ductile deformation during east-west compression. Two lines of evidence, however, suggest that $F1_C$ preceded $F2_H$. Event $F1_C$ clearly predates the intrusion of granitic pegmatites at approx 265 Ma (Brookins, 1980), whereas concordant pegmatites in the Hebron Formation are folded and boudinaged by the $F2_H$ event. In addition, the early foliation of the Bronson Hill rocks is axial planar to the $F1_C$ folds, whereas the $F2_H$ event folded the prevalent foliation in the Hebron Formation.

The Cremation Hill fault zone truncates the $F2_H$ fold system and cuts the $F1_C$ folds and associated early foliation in the Bronson Hill terrane. In addition, the Cremation Hill fault cuts discordant, zoned, tourmaline-bearing pegmatites in the Bronson Hill rocks (fig. 3H). If these pegmatites are part of the large Middletown pegmatite district as they appear to be (London, 1985), then some ductile deformation in the Cremation Hill fault zone occurred after 265 Ma (Brookins, 1980) at *P-T* conditions below those of retrograde garnet growth (approx 550°C and 5 kb). Fabrics of other, similar blastomylonitic schists in the Moodus area (in the Injun Hollow fault zone, fig. 2) do not overprint the granitic pegmatites of the Middletown field; thus, incipient activity on the Cremation Hill may have predated pegmatite intrusion. It is notable also that the Middletown pegmatite field in the Bronson Hill terrane ends abruptly against the Cremation Hill fault, and that the mineralogy, internal fabrics, and attitudes of pegmatites in the Bronson Hill rocks are entirely different from those in the Hebron Formation (see London, 1985, 1988).

The latest pervasive deformation in the Moodus area involved left-lateral strike-slip faulting at lower greenschist-facies conditions (manifested by chlorite slickensides and chlorite-K feldspar recrystallized mylonites). These northwest-tending faults, which span the transition from ductile to brittle conditions, cut the Cremation Hill fault zone. A set of broad, symmetrical low-amplitude folds with subhorizontal east-northeast to west-southwest axes ($F4_H$ of London, 1988) in the

Hebron Formation may be associated with this later stage of northwest to southeast compression.

The tectonic evolution of the Moodus area is consistent with the important aspects of a recent model for the late Paleozoic history of southern New England (Wintsch and Lefort, 1984; Wintsch and Sutter, 1985). In accord with the Wintsch-Sutter (1985) model, rocks in the Moodus area record regional east-west compression ($F1_C$, possibly $F1_H$ and $F2_H$) at metamorphic conditions near 7 kb, 675° to 700°C prior to emplacement of the Middletown pegmatites at 265 Ma. Compressed between the westward-vergent underthrusting of Avalonian terrane (as evidenced by Avalonian gneisses in the window of the Willimantic fault; Wintsch, 1979) and the buttressing Bronson Hill terrane, the Merrimack terrane was thickened by a series of west-dipping imbricate thrust wedges (Peper, Pease, and Snyder, 1975) which thrust Merrimack rocks east-southeast over the Avalonian basement (Rodgers, 1981; Wintsch and Sutter, 1985). In the Moodus area, the $F2_H$ folds, which extend from the Moodus area south into the Hebron rocks near the southern boundary of the Deep River quadrangle, reflect the crumpling and thickening of the western margin of the Merrimack terrane against the Bronson Hill terrane. In the tectonic model of Rodgers (1981), the Cremation Hill-Bonemill Brook fault system represents the western boundary between an island arc (Bronson Hill terrane) and a fore-arc accretionary prism (Merrimack terrane).

One of the most important correlations of this work with the Wintsch-Sutter (1985) model is that the Cremation Hill fault rocks (and other blastomylonitic schists in the Moodus area) record a rotation in the orientation of principal compressive stress to a north-northwest to south-southeast direction. Ductile deformation in the Cremation Hill and similar fault zones may have predated pegmatite intrusion, but the Cremation Hill zone apparently remained active after 265 Ma at lower amphibolite- to upper greenschist-facies conditions.

The Cremation Hill-Bonemill Brook fault system transported the Merrimack terrane southward relative to the Bronson Hill terrane (Wintsch and Lefort, 1984). Within the Bronson Hill terrane in the Moodus area, the competent Monson Gneiss (*mog*, fig. 2) may have formed a thin, inverted keel against which schistose rocks moved southward on either side (left-lateral in the Injun Hollow fault zone, right-lateral in the Cremation Hill zone). The same north-northwest-directed compression thrust the Merrimack rocks south-southeast over the Avalon terrane (Wintsch, 1985; Wintsch and Sutter, 1985). These relations suggest that the Bronson Hill terrane was mechanically coupled to some degree with the Avalon terrane during northward underthrusting that continued after approx 265 Ma. The late system of north-northwest-striking, left-lateral strike-slip faults may represent the continuation of north-northwest underthrusting of Avalonian basement at lower greenschist-facies conditions (Wintsch and Sutter, 1985).

CONCLUSIONS

One important conclusion of this work is that the coarse-grained, augenoid, feldspathic schists and migmatites previously designated as Brimfield Schist (Lundgren, 1963) and Schist of East Hampton (Eaton and Rosenfeld, 1972) in the Moodus area are blastomylonites that delineate the trace of the Cremation Hill fault zone and similar zones of ductile deformation. The migmatites and blastomylonitic schists in the Moodus area record a regional deformation which is not evident in the more competent gneissic units of the Bronson Hill terrane. The fabrics and assemblages of these blastomylonites result from tectonic and metasomatic metamorphic processes or anatexis. Stratigraphic correlations of these rocks with other units in southeastern Connecticut on the basis of textural and mineralogical similarities are therefore invalid (Dixon and Lundgren, 1968; Wintsch, 1975).

A second important conclusion is that the Cremation Hill and Bonemill Brook faults appear to represent one ductile fault zone that stretches from southern Connecticut into Massachusetts. Throughout much of its length, the Cremation Hill-Bonemill Brook fault zone constitutes a structural boundary between Bronson Hill and Merrimack terranes. If Rodgers' (1981) concept of the Merrimack terrane as an Ordovician-Devonian fore-arc accretionary prism is correct, then there is no obstacle to depositional conformity between Bronson Hill and Merrimack rocks west of the Cremation Hill-Bonemill Brook fault zone. The total discordance of small-scale structures and differences in the temporal relations of deformation to metamorphism, however, imply that the Cremation Hill fault has juxtaposed rock bodies that evolved in considerably different tectonic regimes.

Finally, the Cremation Hill-Bonemill Brook fault zone represents one more important piece of an increasingly complicated picture of the tectonic evolution of southern New England. In accord with the interpretations of Wintsch and Lefort (1984), the history of ductile deformation in the Moodus area clearly records a rotation in the regional orientation of principal compressive stress from east-west to north-northwest to south-southeast. The sense and style of ductile strain recorded by blastomylonitic schists throughout the Moodus area suggest that north-northwest compression as the result of northward approach of Gondwanaland (Wintsch and Lefort, 1984) preceded the intrusion of pegmatites at approx 265 Ma. The Cremation Hill fault zone, however, demonstrates that ductile deformation with a clockwise sense of rotation continued in this region after 265 Ma while rocks were still deeply buried and hot.

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