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TECTONIC SIGNIFICANCE OF CAMERON'S LINE IN THE VICINITY OF THE HODGES COMPLEX— AN IMBRICATE THRUST MODEL FOR WESTERN CONNECTICUT*

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ABSTRACT. *Cameron's Line is a major tectonic boundary in the western part of the core zone of the New England Appalachians. It separates metamorphosed shelf and transition-zone rocks to the west from eugeosynclinal rocks to the east. In western Connecticut it separates the Waramaug Formation from the Hartland Formation and is marked by a zone of structural discordance characterized by intense localized folding (F_2), transposition of structures, truncation of Hartland subunits, and shearing under metamorphic conditions. An accompanying penetrative regional schistosity (S_2) formed in both the Waramaug and Hartland Formations.*

The Hodges Complex, which engulfs Cameron's Line in northwestern Connecticut, is a small mass of pyroxenite, hornblendite, gabbro, and diorite. The Hodges pluton is not sheared or offset along Cameron's Line. Rather, a narrow, statically recrystallized contact aureole with coexisting cordierite–kyanite–staurolite–biotite–garnet is overprinted on the fold-fault fabric (S_2). The intrusion, therefore, postdated isoclinal folding, early metamorphism, and the development of Cameron's Line. Thus, it is unlikely that this mafic-ultramafic mass is an ophiolite despite its occurrence at a major tectonic boundary. Nearby, a small (10 m) slice of serpentinite within volcaniclastic rocks is texturally, mineralogically, and structurally distinct from the Hodges Complex and may be a sliver of ophiolite as it occurs at Cameron's Line.

The contact aureole of the Hodges Complex is cut locally by a cleavage that is axial planar to a late dextral fold which has refolded all older structures, the Hodges Complex, and the Tyler Lake Granite into a broad flexure. The peak of metamorphism (Acadian?) may have been synchronous with the intrusion of the Hodges Complex at pressures and temperatures near the Al_2SiO_5 triple-point.

Cameron's Line is interpreted as a ductile fault that developed at the deep levels of a west-facing Taconic accretionary prism. It juxtaposed rocks of the North American shelf and transition zone (Waramaug Formation) with eugeosynclinal rocks of the Hartland Formation. The Hartland in western Connecticut represents a deep-seated, sheared accretionary complex. Ordovician volcanic-arc rocks exposed in central Connecticut and possibly in the subsurface of the Connecticut Valley basin represent the associated arc terrane that accreted to North America during the Taconic Orogeny. The intrusion of the Hodges Complex and younger post-tectonic granites during the Acadian Orogeny may be related to an oceanward migration of subduction and the development of an east-facing Andean-type arc, which was superimposed across the Taconian arc-continent collision zone.

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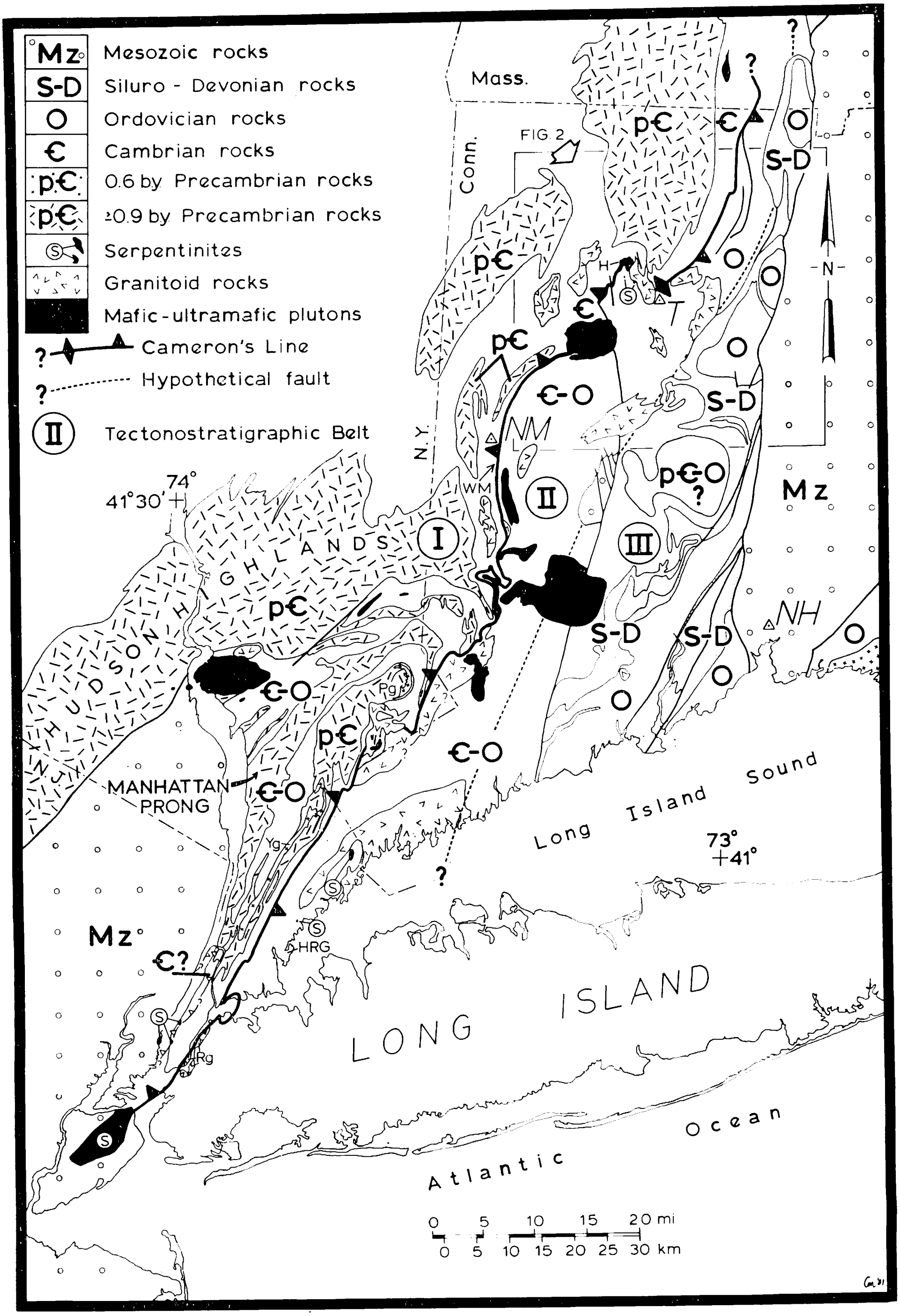

Mz Mesozoic rocks
S-D Siluro - Devonian rocks
O Ordovician rocks
Є Cambrian rocks
pЄ 0.6 by Precambrian rocks
pЄ ±0.9 by Precambrian rocks
Serpentinites
Granitoid rocks
Mafic-ultramafic plutons
Cameron's Line
Hypothetical fault
II Tectonostratigraphic Belt
Mass.
Conn.
N.Y.
N.J.
FIG. 2
HUDSON HIGHLANDS
MANHATTAN PRONG
74°
41°30'
73°
41°
Long Island Sound
LONG ISLAND
Atlantic Ocean
NM
WM
NH
HRG
Rg
Yg
0 5 10 15 20 mi
0 5 10 15 20 25 30 km
N

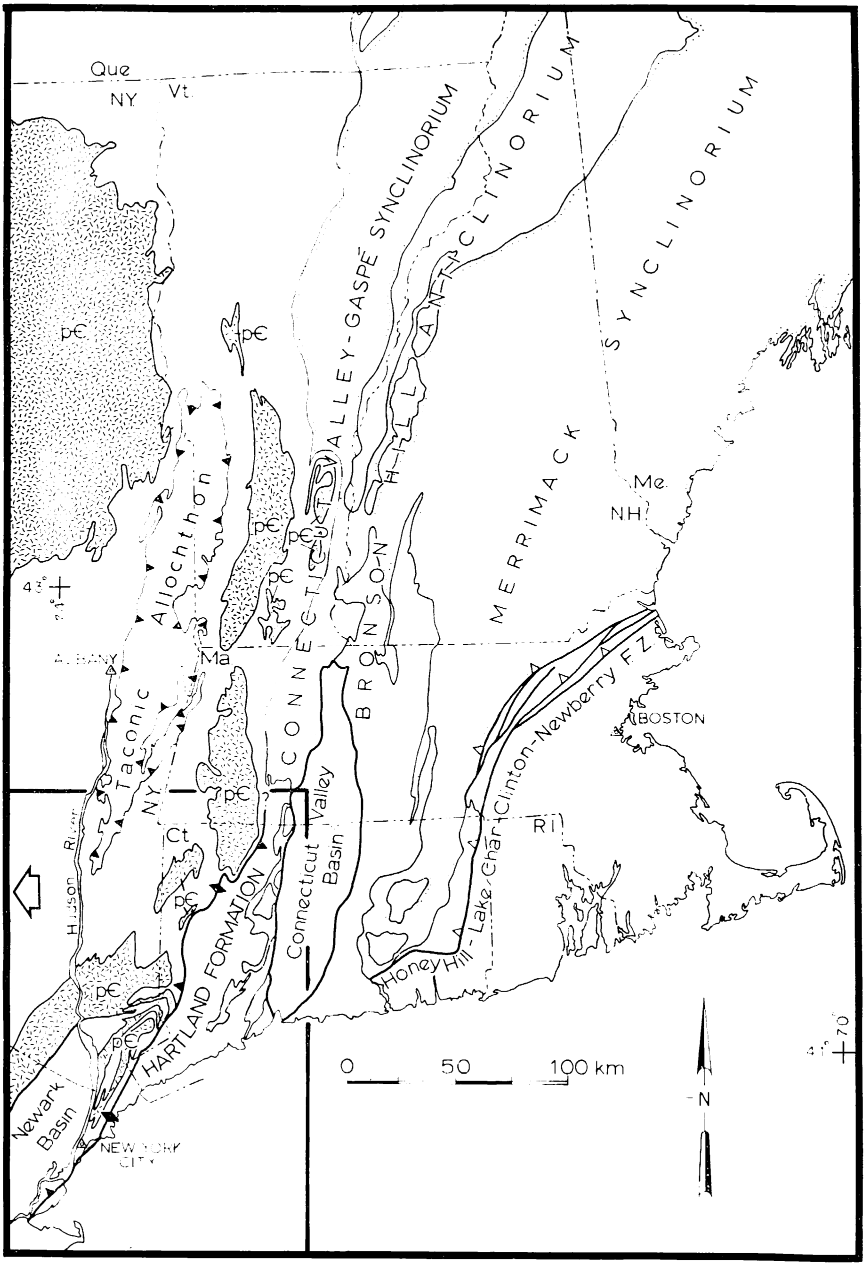


Fig. 1. Index maps of southern New England showing the distribution of Lower Paleozoic metamorphic rocks and related intrusives. Ages can be mixed (Є-O = Cambro-Ordovician) or queried (?) where uncertain. H = the Hodges Complex, HRG = Hutchinson River Group, Pg = Pound Ridge Granite Gneiss, Rg = Ravenswood Granodiorite, WM = Woodville Marble Belt, and Yg = Yonkers Gneiss. Municipalities are marked by a dotted triangle; NH = New Haven, NM = New Milford, and T = Torrington. Regional maps in this paper are compiled from Alavi, 1975; Clarke, 1958; Gates, 1967; Hall, 1980; Hall and others, 1975; Hatch and Stanley, 1973; Ratcliffe, 1970; Rodgers, Gates, and Rosenfeld; 1959; Schnabel, 1973; Scott, 1974; Williams, 1978; and Ziegler, 1911.

INTRODUCTION

The basement gneiss complex in the highlands of western Connecticut and southeastern New York consists of (900 m.y. and older) Precambrian gneisses exposed in the Berkshire, Housatonic, New Milford, and Hudson Massifs and the Manhattan Prong (fig. 1). This zone forms a curvilinear, generally antiformal trend from the northeast to the southwest and is mantled by a sequence of metamorphosed and deformed lower Paleozoic miogeosynclinal cover rocks such as the Stockbridge Marble, Woodville Marble, Inwood Marble, and underlying Cambrian quartzose clastic rocks (Cheshire and Lowerre Quartzites). A portion of the cover sequence also includes the exogeosynclinal Walloomsac Formation, Normanskill Formation, and Manhattan Schist (A member). The basement-cover sequence is structurally overlain by allochthonous, metamorphosed deeper-water lithotopes known as the Taconic Sequence, the Waramaug Formation, the Canaan Mountain Schist, and the Manhattan Schist (B and C members).

Cameron's Line in western Connecticut marks the easternmost exposures of major outcrops of $\geqslant 0.9$ b.y. basement gneiss and lower Paleozoic cover rocks. It separates the Paleozoic miogeosynclinal shelf, slope, and rise facies in the west (Manhattan Prong, Waramaug Formation, and correlatives) from a eugeosynclinal sequence (Hartland Formation and Hutchinson River Group) in the east which forms the west flank of the Connecticut Valley-Gaspé Synclinorium (fig. 1). The lower Paleozoic eugeosynclinal rocks are overlain by metamorphosed Siluro-Devonian sedimentary and volcaniclastic rocks. Cameron's Line is generally recognized as an important tectonic boundary (Agar, 1927; Cameron, 1951; Rodgers, Gates, and Rosenfeld, 1959), but few field data have been presented to support this hypothesis.

Cameron's Line has been traced 200 km southward from Paleozoic rocks on the east flank of the Berkshire Massif in Massachusetts (Hatch and Stanley, 1973). It is delineated by imbricated eugeosynclinal Rowe, Moretown, and Hawley rocks (Knapp and Stanley, 1978) in northern Connecticut. Near Torrington, Conn., it is a zone of syn-metamorphic mylonitization with intense localized isoclinal and shear folding plus significant tectonic intermixing of Waramaug and Hartland lithologies (Merguerian, ms). Cameron's Line is a ductile fault in southwestern Connecticut and northeastern Westchester County, N.Y., separating the Waramaug Formation or rocks of the Manhattan Prong from the Hartland Formation with regionally foliated rocks dipping vertically or steeply toward the west (Alavi, 1975, and personal commun.). The contact appears to be a brittle fault in southern Westchester County, where it marks the contact between the Manhattan Prong in the west and the Hutchinson River Group (Hartland lithostratigraphic equivalent). Cameron's Line is a syn-metamorphic fault in the south-central Bronx, New York City (C. Baskerville, unpub. data) but becomes less distinct southward where it passes beneath Mesozoic and Quaternary cover rocks (fig. 1). It is projected on strike with tightly folded granodioritic intrusives and sheared serpentinite exposed, respectively, in western Queens and Staten Island, New York City (unpub. data). The type-Manhattan sillimanite grade schist, gneiss, and black amphibolite of northern and central Manhattan Island are lithically identical to the Waramaug Formation of western Connecticut (Merguerian, 1981b). These rocks may be older than the miogeosynclinal Inwood Marble and, therefore, allochthonous with respect to the basement-cover sequence of Precambrian-aged Fordham Gneiss and Cambro-Ordovician Inwood Marble.

A composite mafic-ultramafic pluton known as the Hodges Complex intrudes Cameron's Line west of Torrington, Conn. (Gates and Christensen, 1965; Merguerian, ms and this report). The spatial distribution of mafic and ultramafic rocks along Cameron's Line (fig. 1), their association with shearing and dismembered serpentinite, and the eugeosynclinal nature of the country rocks suggest either that the mafic-ultramafic bodies represent obducted ophiolite, or a structurally controlled plutonic trend, or both. This study concentrates on the relationship of the stratigraphy of the metamorphic rocks, the regionally developed structural fabrics, and their relation to Cameron's Line and the Hodges Complex. A preliminary model for the tectonic evolution of western Connecticut based on this study is presented near the end of this report.

STRATIGRAPHY OF THE METAMORPHIC ROCKS

Metasedimentary rocks of the Waramaug Formation (p€-Owg, in fig. 4) of Gates (1952), crop out west, north, and northeast of the Hodges Complex and Cameron's Line and consist largely of brown- and gray-weathering gneiss with minor amphibolitic gneiss, amphibolite, and schist (fig. 2). App. 1 contains detailed descriptions of metamorphic rocks in the vicinity of West Torrington, Conn. The Waramaug gneisses are typically quartz-rich with varying amounts of plagioclase, biotite, and muscovite, and lesser amounts of garnet, kyanite, staurolite, chlorite, and opaque minerals. Gray hornblende quartzite, quartz granofels, biotite schist, tremolite–quartz–calcite granofels and rare amphibolite (p€-Owga) form minor units. The term granofels is used here as a field term to describe massive granoblastic rocks with subordinate micaceous minerals. No traceable individual map units have been recognized within the Waramaug mainly because of the lack of detailed mapping, severe structural complexity, and interlayering and intergradational relationships among rock types.

The Hartland Formation (Cameron, 1951; Gates, 1951, 1952, 1954, 1959) forms the crystalline terrain of western Connecticut east of Cameron's Line. It is bounded to the east by Mesozoic rocks and overlain by metamorphosed Silurian and Devonian rocks (fig. 1). The Hartland Formation consists of a sequence of highly deformed quartzo-feldspathic gneiss, schist, and amphibolite. In the West Torrington quadrangle the Hartland Formation has been subdivided into upper and lower members (fig. 3; app. 1). The lower member (€-Ohl in app. 1) of the Hartland Formation consists of gray-weathering medium- to coarse-grained quartz–

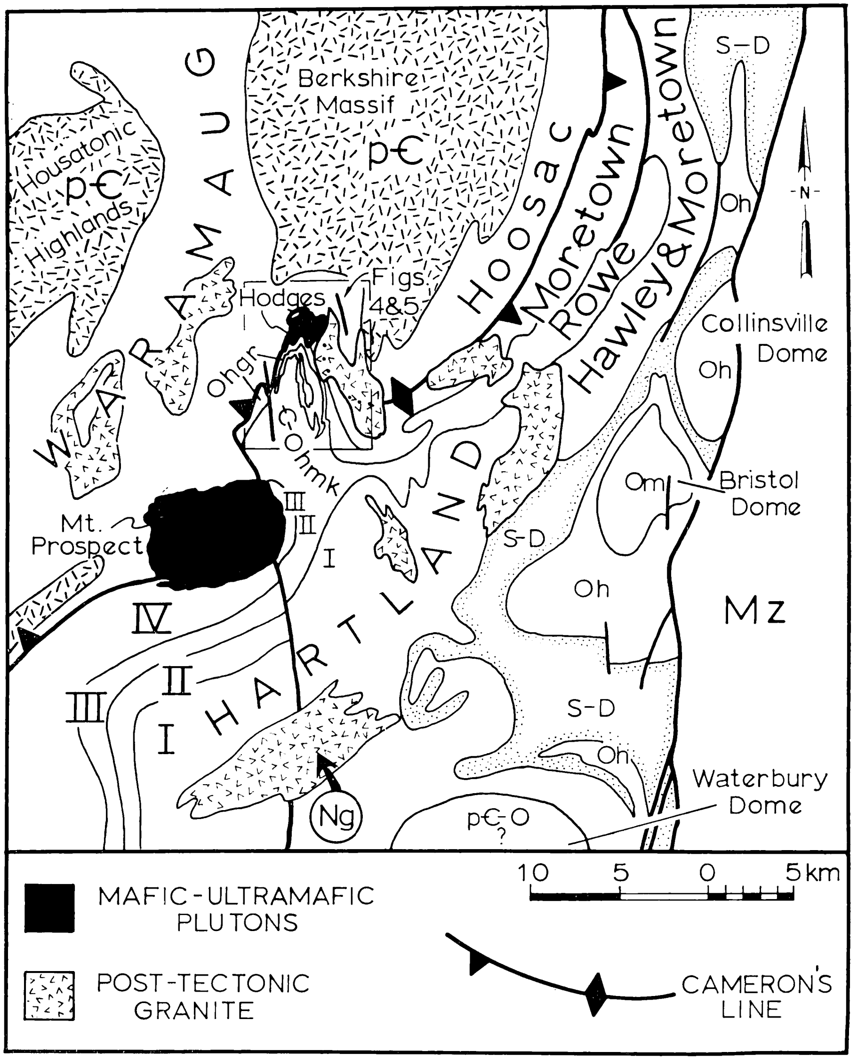


Fig. 2. Geologic sketch map showing the lithostratigraphic correlations between rocks of the West Torrington quadrangle and adjacent regions. Roman numerals refer to Gates' proposed stratigraphy. Sub-units Є-Ohmk and Ohgr of the Hartland Formation exposed near the Hodges Complex are described in app. 1. Same symbols and notation as figures 1 and 4 except Oh = Hawley Formation, Om = Moretown Formation, and Ng = Nonewaug Granite. Heavy lines are faults.

muscovite–plagioclase–biotite–garnet schist with minor ilmenite, apatite, and chlorite (Є-Ohmk). Large porphyroblasts of staurolite, kyanite, biotite, and garnet are conspicuous as large knots protruding from the foliation surface. Interlayered within the lower member is a thick sequence of amphibolites (Є-Oha). These are rusty- to nonrusty-weathering hornblende–plagioclase–biotite rocks with subordinate quartz, epidote, chlorite, ilmenite, sphene, and garnet. The amphibolites exhibit extreme textural and mineralogic variability (see app. 1). Some epidote-rich amphibolites are interpreted as the products of the metamorphism of marls, but most are believed to be the result of subaqueous volcanic flows or tuffaceous ash falls because of their high content of opaque minerals, their association with copper-iron sulfides, and their mineralogic variability.

The upper member (Ohu in app. 1) of the Hartland Formation consists of a sequence of generally nonrusty-weathering gneiss, granofels, and schist (Ohgn, Ohgr, Ohgk), plus layers and lenses of mica quartzite and laminated manganiferous garnet–quartz granofels or coticule (Ohc). Layers of amphibolite (Ohau), lithically similar to amphibolites of the lower member, are not as abundant in the upper member.

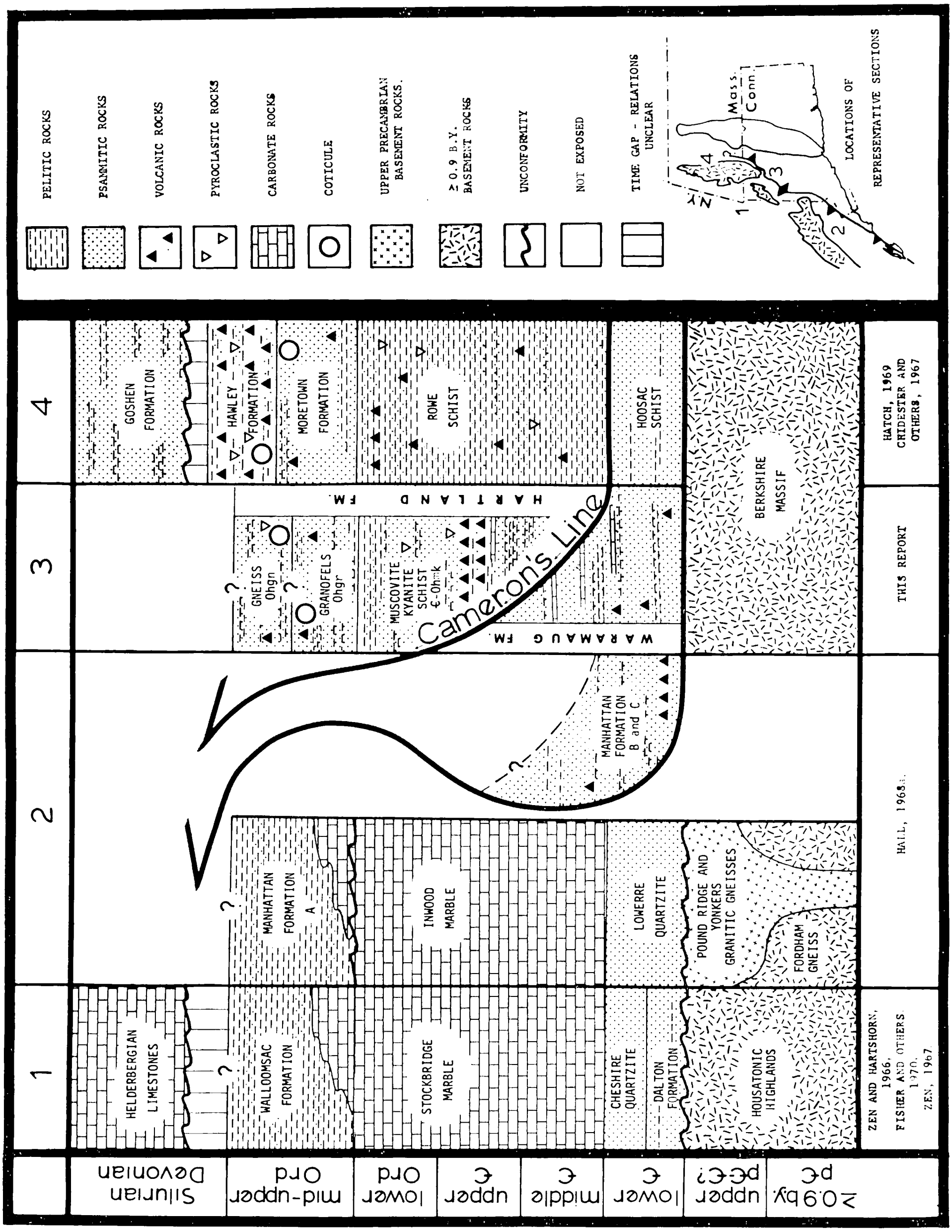
During amphibolite-grade metamorphism significant tectonic intermixing and isoclinal folding of both units at Cameron's Line locally create difficulty in distinguishing between the Hartland and Waramaug Formations. In the field the following criteria were used in deciding whether a given outcrop should be assigned to the Waramaug or Hartland Formations:

Waramaug rocks are generally brown- and gray-weathering, poorly laminated, coarse- to medium-grained, and granular to foliated with quartz and biotite the dominant minerals. Plagioclase and muscovite are present but are typically less abundant than in the Hartland. The apparent lack of layering in the Waramaug may be because the layers are much thicker than outcrop scale. In addition, the Waramaug contains rare amphibolite layers that are typically gray-green to black and granular in texture.

The Hartland Formation, on the other hand, is gray-weathering, commonly laminated, and medium-grained. The rocks of the lower member exhibit a strong crystalloblastic texture, and quartz and muscovite predominate. In the upper member, plagioclase commonly forms augen visible on fresh surfaces cut across the foliation. Thick layers of amphibolite that are typically green, well-foliated, and highly variable mineralogically occur in both members of the Hartland. Well-layered quartzite, calc-silicate rocks, and coticule are also present.

REGIONAL CORRELATION

The following discussion is to be used in conjunction with the stratigraphic correlation chart (fig. 3). The Waramaug Formation forms a belt up to 10 km wide extending from Torrington, Conn. southward to New Milford, Conn. (fig. 1). Clarke (1958) suggested correlating the Waramaug Formation with the Manhattan Formation near New Milford,


PELITIC ROCKS
PSAMMITIC ROCKS
VOLCANIC ROCKS
PYROCLASTIC ROCKS
CARBONATE ROCKS
COTICULE
UPPER PRECAMBRIAN BASEMENT ROCKS.
≥ 0.9 B.Y. BASEMENT ROCKS
UNCONFORMITY
NOT EXPOSED
TIME GAP - RELATIONS UNCLEAR
Mass.
Conn.
N.Y.
LOCATIONS OF REPRESENTATIVE SECTIONS
1
2
3
4
HELDERBERGIAN LIMESTONES
WALLOOMSAC FORMATION
STOCKBRIDGE MARBLE
CHESHIRE QUARTZITE
DALTON FORMATION
HOUSATONIC HIGHLANDS
MANHATTAN FORMATION A
INWOOD MARBLE
LOWERRE QUARTZITE
POUND RIDGE AND YONKERS GRANITIC GNEISSES
FORDHAM GNEISS
MANHATTAN FORMATION B and C
Cameron's Line
WARAMAUG FM.
HARTLAND FM.
GNEISS Ohgn
GRANOFELS Ohgr
MUSCOVITE KYANITE SCHIST
BERKSHIRE MASSIF
GOSHEN FORMATION
HAWLEY FORMATION
MORETOWN FORMATION
ROWE SCHIST
HOOSAC SCHIST
ZEN AND HARTSHORN, 1966. FISHER AND OTHERS, 1970. ZEN, 1967
THIS REPORT
HATCH, 1969 CRIDESTER AND OTHERS, 1967
Silurian Devonian
mid-upper Ord
lower Ord
upper Є
middle Є
lower Є
upper pЄ-Є?
≥0.9 by. pЄ

Conn., as rocks of the Manhattan Prong occur along strike to the south. Recent work by Hall (1968b) and Alavi (1975) shows that the Waramaug Formation correlates with the Manhattan B and C members that are in thrust contact with Manhattan A (metamorphosed Walloomsac Formation).

The structural position of the Waramaug in northern Connecticut and southern Massachusetts suggests it may correlate with the Hoosac Schist with which it is nearly physically continuous along the eastern flanks of the Berkshire and Green Mountain Massifs (Hall, 1971; Hatch and Stanley, 1973). The age of the Hoosac Schist is believed to be early Cambrian or possibly Eocambrian, because it underlies the Rowe Schist which has been traced through east-central Vermont (Hatch, Schnabel, and Norton, 1968) into fossiliferous rocks of demonstrably Cambrian and possibly Ordovician age in the Knowlton-Richmond area, Quebec (Osberg, 1965). The contact between the Hoosac and Rowe has been considered stratigraphic in the past, but it is probably a fault (the Whitcomb Summit Fault), which is almost certainly the northern continuation of Cameron's Line (John Rodgers, written commun.). It is believed that lower Paleozoic eugeosynclinal rocks in western Connecticut are correlative with the Vermont-Quebec sequence. The presence of polyphase folding and medium- to high-grade metamorphism in Massachusetts and Connecticut creates structural complications along strike that makes time stratigraphic correlation in the eugeosynclinal terrane difficult, if not impossible.

To the west and northwest of the Berkshire Massif, the Waramaug Formation probably correlates with the Dalton Formation and the Cheshire and Lowerre Quartzites (fig. 3). Waramaug rocks have not been recognized east of Cameron's Line. The allochthonous Waramaug Formation tectonically overlies the Berkshire Massif in northwestern Connecticut (Harwood, 1975) and is tectonically interleaved with basement in the West Torrington quadrangle (D. Harwood, personal commun.). Significant tectonic intermixing between the Hoosac Schist and crystalline basement has been suggested by Martin (1970) in Connecticut and proven in Massachusetts (Ratcliffe, 1978).

Hall (1971) and Alavi (1975) considered the lower part of the Hartland Formation to be approximately the same age as the Waramaug Formation, whereas Gates (1952), Gates and Christensen (1965), and Martin (1970) suggest the Hartland is entirely younger. A pre-Devonian minimum age is indicated, since Siluro-Devonian rocks overlie the Hartland although the contact is not necessarily an unconformity. Furthermore, the regional schistosity of the Hartland is truncated by the Nonewaug

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← Fig. 3. Stratigraphic correlation chart for southern New England showing the interpreted protoliths of the formations shown. Mixed symbols are meant to indicate relative, non-quantitative abundances of various pre-metamorphic lithologies. 1 = New York, Connecticut, Massachusetts State Line; 2 = Glenville area, Westchester Co., N.Y.; 3 = West Torrington quadrangle, northwestern Conn. Both the upper member of the Hartland Formation [gneiss-(Ohgn) and granofels-(Ohgr)] and the lower member [muscovite–kyanite schist-(Є-Ohmk)] and the Waramaug Formation are described in app. 1; 4 = east flank of the Berkshire Massif, western Mass.

Granite (fig. 2) which yielded a Rb/Sr whole-rock isochron age of 383 ± 64 m.y. (Besancon, 1970).

Gates (1959, 1967) used Roman numerals to denote time-stratigraphic equivalency in the Hartland, but his proposed order of Hartland I (oldest) to Hartland IV (youngest) is not consistent with more recent stratigraphic studies of this report and of Hatch and Stanley (1973), Scott (1974), and Stanley (1964, 1968). Time-stratigraphic relationships have not been proven within the Hartland, except that the rocks are Silurian or older. If the time-stratigraphic relationships of the Moretown (Ordovician) and Rowe (Cambrian or Ordovician) are applicable to Hartland rocks in the West Torrington area, the sequence represents a structurally inverted section that could represent the basal portion of a larger, nappe-like structure.

DEPOSITIONAL SETTING OF THE WARAMAUG AND HARTLAND FORMATIONS

The abundance of metamorphosed volcanic and volcaniclastic rocks, interstratified with mica schist, gneiss, quartzite, and coticule suggests that the Hartland Formation was deposited in a deep-water basin adjacent to the lower Paleozoic shelf edge of North America which provided a source for mature, non-volcanic detritus. Metasedimentary rocks of the Waramaug Formation occupy an intermediate spatial and compositional position between shelf and deeper water lithofacies which suggests a transitional sedimentologic environment. Some workers (L. Hall, D. Harwood, N. Ratcliffe, personal commun.) suggest that the Waramaug Formation could represent a transitional facies deposited near the North American shelf edge, where it interfingered with clastic sediments and carbonate rocks to the west (Cheshire, Dalton, and Stockbridge Formations and correlatives) and more eugeosynclinal rocks of the Hartland Formation to the east. I therefore suggest that the Waramaug and Hartland Formations are, in part, the same age although direct evidence is lacking (fig. 3).

The persistent coticules (manganiferous garnet–quartzites) found throughout the medial Ordovician section of western Massachusetts and western Connecticut have been interpreted as manganiferous chert deposits formed through volcanogenic processes in a marine environment (Merguerian, 1981a). Submarine volcanism and upwelling of metalliferous solutions at a ridge crest or oceanic fracture zone are probable causes for the remarkable spatial association of Cu, Fe ± Zn stratabound sulfides, Fe oxides, and coticules in western Massachusetts. In western Connecticut, wispy, non-metallogenic coticules may represent manganese deposition near a volcanic island arc (unpub. data).

The depositional basin for the Hartland was flanked on the oceanward side by a volcanic archipelago which supplied volcanics and pyroclastic deposits. It is likely that by the middle Ordovician the depositional site was similar to a collapsing foreland basin as found today between Timor and Australia (Hamilton, 1977, 1979; Rowley, 1980).

The Ammonoosuc Volcanics in western New Hampshire, composed of soda-rhyolite tuff, tuff breccia, volcanic conglomerate, biotite and hornblende amphibolite, chlorite ± epidote schist, mica schist, slate, and impure quartzite, overlie dacite and intrusive quartz monzonite of medial Ordovician age (Naylor, 1975). In Massachusetts this volcanic arc sequence is exposed in the Bronson Hill Anticlinorium (fig. 1); it trends southward into the Killingworth Dome of Connecticut, where it is called the Middletown Formation, composed of basaltic, andesitic, and dacitic rocks of volcanic, pyroclastic, and plutonic parentage. The Middletown Formation and underlying Monson Gneiss represent the southward continuation of the medial Ordovician arc terrane found in Massachusetts (Rodgers, Gates, and Rosenfeld, 1959; Brookins and Hurley, 1965; Lundgren and Thurrell, 1973).

In the southeast part of western Connecticut near New Haven (fig. 1), rocks beneath the Siluro-Devonian section (that is, Maltby Lake and Allingtown volcanics) are recognized as metamorphosed arc-derived pyroclastic deposits, lapilli tuff, volcanic breccia, submarine flows, spilites, and associated clastic rocks (Fritts, 1962, 1963; Burger, 1967). Intermixed volcanic, volcaniclastic, and plutonic rocks give way from the southeast to the northwest to a less-volcanic facies of Hartland rocks mainly exposed in western Connecticut against Cameron's Line, a relationship first noted by Crowley (1968). In a later section it is suggested that this is due to a large-scale structural imbrication.

STRUCTURAL GEOLOGY

Mapped structure and megascopic and microscopic analyses reveal evidence of five deformational events in rocks immediately adjacent to the Hodges Complex. An older foliation (S_1), defined locally in the Hartland Formation amphibolite by hornblende–plagioclase–epidote gneissic layering and in the Waramaug Formation by foliated gneissic compositional banding, is axial planar to isoclinal folds. However, the dominant fabric is a later regional schistosity (S_2) defined by oriented micas, by recrystallized quartz and plagioclase in pelitic rocks, and by oriented hornblende, plagioclase, and opaque minerals in amphibolitic rocks of both the Waramaug and Hartland Formations. This schistosity is axial planar to a second set of isoclinal folds (F_2).

D_1.—Evidence for the F_1 folding episode occurs mainly in the Hartland amphibolites where the axial planar S_1 foliation of F_1 folds is preserved at a small angle to S_2. In a streambed 1 km southeast of the crest of Soapstone Hill on Highland Avenue, a gneissic foliation (S_1) of oriented hornblende and plagioclase ± epidote is tightly folded by F_2 (pl. 1-A). Outside of the view of this photograph, S_1 has been traced into the axial surfaces of pre-F_2 isoclinal folds. The F_1 fold axes and amphibole lineations plunge away from the F_2 fold axes. These data suggest that D_1 was an isoclinal, penetrative episode accompanied by metamorphism and that S_1 was redeformed and remetamorphosed during the D_2 event.

The areal extent and degree of penetration of the oldest event (D_1) is difficult to determine. Because the mapped contacts of the amphibolite unit (Ꞓ-Oha) in the Hartland Formation are isoclinally folded with respect to the trace of the F_2 axial surfaces, however, it is concluded that the F_1 folds are of major significance in this area (figs. 4, 5). Moreover, the complex map pattern of the Hartland units appears to be related to the superposition of F_1 and F_2 folds.

D_2.—F_1 folds and related structures were obliterated in most of the more schistose rocks during D_2 because of significant recrystallization of minerals parallel to S_2. Amphibolites apparently preserved the S_1 fabric in places, because they were less ductile than the schists during subsequent D_2 deformation and were more refractory to metamorphic recrystallization. S_1 in the Hartland and S_1 in the Waramaug may have formed during the same deformational episode, although there is no proof of this point, and it is quite possible that pre-D_2 deformation occurred at different times within these belts.

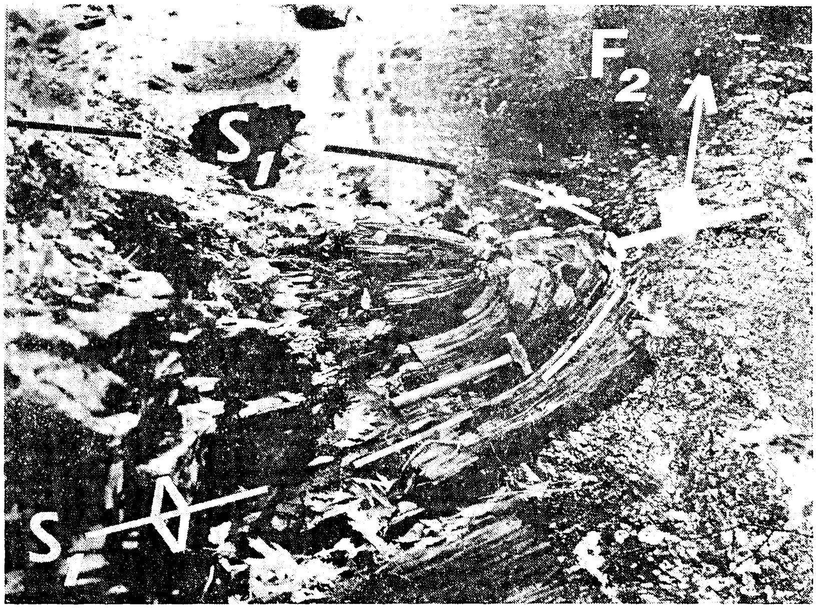
The similarity in prograde metamorphic grade and deformational style suggests that F_1 and F_2 are progressive events of a single orogenic episode that culminated during F_2 folding and metamorphism. The strikes of axial surfaces of F_2 folds and the regional schistosity (S_2), in both the Hartland and the Waramaug Formations, are parallel to the trace of Cameron's Line. A discrete surface has not been observed, but it is likely that the S_2 structures parallel the fault zone mapped as Cameron's Line.

THE WARAMAUG — HARTLAND CONTACT — CAMERON'S LINE

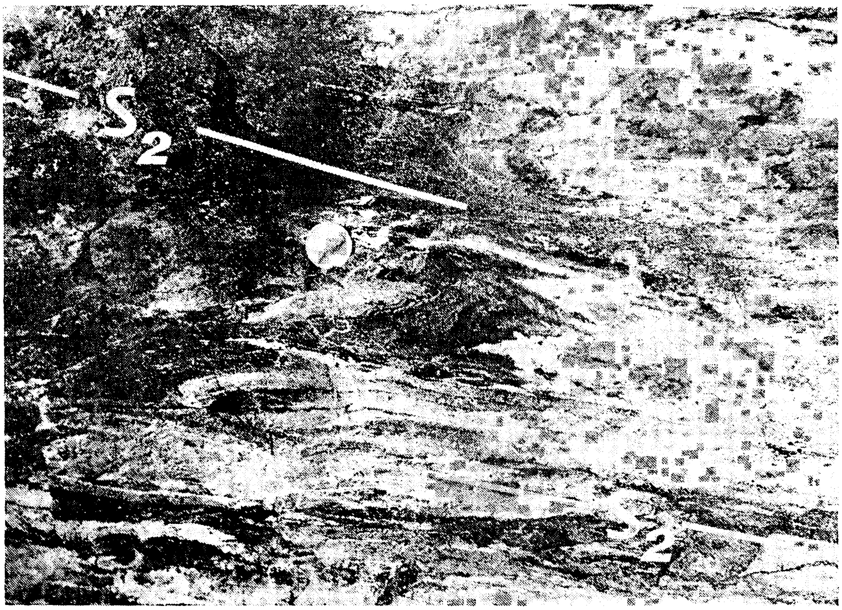
The rarely exposed contact zone between the Hartland Formation (upper member) and the Waramaug Formation is typically heterogeneous and consists of tectonically interleaved rock types from both formations. It varies in thickness from 15 to 90 m and usually incorporates mylonitic amphibolite layers up to 3 m thick. Amphibolites from this zone (fig. 4, loc. 1, 2) differ texturally from amphibolites away from Cameron's Line and show disarticulation of F_1 structures and strong recrystallization parallel to S_2 (pl. 1-B). The intermixed zone between the Hartland and Waramaug Formations has been traced in screens and xenoliths through the Hodges Complex. The contact zone does not represent interbedding (an older concept) because on the map scale (fig. 5) both Hartland subunits and the S_1 metamorphic fabric are truncated against Cameron's Line. Megascopic evidence for tectonic imbrication (fig. 4, loc. 3) consists of blocks of foliated schist (Hartland) measuring 3 by 30 cm, rotated and aligned subparallel to S_2 within the Waramaug at Cameron's Line.

At another exposure of Cameron's Line in the West Torrington quadrangle (fig. 4, loc. 4), the Waramaug Formation is mylonitic parallel to S_2 in outcrop and, to a lesser extent in thin section sample, up to 15 m southeast of the contact with the adjacent Hartland Formation which occurs as screens and xenoliths in the Hodges Complex. Here the Waramaug Formation has a textural appearance in outcrop suggestive of large scale fluxion structure. The long dimension of elliptical bodies of the Waramaug are parallel to the regional schistosity (S_2) and to recrystallized mica bounding them. Quartz is ribboned into 0.5 mm thick laminae

PLATE 1



A. Photograph showing an F_2 fold of the S_1 metamorphic layering in amphibolite of the Hartland Formation (Є-Oha) found in a streambed 1 km southeast of the crest of Soapstone Hill on Highland Avenue. Recrystallization parallel to S_2 is clear in the core of the fold. The hammer is 50 cm in length.



B. Photograph showing mylonitization and syn-tectonic recrystallization of hornblende, biotite, quartz, plagioclase ± epidote parallel to S_2 in Hartland amphibolite (Ohau) at an exposure of Cameron's Line (fig. 4, loc. 2). Note the disarticulation and penetrative shear associated with F_2 folding at Cameron's Line compared to (A). The S_1 gneissic layering of the amphibolite is locally preserved within F_2 fold hinges.

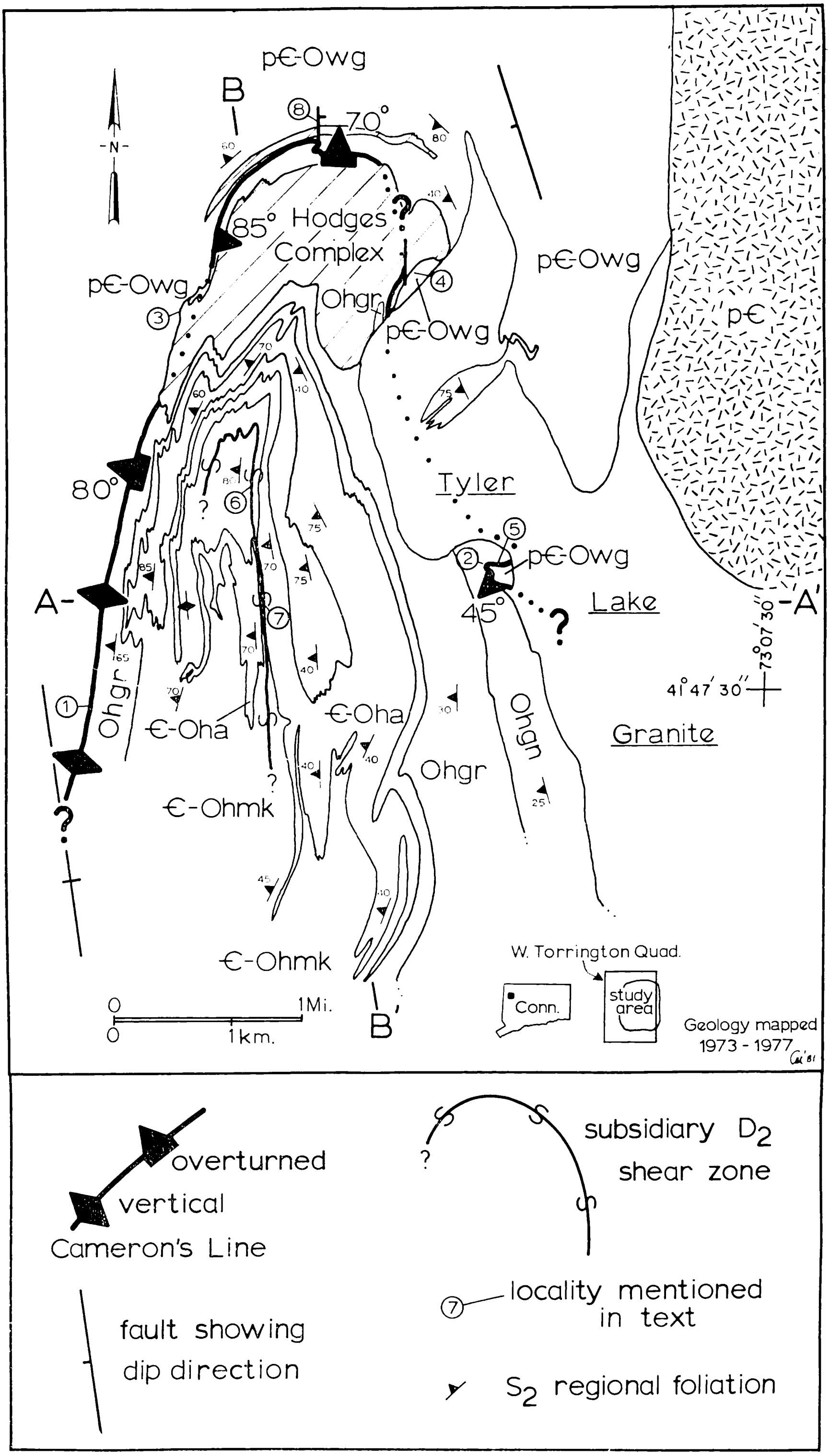


Fig. 4. Simplified geologic map of part of the West Torrington quadrangle, Conn. Cameron's Line is dotted through intrusive rocks. See app. 1 for detailed stratigraphic descriptions of the Hartland and Waramaug Formations.

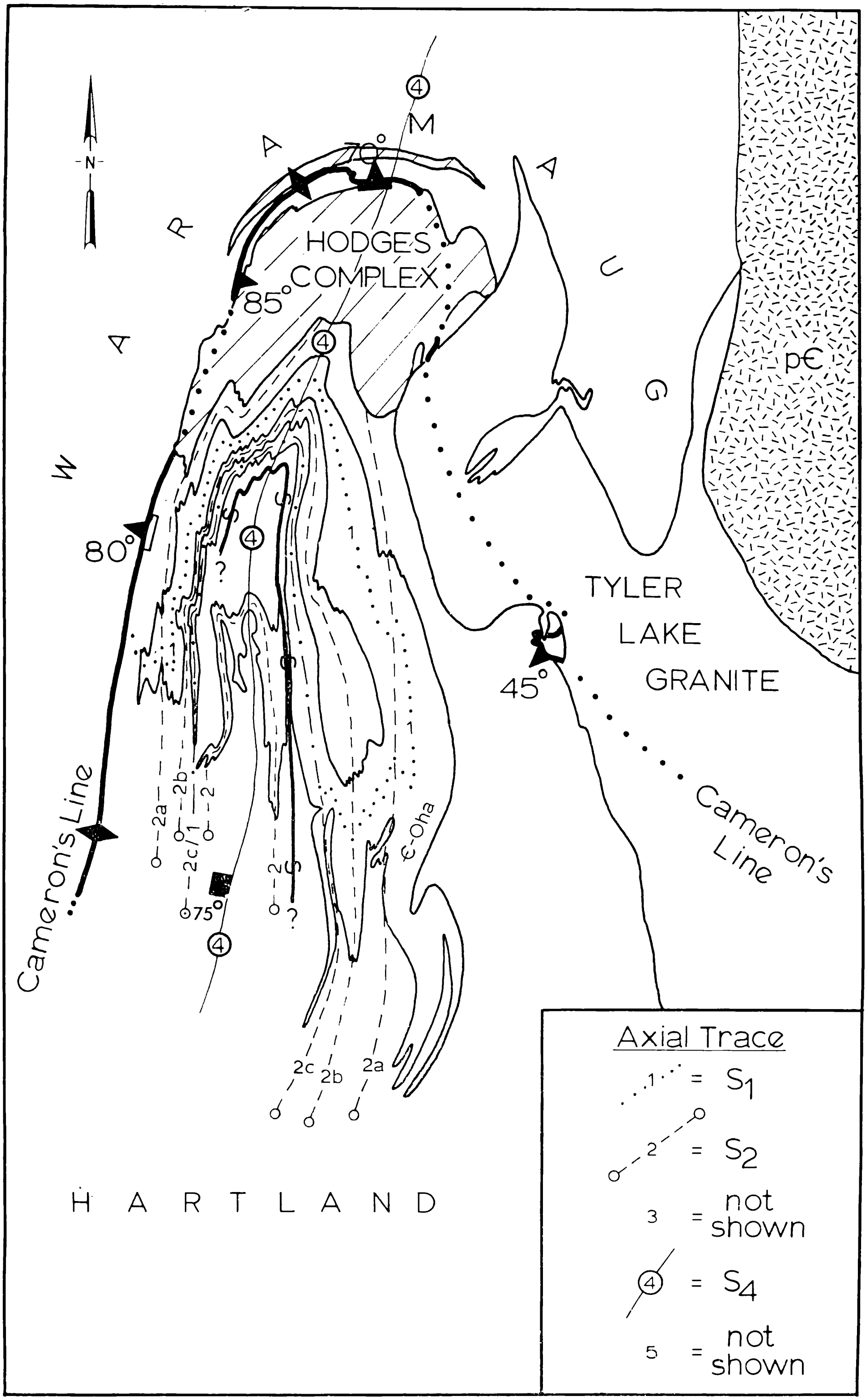


Fig. 5. Sketch map showing the traces of S_1, S_2, and S_4 in the vicinity of the Hodges Complex. F_3 folds are syn-intrusive folds related to the Tyler Lake Granite and the Hodges Complex; they do not affect the map pattern except locally. Hartland amphibolite sub-unit Є-Oha is included as a reference. Same notation as figure 4.

which enclose small flakes of biotite oriented parallel to S_2, suggesting that quartz flowed ductilely during deformation.

The syn-metamorphic nature of the S_2 surfaces and the attendant transposition of the older S_1 foliation suggest that smearing out of pre-existing structures and recrystallization accompanied the formation of S_2. The spatial coincidence of mylonite, intermixed rock types, and disarticulation of D_1 fabrics near Cameron's Line indicate that the intense F_2 structures formed as a result of high strain at this boundary. These data are consistent with the hypothesis that the F_2 structures and synmetamorphic shearing formed during juxtaposition of the Hartland and Waramaug rocks. The intense S_2 fabric at Cameron's Line is therefore interpreted as a fold-fault fabric.

A 10 m body of serpentinite together with metavolcaniclastic rocks, interlayered coticule, and amphibolite, is isoclinally folded by F_2 folds at Cameron's Line (fig. 4, loc. 5). This occurrence is interpreted (Merguerian, 1979) as dismembered ophiolite together with part of its volcano-sedimentary cover, imbricated and deformed during D_2 deformation.

SUBSIDIARY SHEAR ZONE

A 10 m-wide shear zone is marked by a serpentinite–soapstone–talc–chlorite schist body (fig. 4, loc. 6), phyllonitic Hartland schist (fig. 4, loc. 7), and a marked topographic expression south of loc. 7. This zone, parallel to the trace of Cameron's Line and the local trend of S_2, may have developed as a subsidiary shear zone imbricating Hartland amphibolites during the D_2 event. In humid climates shear zones in rock are deeply weathered so that many may remain unidentified. Thus, internally the Hartland may be a highly imbricated eugeosynclinal sequence.

D_3.—Open to tight crenulate folds with axial-surface traces subparallel to the margins of intrusions have little effect on map pattern except in the vicinity of the Hodges Complex and the Tyler Lake Granite (fig. 5). The F_3 folds crenulate the regional schistosity (S_2) and develop an axial-surface slip or crenulation cleavage defined by recrystallized quartz, plagioclase, and mica. These folds formed near the walls of plutons during intrusion and, being local, are not shown in figure 5.

A minor localized brittle thrust (fig. 4, loc. 8) along a north-south-trending, steeply east-dipping fault surface postdates the intrusion of the Hodges Complex and the formation of the S_2 fold-fault fabric at Cameron's Line and possibly is related to east-over-west thrusting in response to doming in the east (Collinsville and Bristol Domes) as suggested by Amenta (1978).

D_4.—The regional schistosity is sharply folded by dextral F_4 folds with moderately steep southwest-plunging axes and steep northwest-dipping axial surfaces. A highly penetrative crenulation cleavage or spaced foliation (S_4) is spaced at 1 cm or less in the axial regions of F_4 folds. Rocks of the Hodges Complex are serpentinized and chloritized along a 70 m-wide zone parallel to the trace of S_4 as shown in figure 5. S_4 is characterized in the schists by the growth of large poikiloblastic biotite,

hornblende, and recrystallized quartz, minute physical disruptions across previously formed minerals, the presence of deformation lamellae in plagioclase, and parting in garnet porphyroblasts. The amphibolites show a spaced foliation marked by neo-crystallized biotite, plagioclase, and quartz. Hornblende is aligned in S_4 in a few areas. The S_4 fabric cuts across all earlier tectonic features, all map units, map contacts, and Cameron's Line.

D_5.—A fifth deformation is suggested by the warping of the S_4 axial surface as shown in figure 5 and by the presence of west- to northwest-trending slip cleavage axial planar to crenulate and open west- to southwest-plunging folds. The F_5 fold geometries are not distinctively different from those of F_3 folds, except that their development is not limited to the borders of plutons.

STRUCTURE SECTIONS

Sections in figure 6 are derived from the surface structural data and the axial-surface traces shown in figure 5. The existence and importance of F_1 folding have been verified, as argued earlier, by field observation of crosscutting metamorphic fabrics and by direct observation of early folds and lineations, but the exact configuration of F_1 closures in the subsurface is hypothetical due to extensive D_2 transposition.

The major structure in the study area is a late dextral synformal fold (F_4) that deforms the regional schistosity (S_2), the older S_1 fabric, Cameron's Line and its subsidiary shear zone, and both the Tyler Lake Granite and the Hodges Complex. The fold has a steep western limb (vertical to locally overturned) and a shallow west-dipping eastern limb. The axial plane of this fold trends north-northeast and dips steeply toward the northwest; the axes trend southwest and plunge 50° to 60°. Section A-A′ (fig. 6) shows these relationships and the truncation of Hartland sub-unit Ohgn against Cameron's Line. The major $F_1 \times F_2$ structure is folded by F_4 and is truncated by the Tyler Lake Granite.

Section B-B′ shows the convoluted structure of twice isoclinally folded Hartland rocks in longitudinal view. The relationship of Hartland sub-units and the Hodges Complex to Cameron's Line is clear, but the effects of F_4 are not evident because the section is nearly parallel to S_4. Section B-B′ also shows the bunching of S_2 axial traces due to shouldering aside by the Hodges intrusion. In addition, the close spacing of S_2 axial traces southwest of the Hodges Complex (fig. 5) and in section A-A′ in figure 6 is apparently a result of the initial thinness of the amphibolite unit.

META-IGNEOUS ROCKS OF THE HODGES COMPLEX AND TYLER LAKE GRANITE

Crosscutting field relationships indicate that the intrusion of both the Hodges Complex and the Tyler Lake Granite can be bracketed by the relative timing of the deformational events. Metamorphosed mafic and ultramafic intrusive rocks of the Hodges Complex occur within a 2.5 km^2 area (fig. 4). The complex is a steep-walled, folded, mushroom-shaped pluton with a core of hornblende gabbro and a chilled border phase of dioritic rocks. A stock-like central intrusive and many smaller separated

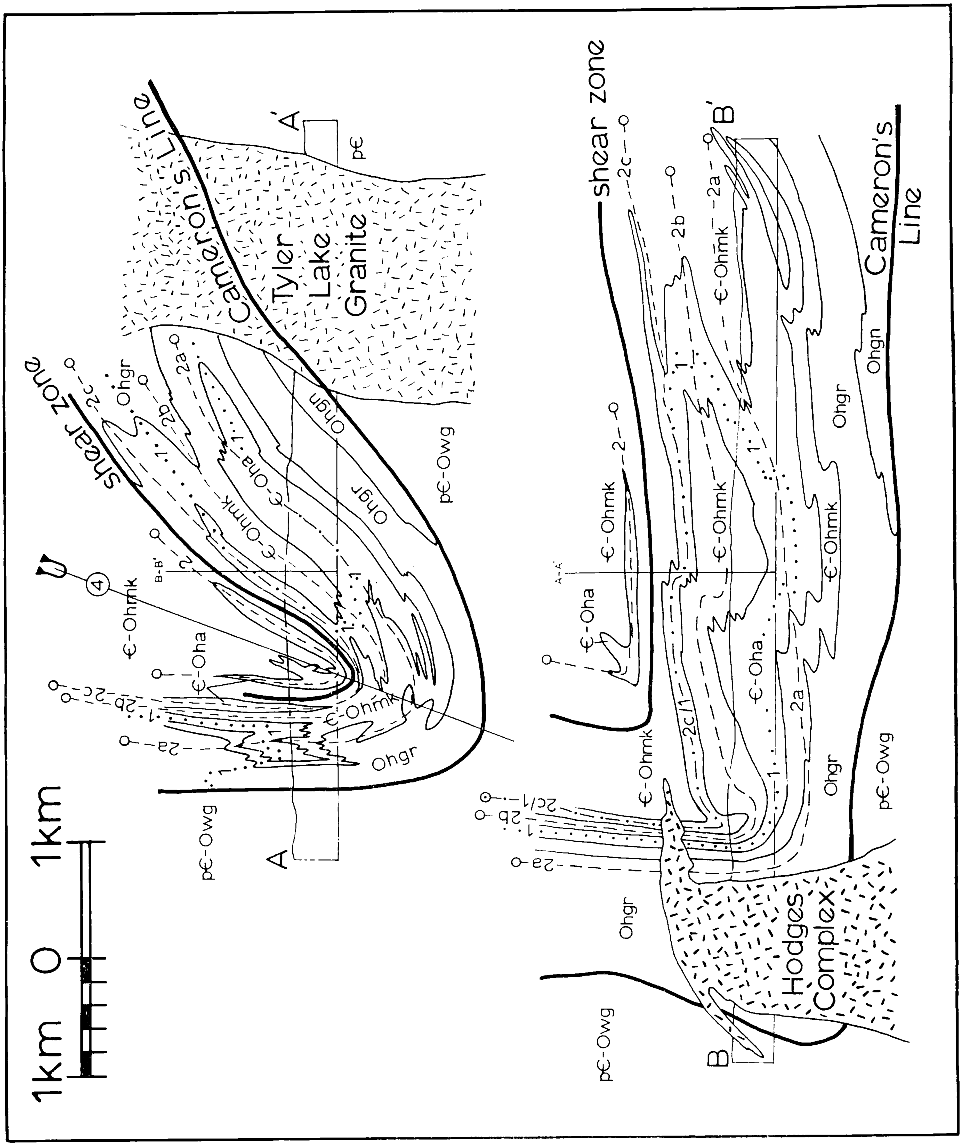


Fig. 6. Geologic structure sections. Section lines are shown in figure 4. No vertical exaggeration.

bodies of pyroxenite and hornblendite crosscut the gabbro-diorite mass and foliated amphibolites of the Hartland Formation (Merguerian and Ratcliffe, 1977). The Hodges Complex is *younger* than, and not genetically related to, the polydeformed Hartland amphibolites to the south — in contrast to the interpretation of Gates and Christensen (1965). The pluton is in direct contact with both the Waramaug and Hartland Formations and is surrounded by a narrow contact aureole which overgrows the S_2 fold-fault fabric developed at Cameron's Line.

All rocks of the Hodges Complex have been metamorphosed. In thin section, changes to foliated textures and replacement of igneous minerals are widespread, particularly in the ultramafic rocks. Gabbro and diorite remain relatively unaltered, although plagioclase and hornblende have recrystallized, and new biotite and chlorite have formed. Rocks of the Hodges Complex are sheared along a north-northeast-trending, 15 to 70 m wide zone of serpentinized and chloritized rocks. This altered zone is parallel to the S_4 axial-surface trace as it is shown in figure 5.

The Tyler Lake Granite also cuts the S_2 fabric and includes xenoliths of the Hodges Complex at its contact zone. The granitic rocks exhibit a faint micaceous fabric subparallel to S_4. These data and the position of the Hodges Complex and the Tyler Lake Granite (along Cameron's Line) suggest that the Tyler Lake Granite was emplaced along a thermally weakened tectonic scar already occupied by the Hodges Complex. The relationship of the S_4 fabric to the Hodges, Tyler Lake, and Cameron's Line suggests they were folded together and implies that the plutons, and perhaps the Hartland amphibolite, acted as immobile plugs in the crust, localizing the F_4 fold.

METAMORPHISM AND METAMORPHIC HISTORY

Field and petrographic data on crosscutting metamorphic minerals indicate that metamorphic recrystallization took place at three different times with respect to the development of structural fabrics. Metamorphic mineral assemblages recorded for the Hartland and Waramaug Formations and their sub-units in the vicinity of the Hodges Complex are shown in table 1. The peak of regional metamorphism (M_2 in fig. 7) reached kyanite–staurolite grade or medium-grade Barrovian metamorphism (Winkler, 1974). Contrary to previous reports (Thompson and Norton, 1968), the Waramaug-Hartland boundary is *not* a sillimanite isograd, although sillimanite does occur locally near mafic-ultramafic intrusives and to the north and northwest of the study area, as shown by reconnaissance mapping. As illustrated in figure 7, M_1 accompanied the development of Cameron's Line, whereas M_2 and M_3 postdate its formation.

A secondary regional metamorphic pulse (M_2 in fig. 1) occurred after the juxtaposition of the Hartland and Waramaug, since porphyroblastic garnet and staurolite overgrow S_2 structures and M_1 minerals in both formations. Kyanite commonly grows mimetically along S_2 folia but with a characteristic random orientation. The M_2 metamorphism was therefore reached after the development of the regional schistosity (S_2) but before the D_4 event, since M_2 kyanite, staurolite, and garnet are deformed by S_4. In addition, retrograde biotite, quartz, and chlorite (M_3 in fig. 7) grow subparallel to the S_4 fabric, suggesting that during the D_4 event the rocks were at higher crustal levels than during older events.

The contact aureole of the Hodges Complex overprints the S_2 fold-fault fabric and is typically enriched in garnet and deficient in muscovite compared to the rest of the study area. The distinctive cordierite–kyanite–staurolite–garnet–biotite ± sillimanite hornfels texture suggests mineral growth during static crystallization. Thus the Hodges Complex was intruded at pressures and temperatures near the Al_2SiO_5 triple-point after the formation of Cameron's Line. In fact, the intrusion of the Hodges Complex may have been synchronous with the regional M_2 (Acadian?) metamorphism as depicted in figure 7.

TECTONIC SIGNIFICANCE

Beginning with the sweeping premise that Paleozoic plate-tectonic mechanisms mimic contemporary examples the significance of the structural elements described above may be interpreted paleotectonically. Lower Paleozoic basement rocks in western and central Connecticut can be divided into three north-south trending tectonostratigraphic belts (fig. 1). Belt I, containing the metamorphosed interlayered clastic and car-

TABLE 1

Listing of metamorphic mineral assemblages recorded for the Hartland and Waramaug Formations and their sub-units

The Waramaug Formation (p€-Owg)
- biotite-garnet–opaque–quartz–plagioclase–muscovite
- biotite-garnet–opaque–chlorite–quartz–plagioclase–muscovite
- biotite-garnet–opaque–kyanite–staurolite–quartz–plagioclase–muscovite
- biotite-garnet–opaque–kyanite–quartz–plagioclase–muscovite

The Waramaug Formation — amphibolite and amphibolitic gneiss (p€-Owga)
- hornblende–biotite–opaque–plagioclase–quartz
- hornblende–biotite–opaque–garnet–plagioclase–quartz

The Hartland Formation — upper member (Ohgr, Ohgn, Ohgk)
- biotite–opaque–quartz–plagioclase–muscovite
- biotite–opaque–quartz–garnet–chlorite–plagioclase–muscovite
- biotite–opaque–quartz–kyanite–staurolite–garnet–chlorite–plagioclase–muscovite

The Hartland Formation — lower member (€-Ohmk)
- biotite–garnet–opaque–quartz–plagioclase–muscovite
- biotite–garnet–opaque–kyanite–quartz–plagioclase–muscovite
- biotite–garnet–opaque–kyanite–chlorite–quartz–plagioclase–muscovite
- biotite–garnet–opaque–kyanite–staurolite–quartz–plagioclase–muscovite
- biotite–garnet–opaque–staurolite–chlorite–quartz–plagioclase–muscovite
- biotite–garnet–opaque–kyanite–staurolite–chlorite–quartz–plagioclase–muscovite

The Hartland Formation — amphibolites (combined) — (Ohau, €-Oha)
- hornblende-biotite–opaque–quartz–plagioclase
- hornblende–biotite–opaque–garnet–quartz–plagioclase
- hornblende–biotite–opaque–epidote–quartz–plagioclase
- hornblende–biotite–opaque–chlorite–quartz–plagioclase
- hornblende–biotite–opaque–chlorite–epidote–quartz–plagioclase
- hornblende–epidote–opaque–quartz–plagioclase
- hornblende–epidote–opaque–chlorite–quartz–plagioclase

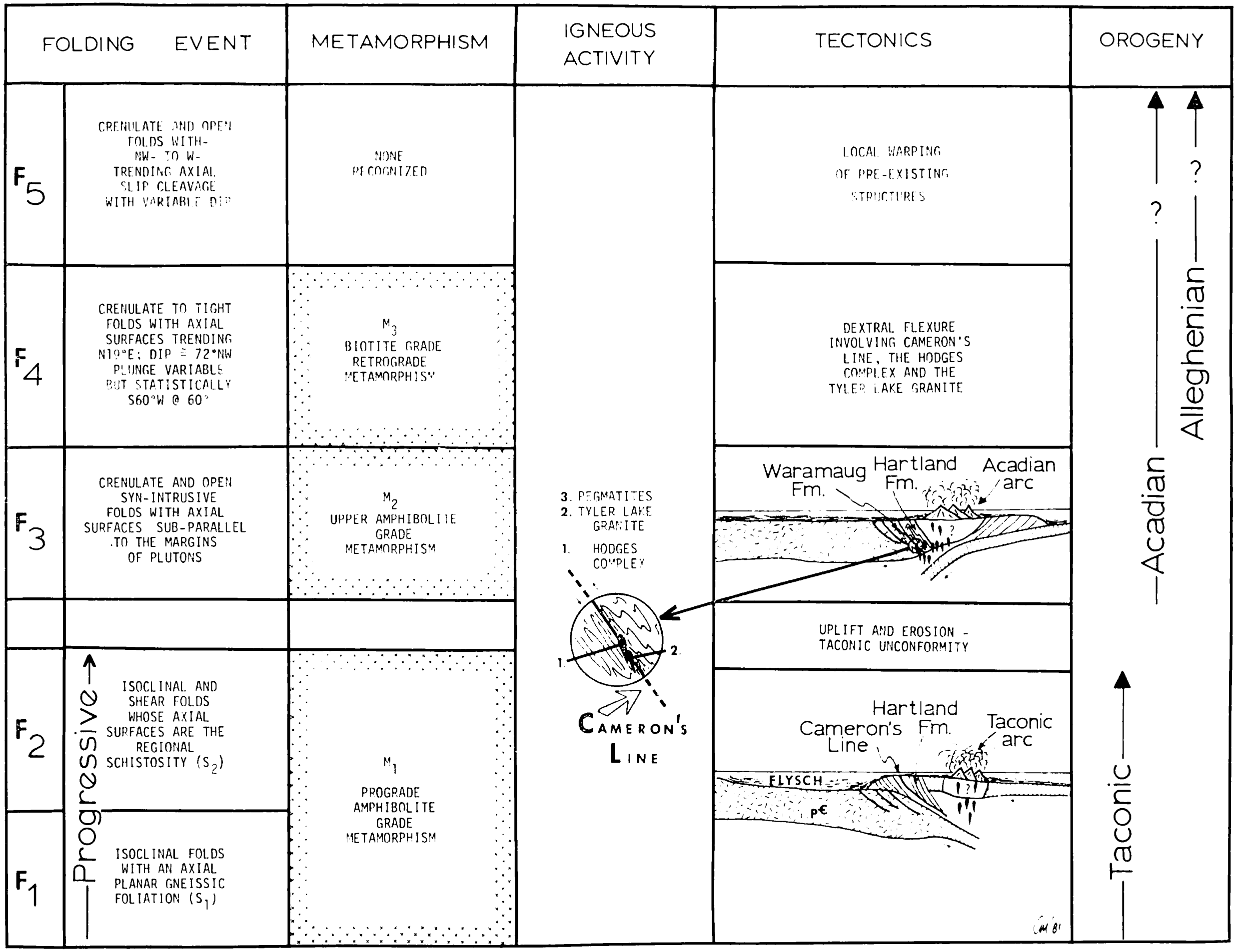


Fig. 7. Chronology of folding, metamorphism, igneous activity, and tectonics in northwestern Connecticut. The paleotectonic cross-sections are drawn approximately east-west in the present position of Torrington, Conn.

bonate rocks of the Manhattan Prong, lies west of Cameron's Line. These highly deformed miogeosynclinal rocks locally include klippen and tectonic slivers of more eugeosynclinal rocks (for example, Waramaug Formation, Manhattan B and C members, Taconic Allochthon) which represent deeper water deposits formed adjacent to the shelf edge of the lower Paleozoic North American continent. The western portion of the Hartland Terrane (belt II) is composed primarily of metaclastic rocks with some interstratified volcaniclastic and volcanic rocks. Belt III contains abundant metamorphosed plutonic and volcanic rocks of andesitic to basaltic composition in the Hartland Formation of the southeast part of western Connecticut and also on the east side of the Connecticut Valley Basin. The volcanics are discordant with respect to Precambrian basement rocks of known Avalonian ($\cong$ 600 m.y.) and possibly Grenvillian ($\cong$ 1.1 b.y.) age. The volcanic-plutonic terrain may represent Ordovician arc activity, as suggested above.

Near Torrington, Conn., Cameron's Line is a zone of syn-metamorphic mylonite with intense localized isoclinal folding. Lenses and isoclinally folded layers of serpentinite close to Cameron's Line throughout the lower Paleozoic strata from western Connecticut northward along the east flank of the Berkshire Massif and southward toward New York City may be slivers of the upper mantle (dismembered ophiolite). These occurrences plus the presence of coticules suggest that the Hartland was deposited in an ensimatic basin. D_1 and D_2 in the study area may represent progressive superposed ductile deformation at depths up to 30 km within a west-facing Taconic accretionary complex (Merguerian, 1979). This being the case, Cameron's Line would be a deep-seated, west-vergent thrust zone between overriding eugeosynclinal deposits (Hartland Formation — belt II) and transitional-shelf deposits (Waramaug Formation — belt I) and the locus of intense D_2 deformation and metamorphism forming the present cryptic suture between "cratonic" and "oceanic" realms (fig. 7). Detachment and continentward obduction of a part of this subduction complex produced the Taconic allochthon.

East-dipping subduction direction is necessary to explain the lack of Ordovician volcanic rocks west of Cameron's Line. It also elegantly explains the continentward vergence of basement and cover during the Taconic Orogeny. Cameron's Line, with its subsidiary shear zone and possibly other intra-Hartland zones of shear (belt II-belt III contact?), formed in response to high strains created by the closure of the Hartland depositional basin and ensuing arc-continent collision.

An imbricate thrust model for pre-Silurian rocks in Connecticut between Cameron's Line and the Connecticut Valley explains the southeast to northwest juxtaposition of a volcano-plutonic arc terrane (for example, Ivoryton Group, Maltby Lake, and Allingtown volcanics (belt III)), a volcaniclastic and clastic eugeosynclinal terrane (western Hartland terrain — belt II), and a transitional shelf terrane (Waramaug Formation — belt I). If so, much of the Taconic arc is beneath the Mesozoic graben deposits of Connecticut and Massachusetts (fig. 1).

The intrusion of the Hodges Complex, the Tyler Lake Granite, and possibly other nearby mafic-ultramafic plutons younger than the regional schistosity along Cameron's Line (fig. 1) could be feeder pipes related to the initiation of Acadian arc volcanism as a new continentward-dipping subduction system formed east of the Taconic arc and migrated outboard after the Taconian arc-continent collision. Apparently these primitive magmas ascended along zones of high ductile strain such as Cameron's Line. The plethora of felsic post-tectonic granites and perhaps the domal uplifts in central Connecticut may suggest a regional plutonic episode of an Andean-arc terrain (fig. 7). As suggested earlier, the intrusion of the Hodges Complex and the Tyler Lake granite may have been synchronous with the M_2 (Acadian?) metamorphism.

A Devonian Andean arc interpretation as discussed above is problematical since there is a paucity of metavolcanic rocks in the Siluro-Devonian section of southern New England. It is possible that the intrusion of the Hodges Complex and similar plutons along Cameron's Line (fig. 1) are Late Ordovician in age with magmas generated by partial melting of the mantle due to some unknown sub-crustal process during the end stages of the Taconic arc-continent collision. Alternatively, the plutons may have been transported as hot bodies (Hall, 1980) in the waning stages of the Taconic collision, but this is the least plausible choice of the three models in my view.

The Taconic arc was apparently erupted through latest Precambrian ($\cong$ 600 m.y.) (compare Hills and Dasch, 1972) and possibly older basement rocks. Hall (1980) suggests that rocks exposed in the Waterbury Dome (fig. 2) may be Grenville-aged ($\cong$ 1.1 b.y.) basement. Clark and Kulp (1968) present a Rb/Sr age of 485 m.y. for these gneisses, but Hall (1980) argues that this is a metamorphic age. The absolute pre-metamorphic ages of rocks occurring in the gneiss domes of central Connecticut are not known (figs. 1, 2). They may be Ordovician in age and therefore a part of the Taconic arc terrane. If they are Precambrian, they probably represent the arc's basement of rifted Precambrian crust that was once part of North America.

The late Precambrian intrusion of the protoliths of the Pound Ridge Granite Gneiss and the Yonkers Gneiss (fig. 1) in southeastern New York (Long, 1969; Mose and Hayes, 1975) may be the products of a late Precambrian rifting event that preceded the formation of the Hartland Basin. Possibly the rifted Grenville-aged crust and late Precambrian intrusions are preserved in the remobilized cores of gneiss domes in central Connecticut. The inception of east-dipping Ordovician subduction beneath the rifted Precambrian block would have predated closure of the Hartland Basin. Alternatively, the Hartland Basin might have formed in a back-arc setting in which case a west-dipping subduction mode would be postulated during the late Precambrian history of the eastern North America craton. No geologic data exist to suggest that the Taconic arc was ensimatic in nature. Even though tectonic models have been proposed recently for New England (see Osberg, 1978; Robinson and Hall, 1980) clearly new geologic and isotopic data on the enigmatic basement rocks in the gneiss domes of western and central Connecticut and data on the plutons will be necessary in deciding among the tectonic models presented above.

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APPENDIX I

Descriptions of metamorphic rocks of the West Torrington quadrangle, Connecticut. Minerals are listed in order of decreasing abundance. Those listed in parentheses are not found in all exposures. The Hartland Formation is subdivided into upper and lower members. The upper member (Ohu) consists of sub-units Ohgn, Ohgr, Ohgk, Ohau, and Ohc. The lower member (Є-Ohl) consists of sub-units Є-Ohmk and Є-Oha.

HARTLAND FORMATION-Upper Member (Ohu)— Gneiss, granofels, amphibolite, and schist 0.15 to 1.5 km thick form a continuous belt through the Hodges Complex between the Waramaug Formation and the lower member of the Hartland Formation. The upper member can be divided into the following sub-units:

Gneiss sub-unit (Ohgn) — A lustrous, typically nonrusty-weathering, gray, quartz–plagioclase–muscovite–biotite–(graphite) gneiss and minor schist with local crumbly feldspathic interlayers up to 15 cm thick. Quartzofeldspathic layers and interlayered thin micaceous folia impart a pin-striped appearance in some exposures, while in others, smoky-gray quartz and granular dark quartz layers are up to 5 cm thick.

Amphibolite sub-unit (Ohau) — Fine- to medium-grained, rusty and nonrusty weathering, gray-green or whitish on weathered surfaces, dark-green to green-black hornblende–plagioclase–biotite–(quartz)–(epidote)–(chlorite)–(ilmenite)–(pyrite) amphibolite. Amphibolites within the upper member of the Hartland Formation are typically dense, dark-green rocks comprised of prismatic hornblende aligned within the regional schistosity. Laminae of plagioclase and minor clear, recrystallized quartz separate the hornblende-rich laminae. In comparison to amphibolites of the lower member Hartland (Є-Oha), the rocks are mineralogically less diverse and tend to be epidote poor.

Granofels sub-unit (Ohgr) — A slabby, well-layered faint to strongly brown-weathering, quartz–plagioclase–mica–(graphite) gneiss or mica-poor granofels. Interlayers of muscovite–plagioclase–quartz–biotite schist are also present.

Quartzite, coticule, calc-silicate sub-units (Ohc) — Mica quartzite, quartz–manganese garnet granofels, and calc-silicate rocks, all are well-layered and generally separated by thin, schistose layers 5 cm to 1 m thick. Mica quartzites are punkyweathering, highly laminated, vitreous, and are coarser grained than other rocks of the sub-unit. Coticule rock is rusty- to gray-weathering, compact, well-layered and interstratified with amphibolite and amphibolitic schist. Coticules are comprised of idiomorphic to sub-idiomorphic manganiferous garnet set in a mosaic of granoblastic quartz. Quartz and garnet each compose roughly 50 percent of the total rock volume, and accessory minerals are numerous. Calc-silicate rock is green to brown-green in color, with a surface appearance similar to the amphibolite mentioned above. These rocks are interlayered within the granofels sub-unit (Ohgr) and are locally associated with a distinctive medium- to coarse-grained purple-gray quartz–biotite–plagioclase granofels, granular mica-gneiss, and schist.

Kyanite schist sub-unit (Ohgk) — A fine- to medium-grained, gray, locally rusty-weathering quartz–plagioclase–muscovite–biotite–kyanite–garnet schist and schistose gneiss. It is found near the contact with the lower member of the Hartland Formation as discontinuous layers, lenses, or possibly tectonic slivers.

HARTLAND FORMATION-Lower Member (€-Ohl) — Muscovite–kyanite schist and amphibolite member occur as a 300 m-thick sequence in the study area and can be divided into the following sub-units:

Muscovite–kyanite schist sub-unit (€-Ohmk) — A highly lustrous, phyllitic to schistose, gray-weathering, medium- to coarse-grained, quartz–muscovite–plagioclase–biotite–opaque–garnet–(ilmenite)–(kyanite)–(staurolite)–(apatite)–(chlorite) schist that often contains large porphyroblasts of kyanite, staurolite, and garnet, and more rarely plagioclase and biotite. Deeply eroded outcrops have a knotted appearance due to differentially weathered porphyroblasts. Fresh surfaces reveal a shiny intergrowth of quartz and muscovite. Quartz and muscovite are roughly equal in proportion and together volumetrically compose more than half the rock. These rocks part readily along both the regional schistosity and a slip cleavage. The resulting fragments are used locally as fence posts. Granular, clear- to smoky-gray quartz pods are conspicuous and occur flattened within the regional schistosity. The lower member becomes markedly hornblende-, chlorite-, and/or biotite-rich near contacts with the interlayered amphibolite sub-unit (€-Oha). Often these minerals are incorporated into elliptical quartz pods. The schist is sometimes non-porphyroblastic though it more typically contains spongy 7 cm staurolite and 10 cm kyanite crystals in random post-regional schistosity growth. Discontinuous layers of hornblende–chlorite–quartz granofels are present near the schist-amphibolite contacts. With an increase in plagioclase content and a decrease in micaceous minerals, the lower member (€-Ohl) of the Hartland Formation grades, with some lensing, into the upper member (Ohu).

Amphibolite sub-unit (€-Oha) — Fine- to medium-grained rusty- and nonrusty-weathering, gray-green to lime-green through dark green to green-black in color. The rocks are comprised of hornblende–plagioclase–biotite–(quartz)–(epidote)–(chlorite)–(opaque)–(ilmenite)–(garnet)–(thulite). The amphibolites are interlayered and laterally variable. Rocks are characterized by one of the three lithic types listed below. Contacts are often gradational.

1. A dense, iron-stained, dark-green to black rock comprised of lineated prismatic hornblende with subordinate biotite, plagioclase, and quartz. Laminae of plagioclase and minor clear, recrystallized quartz define the regional schistosity. Some zones weather into a crumbly mass of hornblende but still retain their green color. Locally, the amphibolite is associated with layers and lenses of more silicic metavolcanic rocks.

2. A light green to yellow-green epidote-rich amphibolite with a layered appearance due to compositional variations. Epidote is locally up to 50 percent of the total rock volume with individual layers up to 15 cm thick. A less abundant variant is a tri-colored, pin-striped epidote amphibolite with folia colored white or yellow-white, light-green, and dark-green. The mineralogic layering creates a dense but easily parted rock.

3. A well-layered green-, pink-, and tan-colored actinolite–plagioclase–quartz granular amphibolite with interpenetrant laths of actinolite set in a fine-grained quartzofeldspathic matrix.

WARAMAUG FORMATION (p€-Owg) — A heterogeneous assemblage of rusty- gray-, and maroon-weathering gneiss, minor schist, amphibolite, and calc-silicate rock which is usually massive or indistinctly layered. Granofels, lithically similar to rocks in the Hartland upper member, is also locally present. The Waramaug is granular and biotitic at or near Precambrian contacts while in facies away from the Precambrian rocks, a heterogeneous admixture of the following lithologies coexist. The internal stratigraphy of the formation is not known.

— A granular quartz–biotite–plagioclase–muscovite–garnet–(opaque) gneiss which can be distinguished by its light gray color on a fresh surface and by the common presence of plagioclase porphyroblasts within the gneissosity.

— A quartz–plagioclase–biotite–garnet–muscovite–opaque–(kyanite)–(staurolite)–(tourmaline) gneiss with minor schist distinguished by its rough surface appearance due to differentially weathered aluminosilicate minerals.

Zones of non-mappable extent include 2-8 cm gray quartzite layers in biotite–quartz–plagioclase schist, quartz–plagioclase–muscovite–biotite schist, and tremolite–quartz–calcite granofels. Some schistose zones are sulfidic, consisting of yellow-stained, rust-colored, friable rocks.

Amphibolite and amphibolitic gneiss (p€-Owga) — Fine-grained, gray-weathering hornblende–plagioclase–biotite–opaque–(garnet) amphibolite occurs as continuous and discontinuous lenses and layers from 0.01 to 30 m thick (greater thicknesses may be due to repetition by folding). The amphibolite lacks the great variety of the Hartland types and is less abundant. It is typically gray-black to gray-green with plagioclase and minor quartz composing the laminae. These minerals vary from less than 5 percent, up to 20 percent of the total rock volume. Amphibolite is often devoid of felsic minerals and is a dense, tough rock. Amphibolite gneiss often forms the transition from pelitic rock to amphibolite. A complete transition consists of mica gneiss going to amphibolitic gneiss and then to amphibolite in its more massive character. In other places, amphibolite contacts are sharp.

Precambrian (p€) — Undivided and unmapped in the present study. Surface distribution from Gates and Christensen (1965) and D. S. Harwood (unpub. data).

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