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Stratigraphy, Structure, and Metamorphism of the 'Dorsal Zone,'" Central New hampshire

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STRATIGRAPHY, STRUCTURE, AND METAMORPHISM OF THE 'DORSAL ZONE', CENTRAL NEW HAMPSHIRE

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INTRODUCTION

The purpose of this field trip is to examine the bedrock geology of the Gilmanton, New Hampshire, 15 minute quadrangle and immediate surrounding area. The stratigraphy, which forms a link between the sections extending east from the Bronson Hill anticlinorium and west from the Campbell Hill Nonesuch River fault zone, and a new structural model for the complexly deformed metasedimentary rocks of this area will be presented. The nature of regional metamorphism and radiometric age dates that constrain the timing of plutonism and metamorphism will be examined. The ultimate goal of this field trip is to present a coherent geologic model for the region, based on structural, petrologic, and geochronologic data.

REGIONAL GEOLOGIC SETTING

This study focuses on a group of rocks belonging to the Kearsarge-Central Maine synclinorium (Lyons and others, 1982) formerly the Merrimack synclinorium of Billings (1956) and also called the Merrimack Belt by geologists in Massachusetts (Zen et. al. 1983). This is interpreted as a large Silurian to early Devonian depositional basin that was multiply deformed and metamorphosed during the Acadian and Alleghanian (?) orogenies.

Since the introduction of the name Kearsarge-Central Maine synclinorium by Lyons and others in 1982, there has been semantic confusion when describing the major geologic features in this region. The recent mapping by students of John Lyons at Dartmouth College, Peter Robinson at University of Massachusetts, and Wallace A. Bothner at the University of New Hampshire has shown that there is not just one synclinorium in this tract of rocks, but several, with intervening anticlinoria (for example see; E. Duke, 1984; P. Thompson; 1985, Eusden, 1984 and 1988). It is clear that the Kearsarge-Central Maine synclinorium is an inadequate descriptive term for the entire region.

Eusden and others (1987) and John Lyons (this volume) now recognize the following major structures in the Kearsarge-Central Maine synclinorium of New Hampshire; the Kearsarge-Central Maine synclinorium (KCMS) proper; the Lebanon antiformal syncline (LAS); the Central New Hampshire anticlinorium (CNHA); the Boundary Mountains anticlinorium; and the Chocorua syncline. For this report the term Central Maine Terrane (CMT) (Zen et. al., 1986) will be used to include the rocks that extend northeasterly from Connecticut to Maine and from the Bronson Hill anticlinorium east to the Campbell Hill-Nonesuch River fault zone (CHNRFZ) (Figure 1). Reference to the KCMS is restricted to axial trace of the synclinorium proper through the Devonian Littleton Formation. This reconcilliation of regional nomenclature will probably not sate geologists that feel the belt should extend southeast beyond the CHNRFZ to include the formations of the Merrimack Group (Berwick, Eliot and Kittery Formations), and hence would prefer to keep the term Merrimack Belt or synclinorium as originally described by Billings (1956). However, many geologists, myself included, believe that the aforementioned Merrimack Group and Massabesic Gneiss Complex is part of a Precambrian exotic terrane quite different in origin from the rocks of the CMT (Bothner and others, 1984; Lyons and others, 1982 and 1986; Gaudette and others, 1984; Naylor, 1985).

PREVIOUS WORK

Mapping within the western part of the CMT, along the axis of the KCMS, from west-central New Hampshire to a fossiliferous Silurian and Lower Devonian section exposed near Rangeley, Maine has revised the stratigraphic interpretation of Billings (1956) (Hatch and others, 1983; Moench and Boudette, 1970; Moench, 1984). Much of what was assigned to the Lower Devonian Littleton Formation is now interpreted as a thick section of Silurian turbidites correlative to the Rangeley, Maine section (Hatch and others, 1983; Nielson, 1981; Thompson, 1983, 1984, 1985; Chamberlain, 1984; G. Duke, 1984 and E. Duke, 1984).

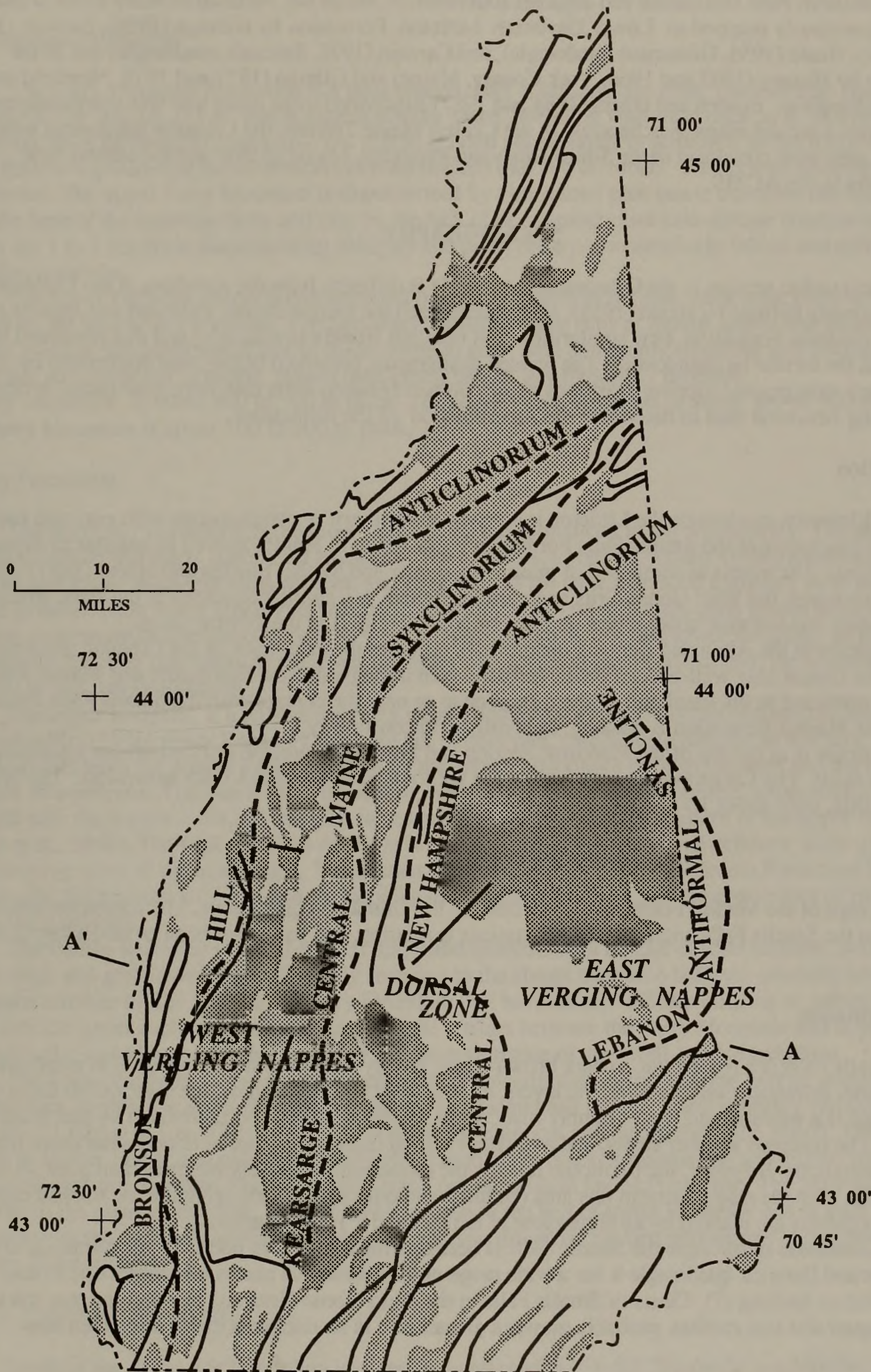


Figure 1. Major fold structures in the Central Maine Terrane. Igneous rocks shaded, faults shown as solid black lines, axial traces of folds shown as bold dashed lines. Vergence of nappes and "Dorsal Zone" also shown.

In southeastern New Hampshire and adjacent southwestern Maine the metasedimentary rocks in this part of the CMT were previously mapped as Lower Devonian Littleton Formation by Billings (1956), Stewart (1961, Alton quadrangle), Heald (1955, Gilmanton quadrangle), and Carnein (1976, Suncook quadrangle) and as the Shapleigh Group by Hussey (1962 and 1968, York County, Maine) and Gilman (1977 and 1978, Newfield and Kezar Falls, Maine quadrangles). Eusden and others (1984 and 1987) subdivided these rocks into five lithostratigraphic units and remapped a second major synclinorium in the Central Maine Terrane, the Lebanon Anitformal syncline. The units in this area were correlated to the Siluro-Devonian Rangeley, Maine section and the central New Hampshire section in the KCMS.

STRATIGRAPHY

The stratigraphic section in the Gilmanton quadrangle is different from the members of the Littleton Formation as originally defined by Heald (1955). Heald recognized the Durgin Brook, Pittsfield and Jenness Pond Members of the Littleton Formation. Few similarities exist between Heald's stratigraphy and that presented here and it is proposed that the former be abandonned. The revised stratigraphy, presented below, was determined by examining primary stratigraphic topping directions at the contacts between units and, once established in critical localities, by using structural data to determine the superposition of the formations.

Littleton Formation

In the Gilmanton quadrangle the Littleton is a coarse-grained grit or conglomerate with gray and rusty-weathering lithic fragments of the Smalls Falls Formation up to 10 cm in length, as well as angular to subrounded vitreous quartz clasts. The matrix is composed of muscovite, quartz and biotite. Eusden and others (1987) informally named the grit exposures the Wild Goose Grits and correlated them to a similiar lithology at the same stratigraphic position in the Alton and Berwick quadrangles mapped by Hussey (1962) as the Towow Grits.

The Littleton in the Alton and Berwick quadrangles occupies the axial trace of the Lebanon antiformal syncline and is the typical gray well-bedded pelitic turbidite seen throughout New Hampshire and Maine. The Wild Goose Grits are restricted to the basal part of the formation at or near the contact with the Smalls Falls Formation. Note that here the Madrid Formation is missing, implying an unconformity.

The Littleton is at the top of the Paleozoic section and because of erosion only minimum estimates of the thickness can be made. The Littleton may have been up to a kilometer or two thick prior to erosion. The Wild Goose Grits are thin, only about 100 to 300 meters thick.

Madrid Formation

No outcrops of the Madrid Formation were found in the Gilmanton quadrangle. The formation which should be found between the Smalls Falls and Littleton Formations is missing, and has either been eroded away or was never deposited.

Smalls Falls Formation

The Smalls Falls is a red-brown to dark brown-black, deeply rusty-weathering schist with pyrrhotite and occasional graphite. Infrequent sulfidic quartzite layers, up to several cm in thickness, are seen within the schist. The overall appearance is a well foliated, very crumbly rusty schist that is almost always crenulated by late small-scale kink-type folds. The outcrops weather easily, and as a result natural outcrops are not as abundant as those from other more resistant formations. However, the pyrrhotite renders the formation moderately magnetic and positive magnetic anomalies coincide with the map pattern in this area (Bothner and others, 1988) allowing it to be tracked easily. The upper and lower contacts are marked by an abrupt loss of the distinctive rusty weathering.

In the Gilmanton quadrangle the Smalls Falls is between 100 and 500 m thick. To the northeast in the Alton quadrangle and Berwick quadrangle it has a wide range of thicknesses. In places it is absent due to non-deposition, erosion or faulting (?). Clasts of Smalls Falls in the Wild Goose Grits suggest that the true thickness was probably greater and that erosion probably played a greater role in its thickness distribution then non-deposition.

Perry Mountain Formation

The Perry Mountain Formation is a well-bedded, gray schist and quartzite. The quartzite can be quite thick, commonly 10 cm and up to 1 m, and is almost always 'clean', meaning with little mica in it. In a few places the Perry Mountain is moderately migmatitic but it is in general not as easliy migmatized as the Rangeley Formation. In the Gilmanton quadrangle the formation has been divided into two members. The style of bedding is identical in each member. The upper Perry Mountain is characterized by pink garnet plus quartz coticules that occur within and toward the base of the quartzite beds, and also by the lack of or extremely rare calc-silicate boudins or 'footballs'. The coticules are 1 to 5 cm thick, discontinuous stringers and pods, often more complexly folded and deformed then the surrounding quartzite.

The lower Perry Mountain is characterized by calc-silicate boudins that occur most often within the quartzite beds, and by the lack of any coticules. The calc-silicate boudins have rims of biotite, quartz and plagioclase and are dark gray in color; the cores are lighter in color, white to gray, and commonly stand out as elliptical resistant knobs. They are composed of quartz, plagioclase, grossular and less frequently diopside.

The Perry Mountain is about 400 to 500 m thick. The upper Perry Mountain is about 200 to 300 m thick and the lower Perry Mountain is about 100 to 300 m thick.

Rangeley Formation

The Rangeley Formation is the most varied of all the formations in the stratigraphy. The three fold subdivision used in this study is not used elsewhere. For example, Lyons and others (1986) subdivide the Rangeley into upper and lower members only. Moench and Boudette (1970) have identified Rangeley A, B and C; though threefold in subdivision, these lithologies are coarse conglomerates and turbidites quite unlike those mapped in the Gilmanton quadrangle or elsewhere in central New Hampshire. The middle and lower Rangeley of the Gilmanton quadrangle are together equivalent to the lower Rangeley of Lyons and others (1986) and, the upper Rangeley is equivalent to their upper Rangeley.

The upper Rangeley is a red-brown, rusty weathering, often graphitic, schist and sulfidic quartzite. Unlike Lyons and others (1986) upper Rangeley there are no, or only rare, calc-silicate boudins in this unit. The upper Rangeley differs from the Smalls Falls formation by the greater abundance of quartzite beds and the much lower abundance of pyrrhotite. The quartzite beds are thin, from 1 to 5 cm. Positive magnetic anomalies, commonly associated with the Smalls Falls, are not seen in conjunction with the mapped pattern of the upper Rangeley (Bothner et al., 1988). The rock weathers easily, and is often crumbly and not well exposed; it commonly crops out in the low-lying areas of the quadrangle. The contact with the overlying Perry Mountain Formation is abrupt and marked by the disappearance of well-bedded turbidite in the Perry Mountain, and the appearance of rusty-weathering schist in the Rangeley.

The middle Rangeley is a well-bedded schist and quartzite with no calc-silicate boudins. Bedding is about 3 to 10 cm thick and graded beds are not usually seen due to the abrupt transition between quartzite and schist. This rock is quite similiar to the parts of the Perry Mountain that have no calc-silicate boudins or garnet coticules. The contact with the upper Rangeley is abrupt, and like the contact between the Perry Mountain and upper Rangeley, it is marked by the loss of rusty-weathering schist and the appearance of gray well-bedded turbidites.

The lower Rangeley is a massive to well-bedded, calc-silicate boudin-bearing, biotite granofels. It is purple to gray in color. Bedding is defined by alternating layers of schist and granofels and is highly variable in thickness, ranging from 1 cm up to 1 m. The calc-silicate boudins are elliptical and mineralogically zoned. They have dark gray rims of biotite, quartz and plagioclase and light gray to white cores of plagioclase and quartz, with green and red spots of grossular and diopside. The cores often stand out as resistant knobs in outcrop. The long axes of the boudins are parallel to the plane of bedding. Almost every outcrop in the belt of lower Rangeley has at least one boudin in it. The contact with the middle Rangeley is gradational and was drawn on the first appearance of calc-silicate boudins as one moves down-section.

Rangeley Formation Migmatites

Much of the Rangeley Formation is extensively migmatized in the Gilmanton quadrangle. The term 'ragged migmatite' has been used by E. L. Boudette to describe these rocks. They also fit the description of stromatic or layered migmatites as classified by Ashworth (1985). The leucosomes are typically blebs, spots or stringers within a melanosomatic schist matrix giving it a ragged appearance. The migmatites display classic gneissic layering. The migmatites are incontrovertibly embrechitic, meaning that the gneissic layering can be tracked to indisputible bedding and that the two fabrics are parallel and essentially one and the same. This has been borne out by following well-bedded Rangeley to migmatitic Rangeley with no change in attitude but only a change in texture and mineralogy. There are many places where calc-silicate boudins in migmatites, which are considered markers of primary layering, are parallel to gneissic layering, again demonstrating that the bedding and migmatitic foliation are similiar fabrics.

There are many possible origins for the segregations, or leucosomes, of quartz, plagioclase, plus or minus muscovite and sillimanite. They could be anatectic leucosomes, replacements after metamorphic K-feldspar, and/or augen that grew during deformation. Though most of the segregations are deformed or show at least some type of kinematic fabric that could be associated with shear zones or mylonites, it is believed that the deformation may have only enhanced the leucosomes and not produced them.

The entire Rangeley in the Gilmanton quadrangle is between 1000 and 1500 m thick. The complete thickness is not well constrained because the bottom of the formation has not been observed. The three members are all of roughly equal thickness. There are places, however, where the middle and upper Rangeley thin to only a 100 m or less in thickness. This may be due either to tectonic or stratigraphic/sedimentologic thinning. The thickness of these members varies considerably across strike; for example in the Alton quadrangle the upper Rangeley thins to only a few tens of meters wide. These thickness variations can be attributed to facies variations within the Siluro-Devonian basin.

STRATIGRAPHIC CORRELATIONS

The stratigraphic section in the Gilmanton quadrangle is very similiar to the sequences of Silurian and Lower Devonian metasedimentary rocks described by Moench and Boudette (1970) in the CMT in west-central Maine, by Hatch and others (1983) in central New Ha mpshire CMT and by Eusden and others (1984; 1987) in the LAS. The sequence and lithologies of the sections match well. It is proposed herein that the Rangeley, Perry Mountain, Smalls Falls and Littleton Formations mapped in the Gilmanton quadrangle correlate to the formations with the same names in the LAS and KCMS of New Hampshire and the type section in the Rangeley, Maine area.

This correlation implies that the ages of the metasedimentary rocks in the Gilmanton quadrangle are Silurian and Devonian, rather than entirely Devonian, and forms a link between the units of the LAS (Eusden and others, 1984 and 1987) and the formations in central and northeastern New Hampshire along the KCMS (Hatch and others, 1983; Nielson, 1981; Thompson, 1983 and 1984; Chamberlain, 1984; G. Duke, 1984; E. Duke, 1984). In spite of the lack of paleontological and isotopic control, lithic type and sequence strongly support this correlation.

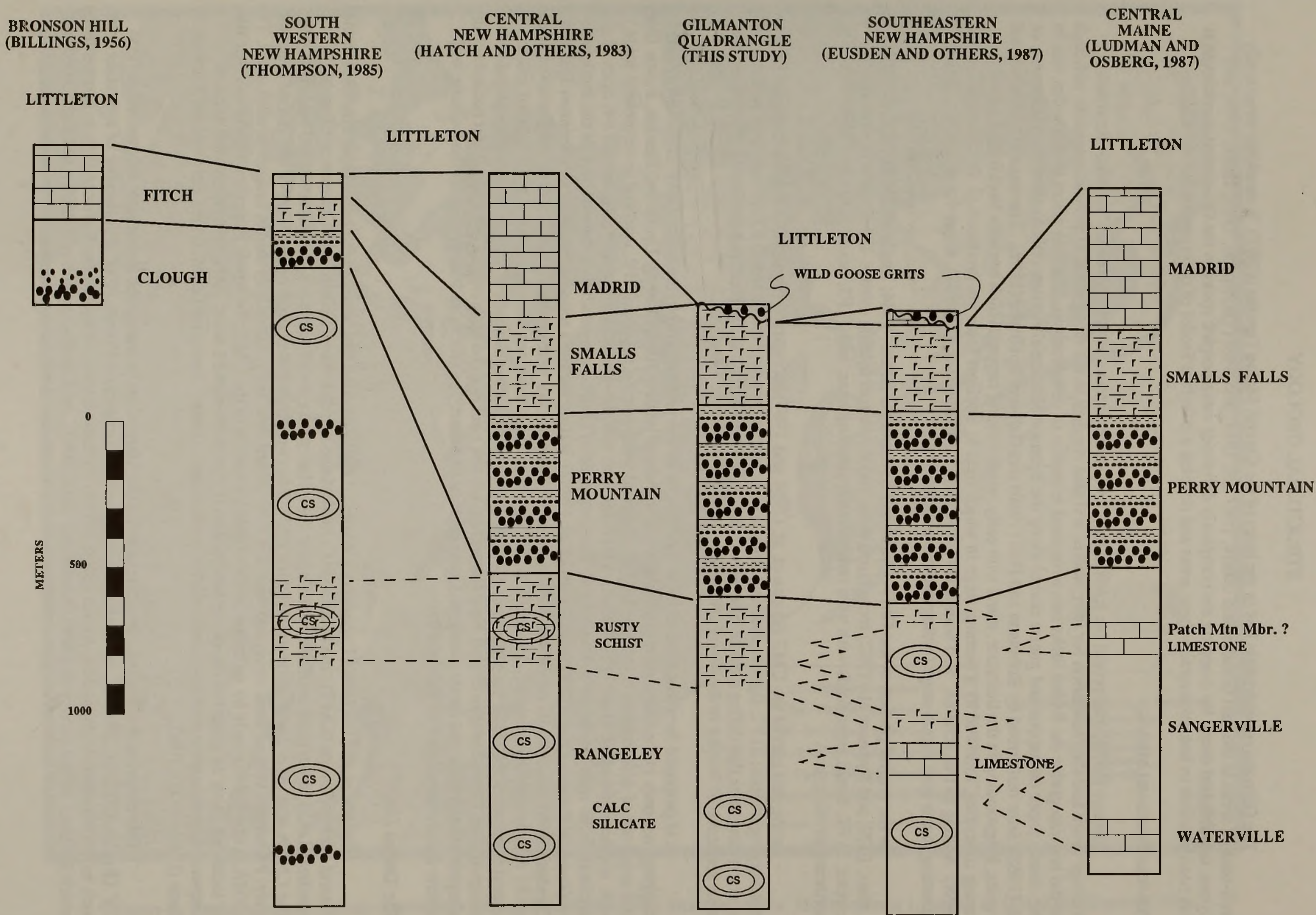
A correlation to the east with the Sangerville Formation of south-central Maine is quite likely for the middle to lower Rangeley exposed in the adjacent Alton quadrangle, where thin sequences of meta-limestones crop out. These are lithically identical to the ribbon limestone Patch Mountain member of the Sangerville. No limestones are found west of the Alton quadrangle and it would seem likely that in this area a regional facies change occurs in the Rangeley Formation where, to the east, more Sangerville-like lithologies are found and, to the west, more typical Rangeley lithologies are found. This is in accord with a recent revision of the stratigraphy by Gilman (1988) in southwestern Maine which is probably along this proposed facies transition. Figure 2 shows the stratigraphic correlations across the CMT.

SEDIMENTOLOGY

The Silurian rocks of the western part of the CMT, near the axis of the Bronson Hill anticlinorium, are nearshore sediments (quartz pebble and polymict conglomerates and fossiliferous limestones) and to the south and east they become more distal (turbidites and euxinic shales) (Hatch and others, 1983). The transition from proximal to distal facies is in places both abrupt and gradual and has been referred to as occurring at a tectonic "hinge" (Hatch and others, 1983). In simplistic terms the hinge probably represents the transition from a shelf to a slope/rise environment.

It has also been suggested from work in Maine that the Devonian part of the section may have been derived from an easterly source (Hanson and Sauchuk, 1986; Hall and others, 1976). The boundary between the Littleton Formation and the Smalls Falls, marked by some reworking and the Wild Goose Grits, may represent the position in the section where the westerly-derived, distal, Silurian section gave way to an onlapping, easterly-derived, late Silurian-early Devonian proximal section.

Figure 2. Stratigraphic correlations across the Central Maine Terrane. Thin proximal Silurian facies become thick distal facies to the east.



STRUCTURAL GEOLOGY

The Gilmanton quadrangle lies in the heart of the Central Maine Terrane (CMT). It straddles structurally well-studied areas to the east (Eusden and others, 1987 and 1984) and west (Thompson, 1985; Duke, 1984; and Lyons, unpublished data). By mapping the complexly deformed metamorphic rocks in the Gilmanton quadrangle it has been possible to link structurally these areas and develop a coherent model of deformation for the CMT.

Previous Structural Models

Billings (1956) interpreted the folds in the CMT as the product of the Devonian "Acadian Revolution." Billings' work laid the foundation for later studies and also resulted in the recognition of polydeformation, although he did not categorize the folded rocks into a regional sequence of deformations. The first effort in doing that was in the classic paper on nappes and gneiss domes along the Bronson Hill anticlinorium (BHA) by J. B. Thompson, et al. (1968), later reaffirmed by Robinson and Hall (1980) and Hall and Robinson (1982). The sequence of structural events, longstanding in the literature, starts with early, west-verging nappes which are later backfolded into east-facing structures, followed by a doming stage in which tight to isoclinal folds are produced (J. B. Thompson, et al., 1968). Adding to this scheme, P. Thompson (1985) and P. Thompson et al. (1987) argue for an early stage of thrusting that is post nappe-stage folding and pre-backfolding.

In the central portion of the CMT, Lyons and his students (Duke, 1984; Englund, 1976; Nielson, 1981; Lyons, 1979; and Lyons et al., 1982) recognized three major Acadian folding events: 1) F1, early west-verging nappes; 2) F2, broad, open folds with west or northwest-trending axes; and 3) F3, isoclinal to open folds with northeast-trending axes.

In the east part of the CMT Eusden et. al. (1984 and 1987) recognized three major folding events: 1) F1, east-verging nappes; 2) F2, tight to isoclinal folds with northeast trending axes; and 3) F3, broad, open warps with west trending axes that define a major map pattern syntaxis. Chamberlain (1985) had independently recognized the same sequence of folding in the Keene, NH area.

It is proposed here that none of these models can be uniquely applied to the entire CMT. Based on detailed mapping, not only in the Gilmanton quadrangle but elsewhere in New Hampshire by Lyons and Eusden, a new four-fold sequence of deformation is proposed: 1) F1, east and west verging nappes; 2) F2, isoclinal to recumbent folds with northeast-trending axes; 3) F3, broad, open folds with west or northwest- trending axes; and 4) F4, open to isoclinal folds with northeast-trending axes. This sequence of folding is essentially a dove-tailing of the models proposed by Eusden et. al. (1987) and Lyons et. al. (1982). Fitting into this scheme would be the Brennan Hill and Chesham Pond thrust faults of Elbert, Robinson, and Thompson (all in this volume) which developed with or after the F1 nappes and before the F2 (?) backfolds. Though these faults have not been recognized in the eastern and central portions of the CMT the arguments for their existence in the western part of the CMT are reasonable and accepted here. Other faults in central New Hampshire are not unlikely, but have not yet been identified because of the complex stratigraphy and facies changes. The field trips of Elbert, Robinson, and Thompson in this volume will review the characteristics of these faults.

The 'Dorsal Zone'

Eusden et al. (1987) and Lyons (pers. comm., 1988) proposed that between the two major synclines in the Central Maine Terrane (CMT), the Kearsarge-Central Maine synclinorium (KCMS) and Lebanon antiformal syncline (LAS), there is an anticline, the Central New Hampshire anticlinorium (CNHA), as named by J. B. Lyons. The CNHA acts as a 'dorsal zone' splitting the CMT into two distinct structural styles. West of the 'dorsal zone' the early, F1 nappes verged west only, and east of it they verged east only; essentially mirror images of each other. The CNHA is marked not only by outcrops of the oldest formation in the CMT, the lower Rangeley Formation, but also by local 'hot spots' of granulite facies metamorphism (Chamberlain and Lyons, 1983) and an unusual trend of soapstones, presumably once ultramafic slivers injected into thinned continental crust, called the Concord Tectonic Zone (Lyons et al., 1982).

This model of the geologic structure across New Hampshire is analogous to that now recognized as "Pop Up" (Butler, 1982) or "Flower" or "Palm-Tree structures" (Ramsay and Huber, 1987) in a number of mountain belts, such as the Southern Irumide Belt, Africa (Daly, 1986). Tectonic interpretations of the Variscan Belt in Europe (from which the term 'dorsal zone' was taken) (Martin and Behr, 1983), the Caledonian Belt of Norway and East Greenland

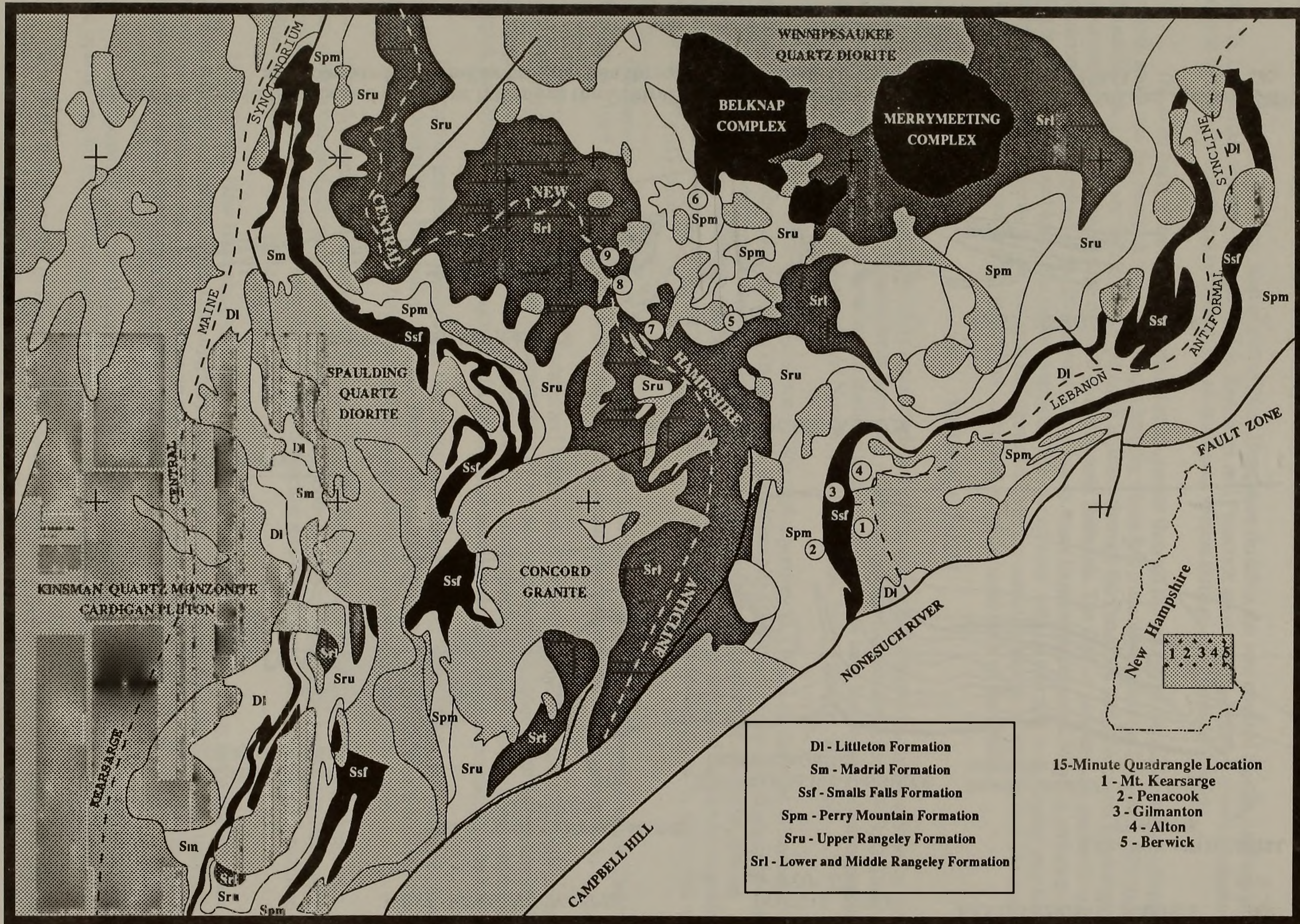


Figure 3. Geologic map of central-eastern New Hampshire. Fieldtrip stop locations shown. Modified from Lyons et. al. (1986) and Eusden (1988).

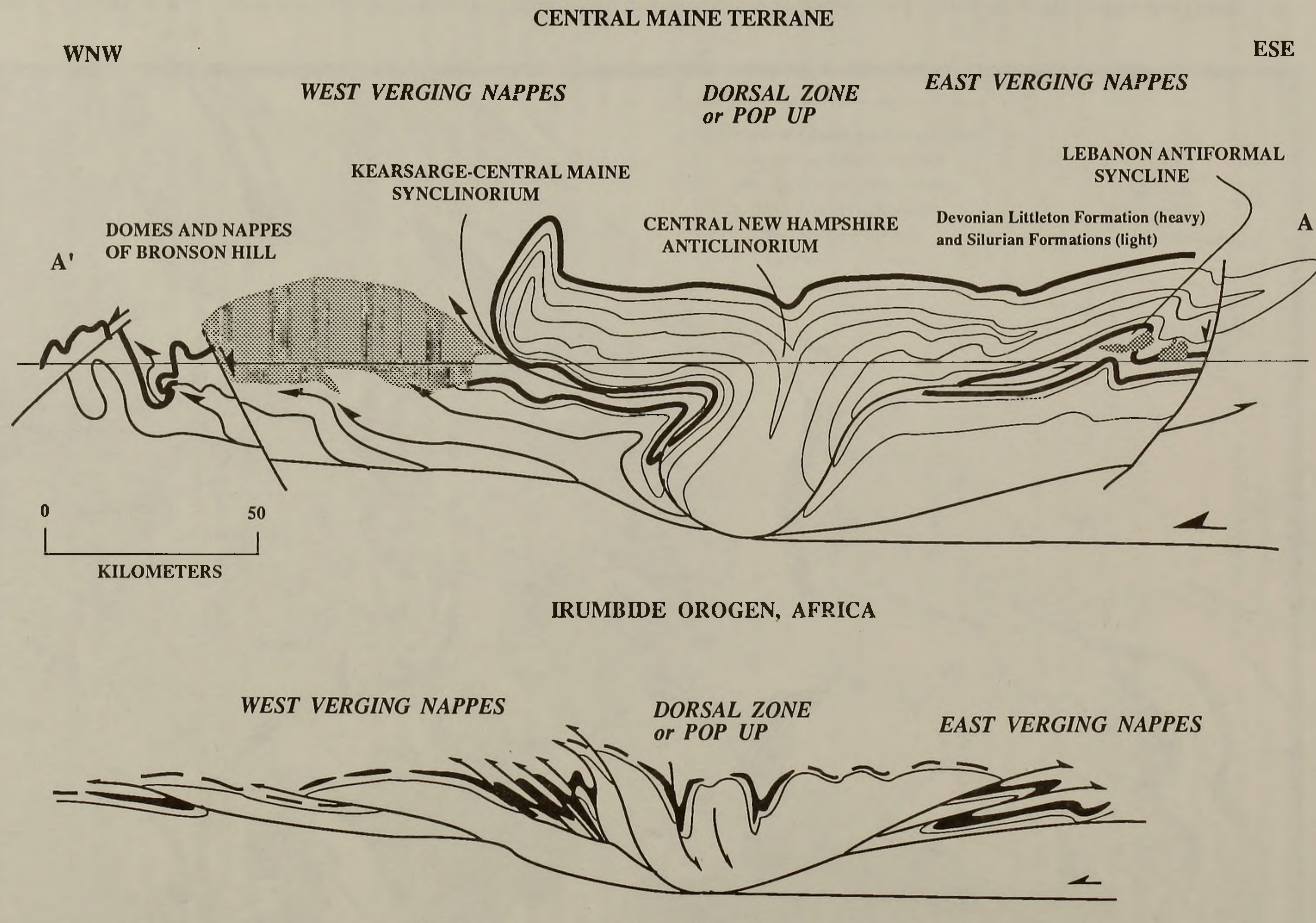


Figure 4. Cross section, located on Figure 1, through the Central Maine Terrane (modified from Lyons et. al., 1986 and Eusden, 1988) and compared to a similiar cross section through the Irumbide Orogen, Africa (after Daly, 1986).

(Ziegler, 1985) and the Grampian/Caledonian of Scotland (Thomas, 1976) also show symmetrical vergence of early thrust-nappes. All of these belts have widths roughly the same as that of the CMT, are also complexly refolded and are very similiar in cross sectional view to the model put forth here.

Figure 3 is a geologic map of part of New Hampshire detailing the area covered by this field trip and that of J. B. Lyons (this volume) through the Mt. Kearsarge and Penacook quadrangles. Figure 4 shows a schematic cross section through the region and compares it to an analogous section through the Irumbide Orogen.

The axial trace of the CNHA, or 'dorsal zone', passes through the middle of the Gilmanton quadrangle. It extends south into the Suncook and Concord quadrangles where it is truncated against the Campbell Hill-Hall Mountain-Nonesuch River fault zone. To the north it passes through the Penacook and Holderness quadrangles, eventually skirting the western edge of the White Mountain Batholith. The CNHA undoubtedly passes through the metamorphic rocks exposed in the Presidential Range but its exact location is unknown. Work is underway in that area to test the model and locate the major structures. The 'dorsal zone' with its east and west verging structures arose during the Acadian orogeny by the collaspe and tight closure of the subsiding trough of Silurian and Devonian age. The axis of this trough was not far from, if not coincident with, the axial trace of the CNHA.

METAMORPHISM

A detailed study of the regionally metamorphosed pelitic schists had not previously been done for the Gilmanton Quadranglerangle. Adjacent areas have been well studied (Chamberlain and Lyons, 1983; G. Duke, 1984; and Eusden, 1984) and several reconnaissance studies and metamorphic maps have been made encompassing the Gilmanton Quadranglerangle (Thompson and Norton, 1968; Robinson, 1986; Lyons et. al, 1986).

Thompson and Norton (1968), Robinson (1986), and Lyons et. al, (1986) all show the Gilmanton quadrangle to be in metamorphic zone III (Tracy, 1975), the sillimanite + muscovite zone. No changes have been made concerning the metamorphic zones previously mapped in the Gilmanton quadrangle. However, intense retrograde metamorphism dominating the majority of the quadrangle has probably obscured earlier higher-grade assemblages possibly those representing zones IV, sillimanite + muscovite + K-feldspar, and V, sillimanite + K-feldspar, of Tracy (1975).

Geothermo-barometry and P–T–t path studies have been done by Eusden (1988) in this region. The following is a brief discussion of the P-T conditions during Acadian metamorphism based on this work.

Garnet core-biotite temperatures (Indares and Martignole, 1985) range from 366° to 712°C with the majority in the 500° to 600°C range. The region is characterized by hot and cold spots or plateaus with little relationship to metamorphic grade. There is a broad 600°C plateau roughly corresponding to the migmatized region, which would be expected. However, also within the migmatized zone there are several cold spots with temperatures in the 400's°C.

This type of temperature pattern was first noted by Chamberlain and Lyons (1983) and has since been found throughout the central New Hampshire CMT (G. Duke, 1984; Chamberlain, 1986; Chamberlain and Rumble, in press). Several different hypotheses have been put forth to explain the origin of the hot/cold spots.

In southwestern New Hampshire Chamberlain (1986) suggests that the distribution of synkinematic metamorphic zones (and concommitant temperatures) was controlled by folding and produced these characteristic hot and cold spots. Hot spots formed over F2 syncline-F3 syncline intersections and cold spots over F2 anticline - F3 anticline intersections.

In the Bristol, New Hampshire area Chamberlain and Rumble (in press) propose that a hot spot there, having no relation to Acadian folds, was formed by the advection of hot metamorphic fluids through the crust concentrated in narrow zones. This hotspot has an abundance of quartz veins and graphite deposits indicative of metamorphic fluid flow (see also Rumble and Chamberlain, this volume).

A third possibility is that the hot spots are spatially related to the numerous granitic sheets in the area. There is, however, no coherent relationship between the thermal spots and the map pattern of the granites.

It is likely that advection of fluids, in part constrained by major structures, was responsible for the observed temperature pattern in the study area. The garnet core - biotite 600°C hot plateau in the Gilmanton quadrangle extends southwest through the Suncook quadrangle contiguous with the hot spot mapped by G. Duke (1984) in the Concord quadrangle. This broad hot plateau interspersed with minor hot (and cold) spots roughly follows the mapped pattern of the Lower Rangeley Formation that is exposed along the Central New Hampshire anticlinorium, the proposed root zone of the Acadian nappes. This structure would be a likely area for extensive fluid flow during metamorphism. The migmatites also show a rough correlation with this structure. This seems to reinforce the suggestion that the migmatites formed, in part, by a structurally confined flow of metamorphic fluid. However, the story must have greater complexities, as both the hot plateau and migmatite zone cut across the Central New Hampshire Anticline in a number of places.

Pressures calculated using the assemblege plagioclase-quartz-sillimanite-garnet (Koziol and Newton, 1988) have a mean of 3.6 kb. This is in excellent agreement with the observed aluminosilicates and is the best estimate of the pressure during metamorphism.

The garnet zoning profiles studied by Eusden (1988) in the Gilmanton quadrangle represent, to various degrees, the combined effects of 1) prograde growth, 2) homogenization by diffusion and 3) retrograde 'growth'. The significance of the Gibbs method P-T-t paths, calculated assuming the garnet zoning is all a product of growth zoning, is dramatically underdetermined with this in mind. At best only the P-T-t trajectories from a few of the garnets are realistic. This is supported by the observation that they generally agree with the trends defined by the geothermo-barometry and the overall four part metamorphic history outlined below.

Due to the complexities of possible thermal spikes superposed on the P-T-t paths (Chamberlain and Rumble, in press), the relationship between intersecting folds and metamorphic grade (Chamberlain, 1985), the effects of homogenization and retrograde reactions on the mineral zoning profiles, the complete P-T-t path may never be known. A single sample from the CMT may have a unique P-T-t path; certainly a handful of samples across the belt cannot adequately characterize the regions' metamorphic history. Similarly, the presumed 'peak' metamorphic temperatures and pressures calculated using garnet core compositions are subject to the same set of complications altering the original prograde garnet profile.

Metamorphic History

Based on the textures and mineral assemblages seen in the Gilmanton, Alton, and Berwick quadrangles a four-part continuum of metamorphism is proposed. The different parts are termed M1 through M4 and are segments of the Acadian P–T–t path in the region. They are not discrete metamorphic events.

M1 is a low-pressure regional metamorphism characterized by the early andalusite pseudomorphs. This is a widespread event recognized throughout the CMT.

M2 represents the highest grade of metamorphism seen in the area. The high-grade zones are probably obscurred by later retrograde metamorphism but may have reached zone IV and V, consistent with metamorphic zones mapped in adjacent quadrangles. Anatectic migmatites may have formed during M2 and metamorphic migmatites formed in association with structurally controlled fluid flux over the Central New Hampshire anticlinorium. In places, prograde garnet zoning profiles were homogenized.

M3 is a complex 'retrograde' event. Decussate muscovite, fibrolite, sympectites of muscovite + quartz and biotite + quartz, and myrmekite characterize this stage of metamorphism. During M3, garnet zoning profiles, already modified by M2, were severely retrograded. M3 assemblages represent the metamorphic field gradient seen in the region and may overprint higher-grade zones. Thermal hot spots formed by concentrated flow of metamorphic fluids and/or exsolved water from crystallizing two-mica granite sheets drove the retrograde metamorphism and may have formed metamorphic migmatites and/or altered the leucosome mineralogy of earlier anatectic migmatites.

M4 represents the waning stages of metamorphism and is characterized by scattered chlorite alteration of ferromagnesium minerals. Swarms of sericite alteration may have occurred during M4 as well.
These periods of metamorphism represent a continuum rather then a series of discrete events. They are similiar to the sequence of metamorphism proposed by Chamberlain and Lyons (1983) in central New Hampshire except their M3 has been subdivided into M3 and M4 here.

GEOCHRONOLOGY

Monazite and sphene U-Pb ages suggest that the timing of peak high-grade metamorphism is Acadian in the CMT and Permian in the Massabesic Gneiss/Merrimack Trough. The belt of high-grade metamorphism in northeastern New England is composite, made up of crustal blocks that experienced discrete pulses of high-grade metamorphism beginning perhaps as long ago as the Precambrian and extending into the Permian. A complete discussion of these data is given elsewhere (Barreiro and Eusden, 1988 and Eusden and Barreiro, in prep.)

The metamorphic ages from the CMT in New Hampshire and Massabesic Gneiss/Merrimack Trough support the hypothesis that these are separate terranes with distinct tectono-metamorphic histories coincidentally juxtaposed at the same metamorphic grade.

The Campbell Hill-Hall Mountain-Nonesuch River fault zone, separating these two terranes, has had an active and complex history, beginning approximately ~ 360 Ma and lasting at least to 250 Ma. if not even into the Mesozoic. This boundary is a likely candidate for the Alleghanian or Variscan Front in New England.

U-Pb monazite ages from two-mica granites in the Gilmanton, Alton and Suncook quadrangles are all Devonian. This period of peraluminous granite magmatism is characteristic of the CMT. These granites are syn- to post-tectonic members of the Concord-type granitoids, part of the New Hampshire Plutonic Series. A coeval pulse of magmatism in the Massabesic Gneiss/Merrimack Trough is absent.

SUMMARY

Figures 5 and 6 are a tectonic reconstruction of the geologic history in the Central Maine Terrane and a small portion of the Merrimack Terrane. This is an attempt to show the close association of deformation and metamorphism in this region and to pictorially synthesise the conclusions outlined above.

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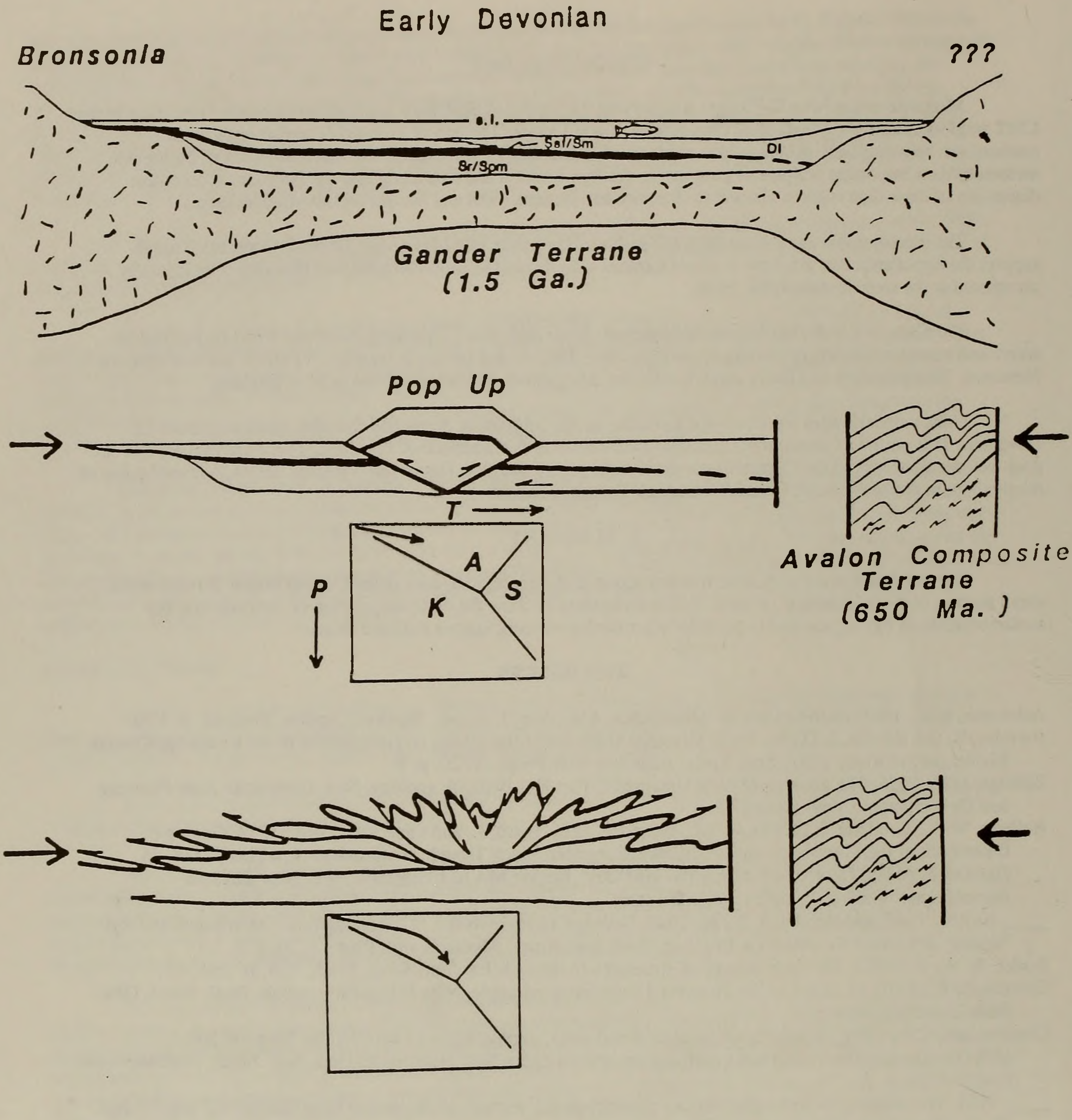

Figure 5. Geologic reconstruction across the Central Maine Terrane in the Early Devonian. P-T path shown with respect to the aluminosilicate triple point. Compression begins immediately after deposition, Pop Up and thrust-nappes develop.

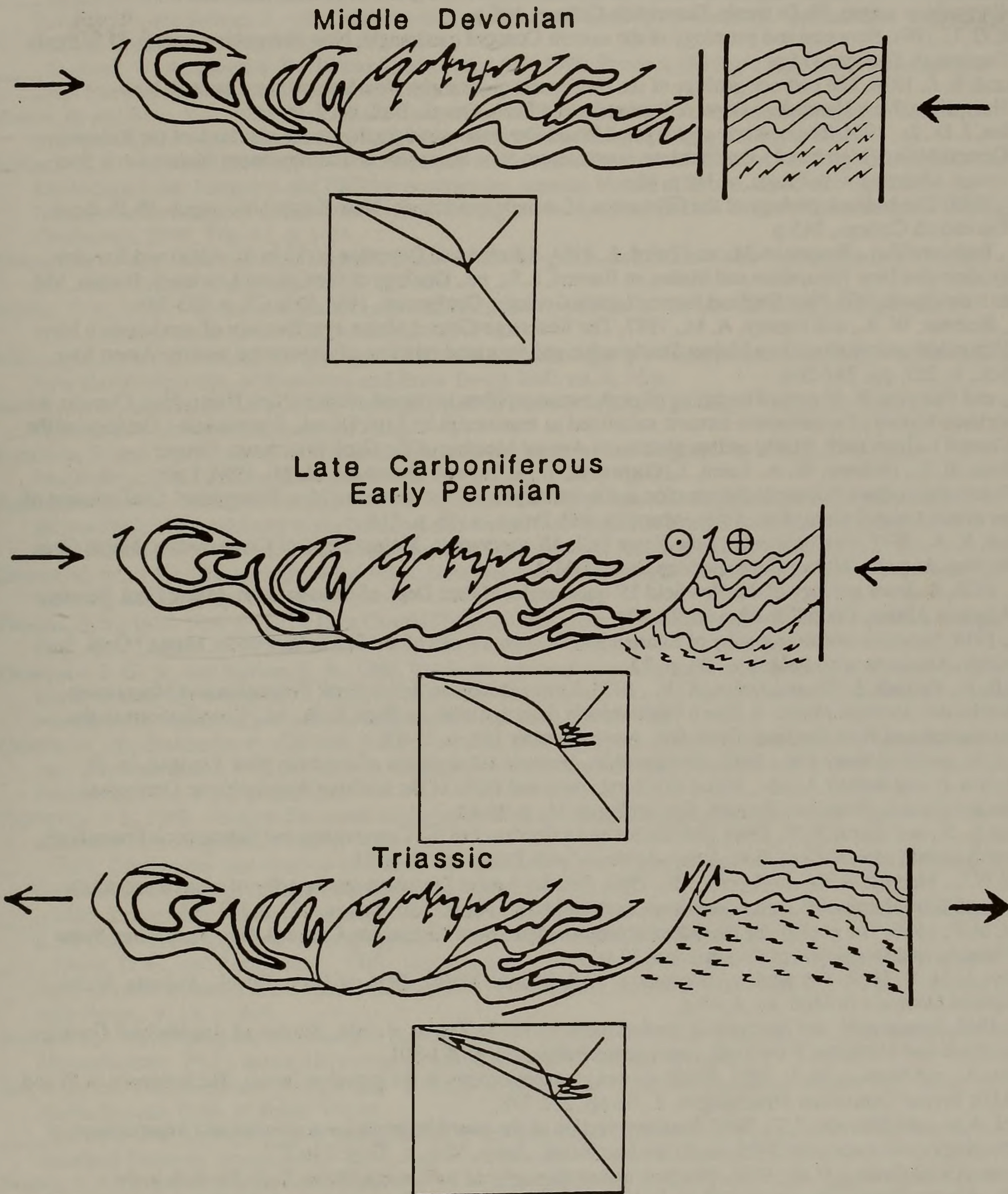

Figure 6. Reconstruction from the Middle Devonian through the Mesozoic. Peak pressures were reached during F2. Thermal spikes occurred during and after this. Alleghanian sliver tectonics were followed by Mesozoic extension exposing basement complexes

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ROAD LOG

Assemble at the junction of Routes 107 and 4 in Northwood Narrows by the Minuteman RV dealer. This is the eastern of two junctions between Routes 107 and 4. Trip begins at 9:00 A.M.. Topographic maps: Gilmanton, Alton, and Suncook 15" minute quadrangles.

Mileage

0.0 **STOP 1**: (Suncook quadrangle) Deformed, 360 Ma. (U-Pb monazite) Barrington, two-mica granite. The S-C fabrics in this granite are associated with motion along the Campbell Hill-Hall Mountain-Nonesuch River fault zone, the terrane boundary between the Central-Maine and Massabesic Gneiss/Merrimack Trough Terranes. Was the granite deformed during Mesozoic extensional faulting or Alleghanian/Acadian thrust faulting, or both ? More work, both detailed struture and geochronology, needs to be done to unravel this faults' history.

Proceed north on Route 107 through Northwood Narrows

0.8 Go straight at top of hill turning off Route 107 which bears to the right.

1.3 Proceed straight on dirt road.

1.6 At end of dirt road where private drive turns off to the right, park on far left edge of road.

Walk along woods road, a continuation of the road we were just on, for about 10-15 minutes, passing outcrops of Smalls Falls and Perry Mountain Formation, to a beaver swamp on your right.

STOP 2: (Suncook quadrangle) Look for a nearby rocky point sticking out into the swamp. Exposed here is well-bedded upper Perry Mountain Formation caught up in a F2 downward facing antiform with well-developed minor folds and axial planar cleavage/foliation fans. These structures are on the west limb of the Lebanon antiformal syncline. Continue along woods road to clearing under the power lines. Exposed here are extensive outcrops of upper Perry Mountain. Under the lines toward the swamp one sees F4 crenulations folding either the S2 cleavage or cross beds, garnet + quartz coticules and a rare calc-silicate boudin. Immediately northwest of the road under the lines and in the woods off to the southwest are well-preserved (M1) andalumps and laminations which may be locally transposed bedding.

Return to vehicles and retrace route to Route 107, proceed north.

4.2 Bear right off of Route 107 with Jenness Pond on your right. Route 107 goes up a hill at this junction.

4.8 Take left at next next junction heading away from the pond. Road turns to dirt shortly.

5.6 At top of hill take left on dirt road marked by mailbox and park immediately on the right.

STOP 3: (Gilmanton quadrangle) Outcrops of Smalls Falls Formation. Rusty-weathering graphite and pyrrhotite bearing schist with well-developed F4 crenulations. In this area the Smalls Falls shows up as a strong positive anomaly on aeromagnetic maps. These outcrops are presumably inverted, however, there are no tops to prove it.

Turn vehicles around and return to intersection that we passed at 4.8 miles.

6.4 Take left at this junction on paved road heading northeast around Jenness Pond.

6.8 Take left on dirt road. Intersection is marked by cemetery on right.

7.5 Take left on dirt road.

8.0 Park in wide part of road at base of small hill where two private drives come into it. Views of Wild Goose Pond through trees to left.

STOP 4: (Alton quadrangle) Wild Goose Grits (lowest part of Littleton Formation). Peeled outcrops are in the woods just east of the road. An inverted section of grits with sub-rounded quartz and elongate rusty-weathering Smalls Falls clasts. Fairly good graded beds in a few localities. We are just west of the axis of the Lebanon antiformal syncline. These grits may mark the position in the stratigraphy where the west-derived Silurian section gave way to an onlapping east-derived Devonian section.

Turn vehicles around and retrace route to the intersection where Route 107 heads west away from Jenness Pond up a hill.

10.2 We passed this junction at mileage 4.2 earlier. Proceed north on Route 107.

10.6 Smalls Falls outcrops at ponds' edge on left.

12.8 Catamount Mtn. Migmatized upper Perry Mountain and schorl pegmatite at height of land.

15.5 Take right at stop sign in Pittsfield following signs for Route 107 and Gilmanton. A good place to pick up food for lunch.

16.2 Cross Route 28. Continue on Route 107 north.

16.5 Take left to stay on Route 107.

20.8 Junction with Route 129. Continue on Route 107 north.

21.7 Park on right just beyond First Baptist Church.

STOP 5: (Gilmanton quadrangle) Upper Rangeley Formation. Gently dipping outcrops of rusty-weathering graphitic schist and minor quartzite. The rocks are partially migmatized here. The late large (M3) muscovite is conspicuous. The Upper Rangeley is widespread in occurrence throughout the Gilmanton quadrangle and often crops out in the low lying areas. Gene Boudette, the State Geologist, lives next door and guards these outcrops!

Continue north on Route 107.

22.5 Views of the Belknap Mountains.

24.0 Turn sharp left into the Loon Pond Beach Club private drive. LUNCH.
Continue north on Route 107.

26.3 Junction of Routes 140 and 107 in Gilmanton Corners. Continue north on Route 107.
29.4 Take right on to dirt road (Rogers Road).

30.1 Take right uphill at T intersection (Middle Route).

31.3 Park at bend in road on righthand side. Walk back about 100 yards to a tree blocked woods road on north side of Middle Route and hike northeast to the summit of Grant Hill.

STOP 6: (Gilmanton quadrangle) Extensive exposures of lower Perry Mountain Formation. The exposures on the southwest and highest point of the hill are chaotic, proceed northeast about 50 to 100 yards to more 'understandable' outcrops. Well-bedded calc-silicate bearing turbidite with thick quartzites typical of the Perry Mountain are exposed. Some good graded beds are seen, however, most are fast-graded and tops are equivical. F1 east-facing folds are exposed as well as F2 and F3 folds. Knots or spots of (M3) muscovite (sericite in thin section) are abundant in the pelitic layers, pseudomorphs after (M2) sillimanite. Excellent views of Mt. Kearsarge, the Belknaps, Mt. Monadnock, Mt. Cardigan, Smarts Mt., migrant raptors, and maybe some late season blueberries.

Return to vehicles and retrace route to Gilmanton Corners.

32.7 Take left back on to Rogers Road.

33.4 Take left back on to Route 107 heading south.

36.3 Take right at Gilmanton Corners (Jct. of Routes 140 and 107) heading west on Route 140 for a short bit.

36.4 Take left on Shellcamp Pond (or Meadow Pond) Road just after fire station on the left.

37.4 Shellcamp Pond on right. Outcrops of upper Rangeley and two mica granites.

37.9 Shellcamp Pond Dam. Upper Rangeley.

38.6 Proceed straight through intersection.

39.8 Take right on Loudon Ridge Road.

40.4 Park off of road on right opposite the Moore Farm.

STOP 7: (Gilmanton quadrangle) A series of outcrops in the fields southwest of the road showing extensively migmatized lower Rangeley Formation. The axial trace of the Central New Hampshire Anticline passes through these outcrops. The stromatic or layered migmatites are folded by F2 and/or F4 folds indicating that high-grade metamorphism occurred during the earliest stages of Acadian deformation. Calc-silicate and granofelsic boudins are preserved and are parallel to the migmatitic layering which is argued to be embrechitic. The leucosomes often coalesce to form early pegmatites which are in turn cut by the later two-mica granites sills and their associated pegmatites. It is possible that the migmatites formed during an intense structurally controlled fluid flux over the Central New Hampshire Anticline in the early Acadian. According to Farmer Moore the ram breeding the ewes may not like us in the same pasture and we should watch for him !

Continue northwest on Loudon Ridge Road.

41.6 Take right onto Route 106 north.

42.0 Rocky Pond on left.

42.4 Take left on South Road (dirt).

42.7 Take left on dead-end dirt road marked by "live bait" sign.

43.2 Park where road forks. There will be a sign saying "Not a through street" and another one , "Monty". Bushwack due west to the cliff about 1/2 to 1/4 mile in.

STOP 8: (Gilmanton quadrangle) Large cliff outcrop of middle Rangeley Formation. Exposed are well bedded and migmatized turbidite with no calc-silicate boudins. Bedding is dipping shallowly or, in places, is nearly flat lying. Tops here are ambiguous but the overall structure and stratigraphy suggests that the beds are upside-down. The Lower Rangeley crops out in the valley floor below us. There are several good examples of two-mica granite sills (some slightly discordant) and "bursts" of quartzo-feldspathic leucosomes. There are zones where bedding has been obliterated by localized shearing (post F1-pre F2 ?). Large late (M3) muscovite is again common and some minor F4 warps and crenulations are present. Good views from the cliff top.

Return to vehicles and retrace route to Route 106 heading north.

45.3 Heading north on Route 106. Two-mica granite sill (359 Ma. U-Pb monazite) and Middle Rangeley.

46.4 Take left for Belmont.

47.3 Take left at Getty station in downtown Belmont, back on to Route 140 heading west.

48.0 Take right into Brox Paving Materials Plant. Go past scales skirting large gravel pile on right to outcrops just north of some catch ponds, a distance of about 200 yards.

STOP 9: (Gilmanton quadrangle) Lower Rangeley Formation. These glacially polished coutcrops are on the axial trace of the Central New Hampshire anticlinorium, ie. the 'dorsal zone'. Bedding dips quite steeply here. Upward facing, F1 folds verge neutrally and are upright. Theoretically, just to the east the F1 folds would verge east and to the west would verge west. A good cross section of the folds can be seen on the blasted face. Follow a calc-silicate boudin-bearing horizon along strike to see the folds on the polished surface. There is a late fabric (S3/S4 ?) oblique to the beds quite visible on the blasted face.

End of trip. To get to Keene, proceed west on Route 140 to Tilton then take I-93 south to Concord. Take I-89 north from Concord to Hopkinton then take Route 9 all the way to Keene. Driving time about 1 hour.