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The nappe theory in the Connecticut Valley region: Thirty-five years since Jim Thompson's first proposal

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ABSTRACT

The nappe theory in the Bronson Hill anticlinorium of the Connecticut Valley region began with Jim Thompson's analysis of the structure of Skitchewaug Mountain in 1954. By 1968 the theory included the recognition of three giant fold nappes formed early in the Devonian Acadian orogeny, with tens of kilometers of east to west overfolding. These were, from lowest to highest, the Cornish, the Skitchewaug, and the Fall Mountain nappes. Recognition of the nappes was based on careful tracing of a previously recognized sequence of distinctive Ordovician, Silurian, and Lower Devonian stratigraphic units that were metamorphosed to the chlorite zone through sillimanite-orthoclase zone. Some of these units proved to be fossiliferous even in the sillimanite zone. Early on, a relationship was recognized between high metamorphic grade and high structural level, implying overfolding of hotter rocks onto cooler ones.

In the 1970s detailed remapping suggested that the system included not three but four fold nappes. Some of the rocks previously assigned to the Skitchewaug level proved to belong to the Bernardston nappe beneath the Skitchewaug. Although sheared and attenuated fold limbs were part of the nappe theory before 1980, it was only after this that major thrust faults were considered to be important. The theory of major thrusts came about through refinements in stratigraphy, particularly in the Merrimack synclinorium. New mapping near Mount Monadnock, based on the new stratigraphic sequence, has shown that the axial surfaces of the early west-directed fold nappes are truncated above by a major west-directed thrust, the Chesham Pond thrust, which carries higher grade metamorphic and plutonic rocks. To the west in the Hinsdale area, folds in Monadnock sequence stratigraphy are truncated below by a lower thrust, the Brennan Hill thrust, which in turn cuts into the Bernardston fold nappe below. Stratigraphic and structural evidence from the Monadnock and Hinsdale areas provides the key for reevaluation of the interaction of fold nappes, thrusts, backfolds, and overturned gneiss domes in west-central Massachusetts.

Metamorphic studies show different *P-T* paths for rocks on opposite sides of the thrusts, thus indicating that the thermal structure was as much related to thrusts as to folds, but the final pattern of isograds appears to have been superimposed on both. The relationship between kinematics and thermal history in the nappes will be studied for years to come.

INTRODUCTION

We discuss an area in the central New England Appalachians along a tectonic belt extending from the Connecticut Valley eastward for about 70 km (Fig. 1). The most striking feature of this region is a row of mantled gneiss domes, the Bronson Hill anticlinorium, in which tonalitic gneisses and related rocks are exposed beneath a well-defined cover sequence of Ordovician, Silurian and Devonian rocks. The domes are believed to have developed during the Devonian Acadian Orogeny. Our title is a paraphrase from the book, *The Nappe Theory in the Alps* (Heritsch, 1929). Our objective is to explain the development of a theory that formation of the gneiss domes was preceded by formation of regional-scale west-directed fold and thrust nappes akin to those of the Pennine Zone in the European Alps. This theory began with Thompson's first proposal published in the Guidebook of the New England Intercollegiate Geological Conference in October 1954 (Thompson, 1954; see also Thompson, 1956).

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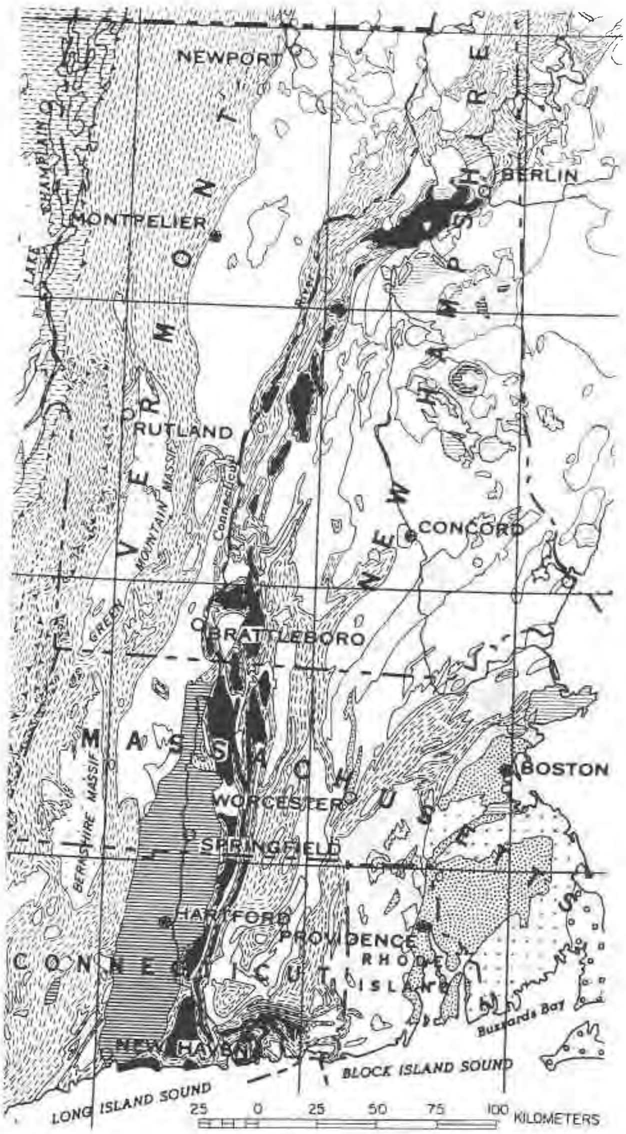

Fig. 1. Geologic index map of west-central New England showing the gneiss domes (black) of the Bronson Hill anticlinorium. From Zen et al. (1968). Owls Head dome mentioned in text lies on latitude line southwest of Berlin.

	CONNECTICUT VALLEY BELT		MERRIMACK BELT	
Lower Devonian	GILE MTN.	ERVING		
	WAITS R.			
	LITTLETON		LITTLETON	
Silurian	FITCH		WARNER	MADRID
			FRANCESTOWN	SMALLS FALLS
	CLOUGH		PERRY MTN.	
			RANGELEY	
Late Ordovician	PARTRIDGE			
	AMMONOOSUC			
	PLAGIOCLASE GNEISSES			
Late Proterozoic	MICROCLINE GNEISS, QUARTZITES			

Fig. 2. Column of stratigraphic units of the Connecticut Valley belt (Bronson Hill anticlinorium) and of the Merrimack belt (synclinorium).

STRATIGRAPHY OF THE BRONSON HILL ANTICLINORIUM

The story is dependent on a superb stratigraphic framework established over decades. A 1949 quotation from Billings (1950) is "And lo! stratigraphy led all the rest," a sentiment fully confirmed by our story here. The key single paper for this stratigraphic framework is Billings's report on the Littleton-Mooselauke area (Billings, 1937). The essential column of stratigraphic units for the Bronson Hill anticlinorium illustrated in Figure 2 comes from this paper with only a few modifications. It was J. B. Thompson's imaginative and creative application of Billings's stratigraphy that made the nappe theory possible.

The oldest strata exposed in the Bronson Hill anticlinorium, in the core of the Pelham gneiss dome, are gneisses, quartzites, and subordinate schists and amphibolites, believed to be a supracrustal sequence of Late Proterozoic age. The stratigraphically deepest unit, the Dry Hill Gneiss (Ashenden, 1973), consisting of microcline-biotite-hastingsite gneiss and interpreted as metamorphosed alkali rhyolite (Hodgkins, 1985), has recently yielded a high-precision zircon age of 613 ± 3 Ma (Tucker and Robinson, 1990). The Dry Hill Gneiss is gradationally overlain by metamorphosed sedimentary units: the Poplar Mountain Gneiss, consisting of metamorphosed arkose and quartzite, and its more southerly facies, the Mount Mineral Formation, dominated by pelitic schists, quartzites, and amphibolites. In the latter, relics of an earlier granulite-facies metamorphism have been detected beneath the predominant overprint of kyanite-staurolite zone metamorphism of Acadian age (Robinson et al., 1975; Roll, 1986, 1987).

The next major stratigraphic subdivision consists of the rocks that overlie the Proterozoic rocks in the Pelham dome and form the cores of all of the other domes. These rocks were originally assigned by Billings (1937, 1956) to the Oliverian plutonic series, which he supposed to be a group of Devonian intrusions. They have been considered to be Ordovician or older since the radiometric dating of zircons by Naylor (1969) from the core of the Mascoma dome. Although most of these rocks resemble deformed intrusive igneous rocks, they include extensive tracts of strongly layered gneisses and amphibolites resembling metamorphosed volcanics. Recent work on such rocks in large exposures in the Quabbin Reservoir area by Hollocher and Robinson (Robinson et al., 1989) suggests that the strongly layered gneisses are probably highly deformed intrusive igneous rocks, originally dominantly tonalite with a profusion of xenoliths and cross-cutting dikes of more mafic rock types. The most recent ages of these rocks in Massachusetts and southern New Hampshire obtained from U-Pb in zircon (Tucker and Robinson, 1990) suggest that they fall in the narrow age range from 454 to 442 + 3/−2 Ma (Caradoc to Ashgill), despite repeated attempts to identify older rocks. Controversy still exists as to the nature of the contact between these rocks, and the overlying Ordovician cover sequence. It has been proposed as an intrusive contact (Billings, 1937; Leo et al., 1984; Zartman and Leo, 1985), as a normal stratigraphic contact (Naylor, 1969), as an unconformity (Robinson, 1979, 1981) based on several quartzite localities at the base of the Ammonoosuc, and most recently as a possible detachment fault (Tucker and Robinson, 1990). Fortunately for our present story it can be treated simply as another contact within an ordered sequence of rock layers.

The basal unit of the Ordovician cover sequence is the Ammonoosuc Volcanics, long thought to be Ordovician on the basis of regional correlation (Billings, 1937; Robinson, 1963, 1979; Zartman and Leo, 1985) and now confirmed as Caradoc by a U-Pb zircon age of 453 ± 2 Ma on a metamorphosed rhyolite from the upper member (Tucker and Robinson, 1990). In Massachusetts and southwestern New Hampshire, where the formation ranges in thickness from less than 30 m to more than 1000 m, the Ammonoosuc Volcanics contain a detailed and complex stratigraphic sequence (Robinson, 1963; Schumacher, 1988). A lower member is dominated by metamorphosed tholeiitic basalts, andesites, and low-K dacites, and their hydrothermally altered equivalents, showing numerous primary features including pillows, conglomerates, agglomerates, and tuffs. The discontinuous middle member is an unusual layer of garnet-amphibole quartzite believed to represent metamorphosed ferruginous chert. The upper member consists of biotite-muscovite-garnet gneiss representing metamorphosed rhyolitic to dacitic tuff.

The upper part of the Ordovician cover sequence is the Partridge Formation, dominated by metamorphosed black shales, now graphite-pyrrhotite schists, with subordinate layers and lenses of metamorphosed volcanics chemically similar to those of the underlying Ammonoosuc Volcanics (Hollocher, 1985). The Partridge has also long been correlated on the basis of rock types with Caradocian graptolite-bearing slates in northwestern Maine and southern Quebec, and this age has now been confirmed by a U-Pb zircon age of 449 + 3/−2 Ma from a bed of quartz-phyric rhyolite tuff near the base of the formation at Bernardston, Massachusetts (Tucker and Robinson, 1990). Striking in the metamorphosed volcanics of the Ammonoosuc and Partridge are the abundant rocks with compositions appropriate for the formation of highly varied assemblages of amphiboles including hornblende, cummingtonite, anthophyllite, and gedrite in combinations with cordierite and other aluminous minerals (Robinson et al., 1982b, 1986; Spear and Rumble, 1986; Schumacher and Robinson, 1987; Schumacher, 1988; Hollocher, 1985). Such assemblages are nearly unknown in the underlying plagioclase gneisses (Hollocher and Lent, 1987) and in other members of the cover sequence.

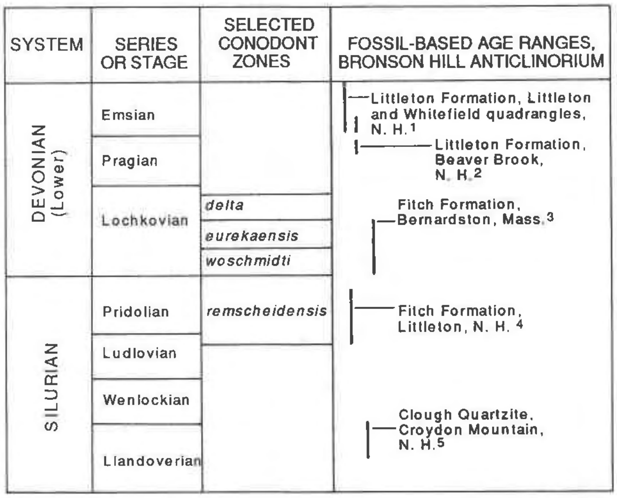

Fig. 3. Correlation chart showing fossil-based age estimates for five sets of Silurian-Devonian strata from Massachusetts and New Hampshire (from Elbert et al., 1988). References: 1 = brachiopods (Boucot and Arndt, 1960), 2 = brachiopods (Boucot and Rumble, 1980), 3 = conodonts (Elbert et al., 1988), 4 = conodonts (Harris et al., 1983), 5 = brachiopods and corals (Boucot and Thompson, 1963; Boucot et al., 1958).

The age of the younger part of the stratigraphic column is more firmly controlled by fossils (Fig. 3), the story of which was punctuated on September 28, 1870, by C. H. Hitchcock's telegram from the Littleton railroad station, "New Hampshire no longer Azoic, Silurian fossils found today" (Hitchcock, 1871). Hitchcock's Silurian designation was assigned to rocks later named the Fitch Formation by Billings (1937), and it still holds today (Harris et al., 1983). However, fossils were found years earlier by Hitchcock's father, Edward (1833), in rocks also now assigned to the Fitch Formation at Bernardston, Massachusetts as recently pointed out by Elbert et al. (1988).

More prophetic was Hitchcock's statement in 1912 concerning the Clough Quartzite at Moose Mountain, "This is the key to the geology of this region." It was essentially Jim Thompson's persistent belief that rocks resembling the Clough Quartzite should be assigned to that unit, despite structural difficulties, that produced the nappe theory as we understand it. The Clough is distinctive for three reasons. It is an easily recognizable unit of buff-to-white quartzite and quartz-pebble and quartz-cobble conglomerate (Robinson, 1963; Hatch et al., 1988) that commonly makes resistant ridges and peaks (Fig. 4). Of greater importance is that it rests on a region-wide unconformity, that can be recognized even in highly deformed locations, and has been found resting on the plagioclase gneisses of the domes, on various members of the Ammonoosuc Volcanics, and on the Partridge Formation, where it is hundreds of meters thick. Such a sig-

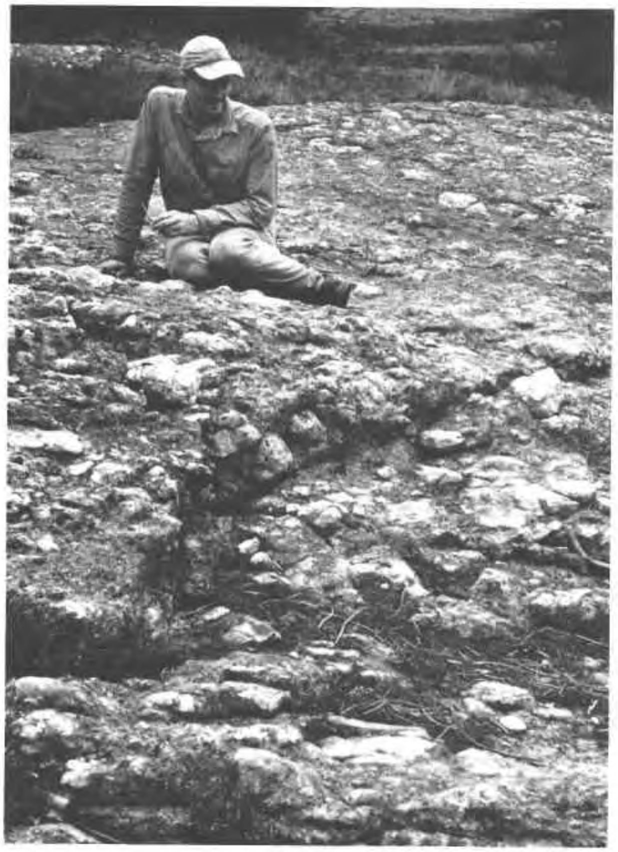

Fig. 4. Jim Thompson on an outcrop of coarse cobble conglomerate of the Clough Quartzite near the summit of Surry Mountain, July 10, 1964.

nificant unconformity cannot be ignored or passed off as a facies relation, and thus served as a firm mental concept in the grueling task of regional mapping. In addition, the upper part of the Clough is fossiliferous, as first reported by B. K. Emerson in 1877 at Bernardston, Massachusetts (Dana, 1877). Persistent chasing by Jim Thompson of the so-called pit rock, even into rocks of the sillimanite zone, coupled with ample collections and diligent paleontologic study by Arthur Boucot, have led to our present firm understanding of the age of the Clough (Fig. 3) as late Llandovery (Boucot et al., 1958; Boucot and Thompson, 1963).

The Clough is locally and discontinuously overlain by calcareous rocks of the Fitch Formation including calc-silicate granulites, biotite-plagioclase granulites and schists, and rare marbles (Billings, 1937; Hatch et al., 1988). (Granulite is used in this paper to denote a metamorphic rock dominated by granular mineral constituents, without any connotation for metamorphic facies.) The Fitch Formation at Littleton, New Hampshire, yielded the fossils first recorded by Hitchcock and the brachiopods studied more extensively by Billings and Cleaves (1934) and by Berry and Boucot (1970) to determine an early Ludlow age. More recent work on conodonts from the same area (Fig. 3) have indicated a latest Silurian Pridoli age (Harris et al., 1983), whereas conodonts from Bernardston suggest the rocks are Lochkovian in the earliest Devonian (Elbert et al., 1988).

Together, the Clough Quartzite and Fitch Formation represent a period of slow shelf-type deposition on the future site of the Bronson Hill anticlinorium, beginning with a coarse but chemically very mature basal unit of stream or beach origin, followed by increasingly more distal and presumably slowly deposited shallow marine deposits. Locally the Clough and Fitch are up to several hundred meters thick, but the Fitch is commonly absent over long distances and the Clough extends over wide areas with a thickness of no more than 10 m. The discontinuous nature of the Fitch as well as the Clough suggests there was probably a period of erosion after deposition of the earliest Devonian part of the Fitch and prior to deposition of the overlying Littleton Formation (Hatch et al., 1988; Elbert et al., 1988).

The Littleton Formation is a key unit of widespread metamorphosed graphitic shale and interbedded quartzose sandstone. It is the youngest unit in the classic Bronson Hill sequence at Littleton, New Hampshire and is thought to represent the "flysch" derived from tectonic lands to the east in the early stages of the Acadian Orogeny (Hatch et al., 1988). The age of the Littleton at Littleton, New Hampshire is firmly tied to the Lower Emsian of the late Lower Devonian (Fig. 3) on the basis of brachiopods originally found by Billings (Billings and Cleaves, 1934; Boucot and Arndt, 1960). The Erving Formation, the Waits River Formation, and the Gile Mountain Formation occur adjacent to the Littleton in the western part of the Bronson Hill anticlinorium and in the Connecticut Valley synclinorium (Hatch et al., 1988; Robinson et al., 1988a). The Erving consists of well bedded biotite-quartz-plagioclase granulite and laminated epidote amphibolite with subordinate interbeds of gray nongraphitic schist, calc-silicate granulite, and rare marble. The Waits River Formation consists of gray schist interbedded with quartzose calcitic marble. The Gile Mountain Formation consists of gray schist and quartzofeldspathic granulite with subordinate quartzose marble. Waits River and Gile Mountain both contain local zones of amphibolite or greenschist representing mafic to intermediate tuffs. The stratigraphic relations of these rocks to the Littleton is uncertain and controversial (Robinson et al., 1988a; Hatch, 1987). In the view favored by Robinson, based on field relations in Massachusetts (Robinson et al., 1988a), the Erving is considered to be younger than and unconformably above the Littleton, and the Waits River and overlying Gile Mountain are considered to be westward facies of the Erving. In this model, the line along which the upward-facing Gile Mountain is overlain to the east by the upward-facing Littleton, known locally as the Chicken Yard line (J. B. Thompson and J. L. Rosenfeld, personal communication, 1961), must necessarily be a thrust (see below).

In addition to the sequence of strata, two major sheet-

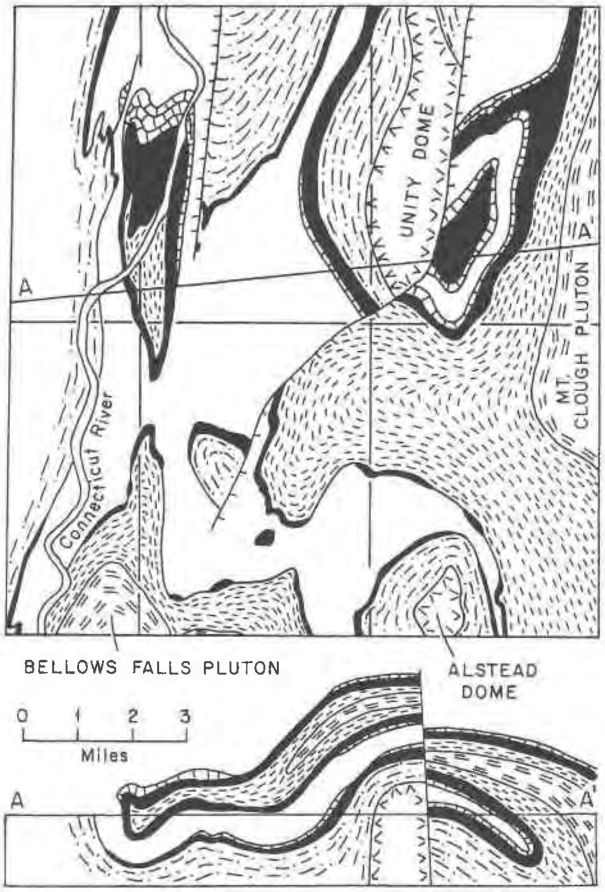

Fig. 5. Map and cross section of the region around Skitchewaug Mountain, Vermont, from Thompson's 1954 guidebook article. For key to patterns see Figure 11 except brick pattern used to distinguish Silurian Fitch Formation.

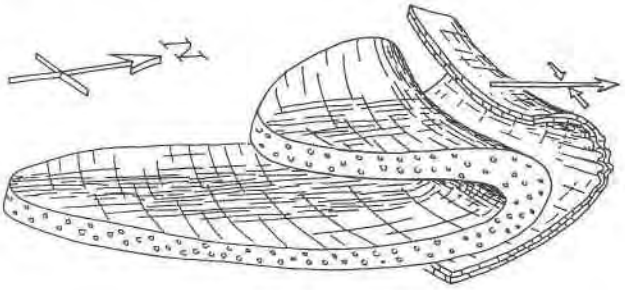

Fig. 6. Cartoon sketch of fold interference pattern at Skitchewaug Mountain. From a field sketch by D.U. Wise. Shows Clough Quartzite wrapped to the north by stratigraphically higher Fitch Formation (brick pattern). East-trending anticlinal hinge of the nappe is refolded by a gently north-plunging syncline.

like intrusions played a quasi-stratigraphic role in the interpretation of the nappes of the Bronson Hill anticlinorium (Thompson et al., 1968). These are the Mount Clough–Bellows Falls pluton of Bethlehem Gneiss, and the Cardigan-Ashuelot pluton of Kinsman Granite (Quartz Monzonite in the obsolete terminology). The subsequently defined stratigraphy of the Merrimack synclinorium plays a role only in the later part of our story and is described later.

Beginning of the nappe theory

In 1954 enters our hero for this volume, Jim Thompson, a thorough and diligent worker in eastern Vermont, but so far repelled from New Hampshire by stern warnings from Marland Billings. The scene is Skitchewaug Mountain near Springfield, Vermont, long before recognized by Richardson (1931) as possibly a piece of New Hampshire geology thrust into Vermont and more recently known for its traces of coral and other calcareous fossils in the Clough Quartzite. This shows as a heart-shaped map pattern bisected by the Connecticut River in the northwestern part of Figure 5, Thompson's map for the 1954 NEIGC Guidebook. Within the heart, a small area of Partridge Formation is surrounded by a continuous layer of Clough Quartzite and an incomplete rim of Fitch Formation, all surrounded by Littleton Formation. Thompson's interpretation of this feature is that of a locally east-trending recumbent anticline refolded by a north-trending open syncline (Fig. 6). In seeking the roots of this isolated structural feature, Thompson ranged to the east side of the Unity dome and north end of the Alstead dome, where he found the appropriate right-side-up autochthon and inverted allochthon, though not yet any synclinal hinges. Thompson's map was drawn at the last minute, and he felt that it was self-explanatory. In editing the guidebook, John Lyons felt that the average reader might need the assistance of a cross section and added his best interpretation at the bottom. Note in this early version that the Bethlehem Gneiss of the Mount Clough pluton lies in the core of the Skitchewaug nappe, rather than on top of it, as was found out shortly later.

During the next several years, the nappe theory flourished and expanded because of Thompson's enthusiasm, the enlistment of Tom N. Clifford (a visiting Commonwealth Fellow from Leeds) and the continuing interest of Arthur Boucot in the newer and better fossil localities. This was but the beginning of the first of three major phases in the development of the nappe theory described below.

Theory of three fold nappes

In the 1950s and early 1960s the nappe theory grew and expanded in its territory. In 1959 Robinson was tempted by Thompson to see if it could be applied in the Mount Grace area in northern Massachusetts previously mapped by Hadley (1949). In 1961 N. J. Trask began a reinterpretation from the Bernardston area into southwestern New Hampshire. The retirement of M. P. Billings in 1968 provided the impetus for the first and only general account of the nappe theory in the region (Thompson et al., 1968).

In the 1968 version there are some changes of detail in the region around Skitchewaug Mountain and the Unity

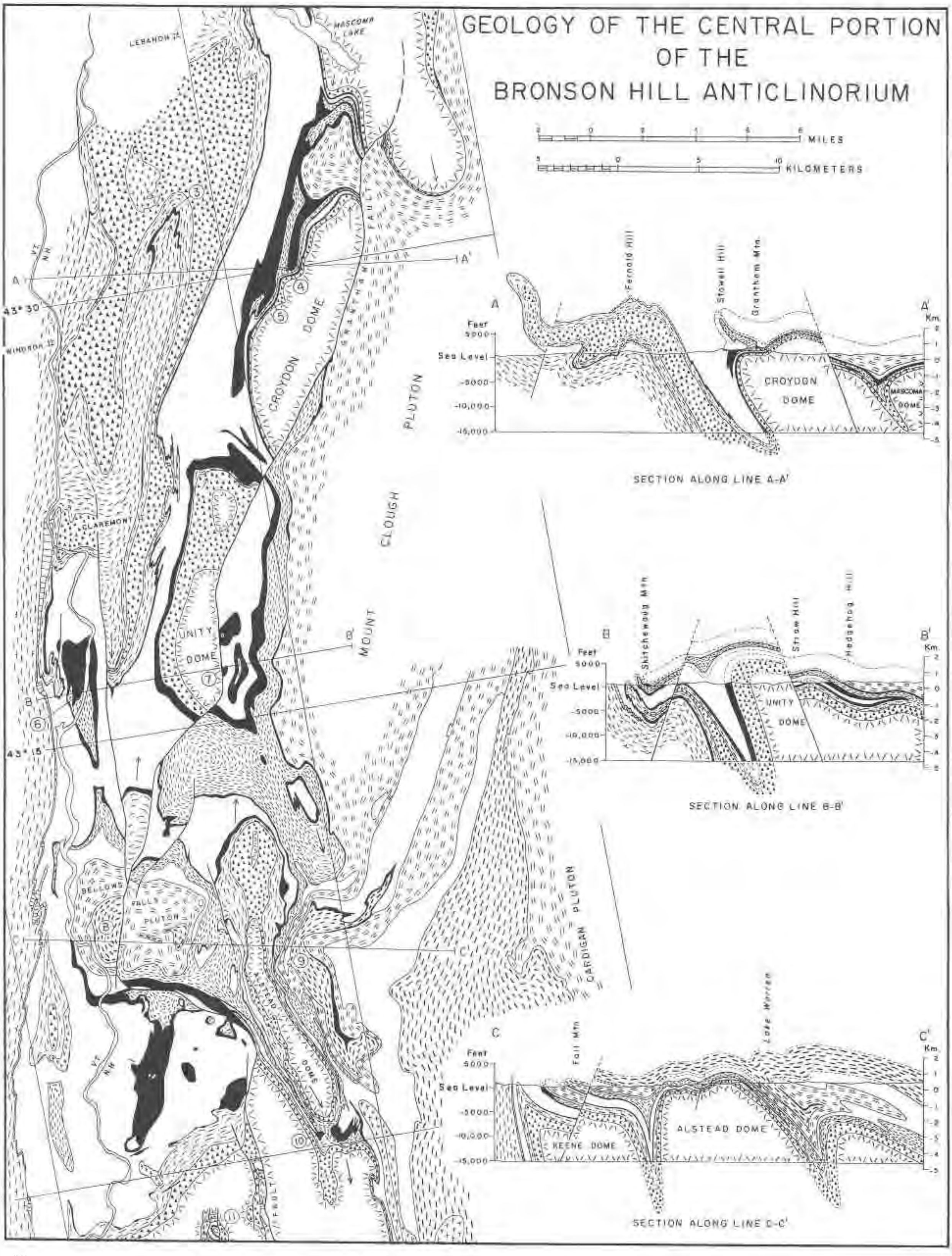

Fig. 7. Northern part of Plate 15-1a of Thompson et al. (1968) with cross sections A-A′, B-B′, and C-C′ from their Plate 15-1b. Map area patterns of original colored version have been modified here for black and white printing and are explained in Figure 11. Key to numbered localities and credit for map coverage are also given in Figure 11.

dome (Fig. 7, map and section B-B′), including the identification of a Mesozoic horst defined by the Connecticut Valley fault on the west and the Grantham fault on the east separating the anticlinal nappe hinge at Skitchewaug Mountain from its root zone to the east. Another notable change was the identification of Clough Quartzite and Fitch Formation on the right-side-up upper limb of the Skitchewaug anticlinal fold east of the Unity dome, thus placing the Bethlehem Gneiss in the "stratigraphic position" of the Littleton Formation above the nappe. From this region northeastward, the three levels of Clough Quartzite could be identified, on the autochthon of the domes, on the inverted limb of the Skitchewaug nappe, and on the right-side-up limb of the nappe. In everyday conversation, Thompson termed these the "lower deck," "middle deck," and "upper deck." On the upthrown west side of the Grantham fault, between the Unity and Croydon domes, only a tiny remnant of the Skitchewaug nappe is preserved from erosion, but in the next axial depression to the northeast, between the Croydon and Mascoma domes, the Skitchewaug nappe is shown with an abundance of complexities (Fig. 7, section A-A′; Fig. 8).

The exposures in the axial depression north of the Croydon dome (Fig. 8) are important to the nappe theory for six reasons. (1) They show extensive areas of all three structural levels ("lower, middle, and upper decks"). (2) They give evidence of a northeast trend of the anticlinal hinge rather than an abnormal east trend as at Skitchewaug Mountain. (3) They show some evidence for a complementary synclinal hinge, suggesting that the amplitude of the nappe at this latitude is about 5 km contrasted with a probable amplitude of at least 20 km farther south (see section B-B′). (4) They demonstrate dramatically the position of the Mount Clough pluton of Bethlehem Gneiss riding above the Fitch Formation on the upper limb of the nappe in the position of the Littleton Formation. (5) They show the variability in thickness of stratigraphic units with respect to the nappe, with thick regions close to the anticlinal hinges, and severe attenuation closer to the root zones, particularly in the middle deck, which locally has nearly the character of a thrust fault zone. They also show an interesting northward "forking" of the nappe shown by the pattern of the Partridge Formation south of Mascoma Lake. (6) The regions of Clough Quartzite close to anticlinal hinges have provided the most crucial fossils (Fig. 3), and they come from rocks in the sillimanite zone (Boucot and Thompson, 1963; see also Robinson et al., 1979; Thompson et al., 1986; or J. B. Thompson, 1988) where the calcite fossils are commonly surrounded by such minerals as diopside and grossular.

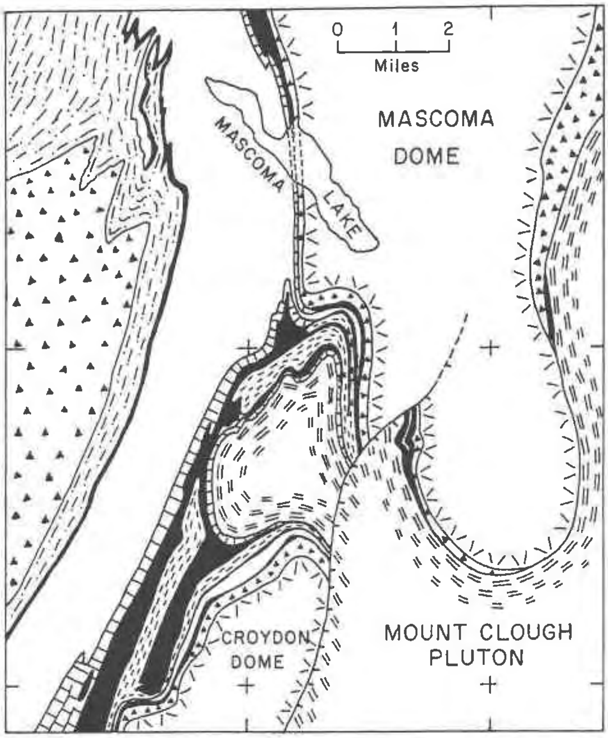

Fig. 8. Thompson's detailed map of the axial depression between the Croydon and Mascoma domes, modified from Robinson et al. (1979; see also Thompson et al., 1986; or J.B. Thompson, 1988). Location is south of Mascoma Lake shown at top of Figure 7.

In the region north of Skitchewaug Mountain and west of the Croydon dome between Claremont and Lebanon, a large fold nappe at a lower level was identified and named for the town of Cornish (Fig. 7, section A-A′). The strata on the upper limb are of the Bronson Hill sequence. The oldest rock unit in the nappe is the Post Pond Volcanics, interpreted by Thompson et al. (1968) to be identical with the Ammonoosuc Volcanics. In the inverted limb, however, the place of the Littleton Formation is taken by the Gile Mountain Formation of the Connecticut Valley synclinorium sequence.

The work of Thompson and Clifford in the Bellows Falls region south of Skitchewaug Mountain led to further discoveries. Here the Skitchewaug nappe was shown to pass under the Bellows Falls pluton and into a large region of gently dipping foliation northwest of the Keene dome. Above the Bellows Falls pluton at Fall Mountain on the west side of the Connecticut Valley fault (Fig. 7, locality 8), a still higher inverted sequence was identified (Fig. 7, section C-C′). At first assigned to a mythical mother nappe above the Skitchewaug, this was eventually named for Fall Mountain. Thus for the first time the system of nappes was seen to consist of three: the Skitchewaug in the middle, the Cornish below, and the Fall Mountain above (Fig. 9).

The root zones of the Skitchewaug nappe were vigorously pursued by Thompson and Clifford in the region around the Alstead dome and eventually by Thompson in the axial depression between the Keene and Alstead domes (Fig. 10). Here at last could be seen three exposures of the same synclinal hinge of the nappe highly deformed by later structural features. On the northeast flank of the Keene dome, an odd sock-shaped hinge plunges steeply into the Surry Mountain syncline, is tight-

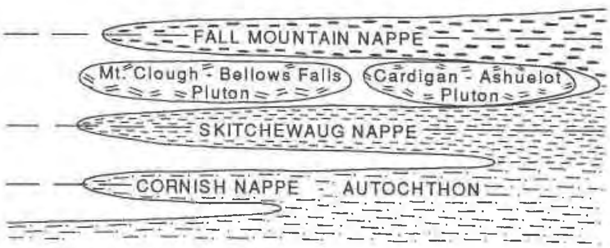

Fig. 9. Schematic east-west cross section illustrating the theory of three fold nappes as developed up to 1968. Patterns for Ordovician strata at three structural levels and foliated Acadian intrusions are the same as used in Figures 5, 7, 8, 10, 11, 12, and 13.

ly bent in the bottom of that syncline, and emerges again on the southwest flank of the Alstead dome. The hinge then passes over the southeast corner of the Alstead dome and plunges northeast into the southeast limb of the dome in a very tight attenuated hinge. Taking the three hinge locations together, the original overall trend of the synclinal hinge appears to have been toward the northeast, and the amplitude of the nappe from this location to the anticlinal hinge near Bellows Falls would have been approximately 20 km. An odd feature of the sock-shaped hinge at Surry Mountain is that the cobble conglomerate of the Clough has nearly spherical cobbles (see Fig. 4), whereas only a few hundred meters away on the limbs, the same conglomerate has cobbles shaped like sword blades. The nature and sequence of development of strain fabrics of this type still awaits a definitive study.

Moore (1949) had mapped the strata in a small graben on the roof of the west lobe of the Keene dome at Hyland Hill (Figs. 7 and 11, locality 11). This included the normal Bronson Hill sequence, and then above the normal Littleton, a second quartzite he labeled "Dlq" overlain by more schist. One afternoon in the summer of 1959, Robinson showed that the Dlq is an inverted limb of Clough Quartzite in turn overlain by typical sulfidic schists and amphibolites of the Partridge Formation.

The early work of Robinson in the Mount Grace area (Fig. 11, localities 12 and 13) showed that there was early recumbent folding, but connections with the synclinal root zone at Surry Mountain were not clear. West of the Connecticut Valley border fault, on the other hand, Trask (1964) could show that an inverted limb, tentatively equated with the Skitchewaug nappe, extends from the Bernardston fossil locality around the east side of the Vernon dome and into the axial depression between Vernon dome and the western lobe of the Keene dome. Thus was shown the identity of the Bernardston inverted limb with the inverted limbs on Hyland Hill and on Surry Mountain. Furthermore, Trask identified a synclinal hinge in the narrow belt east of Spofford Lake between the west lobe of the Keene dome and the Ashuelot pluton. When this hinge is tied to that at Surry Mountain, the hinge trend appears to be about N45E but is considerably more northerly when proper account is made of the horizontal component of the dip-slip displacement on the Connecticut Valley fault. Trask also tentatively identified remnants of the Fitch Formation on the upper limb of the nappe, immediately overlain by the Ashuelot pluton of Kinsman Granite, apparently in the same structural position as the Mount Clough pluton farther north (Fig. 12, section D-D′).

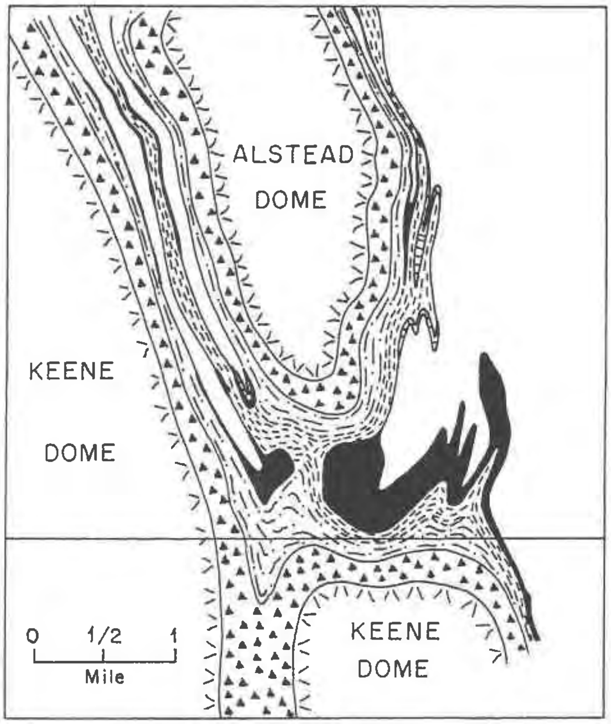

Fig. 10. Thompson's detailed map of the axial depression between the Keene and Alstead domes near Surry Mountain showing three synclinal hinges originally interpreted as belonging to the Skitchewaug nappe. Adapted from Trask and Thompson (1967). Patterns same as in key to Figure 11. For location see number 10 near bottom of Figure 7.

Work in the Mount Grace quadrangle reached a climax in the fall of 1966 when Jim Thompson viewed results of Robinson's remapping of his 1963 thesis area. Standing upon an outcrop of an extensive unit previously mapped as the Gray Member of the Partridge Formation, Thompson offered this quiet prayer, "Oh rock, tell us your age and origin!" Within two hours it was answered. Yet another narrow belt of conglomerate assigned to the Clough Quartzite had been located, suggesting that the "gray Partridge" was in fact Littleton, and setting the groundwork for the interpretation shown in Figure 13. In this, the belt of inverted Clough in the Rum Brook syncline along the east flank of the Warwick dome is interpreted as continuous with the inverted belt at Bernardston, offset vertically about 5 km by the Connecticut Valley fault. From the Rum Brook syncline this inverted contact is traced eastward around the ends of the Camp Warwick

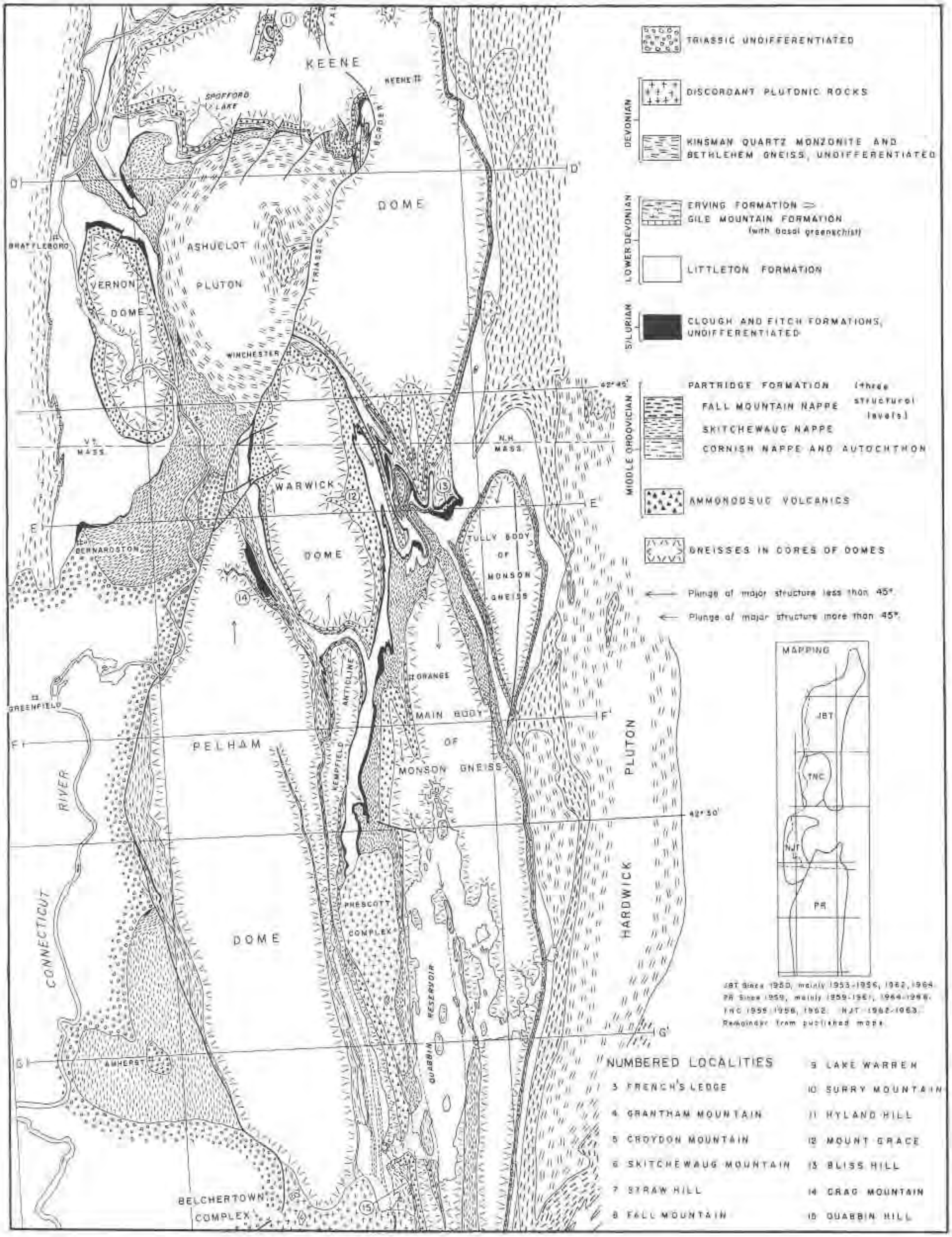

Fig. 11. Southern part of Plate 15-1a of Thompson et al. (1968). Map area patterns of original color version have been modified here for black and white printing. "Triassic" strata are now known to be Late Triassic and Early Jurassic (Zen et al., 1983; Robinson and Luttrell, 1985).

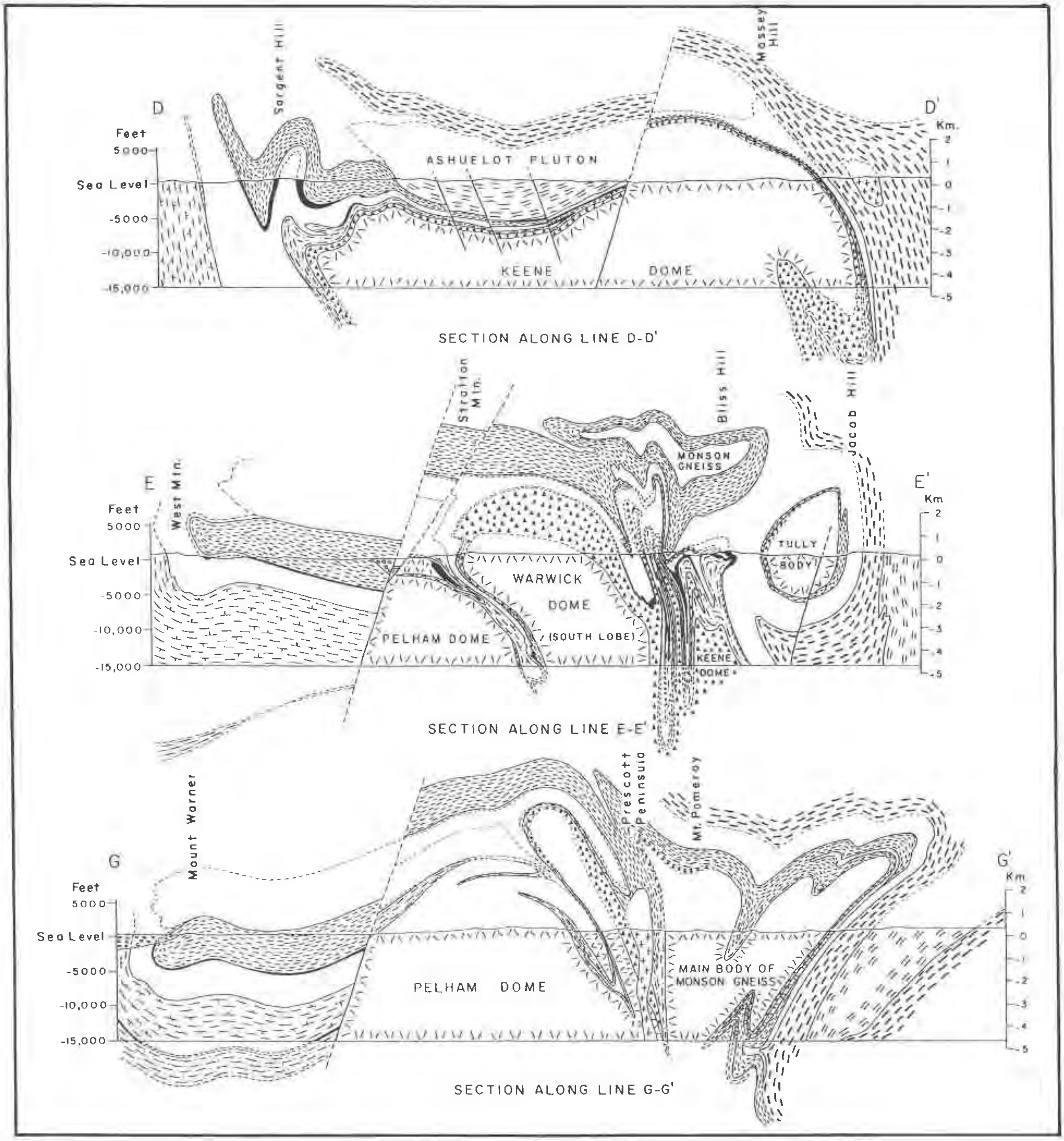

Fig. 12. Cross sections D-D′, E-E′, and G-G′ from Plate 15-1b of Thompson et al. (1968). Map patterns of color original have been modified here for black and white printing and are explained in Figure 11.

and Keene domes to a synclinal hinge identified at Bliss Hill. At this time, the core of the nappe was considered to be highly attenuated by shearing. Thus, in the central part of the Mount Grace quadrangle, it consisted only of some 30 m of true Partridge Formation, with younger rocks on both sides. At Bliss Hill the core of the nappe was considered to be only Clough Quartzite with all other units missing as a result of shearing. These ideas were supported by the evidence for limb shearing already reported from north of the Croydon dome. These considerations were the basis for constructing the cross section from Bernardston through Mount Grace (Fig. 12, section E-E′) and for making sense out of the Amherst inliers in central Massachusetts (Fig. 12, section G-G′) as part of a far-traveled nappe rooted to the east.

At the end of this early phase, an attempt was made to

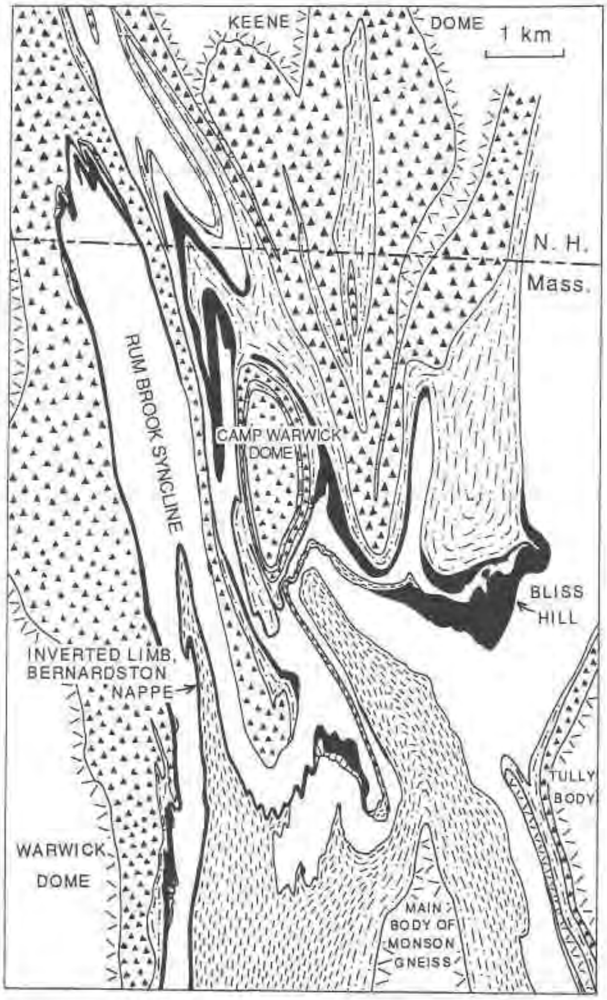

Fig. 13. Map of part of the Mount Grace quadrangle, Massachusetts–New Hampshire (east-central part of Fig. 11), adapted from Robinson (1967). Patterns same as in key to Figure 11 except Fitch Formation shown in brick pattern. For location see also inset in Figure 17.

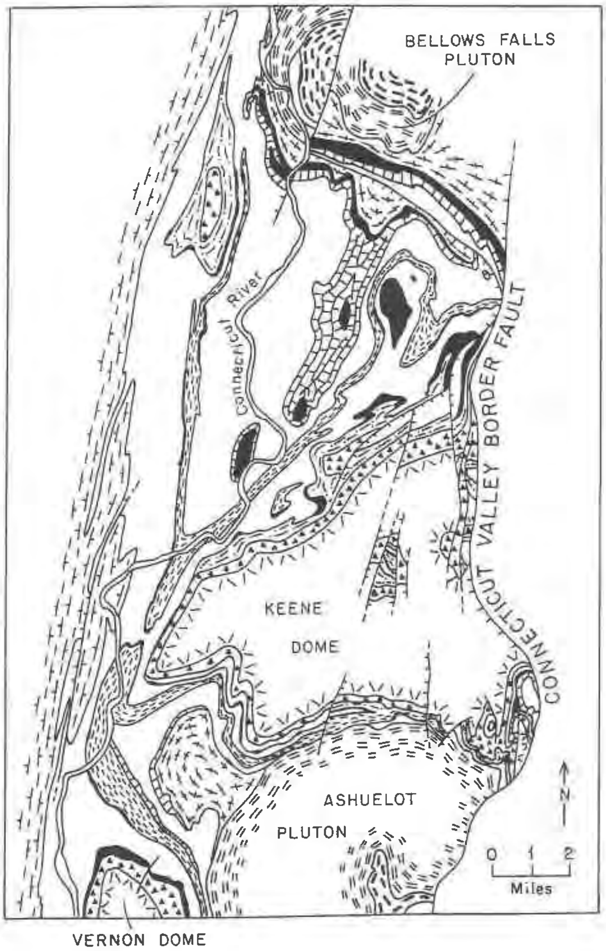

Fig. 14. Map of the area north of the Vernon gneiss dome and south of the Bellows Falls pluton (southwest corner of Fig. 7 and northwest corner of Fig. 11), showing new recognition of the Bernardston nappe as distinct from the Skitchewaug nappe. Adapted from Thompson and Rosenfeld (1979). Patterns same as in key for Figure 11 except for brick pattern for Fitch Formation and different patterns for Partridge Formation in Bernardston and Skitchewaug nappes that are keyed in Figure 16.

rationalize the obvious geometrical relationships between structural development and regional metamorphism. These are obvious in Figures 15-2 and 15-3 of Thompson et al. (1968) where metamorphic zones are compared directly with structural levels shown on a map of traces of the axial surfaces of nappes. What is especially striking is the nearly direct relationship between high metamorphic grade and high structural level near Fall Mountain at Bellows Falls and surrounding the Ashuelot pluton. In addition, in central Massachusetts, the highest sillimanite-grade rocks are found on the western, downthrown side of the Connecticut Valley fault adjacent to lower grade rocks to the east. Furthermore, Robinson had identified several slices of rocks of chlorite grade along the fault, juxtaposed to the west by rocks of sillimanite grade and on the east by rocks of kyanite grade. The most rational explanation, along this purely dip-slip fault with about 5 km of vertical displacement, is that before faulting there was a metamorphic overhang with rocks of the sillimanite zone above, rocks of the kyanite zone below, and rocks of the chlorite zone in the middle, in the right location to be sliced off and preserved in the fault zone. The pattern of isograds cannot be simply a product of recumbent folding of rocks that were previously metamorphosed, because the dominant metamorphic fabric in most of the rocks appears to have been imposed in later stages of metamorphism during formation of the gneiss domes. For this reason it was conceived that the rocks were heated, in part by sheetlike intrusions, at the time they were moving and that the final imprint of metamorphism occurred well after emplacement of the nappes. These concepts have provided fuel for controversy concerning the length of time that such overhanging metamorphic thermal anomalies could endure (Sleep, 1979).

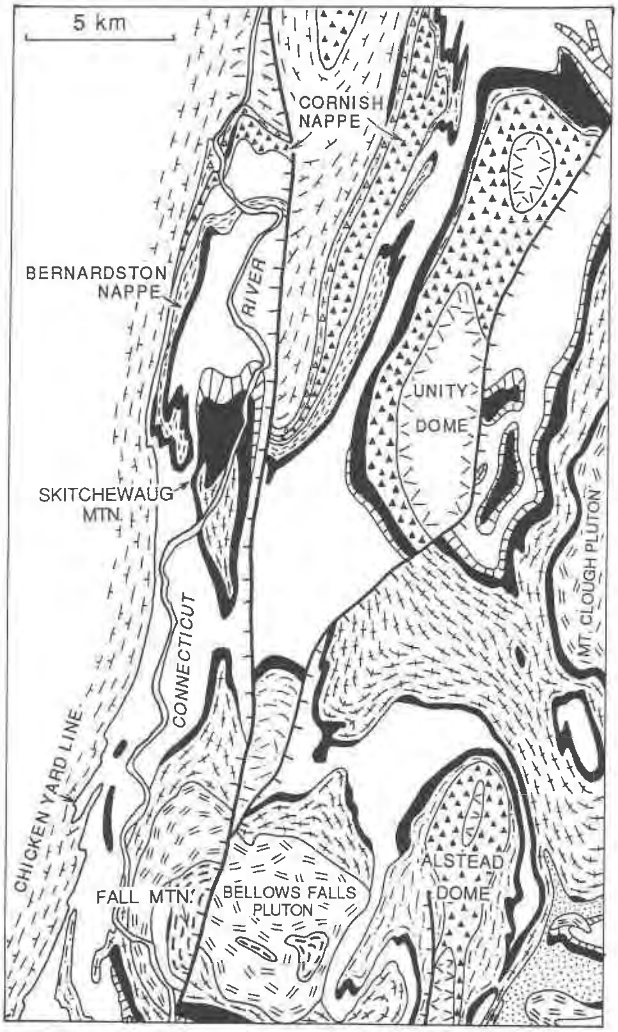

Fig. 15. Revised map of the vicinity of Skitchewaug Mountain (central part of Fig. 7) showing the northward extension of the Bernardston nappe. Adapted from manuscript maps provided by J.B. Thompson. Patterns same as in key for Figure 11 except for brick pattern for Fitch Formation and different patterns for Partridge Formation in Bernardston and Skitchewaug nappes that are keyed in Figure 16.

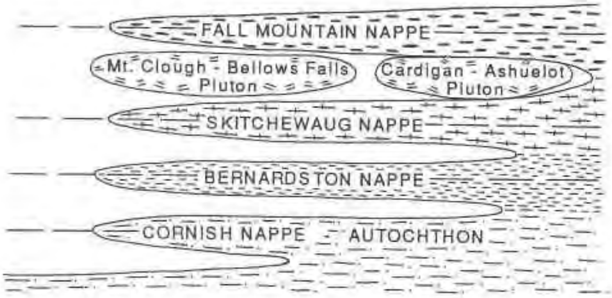

Fig. 16. Schematic east-west cross section illustrating the theory of fourfold nappes as developed in the 1970s. Patterns for Ordovician strata at four structural levels and for foliated Acadian intrusions are the same as in Figures 14 and 15.

THEORY OF FOUR FOLD NAPPES

In the 1970s Thompson reworked the area northwest of the Keene gneiss dome in cooperation with J. L. Rosenfeld (Thompson and Rosenfeld, 1979; Fig. 14). This work showed that earlier investigations had "jumped the tracks," and that the recumbent fold, identified by Trask at Bernardston and extended to the southwest side of the Keene dome, in fact slips in beneath the Skitchewaug nappe southwest of Bellows Falls. This newly identified nappe was named for Bernardston, using Trask's original 1964 terminology when he had rightly been doubtful of the structural correlation. On this basis, the synclinal hinges at Bliss Hill, at the location east of Spofford Lake, and at Surry Mountain all appear to belong to the Bernardston rather than the Skitchewaug nappe.

From near Bellows Falls, Thompson then projected the Bernardston nappe northward to the vicinity of Skitchewaug Mountain (Fig. 15), where it comes in at a level between the Cornish and Skitchewaug nappes. The map pattern in the eastern part of Figure 15 is somewhat puzzling as to the position of the synclinal hinge of the Bernardston nappe, but it appears to be located in the subsurface west of the Unity, Croydon, and Mascoma domes where the Skitchewaug nappe is directly above the autochthon. Thus, this phase of research resulted in the theory that there are four major fold nappes as illustrated in Figure 16.

FOLD NAPPES AND THRUST NAPPES

That some of the early west-directed fold nappes have limbs locally thinned by faulting has long been recognized (Thompson et al., 1968, p. 211, 214), but the idea that there are major thrusts is relatively new. The initial invocation of major thrusting, in addition to folding, to explain the map pattern in the Connecticut Valley region, involved a tentative resolution of the stratigraphic problem of the Erving Formation (Robinson et al., 1984, 1988a) in Massachusetts. In this, the true stratigraphic sequence from oldest to youngest was proposed to be Littleton Formation, Erving Formation, and Waits River and Gile Mountain Formations. Based on complex geometric and stratigraphic relations, the Whately thrust was proposed to lie along the contact known as the Chicken Yard line between the Littleton Formation to the east and the Gile Mountain Formation to the west. The stratigraphically older Littleton from a deeper part of the basin to the east was considered to have been thrust westward over the younger (in this interpretation) Waits River and Gile Mountain Formations. To the east the proposed thrust disappears into bedding within the Littleton. Located along the axis of the Connecticut Valley low grade metamorphic belt, it is considered to have been a premetamorphic or early metamorphic thrust, but its time relations to the fold nappes covered here is uncertain. Because the Chicken Yard line apparently runs north into the Monroe line that bounds pre-Silurian rocks of the Cornish nappe from the Gile Mountain to the west, the Whately thrust may run along the lower side of the Cornish nappe.

Stratigraphy of the Merrimack synclinorium

The main idea of the thrust nappes developed through a new concept of the stratigraphy of the Merrimack synclinorium. Specifically the sequence of Silurian units identified by Moench and Boudette (1970) in northwestern Maine was extended into central New Hampshire (Hatch et al., 1983) and Massachusetts (Field, 1975; Tucker, 1977; Robinson et al., 1982a), and eventually applied by P. J. Thompson (1985) to the Mount Monadnock area, New Hampshire (Fig. 17). As compared to the thin Silurian shelf sequence characteristic of the Bronson Hill anticlinorium, the Merrimack synclinorium contains a much thicker immature clastic sequence (Fig. 2), and the pre-Silurian section is scarce to unknown. The Lower Silurian consists mainly of the thick Rangeley Formation, dominated by gray- to rusty-weathering feldspathic schists with subordinate lenses of calc-silicate and granulite-matrix conglomerate. This is overlain by the Perry Mountain Formation of laminated gray to brown schists and quartzites, followed by the Francestown Formation of pyrrhotite-rich calc-silicates. The Upper Silurian consists mainly of the Warner Formation having a lower member dominated by laminated green and purple calc-silicates, and an upper member of biotite-feldspar granulites with subordinate calc-silicate. The upper Warner appears to grade continuously into the lower Littleton, which on Mount Monadnock contains distinctive lower and upper members with different bedding characteristics and proportions of quartzite. On Mount Monadnock a distinctive zone of seven quartzites in the upper member is a key to local structural interpretation. The Warner Formation in New Hampshire appears identical to the Madrid Formation in northwestern Maine, and the Francestown Formation appears to correlate eastward with the extremely sulfide-rich pelites of the Smalls Falls Formation. Sedimentological evidence in Maine suggests this thick Silurian section, particularly its lower part, had its sedimentary source to the west or northwest toward the Bronson Hill belt; whereas the overlying Littleton Formation was the distal part of a deltaic complex representing early Acadian "flysch" derived from tectonic lands to the east (Hall et al., 1976).

The facies change between the thick Merrimack sequence to the east and the thin Bronson Hill sequence to the west appears to have been rather rapid along a zone described as a "tectonic hinge" (Moench and Boudette, 1970; Hatch et al., 1983). The higher Acadian fold nappes of the Connecticut Valley region are mostly rooted on the east side of the Bronson Hill anticlinorium, and might be expected to have a stratigraphy transitional between that of the Bronson Hill anticlinorium and of the Merrimack belt. Recent work by J. B. Thompson (personal communication) in the Skitchewaug nappe indicates that the Clough Quartzite, as previously mapped, contains members that may be transitional to units in the Rangeley Formation farther east. In the Lake Warren region (Fig. 7, locality 9) Chamberlain (1985) has shown that conglomerates typical of the Clough occur between Rangeley schists (shown as Partridge near locality 9 in Fig. 7) and overlying Francestown Formation, in the approximate position normally occupied by the Perry Mountain. In the Derby Hill window area of the Monadnock quadrangle, P. J. Thompson (1985) has located a lens of Clough-like conglomerate at the contact between the Rangeley and Perry Mountain Formations.

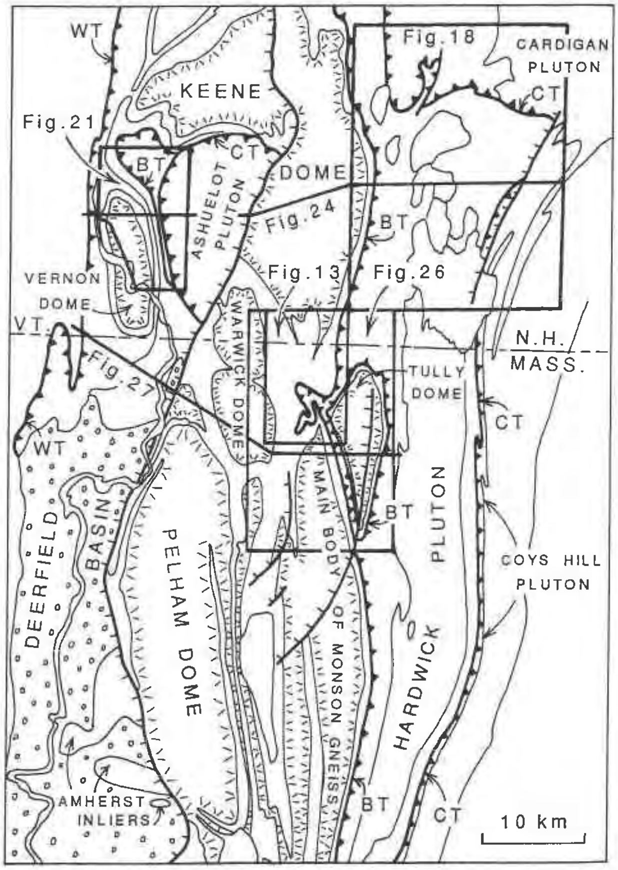

Fig. 17. Geologic index map showing location of the Monadnock (Fig. 18), Hinsdale (Fig. 21), and Mount Grace (Fig. 26) areas significant to the theory of thrust nappes. Also shows lines of cross sections in Figures 24 and 27.

Folds and thrusts of the Mount Monadnock area

Chamberlain (personal communication, 1982) first suggested a major thrust east of the Bronson Hill anticlinorium based on a steep metamorphic gradient in the Lovewell Mountain quadrangle, New Hampshire. This contact has been traced by P. J. Thompson (1985, 1988a) through the Mount Monadnock area as the Chesham Pond thrust (Fig. 18), and its relations with structural features of the underlying Monadnock sequence are critical.

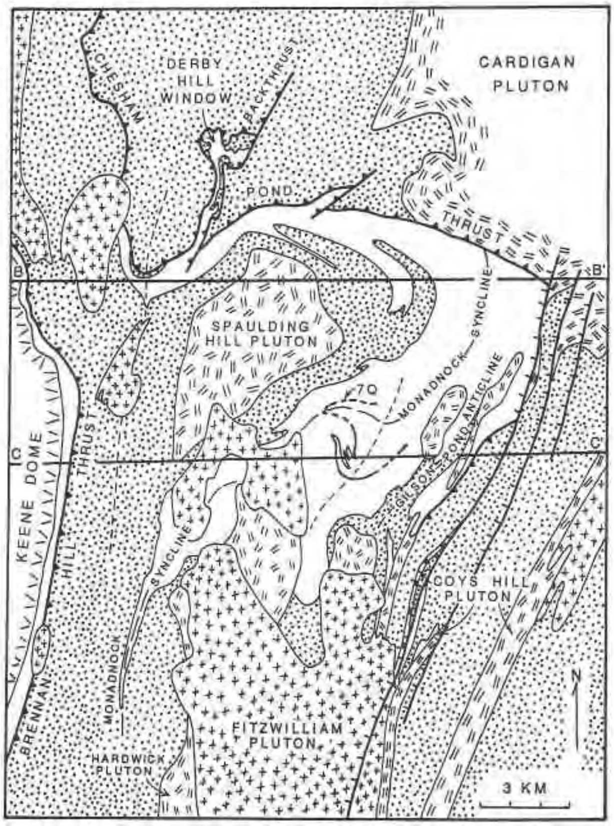

Fig. 18. Generalized geologic map of the Mount Monadnock area adapted from P.J. Thompson (1985), with locations of cross sections in Figure 19 indicated. Patterns are similar to those in key to Figure 19, but all Silurian strata above Brennan Hill thrust are lumped with the Rangeley Formation, and Silurian and Ordovician strata below thrust are lumped with the Littleton Formation. The 7Q indicates seven quartzites within the upper member of the Littleton that have been traced across the summit area of Mount Monadnock.

Structural data on Mount Monadnock itself (Figs. 18, 19) have led to the conclusion that the most prominent set of mapped isoclinal folds in bedding are folds of the nappe stage. In their original setting, they were satellitic folds on the upper limb of a major nappe-stage syncline, the Monadnock syncline, that was overfolded from east to west so that bedding faced west along the nappe-stage axial surfaces (Fig. 20). Subsequently, by backfold- and dome-stage folding, the originally west-facing recumbent folds were overturned toward the east, so that the strata now face east and southeast along the original nappe-stage axial surfaces (Fig. 19). Thus, the strata on the mountain (P. J. Thompson, 1985, 1988b), which were once predominantly upside down on the lower limb of a major anticlinal nappe (Fig. 20), are now predominantly right-side-up again because of the later folding (Fig. 19). Traced northward, the axial surfaces of the Monadnock syncline and satellitic nappe-stage anticlines and synclines are clearly truncated upward by the Chesham Pond thrust. With effects of later deformation removed, as in Figure 20, it can be seen that the east-dipping fold axial surfaces are cut by a thrust that dips less steeply and is not merely the attenuated lower limb of a recumbent fold. Such relationships appear in P. J. Thompson's detailed map of the Derby Hill tectonic window (Fig. 18) where axial surfaces of earlier folds are cut both by the Chesham Pond thrust and by a later related backthrust. Figure 20 is thus a model for the types of contact relationships expected along thrust faults between previously folded sequences in the region. The strong development of augen schists in the Rangeley Formation just above the Chesham Pond thrust (P. J. Thompson, 1985, Plate 4) is extremely similar to the development of augen schists by dismemberment of pegmatites during synmetamorphic shearing on the Sgurr Beag slide in the Scottish Highlands (Powell et al., 1981).

Beyond the Monadnock region, the Chesham Pond thrust may encircle Fall Mountain (Fig. 7) near Bellows Falls, (J. B. Thompson, C. P. Chamberlain, F. S. Spear, personal communications, 1983–1985; Spear and Chamberlain, 1986) and the Ashuelot pluton (Figs. 11, 17, 21) in the Hinsdale area (Elbert, 1986; Armstrong, 1986). It is tentatively extended from the Monadnock quadrangle southward along the west margin of the Coys Hill pluton (= Cardigan pluton) through central Massachusetts (Fig. 17) and probably into Connecticut.

A second proposed thrust, the Brennan Hill thrust, is exposed at a lower structural level in the western part of the Monadnock area (Fig. 18). This is a contact on the east side of the Keene dome separating strata assigned to the Lower Member of the Silurian Rangeley Formation above, from the Devonian Littleton Formation in a Bronson Hill sequence below (Figs. 18, 19, 20). This contact traces southward into the Mount Grace quadrangle, in Massachusetts (Fig. 17), with consequences discussed below. It traces northward into the Lake Warren area (Fig. 7, locality 9) where its consequences are still being evaluated (Chamberlain et al., 1988). To the west near Hinsdale, New Hampshire, west of the Ashuelot pluton (Fig. 17), Elbert appears to have identified the same surface where a complexly deformed Monadnock sequence of strata appears to be in thrust contact with Partridge Formation in the core of the Bernardston nappe (Elbert, 1984, 1986, 1988). On the basis of these considerations and direct lithic comparisons with the Monadnock quadrangle, the rocks mapped by Jasaitis (1983) as Littleton, Clough, and Partridge in the Amherst inliers area (Fig. 17), including outcrops of granulite-matrix conglomerate, are now assigned to the Rangeley Formation above the Brennan Hill thrust.

Fold and thrust relations near Hinsdale, New Hampshire

Field relations in the Hinsdale area, New Hampshire (Fig. 17), are crucial for understanding the Brennan Hill thrust and as a stratigraphic key for other areas (Elbert, 1988). The strata in this area (Fig. 21) lie in a narrow

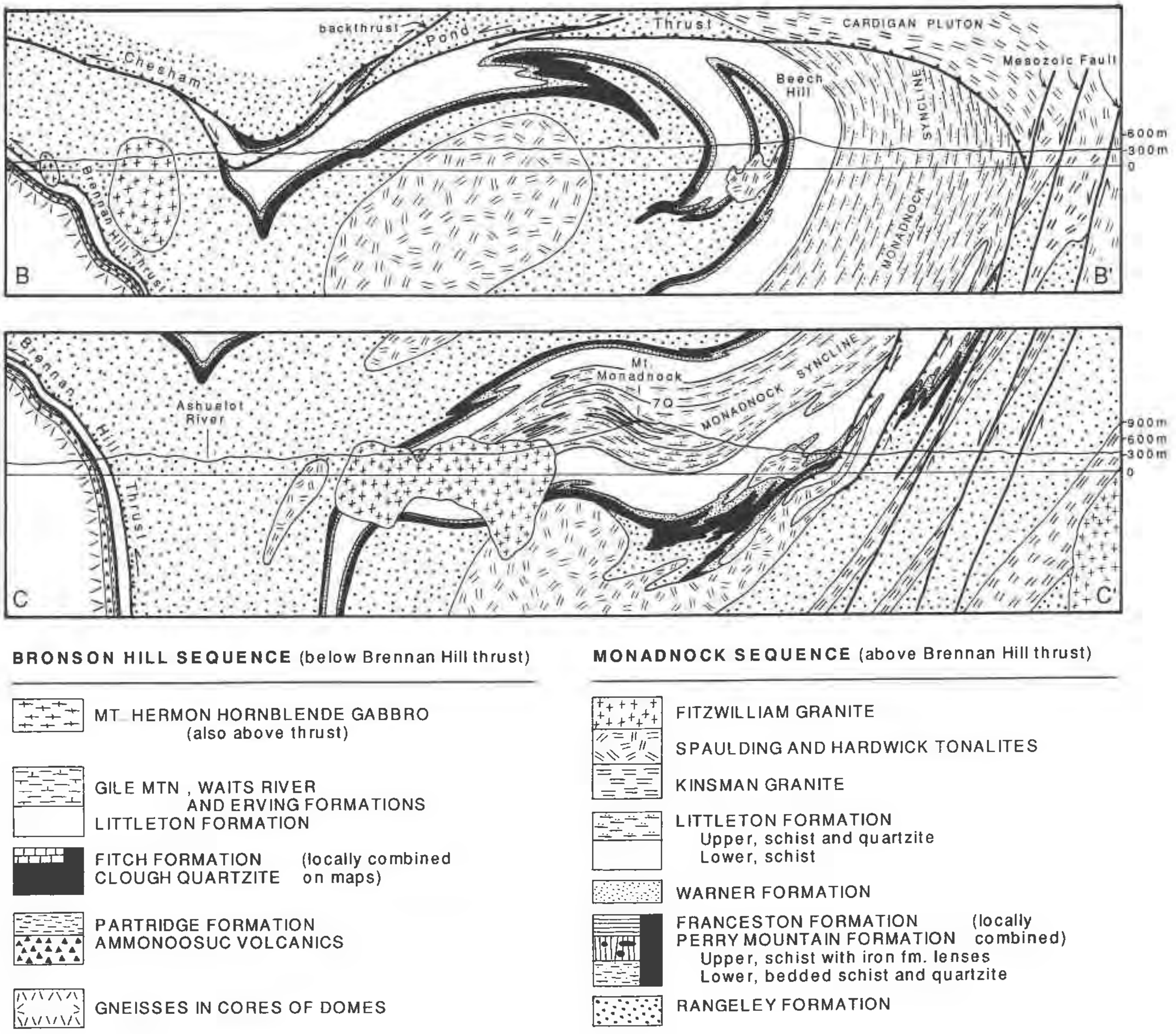

Fig. 19. Generalized geologic cross sections B-B′ and C-C′ across the Mount Monadnock area adapted from P.J. Thompson (1985) and key to patterns used in Figures 18, 19, 21, 23, 24, 26, 27, 28, 30, and 31. Section C-C′ passes through summit of Mount Monadnock.

zone between the core of the Vernon dome to the west and the Ashuelot pluton of Kinsman Granite to the east. The first stratigraphic sequence is the autochthon on the Vernon dome including Ammonoosuc, Clough, and Littleton. This is followed eastward by the inverted sequence of Littleton, Clough, and Partridge that can be traced continuously to the inverted limb at Bernardston (Fig. 11). East of this is the trace of the Brennan Hill thrust, separating rocks of the Bronson Hill sequence to the west from rocks of the Monadnock sequence to the east. Locally the Brennan Hill thrust cuts deep into the Bernardston nappe, so that in one area the preserved core of the nappe includes only about 80 m of Partridge Formation and 160 m of inverted Clough Quartzite. The rocks of the Monadnock sequence above the thrust are arranged on the limbs of a tight isoclinal syncline, the Hinsdale syncline, that formed prior to the thrust and is truncated by it. In the southern part of Figure 21, much or all of the west limb is removed by the thrust so that in many locations a downward or west-facing Monadnock stratigraphy is directly against Partridge across the thrust. In the northern part of Figure 21, both limbs of the Hinsdale syncline are preserved, but the upward-facing strata of the west limb are doubled by imbrication just above the thrust. Thus, in this area early folds in rocks of the Monadnock sequence are truncated below by the Brennan Hill thrust in much the same way that such folds are truncated above by the Chesham Pond thrust in the Monadnock area. These considerations lead to the schematic tectonic diagram of Figure 22.

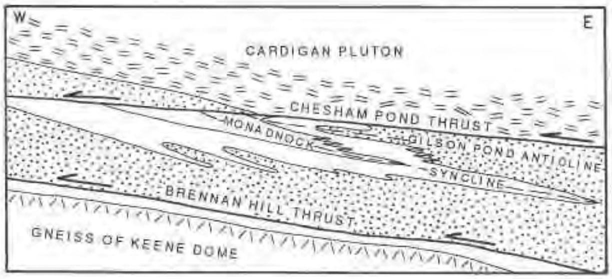

Fig. 20. Schematic restored cross section through the Mount Monadnock area showing the relationship between early recumbent fold nappes and later thrusts. Adapted from P.J. Thompson (1985). Patterns generalized as in Figure 18.

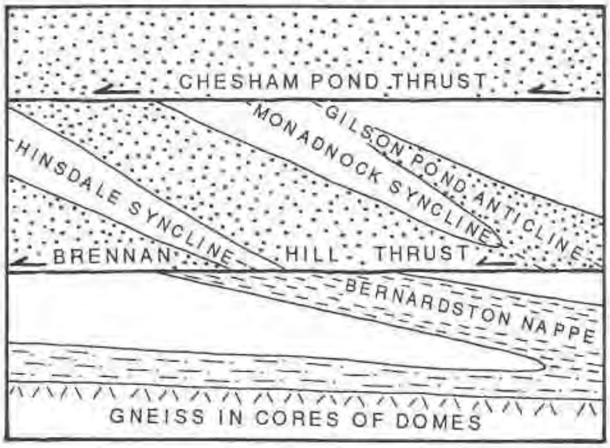

Fig. 22. Schematic structure diagram illustrating the relationship between early isoclinal folds and later thrusts in the Monadnock-Hinsdale region. Patterns for Partridge of Bernardston nappe and autochthon same as Figure 16. Silurian strata of Monadnock sequence are dotted.

The strata of the Monadnock sequence are best displayed in a thin west-facing, east-dipping inverted sequence at Biscuit Hill (Fig. 23A). The stratigraphically lowest and structurally highest unit consists of gray schists with conglomerate lenses of the Rangeley Formation, apparently in fault contact to the east off the map with the Kinsman Granite. This is stratigraphically overlain by thin Perry Mountain Formation with characteristic quartzite beds, some showing inverted graded bedding. Above this is an unusual zone, also assigned to the Perry Mountain, consisting of lenses and boudins of magnetite-garnet iron formation associated with massive gray schist. This is succeeded by typical sulfidic calc-silicate of the

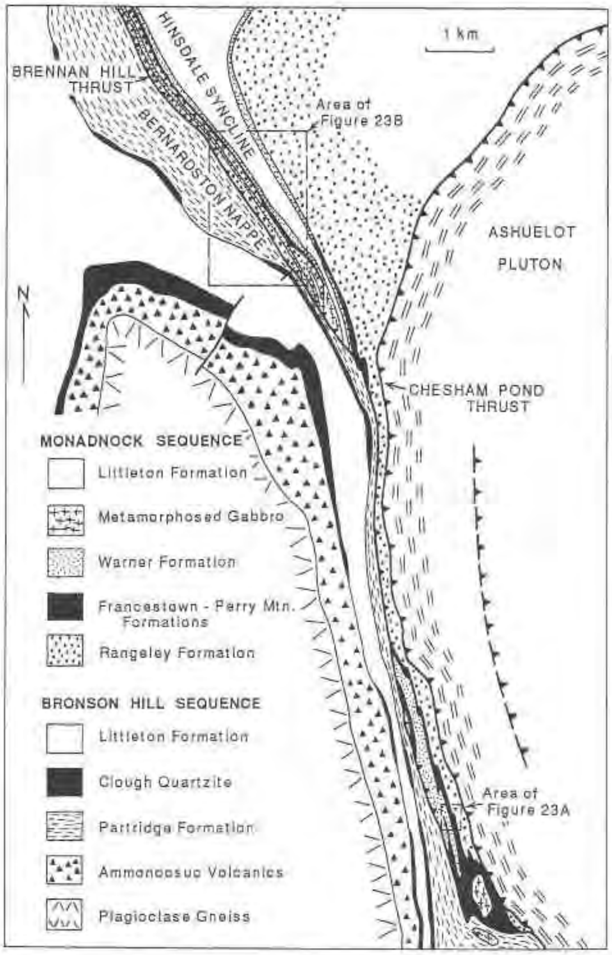

Fig. 21. Detailed map of the Hinsdale area adapted from Elbert (1988). Patterns slightly simplified compared to key in Figure 19.

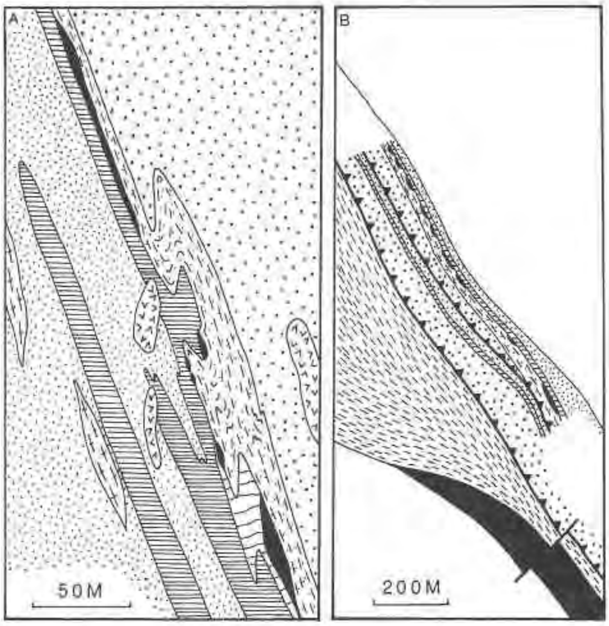

Fig. 23. Detailed maps of two small areas at Biscuit Hill (**A**) and south of Sargent Hill (**B**) near Hinsdale (see Fig. 21). Adapted from Elbert (1988). For key to map patterns see Figure 19. Checked areas in **A** are pegmatite.

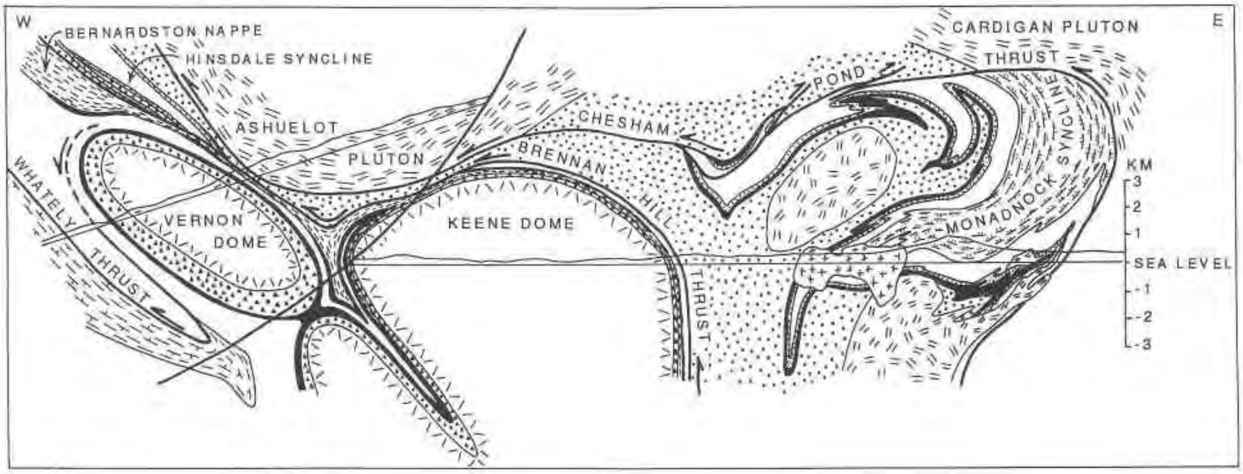

Fig. 24. Restored cross section before Mesozoic faulting from Mount Monadnock through the Hinsdale area. Adapted from Elbert (1988). For key to patterns see Figure 19.

Francestown Formation with subordinate sulfidic pelite. The stratigraphically highest unit is the Warner Formation, dominated by sharply bedded green and pink calc-silicates near the base, and grading into more feldspathic biotite granulite toward the top. The same thin sequence occurs twice by thrust imbrication on the west limb of the Hinsdale syncline near Sargent Hill (Fig. 23B), except that the lenses of magnetite-garnet iron formation occur only in the upper of the two thrust slices. This might indicate that the zones of iron formation are discontinuously distributed or that the imbrication has juxtaposed slices that had sites of deposition originally kilometers apart.

When the structure sections from the Monadnock area and the Hinsdale area are imaginatively connected across a restored Mesozoic Connecticut Valley border fault, making minimal adjustments for the severe deformations related to formation of the gneiss domes, the result is as shown in Figure 24 (P. J. Thompson et al., 1987). If interpreted correctly, this shows the extreme variability in present thickness of the tectonic levels separated by thrust faults as well as the complexity of structure that apparently was already present in the rocks before thrusting. The consequences of this interpretation have not yet been carried northward beyond the southwest flank of the Keene dome to the Bellows Falls region and beyond. To these writers it seems probable that the recumbent fold at Skitchewaug Mountain either represents a higher level fold nappe in the sequence below the Brennan Hill thrust or, more probably, a fold in the sequence above the Brennan Hill thrust. This second concept has been used to construct a schematic diagram (Fig. 25) showing the nappe theory in its present state.

The Mount Grace puzzle

The implications for the Mount Grace area (Fig. 17, inset for Fig. 26) of the new concepts from the Monadnock (P. J. Thompson, 1985, 1988a) and Bernardston-Hinsdale areas (Elbert, 1986, 1988) must now be explored (Robinson et al., 1988b; Springston, 1990). In the western part of the Mount Grace area (Fig. 26) the inverted sequence of Silurian Clough Quartzite overlying Devonian Littleton Formation is again confirmed as the inverted limb of the Bernardston nappe. This can be directly connected to the inverted limb with fossiliferous strata at Bernardston, when about 5 km of vertical displacement on the Mesozoic Connecticut Valley border fault is restored (Fig. 27). Further, the doubled-over layers of Clough Quartzite at Bliss Hill (Figs. 26, 28) are confirmed as the synclinal hinge of the Bernardston nappe, here plunging south.

The large area of gray-weathering schists surrounding the Tully body of Monson Gneiss (Fig. 26), previously assigned to the Littleton Formation, are now mainly assigned to the Lower Silurian Rangeley Formation in direct correlation with the Monadnock area. These include

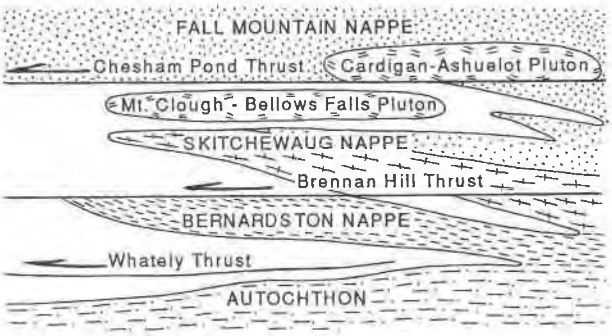

Fig. 25. Schematic east-west cross section illustrating the theory of fold and thrust nappes as developed in the 1980s by the authors. Adapted from Robinson et al. (1988b). Patterns for Partridge of Skitchewaug and Bernardston nappes and autochthon same as Figure 16. Silurian strata of the Monadnock sequence are dotted.

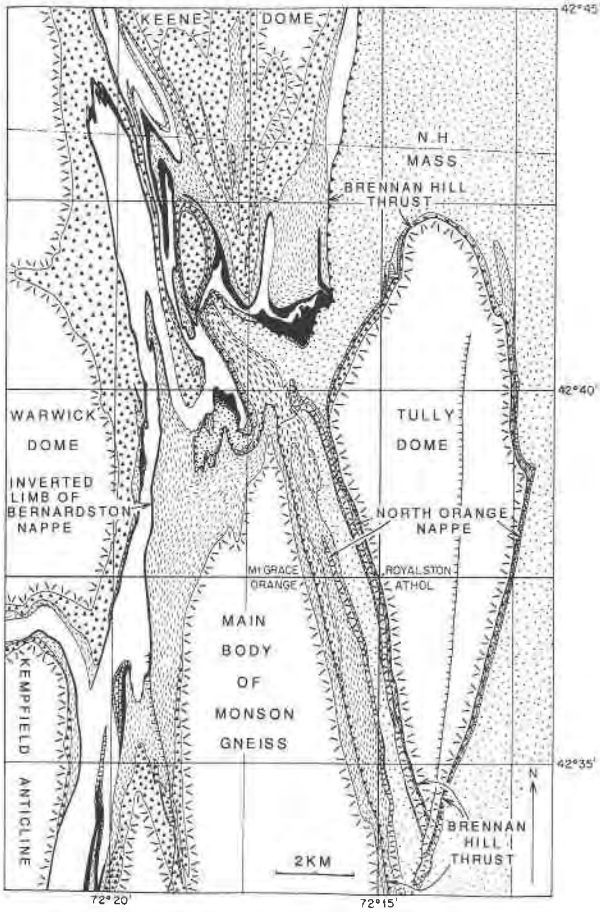

Fig. 26. Generalized geologic map of the northeastern part of the Orange area. From Robinson et al. (1988b). Line of section in part of Figure 27 runs along east-west quadrangle boundary. For key to patterns see Figure 19. Heavy dashed pattern indicates augen gneiss member of Partridge.

a few isolated small areas of conglomerate previously unknown or assigned to the Clough Quartzite. The west margin of the Rangeley Formation is marked by Peter Thompson's Brennan Hill thrust. This traces from the Monadnock area southward into the Mount Grace quadrangle where it is unvoluted by the northward overturning of the main and Tully bodies of Monson Gneiss, and then passes southward along the east margin of the main body toward Connecticut.

In the central part of the Mount Grace area (Figs. 26, 28), on the lower side of the Brennan Hill thrust, the Bernardston nappe is mostly eliminated by the thrust from Bliss Hill southwestward for about 5 km. At different places in this distance the thrust rests on inverted Clough Quartzite, on a thin strip of Partridge Formation in the core of the nappe, and locally on Littleton Formation beneath the nappe. Around the Tully dome, as presently interpreted, the thrust cuts much deeper, resting on Ammonoosuc Volcanics or directly on the Monson Gneiss of the dome.

On the upper side of the thrust, Rangeley Formation predominates, but locally other Silurian units are present and near the northern termination of the main body of Monson Gneiss, the thrust appears to cut down into pre-Silurian strata (Fig. 26). South and southwest of Bliss Hill (Fig. 28), the younger Silurian units include several lenses assigned to the Perry Mountain Formation because of their boudins of magnetite-garnet iron formation, one lens of Francestown Formation, and two lenses of Warner Formation. All of these are localized close to the thrust in such a way as to suggest that the Rangeley was structurally inverted above them, probably on the overturned limb of a nappe-stage recumbent anticline subsequently followed by the thrust. Near Butterworth Ridge, northwest of the Tully dome, there is a narrow complex belt, shown as Perry Mountain on Figure 28, including confused representatives of all Silurian units including iron formation of the Perry Mountain (Springston, 1990). In this vicinity, the Brennan Hill thrust is apparently along the contact between Rangeley Formation and Partridge Formation (not shown at scale of Fig. 28). On the northwest side of the northern tip of the Tully dome (Fig. 28), more extensive Warner Formation appears to be out of order between Perry Mountain Formation and Rangeley.

Near the north end of the main body of Monson Gneiss the Brennan Hill thrust appears to cut through the base of the Rangeley into the augen gneiss member of the Partridge, and some miles south, into the sulfidic schist member (Fig. 26). Near here the Rangeley Formation has a basal conglomerate against the augen gneiss member (Robinson et al., 1988b). East of the north tip of the main body of Monson an earlier recumbent anticline with a core of Monson Gneiss, the North Orange nappe, is believed to be in the upper plate of the Brennan Hill thrust and has an exposed anticlinal hinge in the southeast corner of the Mount Grace quadrangle (Fig. 26). Monson Gneiss in the core of the anticlinal nappe also appears in a continuous belt around the southern part of the Tully dome, with two moderately well exposed anticlinal hinges, one on the northeast flank of the dome (Fig. 26) and one south of Bliss Hill (Fig. 28). The placement of these recumbent fold nappes in the upper plate of the Brennan Hill thrust appears to be necessitated by the configuration of the thrust southwest of Butterworth Ridge (Fig. 28) where Rangeley Formation is resting directly on Monson Gneiss in the core of the Tully dome.

To understand the outcrop pattern and structural evolution of the Mount Grace area it is necessary to recognize the complexity of the backfold-stage and dome-stage deformations that involuted the earlier structural features (Robinson et al., 1988b). This is illustrated in a structural relief diagram (Fig. 29) showing the pattern and local overturning of even the simpler gneiss domes, a swirl in the pattern of dome-stage lineations, minor folds, and transport directions, and the northward overturning and longitudinal transport of the main and Tully bodies of Monson Gneiss. In the core of the Pelham dome it has been proved that the lineation is parallel to the transport

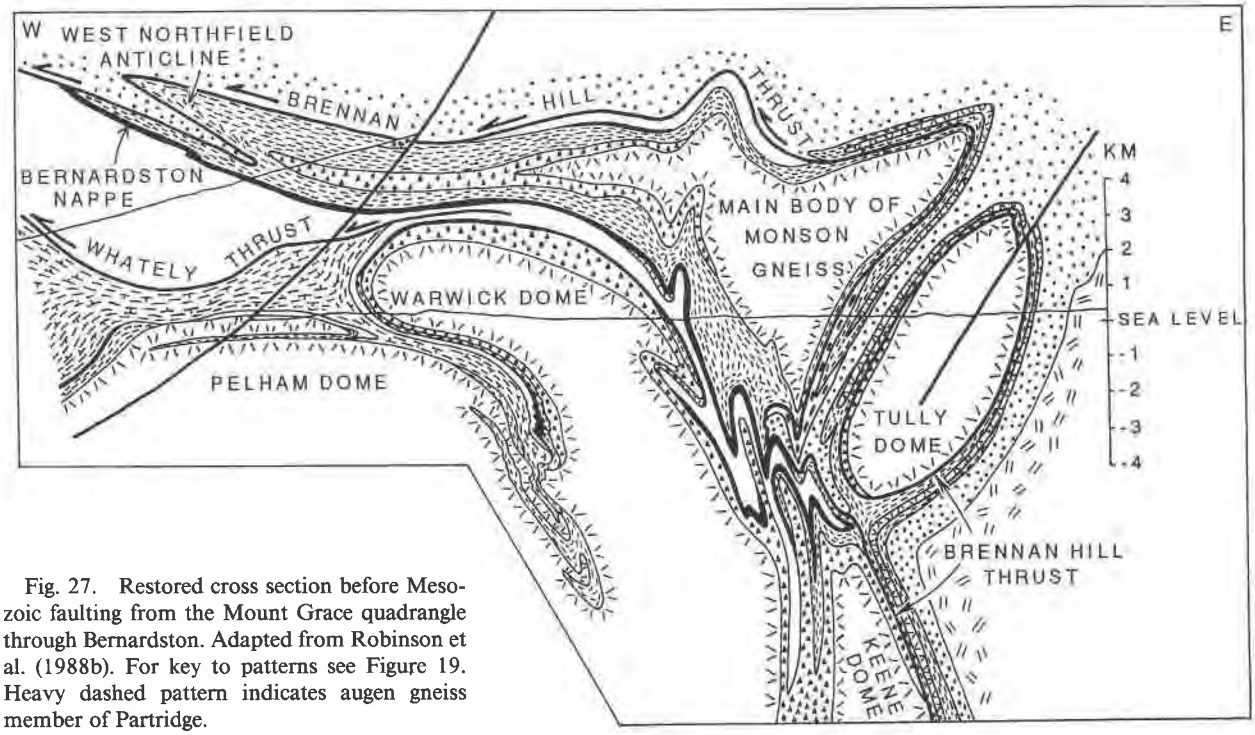

Fig. 27. Restored cross section before Mesozoic faulting from the Mount Grace quadrangle through Bernardston. Adapted from Robinson et al. (1988b). For key to patterns see Figure 19. Heavy dashed pattern indicates augen gneiss member of Partridge.

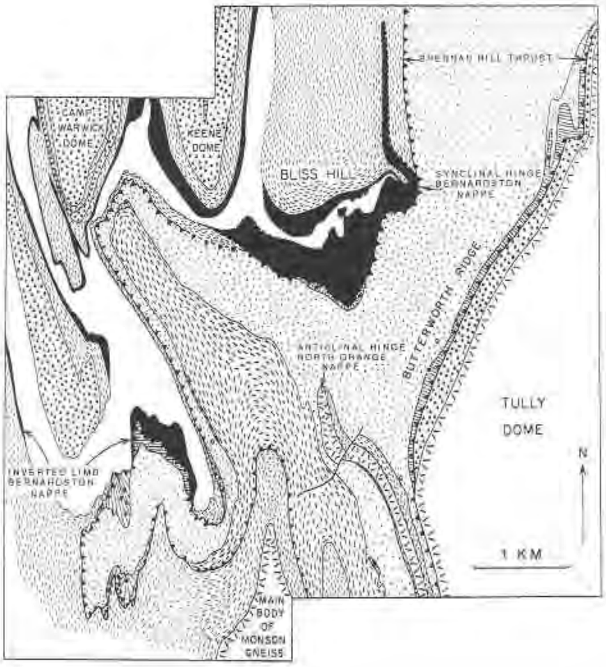

Fig. 28. Detailed map of the central part of the Mount Grace quadrangle showing distribution of rock units on either side of the Brennan Hill thrust and the complex involution of both the Bernardston nappe and the thrust by northward transport of the main and Tully bodies of Monson Gneiss. From Robinson et al. (1988b). For key to patterns see Figure 19. Heavy dashed pattern indicates augen gneiss member of Partridge.

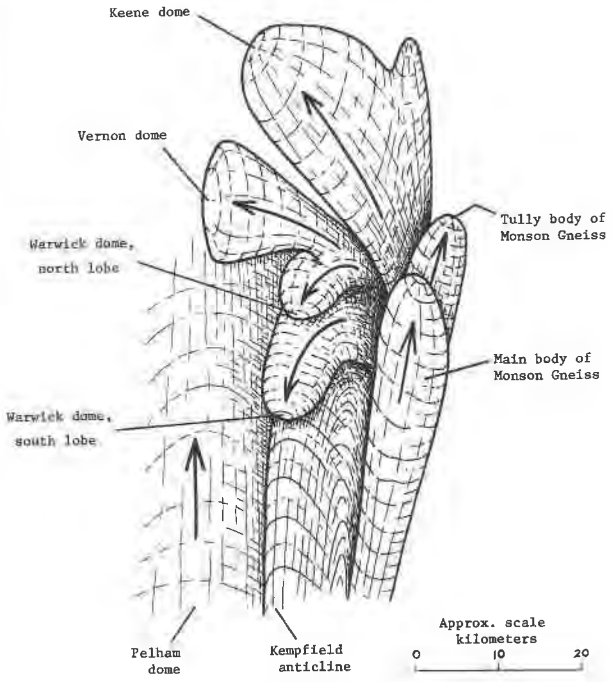

Fig. 29. Schematic restored structural relief diagram showing inferred flow pattern of major gneiss bodies during the backfold and dome stages. The effects of Mesozoic faulting have been removed. This deformation involuted both the axial surfaces of the fold nappes and the later thrusts. Adapted from Robinson et al. (1979, 1988b).

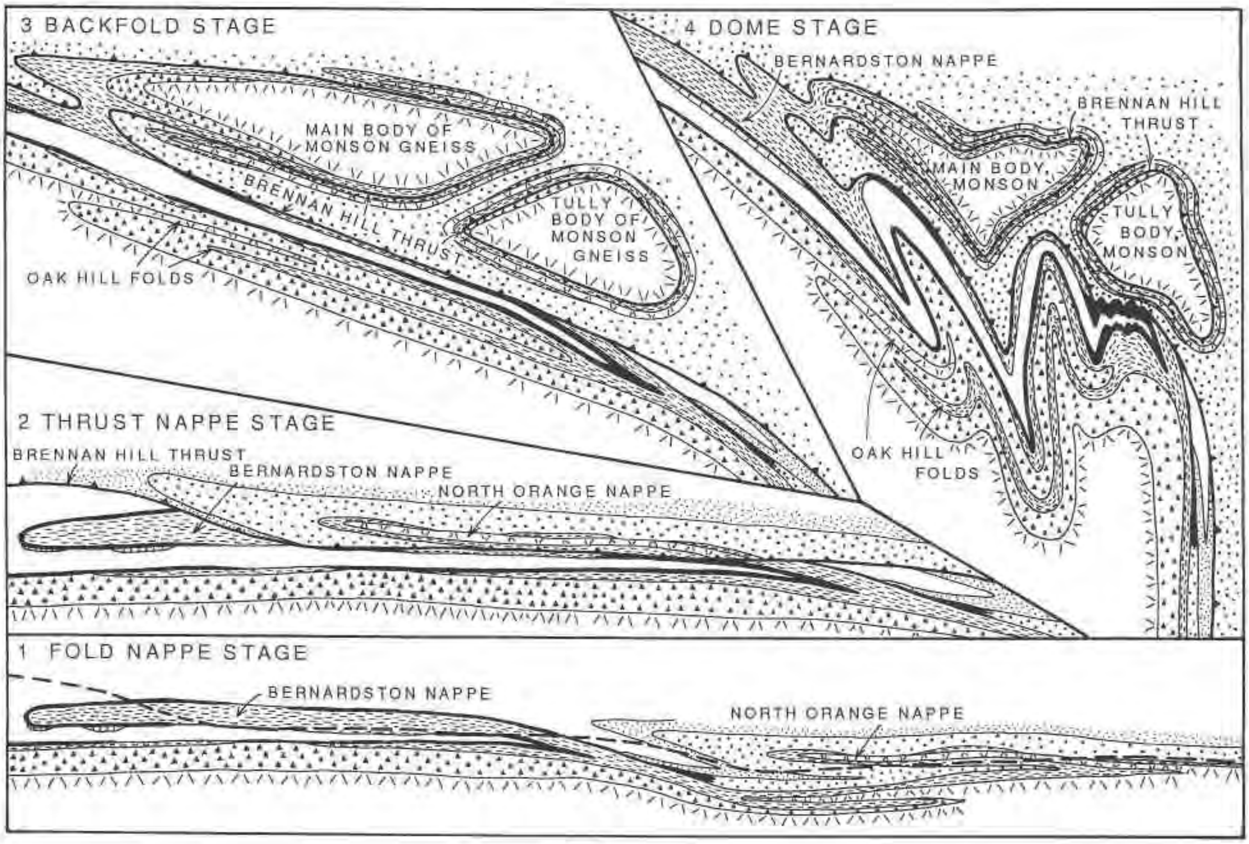

Fig. 30. Schematic east-west cross sections through the Mount Grace area, showing the sequence of structural development: (1) Formation of Bernardston and North Orange fold nappes; (2) thrusting of North Orange nappe onto Bernardston nappe along the Brennan Hill thrust; (3) involution of the fold and thrust nappes by northward longitudinal flow of the main and Tully bodies of Monson Gneiss; (4) formation of gneiss domes and related tight folding. Timing of the east-directed Oak Hill recumbent folds in the Keene gneiss dome is unknown, but they probably formed in the backfold stage. Adapted from Robinson et al. (1988b). For key to patterns see Figure 19. Dotted pattern for Warner Formation is used for all Silurian strata above Rangeley in the Monadnock sequence.

direction of a set of dome-stage minor folds (Onasch, 1973), but it is an oversimplification to apply this to all the domes. For example the northward overturning and transport of the main and Tully bodies had to precede the main dome stage because strata inverted during this longitudinal transport were refolded by major anticlines and synclines of the main dome stage.

The V-shaped exposure of Partridge Formation within the south end of the Keene dome (Fig. 26) indicates an early recumbent fold set, the Oak Hill folds, overturned from northwest to southeast, opposite to the sense of the nappes described here. The relative age of this recumbent folding is uncertain, but it is tentatively assigned to the backfold stage, in part because there are peak metamorphic fabrics in some amphibolites that are parallel to the exposed synclinal hinges of this fold system. Further, similar southeast-directed recumbent folds in the Pelham dome (Ashenden, 1973; Onasch, 1973; Michener, 1983) and its cover are truncated by the Belchertown intrusion with a zircon age of 380 Ma (Ashwal et al., 1979) that was itself deformed and metamorphosed in the dome stage. The southeast-directed recumbent folding may have been slightly earlier than the overturning and northward transport of the main and Tully bodies of Monson Gneiss. With these features in mind, the progressive development of the structure in the central part of the Mount Grace quadrangle is illustrated in a series of tectonic diagrams (Fig. 30) explained in the caption.

Regional implications and extensions

Implications and extensions based on our proposed revisions of the nappe theory are under investigation. Do the Brennan Hill and Chesham Pond thrusts extend northward from the vicinity of the Keene dome past Bellows Falls (Spear and Chamberlain, 1986; Chamberlain et al., 1988) to the latitude of Skitchewaug Mountain? Rumble (1969, 1971) proposed that the Skitchewaug nappe, or recumbent folds like it, can be identified at least as far north as the northwest flank of the Owl's Head dome (Fig. 1). Recently Moench and Hafner-Douglass (1987) have proposed that a large area of rocks northwest of the domes in northern New Hampshire previously assigned to the pre-Silurian, are in fact Silurian units of the Merrimack synclinorium transported across the axis of the anticlinorium in an enormous allochthon with complex contact relations reminiscent of the Brennan Hill thrust. The general interpretation of the map pattern of the Merrimack synclinorium within central Massachusetts is one of originally west-directed recumbent folds subsequently overturned to the east (Tucker, 1977; Zen et al., 1983; Peterson, 1984). Within the synclinorium sequence and its underlying basement in central Massachusetts, east of and tectonically higher than the Chesham Pond thrust, Berry has identified a group of imbricated west-directed thrusts in previously folded strata, all subsequently backfolded into an eastward overturned position (Robinson et al., 1986, 1989; Berry, 1989). Within central New Hampshire, Eusden (1988, Eusden et al., 1987) has proposed a dorsal zone separating regions of west- and east-directed nappes, and has rejected the concept that the east-directed nappes are tectonically overturned.

FOLD AND THRUST NAPPES AND REGIONAL METAMORPHISM

Early on, a relationship was recognized between tectonic level within the stack of nappes and the intensity of regional metamorphism (Thompson et al., 1968). Because many of the metamorphic rock fabrics are clearly related to structural features of the later gneiss-dome stage, it was suggested that the inverted thermal regime produced by the nappes, and by the sheetlike intrusions intercalated within them, persisted into the dome stage. It has been suggested that the nappe stage began concurrently with or soon after the intrusion of the Kinsman Granite at about 400 Ma. The Belchertown intrusion, which cuts recumbent folds assigned to the backfold stage but was deformed and metamorphosed during the dome stage, has yielded a concordant zircon age of 380 Ma (Ashwal et al., 1979). These data imply that overhanging metamorphic thermal anomalies could have been produced and persisted for a period of about 20 m.y., a concept that is contrary to most modern views of heat flow (Sleep, 1979).

Evidence for metamorphic discontinuities in the pile of nappes was one of the original reasons for proposing thrust nappes (Chamberlain, 1985), although most of the evidence given here is stratigraphic. Detailed petrologic studies of rocks closely juxtaposed across proposed thrusts (Spear and Chamberlain, 1986; Spear, 1986; Elbert, 1987, 1988) have produced evidence for differences in *P*-*T* trajectories, based on assemblages, on pseudomorphs, and on garnet-zoning profiles. Deeper structural levels have shown early heating followed by pressure increases thought to be caused by piling on of higher level nappes. Higher level nappes have given evidence of early high *T* metamorphism followed by compression produced either by still higher nappes (Spear and Chamberlain, 1986; Spear, 1986) or by backfolding (Schumacher et al., 1989). Rocks close to the gneiss domes have produced evidence of early loading followed by pressure release thought to be related to the rise of the domes themselves (Schumacher et al., 1989).

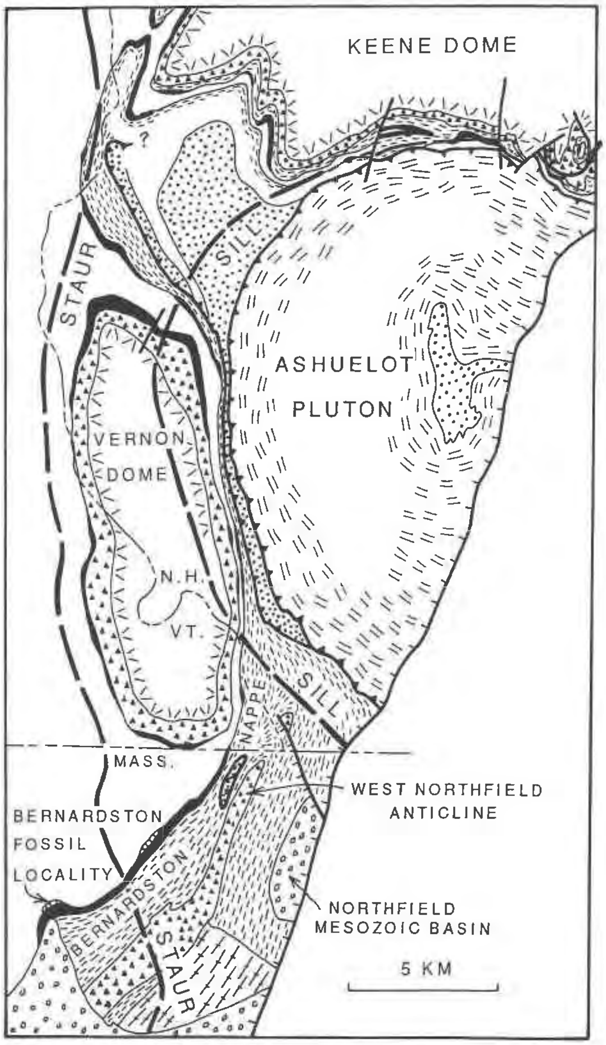

Fig. 31. Generalized geologic map of the Bernardston-Hinsdale area showing the relationship of staurolite and sillimanite isograds to the Ashuelot pluton and to structural features. See Figure 21 for details. Adapted from Elbert (1988). For key to patterns see Figure 19. Pattern for Rangeley Formation is here applied to all Silurian strata of the Monadnock sequence.

A curious example of the ambiguity of evidence is provided in the Hinsdale area studied in detail by Elbert (1987, 1988). In pelitic schists of the low sillimanite zone immediately above and below the Brennan Hill thrust, garnet-zoning profiles suggest rather different *P*-*T* trajectories and imply that all the garnet growth, except the outer rims, took place when the rocks were in different thermal regimes. The pattern of metamorphic zones (Fig. 31) shows a clear spatial relationship with the overriding (apparently hot) mass of the Ashuelot pluton, but in detail the isograds appear to cut cleanly across all the recumbent folds and proposed thrusts, and even across contacts in the autochthon into the core of the Vernon dome. The exploration and resolution of such ambiguities is beyond the scope of this paper. Obviously the relationships among metamorphic isograds, *P-T* trajectories, heat sources, and tectonothermal evolution will be subjects of research for those following in Jim Thompson's wake for some time to come. The results of such work, made possible by the complex setting of the nappes in the Connecticut Valley region, will be of very broad interest to metamorphic petrologists in general.

CONCLUSION

The nappe theory in the Connecticut Valley region has come a long way since Thompson's first proposal and has developed in ways unexpected at the outset. Further surprises of similar or greater magnitude should be expected in the future. The theory has developed mainly through close attention to outcrops and faith that regional stratigraphy can be used to decipher structural history. The metamorphic petrology of this region, though well developed, has far to go before the full story is written, and obviously it will not come easily. Thompson has maintained that the way an outcrop is seen depends on what is going on in the mind of the viewer, and we think that will always be true.

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