1-1-1988

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ROOT ZONE OF THE BERNARDSTON NAPPE AND THE BRENNAN HILL THRUST INVOLUTED BY BACKFOLDS AND GNEISS DOMES IN THE MOUNT GRACE AREA, NORTH-CENTRAL MASSACHUSETTS

by
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PURPOSE OF TRIP

A new stratigraphic and structural interpretation of the Mount Monadnock area, New Hampshire, (P. J. Thompson, 1985 and this volume) and new work by Elbert (1984, 1986, 1987, and this volume) in the Bernardston area, Massachusetts and Hinsdale area, New Hampshire, has pointed the way to yet another reinterpretation of the complex geology of the Mount Grace area. After early work by B. K. Emerson (1898, 1917), Jarvis B. Hadley (1949) mapped the area and was the first to introduce M. P. Billings' (1937) western New Hampshire stratigraphy to Massachusetts. Robinson (1963) found far greater structural complexity than envisioned by Hadley and showed that much of what Hadley had mapped as Lower Devonian Littleton Formation should be assigned to the Middle Ordovician Partridge Formation. In considering a synthesis of the regional fold nappes (Thompson et al., 1968) extensive remapping was done (Robinson, 1967; 1977) bringing the map pattern much closer to the one currently shown (see also Huntington, 1975). The present round of revisions, spurred by the work of P. J. Thompson and D. C. Elbert, was occasioned by the following new factors: 1) The virtual certainty that the gray feldspathic schists previously assigned to an eastern facies of the Devonian Littleton Formation are actually Lower Silurian Rangeley Formation. 2) The iron formation previously assigned to the eastern Littleton should be assigned to the middle Silurian Perry Mountain Formation. 3) Both of these rock types belong to the Monadnock sequence of strata and were transported into juxtaposition with the traditional Bronson Hill sequence by the nappe-stage Brennan Hill thrust.

STRATIGRAPHY

The strata of the region may be divided into four major groups as follows: 1) Gneisses and related rocks exposed in cores of domes that are in the age range Late Precambrian-Ordovician; 2) Middle Ordovician Ammonoosuc Volcanics and Partridge Formation; 3) Silurian-Lower Devonian stratified rocks of the Connecticut Valley and Merrimack belts; and 4)Triassic-Jurassic sedimentary rocks and basalts of the Connecticut Valley Mesozoic basins. These are cut by a variety of pre-tectonic, syn-tectonic, and post-tectonic Silurian-Devonian intrusions ranging from gabbro to granite, and by Jurassic and Cretaceous diabase dikes. General stratigraphic relations and stratigraphic problems have been covered extensively elsewhere and only features related to the present work are summarized here.

The origin and age of pre-Middle Ordovician basement rocks in the gneiss domes continues to be a problem (Robinson, 1981). The stratified gneisses in the core of the Pelham dome (Figure 1) have been considered Late Precambrian on the basis of one zircon age (Naylor et al., 1973, Zartman and Naylor, 1984) and lithic and geochemical similarities to rocks in southeastern Connecticut. This age is confirmed in a new preliminary zircon age of 606 m.y. on the Dry Hill Gneiss by R. D. Tucker (pers. comm. 1988). Hodgkins (1983, 1985) has shown that the dominant felsic gneisses of this sequence,with low normative anorthite and extremely low MgO/(MgO+FeO) ratios, have a major and trace element chemistry consistent with interpretation as a sequence of chemically evolved alkali rhyolites that might have erupted in a rifting environment. The relics of an apparently pre-Devonian granulite-facies metamorphism that survived Acadian kyanite-muscovite overprinting (Robinson, Tracy and Ashwal, 1975; Roll, 1986, 1987) are still of unknown age, but were tentatively assigned to the Late Precambrian (Robinson, 1983). However, preliminary late Devonian U-Pb monazite and zircon ages from a sillimanite-orthoclase pegmatite within this schist raise serious doubts about this conclusion (R. D. Tucker, pers. comm., 1988). The layered plagioclase gneisses and amphibolites that are called Fourmile Gneiss where they overlie the Late Precambrian strata in the Pelham dome, and called Monson Gneiss in most other areas, have not yet been satisfactorily dated. The Monson Gneiss in Massachusetts has yielded a zircon age of about 450 m.y., but the New London Gneiss of southeastern Connecticut, lithically identical to part of the Monson, gives an age over 500 m.y. (Zartman and Naylor, 1984). Earlier views that the Monson Gneiss might represent metamorphosed volcanics just slightly older than the overlying Ammonoosuc Volcanics now seem improbable on the basis of new field, petrologic, and geochemical studies (Robinson et al., 1986; Hollocher, 1987; Lent, 1987). These suggest that Monson Gneiss is dominantly a highly deformed plutonic complex, with a tonalitic matrix filled with inclusions of more mafic tonalite, gabbro, and even gabbroic anorthosite, and cut by mafic dikes metamorphosed to amphibolite. Supracrustal rocks, which may be xenoliths, are limited to a single outcrop area of calcareous quartzite and layered amphibolite blocks that may represent metamorphosed basaltic tuffs. Massive batholithic-looking gneisses in the domes, including the Pauchaug Gneiss of the Warwick dome, appear to give consistent isotopic ages around 450 m.y. (Zartman and Leo, 1984).

The Ammonoosuc Volcanics of presumed Middle Ordovician age, is the basal unit of the cover sequence and its detailed stratigraphy is crucial to understanding the basement-cover relationship. In the early 1970's a basal quartzite and conglomerate lens was found by Robinson where the Ammonoosuc overlies the Monson Gneiss in the Orange quadrangle, and in 1983 thin lenses of quartzite were found precisely on the same contact in two localities in the Quabbin Reservoir area. Despite numerous suggestions that the massive batholithic-looking gneisses are intrusive into the Ammonoosuc (Leo, 1985) and the radiometric dating that appears to make this permissible (Zartman and Leo, 1984), there remains no good documentation of intrusive gneisses substantially truncating a well defined Ammonoosuc stratigraphic sequence, and the balance of field evidence indicates the gneisses are older than Middle Ordovician and possibly as old as late Precambrian. R.D. Tucker of Toronto University (pers. comm. 1988) has recently produced new zircon data based on several carefully selected fractions of a sample of Monson Gneiss from the Quabbin Reservoir area. This indicates an age on Concordia of 435 m.y., which is early Silurian, and adds further vexation to a vexatious problem.

The research of Schumacher (1983, Schumacher and Robinson, 1986, 1987; Schumacher, 1988) and Hollocher (1983, 1985, Robinson et al., 1986) shows that the volcanics of the Ammonoosuc and the overlying Middle Ordovician Partridge Formation are quite similar in their major and trace elements to the low-K tholeiites, andesites, and dacites, as well as K-bearing rhyolites of modern island arcs such as Tonga and New Britain. An important aspect of their conclusions is that the K-bearing peraluminous rhyolites that characterize the upper part of the Ammonoosuc and continue into the Partridge, are not the product of melting of subducted North American continental crust as suggested by Robinson and Hall (1980), nor melting of subducted pelitic sediments, but were produced by melting of amphibolite or granulite of tholeiitic basalt composition within the magmatic arc complex. A curious problem is that the presumed medial Ordovician age of these supposed arc volcanics is the same as the time of emplacement of the Giddings Brook slice of the Taconic allochthon. This was not when Iapetus was beginning to close but essentially when it had virtually completed closing. A possible explanation for the time lag is offered by new models for subduction zone magmatism (Kushiro, 1987) indicating that most arc basaltic magmas are derived by melting of upper plate mantle when influenced by aqueous fluid diffusing slowly upward from the subduction zone.

Stratified Silurian-Devonian rocks occur in two main belts, the Connecticut Valley belt to the west and the Merrimack belt to the east (Zen et al., 1983). In the Connecticut Valley belt there are a host of stratigraphic problems, including the recent finds of both Middle to Late Ordovician graptolites (Bothner and Finney, 1986) and late Lower Devonian (Emsian) plant fossils in similar rocks (N.L. Hatch, pers. comm., 1986). These problems are by no means even partially resolved by the proposed Whately thrust (Robinson, Hatch and Stanley, 1984, and in press) that tentatively solves the stratigraphic dilemma of the Devonian(?) Erving Formation in the western part of the Orange area.

Along the eastern edge of the Connecticut Valley belt, there has been a significant advance in the paleontological control of the thin strata characteristic of the Bronson Hill anticlinorium. Specifically, Elbert, et al., 1988; and Elbert this volume, have identified a rich conodont fauna in garnet-grade marble of the Fitch Formation in the inverted limb of the Bernardston nappe at Bernardston. This marble lens lies stratigraphically above, though structurally below, fossiliferous Clough Quartzite containing a poor fauna suggesting Lower Silurian age (Boucot et al., 1958). The marble lies structurally above, though stratigraphically below, gray garnet phyllites of the Devonian Littleton Formation, and appears to be truncated laterally by an unconformity at the base of the Littleton which is more generally in direct contact with the Clough. The conodont fauna gives a strong indication that the Fitch marbles in this location are earliest Devonian and not middle or upper Silurian as has been found elsewhere.

A key stratigraphic feature for the present studies is the eastward thickening of the Silurian sequence from the thin section of Clough Quartzite and local Fitch Formation in the Bronson Hill anticlinorium, at the east edge of the Connecticut Valley belt, into the thick sequence of the Merrimack belt. This consists of Rangeley Formation (lower Silurian), Perry Mountain Formation (middle Silurian), Francestown Formation (middle Silurian), and Warner Formation (upper Silurian) as defined by Peter Thompson (1985) in the Monadnock area (Figure 1), and correlated in detail by him with Silurian sequences in central New Hampshire and northwestern Maine (Hatch, Moench, and Lyons, 1983). It is the distinctive character of the well defined Monadnock sequence and its differences with the thin Bronson Hill sequence that makes possible the mapping of the early west-directed thrust nappes that have become such an important part of recent tectonic reconstructions. One of these thrust-nappes carried rocks of the Monadnock sequence westward into the Hinsdale, N.H. area (Figure 1), where Elbert has discovered a distinctive horizon of garnet quartzite, and magnetite-cummingtonite iron formation at the top of the middle Silurian Perry Mountain Formation. This has made possible the new interpretation of the Mt. Grace area, Massachusetts (Figure 1) covered in this field trip, where identical rocks had previously been assigned to the Lower Devonian Littleton Formation (Huntington, 1975).The Monadnock sequence appears to extend from southwestern New Hampshire across Massachusetts in a very tight zone east of the main body of Monson Gneiss and west of the Coys Hill pluton (Figure 1). In Massachusetts it has the distinctive graphite-pyrrhotite calc-silicate rocks of the middle Silurian Francestown Formation, but generally lacks the upper Silurian Warner Formation. Stratigraphy still provides the essential control for local and regional structural and tectonic studies.

STRUCTURAL GEOLOGY

Acadian deformations in central Massachusetts and adjacent New Hampshire have been summarized elsewhere (Robinson, 1979; Robinson and Hall, 1979; Hall and Robinson, 1982). These are broadly divided into an early nappe stage, an intermediate backfold stage, and a late gneiss dome stage, each with many complications.

Recent research in the Monadnock area, New Hampshire (P.J. Thompson, 1985), the Hinsdale area, New Hampshire (Elbert, 1986), the Mt. Grace area, Massachusetts (Robinson, 1987), and the Sturbridge area, Massachusetts and Connecticut (Berry, 1987a, 1987b) has shown that the early west-directed fold nappes are truncated by a slightly later set of west-directed thrust nappes. In southwestern New Hampshire and adjacent Massachusetts the two major nappe-stage thrust faults are: 1)The Brennan Hill thrust carrying previously folded Monadnock sequence strata across Bronson Hill sequence strata containing the Bernardston fold nappe. 2) The Chesham Pond thrust carrying Rangeley Formation and Kinsman Granite over previously folded rocks of the Monadnock sequence (Figures 2, 3,). The Brennan Hill thrust appears to trace southward from the Monadnock area through the Mt. Grace area and along the east margin of the main body of Monson Gneiss to Connecticut, where Pease (1982) had previously identified the Bone Mill Brook fault zone . The Chesham Pond thrust appears to trace southward from the Monadnock area along the west margin of the Coys Hill pluton and also may extend into Connecticut.

The structural features tentatively assigned to the backfold stage include the following, not necessarily in chronological order: Evidence for the first three of these is found in the Mount Grace area.

1) Longitudinal flowage of the main and Tully bodies of Monson Gneiss, from a position south of Quabbin Reservoir, 50 km northward to a position overlying strata in the Mt. Grace area. This longitudinal flowage caused recumbent folding that involuted the axial surfaces of early fold nappes as well as the trace of the Brennan Hill thrust.

2) East-southeast directed recumbent folding of the basement-cover contact in the Pelham gneiss dome (Ashenden, 1973) and the Keene gneiss dome (Robinson, 1963, 1967; Schumacher and Robinson, 1986). Amphibole lineation associated with this phase has been identified locally in the Keene gneiss dome and in gedrite gneisses overgrown by cordierite believed to have been produced by

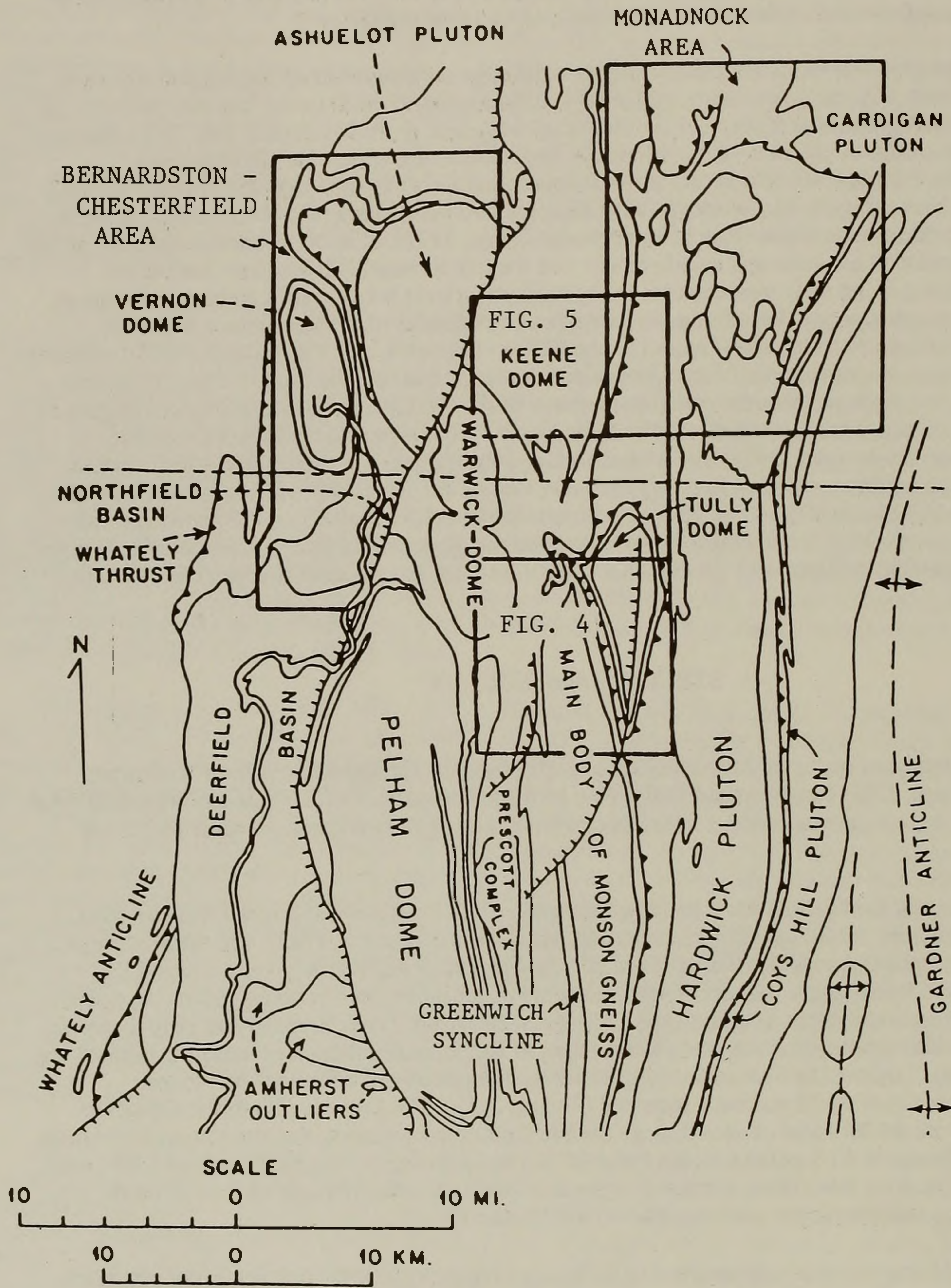


Figure 1. Geologic index map of north-central Massachusetts and adjacent New Hampshire and Vermont showing Mount Grace area (Figures 4 , 5) in relation to Monadnock and Bernardston-Chesterfield areas.

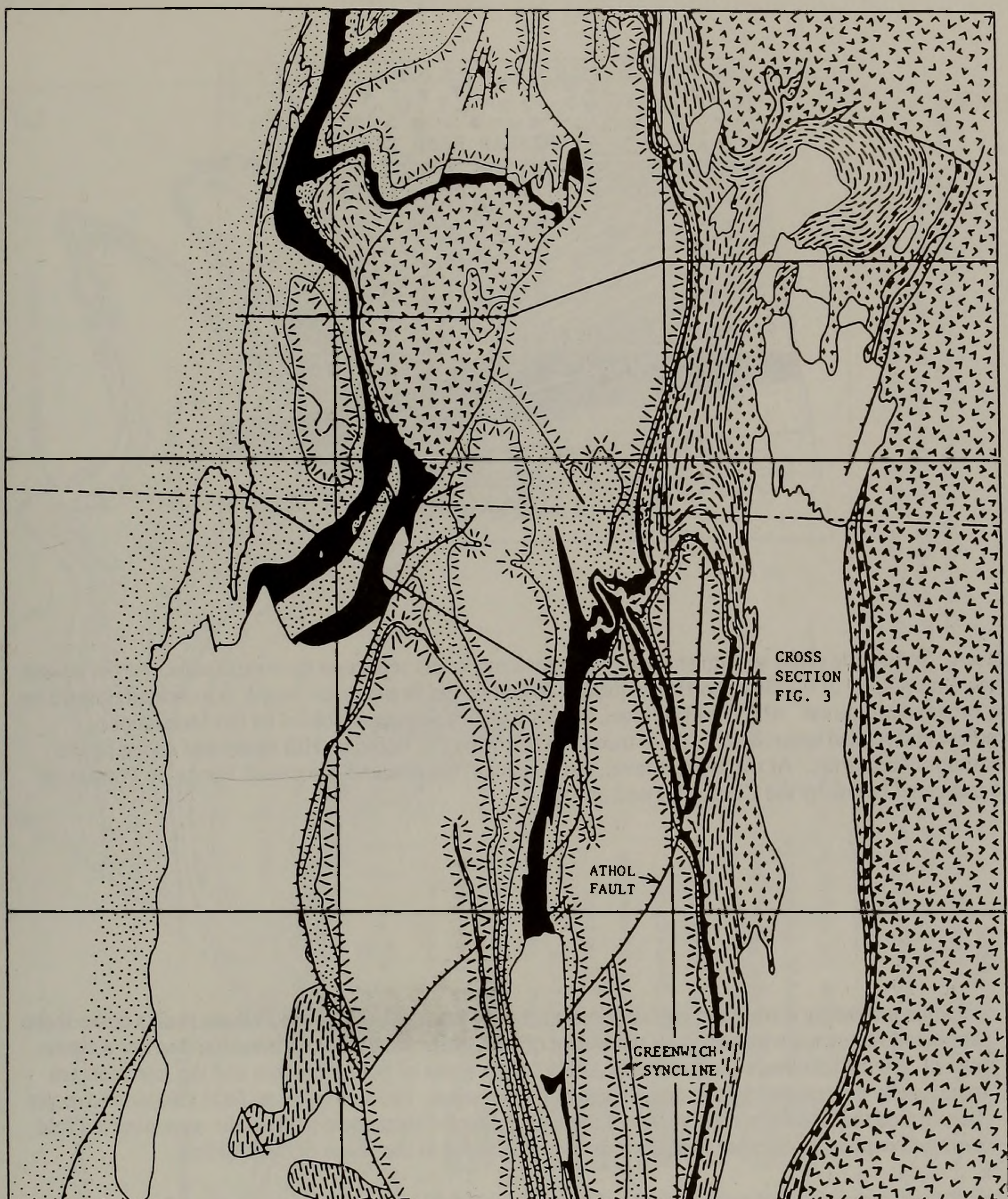


Figure 2. Map of north-central Massachusetts, southwestern New Hampshire, and adjacent Vermont showing distribution of three tectonic levels separated by thrust faults (with teeth). Within the three thrust sheets patterns indicate structural position on earlier recumbent folds. Mesozoic faults are hatchured on downthrown blocks; intrusive rocks and Mesozoic strata are unpatterened. Location of cross section in Figure 3 is also shown in northern Massachusetts. Approximately E-W line in southern New Hampshire is location of cross section of Elbert (this volume). Key to symbols is shown in Fig. 2A.

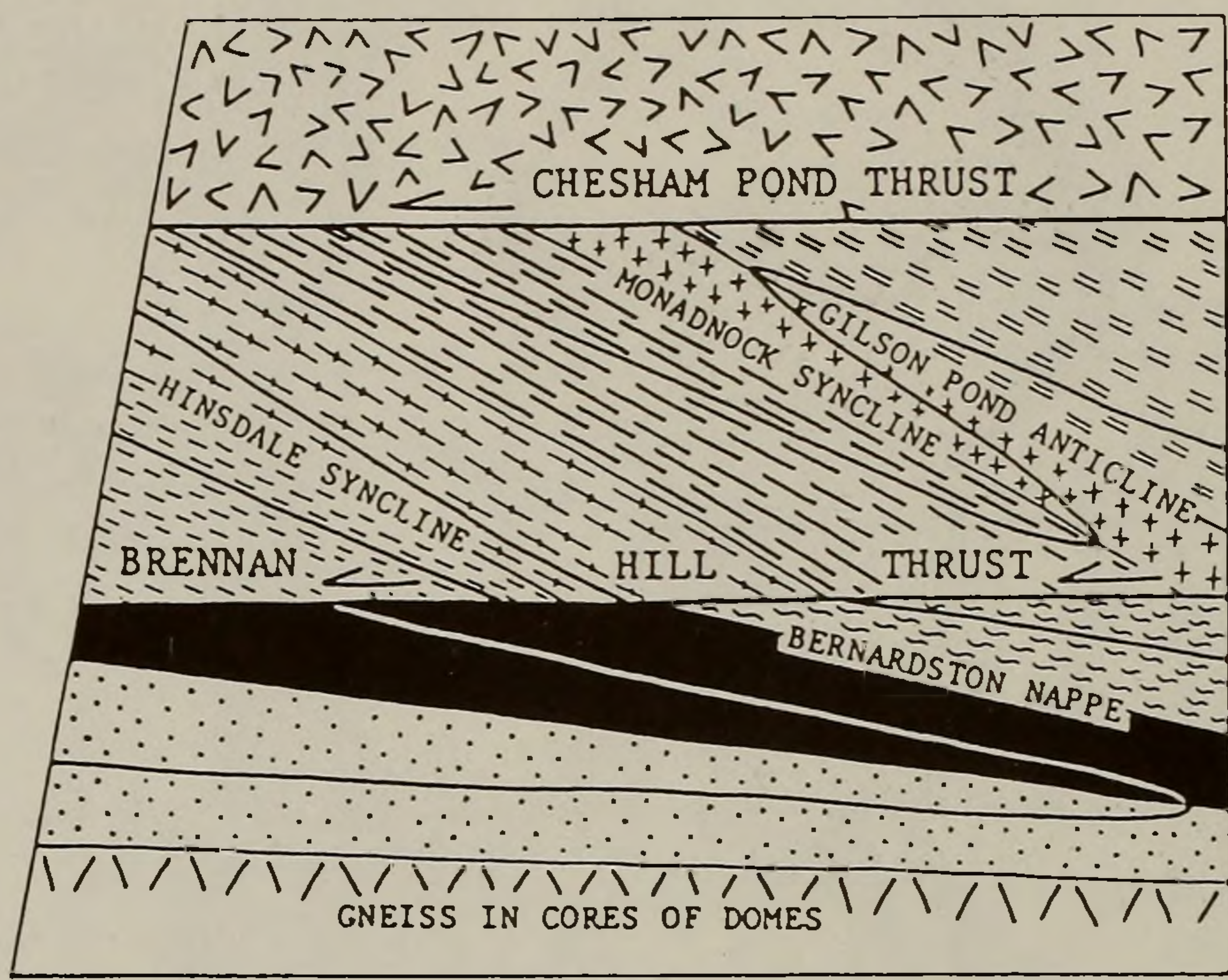


Figure 2A. Schematic cross section showing three tectonic levels separated by thrust faults. At the lowest level, stratigraphy of the Bronson Hill sequence, folded by the Bernardston nappe, is truncated upward by the Brennan hill thrust. At the middle level, the Monadnock sequence, folded by the Monadnock syncline and related recumbent folds, is truncated below by the Brennan Hill thrust and above by the Chesham Pond thrust. At the highest level, the Kinsman Granite and associated Rangeley Formation are truncated below by the Chesham Pond thrust.

tectonic unloading during the gneiss-dome stage. At the south end of the Pelham gneiss dome these structural features are truncated by the Belchertown Quartz Monzodiorite intrusion that has a zircon age of 380 million years (Ashwal et al., 1979). The rocks of both the dome and the intrusion are structurally overprinted by the dome stage of deformation. Unfortunately no field relations have yet been found that show the relative age of these east-directed recumbent folds to the west-directed fold or thrust nappes, or to other features tentatively included in the phase of backfolding.

3) Eastward overturning of axial surfaces of west-directed fold nappes and west-directed thrust surfaces. Earlier it was hoped that major axial surfaces related to this backfolding could be identified in central Massachusetts but nothing conclusive has yet been found. P.J. Thompson (1985) and H.N. Berry (1987) have independently suggested the possibility of grand overturning of the entire eastern part of the orogen from the Monson Gneiss across the entire Merrimack belt and possibly beyond. Tentatively associated with this eastward overturning, but not conclusively linked with it, is an E-W trending linear fabric and E-W trending minor folds (Robinson, 1979, Peterson, 1984) that are progressively overprinted westward by north or northeast-trending folds and fabrics definitely related to the dome stage. The E-W trending fabrics appear both in metamorphosed sedimentary rocks and a wide variety of tonalitic through granitic intrusions.

4) Development of a series of mylonites in metamorphosed sedimentary and intrusive rocks. These mylonites contain an E-W trending lineation believed to be related to the shear direction and this lineation is parallel to the E-W lineation described under 3) above. The mylonites cut across coarse-grained migmatitic schists and gneisses formed during peak granulite-facies metamorphism. The

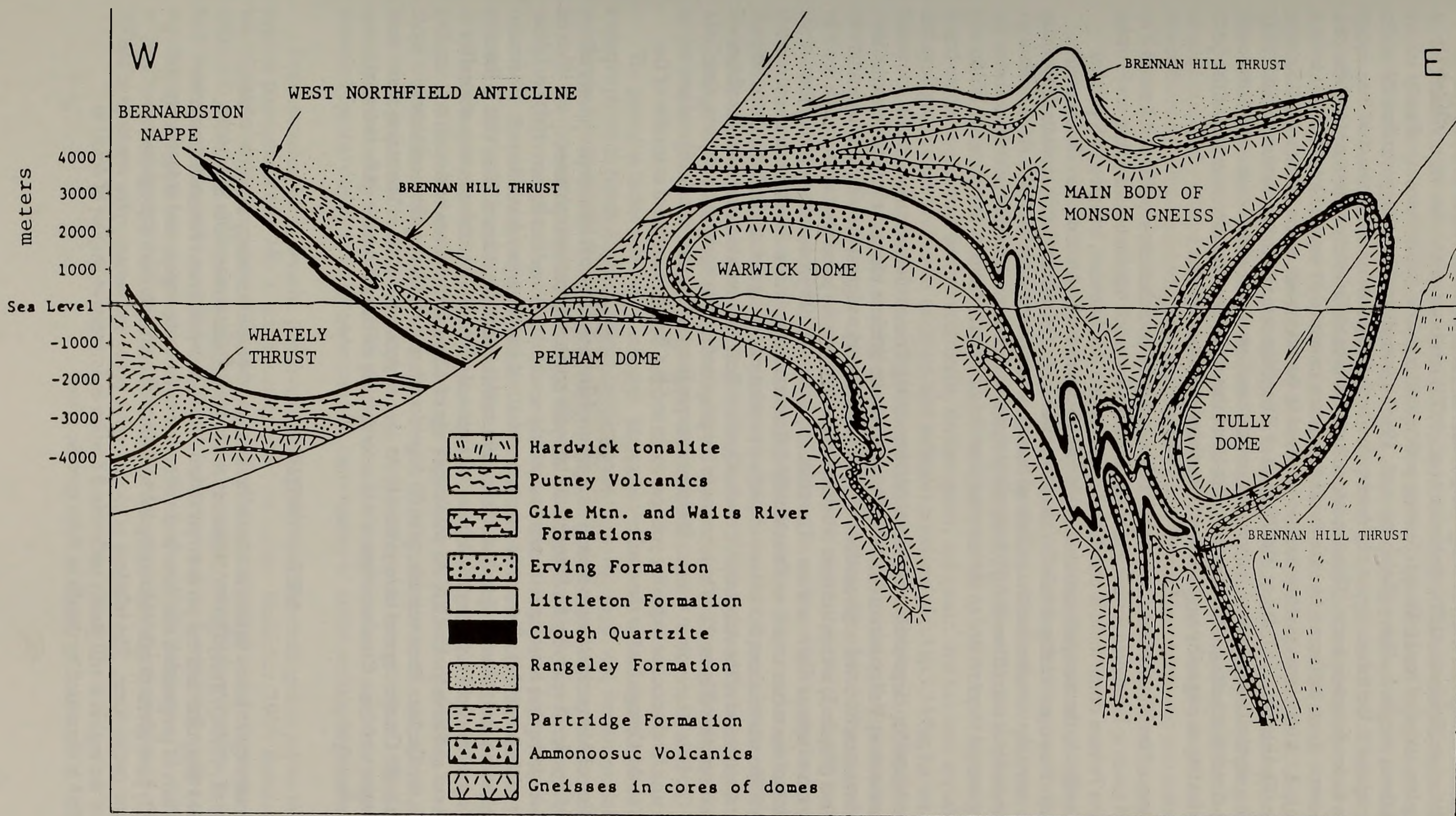


Figure 3. Cross section showing the probable stratigraphic and structural relationships between the Orange area (Robinson, 1977, 1987) and the Bernardston-Northfield area (Elbert, 1984). The Connecticut Valley border fault is shown in simplified form as a listric normal fault with a circular surface. The vertical component of the net slip is about 15,000 feet and the angle of rotation of the hanging wall block was about 16 degrees. For line of cross section see Figure 2.

mylonites are deformed by northeast-trending minor folds related to the dome stage. In an early structural correlation (Robinson, 1979, Robinson et al., 1982) it was proposed that the mylonites formed during late stages of backfolding following peak metamorphism. With discovery of early west-directed thrust nappes by Berry (Robinson et al., 1986) it was alternatively suggested that the mylonites are related to the thrust nappes which were then tentatively considered to post-date the peak granulite facies metamorphism. This alternative has now been definitively disproved for three reasons: a) Several thrust surfaces related to thrust nappes are truncated by tonalite intrusions (Berry, 1987a); b) Many tonalite intrusions are involved in the mylonites, some of them extensively so (Finkelstein, 1987; Berry, 1987b); and c) The shear sense of the mylonites studied so far, including mylonitized tonalites, indicate a consistent west-over-east shear sense inconsistent with the west-directed thrusting. It is thus now concluded that mylonite formation was part of the phase of backfolding as originally suggested, and unrelated to thrust nappes.

The swirling pattern of lineations related to the gneiss-dome stage of deformation, superimposed on all previous features, still needs to be studied further and traced from north-central Massachusetts to the Connecticut line. In the Pelham dome there is conclusive evidence that this lineation, trending N-S parallel to the dome axis, is parallel to the transport direction of a series of sheath folds (Ashenden, 1973, Onasch, 1973, Robinson, 1979). However, nearby detailed features in cover rocks (Michener, 1983) seem to deny this conclusion. The suspicion remains that the pattern of lineations associated with the dome stage, with its evidence of the gravitational rise of low density buoyant basement strata, may also reflect a deep-seated ductile regime of longitudinal shear related to the terminal phase of Acadian collisional tectonics (cf. Ellis and Watkinson, 1987).

The region was subjected to large-scale extensional faulting during Triassic-Jurassic time. Most important was the Connecticut Valley border fault that is thought to be listric in character. At the New Hampshire-Vermont line, reconstructed cross sections of pre-Mesozoic rocks suggest the west side was downthrown about 5 km (Figure 3) and indications are that displacement on the same fault at the Connecticut line may have been as much as 8 km. The chief importance to the present study is that the fault allows observation of the metamorphic rocks at widely different tectonic levels. In addition, more local faults with displacements of about 0.5 km are important in solutions of local structural problems. In particular, a southward extension of the Athol fault into the Quabbin Reservoir area is believed to cut across the Acadian Greenwich syncline (Figure 2). The location of the proposed fault is being traced by magnetic surveys on the ice of Quabbin Reservoir in winter. If the present prognosis is correct, the stratigraphic syncline is actually a structural anticline exposing younger rocks and is a faulted southward extension of the Walnut Hill anticline in the Orange area to the north.

A second indication of Mesozoic tectonic activity is a group of diabase dikes and sills, until recently all presumed to be early Jurassic. A study by McEnroe in the last year combining paleomagnetism, geochemistry, and K-Ar dating has come up with some surprising results (McEnroe and Brown, 1987; McEnroe et al., 1987; McEnroe, 1988). Several of the dikes and sills show 40 degree north normal inclinations consistent with a late Jurassic age. Two distinctive tholeiitic diabase dikes at Bliss Hill in the Mount Grace area (Stop 3, this field trip) give 60 degree north normal inclinations consistent with normal periods in the Cretaceous and have yielded a K-Ar whole rock age of 121 m.y. A system of tholeiitic olivine diabase sills in the Quabbin Reservoir area give 60 degree north reversed inclinations consistent with reversed periods in the Cretaceous and have yielded K-Ar ages as young as 119 m.y. The major- and trace-element geochemistry of these Cretaceous intrusions is completely different from the more abundant Jurassic intrusions in the region.

METAMORPHISM

Details of the metamorphic zones in central Massachusetts, based on the petrology of pelitic schists, are given by Tracy et al., (1976), Tracy (1978), Robinson et al., (1982), and Robinson et al., (1986), although much detailed analytical data has yet to be published. Hollocher (1985) and Renate Schumacher (1986) have given details of progressive reactions in amphibolites in the same region, and Schumacher and Robinson (1986, 1987) have given details concerning the formation of cordierite during progressive unloading in the Keene gneiss dome. The relations of metamorphic zones and metamorphic reactions to the structural evolution of the region is still poorly understood despite an impressive amount of detail in specific locations. This is illustrated by details in three specific areas.

In the Hinsdale area, New Hampshire, it has long been known that the sillimanite isograd is concentric to the Ashuelot pluton of Kinsman Granite (Moore, 1950; Trask, 1964; Thompson et al., 1968). In an earlier tectonic model (Thompson et al., 1968) this was thought to be due to nappe-stage recumbent folding of the Kinsman, possibly still in a partially liquid state, to a position tectonically above the Bernardston nappe and the autochthonous Vernon dome. In the presently favored model (P.J. Thompson, 1985; Elbert, 1986; Robinson, 1987) the Kinsman of the Ashuelot pluton is considered to have been emplaced largely in a solid state by the Chesham Pond thrust, tectonically above the Brennan Hill thrust sheet which was itself tectonically emplaced across the previously formed Bernardston fold nappe and autochthonous rocks. Elbert (1987) has demonstrated significant differences in early growth history of garnets on opposite sides of the Brennan Hill thrust near Hinsdale, with later convergence to similar zoning paths in the outer rims. Despite this evidence that metamorphism was well underway prior to thrusting and that the sillimanite isograd is spatially related to the Chesham Pond thrust sheet, the isograd itself actually cuts far below the lower Brennan Hill thrust, through the axial surface of the Bernardston nappe and into autochthonous rocks of the east limb of the Vernon dome. Thus, the ultimate positioning of the sillimanite isograd must have taken place well after thrusting.

In the Ammonoosuc Volcanics at the south end of the Keene gneiss dome amphibolites and gedrite gneisses contain an amphibole lineation parallel to the axes of local backfold-stage southeast-directed recumbent folds. The gedrite lineation is overgrown by cordierite that forms complex reaction rims around sillimanite and other aluminous minerals as a result of unloading believed to have taken place during the rise of the gneiss dome. Recently Seifert and Schumacher (1986) have developed a pressure calibration based on the equilibrium between cordierite, zincian spinel, and quartz, that has been applied to the assemblages in these aluminous enclaves, and indicates pressures of 6.3 to 3.7 kbar for the time of enclave formation. Gedrite-garnet gneisses commonly contain both kyanite followed by sillimanite, and also conclusive evidence for kyanite forming as a retrograde product with chlorite and quartz after cordierite (Robinson, 1963; J.C. Schumacher, pers. comm. 1987). Garnet with up to 32% pyrope content in some of these rocks may be a relict of an earlier, higher pressure history before the cordierite-forming reactions (Schumacher and Robinson, 1986, Table G-8). Collecting in summer 1987 has led to discovery of previously unrecognized assemblages of coexisting Mn-rich orthopyroxene and augite in the middle Garnet-Amphibole Quartzite Member of the Ammonoosuc (J.C. Schumacher, pers. comm. 1987) where more normal Fe-Mg rich assemblages contain only amphiboles. This appears to be an example where abundant MnO stabilizes an assemblage normally considered characteristic of the granulite facies into P-T conditions of the amphibolite facies for more normal rock compositions.

The granulite facies area near Sturbridge, Massachusetts appears to be the area of most intense Acadian metamorphism in North America and its complex tectonic, mineralogic, and thermal evolution requires much more intense study. The widespread occurrence of sillimanite pseudomorphs after andalusite indicates an early low-pressure metamorphic history. That this low-pressure history involved high temperatures and partial melting is suggested by the occurrence of andalusite pseudomorphs in pegmatites and the widespread occurrence of cordierite-bearing pegmatites. In the one sample of cordierite pegmatite that has been studied in detail (Tracy and Dietsch, 1982) the cordierite has a 10% higher Fe/(Fe+Mg) ratio than typical cordierite in sillimanite-garnet-cordierite-quartz assemblages in the adjacent granulite facies pelites. This is taken to indicate that the partial melting that produced the pegmatite took place at considerably lower pressures than those indicated by peak granulite facies assemblages. Further, this particular cordierite is shown to have been in the process of breaking down on its own composition to an intergrowth of sillimanite, garnet, and quartz plus more Mg-rich cordierite. A pristine suite of 48 samples of such cordierite pegmatites has been collected for study to try to better understand the early history of partial melting in this region.

Peak-metamorphic sillimanite-garnet-cordierite-quartz-biotite assemblages in pelites in the region suggest pressures of 685-740 °C and pressures of 6.1 - 6.3 kbar. Hollocher (1985; Robinson et al., 1986) has reported several occurrences of the classic granulite facies assemblage of orthopyroxene-orthoclase-quartz (Figure 5) and several other occurrences where orthoclase adjacent to orthopyroxene has been replaced by a high temperature retrograde symplectite of Ti-rich biotite and quartz. Several well studied occurrences of the assemblage orthopyroxene-garnet-plagioclase-quartz (Hollocher, 1985; Robinson et al., 1986) can be applied to the pressure calibration of Perkins and Chipera (1985) and yield pressure estimates of 5.2 to 7.0 kbar at 700 °C.

The late metamorphic history of this region is also intriguing. Keys to this late history are found in assemblages developed in mylonites that cross cut the peak metamorphic fabrics. Many of the mylonitic rocks are not distinct petrologically from sheared versions of the peak metamorphic assemblages. However, a few have undergone such severe grain size reduction that they have been able to undergo complete recrystallization to new fine-grained assemblages representative of a different metamorphic facies (Robinson et al, 1977; 1982; 1986). A mylonite in one host rock consisting of coarse quartz, K-feldspar, sillimanite, cordierite and biotite has recrystallized to a new assemblage of quartz, K-feldspar, sillimanite(?), garnet, and Mg-richer biotite. Garnet-biotite Fe-Mg exchange thermometry suggests the mylonite recrystallization took place at around 550 °C and the Mg-rich garnet composition (approx. 30% pyrope) suggests crystallization at a minimum pressure of 7-8 kbar. If these indications are correct, then it would appear that the rocks of the central Merrimack belt may have continued to be compressed as they cooled beyond the peak of metamorphism, a situation that would appear to require special tectonic conditions. This proposed "counterclockwise" P-T path for the Merrimack belt is in sharp contrast to the more traditional "clockwise" path (England and Thompson, 1984; Thompson and England, 1984) for the adjacent Bronson Hill anticlinorium (Figure 10). Tectonic correlations between the two regions would suggest that subsequent to tectonic loading in the nappe stage, rocks of the Bronson Hill anticlinorium were progressively unloaded, while those of the Merrimack belt were being progressively loaded, even in late stages where they were already undergoing cooling. Very recent K-Ar mineral ages on hornblendes from this region by T. Mark Harrison at SUNY Albany (pers. comm., 1987) also hint at early cooling in the east, and later uplift and cooling in the west, that may relate indirectly to these contrasting P-T trajectories.

DETAILED INTERPRETATION OF MOUNT GRACE AREA

In the past two years Robinson and M.S. student George Springston have been studying the implications for the Mt. Grace area (Figures 4,5) of the new stratigraphic and structural concepts developed by P.J. Thompson (1985 and this volume) in the Monadnock area to the northeast and by Elbert (1985, 1987, and this volume) in the Bernardston-Hinsdale area to the northwest. In the western part of the Mt. Grace area (Figure 4) 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, once about 5 km of displacement on the Mesozoic Connecticut Valley Border Fault is restored (Figure 3). Further, the doubled-over layers of Clough Quartzite at Bliss Hill (Figures 4, 5, 6) are confirmed as the synclinal hinge of the Bernardston nappe, here plunging south.

The large area of gray-weathering schists surrounding the Tully gneiss dome (Figure 4), that were once assigned to the Littleton Formation, are now mainly assigned to the Lower Silurian Rangeley Formation in direct correlation with the Monadnock area. These include a few isolated small areas of conglomerate previously unknown or previously assigned to the Clough Quartzite. Within this area north of the Tully dome Springston has been able to subdivide the Rangeley according to the members previously worked out by Thompson (Figure 5). These outline folds roughly parallel to the northern end of the dome, but with an uncertain relationship to it.

The west margin of the Rangeley Formation is marked by the Brennan Hill thrust as defined by Thompson. This traces from the Monadnock area southward into the Mt. Grace quadrangle where it undergoes a complex involution, principally caused by the northward overturning of the main and Tully bodies of Monson Gneiss, and then runs southward along the east margin of the main body toward Connecticut. Detailed work in the vicinity of the Brennan Hill thrust in the central part of the Mt. Grace area (Figures 4,6) has produced some surprising discoveries.

On the lower side of the Brennan Hill thrust the Bernardston nappe is mostly cut out by the thrust from Bliss Hill southwestward for about 5 kilometers (Figure 6). At different places in this distance the Brennan Hill 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 Brennan Hill thrust cuts much deeper, resting on Ammonoosuc Volcanics or directly on the Monson Gneiss of the Tully 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 (Figure 4). To the south and to the southwest of Bliss Hill (Figure 6), the younger Silurian units include several lenses assigned to the Perry Mountain Formation mainly because of their iron formation boudins, one lens of Francestown Formation, and two lenses of Warner Formation. All of these younger Silurian strata are localized close to the Brennan Hill thrust in such a way as to suggest that the Rangeley was structurally inverted above them, probably on the overturned limb of an earlier nappe-stage anticline that subsequently was followed by the thrust. Near Butterworth Ridge northwest of the Tully dome (Figure 6) there is a narrow complex belt including confused representatives of all the Silurian units including iron formation of the Perry Mountain. So far this zone has not been adequately worked out except in one area where a pace and compass map is complete (Figure 6B). This shows a very tight syncline with two members of the Warner Formation, Perry Mountain Formation with iron formation, Rangeley Formation, Partridge Formation, and Ammonoosuc Volcanics. Francestown Formation is missing. In this vicinity, the Brennan Hill thrust is apparently along the contact between Rangeley Formation and Partridge Formation. At the northwest corner of the Tully dome (Figure 6), more extensive Warner Formation appears 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 augen gneiss member of the Partridge, and some miles south, into the sulfidic schist member (Figure 4). In this vicinity 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. An anticlinal hinge of this fold nappe is exposed in the southeast corner of the Mt. Grace quadrangle (Figure 4). The anticlinal nappe also appears in a continuous belt around the southwest and east sides of the Tully dome, with two moderately well exposed anticlinal hinges (Figures 4 and 6). 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 (Figure 6) where Rangeley Formation is resting directly on Monson Gneiss. However, there is a problem with this interpretation in that there are two lenses of Perry Mountain Formation along the northeast margin of the augen gneiss of the Partridge, seeming to support location of a thrust in this position instead.

To understand the outcrop pattern and structural evolution of the Mount Grace area it is first necessary to recognize that the backfold-stage and dome-stage deformations that involuted the earlier structural features were themselves complex. This is illustrated in the structural relief diagram of the entire Orange area in Figure 7A which shows the pattern and local overturning of even the simpler gneiss domes, as well as the northward overturning and longitudinal transport of the main and Tully bodies of Monson Gneiss. In Figure 7A the "swirl" in the pattern of lineations and minor folds is illustrated schematically along the east side of the Warwick dome and Kempfield anticline. In the core of the Pelham dome it can be proved that the lineation is parallel to the transport direction of a set of dome-stage minor folds (Onasch, 1973). One can take this as a cue and treat all of the dome-stage lineation as being parallel to the transport direction of the gneiss domes in the same manner as salt domes. This assumption yields the schematic grand pattern of transport directions illustrated in the restored structural relief diagram in Figure 8. However, this is misleading because 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, such as the Williams Pond syncline.

The refolding of early southeast-directed recumbent folds, the Oak Hill recumbent syncline and the Tully Brook recumbent anticline, by the dome-stage anticlines and synclines, as well as by the Camp Warwick dome, is illustrated in a structural relief diagram in Figure 7B. The relative age of this recumbent folding is uncertain, but it is tentatively assigned to the stage of backfolding on circumstantial evidence, 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 and its cover are truncated by the Belchertown intrusion with a zircon age of 380 m.y. that was itself deformed and metamorphosed in the dome stage. It is tentatively suggested that the southeast-directed recumbent folding may have been slightly earlier than the overturning of the main and Tully bodies of Monson Gneiss.

With the above features in mind, the progressive development of the structure in the central part of the Mt. Grace quadrangle is illustrated in a series of tectonic cartoons (Figure 9). This shows 1) the formation of the Bernardston and North Orange fold nappes, 2) the thrusting of the North Orange nappe onto the Bernardston nappe along the Brennan Hill thrust, 3) the involution of the fold nappes and thrust nappes by

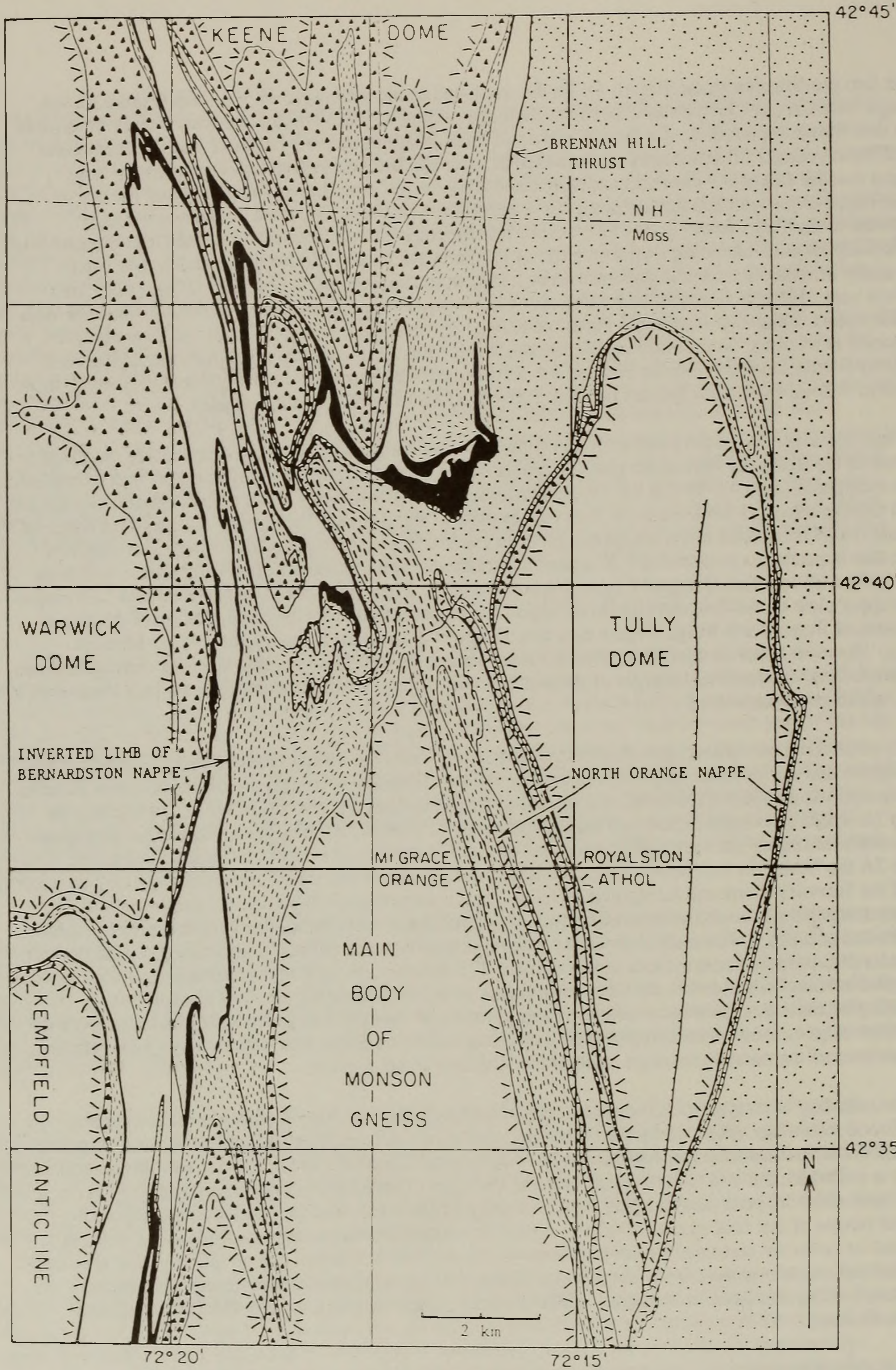


Figure 4. Generalized progress geologic map of the Mt. Grace quadrangle and adjacent parts of the Royalston, Orange and Athol quadrangles west-central Massachusetts and adjacent New Hampshire. For key to symbols see Figure 6A.

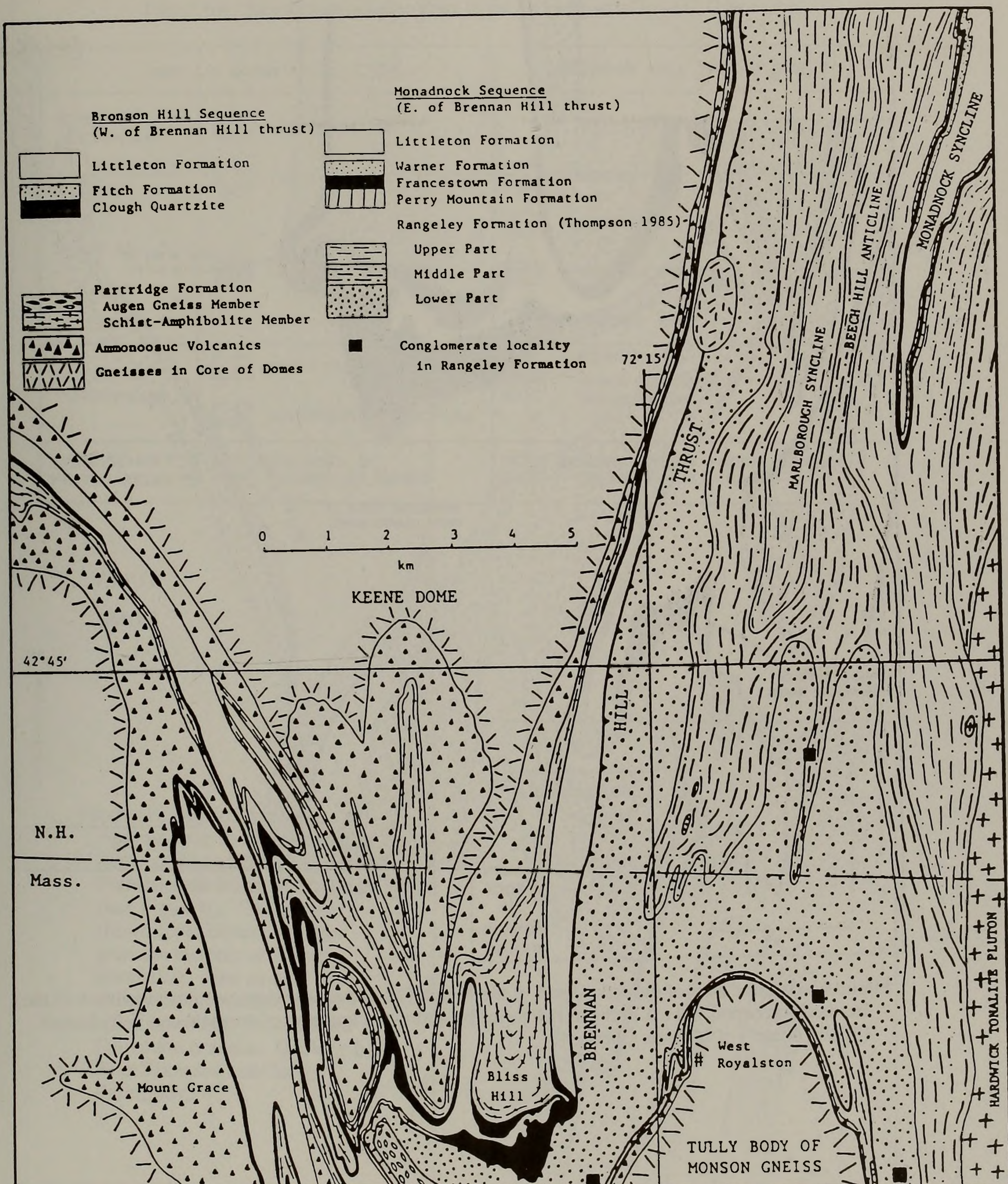


Figure 5. Distribution of members of the lower Silurian Rangeley Formation in the West Royalston area, Massachusetts - New Hampshire (George Springston, map in progress) and the adjacent Monadnock area (P.J. Thompson, 1985). Shows relationship to Brennan Hill thrust and Monadnock nappe-stage recumbent syncline.

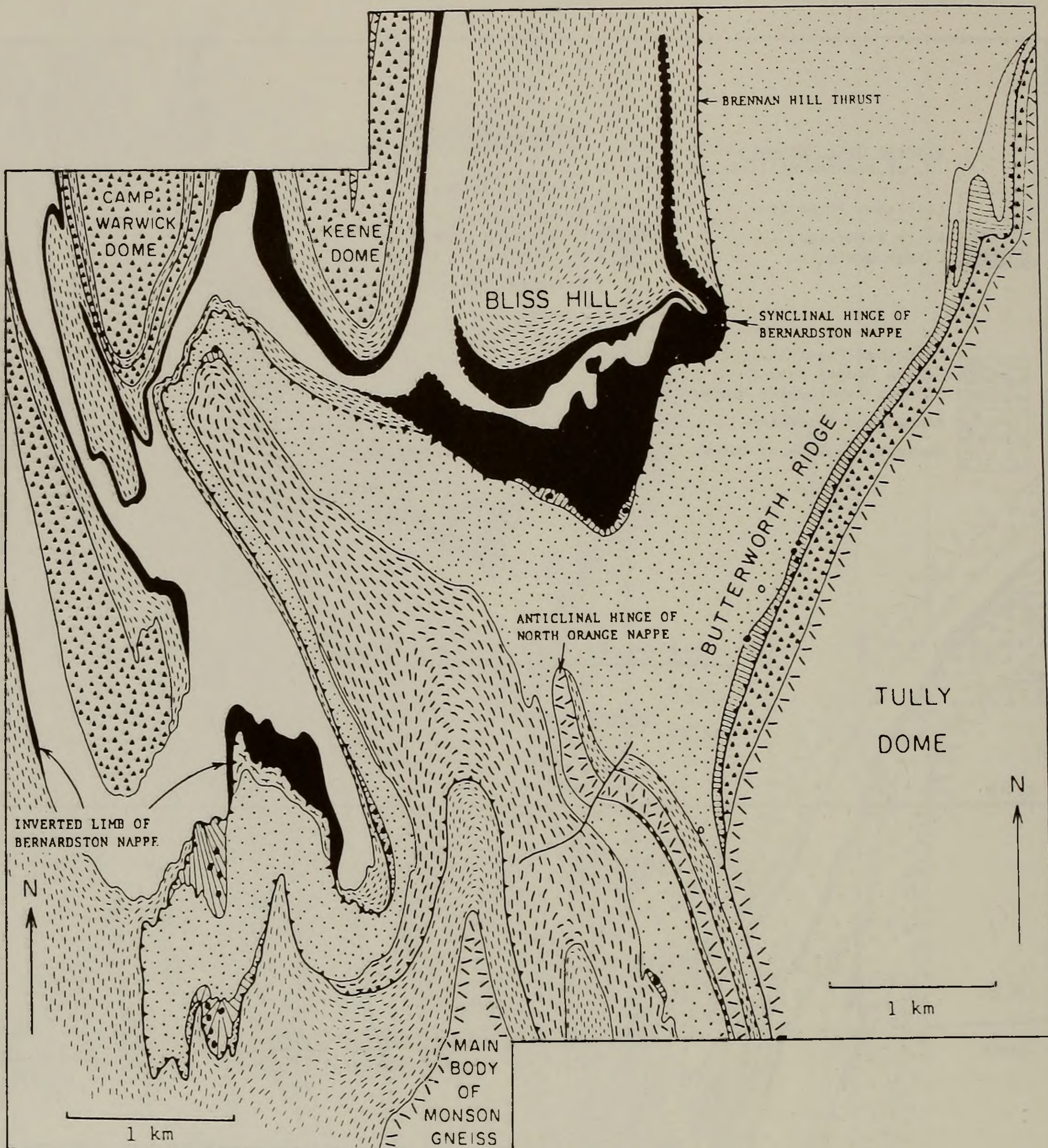


Figure 6. Detailed map of the central part of the Mount Grace area showing complex involution of the Bernardston nappe and the Brennan Hill thrust by northward transport of the main and Tully bodies ("Tully dome") of Monson Gneiss.

Figure 6A. Key to stratigraphic units in the central part of the Mt. Grace area.

	AUTOCHTHON	BRENNAN HILL THRUST SHEET
LOWER DEVONIAN	LITTLETON FM.	
SILURIAN	FITCH FM CLOUGH QUARTZITE	WARNER FM. FRANCESTOWN FM. PERRY MOUNTAIN FM. WITH IRON FM. RANGELEY FM.
MIDDLE ORDOVICIAN	PARTRIDGE FM. AMMONOOSUC VOLCANICS	PARTRIDGE FM. AUGEN GNEISS MEMBER SCHIST MEMBER
ORDOVICIAN ? PRECAMBRIAN ?	GNEISSES IN CORES OF DOMES	MONSON GNEISS – NORTH ORANGE, CREAMERY HILL BANDS

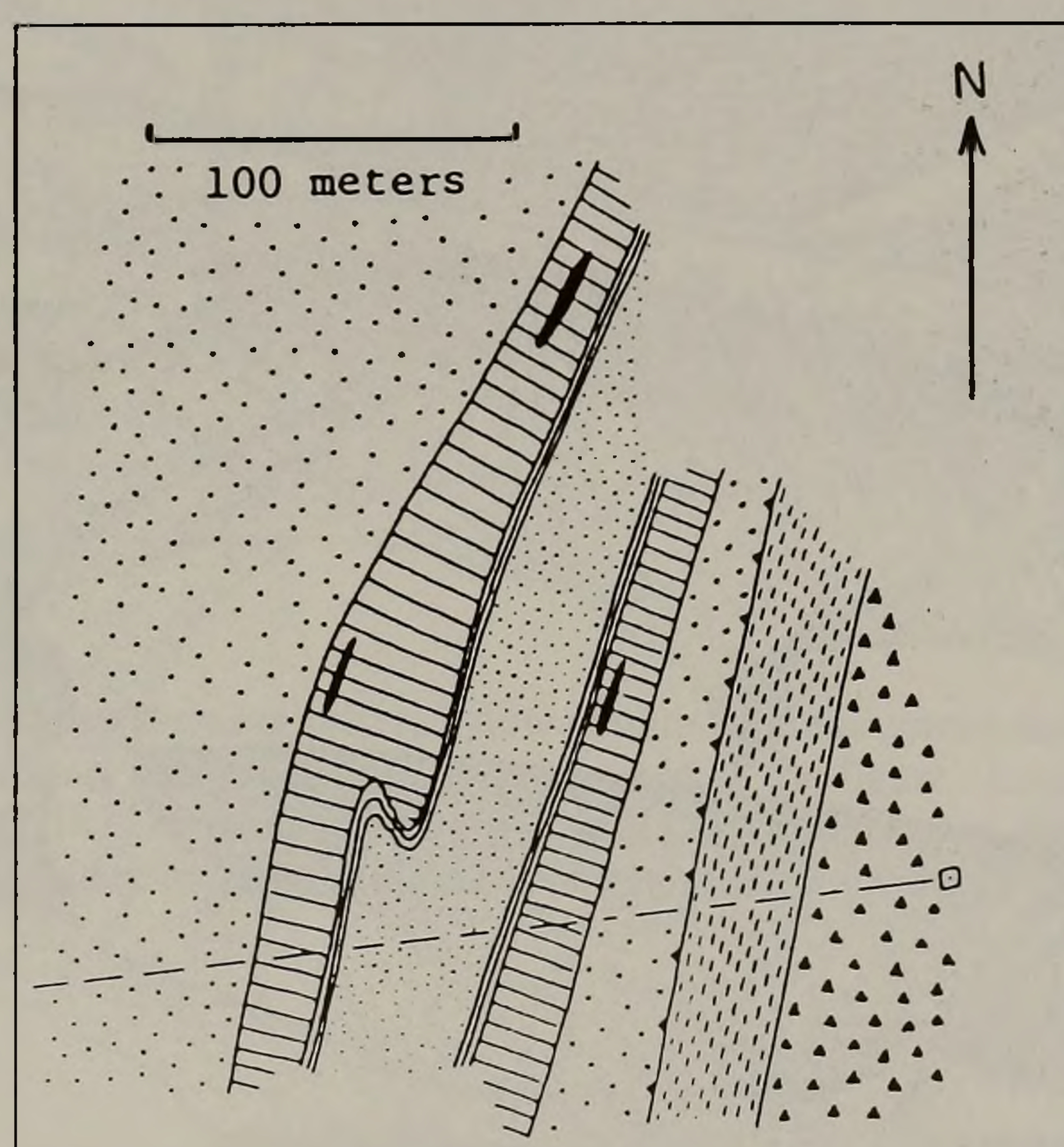
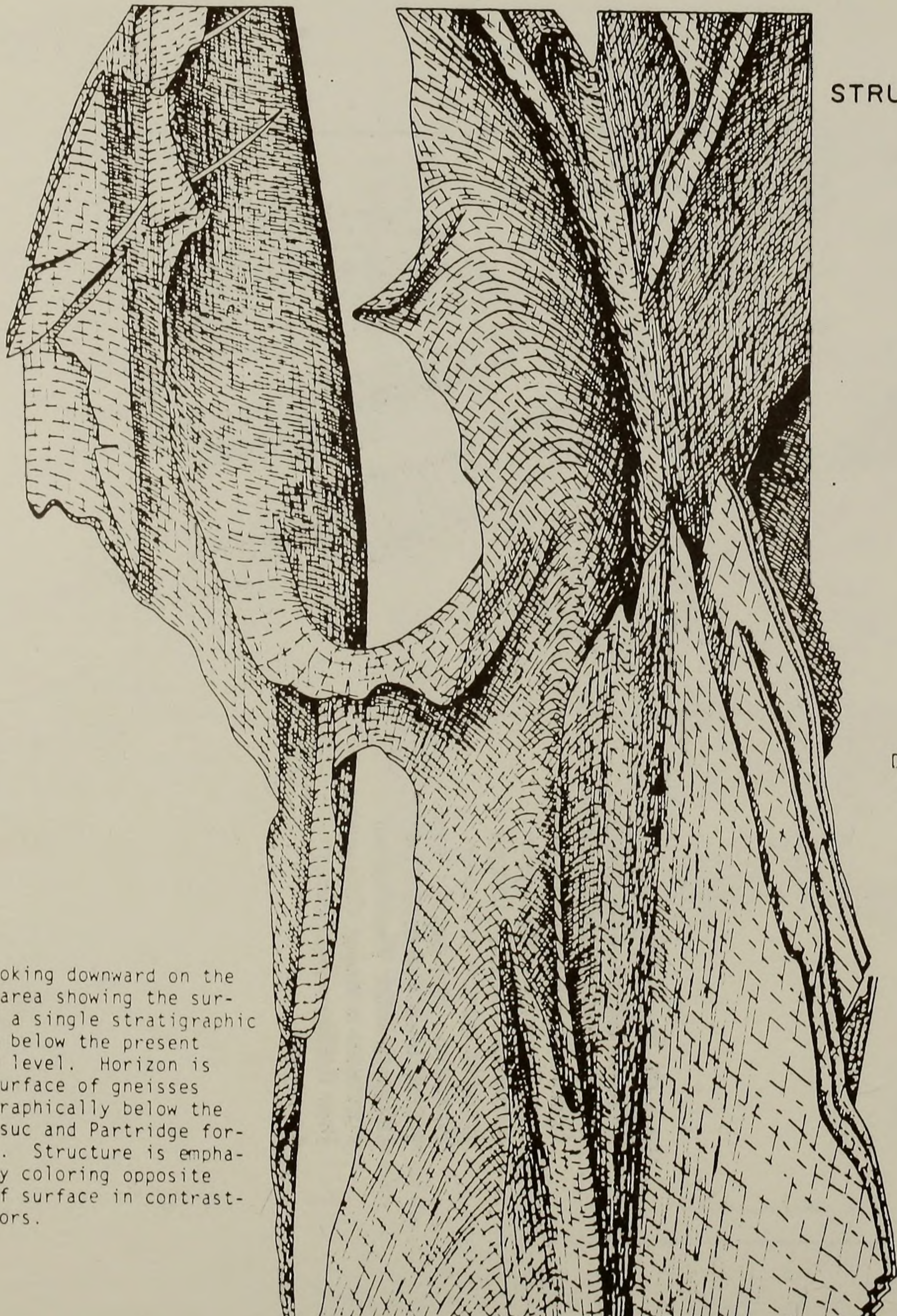


Figure 6B. Detailed pace-and-compass map showing setting of three boudins of Perry Mountain Formation on Butterworth Ridge (see Figure 6). Fine stipple shows upper biotite - feldspar granulite member of Warner Formation. Fine parallel lines indicate lower well bedded calc-silicate member. Francestown Formation is absent. Geology by Peter Robinson and George Springston.

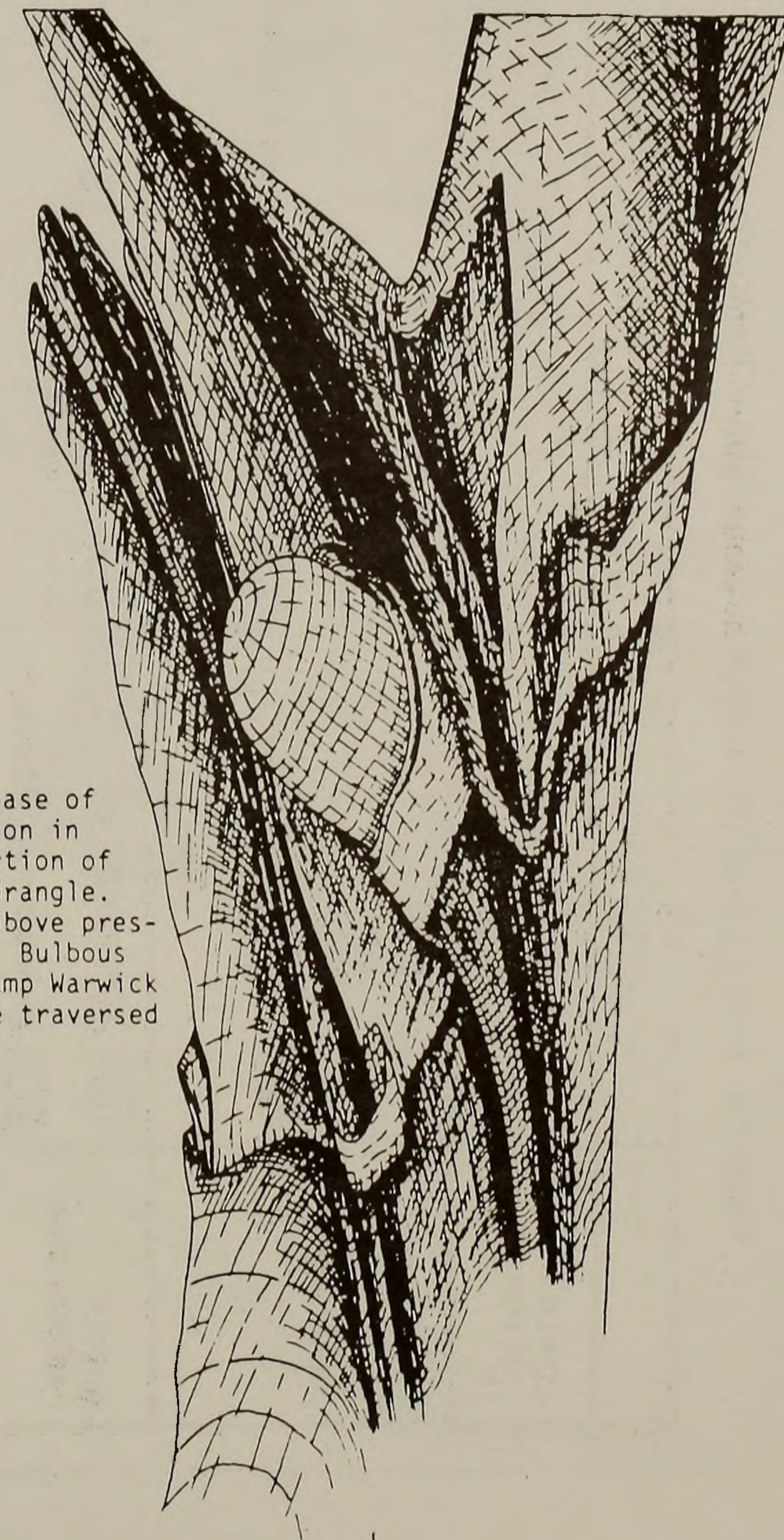
Figure 7

STRUCTURAL RELIEF DIAGRAMS OF THE ORANGE AREA

(from Robinson 1963)



View looking downward on the Orange area showing the surface of a single stratigraphic horizon below the present erosion level. Horizon is upper surface of gneisses stratigraphically below the Ammonoosuc and Partridge formations. Structure is emphasized by coloring opposite sides of surface in contrasting colors.



Detailed view of the base of the Partridge Formation in the north-central portion of the Mount Grace quadrangle. Partially restored above present erosion level. Bulbous structure is the Camp Warwick Dome which will be traversed on Stop 2.

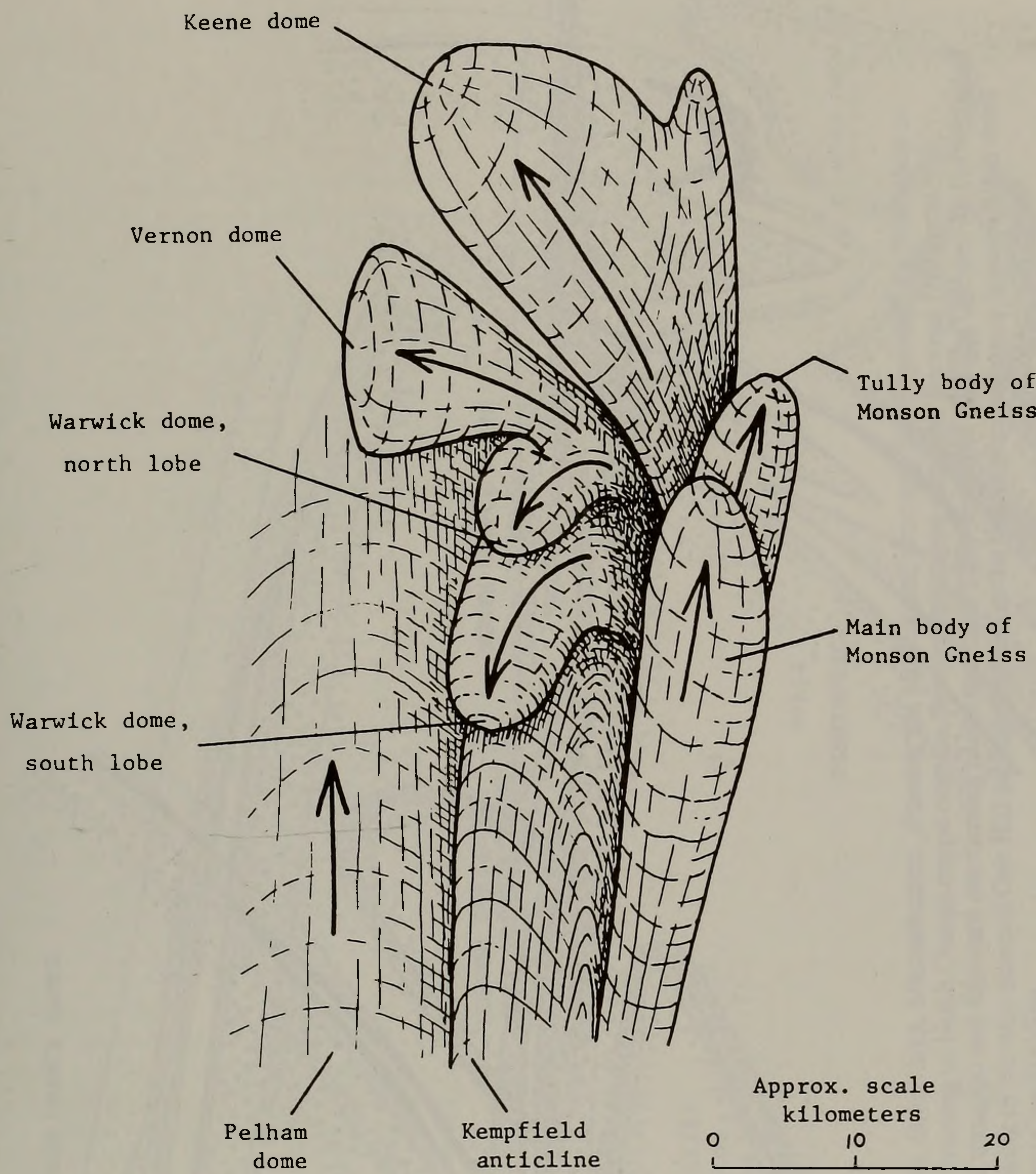
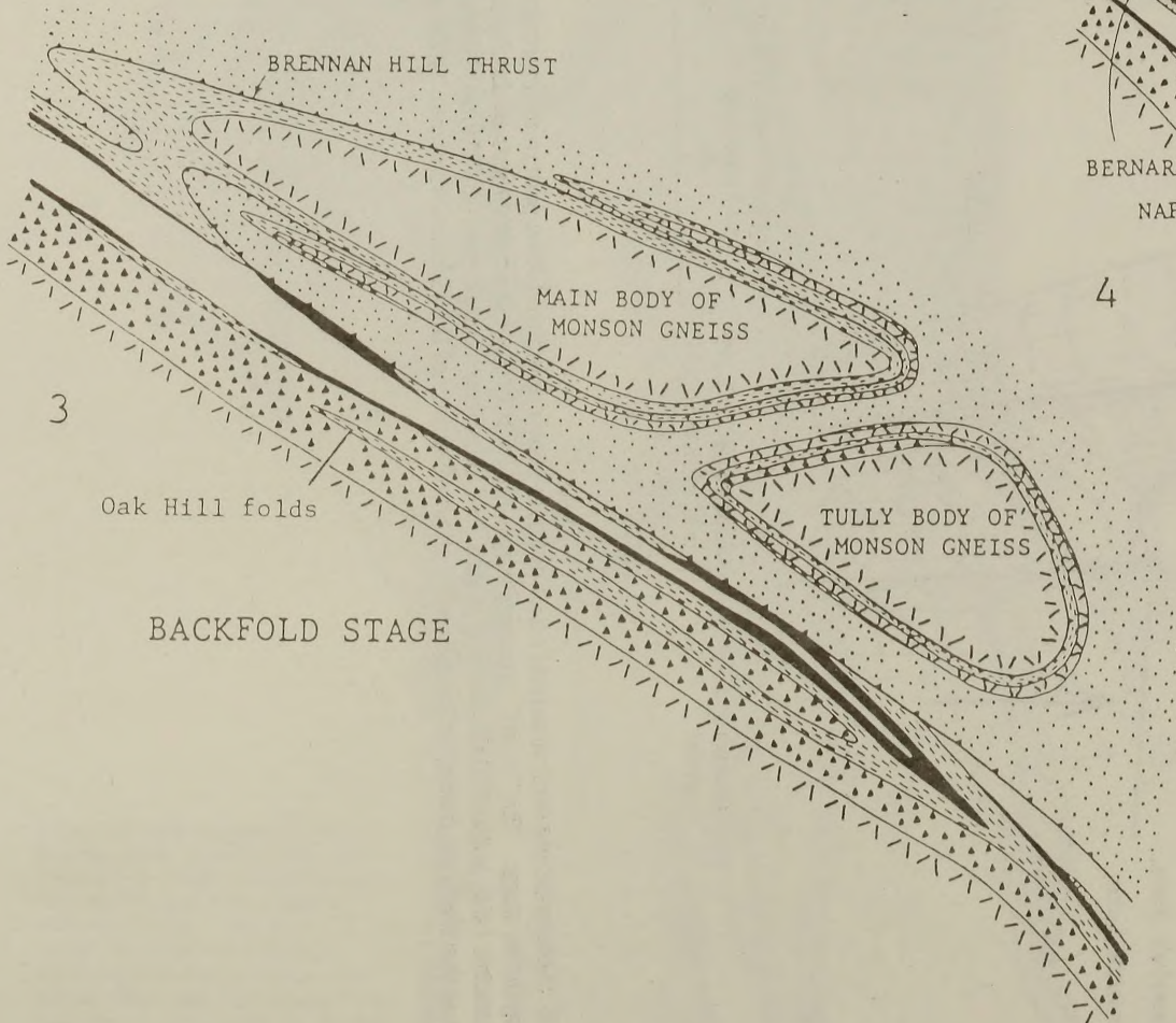
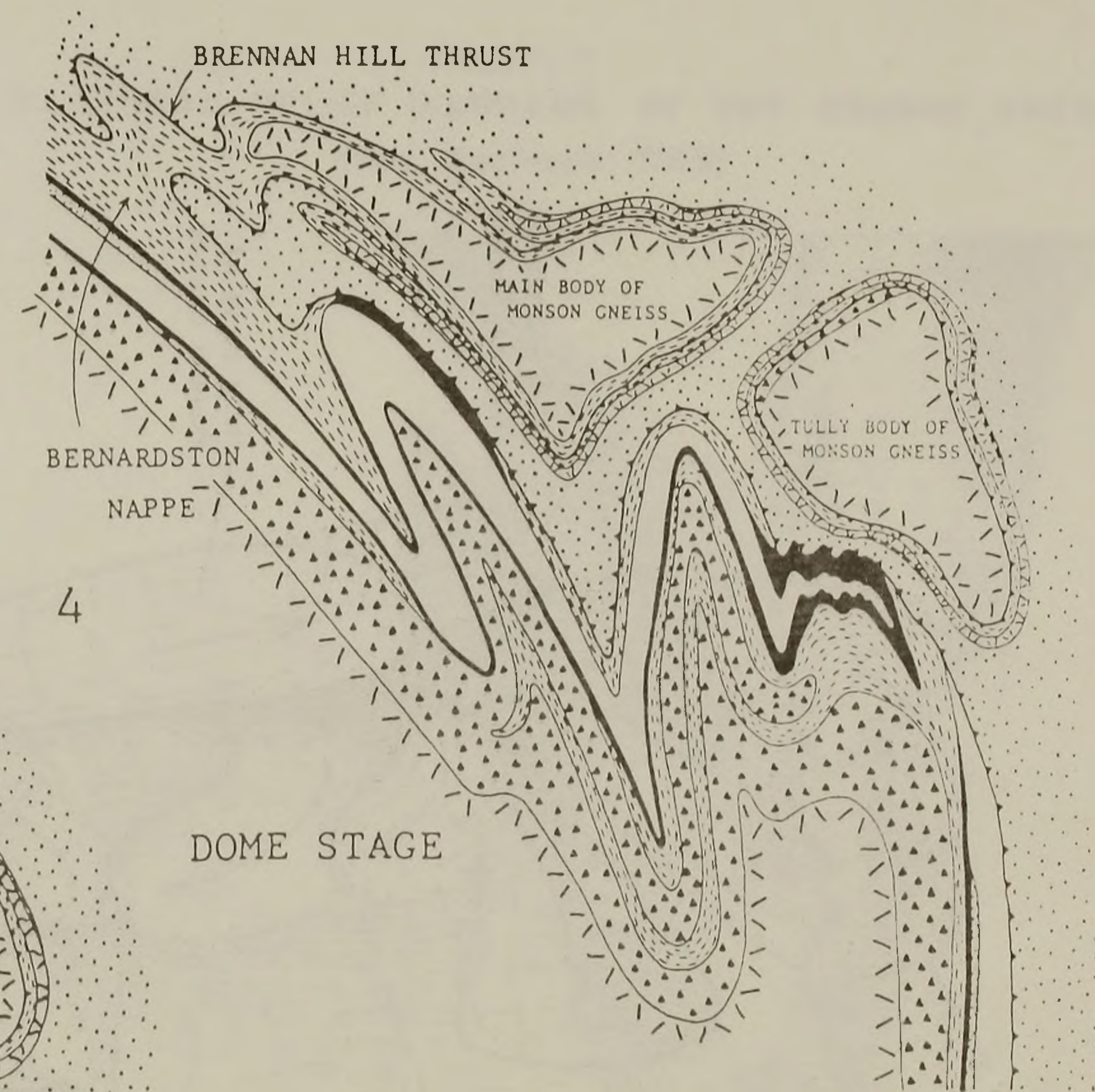


Figure 8. Schematic restored structural relief diagram showing inferred flow pattern of major gneiss bodies during dome stage. The "swirl" runs approximately N-S through the eastern part of the figure. Late asymmetric folds in the Pelham dome (Onasch, 1973) indicate dome cover was sliding southward, the same as the Warwick dome, hence relative northward motion of the Pelham dome core is inferred.



3

BACKFOLD STAGE



4

DOME STAGE

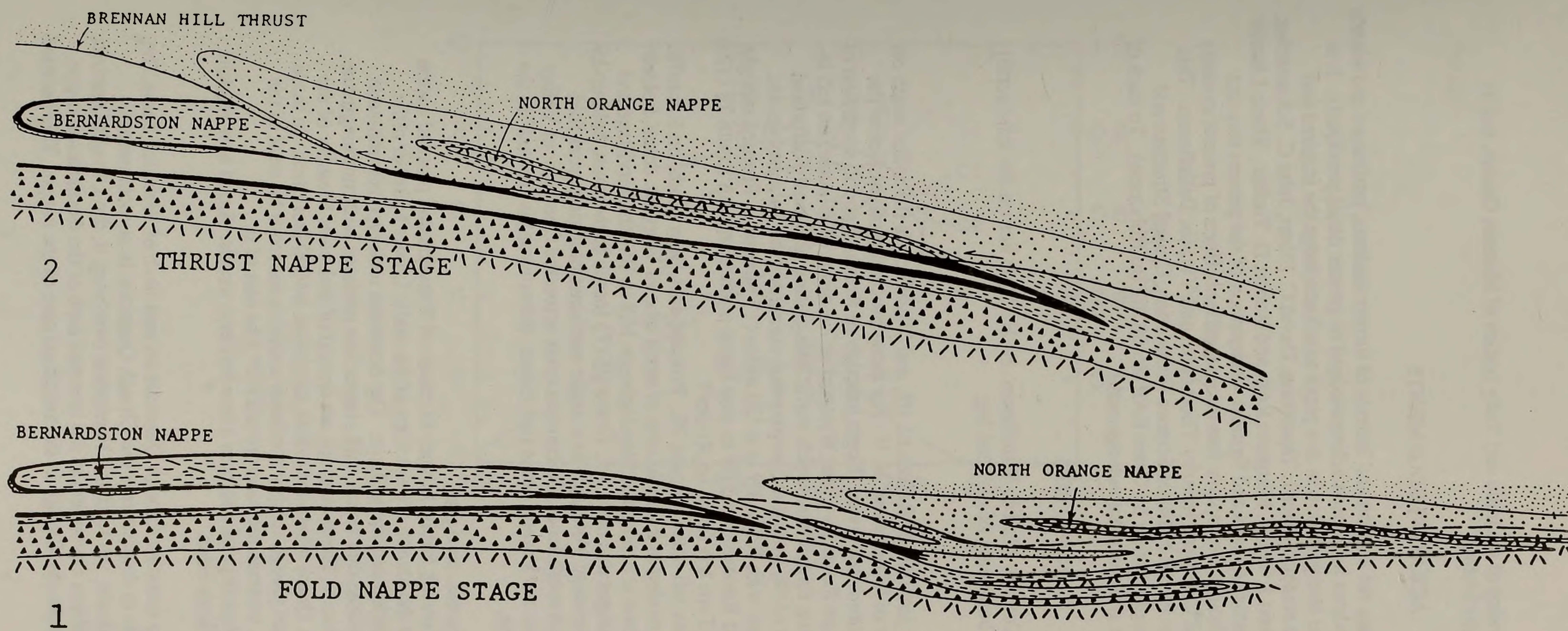


Figure 9. Schematic cross sections through the Mt. Grace area, Massachusetts, showing the sequence of structural development: 1) Formation of Bernardston and North Orange fold nappes. 2) Thrusting of North Orange nappe onto the Bernardston nappe along the Brennan Hill thrust. 3) Involution of fold and thrust nappes by northward transport and eastward overturning of the main and Tully bodies of Monson Gneiss. 4) Formation of gneiss domes and related tight folding. Actual timing of the east-directed Oak Hill recumbent folds in the Keene gneiss dome is unknown, but most recent indications are that these belong to the stage of backfolding.

northward transport and eastward overturning of the main and Tully bodies of Monson Gneiss, and 4) formation of gneiss domes and related tight folding.

ACKNOWLEDGEMENTS

The first author wishes to acknowledge the support and interest of former students, professors and friends too numerous to mention here, many of whom have been acknowledged in greater detail previously. It is necessary particularly in the context of the interpretation in this paper to acknowledge the inspired and dedicated research of former stduents and students Peter J. Thompson, David C. Elbert, John C. Schumacher, Kurt T. Hollocher, Thomas M. Pike, Robert J. Tracy, Margaret Roll, and Robert D. Tucker. Marie Litterer worked over the years in preparing and lettering maps and figures. Completion of the present text and figures would not have been possible without the extensive last-minute selfless efforts of present students Henry N. Berry, Virginia Peterson, David C. Elbert, Jennifer Thompson, and Vincent DelloRusso. This research has been supported over the years by the National Science Foundation, Crustal Structure and Tectonics, and Petrogenesis Programs, most recently by Grant EAR-86-08762 (to Robinson). To each of these persons and institutions we give our grateful acknowledgements.

ROAD LOG

Assemble at 8:30 A.M. at Kulick's Country Mall in Winchester, N. H. This lies on the left (north) side of Route 78 at 0.3 miles beyond the beginning of the road log.

Mileage

0.0 Road log begins at stoplights at junction of Routes 10, 119, and 78, which is 0.5 miles south on Routes 10 and 119 from the center of Winchester, N. H. For those proceeding from Keene the following distances and driving times are given: Begin junction of Routes 9 and 10 southwest of center of Keene. Proceed south on Route 10. Near Westport at 7.4 miles (11 minutes) on left is bush-up pavement outcrop showing folded biotite-rich mafic dike cutting previously deformed granite intruding gabbro, all part of the intrusive complex that composes the Swanzey gneiss. Center of Winchester and junction with Route 119 is at 12.1 miles (17 minutes). Proceed straight past lights in center on combined Routes 10 and 119 to stop lights atjunction with Route 78 (12.6 miles, 19 minutes from Keene). Turn left (east) on Route 7.

0.3 Assembly point , Kulick's Mall on left side of Route 78. Proceed east, then south, on Route78.

1.6 Broad view of topographic basin eroded in granitoid core of north lobe of Warwick dome. Folded cover sequence at north end of dome is exposed at Meetinghouse Hill in Winchestervillage and shows that north end of dome plunges due east. Mt. Grace (1617') looms to thesouth, held up by the Lower Member of the Ammonoosuc Volcanics in a major northeast-plunging cross fold separating the dome into north and south lobes. Reconstructions acrossthe Connecticut Valley border fault (Figure 8) suggest that the Vernon dome (see Elbert, thisvolume) is "rooted" in the northern part of the Warwick dome.

3.7 Massachusetts State Line.

5.8 Picnic grounds, Warwick State Forest, on right.

7.1 Bear left (east) off Route 78 at Warwick Public Library in center of Warwick and proceed easton main road. Northeast and north of the church are outcrops of the mafic Lower Member ofthe Ammonoosuc Volcanics cut by folded pegmatite dikes. The dominant rock type ishornblende amphibolite, but there are also epidote-rich layers, and plagioclase gneisses withcummingtonite, garnet, biotite, and secondary chlorite. These outcrops are typical of theLower Member of the Ammonoosuc Volcanics near Mt. Grace where the whole formation is4000 feet thick. In these outcrops minor folds and lineations plunge steeply northeast andthese outcrops lie west of the lineation "swirl"described above, whereas the outcrops atSTOP 1 lie east of it.

7.6 Park on right near small cut and outcrops of quartzite a few feet into woods. Small new roadcut in gray schist is visible ahead on both sides.

STOP 1A. See Figure 11. Briefly examine Clough Quartzite on east limb of Warwick dome.The purpose of STOP 1 in total (see Figure 11) is to demonstrate the Clough Quartzite in autochthonous position on the east limb of the Warwick dome, the Littleton Formation overlying it, the Clough Quartzite repeated in inverted position above the Littleton Formation in the inverted limb of the Bernardston nappe, and the Partridge Formation structurally above the Clough in the anticlinal core of the nappe. This doubled

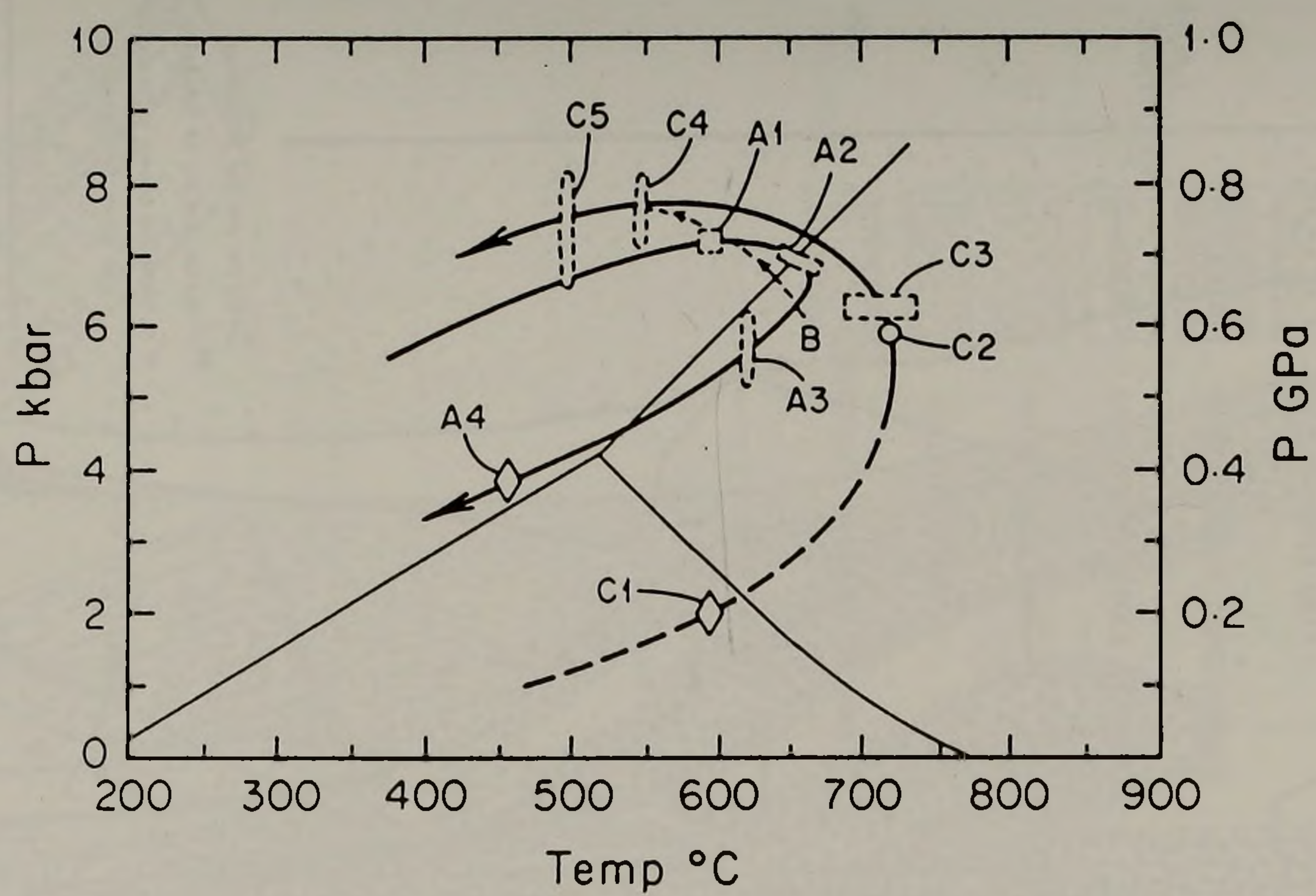


Figure 10. P-T trajectories from central Massachusetts and southwestern New Hampshire. A) central Bronson Hill anticlinorium near Keene dome based on the following: A1 - specimen I34I, garnet-biotite and garnet-cordierite thermometry, sillimanite-kyanite-quartz-garnet-cordierite barometry (Schumacher and Robinson, 1986, Table G-8); A2 -specimen 7AOBX, garnet-biotite and garnet-cordierite thermometry, kyanite-sillimanite-quartz-garnet-cordierite barometry (Schumacher and Robinson, 1986, Table G-8); A3 -cordierite enclaves, cordierite-spinel-quartz barometry with estimated temperature of 625°C (Schumacher and Seifert, 1986); A4 - kyanite-chlorite-quartz intergrowths in coarse cordierite (Robinson and Jaffe, 1969). B) eastern edge of Bronson Hill anticlinorium, Quabbin Reservoir area. Path of epidote formation, (Schumacher et al., 1988). C) Merrimack synclinorium, south-central Massachusetts based on the following: C1 - sillimanite pseudomorphs after andalusite, some of these occur in pegmatite indicating high T formation; C2 - beginning of breakdown of Fe-rich cordierite to quartz-sillimanite-garnet aggregate (data of Tracy and Dietsch, 1982); C3 - range of peak metamorphic T and P estimates from Zone VI (data of Tracy et al., 1976 and Robinson et al., 1982a); C4 - estimated P and T of mylonite recrystallization (Robinson et al., 1982a, 1986); C5 - estimated P and T of garnet rim re-equilibration in quartz-sillimanite-garnet aggregate inside zoned cordierite (data of Tracy and Dietsch, 1982).

Figure 11. Detailed geologic map of the area of STOPS 1-4 in the Mount Grace quadrangle. Teeth are on the upper plate of the Brennan Hill thrust.

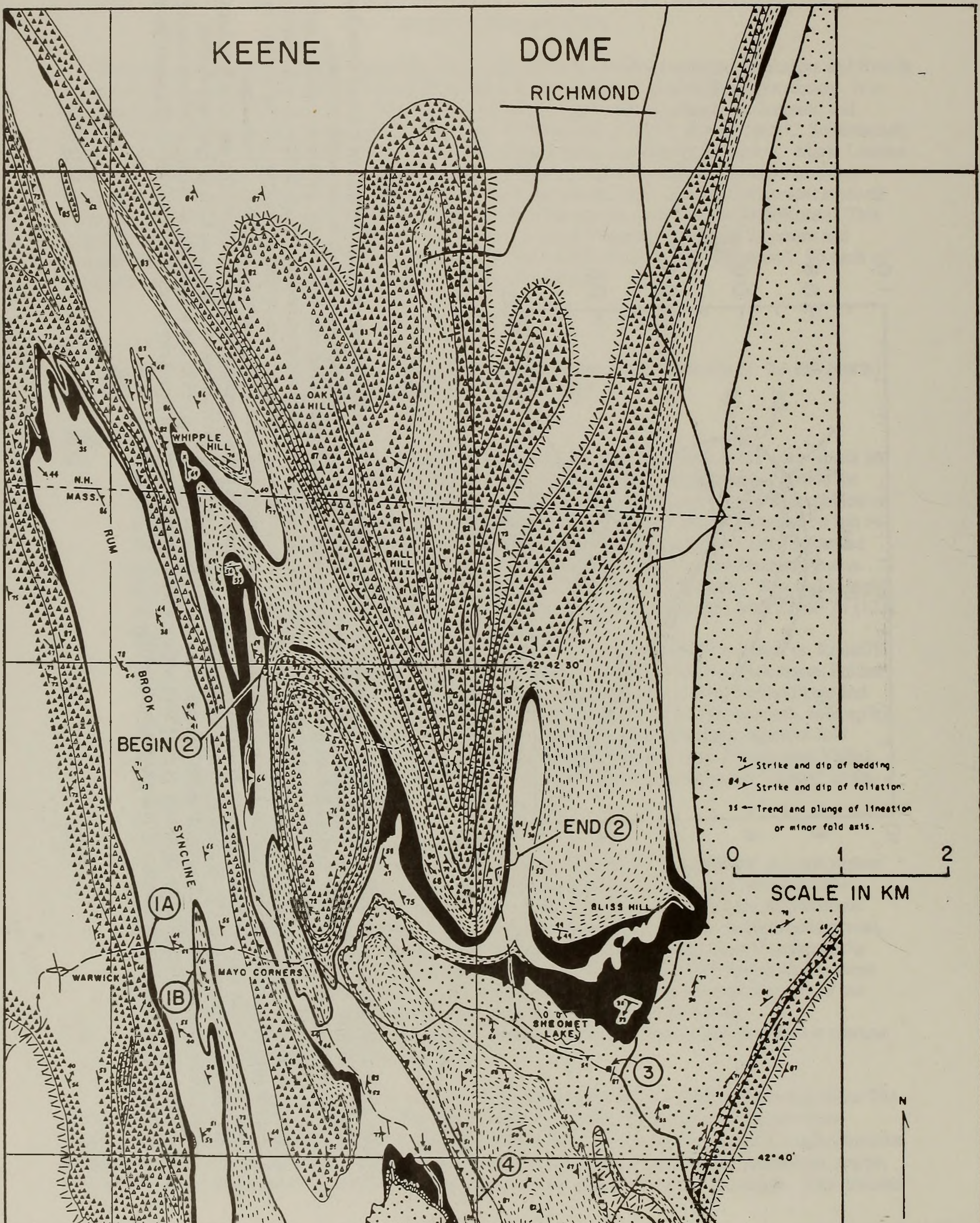
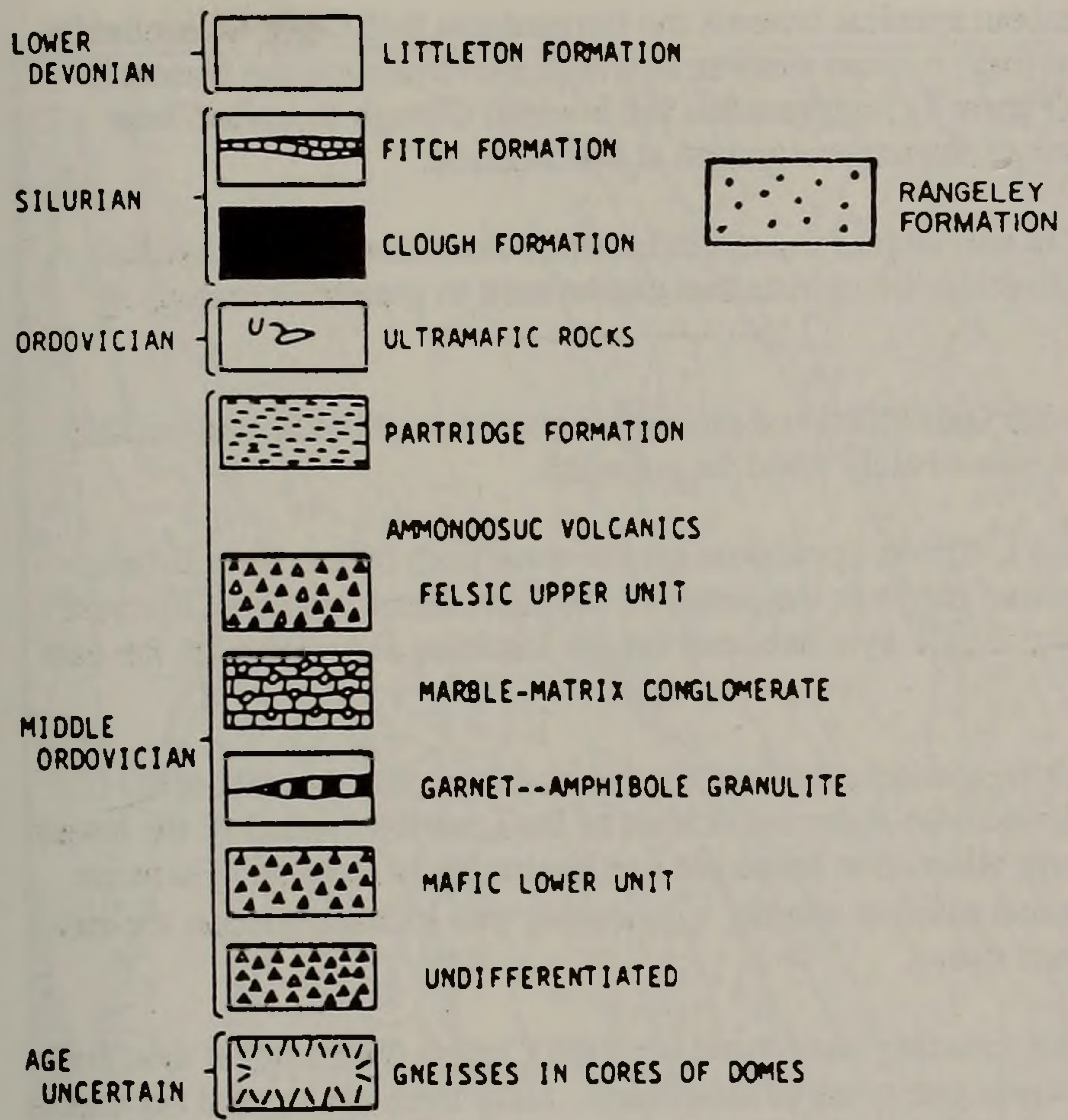


Figure 11 Legend.



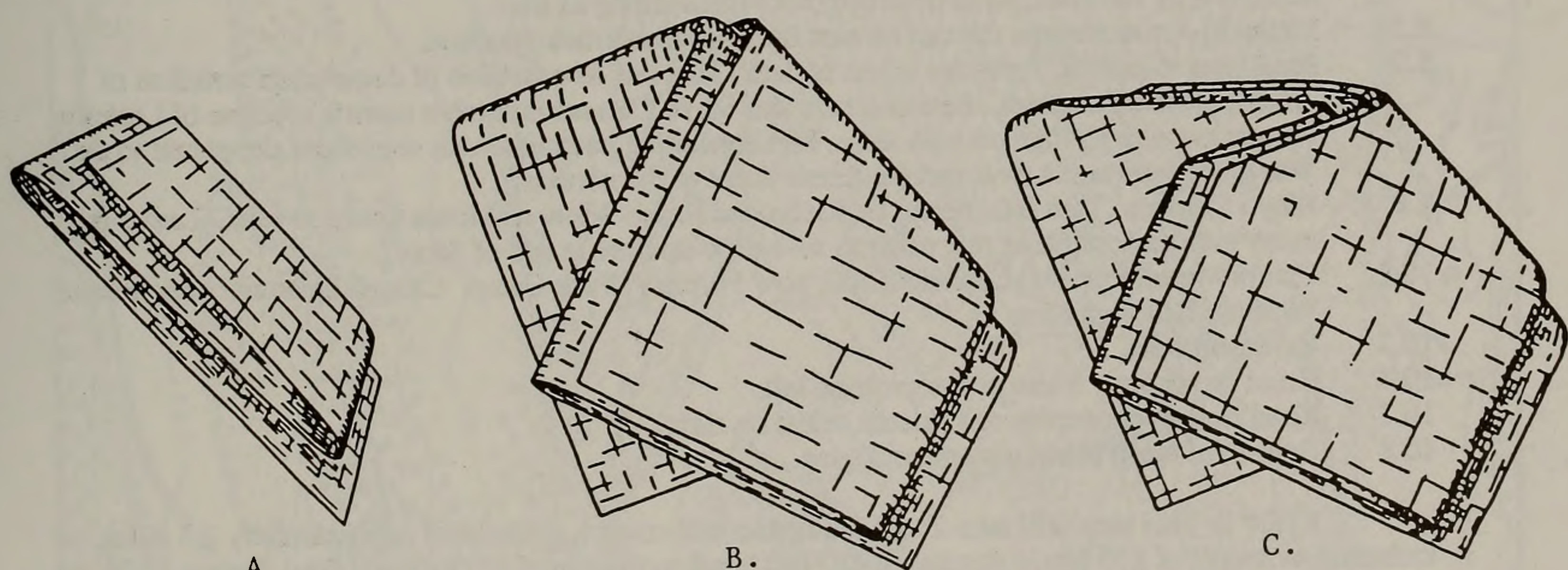


Figure 12. Origin of outcrop pattern at south end of Keene dome to be visited on STOP 2. Stratigraphic horizon shown is contact between Ammonoosuc Volcanics and Partridge Formation. A. Formation of Tully Brook recumbent anticline and Oak Hill recumbent syncline. Axial planes dip southeast and axes trend northeast. B. Folding of recumbent fold about Ball Hill anticline with axis plunging about 45^{o} south-southeast. C. Erosion to give present outcrop pattern.

sequence produced by the nappe-stage recumbent syncline beneath the Bernardston fold nappe is isoclinally refolded by the dome-stage Rum Brook syncline. A cross section, in which movement on the Mesozoic Connecticut Valley border fault is restored (Figure 3), suggests that the inverted Clough described here connects directly in space with the lower limb of the nappe exposed at Bernardston.

Proceed east past small new road cut and larger road cut in Littleton Formation on both sides. These are good looking sillimanite-muscovite-staurolite schists that can be seen to greater advantage in natural exposures at STOP 1B.

8.0 Turn right (south) at intersection with Gale Road and proceed to partial road block at about 0.15 miles. Do U-turn and park on right side of Gale Road facing north.

STOP 1B. At this stop will be seen Littleton Formation on the west limb of the Rum Brook syncline, Partridge Formation of the Bernardston nappe in the center of the Rum Brook syncline, inverted Clough Quartzite on the east limb of the Rum Brook syncline, and finally Littleton Formation on the east limb of the Rum Brook syncline.

Walk south and west past road block in abandoned paved road to outcrops on north side of U-shaped bend. These are superb sillimanite-muscovite-staurolite schists of the Littleton typical of the lowest grade part of the sillimanite zone where quartz-sillimanite knots are just beginning to develop. Foliation dips 50-60° east. Dome-stage mineral lineation plunges steeply southeast in this location just on the east side of the dome-stage lineation swirl described above.

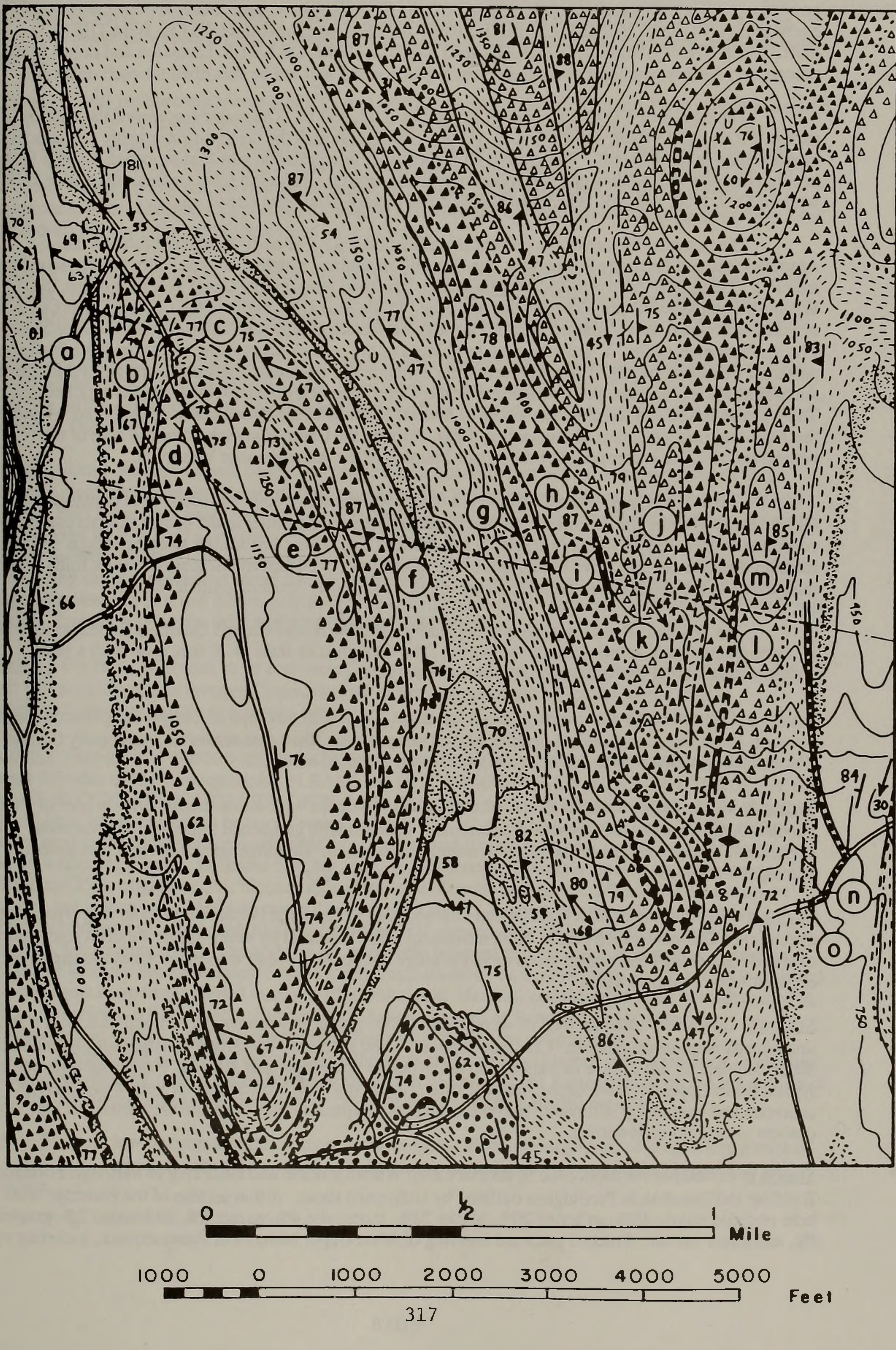
Return to position of parked vehicles, crossing unexposed inverted Clough Quartzite on west limb of Rum Brook syncline. Proceed east into woods just south of new house. Here there are several exposures of rusty-weathering sillimanite schist and amphibolite of the Partridge Formation in the center of the Rum Brook syncline. Proceed east through woods to steep east-facing ledges of Clough Quartzite including conglomerate overlooking swamp. Foliation dips about 60°. These are in the inverted limb of the nappe and on the east limb of the Rum Brook syncline. Follow Clough ledges north along strike and continue north to main E-W road. Just across road to northeast is a small outcrop of Littleton Formation on the east limb of the Rum Brook syncline. Walk short distance west to Gale Road, then south to vehicles. Drive north to main E-W road.

8.3 Turn right (east) off Gale Road onto E-W road and recross allochthonous Clough. Swamp ahead is underlain by Littleton, large outcrops (not visible) north of road.
8.5 Littleton-Ammonoosuc contact on east limb of Rum Brook syncline.
8.7 Small cut in sulfidic Partridge schist on left. This lies on east limb of dome-stage anticline of Ammonoosuc Volcanics. Between here and Mayo Corners is another narrow syncline of Littleton Formation with Clough on both sides, here separating autochthonous sequences peripheral to the Warwick dome to the west and the Keene dome to the northeast.
8.9 Mayo Corners. Turn left (north) on Richmond Road. View of Mount Grace to west. Leave as many cars as possible at this point to save pick-up time at end of Stop 2.
10.1 Camp Warwick on right; former CCC, now Forestry Work Camp. Clough Quartzite near nose of Whipple Hill digitation.
10.2 Pavement ends.
10.4 Cross powerline. View of reservoir on left.
10.7 Road runs over outcrop of Littleton schist on right.
10.8 Bottom of steep pitch, pavement begins.

STOP 2. This stop will take 2 to 3 hours and will cover a distance of approximately 2.3 miles, including an ascent of 270 feet, a descent of 480 feet, a second ascent of 170 feet, and final descent of 240 feet through open woods, wood roads, and a powerline. Boots are essential. One van will proceed to pick up drivers at end of stop and return them to the beginning.

Because the party will be strung out over a considerable part of the route at any one time, it is suggested that the route map (Fig. 13) and itinerary be followed closely. This is a wilderness area. "Drovers" will bring up the rear to make sure none are lost and try to assist any in distress. For those who have "had it" after station f or after station k an "escape route" that involves little further climbing can be

Figure 13. Detailed map of STOP 2.



pointed out. There is excellent collecting to be done on this traverse, particularly the later part, but everyone is URGENTLY REQUESTED TO REFRAIN FROM HAMMERING ON WEATHERED SURFACES THAT SHOW TEXTURAL AND STRUCTURAL DETAILS. Lineation and minor folds plunge very steeply southeast or south in most exposures and will not be described for each outcrop.

The details of STOP 2 are shown in Figures 11, 12, and 13. The major features of the outcrop pattern are similar to those shown by J. B. Hadley (1949), although the present stratigraphic and structural interpretation is far different. The present recumbent fold interpretation was first proposed by John Rodgers in conversations with Hadley and was independently deduced by Robinson from Hadley's map prior to field work in 1959, 1960, and 1961, when a wealth of confirmatory detail was turned up.

The essential feature of the present interpretation is a set of early recumbent folds in the Ammonoosuc and Partridge Formations, the Oak Hill recumbent syncline and the Tully Brook recumbent anticline. These have been refolded over three later structural features, the Camp Warwick dome, the Williams Pond syncline and the Ball Hill anticline. In the Ball Hill anticline, the Oak Hill recumbent syncline is outlined by a V-shaped area of Partridge Formation completely surrounded by Ammonoosuc. The northern ends of the "V' are interpreted as hinges of the recumbent syncline and show it originally had a northeast trend (Figure 12). The same recumbent syncline shows a completely closed ring of Partridge in Ammonoosuc where it has been wrapped over the Camp Warwick dome. In the Ball Hill anticline, the Tully Brook recumbent anticline has a core of Swanzey Gneiss of the Keene dome or the Lower Member of the Ammonoosuc Volcanics (Schumacher, 1988). Around the Camp Warwick dome the core of the recumbent anticline is composed of the Upper Member of the Ammonoosuc Volcanics.

The unique Camp Warwick dome is a flattened piston-like body with both ends plunging about 60° southeast (Figure 8). All lineations and minor fold axes are parallel to the piston axis, so that the body conforms in geometry to forms observed in salt domes (Balk, 1949), but similar steep lineations and minor folds are found in all structures in this part of the quadrangle. The movement sense of minor folds could be interpreted as the result of compressive flattening of a previously existing cylinder of rock.

The Williams Pond syncline is occupied by a narrow belt of Clough Quartzite folded on itself with a "thermometer bulb" termination to the north. The Clough is as little as 70 feet wide with a basal conglomerate resting on Partridge Formation on both sides.

Station a Proceed south along base of slope for about 200 feet to outcrops of Clough conglomerate holding up north-south rib. Long axes of pebbles plunge steeply east. Turn east across rib, cross gully beyond (Partridge Formation poorly exposed here), and begin ascent of main hill.

Station b Felsic Upper Member of the Ammonoosuc Volcanics with minor amphibolite in core of Tully Brook recumbent anticline. Layered peraluminous gneisses with garnet and muscovite are common. Minor asymmetric folds. Prominent flat jointing normal to lineation. Continue up and to right past several outcrops to wood road.

Station c First outcrop at high point in bed of wood road is Partridge Formation in inner ring (recumbent syncline) of Camp Warwick dome. Note movement sense indicated by minor folds. Proceed south just east of wood road along nearly continuous rusty Partridge outcrops. Contact with inner Ammonoosuc is poorly exposed when road rises again.

Station d Low knob outcrops west of wood road. Felsic gneiss and "porhyritic" amphibolite with a strong lineation of plagioclase patches. Continue south on wood road until powerline is barely visible, then bear diagonally left up hill to save elevation, and come out on powerline near hill top. Numerous outcrops of typical felsic Upper Member of the Ammonoosuc, commonly with brown-, red- or yellow-weathering character and containing sillimanite in some examples. Expansive view east and west from hill top. Begin descent to east along powerline.

Station e Contact of Ammonoosuc in core of Camp Warwick dome and inner ring of Partridge Formation. Bedding and lineation in Partridge is outlined by sillimanite knots. A thin section of the Partridge from here contains quartz 46%, andesine 20%, biotite 25%, muscovite 4%, garnet 2%, sillimanite 2%, graphite 1%, and minor sulfide. Proceed eastward into ring of felsic Upper Member of Ammonoosuc, including rare outcrops of gray sillimanite-biotite schist, and then into outer ring of Partridge. Note movement sense indicated by minor folds in Partridge. One schist from this belt has the same minerals as the specimen described above plus about 25% orthoclase, another is similar but contains 20% muscovite and little or no feldspar.

Station f Basal cobble conglomerate of Clough Quartzite on west limb of Williams Pond syncline exposed a few feet east of Partridge Formation on south side of powerline. Not easy to see direction of long axes. Large outcrop to east is well bedded gray quartzose schist assigned to the Clough Quartzite in the axial region of the Williams Pond syncline, although it resembles some Littleton. Where exposures are more complete it appears to grade into conglomerate on both sides. Note pegmatite boudins involved with asymmetric folds. Proceed east past old foundation to north bank of small stream crossing powerline. Bear left (north) off powerline and follow north bank of stream.

Station g Partridge Formation in stream cascade under large trees, well east of Clough of Williams Pond syncline. Below flatter section of stream, felsic gneisses of the Upper Member of the Ammonoosuc Volcanics are exposed in a second cascade. Below this leave stream on south bank and continue downhill.

Station h Large blocks and some outcrop of mafic Lower Member of Ammonoosuc Volcanics including some beds of red-weathering gedrite gneiss. This lies in the axial region of the Tully Brook recumbent anticline on the east limb of the Ball Hill anticline. Follow flags east through evergreens across the west branch of Tully Brook.

Station i Small outcrops of well bedded garnet-grunerite quartzite that is characteristic of much of the Garnet-Amphibole Quartzite Member of the Ammonoosuc Volcanics and forms a distinctive marker unit between the Upper and Lower Members on both limbs of the Tully Brook recumbent anticline. Here it is on the lower limb as well as on the west limb of the Ball Hill anticline. Grunerite from this locality studied by Prof. Howard Jaffe has gamma=1.687 equivalent to FeO/(FeO+MgO) of 0.60. Go south along west-facing slope to powerline where there is a superb outcrop of finely laminated felsic volcanics of the Upper Member just east and structurally below the Quartzite Member. Turn left (east) on powerline to top of rise. You are now on the axial surface of the Ball Hill anticline.

Station j For those who wish to be convinced. Follow blazed trail north along trace of axial surface of Ball Hill anticline across inverted Upper Member of the Ammonoosuc Volcanics to outcrops of Partridge Formation that lie structurally beneath.

Station k Fine-grained quartz-microcline-oligoclase gneiss with white quartz-sillimanite nodules of the Upper Member of the Ammonoosuc. PLEASE DO NOT HAMMER WEATHERED OUTCROPS AND LOOSE BLOCKS ON SOUTH SIDE OF POWERLINE. This rock type is characteristic of the upper part of the Upper Member and can be traced entirely around the "V" of Partridge Formation. Similar rocks farther west in the Mount Grace quadrangle have kyanite and staurolite crystals in the cores of the nodules and have nodules 2 inches thick and 5 inches long. A thin section from this outcrop contains quartz 53%, microcline 35%, oligoclase 5%, biotite 2%, and minor muscovite and garnet. 5% sillimanite occurs only in nodules, but is seen in contact with microcline at nodule edges. X-ray measurements of muscovite laboriously separated from a rock like this from Ball Hill showed only 5% paragonite component (W. P. Freeborn, pers. comm. 1967). The nodules are tentatively believed to have originated as glassy clasts in a crystalline volcanic matrix that underwent hydrothermal alteration or weathering to quartz-kaolinite rock and was subsequently metamorphosed to quartz-sillimanite rock. Identical nodular rocks have been described at this same horizon in Connecticut (Lundgren, 1963, 1964) as well as in numerous localities in metamorphosed volcanics in Precambrian shield regions including the Adirondacks.

Proceed east across low ground where there are excellent low outcrops of amphibolites, including anthophyllite-bearing rocks. These belong to the Lower Member of the Ammonoosuc on the lower limb of the Tully Brook recumbent anticline, east of the axial surface of the Ball Hill anticline.

Station l Single low outcrop to right of tower on west-facing slope. Coarse-grained plagioclase gneiss of Swanzey Gneiss exposed near axial surface of Tully Brook recumbent anticline on east limb of Ball Hill anticline.

Station m Large outcrop on left at steepest place. Coarse-grained anthophyllite-garnet-biotite-hornblende gneiss with bed of hornblende amphibolite containing thin layer of diopside-labradorite-epidote gneiss. This is in the mafic Lower Member of the Ammonoosuc on the upper limb of the Tully Brook recumbent anticline. PLEASE LEAVE DIOPSIDE LAYER INTACT, SAMPLE ELSEWHERE IF YOU WISH. Anthophyllite gneiss contains quartz 15%, andesine 41%, anthophyllite 25%, hornblende 3%, cummingtonite trace, garnet 7%, biotite 7%, ilmenite 2%, and apatite trace. The diopside gneiss contains labradorite 42%, diopside 485, hornblende 5%, calcite 1%, epidote 3%, and sphene 1%. The epidote forms spectacular rims around plagioclase.

Above brow of hill and left of trail is small outcrop of Garnet-Amphibolite Quartzite Member between Lower and Upper Members on upper limb of Tully Brook recumbent anticline. Proceed over hill top to old farm road and turn sharp right (south) down hill. In bed of road are several exposures of schist of the Littleton Formation that have been eroded out since original mapping in the early 1960's. These are on the east limb of the Ball Hill anticline and indicate that the Clough Quartzite shown in Figures 11 and 13 should be moved slightly to the west.

Descend to pick-up point on Royalston Road. For those who arrive well ahead of the main group, two outcrops on opposite banks of Tully Brook are pointed out.

Station n Outcrops and blocks of Littleton Formation coarse sillimanite schist.

Station o Outcrops and blocks of Clough conglomerate on east limb of Ball Hill anticline.

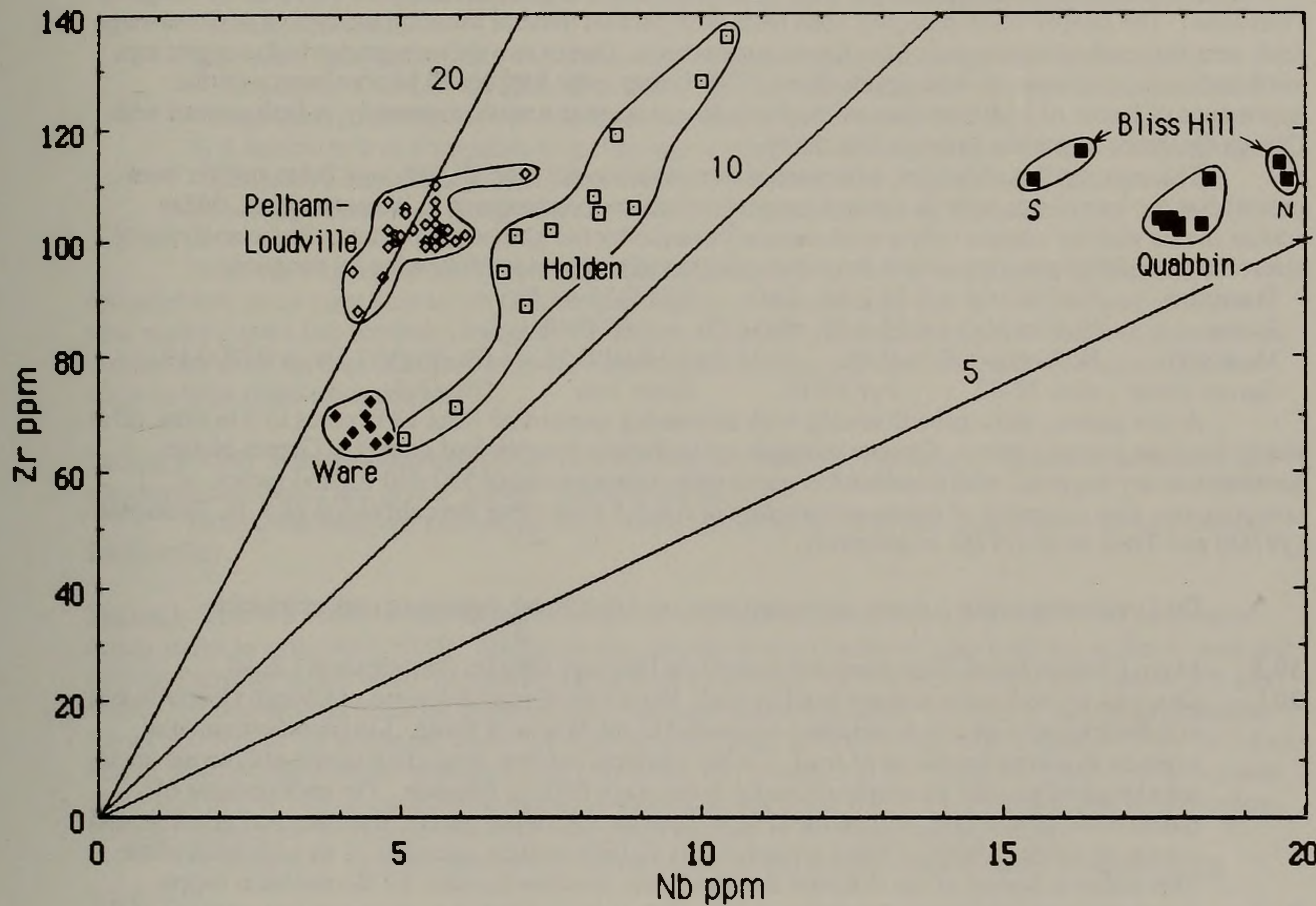
15.4 Road log commences at junction on Royalston Road (mileage to pick-up point included). Proceed west on Royalston Road past Stations n and o.
15.6 Turn left (south) at BM 258' on traveled road. Royalston Road deteriorates west of here.
16.5 Pavement begins.
16.6 Turn left through green gate at State Park entrance.
16.9 Cross brook outlet of Sheomet Lake. Park in lot on left near outlet or drive into lakeside parking. LUNCH STOP. Outcrops and blocks of Rangeley Formation sillimanite schist cut by south-dipping tourmaline veins east of lake outlet. East of the lake is Bliss Hill, underlain by complexly folded Clough Quartzite in a synclinal hinge of the Bernardston nappe. After lunch continue east through a second gate.
17.1 Turn left (east) on Athol Road.
17.2 Warwick-Orange Town Line. Park on right.

STOP 3. The purposes of this stop are two-fold, to examine the newly discovered south Bliss Hill tholeiitic diabase dike of early Cretaceous age, and to examine a large exposure of Rangeley Formation sillimanite-staurolite schist.

Walk west from the Town Line on the south side of Athol Road to exposure of dike in contact with rusty schist in recently built drainage ditch. The dike contains phenocrysts of Mg-rich orthopyroxene and plagioclase in a fine- to very fine-grained matrix of plagioclase, clinopyroxenes, and magnetite. Amygdules filled by calcite, other secondary minerals, and/or devitirified glass are characteristic. A primary flow structure is defined by oriented plagioclase microphenocrysts, and an internal chill has been found about 4cm from the southeast contact. Major- and trace-element analyses by XRF on two samples show that the rock is a quartz-normative tholeiite with the distinctively high Ni, Nb, and Sr, and "LREE-enriched" pattern on PMREE diagrams characteristic of all the Cretaceous intrusions in central Massachusetts (McEnroe, 1988) as compared to the Jurassic intrusions. On the basis of Zr/Nb ratios (Figure 14) the Cretaceous diabase intrusions must have had a source that was completely distinct from the sources of the more abundant Jurassic intrusions. These Cretaceous intrusions are the youngest igneous rocks in Massachusetts and the only known tholeiites in the Cretaceous province of New England and Quebec.

Walk east from Town Line on north side of road to large road exposure. This recently opened outcrop has been pronounced by Ben Harte of Edinburgh University as the most beautiful sillimanite-staurolite schist he has ever seen. Unfortunately, no electron probe analyses have yet been completed from this location although there is fairly abundant unpublished data from the surrounding region. The massive fibrolite sillimanite veins (described by B.K. Emerson, 1895, as "bucholzite") are here studded with euhedral staurolites.

Figure 14. Plot of Zr versus Nb in ppm with Zr/Nb ratios for Mesozoic diabases in central Massachusetts. The Holden and Pelham-Loudville systems are considered to be early Jurassic, the Ware system probably late Jurassic, and the Bliss Hill and Quabbin groups early Cretaceous.



The rock unit at this location was originally assigned by Hadley (1949) to the Lower Devonian Littleton Formation, then by Robinson (1963) to his Gray Member of the Middle Ordovician Partridge Formation, then assigned back to the Littleton Formation by Robinson (1967), and now on the basis of new work in the Monadnock quadrangle (P.J. Thompson, 1985) is assigned to the Lower Silurian Rangeley Formation! The steeply south-plunging open folds with parallel mineral lineation are typical of dome-stage folds near the south-plunging end of the Keene gneiss dome. One or two delicate graded beds suggest tops north indicating the strata are here upside down. This facing sense happens to be consistent with the appearance of lenses of iron formation of the Perry Mountain to the north, apparently in fault contact with Clough Quartzite across the Brennan Hill thrust.

This outcrop lies about one mile west of the staurolite-out isograd, although it has not yet been proved that the loss of staurolite is due to a prograde reaction or a change of bulk composition. Many schists in this vicinity contain only a muscovite-sillimanite-biotite-garnet assemblage. Probe analyses of staurolite assemblages in gray schists from this general vicinity give the following information:

Staurolite	Fe/(Fe+Mg) = 0.83-0.84,	ZnO 0.27-0.54 wt %;	
Biotite	Fe/(Fe+Mg) = 0.53-0.59,	Ti/11 Ox. = 0.09-0.10;	
Muscovite	K/(K+Na) = 0.74-0.78,	Ti/11 Ox. = 0.01-0.02,	(Fe+Mg)/11 Ox. = 0.08-0.10.
Garnet Rims:	Alm 78-82, Pyr 10-13,	Spess 3-6,	Gros 2-5.

A few garnets show growth zoning with decreasing spessartine from 13 in cores to 3 in rims, all at nearly constant pyrope content. Opaque minerals are uniformly ilmenite and graphite. Garnet-biotite geothermometry suggests, with considerable uncertainty, temperatures of 550-630 °C, and garnet compositions give estimates of minimum pressure of 5.4-6.5 kbar using the calibration of A.B. Thompson (1976b) and Tracy et al. (1976), respectively.

Do U-turn near schist outcrop and return west on Athol Road, bypassing park entrances.

19.3 Mayo Corners again. Turn sharp left (south) on Hastings Heights (hastingsites?) Road.

20.1 Outcrops on both sides at sharp bend in road. West side of road is formed of Clough Quartzite that is autochthonous on a tight anticline connected to the Warwick dome. Littleton Formation is exposed in a large knob east of road. On the Littleton outcrop, projecting quartz-sillimanite knots are elongated parallel to steeply plunging dome-stage folds in foliation. The rock consists of quartz 68%, biotite 15%, sillimanite 12%, muscovite 5%, minor garnet, ilmenite, and graphite, and a trace of zircon. Many Littleton schists in this vicinity contain staurolite as an additional phase. This schist is typical of the Littleton that lies in the syncline beneath the Bernardston nappe.

21.1 Small outcrops of Clough Quartzite on left. This is part of a thin remanent at this position of the inverted limb of the Bernardston nappe that is cut off immediately above by the Brennan Hill thrust.

21.2 Warwick-Orange Town Line.

21.5 Junction 985' with Gale Road. Bear left.

21.6 Sharp left turn off pavement onto Poor Farm Road.

21.8 Blue house on left and private road toward Johnsonian Pond. Depending on number of vehicles, walking tour for STOP 4 will begin here or if number of vehicles is small, it may be possible to drive part way in. Route beyond this point is described in walking log.

STOP 4. The purpose of this stop is to show some of the stratigraphic and structural features that led to the new interpretation of the Mount Grace area. Most of the detailed mapping was completed in 1966 and 1967, but stratigraphic reinterpretation is based on new data and interpretations in the Mt. Monadnock areas by P. J. Thompson (1985) and the Bernardston-Hinsdale area by D. C. Elbert (1985, 1986, 1987). The stop is designed as a traverse in a tectonically upward direction to see a series of features in sequence, all on the nearly vertical west limb of the dome-stage Williams Pond syncline. All lineations and minor fold axes, except at one outcrop, plunge 40-60° south-southeast parallel to the axis of the Williams Pond syncline. The one exception is the group of minor folds contained within a boudin of iron formation at <u>station f</u> that plunge 35-40° north and appear to belong to an earlier stage of folding. The features to be seen in sequence are:

1) Typical Littleton Formation from beneath the Bernardston nappe.
2) Sulfidic schist of the Partridge Formation with minor amphibolite boudins in a belt 100 feet wide that constitutes what remains of the anticlinal core of the Bernardston nappe. This is in direct contact with Littleton to the west, indicating absence or shearing out of Clough Quartzite in this location on the nappe.

3) Boudins of quartz pebble conglomerate with pitted matrix along contact between Partridge and gray feldspathic schist of Rangeley Formation to east. This is the inferred location of the Brennan Hill thrust. Along this contact to the south, large boudins of iron formation assigned to the Perry Mountain formation will be seen, indicating the stratigraphic sequence above the thrust is inverted.
4) A belt of gray feldspathic and sillimanitic schist and granulite assigned to the Rangeley Formation. This belt occupies an isoclinal syncline believed to have formed in the backfold stage during northward over folding of the main body of Monson Gneiss.
5) A narrow belt of feldspathic granulite-matrix conglomerate assigned to the lower member of the Rangeley Formation. This is in contact to the east with the Augen Gneiss Member of the Partridge Formation along a contact tentatively believed to be an unconformity .

From the blue house (see Figure 15) walk or drive north to fork in wood road. Where more travelled fork bears right bear to left (limited parking here). Continue on foot on left fork past old stone post marking town line between Orange and Warwick. Continue on wood road until evergreen trees end and continuous grass appears in middle of road. Turn right (north) across stone wall and walk about 200 feet north to large ridge-top outcrops.

Station a Gray homogeneous sillimanite-rich schist of the Littleton Formation. Quartz-sillimanite knots are evenly distributed and give a "braille" effect to the outcrops.

From these outcrops move diagonally down hill about S35E to east-facing outcrops overlooking small valley.

Station b This is a series of east-facing outcrops on west side of small valley to be traversed diagonally across strike in a direction N40E. Southernmost outcrop shows contact of gray Littleton schist to west and sulfidic Partridge schist of the Bernardston root zone to the east. At this location the root zone is 105 feet wide. The next several outcrops show sulfidic Partridge schist with small boudins of biotite amphibolite. About 200 feet to the northeast where the outcrop is steepest, sulfidic schist is in contact with a 1- to 2-foot lens of pebble conglomerate beyond which gray schist and granulite of the Rangeley Formation is exposed. A 10-inch pod of biotite amphibolite occurs in sulfidic schist about ten feet west of the conglomerate lens. The east edge of the sulfidic schist is the postulated location of the Brennan Hill thrust.

From base of highest outcrop walk south about 50 feet across shallow valley to north-facing outcrop.

Station c A thin layer of pitted conglomerate is in sharp contact with sulfidic schist to west and in contact with gray schist and feldspathic granulite to the east. This was originally interpreted as Clough Quartzite between Littleton and Partridge on the upper limb of the Bernardston nappe. However, the conglomerate and the gray schist and granulite are much more like rocks in the Rangeley Formation as defined in the Monadnock area. Traverse east across north slope and then northeast and downhill through a series of large outcrops of gray schist and feldspathic granulite of the Rangeley Formation, heading for a small southeast-trending stream gully shown on topographic map.

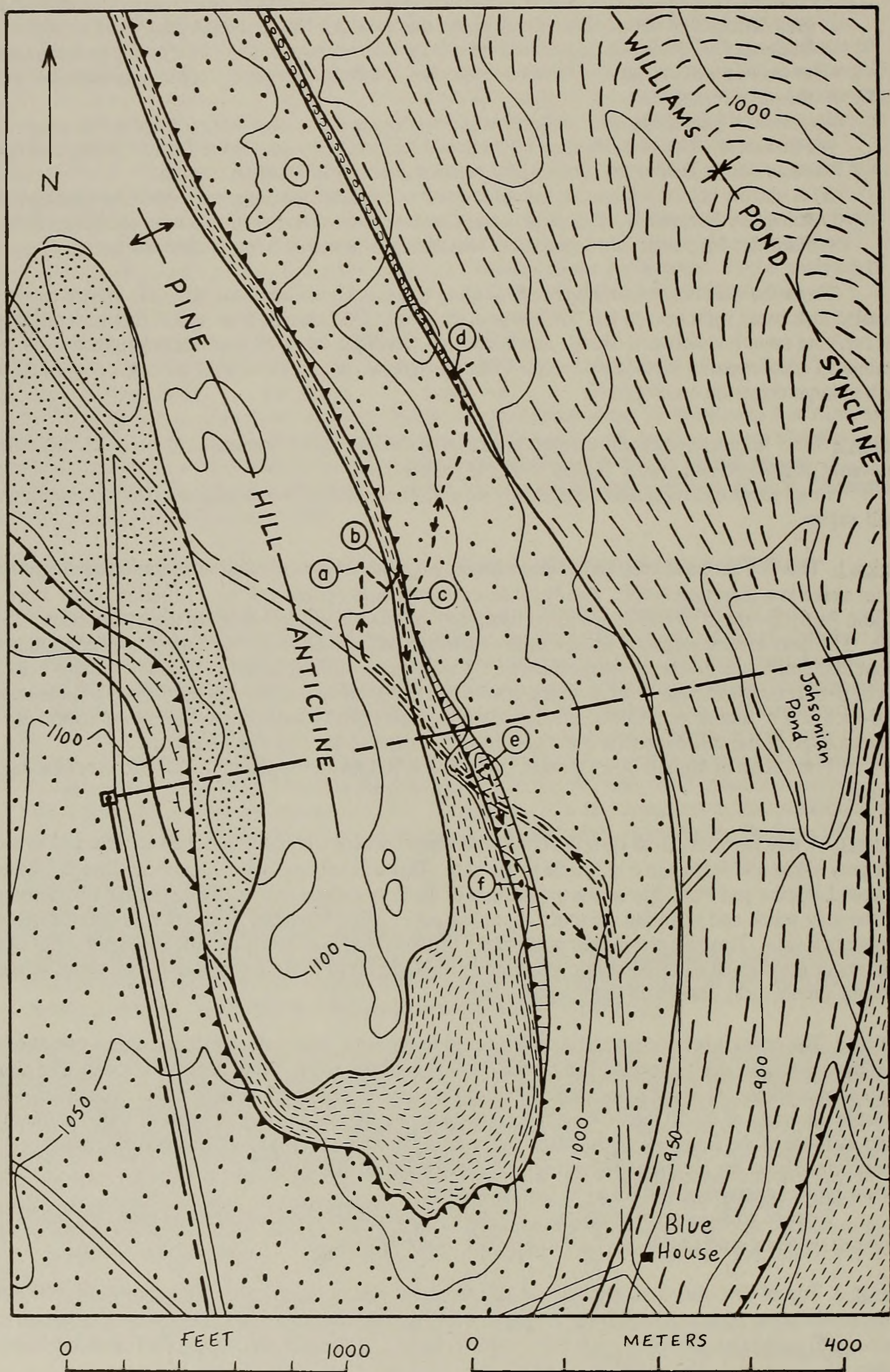
Station d The contact between gray Rangeley schist to the west, and rusty schist and augen gneiss of the Partridge to the east can be located just on the north side of the gully. From here for a distance of about 250 feet north there are small outcrops and numerous loose blocks of granulite-matrix conglomerate with a probable thickness of 20-40 feet. These resemble the granulite-matrix conglomerate describe in the the lower member of the Rangeley in the Monadnock area (Thompson, 1985) and here may be resting unconformably on the Partridge Formation. Walk east 100 to 200 feet to view typical exposures of the Augen Gneiss Member.

Retrace walking route to station c and follow shallow valley south to wood road. Proceed southeast on wood road past Warwick-Orange Town Line marker.

Station e Top of obvious small knob about 100 feet northeast of wood road. This shows the northernmost of several boudins of iron formation assigned to the Perry Mountain Formation based on the section at Biscuit Hill near Hinsdale, N. H. (see Elbert, this volume). It lies exactly along strike from the contact at station c.

Walk southward parallel to strike across wood road to small steep outcrop on south side. Here is exposed an unusual lens of conglomerate tentatively assigned to the Perry Mountain. It consists of dark

Figure 15. Detailed map of STOP 4 showing the Brennan Hill thrust above an attenuated anticlinal root zone of the Bernardston nappe.



pebbles in a quartz-rich matrix. The dark pebbles consist of garnet, grunerite, apatite, dark green ferric chlorite and a trace of magnetite. The matrix consists of quartz, apatite, grunerite, hornblende, and minor chlorite and garnet. The pebbles appear to be redeposited fragments from the iron formation. Continue south at same elevation across woods trail to high-standing knob held up by two large boudins of iron formation.

Station f This large outcrop was discovered by Robinson in 1966 and mapped in detail following appropriate cleaning by Huntington (1975). Figure 16A, based on his Figure 2 shows the distribution of rock types in the outcrop, including gently plunging early folds and the steeply plunging boudin neck line separating the two parts of the outcrop. Figure 16B shows details of delicately folded apatite-rich beds in the southern part of the outcrop. Except for the fact that the rocks are now assigned to the Perry Mountain Formation rather than the Littleton, there is little to add to Huntington's detailed mineralogical and petrological analysis. Yet to be accomplished is an analysis of the sedimentary environment and paleogeography at the time of deposition of these unusual rocks during the late early Silurian.

The low area west of the knob contains small outcrops of sulfidic schist and amphibolite of the Partridge Formation in the Bernardston root zone.

From the knob walk east on woods trail over pavement outcrops of feldspathic granulite of Rangeley Formation. Trail connects with fork in road. From there return south (right) back to blue house on Poor Farm Road.

Following Stop 4 continue driving down Poor Farm Road. Bottom of valley coincides almost exactly with position of synclinal keel of main body of Monson Gneiss.

22.7 Farm views on right showing valley eroded in main body of Monson Gneiss.

23.2 Junction and beginning of pavement at Athol Road. Turn sharp right (northwest) on Athol Road and descend again into basin of Monson Gneiss.

23.6 Turn sharp left (south) at bottom of hill onto North Main Street, Orange. On left is Williams Pond, for which the dome-stage structural syncline is named, here expressed as a south-plunging keel of inverted Monson Gneiss. Proceed south through basin eroded in Monson Gneiss. As one approaches northern outskirts of Orange there are fine views to the southwest showing the prominent topographic ridge of Partridge Formation and Ammonoosuc Volcanics that bounds the Monson Gneiss to the west.

27.9 Stop lights in center of Orange. Proceed straight through and cross bridge over Millers River.

31.4 Turn right onto eastbound entrance ramp of Route 2. Part way up ramp on left is cut in Monson Gneiss from which sample was collected on which R. E. Zartman obtained a zircon age of 440-450 m.y. Proceed east on Route 2.

32.6 Exit for Route 202. Continue east on Route 2.

34.3 Bushed-over road cut on right. Gneisses in eastern part of main body of Monson Gneiss.

35.4 Athol road cut. Larger, long trench cut, both sides. STOP 5. If traffic permits, particularly if you intend to proceed west after this stop, bear left across highway to broad and firm grass strip on north side. This area is much safer and better for viewing the geology than the narrow area on the south side. Since Figure 18 was drafted in 1979 the south side of the Athol cut has been blasted back about ten feet. This has changed some details, but has not altered any essential features.

STOP 5. See Figures 17 and 18. This outcrop is dominated by a Mesozoic normal fault cutting the south end of the Tully body of Monson Gneiss. The south end of the Tully body is a simple anticline overturned to the east and plunging gently south-southwest. Dome-stage normal asymmetric folds occur on both limbs. The exposures at Stop 5 are the southernmost ones of the gneiss in the core of the Tully body. At this point the anticline is cut just west of its crest by a west-dipping normal fault, the Athol fault, bringing gray schists of the Rangeley Formation on the west limb down about 1300 feet into contact with Monson Gneiss of the core. The actual fault zone is about ten feet wide and contains gouge zones, hematite-stained and cemented breccia, intense silicification, and vuggy quartz veins, all features characteristic of known Mesozoic faults. Secondary alteration extends into the metamorphic rocks on both sides for a considerable distance. Here the fault strikes N4W, but regionally it strikes N15E.

On the east limb of the anticline, east of the gneiss of the core, is a thin layer of rusty Partridge schist which has been traced for many miles. Well bedded amphibolites at both contacts probably belong to the Partridge, although it is tempting to consider that they might represent the Ammonoosuc Volcanics highly attenuated. Next east of the schist and amphibolite is a layer of Monson Gneiss (Creamery Hill

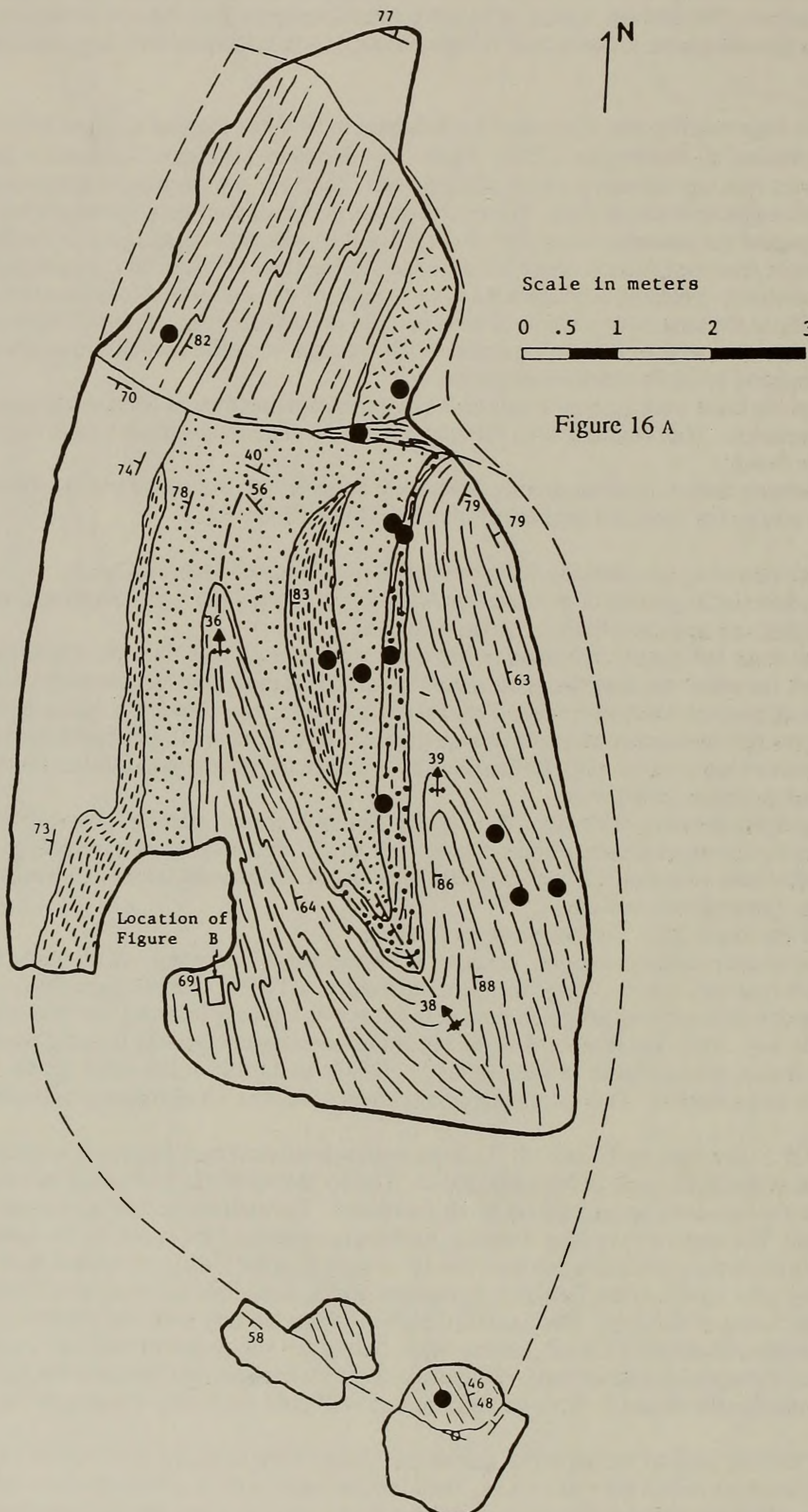

N
Scale in meters
0 .5 1 2 3
77
82
70
74
78
40
56
79
79
83
36
63
39
73
86
Location of
Figure B
64
69
88
38
58
46
48

Figure 16 A

Grunerite-garnet-pyrrhotite granulite

Olivine-magnetite granulite

Olivine-pyroxmangite granulite

Garnet-grunerite-quartz granulite

Mica-garnet schist

Sillimanite-muscovite schist

● Sample location

Strike and dip of foliation

Trend and plunge of fold axis

Trace of axial surface of syncline

Trace of axial surface of anticline

Offset sense of fault in boudin neck zone

Fault

Known contact

Inferred contact

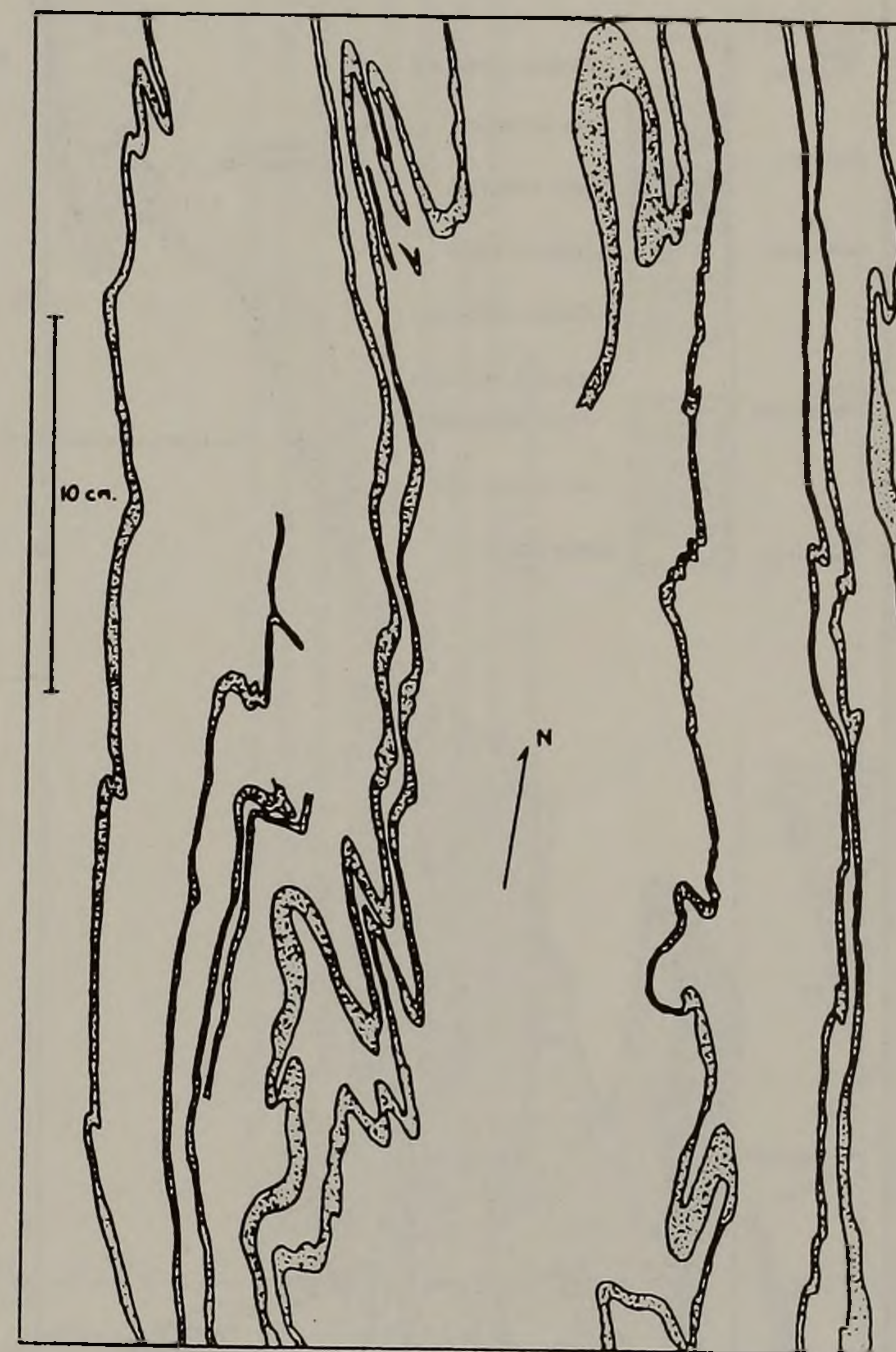


Figure B

Figure 16. Detailed outcrop map of boudins of iron formation in Perry Mountain Formation at STOP 4, station f (from Huntington, 1975). A. Outcrops of two boudins surrounded by sillimanite schist. B. Detail map of inset area showing complexly folded apatite beds.

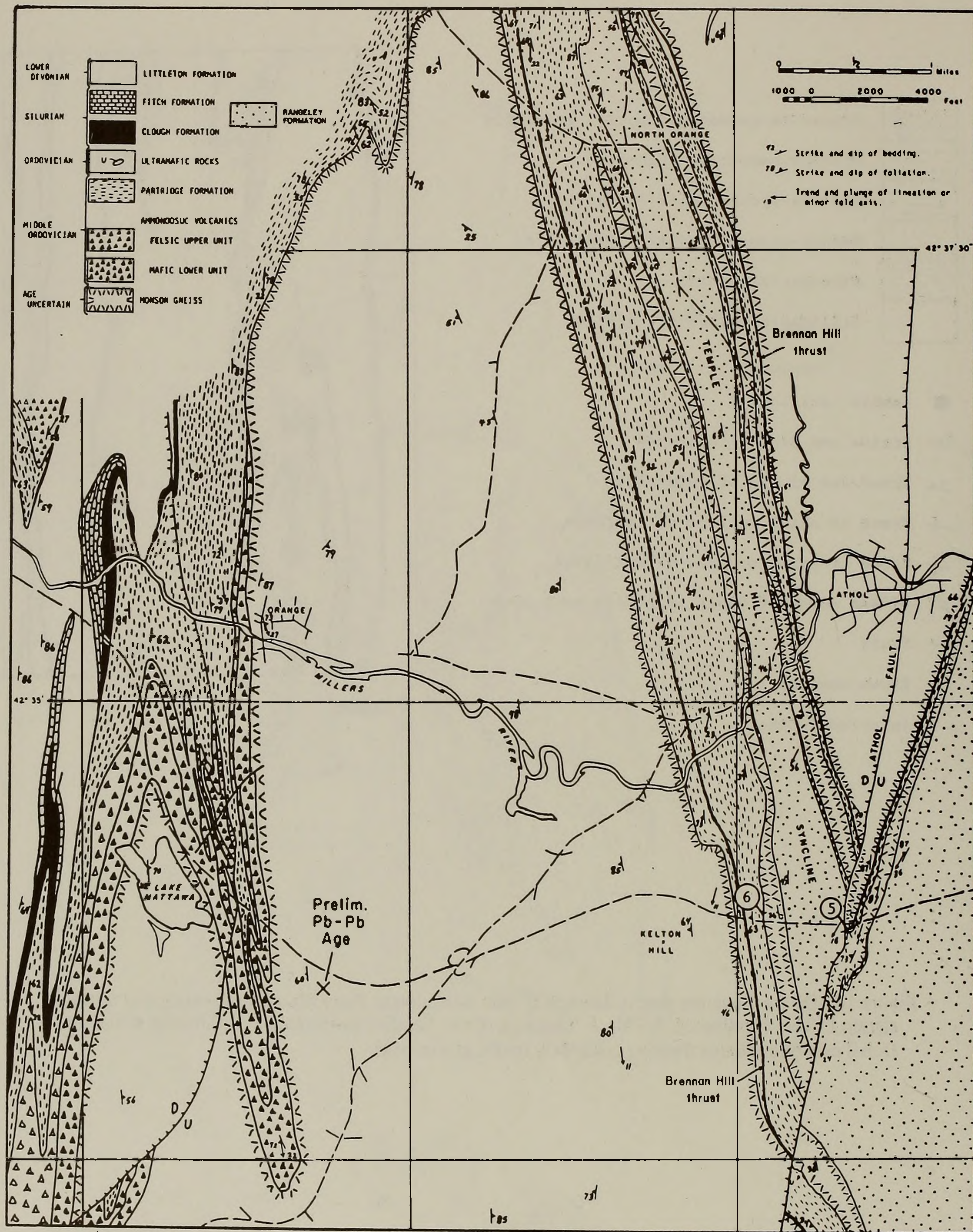
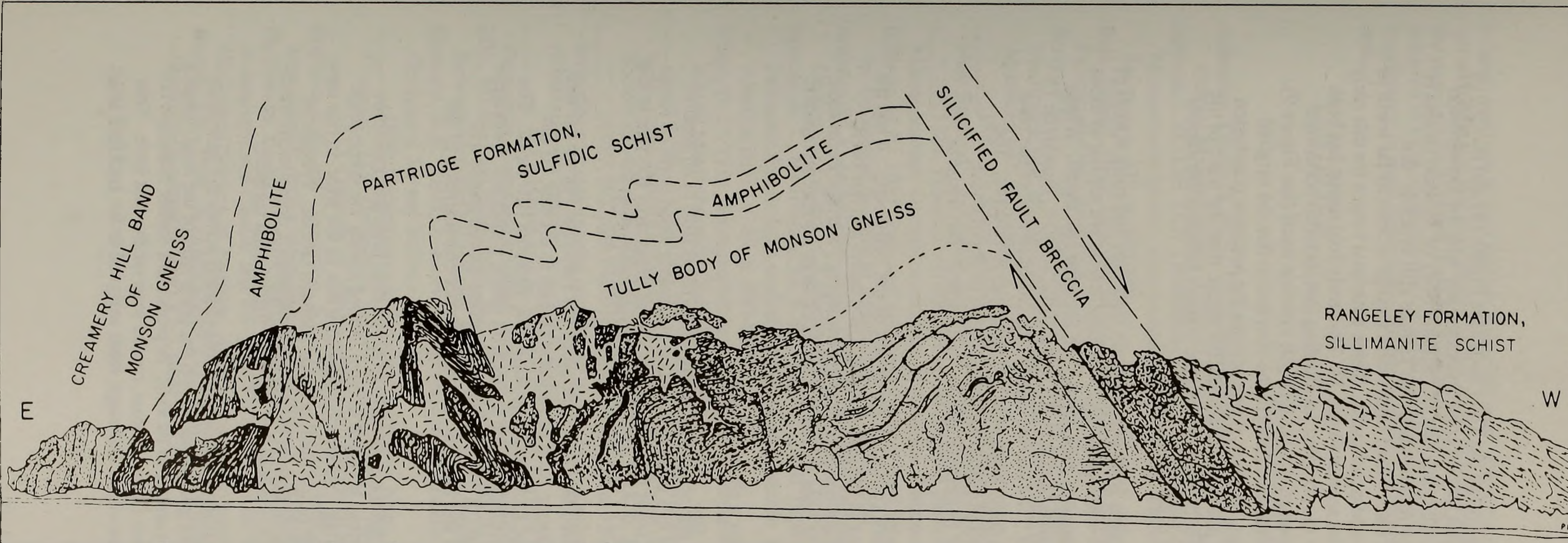


Figure 17. Geology of the eastern part of the Orange area, showing postulated position of North Orange nappe and Brennan Hill thrust in relation to STOPS 5 and 6.



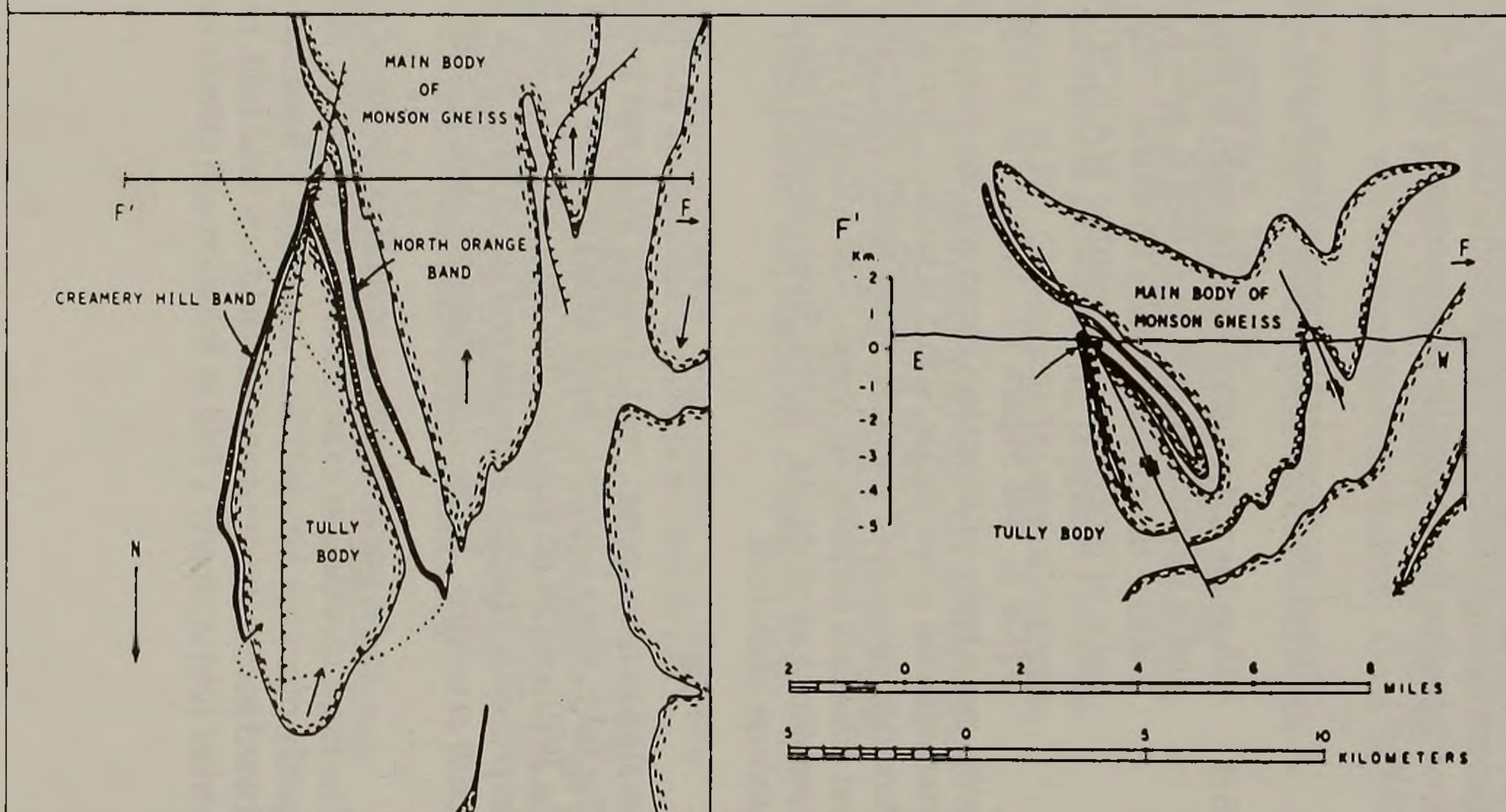


Figure 18. Sketch of south wall of rock cut at STOP 5. Mesozoic Athol fault cutting crest of Tully body of Monson Gneiss. Approximate location of cut is shown by tiny stippled rectangle in inset cross section. The major anticlinal or dome axis and satellitic folds and mineral lineations are parallel to a strong Beta maximum (10% per 1% area) with trend N22E, plunge 18SW (Robinson, 1963). The Creamery Hill band of Monson Gneiss in interpreted (see insets) as an extremely attenuated basement nappe separated from the main and Tully bodies by an extremely attenuated isoclinal syncline and by the Brennan Hill thrust. This can be interpreted as a fold of the same generation as the Bernardston nappe but lying tectonically higher and more easterly (see Figure 9). Drawing does not have constant scale. Outcrop is approximately 50 feet (15 meters) high at highest point.

band) that has been traced entirely around the southern part of the Tully body (see Figure 18) and is interpreted as an early anticlinal fold nappe of gneiss that formed contemporaneously with the Bernardston nappe. A similar band of Monson Gneiss (North Orange band) east of the main body of Monson Gneiss is interpreted as the same recumbent anticline repeated by folding about the Temple Hill syncline that separates the two bodies. The North Orange band has been traced from North Orange at least as far south as the northern edge of the Palmer quadrangle in southern Massachusetts. Three anticlinal hinges for this early fold nappe, now named the North Orange nappe, can be seen in Figure 17. This early fold nappe has been severely involuted, both by dome-stage folding and by the complex backfolding that included northward transport of the main and Tully bodies and the formation of the Temple Hill syncline itself (see Figure 9). Nevertheless a rational unwinding of these later deformations leads to the conclusion that the original transport direction for this nappe was from east to west. Further, if one accepts the tentative conclusion that the North Orange nappe lies in rocks structurally above the Brennan Hill thrust, then the trace of the Brennan Hill thrust must also lie in this outcrop, probably at or close to the contact between the narrow belt of Partridge Formation and the gneiss in the core of the Tully body.

The next outcrops to the east on Route 2 (visible from here) contain both gray and rusty schists of the Rangeley Formation on the east limb of the dome-stage anticline. The gray schists are similar to those on the west limb. These rocks are typical of a wide range of rocks above the Brennan Hill thrust. Where the schist has not suffered secondary alteration it consists of quartz 30-50%, biotite 20-40%, muscovite 15-30%, garnet 2-5%, and minor sillimanite and graphite. The assemblage is thus characteristic of the zone above the breakdown of staurolite, but below the first occurrence of sillimanite plus K-feldspar. The abundant pegmatite segregations that may be a product of partial melting, consist of about equal proportions of quartz and sodic oligoclase with minor muscovite, biotite, and garnet. The schist is commonly rich in biotite at contacts of segregations.

A curious pegmatite dike occurs on the eastern contact of the gneiss of the Tully body. It has the appearance of having been generated by partial melting in the gneiss of the Tully body, and has been injected through the contact amphibolite (note discordant contacts) into the overlying Partridge Formation. Since intrusion the pegmatite and its country rock have been folded in a series of large normal asymmetric folds.

Return to pavement westbound on Route 2 for a short distance.

36.3 Go to far end of grass strip on right beyond one section of guard rail. This is firm in all weather and is the parking spot for STOP 6, which is in a large road cut on Bachelder Road north of Route 2 where there is essentially no traffic. Trail leads from northwest end of grass strip 100 feet to low point of fence. In clear weather WATCH OUT FOR FALLING PARACHUTISTS!

STOP 6. See Figure 17. In this cut is exposed the contact between the Partridge Formation next to the main body of Monson Gneiss and the North Orange band of Monson Gneiss to the east. If the interpretation given under Stop 5 is correct, then all of these rocks lie above the Brennan Hill thrust. The Partridge consists of purplish, rusty-weathering plagioclase-biotite schist with minor garnet and sillimanite and abundant amphibolite layers. The Monson consists of interlayered plagioclase-biotite gneiss and hornblende amphibolite. A few layers contain garnet and anthophyllite that are not characteristic of the Monson elsewhere.

The dominant structural features are gently plunging, open to isoclinal anticlines and synclines parallel to the regional trend of minor folds and lineations believed to have formed during the dome stage. The folds show a normal sense of asymmetry indicating a major synclinal structure to the west, in this case the Williams Pond syncline that runs down the center of the main body of Monson Gneiss. Prominent amphibolite boudins in gneiss and schist have neck lines normal to fold axes suggesting dome-stage north-south extension. In the schist there are several examples of earlier folds with folded axial surfaces.

In the gneiss there are several examples of earlier lineations and folds folded across the later folds. The most spectacular example is at the top of the third gneiss outcrop on the north side of the road. Here a gently plunging late anticline has a biotite lineation parallel to its axis. A prominent earlier lineation is folded across the crest and a related isoclinal fold, plunging southeast, can be seen on the east limb. This earlier fold is clearly a fold in foliation and closely resembles 2nd-stage folds assigned to the backfold stage in large outcrops in the Quabbin Reservoir area. Even the movement sense of this early fold can be worked out and indicates that structurally higher rocks moved north. This is at least conceptually consistent with the postulated northward flowage of the main body of Monson Gneiss during the backfold stage, which is believed to have involuted the earlier North Orange nappe. This is the best exposure showing fold interference in three dimensions that has been seen in central Massachusetts outside the Quabbin Reservoir area.

END OF TRIP.

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