1-1-1985

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Recommended Citation

John L. Rosenfeld and Eaton, Gordon P., "The Middle Haddam Area, Connecticut, Revisited" (1985). *NEIGC Trips*. 376.
https://scholars.unh.edu/neigc_trips/376

THE MIDDLE HADDAM AREA, CONNECTICUT, REVISITED*

by
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Introduction

It has been 27 years since we led a field trip to the Middle Haddam area on the occasion of the 50th NEIGC in 1958. That area is largely contained within the U.S.G.S. Middle Haddam Quadrangle as shown in **Appendix A**, modified after Figure 16-2 of Dixon and Lundgren (1968). The field mapping, started in 1955, had been carried on part-time by both of us while we were teaching at Wesleyan University. Thus the results and interpretations presented at that time were preliminary at best. In 1957 Rosenfeld went to UCLA and left most of the continuation of the field mapping to Eaton with Rosenfeld's minor contributions during parts of some summers thereafter. After 1959, when Eaton left Wesleyan for stints at both UC Riverside and the U.S.G.S., the field work was carried out in a much more interrupted manner with Eaton, largely supported by the U.S.G.S., still carrying the major load until completion of the Geologic Map of the Middle Haddam Quadrangle. That map has been available, open-file, from the U.S.G.S. since 1972. We currently are completing the detail work preparatory for submission of the map for publication in the U.S.G.S. GQ series with Eaton as principal author. Condensed versions of both that map and its accompanying tentative cross sections, accompanied by reinterpretation of the sequence of units, are presented here as Figures 1, 2, and 3 respectively. Table 1 is the description of the map units keyed to unit symbols appearing in those figures. For brevity, after introductory reference to a unit, its symbol rather than name will be used in the text. The purpose of this field trip will be to explore some of the geological relationships so as to expose participants to both the general bedrock geology and some of the facts that have forced us to revise a number of the 1958 interpretations.

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*Because a "dry run" is difficult to do from Los Angeles or College Station, the road log, with locality map, will be supplied to registrees at the NEIGC. The stops will be chosen to expose field evidence for major points discussed in the text. There will be about 10 stops. Participants should be prepared for some scrambling in the woods.

Major structures

The Middle Haddam area contains parts of three gneiss-cored anticlines mantled predominantly by schists. Within the southern part of the Bronson Hill Anticlinorium and like most of that major structure's subordinate anticlines, two of these anticlinal structures share many of the characteristics of "mantled gneiss domes" (Eskola, 1949). On the north is the southern end of the elongate Glastonbury Dome, which extends to the north through Connecticut and most of Massachusetts, where it is called the Pelham Dome. Coming into the area from the south is the narrow northern end of the more-or-less pear-shaped Killingworth Dome. The western limbs of these two domes are truncated against the eastern border fault of the Triassic-Jurassic Newark Series. East of the Glastonbury and Killingworth Domes is the relatively narrow Monson Anticline, which extends north almost into New Hampshire and south almost to Long Island Sound, where its gneissic core forms a spur off of the Killingworth Dome.

The Monson Anticline differs in character from the two domes. Since the the work of Lundgren (1964) in the Essex quadrangle to the south, the Monson Anticline should be characterized more specifically as the Monson Nappe. That nappe shows its root in the core gneisses of the subsequently developed Killingworth Dome in Essex. It must have been originally displaced toward the west like many other Acadian nappes to the north, the first one of which was brought to the attention of geologists in 1954 by J. B. Thompson in an NEIGC guidebook (cited *in* Thompson *et al.*, 1968, p. 218). The "Colchester Nappe," (Dixon and Lundgren, 1968; but see also Lundgren, 1964, p. 24 - 29), a large recumbent fold lying in the Hopyard Basin to the east of the "Monson Anticline" and overturned to the east, is then the backfolded part of the Monson Nappe. Thus the name, "Colchester Nappe," should be abandoned. The fold in the Monson Nappe should be called the Dickinson Creek Backfold, named for its axial exposure where a north-south stretch of Dickinson Creek in Marlborough and Colchester (Lundgren *et al.*, 1971, Map) has eroded through the schist of East Hampton (Oeh) or "Brimfield Schist" of Dixon and Lundgren (1968; see **Appendix A** here) on the gently dipping now inverted, but formerly upper, limb of the Monson Nappe. The northeast end of Section C – C' in Figure 2 cuts across the west limb of the Dickinson Creek Backfold of the Monson Nappe. It should of course be recognized here that the validity of the interpretation of the Monson Nappe depends on the correlation of units across the gneissic core containing its axial surface, a subject treated briefly in the next section. We here emphasize backfolding to the east because we show below that there is, within the root zone to the west in the Middle Haddam area, internal evidence of both the kinematic process accompanying such folding and simultaneous progressive metamorphism during the later stages of the Acadian orogeny. Furthermore the geology of the whole of southeastern Connecticut cannot be properly comprehended without explicitly taking into account the effects of that backfolding. Although our view of its genesis (cf. Hepburn *et al.*, 1984, p. 97 - 99) differs somewhat from that of Robinson and Tucker (1982) for the area on structural trend to the north in central Massachusetts, it will be seen below that our view of the timing, nature, and importance of backfolding as a phase of the Acadian orogeny independently parallels their view that takes into account historical evidence.

While Lundgren's work in the Essex quadrangle was published just about the time of the plate tectonic "explosion," a retrospective look at his map, coupled with the later recognition of Avalonian cratonal rocks to the east, suggests that a main Acadian suture, postulating its presence, must lie either east of the Selden Neck "Nappe" or under the nappes of the Bronson Hill Anticlinorium. There appears to be continuity of structures in between. The Honey Hill - Lake Char Fault Zone, though conspicuous because of its relative recency may well have had relatively small displacement, judging from Lundgren's geologic mapping (1964) at its western terminus. Figure 16-2 (**Appendix A**) in Dixon and Lundgren (1968) describes the regional structural relationships, uncomplicated by unnecessary detail. That figure provides a fascinating view of the nappes to the east in the Merrimack Synclinorium affecting strata continuous with those of the Bronson Hill Anticlinorium.

In 1958, because of lithologic similarity to much of Og, we thought the Maromas Gneiss (Pm) formed the recumbent core of a fourth gneissic anticline between the Glastonbury and Killingworth Domes. As will be seen below, we now think that interpretation is untenable for a number of reasons. The reinterpretation of the nature of Pm is part of a rather radical reinterpretation of the geology of the whole area that integrates a number of stratigraphic, geochemical, structural, and kinematic facts into a more coherent picture. The old interpretations will be alluded to henceforth only to the extent that they are relevant to our present interpretations.

The relatively tight synclines separating the anticlinal masses of gneiss show complications because of a history of multiple folding evident both within the area and to the north and south. We infer that important folding in the Middle Haddam Area took place in the Taconic, Acadian, and Alleghenian orogenies. In 1958 we recognized that the Collins Hill Formation (Oc) lay in a proto-Great Hill Syncline before deposition of the Silurian Cough Formation (Sc) and that Acadian folding of Sc, the Silurian Fitch Formation (Sf), and the Devonian Littleton Formation (Dl) into the NNE - trending Great Hill Syncline between the Glastonbury dome and the Monson Nappe took place about an axis now slightly clockwise from, but almost coincident with, that of the earlier folding. The ancestral syncline and proto-Monson Anticline to the east must have served as guiding loci for placement of the later Monson Nappe, of which the original Great Hill Syncline must have been the pre-doming, west-opening complementary underfold. While the axial surface of the isoclinal Great Hill Syncline dips WNW today and its axis projects into the sky to the south of Great Hill, the dip of its axial surface must steepen downward, reverse its direction of dip to ENE, and come back to the surface within Oc in the Ivoryton Synform between the Killingworth Dome and the Monson Nappe (Lundgren, 1964, Geologic Map). Such reorientation at the earth's surface is a likely consequence of the fact that the downward extension of the axial surface of the Great Hill Syncline coincides with the east-northeast-dipping part of the west or lower limb of the gently north-plunging Dickinson Creek Backfold (cf. Appendix A) and/or the perturbation due to the presence of the Killingworth Dome. Also, if the axial surface did not bend in this way, it would be expressed to the south in folding of contacts between older units to either the east or west.

The other syncline of interest is the post-Acadian almost NNW-trending nearly isoclinal Maromas Syncline with its axial surface dipping NE except where it borders the SW and W flanks of the Glastonbury Dome. As outlined by the base of Pm that syncline appears to project into the sky between the NE flank of the Killingworth Dome and the Monson Anticline. Also its axial surface must lie in the Ivoryton Synform . In fact the folding of the axial surface of the early-stage Great Hill Syncline by development of both the (here) gently north-plunging late-Acadian Dickinson Creek Backfold and the Alleghenian Maromas Syncline would seem to have reoriented the axial surface of the Great Hill Syncline, as discussed above. Hence the major part of the difference in orientation between the Great Hill and Ivoryton Synclines. To a limited extent, earlier synforms and contrasts in basement rocks (as between the Glastonbury and Haddam or Monson gneisses) would seem to have served as zones of weakness for development of later synforms.

Rock units and their relationships

Table 1 and Figure 3 concisely describe the units and their relationships as presently interpreted, and we rely on them to communicate that information.

Those familiar with our 1958 interpretations will notice significant changes. The geochronologic work of Brookins and Hurley (1965) and Brookins (1980) establishing the ages of certain units, particularly Pm (the Maromas Granite-Gneiss of Westgate, 1899) as Pennsylvanian - Permian and the pegmatites of the area as both Devonian and Permian, has perhaps had the greatest influence in this regard. Those findings were reinforced by our subsequent field work showing that Pm truncated the coticules of Bible Rock Brook (Obc) and the metavolcanic rocks of Bible Rock Brook (Oba) and that therefore Pm and the amphibolite of Reservoir Brook (Pr) are the youngest metamorphic rocks in the area, lying in the core of a syncline. Whether that contact is depositional or intrusive then remains to be decided. The discordance in turn agrees with the fact that the north-northeast-trending, Acadian, Great Hill Syncline, folding rocks as young as Devonian and, in plan oriented almost perpendicularly to the Maromas syncline, is not reflected where it projects into the latter structure. Consistent with a stratigraphic interpretation of Pm is the presence in Rhode Island not far to the east of protolithically similar volcanics of the right age, the Wamsutta Volcanics. Attractive to a volcanic interpretation is the association of Pm as volcanic protolith with the less metamorphosed slightly gneissoid large subangular clasts of volcanic-like quartz-porphyry observed in the early Jurassic Portland Formation (Jp). The Wamsutta Volcanics and these abundant large pebbles and boulders cry out for geochemical comparison by isotopic methods to test their compatibility with Pm. While we favor interpreting the discordant relationship of Pm to represent an angular unconformity, another credible possibility is that of an intrusive relationship, favored by Westgate (1899). If so, because of the gravitational evidence discussed below, the intrusive must be in the form of a folded thin tabular mass. We slant against the Westgate interpretation because of presence in Pm of mica schist septa, interpreted as metasedimentary layers and the above-mentioned evidence of the clasts. Perhaps more ambiguous is the relationship of Pr to Pm. It is possible that Pr could have been emplaced originally as a mafic sill, but there is still ambiguity in the field relations of Pr.

We retain our belief that Sc is unconformable upon the Glastonbury Gneiss (Og) (Fig. 3), based on absence of cross-cutting relationship over many miles of mutual contact, the absence of expansion of high-grade metamorphic zones into the Siluro-Devonian strata, and regional evidence of similar relationships to the north in Massachusetts and New Hampshire (see for example: Leo *et al.*,1984). Both on the basis of field relationships and Brookins' ambiguous isotopic data, contrary to our views in 1958, we, like Brookins (1980) and Leo *et al.* (1984), are uncertain of the age relationship between Og and Oc. That uncertainty about the age relationship at the base of Oc carries over to the character of its relationship to the Middletown Gneiss (Omi). Formerly we had interpreted discoid quartz-rich nodules in a band near its base (Ocg) as pebbles of a conglomerate, indicating, perhaps, a more important stratigraphic break than might have been the case. The fibrolitic character of these "pebbles," possibly indicating a concretionary/ metasomatic origin, caused us to question that interpretation.

It will also be noted in Table 1 and Figure 3 that we have subdivided the "old" Collins Hill Formation into four units and that we have correlated the oldest, or "new" Collins Hill Formation (Oc) with Oeh to the east of the Monson Anticline. The youngest of the new units, the calc-silicates and schists of Bodkin Rock (Osb), has been correlated with the Hebron Formation (Oh) to the east. Both of these units may well be as young as Silurian if Robinson and Tucker (1982, p. 1738) are correct. After we had made Osb - Oh correlation, we asked ourselves: "What then happens to Obc and the metavolcanic rocks of Bible Rock Brook (Oba) to the east?" The outcrop along the contact between Oeh and Oh is not particularly good, and the contact barely enters the area on the east. A few years ago we decided to check more closely the most promising hilltop along that contact and, to our delight, found a very thin amphibolite and some loose blocks of coarse garnet-rich rock (coticule?) whose probable nearby source bears an uncertain stratigraphic position relative to the amphibolite. There is need for further field checking.

Metamorphism

The metamorphism of the Middle Haddam Area bears both similarities and dissimilarities to other areas to the north. To the north the main observed metamorphic imprint is Acadian. In the Middle Haddam Area Pennsylvanian rocks are metamorphosed, probably into the sillimanite zone (while the schist opposite the entrance to Hurd State Park (Ph) may be of insensitive composition, amphibolites of Pr appear to be of the character commonly found in the sillimanite zone). W-side-up snowball garnets in Ph on the E limb of and approximately coaxial with the Maromas Syncline indicate the syntectonic character of that metamorphism. That Permian metamorphism and its accompanying tectonism cannot extend very far north of the Middle Haddam Area; for E-side-up snowball staurolites in Dl on the E limb of and rotationally coaxial with both the Great Hill Syncline, where it intersects the New London Turnpike (Route 2), and the Dickinson Creek Backfold indicate a relatively undisturbed, syntectonic, Acadian metamorphism at the latter locality. Thus at least two metamorphisms have affected the area. It is uncertain whether Taconic metamorphism has affected Ordovician and older rocks of the area.

Isograds are delineated on Figure 1 without regard to their time of development. It should be noted that, where a relatively high metamorphic grade is most recent, it will tend to mask an earlier lower grade. In such a case the polymetamorphism will be hard to determine. There are two well-defined staurolite - kyanite zones, one along the west sides of the Glastonbury and Killingworth Domes and the other essentially coincidental with the Siluro-Devonian rocks [Snyder (1970) has found sillimanite within these rocks on the east limb of the Great Hill Syncline just north of the area]. Determination of isogradic locations is probably strongly biased by the distribution of those rocks sensitive to their determination. Thus location of the sillimanite isograd along the east flank of the Glastonbury Dome is less than satisfactory because the core gneisses don't have appropriately sensitive compositions, and the bounding Siluro-Devonian rocks are clearly already in the staurolite - kyanite zone along their western side. East of the areas in the staurolite - kyanite zone rocks of sensitive composition commonly contain sillimanite. In the areas so delineated in Figure 1, it is not rare to have both kyanite and sillimanite in the same rocks, the latter in some cases obviously formed at the expense of the former. In 1958 we associated that reaction with a looping pressure - temperature - time path in which tectonism transported the rocks from the kyanite field of stability into that of sillimanite during a single metamorphic event. Now we do not rule out polymetamorphism as a causative factor, as it is easily possible that the Ordovician rocks of the area could have been affected by as many as three epochs of Paleozoic tectonometamorphism: the Taconic, the Acadian, and the Alleghenian. Just inside the east edge of the area is the orthoclase - sillimanite isograd, difficult to locate in many rocks of the right composition because of extensive retrograde metamorphism, evident in coarse, unbent, transverse muscovite flakes. Extensive retrograde metamorphism has also affected the rocks up to a few hundred meters east of the Eastern Border Fault (Figure 1).

Immediately west of the Eastern Border Fault of the Mesozoic, coarse relatively angular (therefore near-source) rock clasts in Jp of units recognizable east of that fault bear witness to the vertical distribution of metamorphic grade in the Eastern Highlands near the fault. This conclusion follows because of one noticeable contrast, apparently missed by Krynine (1950). Where the clasts have sensitive compositions, they are uniformly of lower metamorphic grade than is observed today in the same units in the Eastern Highlands. This observation, discussed in more detail in the 1958 field guide, obviously results from a combination of three geologic processes: upward decline in the grade of metamorphism in the Eastern Highlands at the end of metamorphism, downward displacement of sediments of the Newark Series along the Eastern Border Fault during their deposition, and the net erosion of the rocks on both sides of the fault to the present surface. The "sedimentary inversion" brought about by erosion of the eastern Highlands and deposition of the resulting detritus in the Newark Series, combined with the observed contrast, mandate such an interpretation.

It is perhaps worth mentioning that specimens of metamorphic rocks from this area have been studied by many laboratories and from many points of view in order to gain insight concerning metamorphic processes. Geochemical studies have included oxygen isotope fractionation (and study of other exchange reactions) with thermometric goals and the use of unstable isotopes with geochronological goals (cf. Brookins, 1980). Garlick and Epstein (1967) used a number of our specimens from the Middle Haddam area in their pioneering study of oxygen isotope fractionation among the minerals of metamorphic rocks as a function of metamorphic grade.

Petrographic observations on rocks from the area stimulated the extension of solid inclusion piezothermometry (interestingly, a field with its roots in some observations made by Sorby in the middle of the Nineteenth Century) to a common metamorphic combination, quartz - garnet (Rosenfeld, 1969, p. 318 - 320, 335 - 340). Adams *et al.* (1975, p. 593 - 596) used a specimen of Sc from the east limb of the Great Hill Syncline near the New London Turnpike as an important check on the internal consistency of observationally and experimentally based (for the first time) solid inclusion piezothermometry with experiments on the aluminum silicates, field observations of their occurrence, and oxygen isotopic information obtained for the same and nearby specimens. The combined data, with some redundancy, indicated a depth of metamorphism for that specimen of about 17 km near the temperature maximum of its pressure - temperature - time path.

Pegmatites

The Middle Haddam Area is famous for its pegmatites. Minerals from some of those pegmatites have played a prominent role in the development of radiometric dating from its launching early in this century by Rutherford, Boltwood, and Holmes. In 1958 it could be said that this area "probably contains more pegmatites on which absolute age determinations have been made than any other similar area in the world" (Stugard, 1958, p. 650). As in the case of other geochemical/ petrological methods, the area has played the role of "Rosetta Stone" for comparison of many geochronological methods; and, indeed, one of the principal initiating motivations for our study of the geological relationships around those pegmatites was to put the quantitative data into a full-blown geological context and pose new questions to test the skills of the quantitative geochronologists. Brookins (1980) has established what had previously been inferred on geological grounds alone, namely that the abundant highly deformed pegmatites of the area are of Acadian age and that the relatively undeformed ones, famous among mineral collectors for their beautiful mineral specimens, are of Permian age.

Utility of gravity measurements

Our measurements of gravitational acceleration throughout the area have placed useful restrictions on our structure sections because of significant density variations among units (cf.: Eaton and Rosenfeld, 1972). Thus, we found out that the low-density Maromas Gneiss could not extend very far down. This contributed to its interpretation as a thin and sheet-like mass that was folded into an almost isoclinal syncline. Data on rotated garnets, aquired later and discussed below, support that structural interpretation. Gravity measurements also helped us infer that pelites along the axis of the Great Hill Syncline and its Ordovician progenitor extend to a depth as much as 9,000 feet some distance north of the area and that its axial surface assumes a more nearly vertical attitude at depth, consistent with the backfolding interpretation above. Gravity measurements also helped support the interpretation that the structural basin (Hopyard Basin) containing the backfolded Monson Nappe is a shallow one with relatively dense schistose units extending no deeper than about 2,500 feet.

Rotated porphyroblasts, fold kinematics, and tectonics

With discovery of the utility of snowball garnets in unscrambling tectonometamorphic sequence and kinematics in Vermont (cf.: Rosenfeld, 1968, 1970; Hepburn *et al.*, 1984, p. 93 - 101), in 1959 we tried out some of the procedures used in Vermont on unit Dl in the Great Hill Syncline where it crosses the New London Turnpike. While snowball garnets were not observed, large strike - parallel elongate staurolite porphyroblasts were found to show snowball microstructure. Further that microstructure indicates something startling about the kinematics within the Great Hill Syncline during growth of staurolite. *The sense of rotation does not reverse across the axial surface as might be expected during the flexural folding of a syncline.* Rather the sense appears to be east-side-up and invariant with position in the syncline. That is, the under side of the Great Hill Syncline had been displaced upward relatively. This perplexing relationship remained a provocative fact for many years, with provocation amplified when one of us made observations of the same kind in the Piora isoclinal syncline of the southern Gotthard region, Switzerland, in 1963. *Finally* it was realized that the peculiar tectonometamorphic phenomenon was a synmetamorphic kinematic record of the rotations accompanying backfolding, or *retrocharriage*, in the Alps (Rosenfeld, 1978; 1985, p. 445 -449; figure 4) *after* the syncline had become isoclinal. There had been an inclination from the early part of this century to attribute the rotational senses to the overriding of the Alpine nappes, even though there was much evidence that peak metamorphism had *post-dated* those structures. Also the phenomenon evidently had the same significance in eastern Connecticut that it had in the Alps.

The relationship to *retrocharriage* appears to be as follows (viewing the developing cross sections in both areas in the direction of counter-clockwise rotation for the ensuing snowball porphyroblasts, i.e. to the north in Connecticut and to the east in the Alps): First there is the over-riding of the nappes toward the left, somehow related to a rightward dipping suture at depth and presumably near the root zone of the highest nappe. Then there is the development of the domes/massifs due to some combination of regional compression and buoyant upthrusting. This is accompanied or followed by regional clockwise rotation of the substrate lithosphere as, to the left, the lithosphere starts to override a second right-dipping suture, causing the rightward gravity-induced synmetamorphic slump or *retrocharriage* of material at higher crustal levels atop the domes. It is here that we appear to differ with Robinson and Tucker (1982, p. 1739), who seem to accept a stage of leftward subduction ("westward underthrusting") to explain the backfolds after the main rightward subduction along a right-dipping suture accompanying nappe-formation. We credit the *retrocharriage* to a secondary gravity-sliding *without need for change of suture orientation, only a shift in suture location to the left*. The counter-clockwise rotation evident in the porphyroblasts within the isoclinally folded schist-filled synclines and/or nappe underfolds is caused by shear between the less easily deforming gneiss-cored anticlinal masses as the latter are rotated clockwise due to the *retrocharriage* that simultaneously causes the rightward rolling-back or backfolding of the preexisting nappes. The same rotation accounts for the clockwise rotation and overturning of the axial surfaces of the intervening isoclinal synclines. The rightward shift of thermally blanketing material at shallower levels helps explain in both cases the positioning of isogradic surfaces for their subsequent intersection with the earth's surface during uplift and denudation. Thermal relaxation would cause isograds during development (approximately isotherms for devolatilization reactions) to rotate counter-clockwise relative to the buried rocks, with higher grade rocks on the right- or under- sides of the subsequently left-dipping isograds.

During the period of perplexity concerning rotational senses of porphyroblasts in the Great Hill Syncline, Dixon and Lundgren (1968) had discovered to the east the Dickinson Creek Backfold mentioned earlier. That fold bears the same spatial and kinematic relationship to the Great Hill Syncline that the Chiera and Alp Campolungo Backfolds bear to the Piora Syncline. Thus *retrocharriage*, noted at the same time as the Dickinson Creek Backfold, but offset west in Vermont (Rosenfeld, 1968, p. 200), is apparently an important aspect of the later stages of the Acadian Orogeny in parts of New England (for more on a relationship to plate tectonics in Vermont, see: Hepburn *et al.*, 1984, p. 93 - 101) as it is of the Alpine Orogeny in Europe.

We also looked at the Maromas Syncline from the standpoint of rotated porphyroblasts. That fold shows evidence of having behaved kinematically like a "normal" flexure-slip syncline with rotations of opposite senses on its two limbs during the Alleghenian tectonometamorphism. Thus, in Ph on the east limb near the entrance to Hurd State Park, snowball garnets show west-up rotation like the asymmetric chevron folds with which they are associated. In an amphibolite of the Collins Hill Formation, Oca, on the southwest limb, rotated garnets show about the same amount of rotation with the opposite sense, again like the asymmetric chevron folds with which they also are associated.

There is much more to be done with rotated porphyroblasts in the Middle Haddam area, as we have not done a thorough study of their behavior throughout the area. There may yet be surprises.

Summary

Figure 3 concisely summarizes the geological history of the area. Within the Paleozoic there are three major breaks, each consisting of major tectonism followed by substantial erosion. There is also strong evidence that, at least, the latest two tectonisms were accompanied by medium- to high- grade metamorphism. The earliest tectonism, the Taconic, not well defined within the area, was apparently fairly closely coincident in orientation to that of the later Acadian. Late-stage backfolding was an important phase of the Acadian Orogeny in eastern Connecticut. The latest Paleozoic orogeny, the Alleghenian, was strongly discordant; and the boundary of its effects is not well defined. Given that boundary's presence west of New Haven, its fairly well-defined location to the east in Rhode Island, and the evidence mentioned earlier along the New London Turnpike, it seems probable that the Middle Haddam area is very near that boundary. It would seem that there remain many opportunities for isotopic geochemists in further testing some of the, what may appear to be, rather speculative interpretations that have been put forward above. There's probably even some opportunity for more field study, especially taking advantage of rotated porphyroblasts.

Acknowledgments

Most of our acknowledgments are of those who helped us almost three decades ago, especially our then contemporaries working in nearby areas and areas to the north: Janet Aitken, Bobbie Dixon, Dick Goldsmith, Larry Lundgren, John Lyons, John Sanders, George Snyder, and Jim Thompson. In particular, it is important to recognize the significance of the field work of Lundgren and Goldsmith, who took advantage of Nature's gift in the form of the northward-plunging structures in southernmost Connecticut to provide some of the most important data yet for geological relationships east of the Bronson Hill Anticlinorium. Since the earlier time we have benefitted from extensive interaction with Dick Naylor, Pete Robinson, and, recently, Peter Bird. E-an Zen has been helpful with regional ideas. Since 1958 we have also benefitted from the input of a host of isotopic geochemists, cited in the references. In fact studies of this area reflect the continuing tradition of exemplary cooperation between both the field geologists and the isotopic geochemists working in eastern Connecticut that has resulted in many synergistic benefits to our understanding. Particularly we have interacted frequently, both in the field and in-house, with Doug Brookins; and he has been a principal factor in forcing us to reexamine some of our old ideas. We have also benefitted from advice and encouragement (including prodding) from Marland Billings, the late John Lucke, Joe Peoples, John Rodgers, and Jim Thompson. Also Howard Day, Ed Grew, and our friends over at Brown University, including the late Bill Chapple and Lonny Quinn, kept us sensitive to the fact that something went on during the Permian in this part of New England!

Sources of financial support for the study included The National Science Foundation, the Committees on Research of Wesleyan University and UCLA, and the U.S.G.S.

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TABLE 1
DESCRIPTION OF MAP UNITS

[Jp]PORTLAND ARKOSE – reddish-brown to pale-brown arkoses ranging from micaceous mudstones to coarse sandstones and polymict cobble and boulder conglomerates containing angular to rounded clasts of the rock units present east of the border fault (but of lower metamorphic grade), pegmatite, and, rarely, vesicular basalt. Conglomerates become more abundant and coarser, and clasts become more angular toward the border fault. Clasts show varying degrees of retrograde or diagenetic alteration. Clasts of quartzite, probably derived from the Clough Formation, are found only from the latitude of Duck Hill north.

[TRJd]DIABASE DIKE–dark-gray, tough, ophitic, hypersthene-bearing augite-plagioclase-magnetite diabase, locally containing biotite and hornblende; characterized by interstitial micrographic granite and microclusters of augite.

STRONG ANGULAR TECTONOMETAMORPHIC UNCONFORMITY

[ℙDp]PEGMATITE, UNDIVIDED–pink to white granitic pegmatite possibly of more than one age; it contains, in addition to microcline, microperthite, and (or) albite: quartz, highly variable amounts of muscovite and biotite, and minor beryl, apatite, black tourmaline, sphalerite, and several uranium minerals. Includes foliated and nonfoliated, bodies, both concordant and discordant [not delineated on this map].

[Pr]AMPHIBOLITE OF RESERVOIR BROOK–dark-gray to black, massive to flaggy, mainly schistose to granulose, biotite-hornblende amphibolite containing oligoclase or andesine; minor sphene, apatite, and ilmenite; oligoclase schist and gneiss and masses of granite augen gneiss, locally containing few dark minerals and resembling the Maromas Gneiss. Rocks show extensive alteration near the Triassic border fault.

[Ph]SCHIST OPPOSITE HURD PARK ENTRANCE–very fissile, silvery muscovite schist containing rotated garnets.

[Pm]MAROMAS GNEISS–very light gray to orangish-gray, massively to coarsely foliated microcline- and oligoclase-bearing biotite, biotite- hornblende, and biotite-muscovite granite gneiss, with subordinate granodiorite to quartz diorite gneiss containing minor sphene, zircon, and garnet. Some of the gneiss has large augen and flaser of orthoclase, easily observed in curbstones in Middletown. Includes abundant lenses, strata and bands of feldspathic biotite-muscovite schist, plagioclase-quartz, diopside-garnet granofels, hornblende-biotite-quartz plagioclase gneiss, and garnetiferous hornblende-biotite schist, the largest of which may be culminations of infolded Collins Hill Formation.

STRONG ANGULAR TECTONOMETAMORPHIC UNCONFORMITY

[Dl]LITTLETON FORMATION–Mainly silvery-gray to lead-gray muscovite - biotite - staurolite -garnet-plagioclase schist, with subordinate interbedded light-gray "sugary" feldspar-quartz-mica-garnet granofels, and distinctly subordinate muscovite- biotite- garnet-albite schist and bytownite- hornblende-clinozoisite- garnet granofels. Lengths of staurolite crystals commonly exceed 2 inches; and, where elongate parallel to strike, staurolite shows "snowball" microstructure, indicating syntectonic growth. Lead-gray color due to finely disseminated graphite.

[Sf]FITCH FORMATION–medium-gray, finely laminated, fine-grained calc-silicate schist and granofels containing highly variable proportions of plagioclase (commonly bytownite), quartz, biotite, muscovite, microcline, calcite, diopside, clinozoisite, tremolite-actinolite, garnet, sphene, and scapolite. Minor tourmaline, apatite, graphite, pyrrhotite, ilmenite, allanite, and zircon. Outcrops are characteristically fluted and pitted due to weathering of common calcitic layers and nodules and commonly display extremely tight folding.

[Sc]CLOUGH FORMATION–white to very light, gray, muscovitic, locally garnet-bearing, quartzite and quartz pebble conglomerate, with subordinate laminae and stringers of silvery muscovite-biotite-garnet schist. Contains subordinate kyanite, staurolite, tourmaline, rutile, and zircon. Garnet in schist laminae commonly occurs as thin wafers having the thicknesses of including laminae.

ANGULAR TECTONOMETAMORPHIC UNCONFORMITY

[Og]GLASTONBURY GNEISS [undifferentiated on map; may be older than Collins Hill Formation]

Muscovitic phase–light-gray, massive to moderately well foliated, prophyroblastic to augenoid, muscovite- and (or) sericite-bearing granite gneiss consisting primarily of microcline (and locally orthoclase), oligoclase, and quartz (the aggregate total of which constitutes about 92 percent of the rock), and biotite, locally with minor sphene, garnet, zircon, allanite, and magnetite and sparse calcic scapolite. Potash feldspar commonly in the form of augen.

Biotitic phase–light- to medium-gray, locally orange-stained, massive to foliated, microcline-bearing biotite granite and granodiorite gneiss; distinguished from muscovitic phase by absence or near-absence of muscovite and the local presence of epidote, a trace of hornblende, and a little garnet. Locally contains minor coarse-grained allanite. Here and there are flattened clots and spindles of dark-gray hornblende gneiss of probably xenolithic origin.

Hornblendic phase–medium- to dark-gray, massive to subschistose hornblende-biotite granodiorite to quartz diorite gneiss; distinguished from biotitic phase by the presence of abundant hornblende, a much greater abundance of epidote and a lower proportion of microcline.

[Oh]HEBRON FORMATION–interbedded gray to brownish-gray quartz-biotite-plagioclase schist and pale-greenish-gray, quartz- plagioclase-biotite-microcline-actinolite or hornblende-diopside calc-silicate rock, containing subordinate sphene, graphite and, rarely, calcite; locally contains major amounts of scapolite (probably equivalent to Osb).

[Osb]CALC-SILICATE ROCKS AND SCHISTS OF BODKIN ROCK (PROBABLY HEBRON EQUIVALENT)–Highly varied, well-bedded formational unit consisting largely of three major rock types (all showing considerable cataclasis and alteration near the Triassic-Jurassic border fault):

(1) Greenish-gray calc-silicate granofels and light-gray calcite marble containing highly variable proportions of calcite, diopside, calcic amphibole (mainly hornblende), calcic plagioclase, clinozoisite, garnet, quartz, sphene, and apatite. Although natural outcrops suggest that this rock type is subordinate to that of the schists, artificial cuts reveal that it is abundant throughout the section.

(2) Rusty-weathering muscovite-biotite-garnet schist commonly containing albite, coarse kyanite (with or without fibrolitic sillimanite), graphite (either finely divided or in coarse flakes), and staurolite; also subordinate, but nearly ubiquitous, are rutile, brown tourmaline, apatite, ilmenite, and pyrite

(3) Light-purplish-gray well-banded plagioclase-biotite gneiss and granofels commonly containing muscovite, scattered small garnets, and subordinate brown tourmaline, ilmenite, and graphite.

[Oba]METAVOLCANIC ROCKS OF BIBLE ROCK BROOK

Dark-gray to very dark gray laminated feldspathic amphibolite and hornblende schist containing hornblende, plagioclase (An 35-An 70; not uncommonly in the form of larger insets), fine-grained garnet, and lesser amounts of biotite, diopside, epidote, ilmenite, and sphene. Locally some massive amphibolite and epidote-rich lenses are present.

[Obc]COTICULES OF BIBLE ROCK BROOK

Pinkish-gray finely-laminated highly resistant rock (coticule) composed largely of very small garnets, quartz, and oligoclase and containing variable, but usually lesser, amounts of hornblende, biotite, cummingtonite (?), apatite, and locally coarse-grained euhedral magnetite. This rock is finely interlaminated with a subordinate gray feldspar-quartz-biotite schist and granofels. It is a prominent ledge and cliff former throughout its mapped length.

[Oeh]SCHIST OF EAST HAMPTON (EQUIVALENT TO BRIMFIELD SCHIST of Dixon and Lundgren, 1968)—principally gray to rusty-weathering relatively coarse-grained muscovite-biotite schist commonly containing subordinate garnet, sodic plagioclase, coarse graphite, ilmenite, pyrrhotite, tourmaline, sillimanite (not uncommonly associated with orthoclase porphyroblasts), rutile, and zircon. Unit is locally characterized by the presence of pegmatitic stringers and a migmatitic appearance. Relatively poorly developed schistosity with coarse discordant muscovite due to widespread retrograde metamorphism. Quartz contains dispersed hairlike rutile needles. A less abundant rock type within this unit is bytownite-hornblende gneiss containing subordinate biotite and garnet. Probably correlative with the Collins Hill Formation. Supporting that interpretation and the correlation of Osb with Ohb is the predicted and recently detected presence of thin amphibolite and coticule along its eastern contact with the Hebron, probable easterly correlates of Obc and Oba.

[Oc]COLLINS HILL FORMATION (PROBABLY EQUIVALENT TO PARTRIDGE FORMATION TO NORTH) [undifferentiated on map]

Main rock types – Highly varied unit somewhat similar, except for the common presence of feldspathic amphibolites, to the calc-silicate rocks and schists of Bodkin Rock and consisting largely of four principal rock types, listed in order of their decreasing abundance:

(1) Rusty-weathering muscovite-biotite-garnet schist, commonly containing sodic plagioclase, kyanite, sillimanite (commonly in fibrolitic clusters approximately equal in size to associated kyanite), staurolite, and graphite. Minor rutile, brown tourmaline, apatite, and ilmenite.

(2) Greenish-gray calc-silicate granofels containing highly variable amounts of calcite, diopside, calcic amphibole (mainly hornblende), plagioclase (mostly bytownite), scapolite, clinozoisite, biotite, garnet, quartz, sphene, apatite, and, rarely, zoisite and microcline.

(3) Gray-banded plagioclase-biotite gneiss and granofels, commonly containing muscovite, scattered small garnets, and minor rutile, graphite, ilmenite, and apatite.

[Oca] *(4)* Dark-gray to very dark-gray, massive to laminated amphibolite,hornblende gneiss, and hornblende schist, containing intermediate plagioclase (some as insets) and locally containing biotite, garnet, sphene, and ilmenite. Locally associated with laminar coticule. Some outcrops display euhedral porphyroblasts of dark-red garnet, as much as 10 mm across, weathered into sharp relief and commonly showing rotation [undifferentiated on map].

Subordinate rock types:

[Occ] *(1)*Beds, laminae, and contorted nodules consisting largely of pinkish-gray, fine-grained coticule (garnet-quartz granofels) with subordinate plagioclase, biotite, and, locally, cummingtonite. [undifferentiated on map]

[Ocm] *(2)*Mottled dark-gray and light-greenish rock consisting of interdigitating and irregular flat lenses, from 6 inches to several feet long, of hornblende-plagioclase rock (amphibolite) and diopsidic calc-silicate rock. [undifferentiated on map]

[Ocq] *(3)*Rusty-weathering muscovite quartzite, locally garnetiferous. [undifferentiated on map]

[Ocg] *(4)*Basal unit on north flank of Killington dome: very light gray oligoclase-quartz-biotite-muscovite gneiss, commonly containing considerable magnetite. Locally displays abundant small pebble-like discoid lenses composed primarily of quartz and fibrolite, etched into relief by weathering. [undifferentiated on map]

[Omi]MIDDLETOWN GNEISS

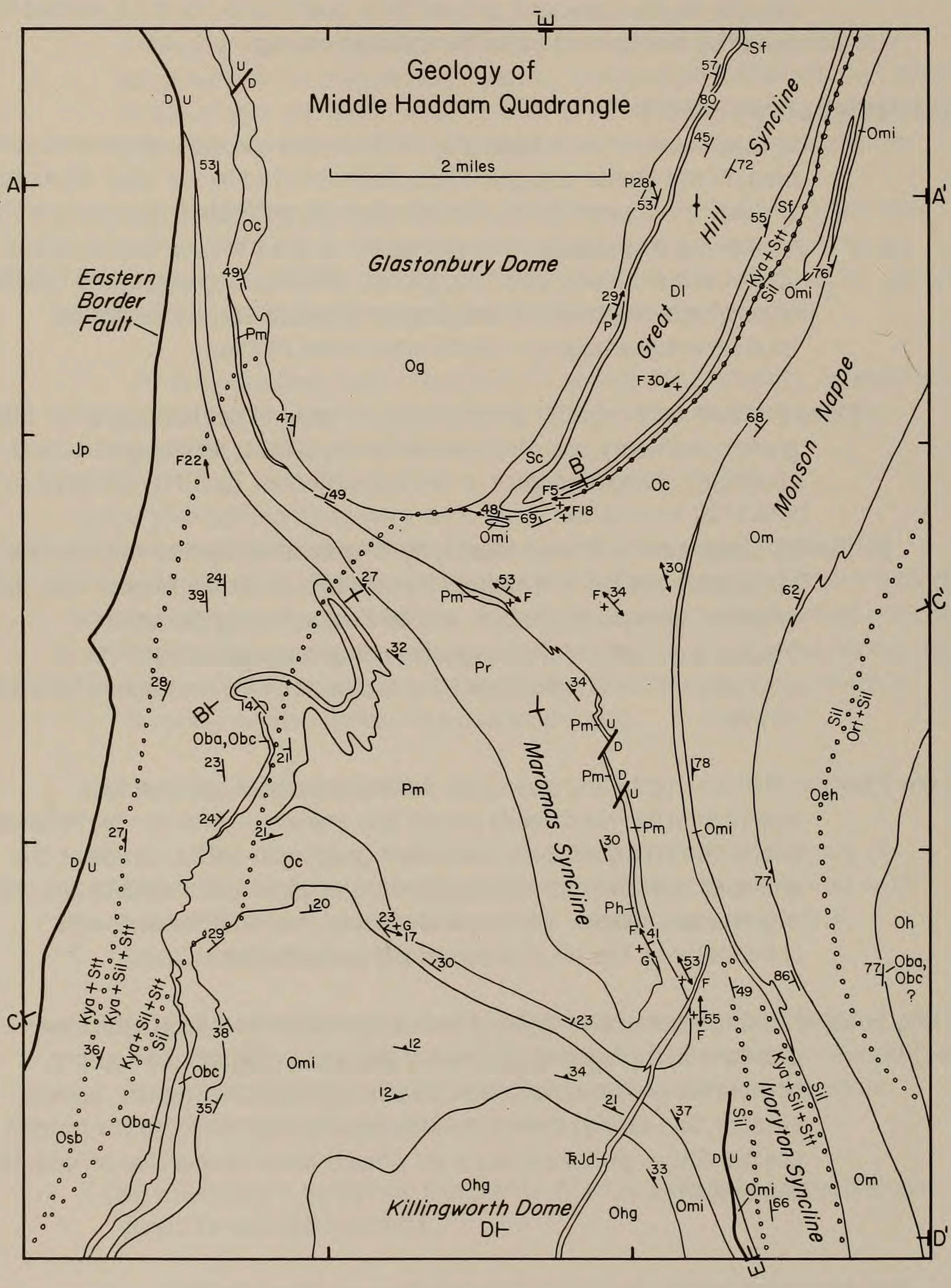
[Omu] *Upper unit* – very light gray to rusty orange-stained layered sodic plagioclase gneiss and granofels characterized by variable amounts of the subcalcic amphiboles, cummingtonite, anthophyllite, and gedrite (commonly as large radiating clusters in the plane of the foliation). Also contains hornblende, chlorite, garnet, biotite, magnetite, and ilmenite. Subordinate amphibolite and plagioclase-quartz-biotite gneiss interlayered throughout. [undifferentiated on map]

[Omm] *Middle unit* – Light-gray to medium-gray oligoclase- quartz- biotite gneiss commonly containing hornblende, garnet, and magnetite and, less commonly, cummingtonite or orthoamphiboles. [undifferentiated on map]

[Oml] *Lower unit* – Predominantly dark-gray interlayered amphibolite and hornblende gneiss containing intermediate to calcic plagioclase, epidote, diopside, garnet, magnetite, and sphene; some lighter colored plagioclase-quartz-biotite gneiss containing cummingtonite or orthoamphibole is interlayered with the amphibolites. [undifferentiated on map]

[Om]MONSON GNEISS–light- and dark-gray interlayered sodic plagioclase-quartz-biotite-hornblende gneiss and granofels, biotite- hornblende gneiss, biotite gneiss and very dark gray amphibolite. Some of the gneisses contain microcline, garnet, and garnet, and epidote and minor allanite and sphene. Distinguished from the Middletown Gneiss principally by the total absence orthoamphiboles.

[Ohg]HADDAM GNEISS–generally light-gray thickly layered sodic plagioclase-quartz-biotite-hornblende gneiss and sodic plagioclase- quartz-hornblende gneiss commonly containing magnetite, garnet, sphene, epidote, and rarely, clinopyroxene. May be equivalent to the Monson gneiss, although it displays a very much lower proportion of interlayered amphibolites.


Geology of
Middle Haddam Quadrangle
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Glastonbury Dome
Og
Eastern
Border
Fault
Jp
Great Hill Syncline
Monson Nappe
Maromas Syncline
Ivoryton Syncline
Killingworth Dome
Ohg
Omi
Om
Oc
Oeh
Oh
Pm
Pr
Ph
Sc
Sf
Dl
Osb
Oba
Obc
Oba,Obc
Oba,
Obc
?
TRJd
Kya+Stt
Kya+Sil+Stt
Kya+Sil+Stt
Sil
Sil
Ort+Sil
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B
B'
C
C'
D
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E
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U
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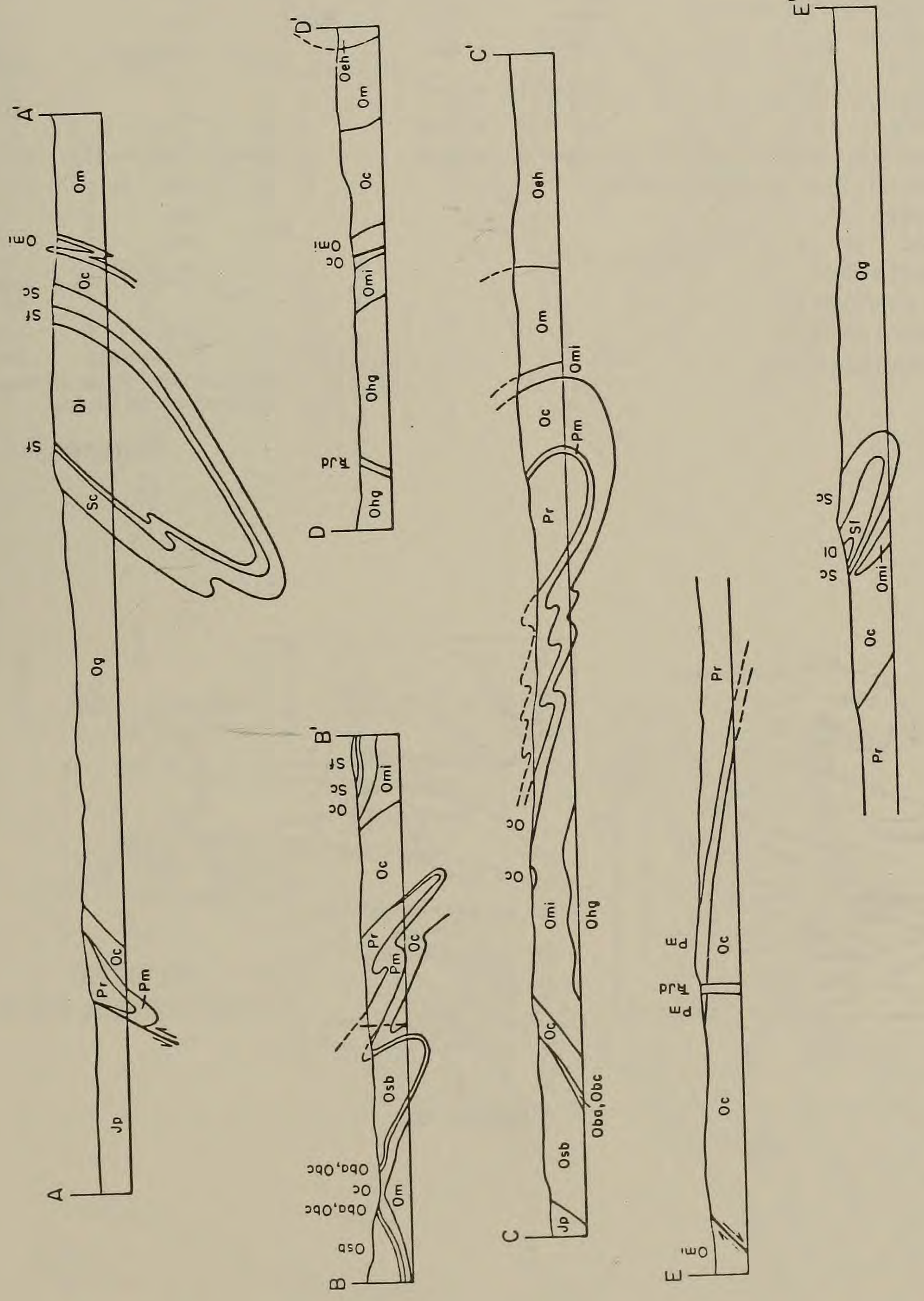
Figure 1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A'
Jp
Pr
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Oba, Obc
Pr
Pm
Omi
C
C'
Ohg
Oeh
D
D'
RJd
E
E'
pЄ
Sl

Figure 2

LEGEND FOR MAP

See Table 1 for unit symbols

Boundary between units

Fault

Attitude

compositional banding

foliation

Lineation

fold or crinkle

pebble

rotational axis of garnet

+ on "up" side gives rotation sense

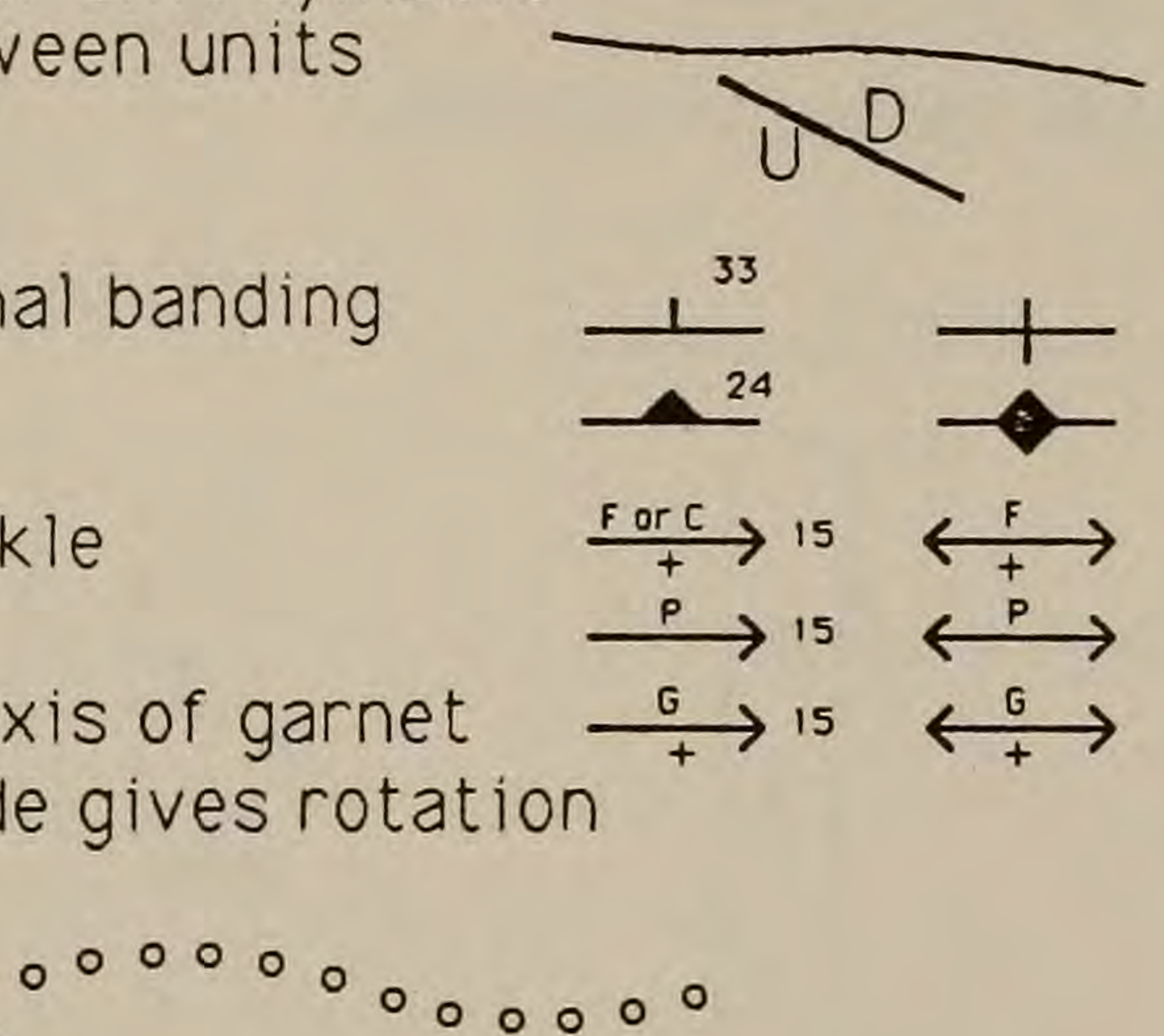
Isograd

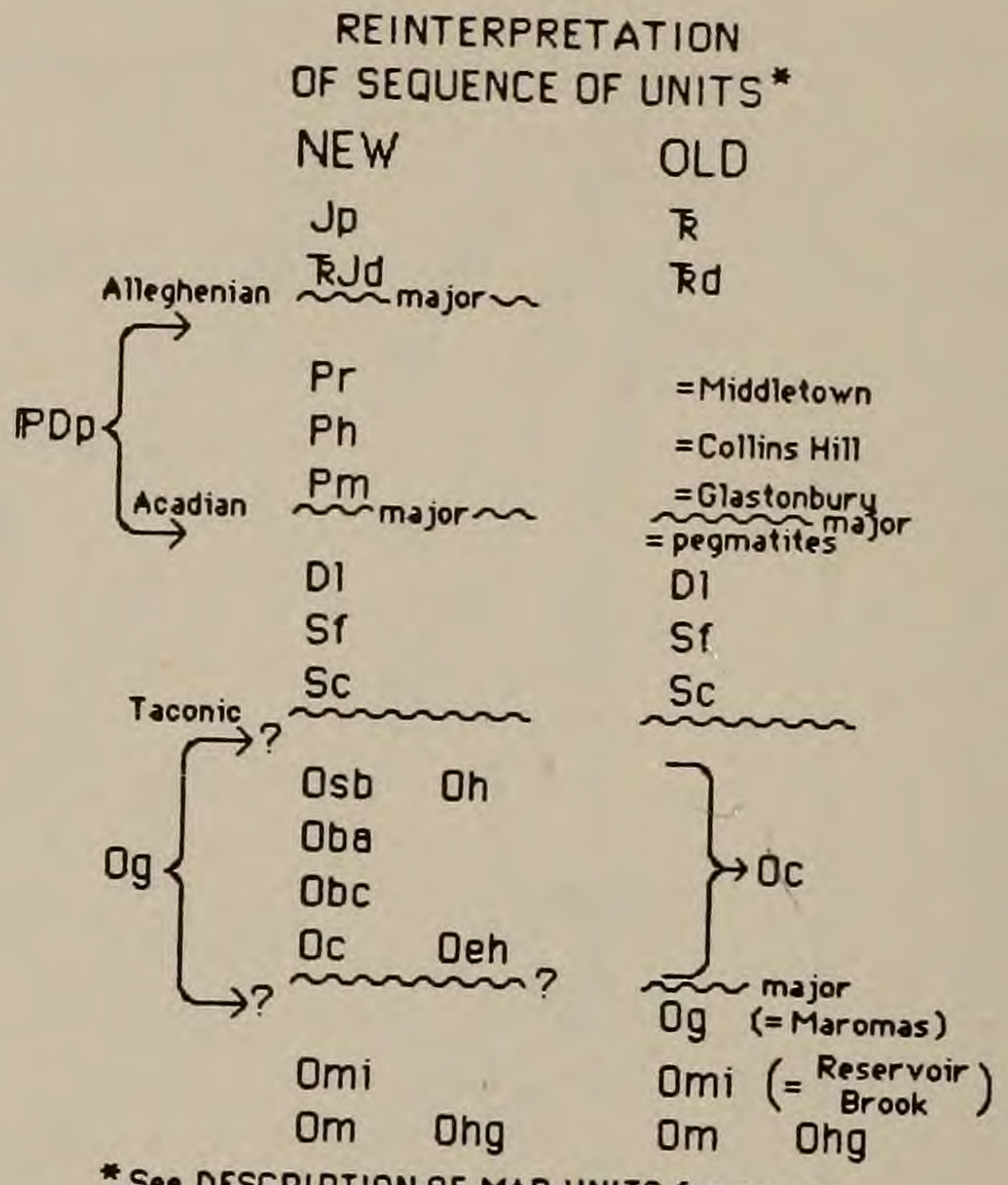
Kyanite=Kya

Sillimanite=Sil

Staurolite=Stt

Orthoclase=Ort





*See DESCRIPTION OF MAP UNITS for names associated with unit symbols.

Figure 3

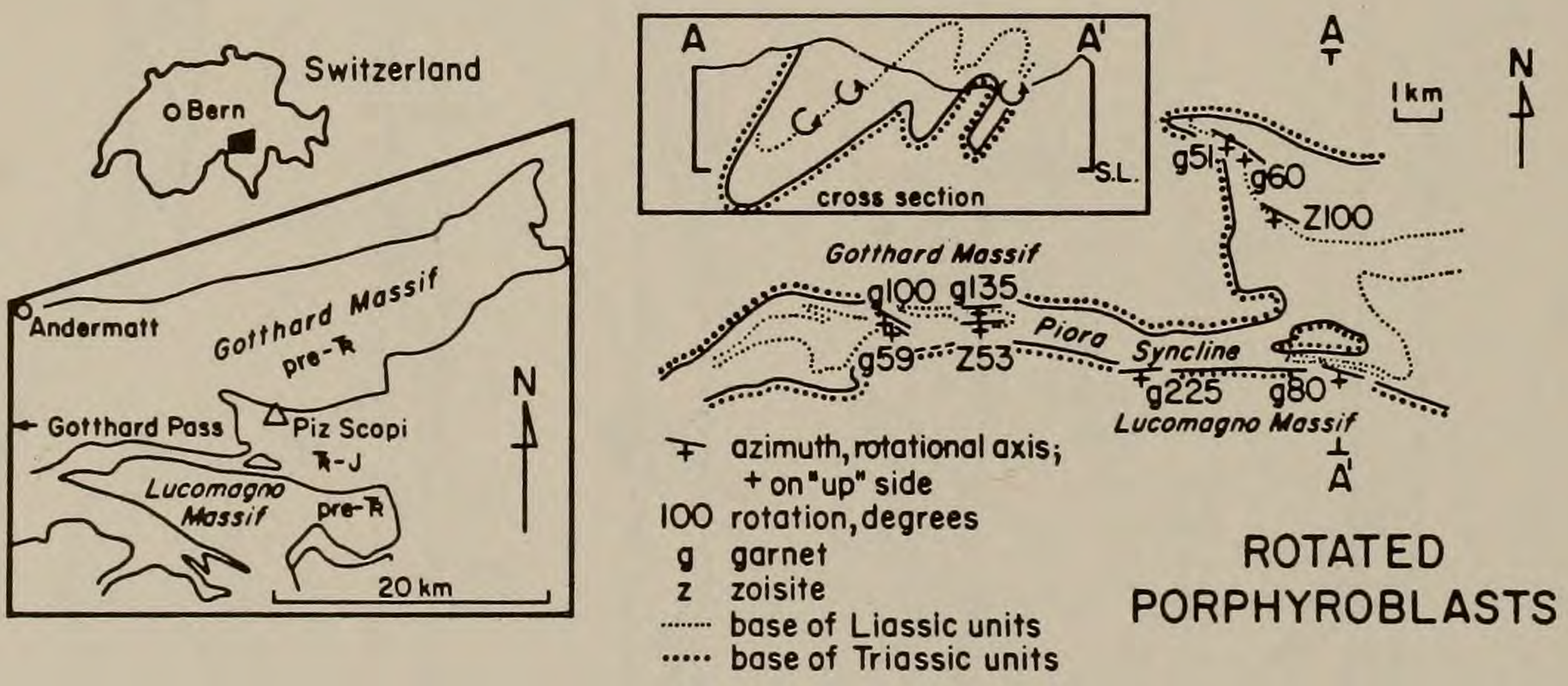
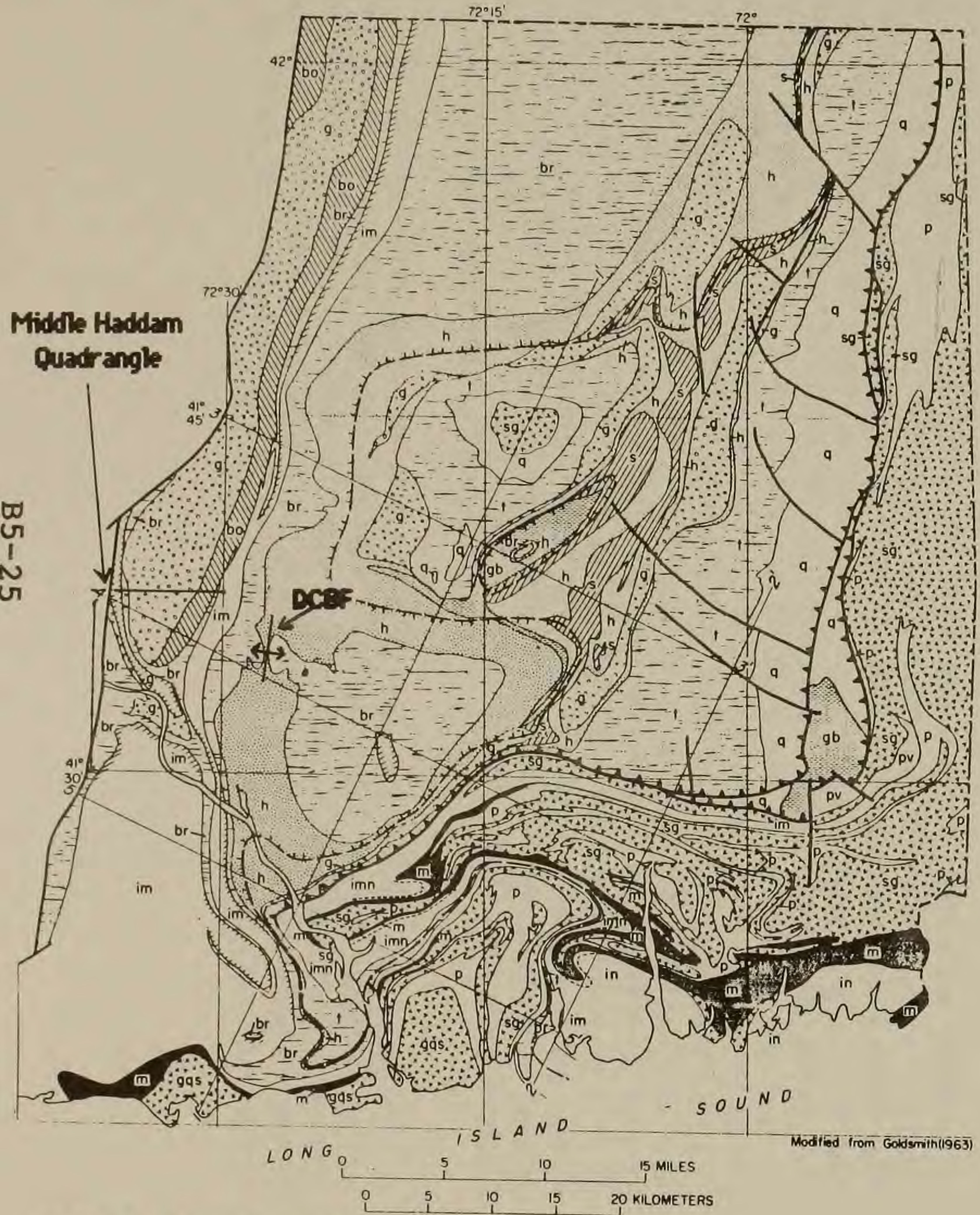


Figure 4



Modified from Goldsmith(1963)

DCBF = Dickinson Creek Backfold

Appendix A

EXPLANATION

Metasedimentary and metavolcanic rocks

WEST

▨ bo — Bolton Group of Rodgers and others (1959) *Includes Littleton Formation, Fitch Formation, and Clough Quartzite*

UNCONFORMITY

br — Brimfield Schist

imn — Ivoryton Group of Lundgren (1966)
- imn, *Ivoryton undifferentiated*
- ▨, *Middletown Gneiss*
- im, *Monson Gneiss*
- in, *New London Gneiss*
- ----, *trace of aegerine-augite gneiss*

■ m — Mamacoke Formation

p — Plainfield Formation

EAST

SILURIAN AND DEVONIAN

▨ s — Scotland Schist

h — Hebron Formation

PRE-SILURIAN

t — Totnic Hill Formation

q — Quinebaug Formation

p pv — Plainfield Formation pv, *associated metavolcanic rocks*

Plutonic rocks
Order does not reflect age

gb — Paleozoic gabbro

g — Paleozoic granitic gneisses

sg — Mississippian(?) or older Sterling Plutonic Group

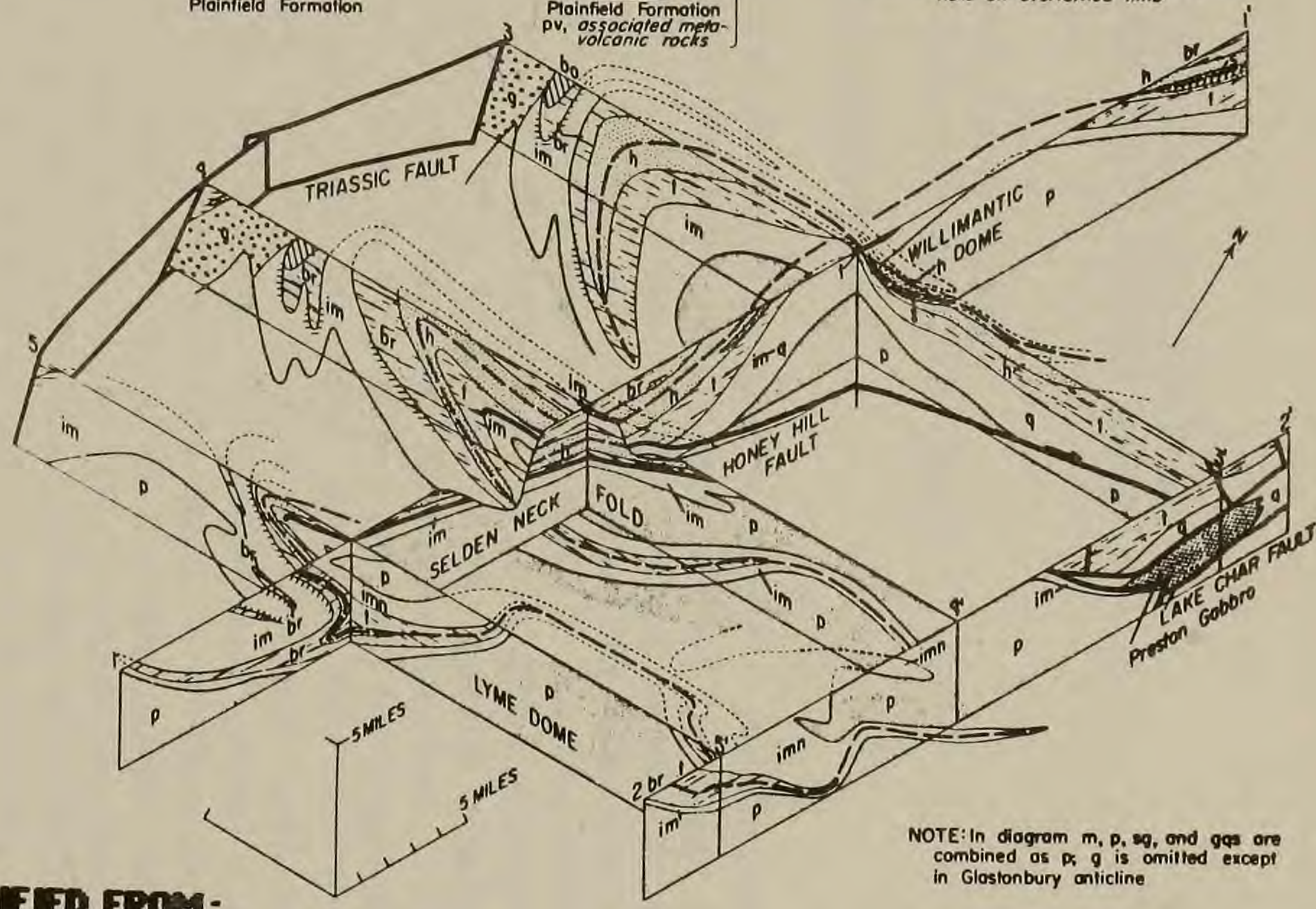
gqs — Paleozoic and Precambrian(?) granitic gneiss, quartzite, and mica gneiss

Contact

High-angle fault

Thrust fault *Sawteeth on upper plate*

Trace of axial plane of recumbent syncline *Ticks on overturned limb*



NOTE: In diagram m, p, sg, and gqs are combined as p; g is omitted except in Glastonbury anticline

MODIFIED FROM:

Dixon, H.R., and Lundgren, L.W., Jr, 1968, Structure of eastern Connecticut, *in* Studies of Appalachian Geology: Northern and Maritime, Zen, E-an, White, W.S., Thompson, J.B., and Hadley, J.B., eds.: New York, Wiley-Interscience, p. 219-229.