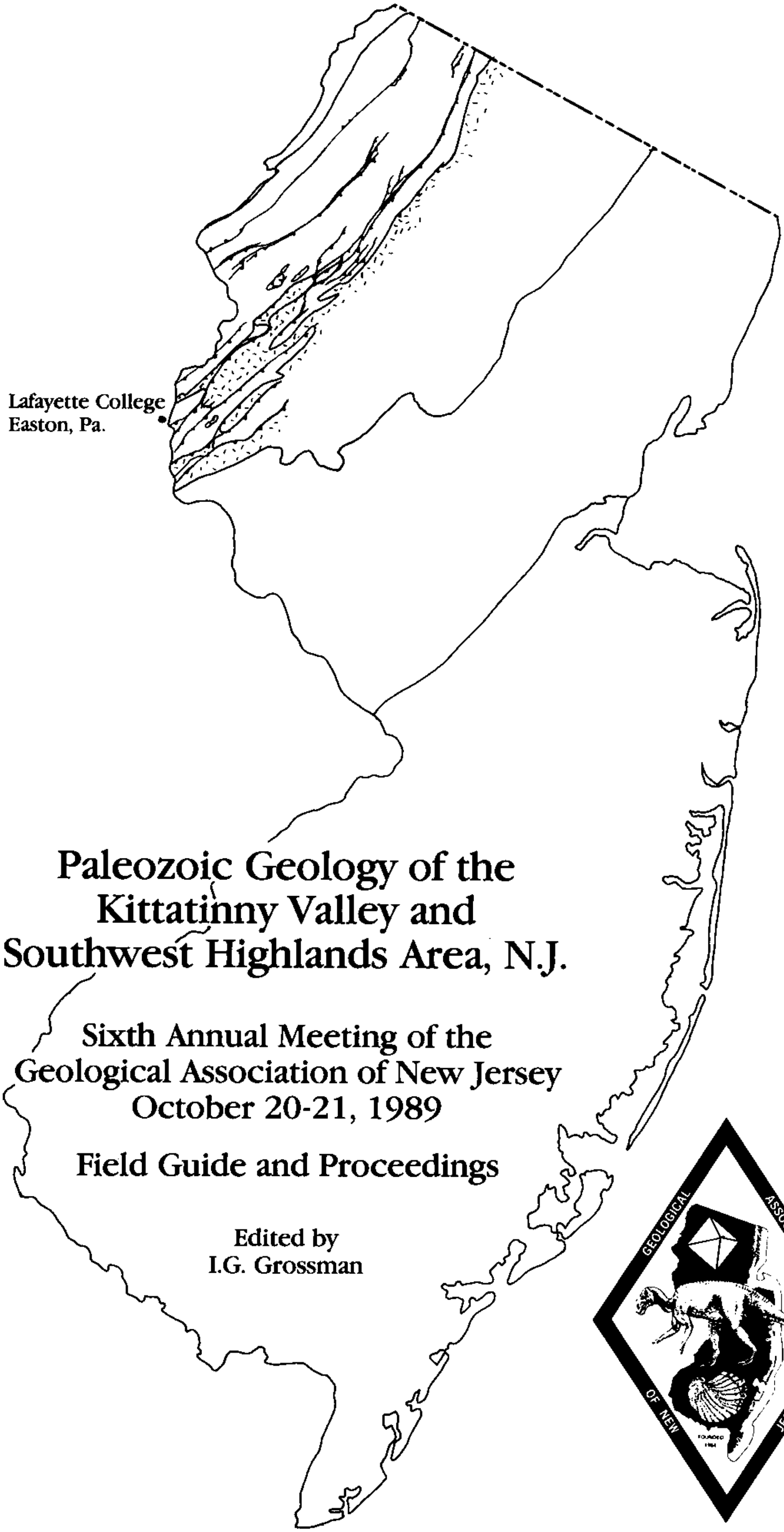

Paleozoic Geology of the Kittatinny Valley and Southwest Highlands Area, N.J.

Sixth Annual Meeting of the Geological Association of New Jersey
October 20-21, 1989

Field Guide and Proceedings

Edited by
I.G. Grossman

PALEOZOIC GEOLOGY OF THE KITTATINNY VALLEY AND SOUTHWEST HIGHLANDS AREA, NEW JERSEY

Edited by

I.G. Grossman
New Jersey Geological Survey
Trenton, New Jersey 08625

Sixth Annual Meeting of the
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PALEOZOIC GEOLOGY OF THE KITTATINNY VALLEY AND SOUTHWEST HIGHLANDS AREA, NEW JERSEY

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FIELD GUIDE

FOREWARD

The Sixth Annual Meeting of the Geological Association of New Jersey (GANJ) follows the example of the first five meetings in promoting dissemination of knowledge of the geology of the state. The earlier meetings demonstrated that GANJ is alive and well and is actively promoting professional field, laboratory, and academic work in several branches of the earth sciences. It is therefore appropriate that this meeting is led by the N. J. Geological Survey (NJGS), believed to be the second oldest state survey in the United States[1] .

Fortunately, none of us needs to do what Henry Darwin Rogers, the first State Geologist (1835-40) did; map the entire state in 5 years!. Despite the primitive transport and communication facilities available at the time, he met his deadline and produced a 300-page report with a colored geologic map. Also, fortunately for us, we don't have to work without a salary check, a fate that befell William Kitchell and George Cook, the second and third State Geologists respectively. Cook College, of Rutgers, commemorates the eponymous scion of native New Jersey geology and testifies to the continuing link between academia and non-academic geology.

The papers by Gregory Herman and Donald Monteverde present new interpretations and are bound to engender controversey. The paper by Richard Dalton rekindles a stratigraphic controversey. It is hoped that the resulting fire and fury generate light as well as heat.

Thanks are due to Mark Fiorentino for ably drafting many of the illustrations and for "desk-top publishing" the manuscripts. Jo Valencia and Lillian Allar churned out the word processing under tight time constraints. We appreciate their help; it couldn't have been done without them.

-- I.G. "Butch" Grossman
Editor

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[1] In terms of continuous operation, not inception. A short history of the State Survey was published as part of a volume "The State Geological Surveys -- A History", published by the Association of American State Geologists in 1988. The chapter on the New Jersey Survey is expected to be published separately by the NJGS in 1990.

Tectonic framework of Paleozoic rocks of northwestern New Jersey;

Bedrock structure and balanced cross sections of the Valley and Ridge Province and southwest Highlands area

Gregory C. Herman and Donald H. Monteverde

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Abstract

The early Paleozoic tectonic framework of northern New Jersey is marked by a Taconic orogenic foreland sequence involving block-faulted basement and attendant Lower Paleozoic cover layer folds. These structures were segmented and transported by a subsequent foreland fold-and-thrust sysytem resulting from the Alleghanian orogeny. This thrust system, the Ridge and Valley Thrust System, involves both emergent- and blind-thrust components.

New methods of balanced cross section analysis enable one to retrodeform pre-thrust cover layer folds. The cross section analysis indicates that involvement of Lower Paleozoic cover folds is limited in the footwall area of the major overthrust imbricate sheets. Prior models had the entire Highlands province translated towards the foreland over an extended Lower Paleozoic footwall sequence in some continuous form.

Regional structural relations elucidate the timing and styles of deformation of the Taconic and Alleghanian orogenies. Sedimentary rocks of Middle Ordovician age, though in part restricted in distribution, clarify the tectonic environments of deposition during the Taconic orogeny and correlate with the proposed structural framework.

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Introduction

Recent mapping of the Kittatinny Valley and part of the southwest Highlands area of northwestern New Jersey (Figure 1) has led to a reinterpretation of the structure and tectonic history of the Paleozoic rocks and the platform on which they were deposited. The area contains structural elements that reflect episodic tectonism of an active convergent plate margin during the Taconic and Alleghanian orogenies. This is illustratated by a series of maps and balanced cross sections. Some new methods of cross-section analysis are used to balance redeformed structures. Lower Paleozoic stratigraphic variations are shown to integrate into this structural framework. The tectonic reinterpretation is compared with previous work.

This paper is based on mapping by the N. J. Geological Survey completed as part of the COGEOMAP program with the U. S. Geological Survey. It is part of the program to produce a revised State geological map at the 1:100,000 scale. The provisional maps and cross section interpretations presented here are those of the N. J. Geological Survey and are based on unpublished field maps at the 1:24,000 scale. Responsibility for the principal conclusions rests with the authors and does not imply agreement with interpretations of the U. S. Geological Survey.

Acknowledgements

We gratefully acknowledge the help of Avery Drake, Peter Lyttle, Jack Epstein, Nicholas Ratcliffe, and Jules Friedman, all of the U. S. Geological Survey, who provided stimulating discussions and periodic, interim reviews. Peter Lyttle also provided unpublished field data for the Lower Paleozoic rocks of the Tranquility 7-1/2' quadrangle (Figure 2) . Richard Dalton and Robert Canace of the N. J. Geological Survey also provided unpublished field data for compilation of parts of the Kittatinny Valley. Robert Metsger provided unpublished maps and internal reports of the New Jersey Zinc Company, and his valuable discussions aided the early structural interpretations. Walter Spink provided unpublished gravity data for the Beemerville Complex area. Joe Hull, Robert Sheridan, Randy Forsythe, and William Muehlburger discussed the interpretations and alternative models. Finally, we thank the staff of the N. J. Geological Survey for their comments, reviews, and technical support.

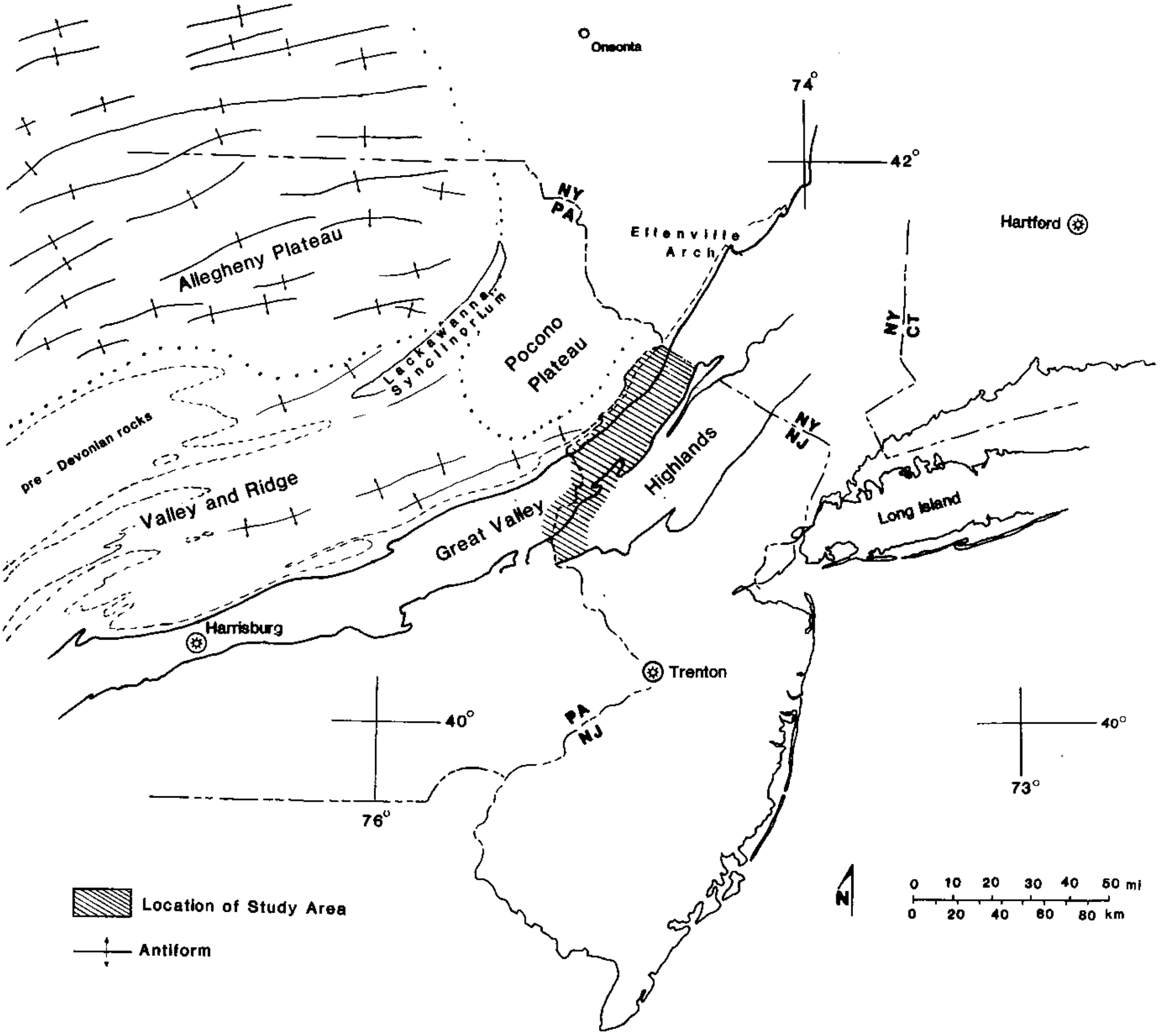


Figure 1 - Regional map of study area and northern tectonic provinces of the northeast central Appalachians, New Jersey and Pennsylvania. Modified from Wood and Bergin (1970) and from the tectonic map of the mid-Atlantic region, Bennison, A. P., compiler, 1976, U. S. Geologic Highway Map Ser., Map no. 10, Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma.

Geological setting

The Kittattiny Valley of New Jersey comprises the southeast part of the Valley and Ridge province of New Jersey (Fig. 2) and lies along the northeast extension of the Great Valley province of the Central Appalachians (Fig. 1). Folded and locally faulted middle Paleozoic rocks underlie the northwest part of the New Jersey Valley and Ridge province. The Pocono Plateau of Pennsylvania borders the Valley and Ridge province to the northwest and is comparatively less deformed than the Valley and Ridge province. The lower-Cambrian-through-Middle-Ordovican rocks within the Kittatinny Valley are multiply tectonized, intruded by igneous rocks, and contain abundant northwest-verging structures indicative of fold-thrust belt deformation
(Pl. 1).

The Highlands province borders the Valley and Ridge to the southeast and contains the New Jersey part of the Reading Prong of Middle and Upper Proterozoic age (Fig. 2). The Reading Prong has infaulted and infolded outliers, which include abundant Lower Paleozoic rocks in the southwest part of the Highlands and in the marginal area with the bordering Valley and Ridge province.

Previous interpretations

Various tectonic models have been proposed for the deformed sequence of Lower Paleozoic rocks within the Highlands and the Valley and Ridge province. The diversity of these interpretations testifies to the structural complexity of the region. The Paleozoic rocks were deformed by at least two orogenic events, first by the Ordovician Taconic orogeny and subsequently by the late Paleozoic Alleghanian orogeny (Bayley and others, 1914; Kummel, 1940; Drake, 1969; etc.).

Large scale overthrust faulting of the Lower Paleozoic rocks was first recognized by Bayley and others (1914) who suggested that folding and large scale thrust faulting were coeval and dated from a late Paleozoic deformational period. Merchant and Teet (1954) first suggested that an earlier fold sequence was subsequently faulted by a northwest-verging imbricate splay thrust system. They depicted the subsurface structure of the lower Paleozoic rocks to a depth of a few kilometers by a series of cross sections showing the east-northeast part of the Kittatinny Valley. The sections portray branching thrust faults that translate earlier folds northwestward, and the folds display an open and upright geometry.

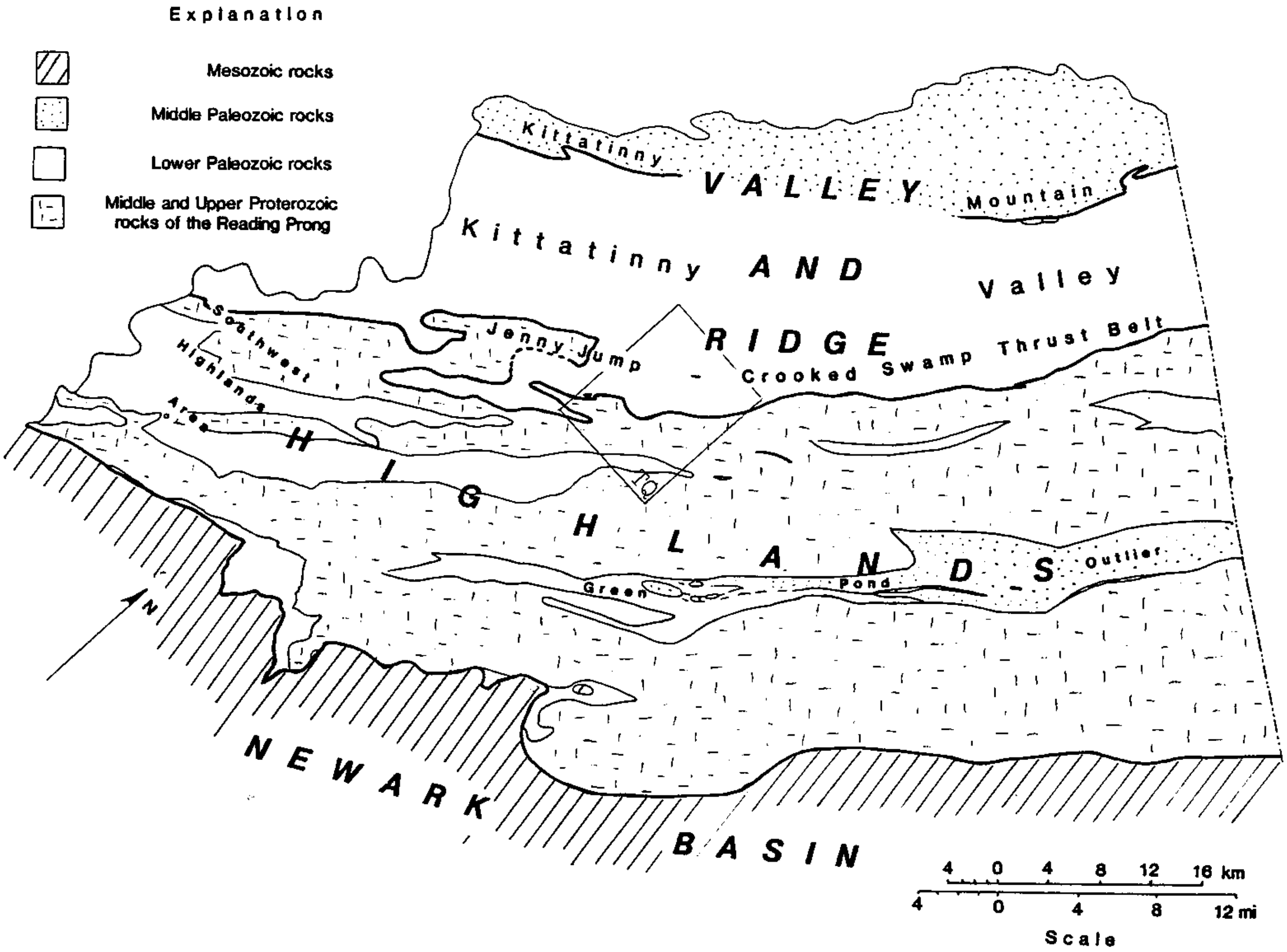


Figure 2 - Generalized geology of the Highlands and Valley and Ridge provinces of New Jersey. Modified from Lewis and Kummel (1910 -1912). Tranquility 7 1/2' quadrangle.

More recent fold-thrust belt models include the foreland components of the Reading Prong nappe megasystem of Drake (1969, 1978, 1980), Drake and others (1969, 1985) and Drake and Lyttle (1980, 1985). This model involves regional recumbent folds and attendant thrusts of Taconian age which are subsequently thrust faulted and warped by upright and open folds assigned to Alleghanian deformation. Another structural model (Lyttle and Epstein, 1987) depicts imbricated thrust sheets of coupled Proterozoic and Paleozoic strata but excludes deep bedrock structures in New Jersey. However, a cross section through an adjacent area of the Pennsylvania depicts imbricate allocthonous thrust sheets of coupled basement and cover above a master décollement occurring within the Lower Cambrian sedimentary rock. The intact part of the cover layer beneath the master décollement is shown on the sections to continue hindward beneath the Reading Prong and the Mesozoic Newark Basin. This resembles the regional interpretation accompanying the Pennsylvania State Geological map (Berg and others, 1980).

The interpretation presented here links emergent thrust faults in the Highlands province to both emergent and blind thrust components in the Valley and Ridge province. The blind thrusts continue towards the foreland beneath the Pocono Plateau. The array of thrust faults is interpreted as a decollement thrust system; the master decollement is rooted in basement rocks beneath the Highlands province but it pierces the Lower Paleozoic cover layer beneath the northwest margin of the Valley and Ridge province. This alternative interpretation significantly differs from previous models on the amount of tectonic contraction strain accomodated by the foreland components of the respective thrust systems. The new interpretation is here called the Ridge and Valley Thrust System of New Jersey.

Stratigraphy

In the New Jersey Highlands and in the Valley and Ridge province, Paleozoic rocks range in age from Lower Cambrian through Middle Devonian. The Valley and Ridge province contains Silurian - Devonian rocks which form the northwest border of the Kittatinny Valley (Great Valley) sequence (Fig. 2). The Cambrian-Ordovician carbonate, clastic, and Ordovician intrusive rocks underlie the Kittatinny Valley and occur as outliers within the Highlands province (Fig. 2). Only the Green Pond outlier contains post-Ordovican rocks within the Highlands province, except for a fault-bounded slice similar to the Silurian Green Pond Conglomerate, that crops out along the Newark Basin Border Fault farther to the southeast in the Pompton Plains 7-1/2' quadrangle (Richard Volkert, oral commun., August 16, 1989, N. J. Geol. Survey, Trenton, N.J.).

The Paleozoic rocks were deposited on a continental plate margin underlain by previously tectonized Middle and Upper Proterozoic basement rock of the

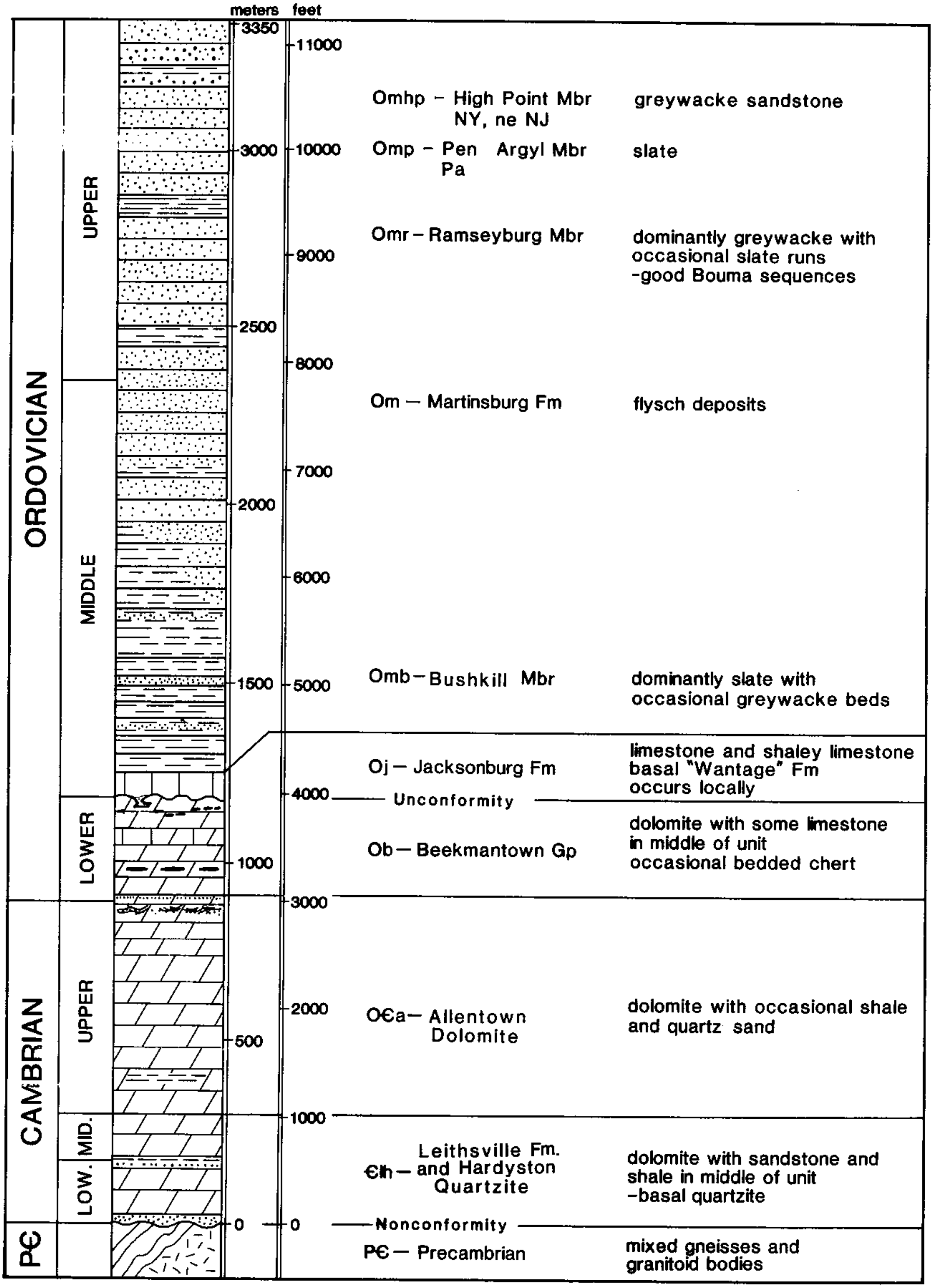


Figure 3. Generalized stratigraphic column for the Kittatinny Valley and southwest Highlands area

Appalachian Grenville terrane (Drake, 1984). Stratigraphic variations in the Lower Paleozoic sequence reflect eustatic fluctations and the change from a passive to a convergent margin from Early Cambrian through Late Ordovician time. The tectonic environments of deposition of the Lower Paleozoic rocks are summarized by Monteverde and Herman (this volume). Epstein and Epstein (1969) discuss the tectonic environments of deposition for the Middle Paleozoic rocks which lie mostly outside the area of this study. A brief explanation of map units of the Paleozoic rocks included in this study is given in Plates 1 and 2b. Figure 3 is a generalized stratigraphic column of the Lower Paleozoic rocks showing the lithotectonic units used for the maps and cross sections.

Structure

Within the study area, overthrust faults are readily apparent where older rocks overlie younger ones. However, overthrusts have often been abandoned as interpretations where younger strata occupy the hanging wall (Lewis and Kummel, 1910-1912; Bayley and others, 1914). Such cases are "out of sequence" for simple break-forward thrust-fault relations in flat-lying strata (Morley, 1988). The true character of these seemingly normal faults is locally revealed by northwest-verging and shallow- to intermediate-dipping tectonites that show reverse motion, or by the lateral continuation of the faults into structural domains having older-over-younger thrust-fault relations. As demonstrated below, the anomalous structural style is a result of segmentation of parts of an early set of large-scale folds and their juxtapositon with a system of later thrust faults. The early folds involve Cambrian-Ordovician cover-layer strata coupled to Middle Proterozoic basement rocks. Cross-cutting mesostructural relations support the presumed deformation of the earlier structures. Construction of balanced cross sections of such redeformed terrane makes it necessary to constrain the geometry of the redeformed structures and sequentially retrodeform the current structures to their earlier forms.

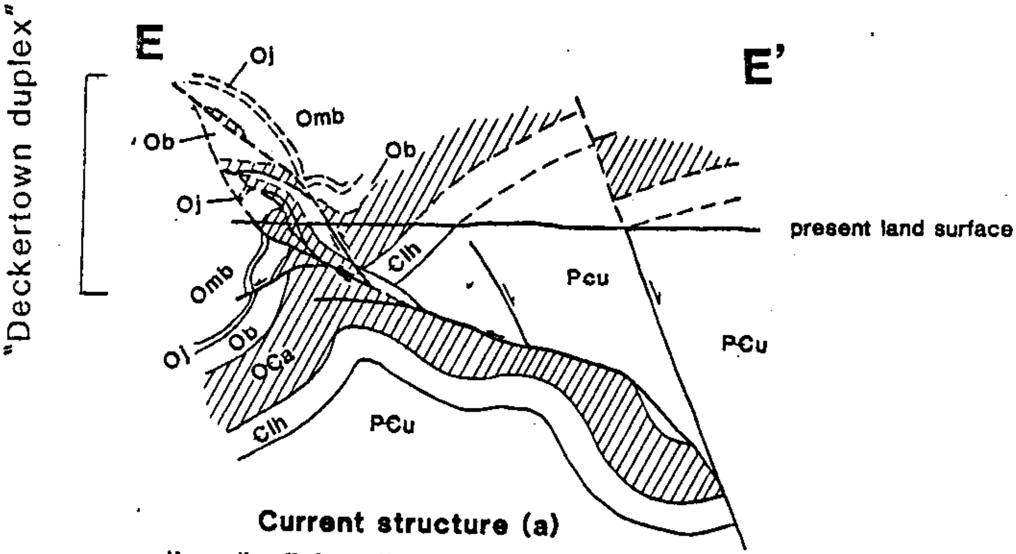
The Ridge and Valley Thrust System is illustrated by maps and cross sections that clarify its structure. The map components are subdivided into emergent-thrust and blind-thrust terranes. The emergent-thrust terrane includes two thrust belts that crop out in the Valley and Ridge province (Pl. 1) and the southwest Highlands area (Pl. 2a). The two thrust belts, the Paulins-Kill and the Jenny Jump - Crooked Swamp (JJCS), occur in the central and southeastern parts of the Valley and Ridge province respectively (Pl. 1). The Paulins Kill thrust belt, first defined here, marks the northwest limit of major emergent thrust faulting in New Jersey. It consists of imbricate thrust sheets displaying only Lower Paleozoic rocks at the land surface. The JJCS is a belt between the Highlands and Valley and Ridge provinces(Fig. 2). It contains imbricate thrust sheets consisting of both basement and cover rocks. High-angle faults and thrust faults obscure the contact between the two provinces by locally juxtaposing basement and cover rocks. The emergent thrust faults in the southwest part of the Highlands occur in a belt extending south-southwest from the JJCS which consists of alternating, longitudinal ridges and valleys of basement and cover rocks, respectively(Fig. 2).

The two emergent thrust belts in the Kittatinny Valley are separated by a longitudinal belt of blind-thrust Lower Paleozoic rock mostly comprised of Martinsburg Formation at the surface (Pl. 1). This blind-thrust cover-layer sequence envelopes both plunging terminations of the Paulins Kill thrust belt in New Jersey and Pennsylvania, and separates the thrust belt from Silurian-Devonian rocks of the foreland.

Emergent-thrust terrane

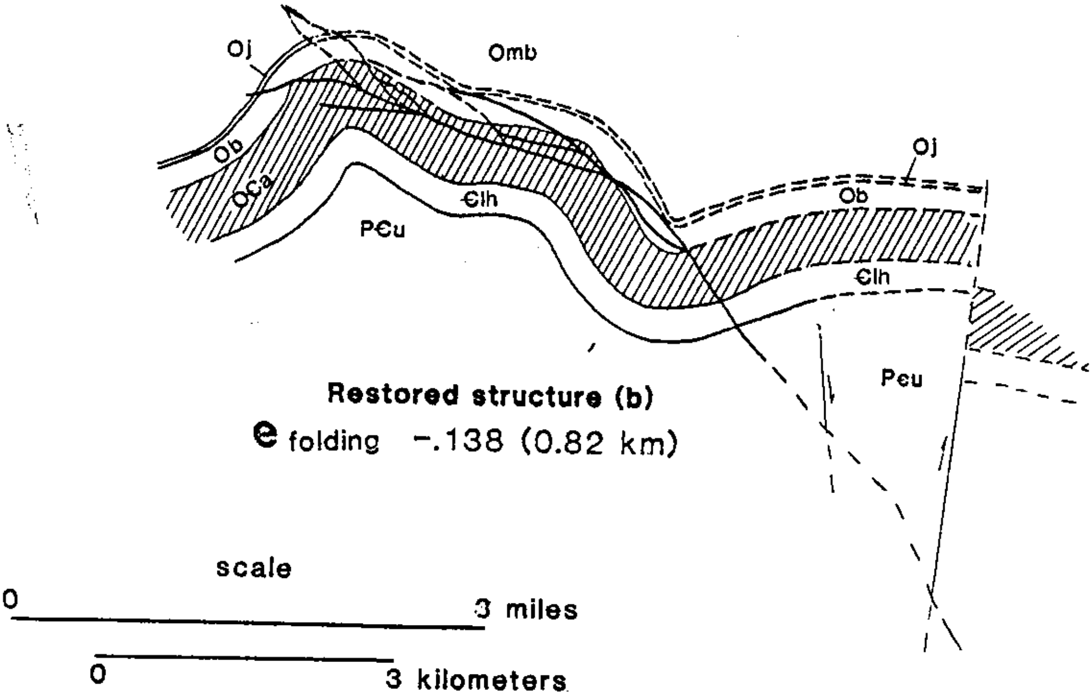
The emergent-thrust terrane of the southwest Highlands area (Pl. 2a) consists of redeformed basement and cover-layer rocks. The delineation of thrust faults in this area differs from the those of Drake (1967a, 1967b), Davis and others (1967), Drake and others (1969), and Lyttle and Epstein, (1987). The Jenny Jump fault is interpreted here to continue southwestward into the foreland of the southwest Highlands area where it becomes the Harmony Fault southwest of Lommasons Glen (Pl. 2a). Here, a splay fault connects the Jenny Jump - Harmony fault with the hindward bounding Shades of Death - Lower Harmony fault. Farther southeast, towards the Mesozoic Border Faults, the remaining emergent thrust faults within the southwest Highlands include the Brass Castle, the Broadway, the Pohatcong, the Kennedys, the Asbury, and the Musconetcong. The Lower Harmony fault is a complex set of rejoining splays around the Phillipsburg - Easton area (Pl. 2a). The composite array of faults displays variable thrust geometries which include rejoining and connecting splay thrust faults, and sets of diverging splay faults that comprise imbricate-fan fault terminations. A set of moderate- to high-angle shear zones and block faults also occurs in this emergent thrust terrane, some of these were locally segmented, or possibly reactivated by the thrust faults. These faults include the Morgan Hill shear zone (STOP 1, this volume), the Marble Mountain fault, and a set of lower-order block faults at the southwest termination of Scotts Mountain (Pl. 2a). They involve both basment and cover rocks and show both normal and reverse dip-slip components. Associated basement deformation fabrics consist of brittle-ductile deformation zones involving chlorite- grade cataclasites, mineralized shear planes, and veins. The Marble Mountain fault is shown to be segmented at its margins by the Harmony and Lower Harmony thrust faults respectively (Pl. 2a).

The JJCS is a highly complex thrust belt containing a diverse assemblage of thrust faults, high-angle faults, folds, and corresponding mesostructures. The styles and relative timing of deformation for the Ridge and Valley Thrust System were first established in the JJCS (Merchant and Teet, 1954; Herman and Monteverde, 1988). A set of early cover-layer folds (F1) was shown as being cut



Current structure (a)

dip-slip finite displacement 4.20 km



Restored structure (b)

e folding −.138 (0.82 km)

Figure 4 - Current and restored cross section E-E', northeast Kittatinny Valley. The "Deckertown duplex" (a) retrodeforms to a pre-thrust (F1) anticlinorium (b). High-angle faults are cut and translated by the later thrusts. The locations of E-E' and the "Deckertown" duplex are shown on Plate 1.

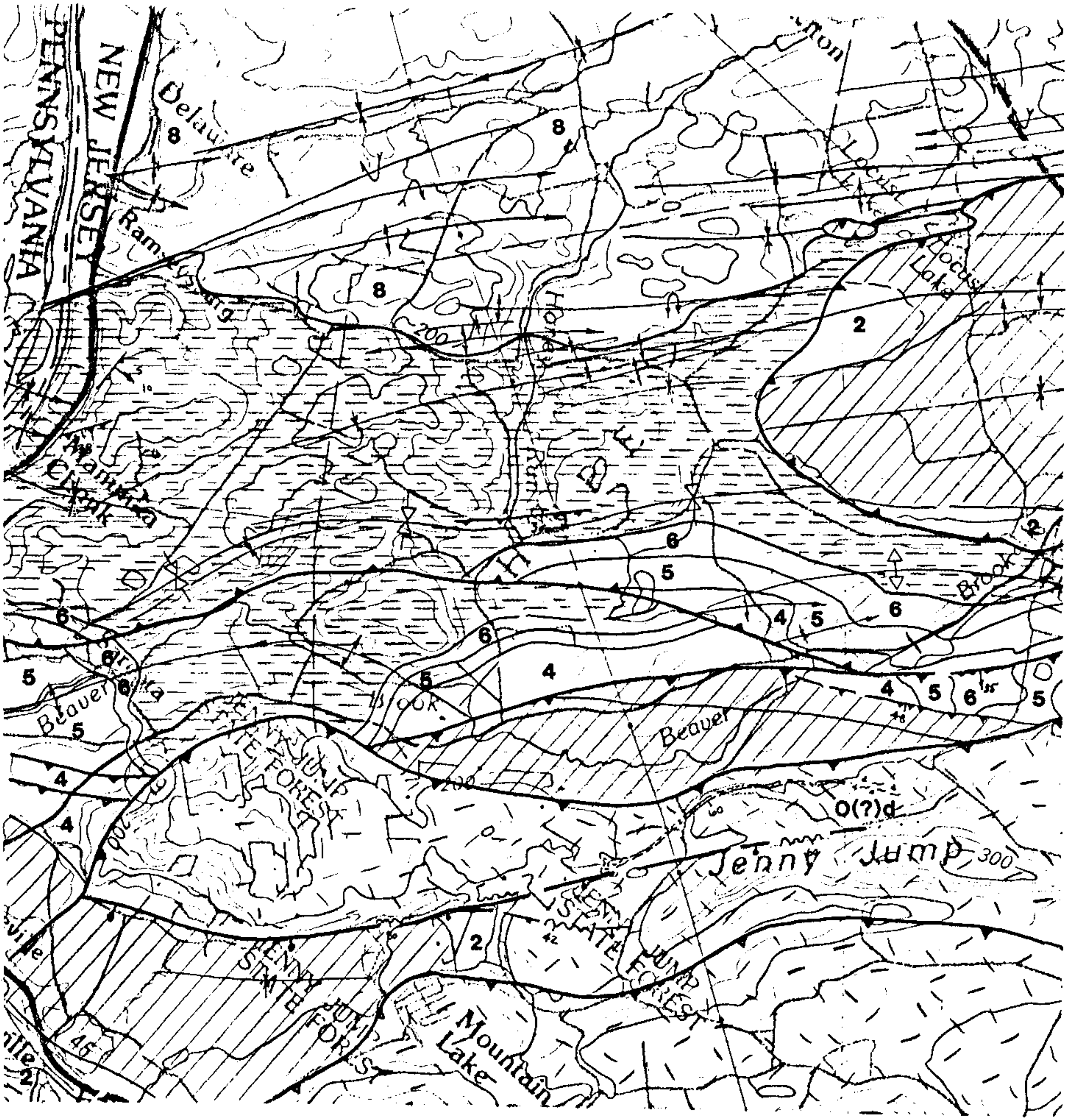
by the later thrust faults. They were restored into their pre-thrust fault form with balanced cross sections delineating the northeast part of the JJCS around the "Deckertown duplex" (Pl. 1). As shown in figure 4, the duplex retrodeforms into a pre-thust anticlinorium. The methods and assumptions on which this retrodeformation is based are detailed below.

The F1 folds in the JJCS are commonly segmented along their map trace and plunge beneath bounding thrust slices. This relation is exemplified on the map in the south-southwest part of the Kittatinny Valley around Johnsonburg and Greendell (Pl. 1) where the trace of the Johnsonburg anticline and other F1 folds directly to the southeast are truncated by thrust faults.

Most of the emergent thrust faults in the JJCS are northwest-verging and are shown on Plate 1 as comprising complex arrays of diverging, connecting, and rejoining splay thrust faults that locally comprise duplex structures (Boyer and Elliot, 1982). The thrust faults typically show propagation trajectories that are influenced by pre-existing fold forms as illustrated in figure 4, where uplimb thrust faults in synthetic (southeast-dipping) fold limbs flatten and splay through fold hinge areas.

The synthetic thrust faults in the JJCS that account for most of the dip-slip displacement are the Jenny-Jump fault to the southwest and the Crooked Swamp fault to the northeast. Many subordinate thrust faults occur in the footwall area near the larger overthrust faults as a result of progressive foreland imbrication and displacement transfer (Dahlstrohm, 1969) within the developing thrust system. This relation is clarified in the section on cross-section analysis.

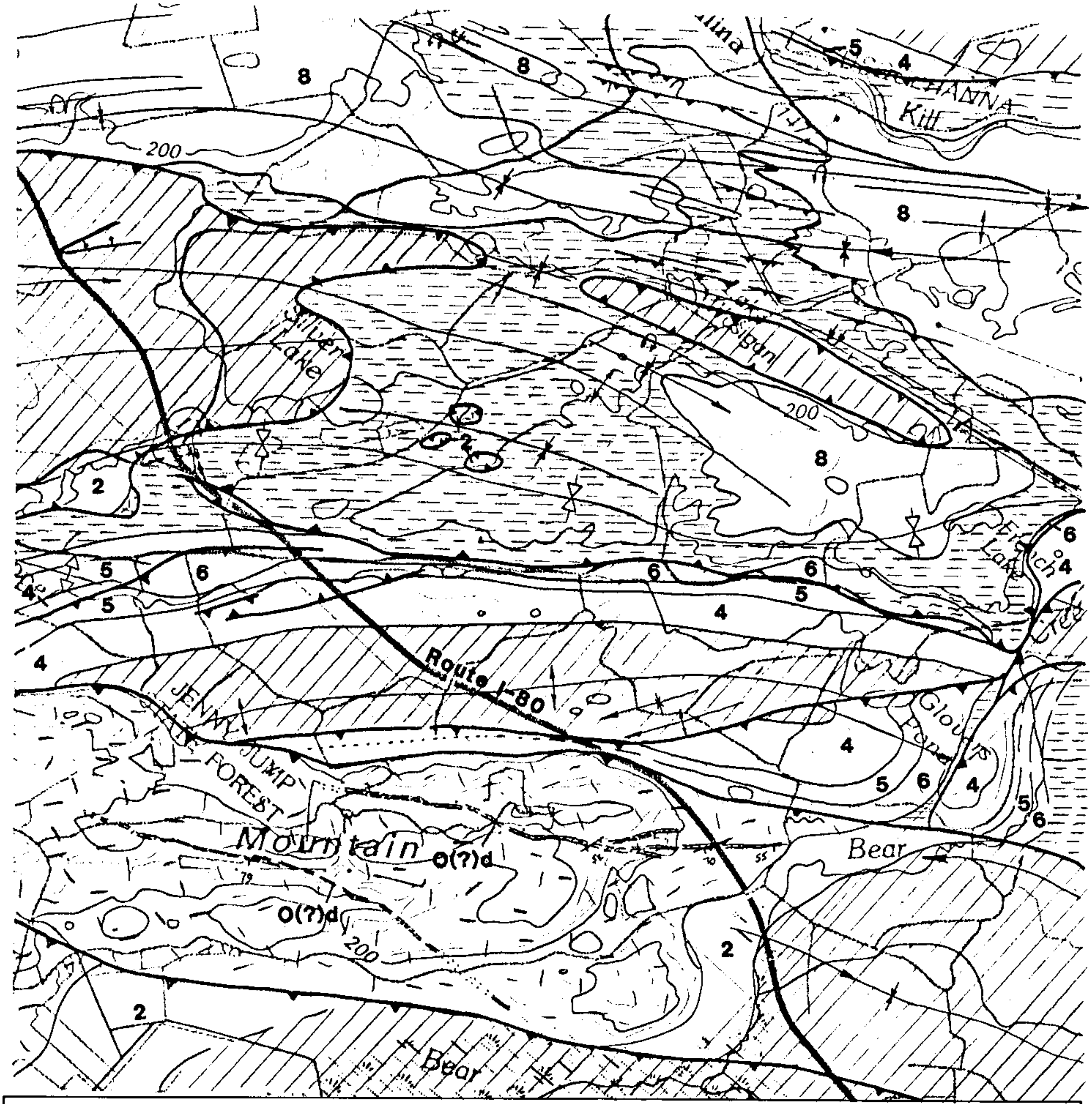
Although most of the thrusts in the JJCS are synthetic, southeast-verging (antithetic) thrusts also contributed to the kinematic evolution of the composite thrust system. For example, one set of moderately dipping antithetic thrust faults occurs in the southwest part of the JJCS along the boundary between the Cambrian-Ordovician carbonate rocks and the Martinsburg Formation (Fig. 5, Pl. 1). This sequence of faults includes the Honey Run fault (Drake and Lyttle, 1985) to the southwest and the Federal Springs fault (Drake and Lyttle, 1980; Forsythe and others, 1988) directly to the west of Johnsonburg. These faults define the intermediate boundary of a paired set of tectonic wedges, similar to those described by Price (1986), which delaminate a cover sequence with faults of opposite vergence (Fig. 6). This set of southeast-verging faults propagated as the antithetic conjugate member of a paired set of faults and resulted in subhorizontal contraction and positive vertical extension. In contrast, other southeast-verging thrust faults with shallow to intermediate dips also commonly bound klippen on their southeast margin (for example, the Hope klippe, Fig. 5, Pl. 1). These latter faults may have propagated with shallow southeast dips but



EXPLANATION OF MAP UNITS

▨	O(?)d - Diabase dike (Upper Ordovician ?)
8	Omr - Ramseyburg Member of Martinsburg Formation(Middle Ordovician)
▤	Omb - Bushkill Member of Martinsburg Formation (Middle Ordovician)
6	Oj - Jacksonburg Limestone (Middle Ordovician)
5	Obu - Upper part of the Beekmantown Group (Lower Ordovician)
4	Obl - Lower part of the Beekmantown Group (Lower Ordovician)
▨	O-Ꞓa - Allentown Dolomite (Uppermost Ordovician and Cambrian)
2	Ꞓlh - Leithsville Formation and Hardyston Quartzite undivided (Cambrian)
▧	P-Ꞓu - Upper and Middle Proterozoic metasedimentary, metaigneous and plutonic rocks undivided

Figure 5. - 1:48,000 generalized geology and tectonic map of the Jenny Jump Mountain area. Base from USGS unpublished 1:100,000 map. Contour interval 20 m. Geology from 1:24,000 unpublished maps by the authors, on file at the New Jersey Geologic Survey, Trenton, NJ.



EXPLANATION OF MAP SYMBOLS

Contact - solid where known, dashed where inferred

Cleavage shear zone - with attendant mineral and shear fractures.

Thrust fault - sawteeth on upper plate.

High-angle fault - ball and stick on downthrown block.

Basement shear zone - zone of chlorite, epidote, and quartz-mineralized shear fractures and veins. Cataclastic brecciation indicated by open triangles.

Slip lineation - showing bearing and plunge

Anticline

Syncline

Overturned anticline

Overturned syncline

Steeply-inclined anticline, arrow tail shows dip direction of upper limb.

Steeply-inclined syncline, arrow tail shows dip direction of upper limb.

Cleavge arch

Cleavage trough

were subsequently folded into their current trajectory by progressive footwall imbrication or wedging as illustrated on plate 1b and figure 6. This latter type of thrust fault accounts for many map-scale cleavage folds (Fig. 5, Pls. 1 and 2a) and explains such structures as the "Grand Union" klippe (Drake and Lyttle, 1980) situated east of Newton in Sussex County (Pl. 1).

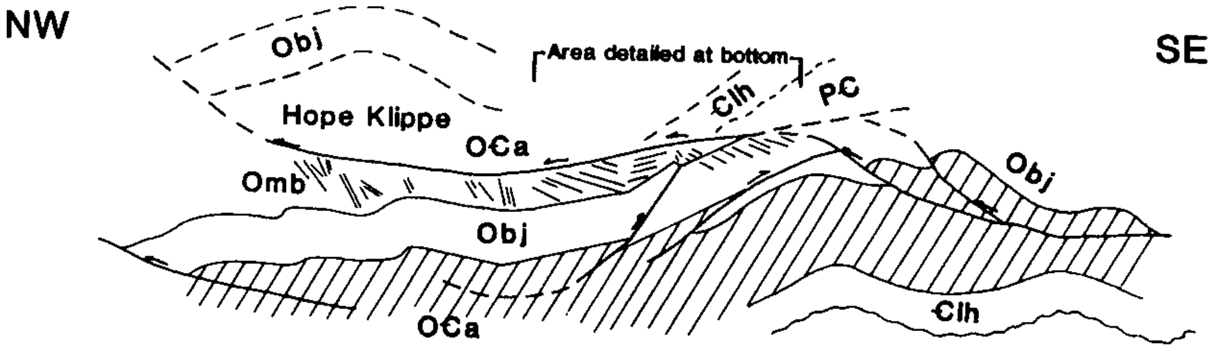
High-angle block faults occur along the southeast margin of the JJCS that are similar to the previously - described ones in the southwest Highlands area. These include the Mountain Lake fault southeast of Jenny Jump Mountain, and a series of faults in the northeast along the margin of the Highlands and Valley and Ridge provinces (RAIA, Hamburg, and Pochuck faults, Pl. 1). These faults show dip-slip components with lower Paleozoic rocks in the southeast block.

A break-forward thrust fault sequence is generally assumed for the Ridge and Valley thrust system. This assumption is supported by the emergent fault relations along the footwall of the JJCS, where isolated, diverging splay faults terminate in the immediate foreland within the Martinsburg Formation east-southeast of Halsey (Pl. 1). This relation is reexamined in the following sections.

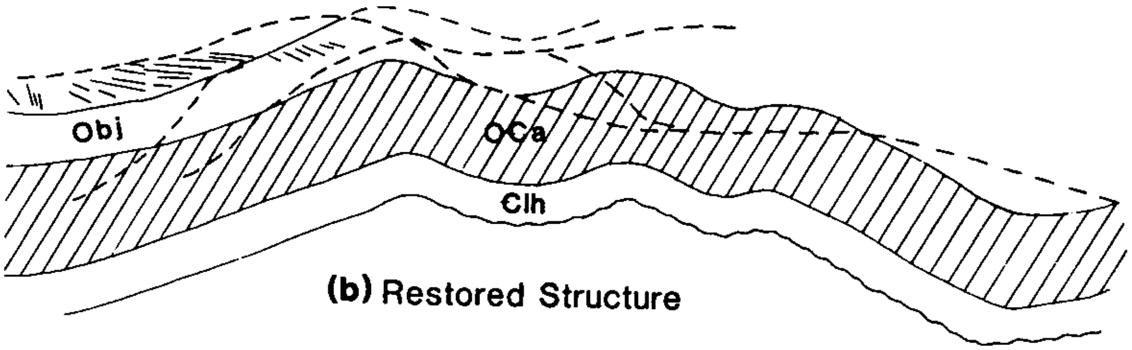
The imbricate thrust sheets that comprise the JJCS and occur in the southwest Highlands are generally northeast-plunging so that successively higher thrust sheets are visable on the map in a progressive northeast direction. In contrast, the Paulins Kill thrust belt is doubly-plunging away from the central part of the Paulins Kill Valley (Pl. 1).

As with the JJCS, the Paulins Kill thrust belt also contains imbricate thrust sheets of coupled basement and cover-layer strata with open and upright fold geometry. Although no basement rocks occur at the surface, the coupled nature of the thrust sheets in this area is indicated by the strong, positive aeromagnetic anomolies associated with the F1 cover folds within the Valley (LKB Resources, 1980). The emergent thrust faults are dominantly synthetic and are arranged in bilateral symmetry about a parautocthonous cover sequence occupying the northwest-central part of the Paulins Kill valley (Pl. 1). The axis of symmetry trends northwestward along the Sussex - Warren County boundary.

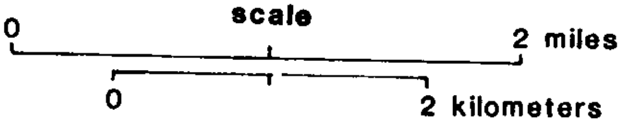
In the vicinity of Blairstown, two component thrust faults of the Paulins Kill thrust belt change their positions within and marginal to the Paulins Kill Valley and sequentially splay into the northwest limb of the hindward-bordering slate belt where they plunge laterally into blind-thrust fault-propagation folds (Pl. 1). This interpretation differs from those of previous maps which show the Paulins Kill Valley to be completely fault-bounded on the southeast side (Lewis and Kummel, 1910-1912; Drake, 1978; Drake and others, 1969; 1985). The



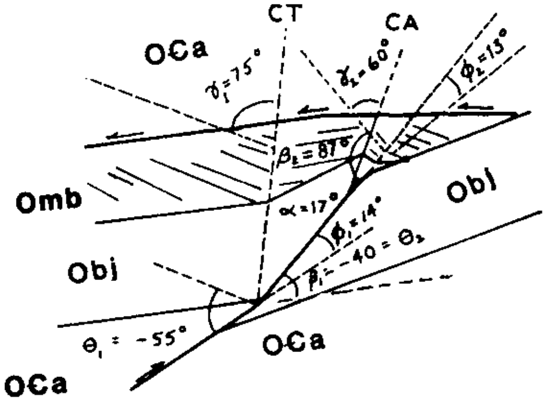
(a) Current Structure



(b) Restored Structure



(c) Restoration of F1 folds from cleavage fold relations



For the cleavage trough (CT) when $\gamma_1 = 75°$ and $\Theta_1 = 55°$, $\beta_1 \cong -40°$ and $\phi_1 = 14°$

For the cleavage arch (CA) when $\gamma_2 = 60°$ and $\Theta_2 = -40°$, $\beta_2 = 87°$ and $\phi_2 = 13°$

Figure 6 - Detail of part of regional cross section C-C' (fig. 14) showing footwall of the Jenny Jump overthrust fault and retrodeformation technique. (a) Current structure. (b) structure restored to pre-thrust (F1) alignment. (c) Restoration of F1 fold geometry from (C1) cleavage folds. Fault-bend fold angles from Suppee (1983).

interpretation shown here is based on the occurrence of a complete stratigraphic sequence southwest of the fault-tip shown on Plate 1 at the boundary between the Paulins Kill valley and the slate belt, and on the occurrence of blind-thrust cover-layer structures which link with the lateral termination of the aforementioned thrust faults.

Farther to the northwest in the vicinity of Walnut Valley, a paired thrust fault sequence locally forms the valley's northwest margin and extends to the southwest into the foreland margin of the Paulins-Kill valley (Pl. 1). One of these faults originates in the center of the Paulins Kill thrust belt and veers to the foreland, across bedding strike into the slate belt that comprises the foreland interval. This trend is displayed at the northeast end of the Paulins Kill valley and defines the symmetric fault arrangement about the parautocthonous footwall sequence noted above. Previous interpretations show the valley either completely fault bounded (Drake, 1978; Drake and other 1969; 1985) or discontinuously faulted (Lewis and Kummel, 1910- 1912). Branching footwall splay thrusts also accompany these faults at both lateral margins. The lateral termination of these thrust faults involves a complex set of plunging fault-propagation folds which occur in the surrounding blind-thrust cover sequence in a manner similar to that described for the hindward and southeast set of thrust faults propagating into the northwest limb of the Halsey synclinorium (Pl. 1). A sequence of large- and intermediate-scale bedding folds occurs directly adjacent to the emergent thrust faults and within the parautocthonous cover interval. The emergent- to blind-thrust structural link wihtin the Paulins Kill thrust belt is detailed below.

Blind-thrust terrane

Map structures in the blind-thrust cover layer sequence generally occur in the Martinsburg Formation and to a lesser extent in the Cambrian-Ordovician carbonate rocks (Pls. 1 and 2a). However, blind-thrust structures contract the entire lower Paleozoic shelf sequence in the Valley and Ridge province; branch and splay faults continue into the foreland beneath the Pocono Plateau as inferred from regional cross section intepretations of Wood and Bergin (1970), Berg and others (1980), and Wilson and Shumaker (1988) for adjacent areas in Pennsylvania. Blind thrust faults are inferred to terminate upwards into roof detachments, mostly within the shaly sections of the Jacksonburg Limestone and the Bushkill Member of the Martinsburg Formation (Fig. 3). This is based on the common occurrence of folds and slip cleavage in cover rocks within these stratigraphic intervals, which are common blind-thrust cover responses (Dunne and Ferrill, 1988).

Refolded bedding folds and folded cleavage within the blind-thrust cover indicate that at least one additional deformation episode has affected the

Paleozoic cover in addition to the earlier F1 folds preserved within the emergent thrust belts. Each period of folding of the cover layer may have a related cleavage set, and only two disjunctive cleavage sets are visible in any outcrop. The distribution and character of these cleavage sets are detailed by Broughton (1946), Maxwell (1962), Epstein and Epstein (1969), and Drake and Lyttle (1980, 1985), among others. An early (C1) cleavage set includes the regional slaty cleavage in the claystone slate of the Bushkill Member and a spaced solution cleavage in the siltstone-graywacke of the Ramseyburg Member of the Martinsburg Formation. The second (C2) cleavage set includes variable types of crenulation cleavage. The C2 cleavage sets are typically widespread near thrust fault traces, and occur in fold hinge areas of refolded bedding and cleavage folds and are therefore correlated with the regional thrust fault deformational event. The blind-thrust cover sequence is examined below in terms of three spatial components: 1) the Halsey synclinorium, 2) the Beemerville-Unionville interval, and 3) the Paulins-Kill foreland (Pl. 1).

The Halsey synclinorium defines the interval located immediately northwest of the JJCS which is folded into a broad, open, regional synform having a series of en echelon, lower-order synclines and anticlines in the hinge area (Pl. 1). The synclinorium trough extends southwest from the Sussex area through Halsey across the Delaware River into Pennsylvania at Ramseyburg where it includes the Stone Church syncline of Drake and Lyttle (1985). The southeast limb of the synclinorium contains a spaced set of diverging-splay thrust faults in the footwall of the JJCS as previously indicated. Erosional remnants of overthrust sheets that were emplaced from the hindward JJCS are scattered across the southeast limb of the synclinorium along its length (Pl. 1). The synclinorium is almost entirely bound to the foreland by the hindmost thrust fault of the Paulins Kill thrust belt (Portland fault), and it contains a set of diverging thrust fault splays from the thrust belt in its southwestern extension as previously indicated.

The fold geometry and cleavage relations in the Halsey synclinorium indicate that a sequence of F2 folds has redeformed earlier fold structures in the Paleozoic cover sequence. Fold phases recognized within the Halsey synclinorium include: 1) the regional synclinorium, 2) a set of open to tight, asymmetric kink folds displaying northwest vergence and upright-to-recumbant geometry (hogbacks of Maxwell, 1962) within the limbs of the Halsey synclinorium, and 3) cleavage arches and troughs. The C1 and C2 cleavage relations are most clearly visible within the Ridge and Valley thrust system in the Halsey synclinorium.

Representative fold and cleavage relations within the Halsey synclinorium are illustrated in figure 7 along three transects through the fold hinge area. Additional fold and cleavage relations are shown for the southeast limb in figure 6. The synclinorium is probably a regional F2 fold that reflects regional thrust

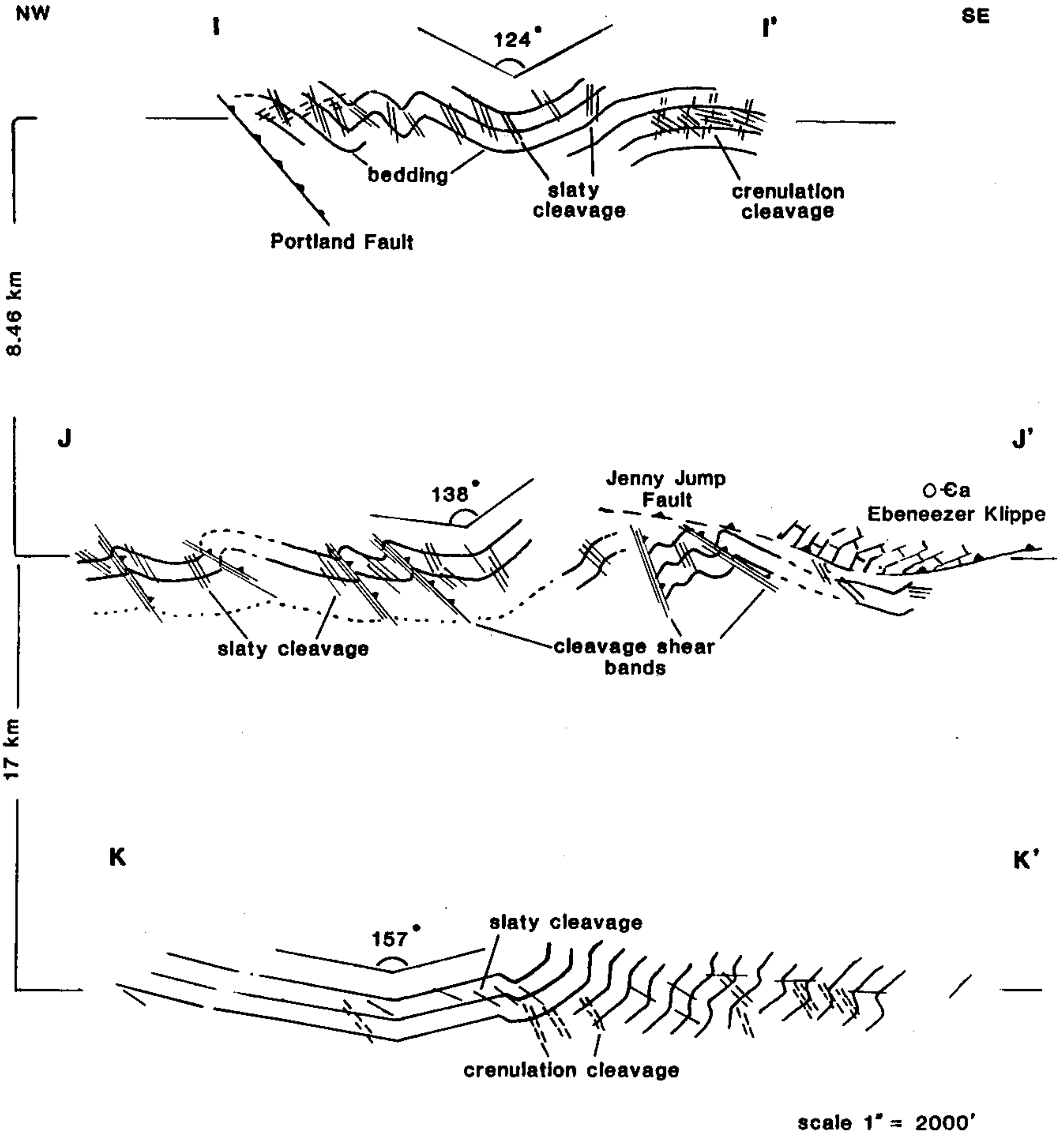


Figure 7 - Halsey synclinorium, cross-section details along three transects. Location of transects shown on Plate 1.

fault processes. The northwest limb of the synclinorium has probably been rotated upward in a clockwise direction because of ramping up the backlimb of the hindward thrust sheet of the Paulins Kill thrust belt. The southeast limb of the synclinorium has probably rotated upward in a counterclockwise direction as a result of blind-thrust imbrication in the footwall of the JJCS as seeen in figure 6. However, internal cleavage relations suggest that the Halsey synclinorium may originally have been a broad and open regional F1 fold before thrust fault modifications. This is because the C1 cleavage typically maintains an orientation that is subparallel to the axial plane of the synclinorium hinge. The local divergence of the C1 cleavage from the axial plane may reflect the effect of shear strain imposed on the early fold and cleavage relations by subsequent overthrusting.

Parasitic F2 bedding folds in the limbs of the synclinorium (Figs. 7 and 8) result from C2 cleavage shear bands (Maxwell, 1962) that consist of abundant swarms of strain-slip crenulation cleavage. The C2 cleavage shear bands are in roughly coaxial alignment with C1 cleavage. These F2 folds are correlated with thrust faulting because they display a consistent northwest vergence on both limbs of the synclinorium and occur mostly near the overthrust klippe. The cleavage shear bands may result from basal shear strain beneath overriding thrust sheets, or they may be fault-propagation folds resulting from upward-propagating, blind thrust faults that splay from lower-level detatchments as illustrated on Plate 2b for the southwest Highlands.

As previously indicated, most of the mappable F2 folds in the Halsey synclinorium can be directly correlated with delamination and fault-propagation fold structures. However, the kinematic link between thrust faulting and other F2 folds that contain normal-slip crenulation (C2) cleavage (Fig. 9) is poorly understood. This type of F2 folding and attendant C2 cleavage may result in flattening and squeezing of intervals between bounding shear zones as illustrated from the microscopic to the megascopic scale in other tectonic terranes (Simpson, 1986; Ratschbacher and others, 1989; and many others). This phenomenon is also illustrated for field trip STOP 2 of this volume.

The Beemerville-Unionville interval continues to the east and north from the Halsey synclinorium and extends from the Ordovician- Silurian contact to the JJCS (Pl.1). This interval combines features related to 1) the northeast termination of the Paulins- Kill thrust belt, 2) both imbricate blind-thrust and lesser emergent structures in the footwall of the JJCS, and 3) the igneous Beemerville complex. Doubly-plunging, upright to recumbent kink folds, similar to those described by Faill (1969, 1973) in the Pennsylvania Valley and Ridge province, occur throughout this interval and represent blind-thrust-accommodating structures (Dunne and Ferrill, 1988) above roof-thrust detachments probably located in the Jacksonburg Limestone and the

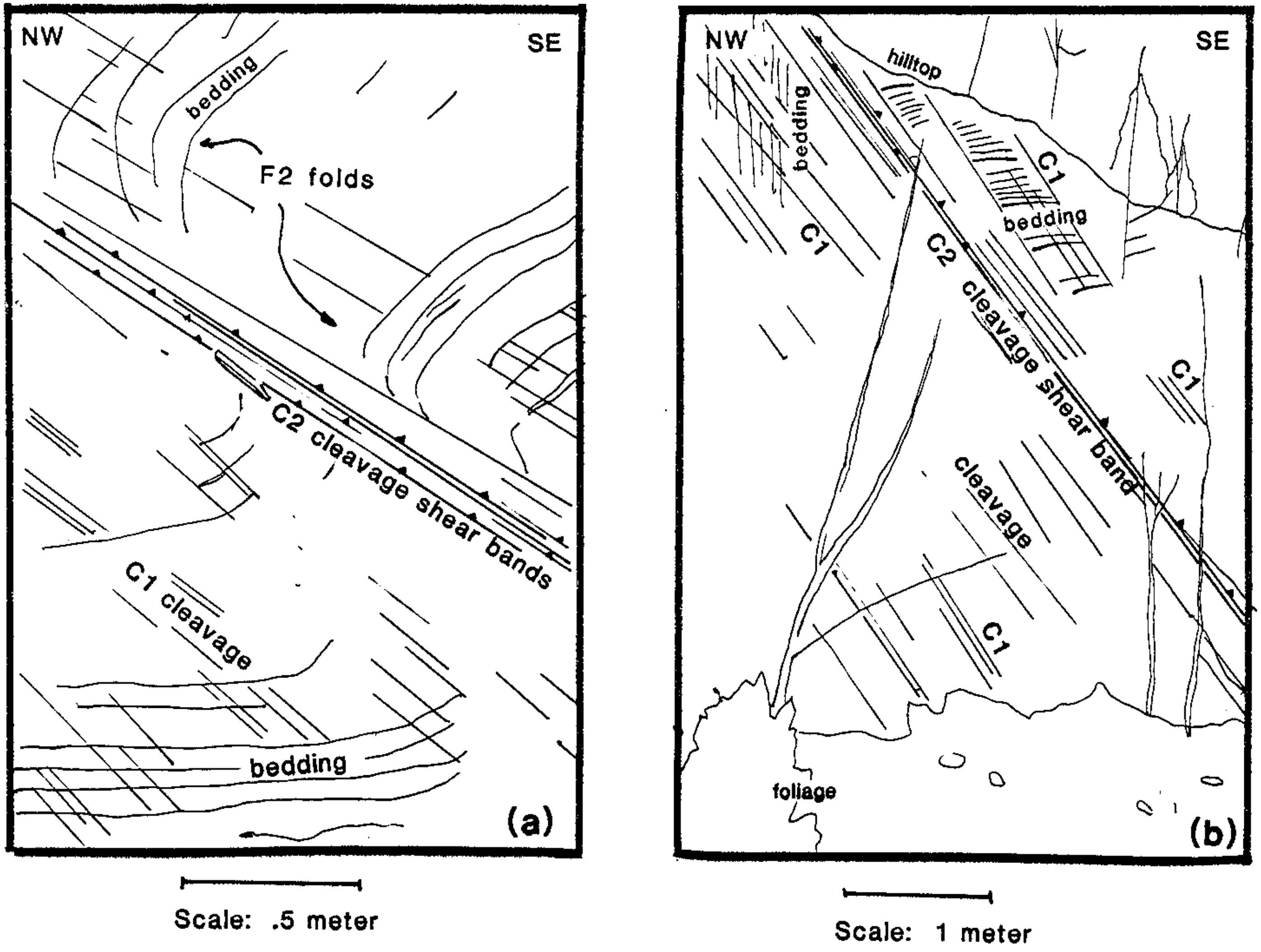


Figure 8 - Sketch of F2 folds - detail from Halsey synclinorium (pl. 1), cross section J-J' (fig. 7). Drag folds (fig.a), kink folds (fig. b), and slaty cleavage (C1) shown in relation to cleavage shear bands (C2) as defined by Maxwell (1962).

Bushkill Member of the Martinsburg Formation. These folds are most abundant northeast of the Paulins Kill Valley where they accomodate the gradual loss of dip-slip displacement from the Paulins Kill thrust belt along a northeastly trend (Pl. 1).

Other folds situated southeast of the termination of the Paulins Kill Valley are blind-thrust structures in the footwall of the JJCS. The Unionville window (Pl. 1) is probably a blind- thrust imbricate thrust sheet subsequently breached by lowering of the erosion surface. A similar, blind-thrust arch also occurs midway between the Unionville window and the lateral termination of the Paulins-Kill Valley. This structure illustrates the break-forward sequence of faulting in the footwall of the JJCS and the emergent- to blind-thrust link of foreland-propagating imbricate structures. This arch occurs along the continuation of the isolated splay faults situated east-southeast of Halsey. However, correlation of this arch with the latter splay faults is obscured by glaciolacustrine deposits which mask the seeming emergent- to blind-thrust link.

Most of the cover-layer folds in the Beemerville-Unionville interval lie behind the Beemerville carbonatite-alkalic complex (Maxey, 1976) of Late Ordovician age (Zartman and others, 1967; Ratcliffe, 1981). Rocks of the Beemerville complex are most abundant near the surface at the northwest margin of the Kittatinny Valley where two nepheline syenite plutons crop out directly below the Ordovician-Silurian contact (Pl. 1). A diverse assemblage of alkalic-calcic diatremes, stocks, dikes, and sills intrude both the Lower Paleozoic cover and the basement rocks to the east-southeast; they are more sparsely distributed at the surface in that direction. No other igneous rocks are known to crop out in the Kittatinny Valley. The igneous complex acted as a tectonic buffer in the cover layer by its apparent resistance to tectonic contraction in comparison with the adjacent rocks. This strain effect is indicated in the map pattern by the decreasing frequency of folds with progressive proximity to the main intrusive bodies from the southeast (Pl. 1). The Silurian-Devonian rocks are also less deformed in the foreland of the intrusive complex than in adjacent areas. This strain effect is readily apparent in the map pattern (Pl. 1) by the increased width of the Silurian rocks behind the nepheline syenite plutons when compared to adjacent areas Spink (1972).

The Paulins Kill foreland-cover sequence continues southwest from the the Beemerville-Unionville cover sequence and spans the interval between the Paulins Kill valley and the Shawangunk Formation underlying Kittatinny Mountain. This interval primarily involves the Martinsburg Formation at the surface but also includes a lower Paleozoic anticlinorium with a core of Cambrian-Ordovican carbonates north of Swartswood Lake (Pl. 1). A synclinorium occurs directly south of the anticlinorium; both of these F2 structures are related to blind thrust faulting in the footwall of the Paulins Kill

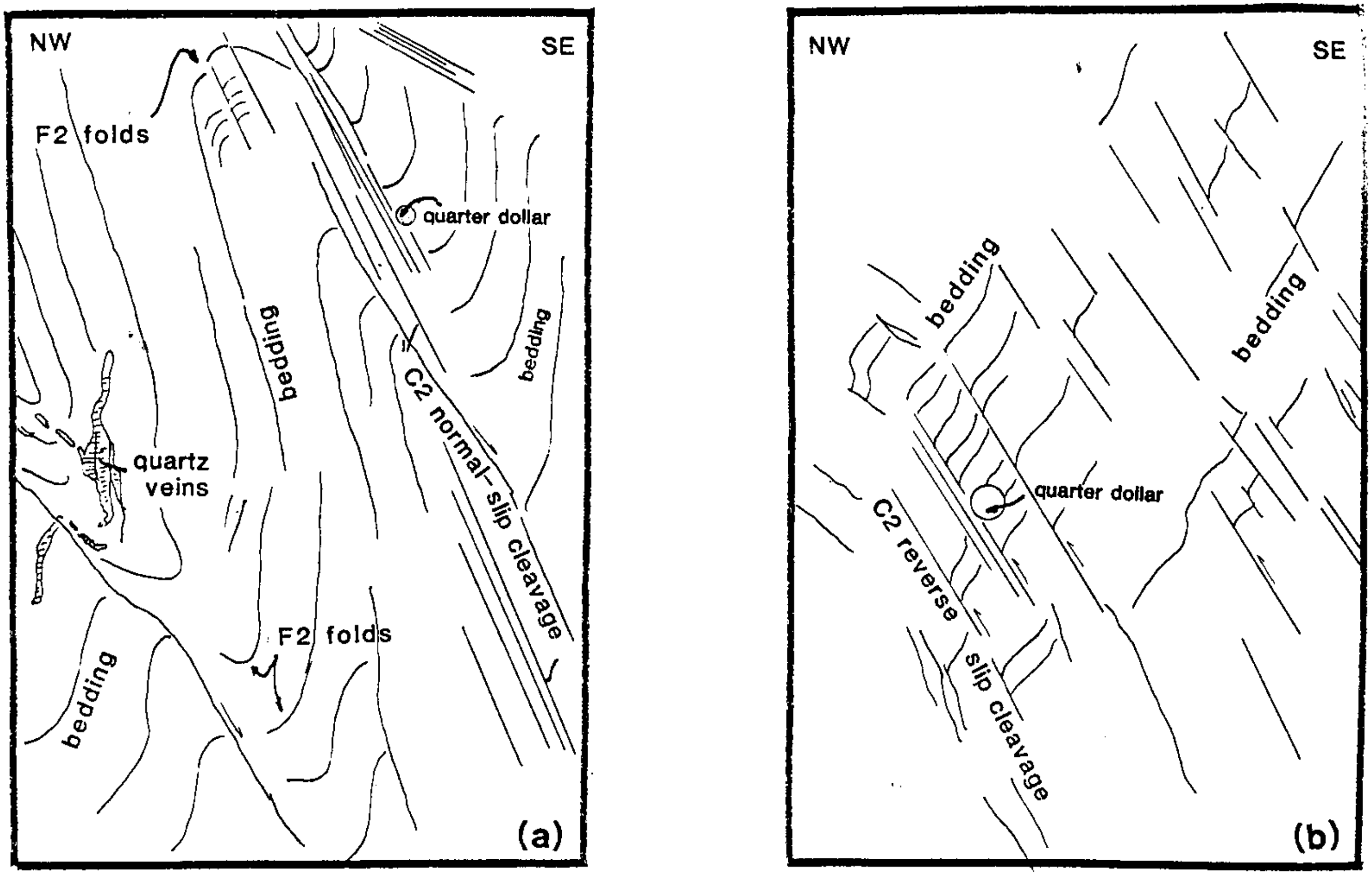


Figure 9 - Sketch of F2 folds and C2 cleavage from the Halsey synclinorium (pl. 1), cross section K-K' (fig. 7). (a) Normal- slip cleavage and F2 bedding folds. (b) reverse-slip crenulation cleavage in the same outcrop.

thrust belt. Large-scale cleavage folds also occur in this interval (Pl. 1). These indicate blind delamination structures similar to those in the footwall of the Jenny Jump thrust fault.

The slight angular divergence of bedding along the Ordovician-Silurian contact in the Paulins Kill foreland sequence (Epstein and Epstein, 1969) indicates little deformation here prior to the Silurian. Within the blind-thrust cover layer the Martinsburg Formation has a minimum thickness of approximately 790 meters (2600 ft) in the southwest part of this interval compared to its thickness of 1220 meters (4000 ft) in the Halsey synclinorium and an estimated 1524 meters (5000 ft) in the northeast in the Beemerville- Unionville interval). This relation is apparent by comparing the outcrop widths of the Martinsburg Formation for the different areas (Pl. 1). However, the discontinuous extent of the Blue Mountain décollement along the southwest margin of the Paulins Kill foreland interval (Pl. 1) indicates that the Ordovician-Silurian contact has been modified locally by thrust faulting that undoubtedly affected the anomalously thin outcrop width of the Martinsburg sequence here. This interpretation of the discontinuity of the Blue Mountain décollement is suggested by the occurrence of arcuate, steeply-inclined F2 fold pairs in the Martinsburg Formation that plunge beneath Kittatinny Mountain and reemerge along strike (Pl. 1). The limited extent of the Blue Mountain décollement is a consequence of the lack of faulting at the nonconformable to gradational Ordovician-Silurian contact directly northeast at the Yards Creek excavation (Smith, 1969). The nature of the Blue Mountain décollement is explicated in the cross-section analysis which follows.

The southwest termination of the Paulins Kill thrust belt is in an area of thick glaciolacustrine sediments where bedrock exposures are scarce. The thrust sheets comprising the Paulins Kill Valley plunge southwestward beneath a folded sequence of Martinsburg rocks (Epstein, 1973) in a manner similar to its northeast termination.

Regional cross-section analysis

The vertical cross-section interpretations are based on standard methods of down-plunge projection for planar and parallel-folded structures (Ragan, 1985; Ramsay and Huber, 1987; DePaor, 1988). They assume plane strain and the conservation of volume and bed lengths (Dahlstrohm, 1969). Apparent-dip values for bedding, cleavage, and fault-dip data have been projected into the plane of section based on the pitch calculation outlined by De Paor (1988, equation 9). The projection of F1 bedding folds utilized actual field measurements of bearing and plunge of bedding and early cleavage (C1) intersection lineations. The projection of later fold sets (F2) and thrust fault planes is based on bearing and plunge values from C1 and C2 intersection lineations as available. Otherwise, projection values are based on trial-and-error section balancing. The three-dimensional thicknesses of cover-layer strata have been used in the cross section constructions to approximate apparent thicknesses. Cross section traverses are oriented normal to regional strike to minimize aberrations in apparent stratigraphic thickness.

The redeformed nature of the cover layer necessitated additional modeling assumptions and the development of cross-section restoration methods. The primary assumption was that a sequence of basement-cored, cover-layer folds were subsequently thrust faulted and locally refolded. The early (F1) cover layer folds are typically parallel, open, upright, and doubly-plunging in the Kittatinny Valley. They become tighter and inclined towards the hinterland in the Paleozoic outliers of the Highlands. This progressive contrast is evident in the map view and in the cross sections. It is also consistent with the regional interpretations of Merchant and Teet (1954).

The primary assumption complicates the cross-section balancing procedure because the F1 folds retrodeform to a pre-thrust fold configuration rather than a flat-lying sedimentary wedge (Figs. 4 and 6). Therefore, restoration of the F1 folds to a pre-thrust configuration requires the interpretation of blind footwall fold forms and the removal of strain effects associated with the later thrust system, including any subsequent (F2) folds.

The projection, construction, and restoration of the F1 folds in the subsurface is intricate because of their doubly-plunging fold geometry. Interpretive error is liklier because of projecting surface structures and failure to account for blind variations in the actual fold geometry at depth. Fewer complications ensue where imbricated thrust sheets are bounded on their lateral margins by thrust faults that locally dip in the direction of the regional strike (lateral ramps) and therefore expose both hanging wall and footwall fold segments in adjacent positions. This is the case for the imbricate thrust sheets in the Johnsonburg - Greendell area (Pl. 1) where the average projection axes and fold forms for hanging wall and footwall segments are readily available for projection and restoration. However, the interpretation of an F1 footwall sequence is elusive where faults show little or no lateral variation in dip throughout large areas and where erosion has removed a substantial part of the hanging wall fold form. In such instances, as with the Crooked Swamp synclinorium (Pl. 1), little is known about the corresponding "blind" footwall sequence extending hindward beneath the overthrust hanging wall. However, as illustrated in Figures 10 and 11, the wavelength and extent of the blind F1 footwall sequence is constrained by restoration of the remnant F1 hanging wall geometry to a subsurface footwall fold form that is consistent with the observed aeromagnetic profiles. Such aeromagnetic correlations have been applied based on the assumption that basement rocks generally possess an increased magnetic susceptibility compared to cover-layer rocks. The geometry of the F1 folds is further refined by simaltaneous bed-length, area, and stratigraphic/fault cut-off adjustments between current and restored cross-section diagrams.

A "minimum strain" assumption has also been applied to cross-section interpretation for areas that lack lateral ramps and detailed aeromagnetic coverage, or for which aeromagnetic coverage is available but inconclusive. This required the simplest, blind-footwall fold sequence necessary to complete the restored F1 cover-fold sequence. For example, the "Deckertown duplex" retrodeforms to an existing anticlinorium (Figs. 4 and 10), but only the southwest limb of an antiform exists in the bordering hanging wall segment (Pl. 1 and Fig. 4). This implies that a blind footwall sequence involves at least a missing synform hinge area. Because the aeromagnetic data are relatively ambiguous for this area in comparison to areas down-strike (Figs. 10 and 11), this required construction of only a single synform in the blind footwall segment to complete the restored fold panel. More complicated reconstructions based on addditonal fold pairs can be developed, but finite dip-slip values between adjacent, serial sections (Figure 5) demonstrate uniformity using this "minimal strain" first estimate. This method also assumes that all of the "blind" folds consist of the same lithic units and structural family and therefore should not vary in fold and thrust geometry for the same tectonic environment (Woodward and others, 1985).

In order to restore the F1 folds into a pre-thrust configuration it was necessary to remove the geometric effects of superimposed F2 folds resulting from thrust-fault processes. The set of F2 folds includes fault-bend, fault-propagation, and drag folds. For this study, the F2 fault-bend folds typically proved to have only localized and subtle strain effects on F1 fold segments because thrust faults propagating through F1 structures generally climb through inclined planar limbs and gradually flatten and splay through F1 hinge zones (Figs. 4, 6, 10, and 11). The resulting faults are broadly undulating and relatively smooth in contrast to the sharper fault bends described for fault trajectories in flat-lying sedimentary wedges (Rich, 1934; Suppee,1983). The associated fault-bend fold strains therefore typically consist of slight, large-scale flexures of F1 fold segments resulting from regional imbrication processes. These mostly require minor trial-and-error realignment adjustments of the F1 fold segments. Therefore, for inital construction and restoration attempts, thrust-translated F1 fold segments were restored using their current form except where imbricate processes provided compelling evidence of F2 strain effects. An example of such compelling evidence occurs where folded limb segments display large-scale C1 cleavage folds. For instance, a sequence of such cleavage folds in the footwall of the Jenny Jump thrust fault (fig. 5, Pl. 1) is spatially related to the aforementioned sequence of antithetic delamination faults (backthrusts). By assuming a kinematic link between these two structures, the subsurface configuration of the thrust faults can be derived and the pre-thrust fold forms can be restored.

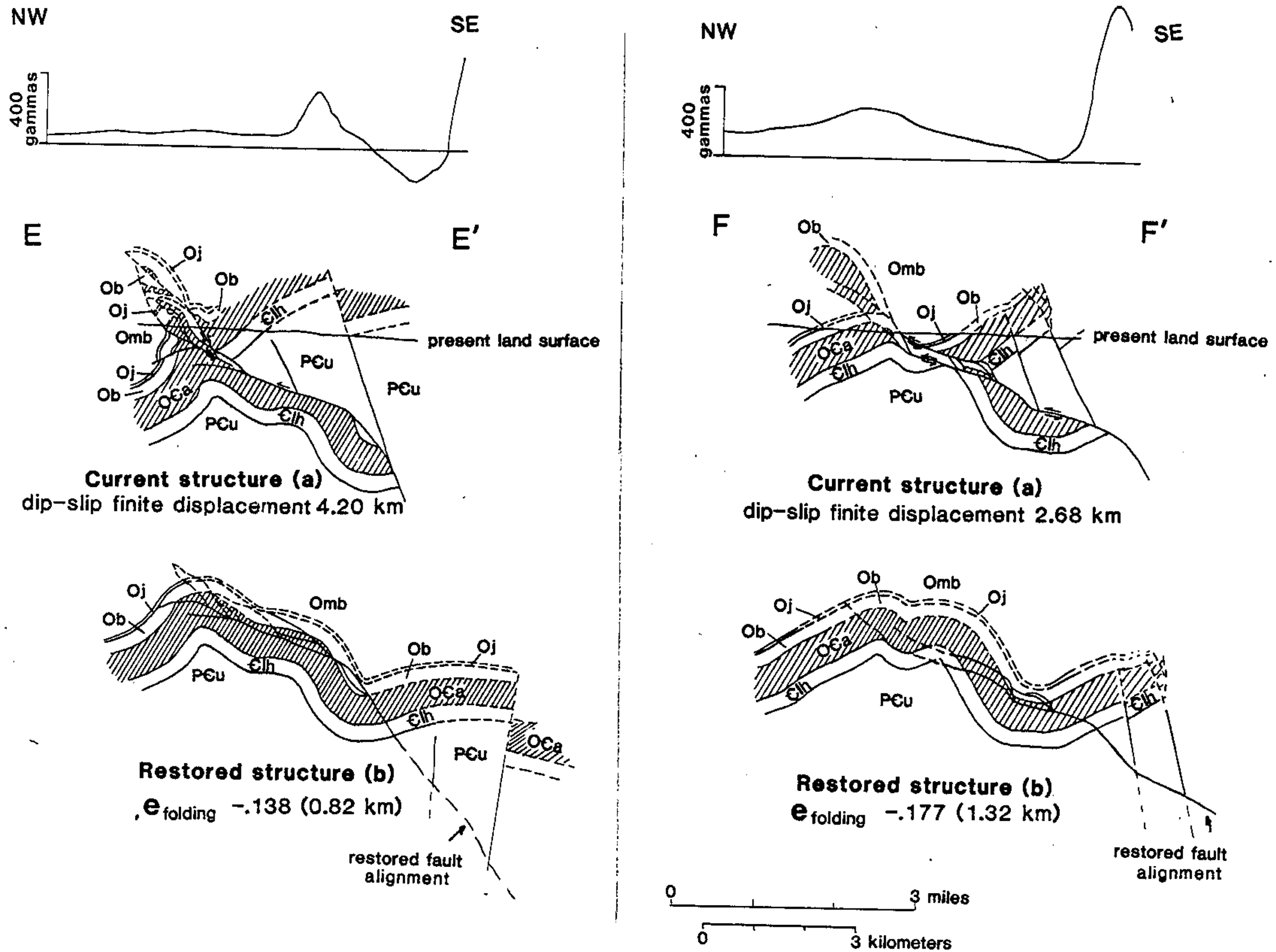


Figure 10 - Cross sections E-E' and F-F' for the northeast Jenny Jump - Crooked Swamp thrust belt. (a) Current sections and corresponding NURE aeromagnetic profiles (LKB Resources, 1980). (b) Restored sections showing pre-thrust cover layer, thrust propagation, and block-fault alignments. Location of sections and description of units shown on Plate 1. Omr - Ramseyburg Member of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Oj - Jacksonburg Limestone, Ob - Beekmantown Group, OЄa - Allentown Dolomite, Єlh - Leithsville Formation and Hardyston Quartzite undivided.

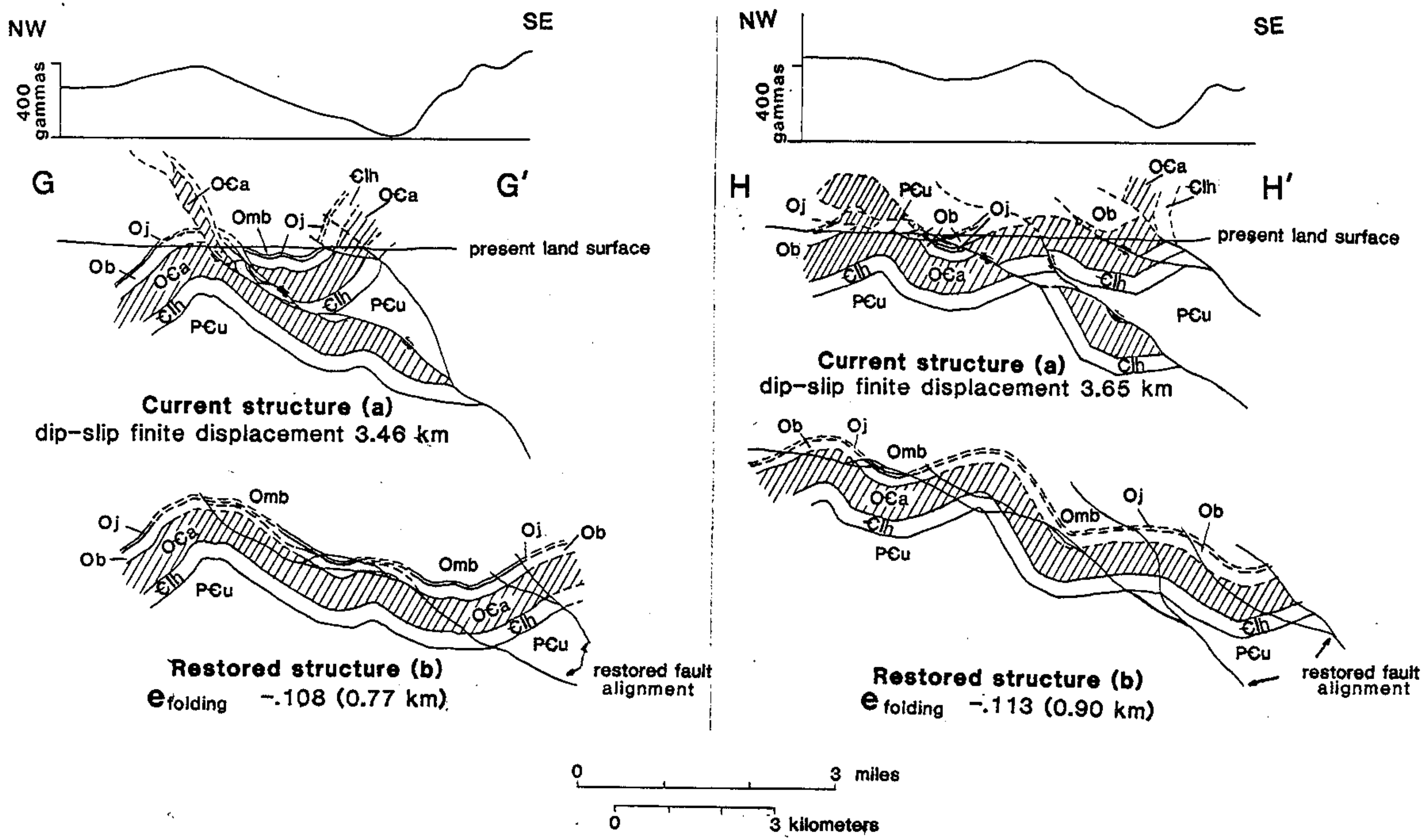


Figure 11 - Cross sections G-G' and H-H' showing the central Jenny Jump - Crooked Swamp thrust belt. (a) Current sections and corresponding NURE aeromagnetic profiles (LKB Resources, 1980). (b) Restored sections showing pre-thrust cover layer and thrust propagation alignments. Location of sections and description of units shown on Plate 1. Omr - Ramseyburg Member of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Oj - Jacksonburg Limestone, Ob - Beekmantown Group, OЄa - Allentown Dolomite, Єlh - Leithsville Formation and Hardyston Quartzite undivided.

As illustrated in figure 5, the subsurface fault geometries were derived for the current cross section from fault-bend fold relations listed for interlimb fold and cutoff angles by Suppee (1983). For this application however, the cutoff angles were employed with folded cleavage planes rather than bedding planes, whereas cleavage and bedding angles were assumed to remain constant throughout restoration. The application of fault-bend fold angular relations for cleavage planes assumes flexural-slip folding strain on cleavage. This is substantiated by widespread cross-strike slip lineations on involved cleavage planes. Refolded bedding panels were considered to have been restored to a F1 fold form when pre-thrust cleavage folds were unfolded and restored into planar arrangement.

Aside from the localized F2 strain effects detailed above, thrust-faulted F1 fold segments in the Valley and Ridge province are assumed to have been subjected to negligible bulk strains and therefore to require little change from current to restored states. Mesostructural field relations support this interpretation in view of the general absence of disjunctive mesostructures internal to the thrust sheets and distant from emergent thrust fault zones. However, pre-thrust structures are commonly subject to localized but significant shear strain near thrust faults where smaller-order cleavage folds and other cross-cutting mesostructures show fault-propagation or drag-fold strains. Restoration of early fold forms for these localized near-fault intervals relies heavily on trial-and-error line-length and area-balancing manipulations. Also, comparatively high degrees of bulk strain are interpreted for the thrust sheets in the southwest Highlands area as compared to the Valley and Ridge. Accordingly, more trial-and-error balancing manipulations were required to remove these bulk-strain effects for this more hinterland margin.

The second modeling condition for this cross-section analysis therefore assumes that the internal strain in a thrust sheet resulting from thrust faulting is negligible except where it is modified by recognizable faults or fault-related fold strains. This allows the restored fold forms to be a modification of a down-plunge projection of current structures following removal of later fault-related fold forms.

A third assumption aligns pre-thrust faults that cut the cover layer along the southeast margin of the Kittatinny Valley (Pl. 1) and extend hindward into the Highlands province. These pre-thrust emergent faults are cut by the later thrust faults in the map view or show cross-cutting mesostructural relations. They are typically basement shear zones with apparent normal and reverse dip-slip components and various dip angles. These faults are most most readily apparent where they juxtapose basement and cover blocks along the southeast margin of the Kittatinny Valley (Pls. 1, 2a). The cover usually occurs in the downdropped, southeast block. Other basement shear zones occur in conjugate arrangements that are cut by later mesostructures and show a strain relation with probable F1 cover folds (for example the Morgan Hill shear zone, field trip STOP 1). This assumption also requires that other folds related to emergent faults within the Kittatinny Valley, such as fault-propagation-folds or drag folds, be assigned to the later deformation event.

A fourth set of additional modeling assumptions is also necessary because the cover layer retrodeforms to a fold sequence instead of a flat-lying sedimentary wedge. Without this planar reference for retrodeformation, many different restored alignments between cover fold forms in adjacent thrust sheets are possible. This situation is particularly sensitive to strained bedding-fault cutoff intervals which are subject to drag folding and trial-and-error balancing manipulations. However, the restored alignment of the cover layer is limited by retrodeformation of the composite basement-cover thrust sheets based on the location of the master decollement and a structural relief assumption. Use of the master decollement as a lower boundary limit constrains the basement area available for the adjacent, stacked thrust sheets that occupy the interval above the decollement and below the basement-cover layer contact (upper boundary). The vertical thickness of basement area for individual sheets is further constrained by the assumption that each cover-layer segment originates from a position of lower structural relief than the one it currently occupies. When each thrust sheet is restored to its postion along the master décollement, the adjacent configuration of cover-layer segments is constrained by the limited amount of basement area available for adjacent sheets between the respective upper and lower boundary limits, and because the basement and cover layer are coupled (Fig. 12).

The current and restored regional cross sections for the Valley and Ridge province are shown in Figures 13, 14, and 15; the corresponding map locations are shown on Plate 1. The current and restored sections for the southwest Highlands area are shown on Plate 2b, and 12, and the respective map location is indicated on Plate 2a. The current sections through the Kittatinny Valley are shown in serial arrangement in Figure 16 to provide a three-dimensional comparison of the fold and fault geometry within the thrust system. Similarly, the restored sections are shown in serial arrangement in Figure 17.

Deep-level structures have been extrapolated from the near-surface structures based on surface projections, aeromagnetic data, and the balancing methods previously outlined. The lower boundary limits are constrained from the seismic reflection and gravity data detailed below.

Major thrust faults are interpreted as branching from an unnamed master décollement which is rooted in basement and which generally lacks any cover layer involvement until it first pierces the cover layer at the northwest margin of the Valley and Ridge province (Figures 13-15, Plate 2b). The structure beneath the northwest part of the province shows blind-thrust translation of cover-layer

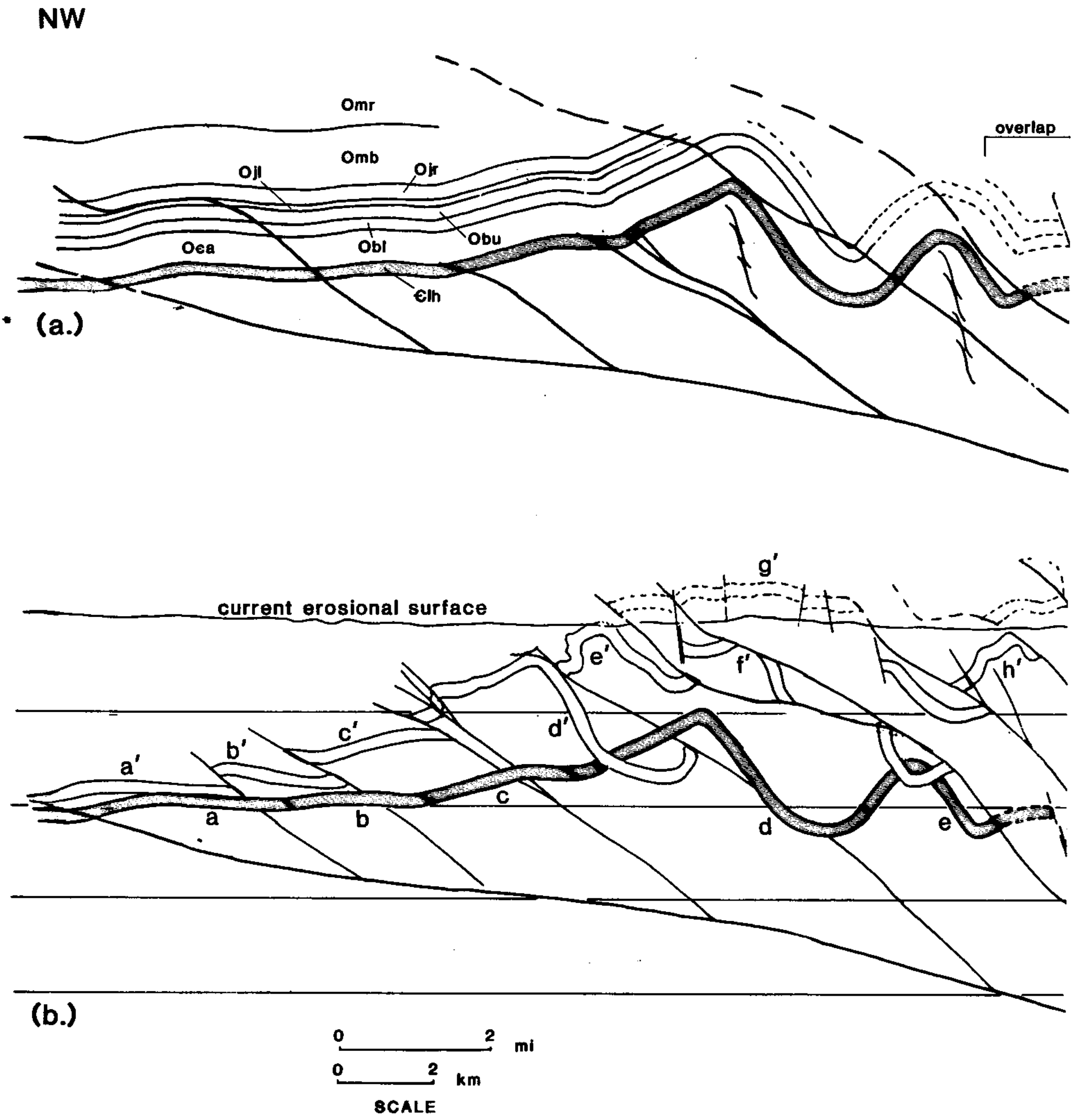
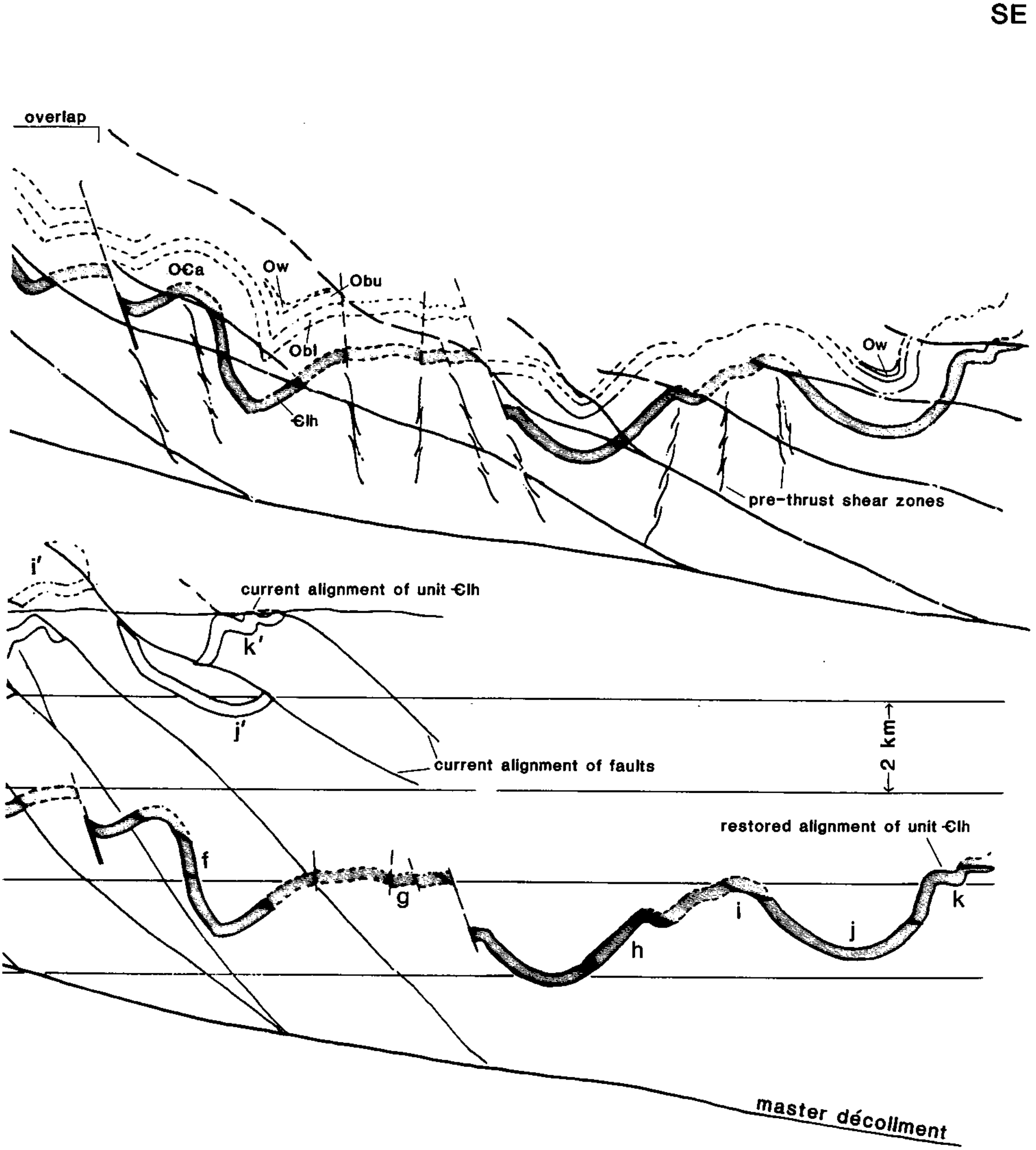


Figure 12 (a.) Restored structure of cross-section D-D′ (Plate 2b)

(b.) Structural relief diagram comparing Ꞓlh unit for current and restored alignments

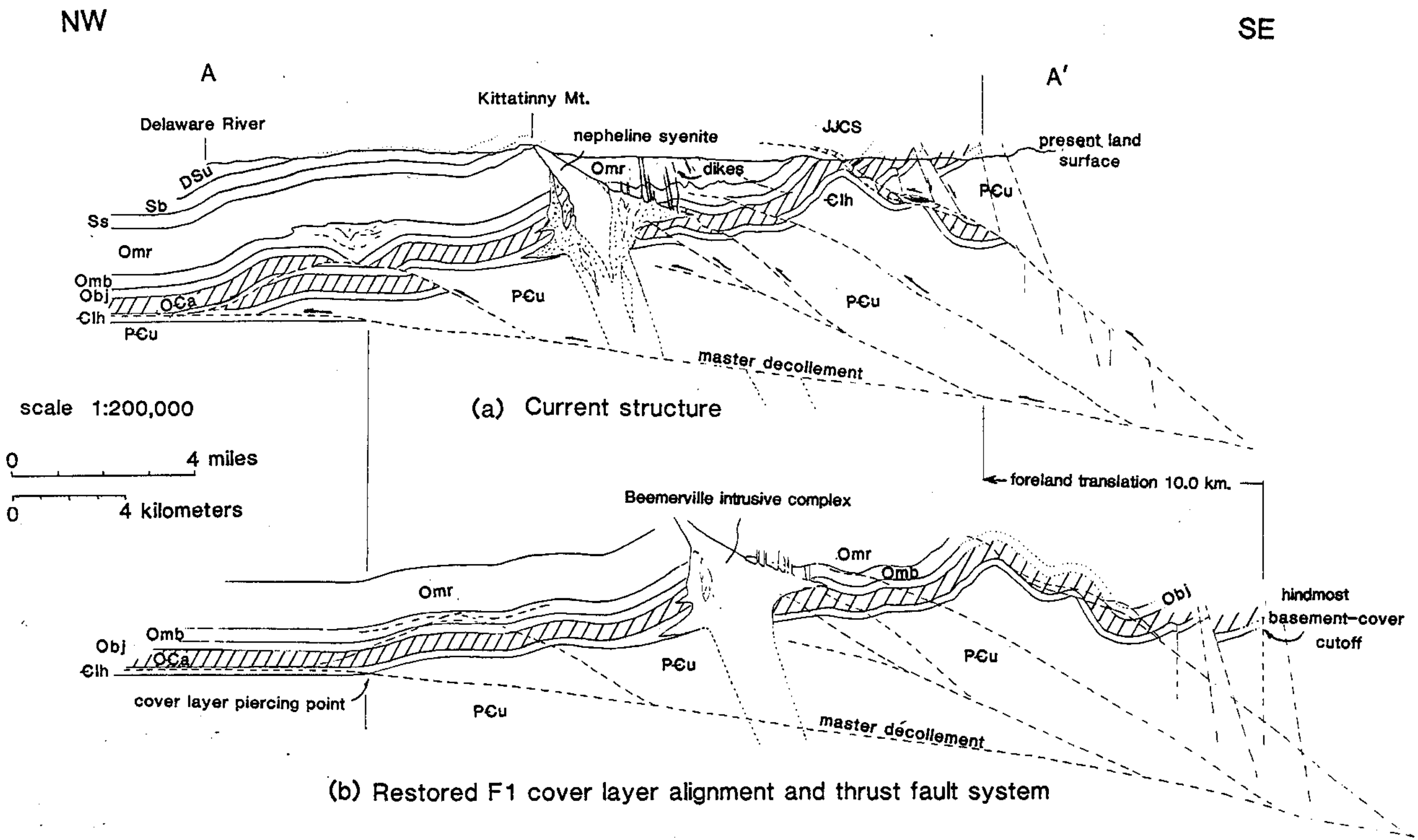

SE
overlap
OꞒa
Ow
Obu
Obl
Ꞓlh
Ow
pre-thrust shear zones
i'
current alignment of unit Ꞓlh
k'
j'
current alignment of faults
2 km
restored alignment of unit Ꞓlh
f
g
h
i
j
k
master décollment

strata continuing into the foreland beneath the Pocono Plateau.
This interpretation is constrained by an unpublished seismic reflection profile oriented obliquely across strike between regional cross sections A - A' and B - B' (Pl. 1). The data show that a pair of reverse faults have opposite vergence within the Cambrian-Ordovician cover beneath the northwest part of the Valley and Ridge province. They also provide thickness estimates of the cover layer and depth values for both the master decollement and the basement-cover contact. The depths are considered minimum values based on only a single thickness of cover layer below the central roof thrust located within the Jacksonburg Limestone and the Bushkill Member of the Martinsburg Formation (Figs. 13-15). The master décollement depths for the southeast boundary are interpolated between those used for the foreland, and depths for the southeast part of the Highlands province from seismic reflection data of Ratcliffe and Costain (1985). The 8 - 10 range of wedge-taper values indicated for the interpretations (Table 1) is representative of the wedges discussed by Davis and others (1983) for other subaerial accretionary wedges.

In the longitudinal direction, the Harmony and Lower Harmony faults in the southwest Highlands area and the major component faults in the JJCS comprise a displacement transfer zone (Dahlstrohm, 1969) where most of the translation strain is transferred from the leading edge fault in the southwest (Harmony-Jenny Jump fault) to the trailing edge fault (Crooked Swamp) in the northeast (Fig. 16). The transfer of displacement involves an intervening series of splay faults which locally combine in duplex fault arrangements.

The Beemerville intrusive complex, shown in cross sections A - A' (Fig. 13), is a stylized rendition of a geometric solution based on gravity models of Ghatke and others (in press) as shown in figure 18. Estimated offset of the complex along the master décollement is based on the amount of foreland translation beneath the Pocono Plateau to the northwest derived from the regional cross sections of Wood and Bergin (1970), Berg and others (1980), and Wilson and Shumaker (1988). Translation of the basement-cover layer cutoffs along the decollement was derived the same way. The steepening of fault trajectories southeast of the main intrusive bodies (Fig. 13) indicates how the intrusive complex acted as a tectonic buffer.

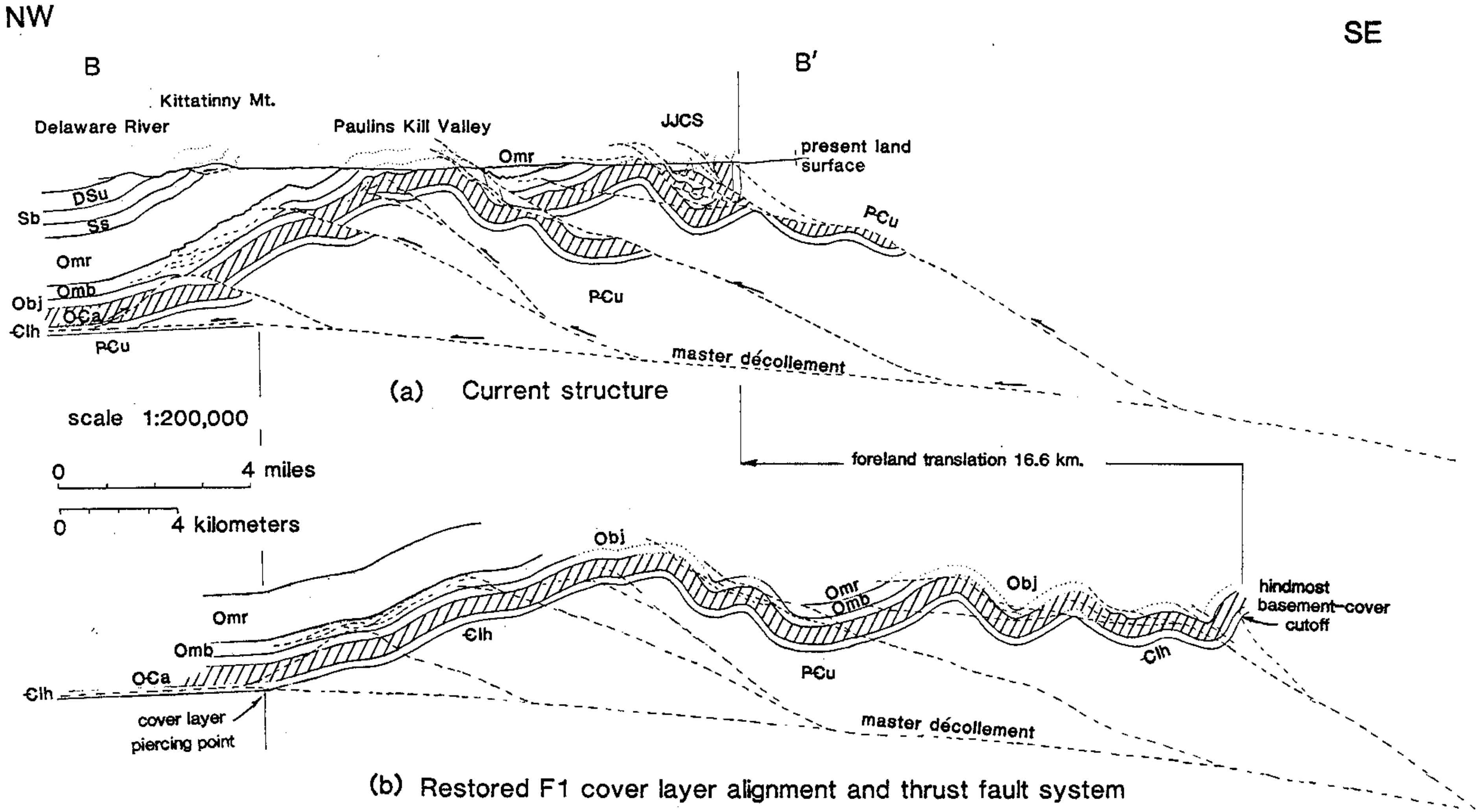
The limited extent of the Blue Mountain décollement shown on Plate 1 is attributed to the location of the emergent thrust faulting in the Paulins Kill Valley relative to the location of the Shawangunk Formation underlying Kittatinny Mountain. Apparently, where the emergent thrust faults in the Paulins Kill Valley swing towards the foreland at the lateral margins of the thrust belt, the Shawangunk is locally bent upward and translated along the Ordovician-Silurian contact toward the foreland. Whether these shears are antithetic splays from the emergent thrusts or merely localized faults accompanying drape folding processes



(a) Current structure

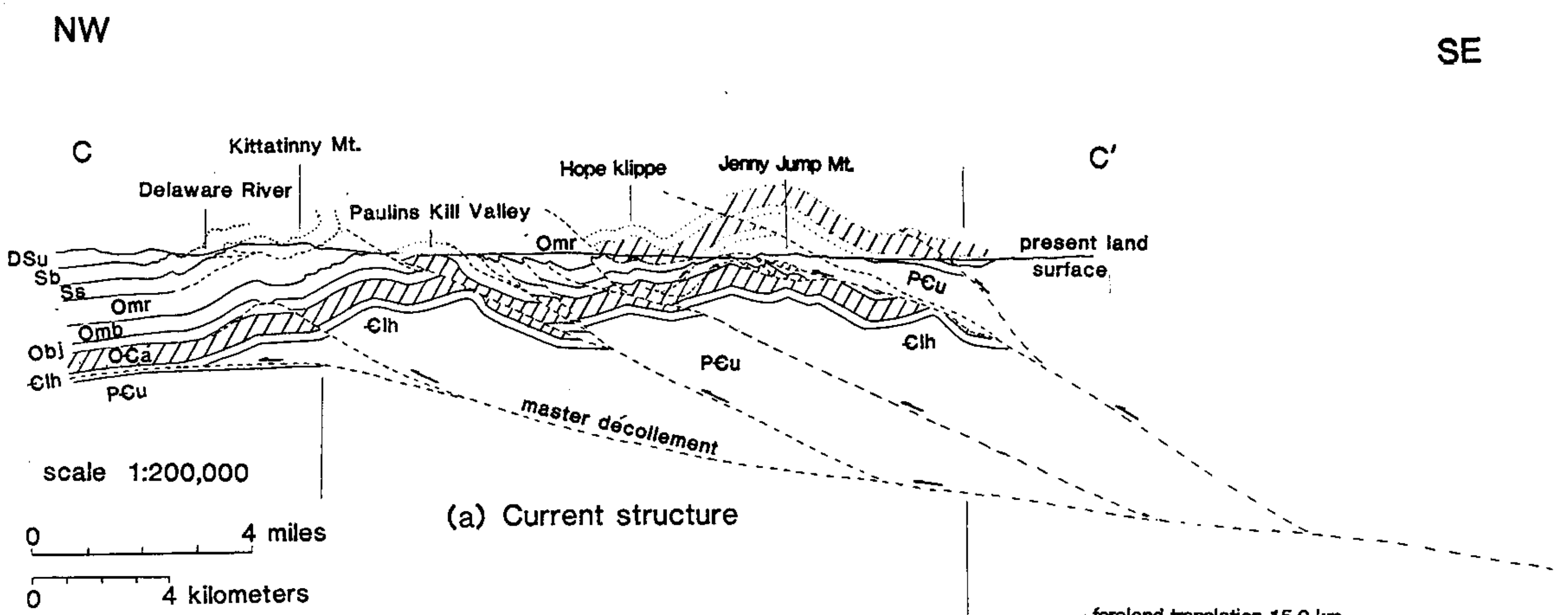
(b) Restored F1 cover layer alignment and thrust fault system

Figure 13 - Regional cross section A-A'. (a) Current structure, (b) Restored pre-thrust cover layer, thrust-propagation, and block-fault alignments. Section location and description of units given on plate 1. DSu - Devonian rocks through Poxono Island Fm. undivided, Sb - Bloomsburg Red Beds, Ss - Shawangunk Fm., Omr - Ramseyburg Member of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Obj - Jacksonburg Limestone and Beekmantown Group undivided, OЄa - Allentown Dolomite, Єlh - Leithsville Fm. and Hardyston Quartzite undivided, PЄu - Precambrian undivided.

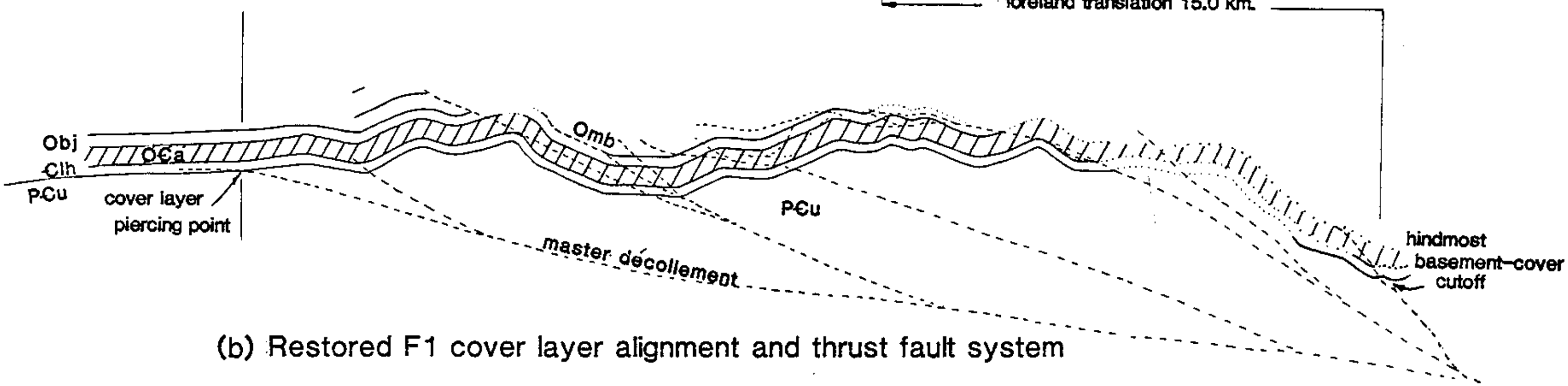

(a) Current structure

(b) Restored F1 cover layer alignment and thrust fault system

Figure 14 - Regional cross section B-B’. (a) Current structure, (b) Restored pre-thrust cover layer and thrust-propagation alignments. Map location of section and description of units given on plate 1. DSu - Devonian rocks through Poxono Island Fm. undivided, Sb - Bloomsburg Red Beds, Ss - Shawangunk Fm., Omr - Ramseyburg Member of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Obj - Jacksonburg Limestone and Beekmantown Group undivided, OЄa - Allentown Dolomite, Єlh - Leithsville Fm. and Hardyston Quartzite undivided, PЄu - Precambrian undivided.



(a) Current structure



(b) Restored F1 cover layer alignment and thrust fault system

Figure 15 - Regional cross section C-C′. (a) Current structure, (b) Restored prethrust cover layer and thrust propagation alignments. Map location and description of units given on Plate 1. DSu - Devonian rocks through Poxono Island Fm. undivided, Sb - Bloomsburg Red Beds, Ss - Shawangunk Fm., Omr - Ramseyburg Member of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Obj - Jacksonburg Limestone and Beekmantown Group undivided, OꞒa - Allentown Dolomite, Ꞓlh - Leithsville Fm. and Hardyston Quartzite undivided, PꞒu - Precambrian rocks undivided.

in front of or beneath overriding thrust faults is unclear. The relation of the Blue Mountain décollement to the emergent thrust faults is ilustrated in Figure 15.

Tectonic measurements for the regional interpretations are shown in Table 1. The strain values are partitioned into strain components that include 1) horizontal foreland contraction from thrust translation, 2) the contraction ratio for the respective cross sections, and 3) negative extension (e) from pre-thrust folding. The measured translation strain is a linear measurement from the hindmost basement-cover cutoff showing reverse displacement for each section measured between the current and restored positions in a horizontal plane relative to the erosion surface. The folding strain values are sinuous bed lengths along the basement-cover contact in the restoration diagrams and do not include penetrative volume-loss strain. Thrust-fault aspect ratios of maximum displacement versus map length for component faults in the Ridge and Valley Thrust system are compatable with those reported for other foreland fold-and-thrust belts where an average ratio of 1:14 (approximately 7 percent) is reported (Elliot, 1976). For example, the Portland fault and subsidiary splay faults accomodate 3.5 kilometers of cross-strike, finite dip-slip displacement across an outcrop width of 45.3 kilometers for an aspect ratio of 1:13. However, as Elliot (1976) noted, faults with outcrop patterns showing extensive branches prove awkward to handle for determination of aspect ratios. This was the case for the JJCS - southern Highlands area.

Table 1. Regional cross-section tectonic dimensions

Cross section	Foreland translation km [mi]*	Contraction ratio (L'/Lo)*	e (F1) [km/mi]	Wedge-taper angle
A - A'	10.0[6.2]	0.69	-.05[1.6/1.0]	8°
B - B'	14.8 [9.2]	0.50	-.08 [2.8/1.7]	8°
C - C'	15.4 [9.5]	0.57	-.04 [1.6/1.0]	9°
D - D'	15.8 [9.8]	0.61	-.11 [5.5/3.4]	10°

* km = kilometers, mi = miles, L' is the current length, and Lo is the restored length.

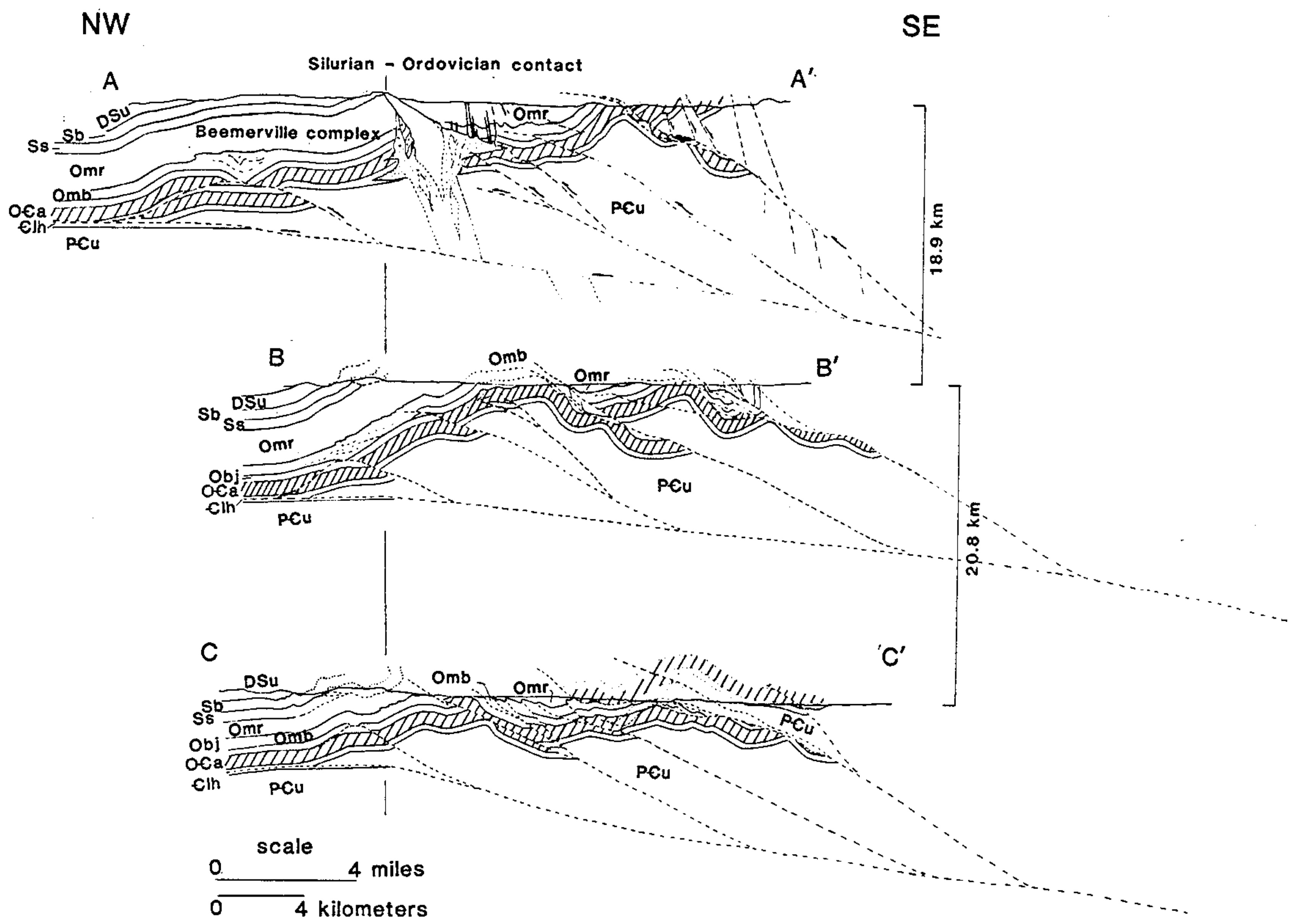


Figure 16 - Series showing current regional cross sections A-A', B-B',and C-C'relative to the Ordovician-Silurian map contact. Location and description of units given on plate 1. DSu - Devonian rocks through Poxono Island Fm. undivided, Sb - Bloomsburg Red Beds, Ss - Shawangunk Fm., Omr - Ramseyburg Member of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Obj - Jacksonburg Limestone and Beekmantown Group undivided, OЄa - Allentown Dolomite, Єlh - Leithsville Fm. and Hardyston Quartzite undivided, PЄu - Precambrian undivided.

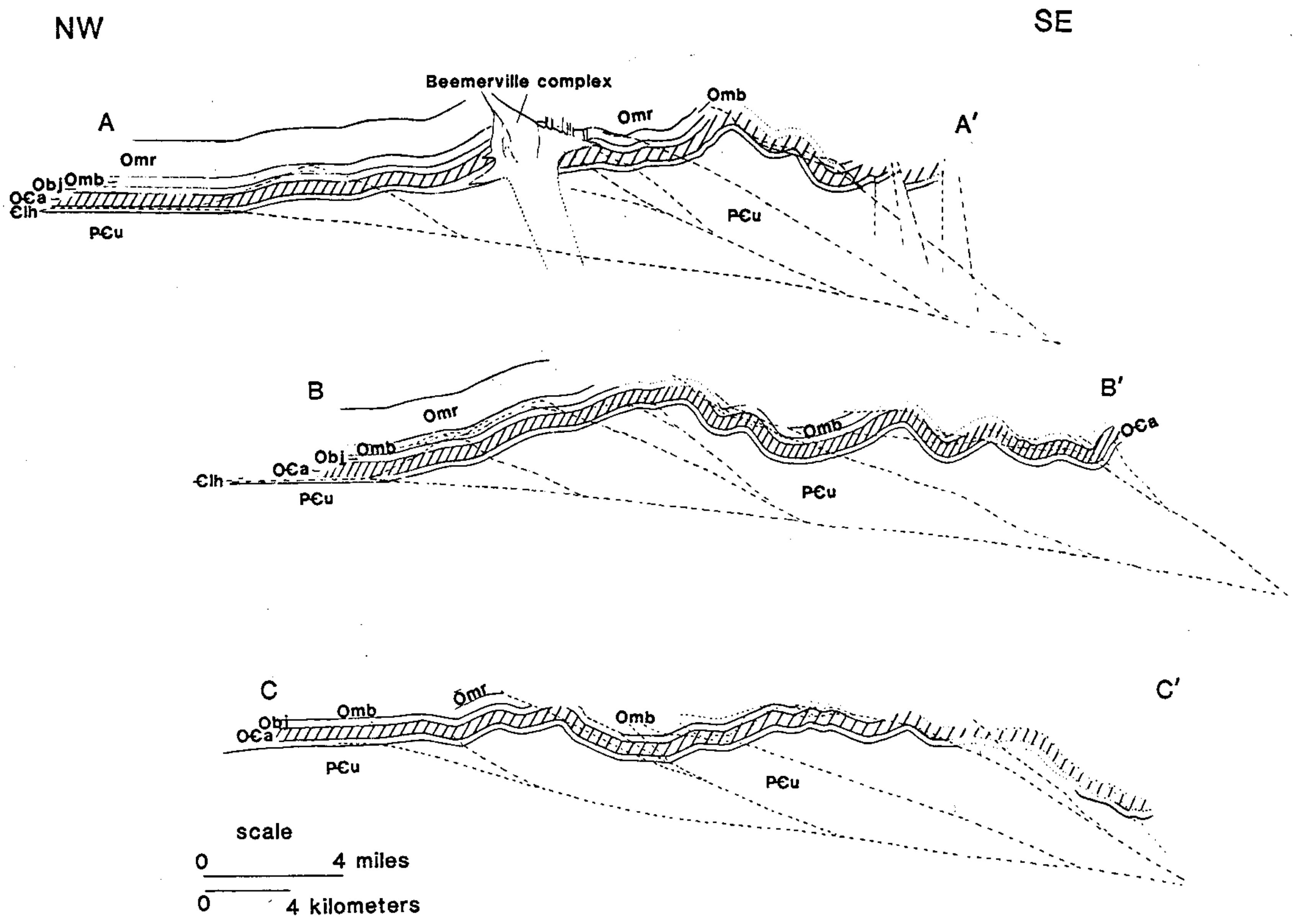


Figure 17 - Series showing pre-thrust restored regional cross sections A-A', B-B', and C-C' relative to current Ordovician- Silurian map contact. Section location and description of units given on plate 1. DSu - Devonian rocks through Poxono Island Fm. undivided, Sb - Bloomsburg Red Beds, Ss - Shawangunk Fm., Omr - Ramseyburg Member of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Obj - Jacksonburg Limestone and Beekmantown Group undivided, O€a - Allentown Dolomite, €lh - Leithsville Fm. and Hardyston Quartzite undivided, P€u - Precambrian undivided.

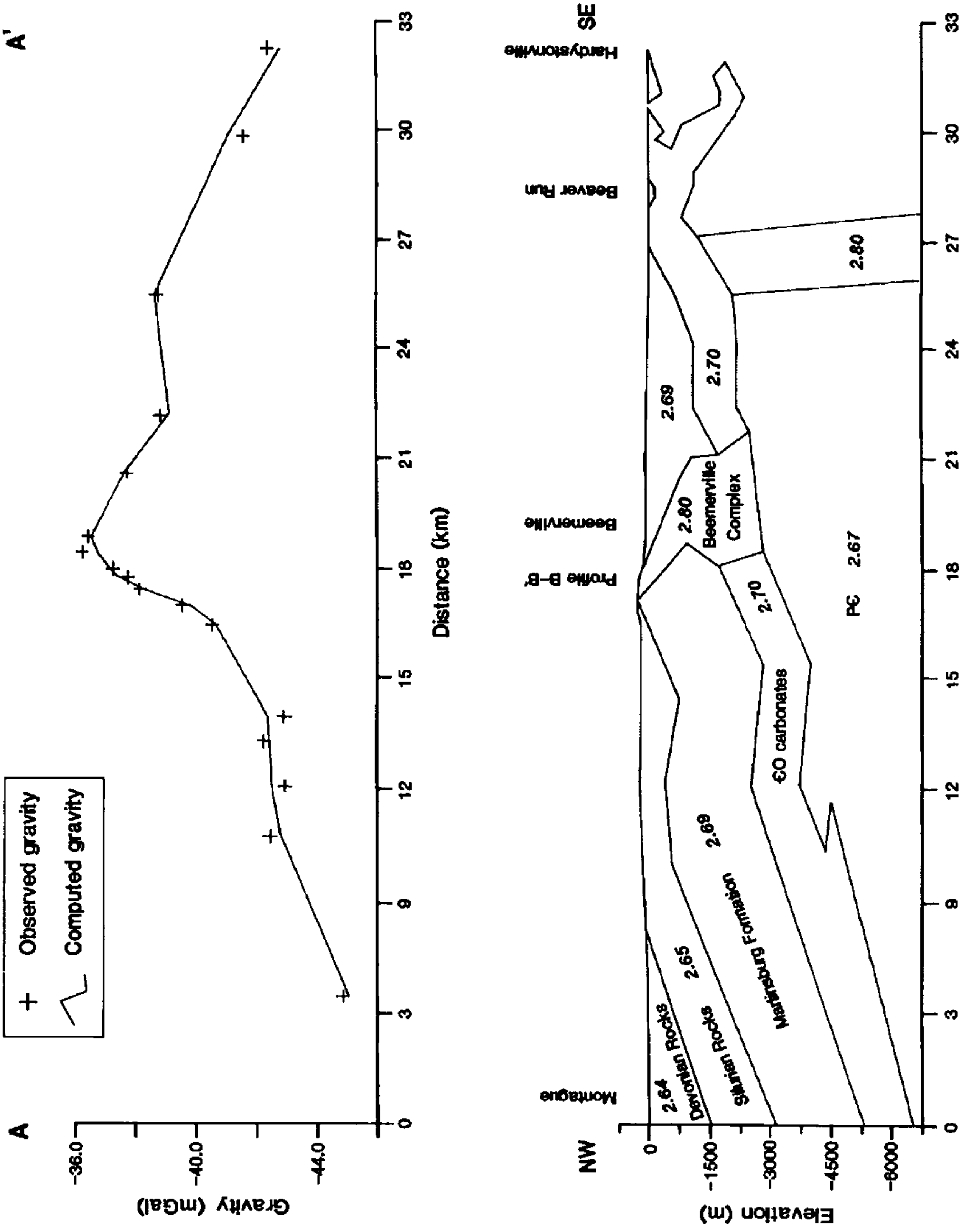


Figure 18. Gravity profile A-A' and interpreted cross-section from Ghatke and others (in press)

Styles and timing of deformation

Previous studies ascribe regional deformation to the Alleghanian and Taconic orogenies. However, the structural evolution of the cover sequence is moot with much uncertainty remaining regarding 1) the relative intensities of the separate deformation events, 2) the number of fold phases, 3) the fold geometry assigned to each tectonic event, and 4) the origin and timing of the slaty cleavage in the Martinsburg Formation. Recent summaries of diverse interpretations are given by Epstein and Epstein (1969), Epstein (1980), Drake and Lyttle (1980), Ratcliffe (1981), Drake and Lyttle (1985), and Epstein and Lyttle (1987). Some of the recent theories are discussed below.

Alleghanian thrust faulting and folding

The evidence cited indicates two episodes of faulting, two episodes of folding, and two sets of cleavage. Structural relations of the blind-thrust cover sequence show that the F2 folds and C2 cleavage sets are strain mechanisms accompanying the regional thrust system. The thrust system is believed to be Alleghanian because deformed rocks of Devonian age occur both to the hinterland (Green Pond Outlier) and foreland (Pocono Plateau) of the thrust system, and the thrust system is the youngest contractional deformation observed in the study area. The mesostructure azimuths are beyond the scope of this paper but they also coincide with Alleghanian strain azimuths reported for the Allegheny Plateau (Geiser and Engelder, 1983). Accordingly, they support the proposed Alleghanian age for the Ridge and Valley Thrust System.

The Alleghanian style of deformation is thus characterized as a foreland fold-and-thrust system involving emergent and blind-thrust faults which splay off of a master décollement that is rooted in the Precambrian basement beneath the Kittatinny Valley and Highland province. Attendant cover-layer folds include fault-propagation, fault-bend, and drag folds. Crenulation cleavage is commonly associated with these folds and faults.

Taconic folds and faults

The restored versions of the F1 folds shown above in figures 10, 11, 12-14, and 17, are assigned to the Taconic orogeny on the basis of structural and stratigraphic evidence outlined below. Associated C1 cleavage and high-angle block faults in the thrust system are also assigned to this orogeny, although these are more ambiguous.

The folds that predate the thrust faults (F1 folds) include the open, upright, and doubly-plunging folds that are segmented by the emergent thrust faults; they may also include early forms of other large cover-layer folds such as the Halsey synclinorium. Cross-strike fold forms of F1 age are locally preserved in the emergent thrust sheets and indicate the doubly-plunging, en echelon arrangment of the F1 folds. The pre-thrust development of these folds is supported by refolded bedding folds, folded C1 cleavages, disjunctive cleavage relations, and restricted stratigraphic variations influenced by their geometry.

As shown in Figures 12 and 17, the F1 folds are interpreted to have corrugated the lower Paleozoic cover layer, which had been regionally arched and locally segmented by a system of moderate -to high-angle faults along the southeast margin of the sequence prior to Alleghanian thrust faulting. Chlorite-grade tectonite fabrics are typically associated with these faults as indicated in the Morgan Hill shear zone (field trip STOP 1) and Scotts Mountain (Plate 2a). These faults show both northwest and southeast dips and both normal and reverse dip-slip components, all characteristic of block-faulted terrane. The chlorite-grade, brittle-ductile basement deformation linked to the F1 cover folds has previously been described in other basment deformation zones throughout the Highlands province (Hull and others, 1986).

The basement strain mechanisms responsible for the F1 folds in the Valley and Ridge province are blind. However, the basement-cover structural relations described above also suggest an Ordovician shear zone origin for the F1 folds in the Valley and Ridge, with the upward-propagating basement shear zones having produced cover-layer folds along their blind terminations (tip-line). These folds are a result of both reverse and normal dip-slip basement block movements. For example, reverse dip-slip displacement is indicated for the Morgan Hill shear zone (STOP 1 field trip, this volume), while normal basement faults have drape folds in other areas (northeast JJCS, RAIA and Pochuck faults (Pl. 1). Block-faulting as a result of the Taconic orogeny is proposed for parts of western New England by Thompson (1967), Zen (1968, 1972) and Bird and Dewey (1970) and, directly to the northeast of the study area, by Rickard (1973). Shanmugam and Lash (1982) depict block-faulted Taconian terrane directly southwest of the study area.

Other regional structural and stratigraphic relations support the proposed Taconian structures. Epstein and Lyttle (1987) show that F1-type folds predate the Shawangunk Formation near the Ellenville arch in New York State (Fig. 1). They also report diminishing Taconian strain effects towards the foreland; this resembles the tendency of the F1 folds in Paulins-Kill thrust belt to be more broad and more open than the more hindward folds (Figure 12, 17). A Taconic origin for both the F1 folds and the C1 cleavage was proposed by Offield (1967) based on restored bedding fold and cleavage relations in the Martinsburg Formation of Orange County N.Y. to the east-southeast. A pre-Silurian slaty cleavage is also reported in the Martinsburg Formation xenoliths from the Late

Ordovician Beemerville complex (Ratcliffe, 1981). However, the C1 cleavage set may not have been pervasively distributed during the Taconic orogeny, for Epstein and Epstein (1969) proposed a mechanism for the post-Silurian origin of the C1 cleavage set at the foreland margin of the Kittatinny Valley in eastern Pennsylvania and western New Jersey. Therefore, the C1 cleavage may have developed locally during the Taconic orogeny in conjunction with the F1 folding processes or it may have progressively migrated toward the foreland with time as suggested by Drake and Lyttle (1980) and Ratcliffe (1981). The nearly coaxial arrangement of C1 cleavage with the C2 cleavage shear bands in the Halsey synclinorium supports the concept of a continuum of cleavage development for the cover layer extending from initial folding through overthrusting.

The regional stratigraphic variations of Middle to Lower Ordovician age discussed by Monteverde and Herman (this volume) reflect a basin morphologic influence that is consistent with the proposed F1 fold geometry and that support a Taconic origin. To briefly summarize here, the first indication of sedimentation associated with convergent-margin tectonics and the onset of the Taconic orogeny is in the Lower Ordovician system in the upper part of the Beekmantown Group. The dark, fetid dolomites that occupy the lower part of this interval (Ontelaunee Formation of Markewicz and Dalton, 1977) imply poor water circulation during deposition in restricted or partially restricted basins (Hobson, 1963). The restricted circulation may have resulted from sedimentary upbuilding relative to slow rates of subsidence (Hobson, 1963). However, the extension of a regional unconformity into the Beekmantown Group, with the attendant alluvium of the overlying "Wantage Formation", suggests that the basin restriction was tectonically affected "due to actual positive movements of adjacent parts of the basin floor..." (Hobson, 1963).

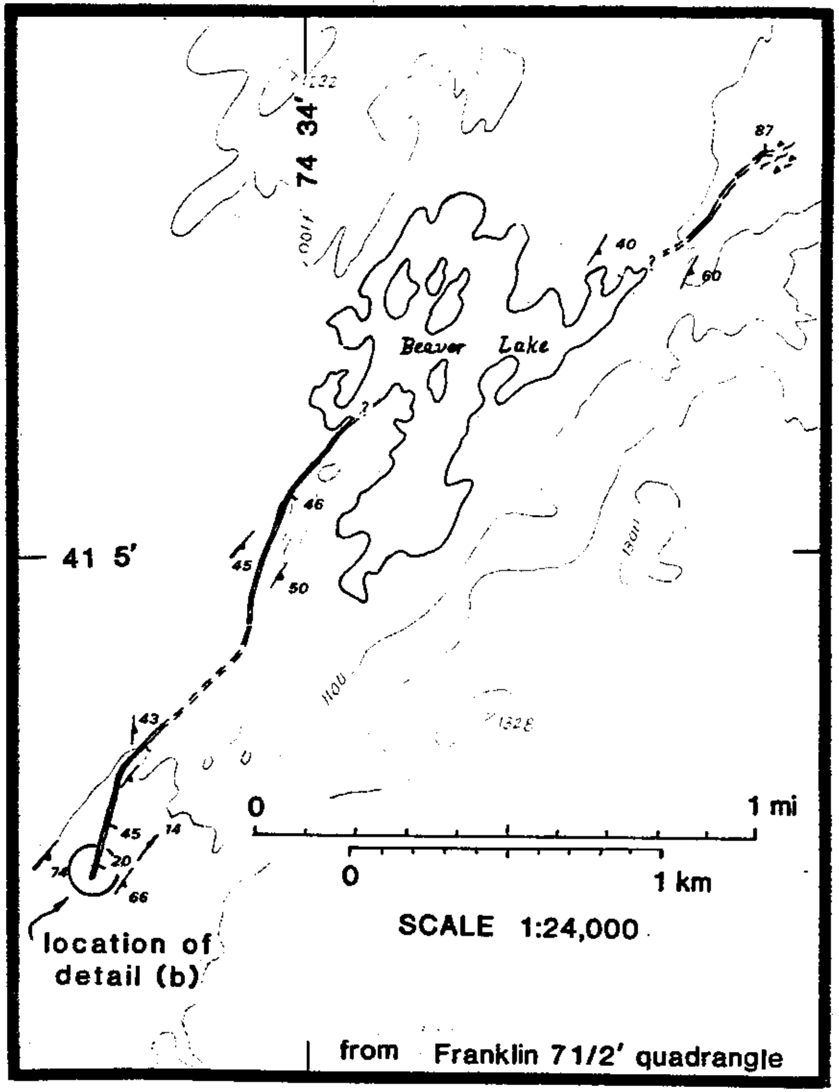
Beginning as early as the uppermost Early Ordovician (Arenigian), the carbonate platform was developing a foreland-migrating peripheral bulge, possibly as shown for the Appalachian margin by Jacobi (1981) and Shanmugam and Lash (1982). Foreland lithospheric block faulting and associated cover layer folding which accompanied these regional flexures are likely to have locally segmented the cover where basement shear zones became emergent in the overlying cover layer, or resulted in broad, open folds in the platform cover sequence above blind shear-zone terminations. Any of these lower-order perturbations in the platform sequence could have initially provided the structural barriers necessary to restrict the circulation of waters through intervening troughs, and eventually promote the necessary structural relief to result in the subaerial erosion identified as the regional Knox-Beekmantown unconformity. Partial restriction of sedimentary deposition in the New Jersey region continued through the middle Ordovician as evidenced by the distribution of Ontelaunee, Annville, and Meyerstown Formations in Lebanon county, eastern Pennsylvania (Hobson, 1963).

The F1 folds therefore probably originated during the uppermost Early Ordovician at the onset of the Taconic orogeny and resulted in a foreland fold sequence within the current Valley and Ridge province. Although the available evidence suggests Taconic orogenic effects for the proposed F1 folds, finite-amplitude folding directly preceding thrust faulting cannot be ruled out.

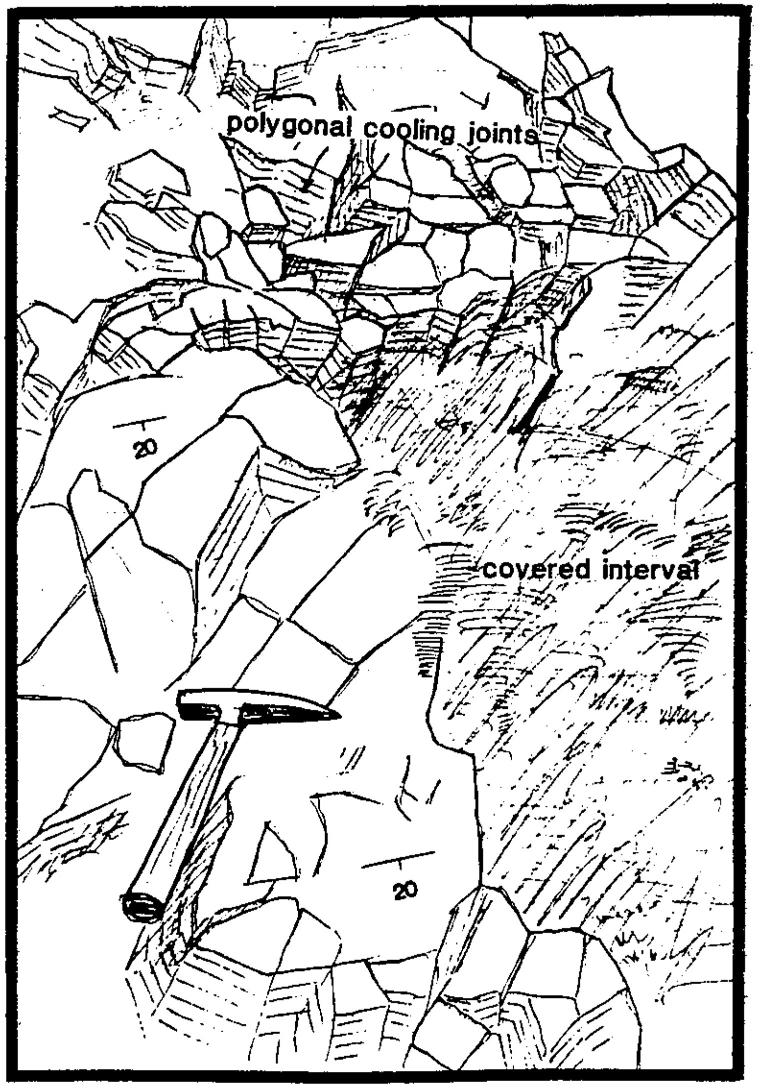
Additional evidence in support of the Ordovician age of the early basement shear zone and cover folds stems from the spatial relation of these structures with a series of diabase and lamprophyre dikes of proposed Ordovician age that occur within and near the study area. Hull and others (1988) assign a late Ordovician age to the diabase dikes that intrude the Reading Prong in New York, New Jersey, and Pennsylvania. They also intrude the Cambrian-Ordovician cover in the Great Valley of eastern Pennsylvania (Drake, 1984). These dikes are mineralogically and structurally distinct from the Mesozoic dikes that occur toward the hinterland and typically contain mesostructures and shear zones related to Alleghanian thrust faulting.

Recent mapping (this paper) supports the proposed Ordovician age of these dikes. Additional support stems from the spatial relation of the dikes to the block faults that locally offset and fold the Cambrian-Ordovican cover rocks, and from limited mesostructural data. For example, a dike that crops out along the southeast flank of Marble Mountain in the Phillipsburg area (Drake and others, 1969; and Plate 1a and 2b) is aligned with the trace of a fault that juxtaposes the Allentown Dolomite in the southeast block of the Marble Mountain fault with basement rocks in the foreland. This dike is highly fractured. Moreover, a set of dikes on Jenny Jump Mountain (Fig. 5, Pl. 1) first mapped by Westgate (1896) is directly aligned with basement cataclastic shear zones and some cover folds along their lateral terminations. One of these dikes occurs along the extension of the Mountain Lake fault that involves Cambrian rocks in the southeast block. Cross-strike, mineralized shear fractures and shear zones (Hull and others, 1986) cut these dikes (Fig. 5) thus indicating their pre-thrust age. Also, a dike of comparable morphology and minerology crops out in the basement rocks in the Franklin 7.5' quadrangle first mapped by Buddington and Baker (1961). Recently the dike was found to contain polygonal cooling joints (Fig. 19) indicating hypabyssal intrusive conditions at least locally for this suite of dikes of probable Ordovician age.

Other Phanerozoic intrusive rocks in the Highlands area that are of uncertain age may also be Ordovician and related to F1 cover layer folding processes. For example, Drake (1969) described post-Precambrian pegmatites from Morgan Hill, Pennsylvania resembling those recorded by Markewicz and Dalton (1977) in nearby Phillipsburg, New Jersey (field trip STOP 6, this volume). Both pegmatites intrude the Cambrian-Ordovican cover.


74 34'
41 5'
Beaver Lake
87
60
40
46
45
50
43
45
14
20
74
66
1100
1300
1328
1322
location of detail (b)
0
1 mi
0
1 km
SCALE 1:24,000
from Franklin 71/2' quadrangle

(a)


polygonal cooling joints
covered interval
20
20

(b)

From the above relations, the Taconic style of deformation can be characterized as a block-faulted foreland terrane involving chlorite grade basement shear zones and attendant cover-layer folds. Stratigraphic variations in the basal rocks of the middle Ordovician system reflect the open and longitudinal arrangement of these early folds. However, the relative timing of the dike emplacement, the emergent-versus-blind nature of the block faults, and the timing of reverse-versus-normal basement shear zones is vague. Hull and others (1988) suggest that the diabase dikes record a late Taconic extensional phase commonly seen in the late tectonic stages of other compressional orogenic belts. However, the spatial relation of the faults, dikes, and folds in the Jenny Jump Mountain area suggest a synchronous origin for at least this set of faults, F1 folds and dikes.

Tectonic considerations

Regional tectonic strain values reported here for the Ridge and Valley Thrust System significantly depart from prior interpretations. Recent work by Ratcliffe (1980), Lyttle and Epstein (1986), and Berg and others (1980) has shown regional tectonic profiles marginal to the New York Promontory indicating that the basement massifs of the Reading Prong and attendant cover-layer segments were structurally emplaced upon a continuous lower Paleozoic shelf sequence in various contracted forms. An extended footwall lower Paleozoic shelf sequence is consistent with regional interpretations of other Appalachian provinces (Cook and Oliver, 1981; Harris and others, 1982; Ando and others, 1983, 1984; Brown and others, 1983, among others). However, the profiles shown here limit the footwall cover-layer involvement for each thrust sheet to that based on down-plunge projection and balanced cross section methods. The balanced cover-layer fold geometry is consistent with the map, aeromagnetic, gravity, and seismic data.

The disparity in tectonic shortening between alternative structural styles is on the order of tens of kilometers. Previous interpretations that show cover-layer involvement in regional recumbent nappes, or require solutions that depict large expanses of hanging wall flats over footwall flats ("flat-on-flat" solutions of Geiser, 1988) require, at least double the tectonic strain estimates derived here. Larger strain discrepancies result if a continuous cover-layer sequence extends from the Valley and Ridge province southeastward beneath the Highlands. Such solutions raise serious cross-section-balancing problems. Specifically, a thrust-fault-segmented recumbent-fold nappe system necessitates a triple thickness of cover layer in some form, and requires accommodating fault-tip structures showing more stratigraphic separation than is available from the projection of plunging structural elements at the surface. Also, regional recumbent folds require expansive panels of overturned cover-layer strata; these have not been observed. The scarcity of deformation and structural relief in the Pocono Plateau disqualifies the concept of blind accommodating structures in the foreland of the Valley and Ridge province. An extended footwall sequence beneath the Highland province, or a "flat-on-flat" solution within the Valley and Ridge province also necessitates accommodating fault-tip structures showing much greater stratigraphic separation than can be demonstrated. On the other hand, the thrust system solution presented here has "bow-and- arrow" aspect ratios for some thrust-belt components that agree with expected values for foreland-fold and thrust belts (Elliot, 1976). The thrust-system contraction ratios for the respective cross section interpretations(Table 1) also agree with duplex contraction ratios for other thrust systems (Boyer and Elliot, 1982). Therefore, it is doubtful that the lower Paleozoic cover layer extends beneath the hinterland Highlands province in some form of a continuous footwall sequence. Instead, the lower Paleozoic cover sequence probably was structurally arched over individual, basement-cored fault slices of the Reading Prong. The cover layer footwall involvement beneath other hindward thrust faults in the Highlands province probably resembles that of the Ridge and Valley Thrust System.

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STRATIGRAPHY OF THE "KITTATINNY LIMESTONE"

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INTRODUCTION

This article is based on data from the "42nd Field Conference of Pennsylvania Geologists" (Markewicz and Dalton (1977) as modified by Dalton (1989). The subdivisions of the Kittatinny Limestone are currently in use by the New Jersey Geological Survey and have helped to solve site-specific problems related to ground-water supply and ground-water pollution. The detailed stratigraphy has also been a significant aid in unraveling the geology of structurally complex areas of New Jersey.

The article also presents some of the biostratigraphic data on the Kittatinny Limestone, which have been collected over the last few years. These data, namely conodont data, have led to two different styles of mapping, one lithostratigraphic and the other biostratigraphic without regard to the lithology.

PRECAMBRIAN-PALEOZOIC UNCONFORMITY

The Hardyston Quartzite unconformably overlies the Precambrian crystalline rocks throughout most of the New Jersey Highlands, however, in some areas the basal Leithsville Formation was deposited directly on the Precambrian. Although poorly exposed, the Precambrian-Lower Paleozoic contact has been observed at enough localities to understand some of its characteristics. At some exposures in northern New Jersey the Hardyston may be less than 2 feet thick, including 1 foot of dirty sandy dolomite to calcareous sandstone or calcarenite that is transitional into the basal Leithsville. At one outcrop now quarried away, north of Hamburg in Sussex County the unconformity could be traced for more than 100 feet and it was observed that the Hardyston (less than 2 feet thick) was deposited in only the deeper troughs in the Precambrian. In the highs above the troughs, a dirty sandy dolomite is in contact with the Precambrian. Several thousand feet northeast along strike, the Hardyston thickens from 30 feet to over a hundred feet in a distance of about 300 feet. This indicates that the Hardyston was not deposited above certain elevations and thick sequences were deposited in the troughs during Lower Cambrian time. Hague and others (1956, page 456) indicated that:

> "Locally, the Hardyston is missing and the rock just above the Precambrian unconformity is a pure dolomite, which indicates that the Precambrian erosion surface was quite irregular and that the Hardyston was probably formed in depressions on this surface. Hardyston-like conglomerates have been found as fissure and cave fillings in the Franklin band of marble considerable distances below the Precambrian erosion surface."

Ludlum (1940, page 18) on the other hand suggests that:

> "The pre-Cambrian land surface must have been one of gentle relief just prior to submergence. Its submergence at the beginning of the Cambrian period was sudden and yet not to great depths. This resulted in the apparent poor sorting near the base of the Hardyston. Furthermore, the land mass supplying the sediments had little relief so that deposition of coarse material was limited and probably localized."

It is difficult to imagine that the Precambrian, with its long period of exposure prior to Hardyston deposition, was without appreciable relief. The compositional and textural variability of the granites, gneisses, and marbles with their respective resistance to erosional processes, strongly suggests that an irregular surface must have existed prior to Hardyston deposition. In contrast, if the Precambrian surface was basically gentle, then the Hardyston would have been deposited on a moderate to possibly thick regolith zone. All known paleosol zones are not in excess of several inches.

It is believed that the Precambrian topography just prior to Cambrian deposition was irregular, with local deeply weathered joints, shallow basins, and intermediate uniformly sloping to fairly level plateaus with interspersed irregular topography. This helps explain the variable thickness and lithology of the Hardyston. Kummel (1940) stated that the Hardyston is 5 to 200 feet thick.

The Precambrian surface, upon which the Hardyston was deposited, probably ranged from smooth, clean bedrock to strewn with sand, pebbles and boulders. At some places it was mantled with a true soil horizon. Miller and others (1939) mention the presence of an amorphous material called "pinite" at the contact in Northampton County, Pennsylvania. In the Clinton-Allerton-Califon region, several observed Precambrian-Hardyston contacts contain very coarse-grained to boulder-size Precambrian material.

HARDYSTON FORMATION

Rogers (1840) first mentioned the occurrence of "a white quartzose sandstone, somewhat coarse and friable" overlying the Primary (Precambrian) rocks in New Jersey. This related to his formation I of the Lower (Paleozoic) Secondary rocks. Until 1890, geologists suggested that this formation was correlative with the Upper Cambrian "Potsdam" of New York. Nason (1891) described a trilobite, *Olenellus* fauna from rocks near Franklin as being Lower Cambrian in age. Wolff and Brooks (1898), named this formation "Hardistonville" from the town in Sussex County near Franklin Furnace.

Kummel and Weller (1901) named the formation Hardiston, as a correction of Wolff and Brooks "Hardistonville". The name was later changed to Hardyston by the United States Board on Geographic Names. All later workers refer to this Lower Cambrian sedimentary sequence as Hardyston and regionally correlate it with the Hardyston Formation in the Lehigh Valley in Pennsylvania and the Poughquag quartzite in New York.

Fossils identified as *Olenellus thompsoni* and *Skolithos linearis* have been found at various locations in the state. *Olenellus* occurs in the upper calcareous beds of the formation, most abundantly in Warren County. *Skolithos* typically occurs in the lower-massive gray, brown or purplish siliceous quartzite and/or sandstone beds. Howell (1943) published a paper on "Skolithes" from eastern Pennsylvania. Large blocks of Hardyston talus containing numerous *Skolithos* tubes occur just north of the New Jersey-New York border near Glenwood, New Jersey.

The topographic form at or near the contact of the Precambrian-Hardyston varies from a smooth uniform slope without any visible "Hardyston bench" to a moderately well defined bench that is readily recognized in the field or on air photos. In some areas a subtle to well developed depression along the Precambrian-Hardyston contact is due to weathering of the greater feldspar content in the basal Hardyston. This is usually followed downslope by a slight to prominent topographic bench formed by the more resistant siliceous beds that lie above the basal feldspar bearing units. The typical Hardyston landform, where it is more than 50 feet thick, is a narrow to broad bench perched on the slope surface above the valley bottom. Complete sections of Hardyston are rarely exposed except where it is very thin, less than 5 to 10 feet thick. The Precambrian-Hardyston contact is more commonly observed than the Hardyston-Leithsville contact, which is generally at a lower downslope elevation and always covered with colluvium.

Basal Hardyston composition and rock texture can vary from one area to another or even within a single outcrop. This reflects the provenance of the sediments in the Cambrian sea and the residual detritus lying on the Precambrian surface. This is not surprising, considering the irregularity of the Precambrian surface and the variable composition of the Precambrian rocks which supplied the source materials for the Hardyston.

The Hardyston varies in lithology and color, but generally consists of a vitreous, light pink, steel gray or brown, locally arkosic, fine to coarse-grained, resistant quartzite that varies horizontally and vertically. Quartzitic calcarenites generally form the very thin Hardyston occurrences. Basal beds are commonly a pebble conglomerate containing Precambrian gneiss and granite clasts. The overlying rock is finer grained, but can contain medium to coarse-grained interbeds with local coarse conglomerate consisting of light to dark gray to pink locally iron-stained pebbles or granules. Some shaly interbeds may occur but these are more abundant in the upper or transitional facies of the Hardyston. Cross bedding, cut and fill, and graded compositional bedding are strictly local features. Typically, the siliceous facies of the Hardyston is massive and blocky. Its poorly developed sedimentary features, make it difficult to interpret depositional information. This is especially true of small isolated outcrops. Occasional streaks or lenses of heavy minerals, fine grained detritus, or heterogenous compositional layering provide the information for sedimentary origin.

Quartz, the dominant mineral, is clear to milky, angular to well rounded, and ranges from fine sand to pebbles more than 2 inches in length. Feldspar, white to pink perthite and microcline, is variable in content, but is most abundant in the basal section. Plagioclase is subordinate to rare. Heavy mineral content is generally low; black opaques and zircon are the most common. Depending upon the immediate source area, monazite, garnet, sphene, and tourmaline can be important accessory minerals. In the vicinity of Chester, where Markewicz (permanent notes on file at the New Jersey Geological Survey) had mapped a monazite bearing gneiss, monazite is an important detrital heavy mineral in the Hardyston. Also, near its contact with the Franklin ore body, just northeast of the Franklin, detrital Franklinite has been found in the Hardyston (Hague and others, 1956 p.470) indicating a local source area for the sediments.

At some outcrops where the Hardyston is less than 10 feet thick, it is a fine- to medium-grained, gray, pyritic quartzite, grading into a dark-gray dolomitic sandstone. Is the dolomitic sandstone still Hardyston? Other variants of the formation consist of 1 to 2 feet of quartzitic material overlain by a pebbly, locally calcareous shale to sandstone grading upward into a very dense, exceptionally hard dolomitic quartzite. This is succeeded by an undulating transition zone overlain by a sandy dolomite. Many depositional variants of the Hardyston are poorly understood especially those that are less than 50 feet thick.The lithologic sequence and transition-zone thickness between the Hardyston and Leithsville vary from one locality to another. There are two general transitions:

(1) A generally thin transition zone of quartzitic sandstone to calcareous sandstone or siltstone to sandy impure dolomitic rock grading upward to siliceous Leithsville dolomite;

(2) A much thicker alternating section of varicolored, dense, locally pebbly, quartzitic sandstone, shale, argillitic shale, and siltstone with thin, interbedded to lenticular, sandy, and/or dolomitic stringers and more calcareous beds that grade upward into lower Leithsville lithology.

The following relationships are given as a possible rule of thumb but not an infallible field criteria.

(1) Where the Hardyston-Leithsville transition zone is predominatly sandy or a calcarenite, the Hardyston Formation is thin, less than 50 feet thick.

(2) If a varicolored shaly-silty Hardyston-Leithsville transition zone occurs, it may indicate a much thicker Hardyston section.

If the Hardyston is more than 50 feet thick, the potential for sulfides in the lower Leithsville is low; if the Hardystone is 25 feet thick or less, the potential for sulfide is greater.

LEITHSVILLE FORMATION

Weller (1900b) used the general term "Kittatinny Limestone" for Cambrian-Ordovician carbonate rocks of northern New Jersey and compared them with similar units in Virginia, Maryland, Pennsylvania and New York. In his "Annual Report of the State Geologist, 1900," page 4, he stated: "This limestone formation has a great thickness which is estimated at from 2,700 to 3,000 feet. It is designated the Kittatinny Limestone because it is the great limestone formation of the Kittatinny Valley..."

The Lower Cambrian Leithsville Formation named by Wherry (1909) in Pennsylvania is the equivalent of the Tomstown Formation described by Miller and

	formation name on N.J. Geologic map	formations recognized by H.B. Kummel & others	formations recognized by Drake, 1969 & Markewicz, 1967	formations and members Markewicz & Dalton, 1977		
LOWER ORDOVICIAN	KITTATINNY LIMESTONE	BEEKMANTOWN	EPLER	ONTELAUNEE FORMATION	HARMONYVALE MEMBER	
					BEAVER RUN MEMBER	
				EPLER FORMATION	LAFAYETTE MEMBER	
					BIG SPRINGS MEMBER	
					BRANCHVILLE MEMBER	
			RICKENBACH	RICKENBACH FORMATION	HOPE MEMBER	CROOKED SWAMP DOLOMITE FACIES
					LOWER MEMBER	
CAMBRIAN		ALLENTOWN	ALLENTOWN	ALLENTOWN FORMATION	UPPER MEMBER	
					LIMEPORT MEMBER	
		TOMSTOWN	LEITHSVILLE	LEITHSVILLE FORMATION	WALKILL MEMBER	
					HAMBURG MEMBER	
					CALIFON MEMBER	

Table 1. Subdivision of the Kittatinny Limestone. The table indicates the present stratigraphy used in New Jersey and its correlation to those formational names used by earlier workers.

others (1939) in eastern Pennsylvania and New Jersey. Stose (1906), Hills (1935), Howell and others (1950) studied the Leithsville in eastern Pennsylvania.

Drake and others(1961)and Drake(1967b) mapped the Leithsville Formation in the Frenchtown and Bloomsbury Quadrangles and Markewicz (1967) used the term Leithsville for similar strata in the High Bridge Quadrangle. Wherry (1909) assigned a Lower-Middle Cambrian age to the Leithsville, whereas Willard (1961) inferred that it is Middle Cambrian. Discovery of the index fossil *Hyolithellus micans* in the early 1960's, by Markewicz (1964 unpublished), in rubbly dolomitic beds in the basal Leithsville at Califon, New Jersey and also near Monroe in southern New York State established a Lower Cambrian age. A single operculum was found north of Easton, Pennsylvania. In addition, the fossil *Archaeocyathus* has been found in basal Leithsville dolomite at Franklin, Califon, Wantage, New Jersey and Easton, Pennsylvania. It is most abundant immediately above the Hardyston-Leithsville contact, but a similar fossil has been noted in the lower part of the Wallkill Member. Palmer and Rozanov (1976) describe the original *Archaeocyathus* found in New Jersey by George Banino at Franklin. Kummel (1940, p. 68) referring to the lower part of the "Kittatinny" limestone stated:

> "They are correlated with the Tomstown Limestone of southern Pennsylvania because of their position and character. If the correlation is correct, they are Lower Cambrian in age."

The Leithsville Formation is subdivided into three members,(Markewicz and Dalton 1977). The members from youngest to oldest are:

Wallkill Member

Hamburg Member

Califon Member

Califon Member

The Califon Member is the basal Leithsville unit and is named after the *Hyolithellus micans* and *Archaeocyathus* bearing dolomite exposed in an abandoned quarry near Califon, New Jersey. It can be 40 to 150 feet thick, but is typically about 100 feet thick. The entire member, from the undulating contact with the Hardyston to the upper contact with the Hamburg member, can be seen at the type section at the Califon quarry.

The Califon Member consists essentially of two distinct lithologies:

1. The upper section, which directly underlies the Hamburg Member, and is 20 to 50 feet thick. It consists of very fine to cryptogranular, light gray to locally light greenish gray, dense, sharp-breaking dolomite, locally laminated, in beds 6 to 20 inches thick, containing scattered quartz grains and micro- to mega-wedges or clots of crystalline carbonate floating in a fine grained dolomite matrix. The unit weathers into distinct, uniform, planar beds that have a buff to cream color, smooth surface, and thin exterior rind in contrast to the dark- to medium-gray, raspy- to silty-textured, weathered surface of the lower part of the member.

2. The lower 20 to 100 foot section (thickness dependent on locality) varies from gray to dark gray, sparkly to bright (on fresh surface), fine to medium megacrystalline, strongly stylolitic, ruditic, patchy-textured dolomite.

   Bedding appears massive and somewhat indistinct except on weathered surfaces which reveal the undulating profusely stylolitic, lumpy to thinly-bedded dolomite. The weathered surface readily shows the lumpy nature and ruditic texture of the rock. Quartz, typically frosted, occurs in the lower 6 to 8 feet of the member.

   Discontinuous seams, masses, lenses or clots of pyrite, generally occurs along a given plane. Pyrite is typically oxidized on weathered surfaces, resulting in strong staining of the surface. Where the oxidation is mature, only a rust-stained vug remains.

   At some localities, the lower part of the Califon Member consists, in part, of a massive-bedded, well-healed, internal breccia, giving the rock a mottled-gray, mosaic pattern that is best seen on the weathered surface. This internally crackled or brecciated rock, which may be a biorudite, in part, is not as strongly stylolitic as the lumpy, thinly-bedded facies. Scattered clots, or open geode-like vugs, lined with white to light gray dolomite, give the rock a distinctly mottled appearance. This rock type has been observed in drill core north of Hamburg and in outcrop on Bushkill Drive in the northwestern part of Easton, Pennsylvania.

Where the Califon Member is very thin, Markewicz and Dalton (1977) postulated that the lower section was not deposited, possibly because of highs in the Precambrian surface.

Hamburg Member

The type section for the Hamburg Member is approximately half of mile south of the town of Hamburg, where it forms a sharp, razorback hill. At this locality it is approximately 85 to 100 feet thick. The section is covered at its base and top, however the position and location of the nearby outcrops indicate that a major part of the member is exposed. The Hamburg Member has been found in southern New York, New Jersey and eastern Pennsylvania.

The member is best described as a rhythmically bedded series of sedimentary cycles, representative of mud flat to intertidal and possibly lagoonal environments. The member is estimated to be 35 to 100 feet thick, depending upon locality. Typically, the lithology of a complete cycle is repeated throughout the member at any given locality; however, the overall lithology at any given exposure generally consists of one of the following types:

1. Dark, organic, laminated to thinly bedded, dense dolomite and shale with intercalated, thin siltstone and fine sandstone beds, lenses or stringers. The thinly-bedded, ribbony units are distinctive and are similar to the ribbony units found in the Shady Formation at Austinville, Virginia, which is the host rock for a major zinc-lead deposit. Small-scale cross bedding, scour and fill, compaction, and sediment flow structures are readily evident on the fresh surface and in drill core. Pyrite occurs as disseminated grains, small masses and veins.

2. Light- to dark-gray, locally brownish-gray to green cyclical units of fine to coarse sandstone (locally quartzitic), siltstone, shale and very fine-grained to cryptogranular, dense, conchoidal-breaking dolomite. A cycle consists of a lower siliceous unit grading upward into carbonate. A typical cycle begins with fine to coarse (occasional 1/2 inch pebbles) sand in beds from 2 inches to more than 12 inches in thickness deposited on the scour-and-fill surface of the underlying dolomite which forms the top of the previous cycle. The sandstone grades upward through thin-bedded to laminated arenaceous shale or siltstone into laminated calcareous shale or siltstone that grades upward into dense, sharp-breaking dolomite. Typically, the beds weather to a yellowish brown, tan, or pinkish-gray color depending on the lithology.

3. Thinly bedded to ribbony, brown to brick or bright red, occasionally green shale, siltstone and sandstone, to low-grade orthoquartzite. This facies has been mistaken for some of the varicolored lithologies which occur in the "Martinsburg" near Clinton, New Jersey. A distinctive "red" section formed a prominent sharp knoll south of Andover before being removed by a quarry operator. The red color at this latter location may have been derived from the decomposition and deposition of iron bear-

ing minerals from the iron-rich Precambrian rocks in the vicinity of Andover.

4. Brownish-weathered, thin-bedded, to strongly-laminated siliceous to calcareous phyllite intercalated with thin-bedded, locally lenselike to laminated dolomite and chert containing sandstone and sandy phyllite. This is the "damourite shale" as described in the early reports on the "Kittatinny" of New Jersey. Overall, this facies is generally thinner than others.

Wallkill Member

The Wallkill Member, which overlies the Hamburg Member, forms the upper part of the Leithsville Formation. It is poorly to rarely exposed because it generally forms a topographic low in stream valleys or other low-lying areas, and is covered by alluvium or glacial deposits.

The Wallkill Member is named after the dark-gray, patchy dolomite that overlies the shaly, arenaceous Hamburg Member on the east side of the Wallkill Valley, north of Hamburg. It consists in the lower part of fine- to medium-grained, rub bly to lumpy-bedded, stylolitic, locally vuggy, mottled, patchy to ruditic textured, sparkly dolomite, in beds from several inches to more than 1.5 feet thick. The beds weather dark-gray and are lumpy to irregular in form, with a mosaic patchwork because of the clast- to breccia-like texture of the rock.

The upper half of the Wallkill is not exposed at the type locality, but based upon other isolated exposures in northern New Jersey, it is considered to be a fine- to medium-grained, locally coarse crystalline dolomite with some beds of algal-like structures and large oolites and pisolites. The upper part appears to be transitional into the lower part of the Limeport Member of the Allentown Formation. Overall, the Wallkill Member is 350 to 500 feet thick and at the type section, it is estimated to be 400 to 500 feet thick. This would make the Leithsville at this location 650 to 700 feet thick.

It is estimated that the Leithsville in New Jersey varies from 500 to 800 feet thick. Drake (1969) estimated that the Leithsville is 1,000 feet thick. However, on the basis of field work in many parts of northern New Jersey the Leithsville is variable in thickness but is generally less than 1,000 feet thick.

The lower part of the Wallkill, and the entire Hamburg and Califon Members are considered to be potential sulfide-bearing zones. Sphalerite, galena, fluorite, and some chalcopyrite have been found at several localities. A significant prospect containing sphalerite and galena was found by Markewicz and Dalton in 1969 (written notes dated 1969 to 1974 on file at the New Jersey Geological Survey) in the lower part of the Wallkill member and in much of the Hamburg Member in Lafayette Township of Sussex County.

ALLENTOWN FORMATION

The name Allentown was proposed by Wherry (1909) for the thick sequence of oolitic dolomite overlying the Leithsville in eastern Pennsylvania. Miller and others (1939) mapped the Allentown. B.L. Miller (1939) used the name Conococheague in the Lehigh Valley instead of Allentown, but later he reverted to the local name. Howell and others (1950) subdivided the Allentown into the Limeport and Allentown Formations. This was based on the presence of both early and late upper Cambrian faunas. Late Cambrian faunas were first recognized in New Jersey by Weller (1900a, 1903) at Newton and Andover and occur in the upper 200 feet of the Allentown.

Drake (1965) mapped the entire sequence as the Allentown. He placed the lower contact at the first appearance of cryptozoa and oolites, and the upper contact at the last cryptozoon bed. Drake (1969) stated that the Cambrian-Ordovician boundary in Maryland is 400-500 feet below the Conococheague-Beekmantown contact.

In New Jersey, two mappable units are present within the Allentown. For the lower member, the name "Limeport" was reintroduced (Markewicz and Dalton 1977) as a mappable unit. The upper member, pending further work, is referred to as Upper Allentown.

Limeport Member

The Limeport Member consists of finely- to medium-crystalline, thin to thick, cyclically bedded, light- to dark-gray dolomite. The rock weathers to an alternating sequence of buff-cream, light and dark beds. Oolites, cryptozoa, ripple marks, mud cracks, cross-bedding and chip conglomerates predominate. Many algal structures are present, ranging from thin mats to large thick colonies.

Quartz occurs as floating grains or in thin beds and lenses. Black chert lenses, beds or nodules are more common than in the underlying Leithsville. Many thin argillaceous dolomite to shaly beds occur throughout the section. Dessication features and possible paleo-soil zones can be found. The Limeport Member varies in thickness from 400 to 700 feet throughout most of New Jersey. In the northwestern part of the state, the unit thickens greatly at the expense of the upper member.

The transition zone between the upper member and the Limeport is gradational with oolites and cryptozoa become less abundant. The contact in the field is placed at the last common appearance of oolites and cryptozoa and the appearance of uniformly textured, thick-bedded dolomite.

Upper Member

The upper member of the Allentown is equivalent to the Allentown as defined by Howell and others (1950) which they estimated to be 400 to 500 feet thick. In the Hamburg area it is about 1,000 to 1,200 feet thick. Near Columbia, New Jersey the upper member thins to less than 500 feet thick.

The upper member is generally much more massive and thick-bedded than the Limeport Member and some beds are finely laminated. The beds are 1 to 6 feet thick and vary from a fine to medium crystalline, light to dark gray dolomite. Some beds may be mottled and/or pitted. Chert occurs as thin beds, discontinuous lenses and knots. In contrast to the Limeport member, stromatolite and oolite beds are infrequent.

The upper 100 to 200 feet of the Allentown is more siliceous because of a greater content of sandy dolomite and local quartzite beds. At least two distinct interbedded quartzites as much as 20 feet thick occur in the upper 100 feet. The upper quartzite horizon consists of a very sandy conglomerate zone overlain by a steel gray, dense, quartzite which is a distinct scour and fill. The contact between the Allentown and the Richenbach is placed at the quartzite conglomerate which is about 75 feet above a distinct section of thin-bedded, mottled dolomite containing local oolites, cryptozoa, and silt beds.

RICKENBACH FORMATION

The Rickenbach Formation, as defined by Hobson (1963), consists of a thick- to thin-bedded, light- to medium-dark gray, microcrystalline to coarsely megacrystalline dolomite which overlies the Allentown Formation. He subdivided it into a lower and upper member.

Markewicz and Dalton (1977) divided the Rickenbach into a lower unnamed member and the Hope Member as well as a distinct facies named the Crooked Swamp Dolomite.

Lower Member

The lower member of the Rickenbach is a thin- to medium-bedded, cream to dark-gray weathering dolomite beds which contains thin, sandy dolomite bands and locally quartzose beds containing some chip conglomerates. Some beds are massive, with local mottling, and weather to a lumpy, raspy surface. The overall texture is fine- to medium-grained, with local coarse-grained beds containing pits, partially filled clots, lenses, knots, and beds of chert. Pyrite can be scattered throughout. The lower member is 75 to 150 feet thick and is well developed near Hope, New Jersey.

The transition between the lower member and the overlying Hope Member is gradational; the rock is darker and very fine-grained to aphanitic, with interbeds of very dark gray to almost black dolomite.

Hope Member

The Hope Member can be as much as 175 feet thick. It consists of light- to medium-gray, gray weathering, aphanitic to finely crystalline, medium-bedded dolomite that is interbedded with darker gray, dark-gray weathering, more coarsely crystalline, medium- to massive-bedded dolomite. The aphanitic beds may contain a sandy zone at their base. There can also be a very distinctive internal brecciation or crackling which seems to be related to the paleokarstification of the carbonate sequence. The coarser beds can contain clots of quartz and white dolomite. Along Route 80, a black, botryoidal, hydrocarbon mineral has been found in the Hope Member in the quartz clots along with sphalerite, both in veins and as disseminated grains.

Several chert beds and zones occur in this member. The most distinctive of these is a marker bed which Markewicz and Dalton (1977) termed the "7 cherts". This marker bed occurs in a dark gray, finely- to medium-crystalline, massive dolomite bed approximately 5 feet thick. The upper half contains seven distinct beds of arching cherts 3 to 6 feet long and as much as 3 inches thick. These cherts have been recognized at various localities from southern New York to eastern Pennsylvania.

Approximately 50 feet above the "7 cherts" is a second zone of discontinuous knots and lenses of chert, some of which are convex upward; in addition, algal structures occur in and above this zone.The contact between the Rickenbach and the Epler Formations is placed 50 feet above the upper chert.

Crooked Swamp Dolomite Facies

The Crooked Swamp Dolomite facies of the Rickenbach Formation consists of light-gray to medium gray, light-gray weathering, fine- to coarse-grained, euhedral dolomite and is best developed near Crooked Swamp, 1.5 miles north of the town of Lafayette in Sussex County. Individual beds occur throughout the Rickenbach, but the thicker beds are more common in the upper part. The dolomite crystals may be surrounded by a fine, clayey material, possibly kaolinite. Many of the beds contain pits and clots commonly filled with dolomite, quartz and kaolinite. The individual beds range in thickness from 2 to 6 feet; some being indistinctly laminated.

At its type location, the Crooked Swamp dolomite is 150 to 200 feet thick and thins abruptly both northeast and southwest to about 25 feet. As the unit thins, a distinctive conglomerate occurs in the upper Rickenbach and in the basal part of the Epler Formation.This facies may represent a series of reefs or a later dolomitization replacement of finer grained rock.

Samples of the Crooked Swamp Dolomite have been compared to samples of the Kingsport Formation of eastern Tennessee. The two units cannot be separated visually. The basal part of the Epler, especially where the conglomerate is developed, is lithologically similar to the Mascot Dolomite of Tennessee. The Kingsport and Mascot occupy a similar stratigraphic interval to the Rickenbach and Epler. It is possible that the light gray to medium gray, medium to coarse crystalline facies of the Kingsport is correlative with the Crooked Swamp Dolomite facies.

EPLER FORMATION

The Epler as defined by Hobson (1963) consists of an interbedded sequence of dolomite and limestone. Drake (1965) following Hobson, placed the lower contact at the lowest limestone bed. Drake placed the upper Epler contact at the unconformity between the "Kittatinny" and the Jacksonburg. Drake (1969, p.87) stated that:

> "The Ontelaunee of Pennsylvania is absent in the Delaware Valley because of the pronounced unconformity at the top of the Beekmantown" and that "A different Epler lithology is present at each place the upper contact has been observed . . . Epler lithologies, however, appear to underlie the Jacksonburg as far west as Nazareth, Pennsylvania".

In the outcrop area northeast of Drake's field area, the Epler is mainly dolomite, except for occasional limestone lenses in the middle of the formation (Figure 1). The New Jersey Geological Survey places the Rickenbach-Epler contact at a massive chert zone instead of at the lowest limestone bed above which the lithic features differ from those of the underlying rock. The Epler Formation has been subdivided by Markewicz and Dalton (1977) into the following members from youngest to oldest:

Lafayette Member

Big Springs Member

Branchville Member

Branchville Member

The Branchville Member typically contains two distinct lithic units. The lower unit ranges from 0 to 50 feet in thickness and is a variable sequence of very fine-

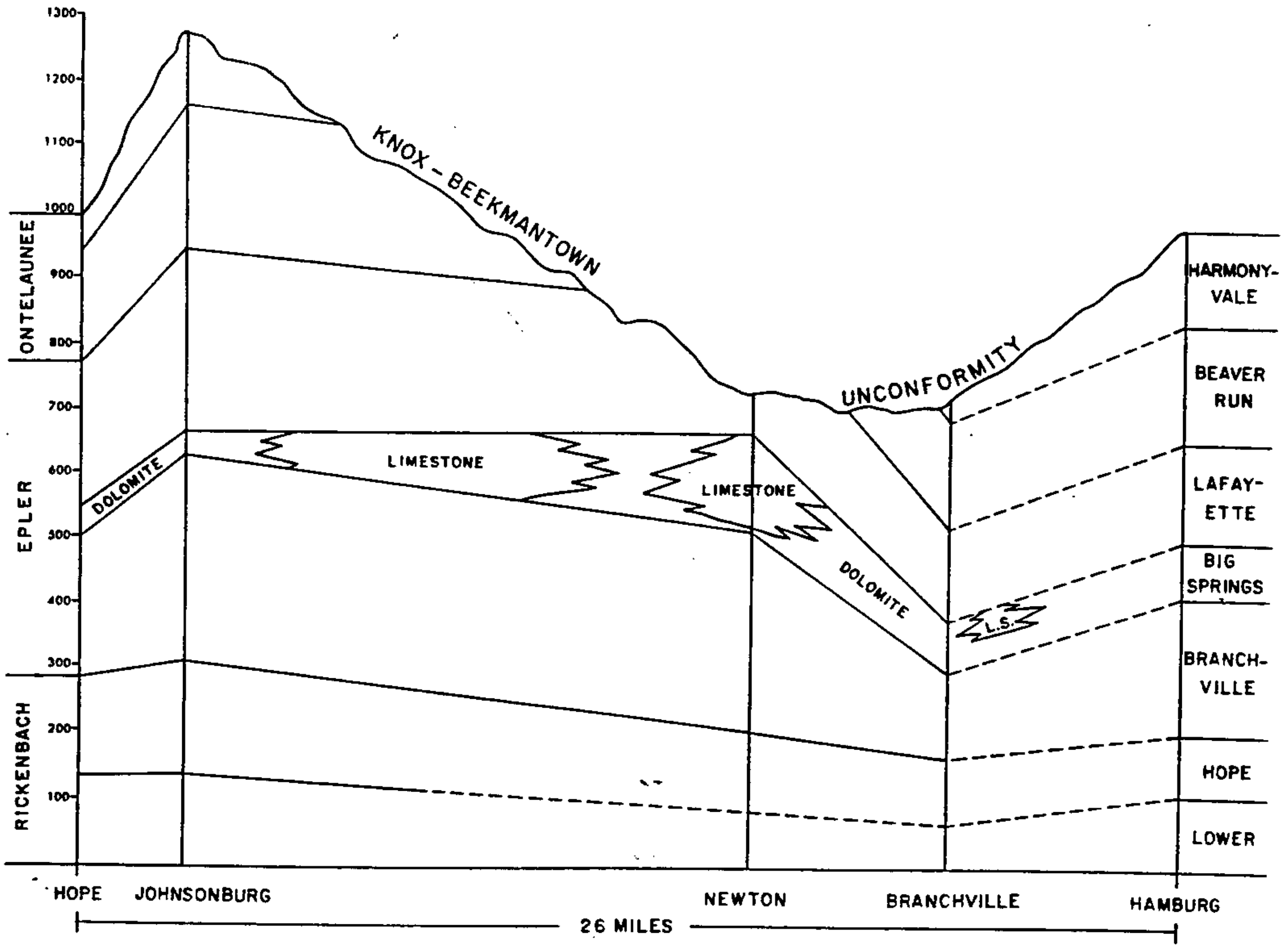

Figure 1. Diagram showing member correlation for the Rickenbach, the Epler, and the Ontelaunee formations from Hope to Hamburg, N.J. (from Markewicz and Dalton, 1977)

to coarse grained, light- to dark-gray, medium- to massive-bedded dolomite with some distinctly laminated beds. Chert, shale, oolites, and crypotozoa also occur. At some localities the lowermost part of the lower unit consists of a variable thickness of reddish, pinkish and/or greenish, cryptocrystalline, conchoidal fracturing, sandy dolomite with some white porcelanite chert.

Above the lower part of the Branchville Member is a 150 to 200 foot thick unit that consists of a very fine to fine-grained, medium- to dark-gray, massive, finely laminated dolomite. The upper part of this member includes some thin, siliceous to shaly interbeds similar to those of the Big Springs Member. Weathered surfaces generally are reddish-brown to buff colored and the laminae stand out in relief

Big Spring Member

Above the Branchville is a 40 to 150 foot thick section of variable dolomite and limestone named the Big Springs Member by Markewitz and Dalton (1977). In the type area near Hamburg, the Big Springs generally consists of a light- to medium-gray, fine- to medium-grained dolomite with local green to pink bands or lenses consisting of siliceous dolomite, quartzite and/or siliceous shale. The dolomite beds are 1 to 3 inches thick with shaly and quartzitic interbeds ranging from 1/4 to 1 inch thick. The siliceous beds weather in strong relief, giving the rock a ribbed appearance. This unit contains cross-bedding, chip conglomerates, cut and fill, oolites, chert, and red and green argillitic dolomite. The weathered surface has a distinctive bright-red to yellow-orange rind. Some of the interbeds may weather to porous, siliceous ribs.

In the northern part of the outcrop area in New Jersey, occasional limestone lenses may replace all or part of the member, but its distinctive sedimentary features are generally retained. The limestone weathers to powder blue with green or red-brown siliceous interbeds. From Newton, southwest toward the Delaware River, limestone is more common but may change laterally and vertically to a dolomite in the same outcrop. The dolomite lenses are generally encased by a siliceous rind.

Lafayette Member

The Lafayette Member ranges from 50 to 250 feet in thickness and is similar to the Branchville Member. Two recognizable units occur within the Lafayette Member. The lower unit, which is generally a fine- to medium-grained, black, sparkly, massive bedded dolomite, contains some beds of light- to medium-gray, fine-grained dolomite with shaly laminations. The fine-grained beds weather orange-gray. Some chert occurs along with some siliceous beds. The upper unit is a finely laminated, massive, light- to medium-gray, very fine to fine-grained, cream- to orange-gray weathered dolomite. The laminations stand out in relief on the weathered surface. Chert occurs as beds and clots. The Lafayette Member is transitional with the Ontelaunee Formation through an intercalation of medium gray, very fine grained, laminated dolomite and medium-gray, slightly sparkly, fetid dolomite. The Lafayette Member contains zones of breccia, which have confused many workers in the "Kittatinny" of New Jersey. These have been identified as paleosolution breccia (Markewicz and Dalton, 1977).

ONTELAUNEE FORMATION

The Ontelaunee Formation was recognized in New Jersey by Dalton and Markewicz (1972). Field work on the Ontelaunee in Pennsylvania by Markewicz during 1965-66 indicated that it is similar to the upper part of the "Kittatinny" in New Jersey. Hobson (1963, p. 75), in referring to the Ontelaunee in Pennsylvania states that "A mappable unit of dolomite has not been recognized to date in the Lehigh River and Delaware River areas...". Drake (1969, p.87), also, did not recognize the Ontelaunee in New Jersey.

The thickness of the formation depends on the amount of erosion represented by the Knox-Beekmantown unconformity. The unconformity is exposed near Belvidere at Sarepta Quarry and there is evidence for more than 200 feet of erosion in a distance of a few hundred feet. In the Phillipsburg area the Ontelaunee probably exceeds 800 feet in thickness. The formation has been subdivided by Markewicz and Dalton (1977) into the following members from youngest to oldest:

Harmonyvale Member

Beaver Run Member

Beaver Run Member

The Beaver Run Member is 150 to 200 feet thick and contains three recognizable units. The lower part, about 50 feet thick, is a massive, medium- to coarsely crystalline, black, sparkly, fetid dolomite. The individual dolomite euhedra are characteristically zoned. Some laminated beds, along with a little chert, can be present. Above this is a 50- to 100- foot thick, massive dolomite similar to the lower part, except for a large amount of bedded, anastomosing, rugose, and knotted chert. Individual chert beds can be as much as ten feet thick. Many silicified fossils occur in this section. The upper portion, which may be as much as 50 feet thick, is a massive, fine- to medium-grained, black sparkly, fetid dolomite, generally with little chert.

Fossils in the member include straight nautiloids, brachiopods, gastropods, corals, bryozoa, and conulariids. Typically they occur in the middle part of the member. Occasional fossils, along with an asphalt-like hydrocarbon, may occur in the upper part of the member. The hydrocarbon occurs both as small masses or clots and as an interstitial material between the dolomite euhedra.

The transitional zone with the overlying Harmonyvale Member is an alternating sequence of thin, coarse-grained beds, alternating chert beds, and dense, fine-grained beds.

Harmonyvale Member

The Harmonyvale Member is the youngest of the Lower Ordovician rocks in New Jersey. Its thickness, which exceeds 220 feet, is determined by the amount of erosion on the unconformity. At many localities, the Harmonyvale has been completely eroded away and the Jacksonburg Formation was deposited directly on the Beaver Run member. The Harmonyvale consists of a dense, fine-grained to cryptocrystalline, conchoidal fracturing, stylolitic dolomite in 1 to 5 foot beds that weather to a light cream-gray color. Some of these beds make a ringing sound when struck with a hammer. Many medium-crystalline, mottled, fetid beds weather to a silty, gray surface. Floating frosted quartz grains, some rutilated, and chert beds as much as several feet thick may occur. Some beds weather to a strongly dissected crosshatch surface referred to as elephant-hide rock (Hobson 1963). This surface is due to solutional action on a myriad of closely spaced fractures. The fractures are filled with a siliceous material that weathers out to thin raised ribs on the rock surface. Also many sets of thin, wispy, carbonaceous microfractures or seams occur in some beds.

At the type locality, near Hamburg, about 50 to 60 feet above the base of the member, a zone of grayish chert occurs which grades into a 4-foot-thick lenticular slightly fossiliferous limestone bed. About 20 feet above the limestone is a very fine-grained bed containing peculiar structures composed of ovoid concentric rings as much as 8 inches in length. These structures, termed oncolites, occur in most Harmonyvale sections at about the same distance above the Beaver Run-Harmonyvale contact. Fossils in the Harmonyvale include gastropods, brachiopods, and trilobites as well as the oncolites.

Markewicz and Dalton (1977) correlated the Beaver Run and Harmonyvale Members with the Ontelaunee of Pennsylvania (Figure 2) based on the following: (1) The Big Springs Member of the Epler is lithologically similar to Hobson's (1963) "60 foot fossil zone"; (2) Hobson (1963) placed his Epler-Ontelaunee contact in Berks County, Pennsylvania, at the highest limestone bed and approximately 100 feet below a massive chert zone. This chert section is probably equivalent to the middle part of the Beaver Run. Hobson (1963) states that the cherts are characterized by rugose or colloform chert; and (3) he also stated that no nautiloids occur in the Epler. In the Beaver Run Member we have found many nautiloids, gastropods, and other fossils. In the Harmonyvale Member, linguloid brachiopods, trilobites and gastropods have been found. The gastropods look similar to those seen high in the Ontelaunee of Pennsylvania by Markewicz. The

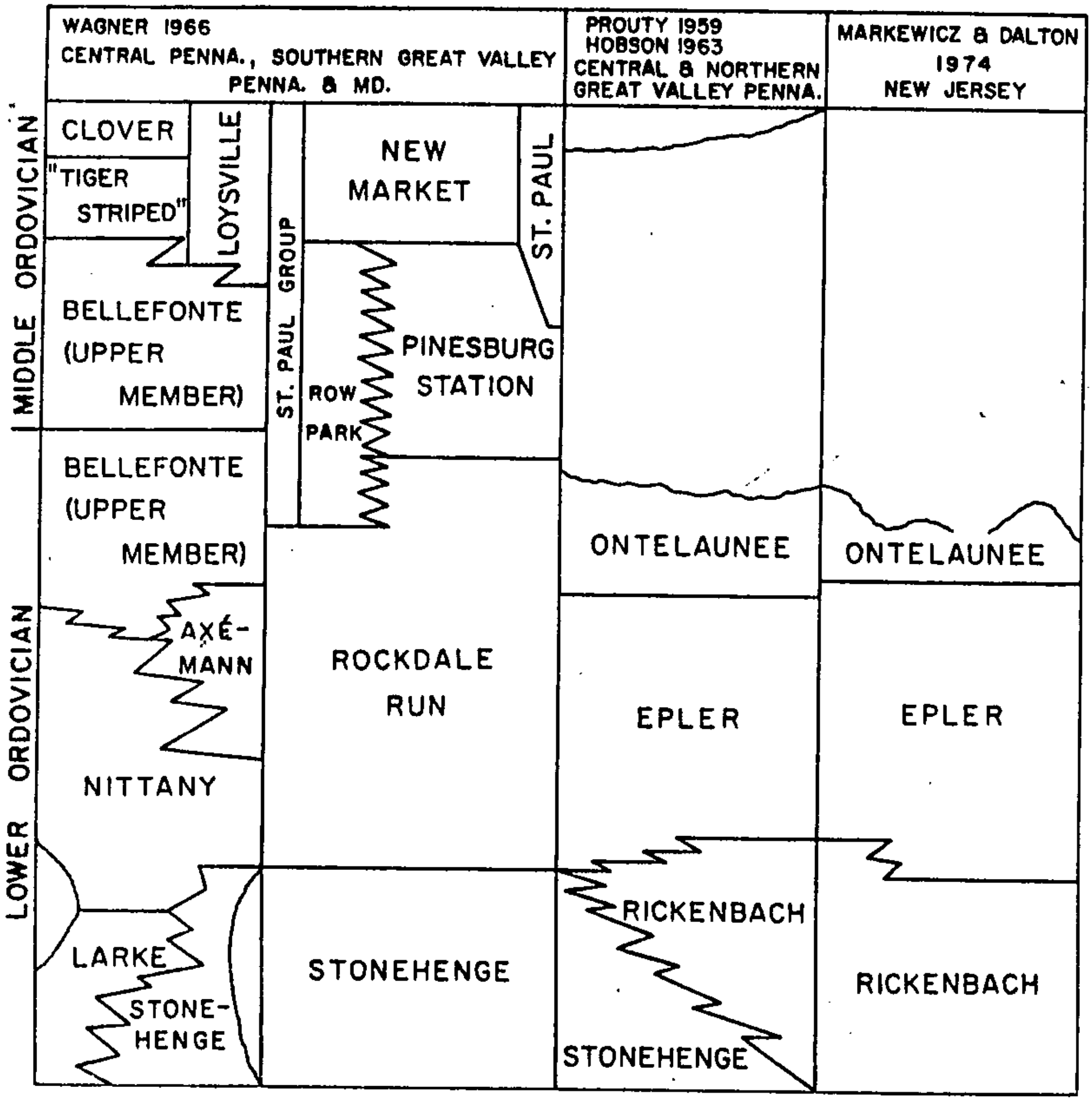

Figure 2. Composite correlation chart (from Markewicz and Dalton, 1977)

base of the Ontelaunee as defined by Markewicz and Dalton (1977) did not coincide exactly with that of Hobson (1963). He placed the contact at the change from limestone to dolomite and they placed it at the change from the fine-grained laminated dolomite of the Lafayette Member to the coarser-grained dolomite of the Beaver Run Member. From the description of Hobson's measured sections, it appears that he included a part of the Lafayette Member in the Ontelaunee.

Paleokarst Breccia

As mentioned under the description of the Lafayette Member, zones of paleosolution breccia occur in the upper part of the "Kittatinny". These breccias have been interpreted as fault breccias by some and as intraformational conglomerates by others. Hobson (1963, p. 65) stated that the massive breccia zones at Carpentersville are possibly fault related, although they do not look like fault breccias. They are commonly found in the Lafayette Member of the Epler Formation. Similar breccias occur in the Rickenbach and Ontelaunee. At some localities, the breccia has been traced from the lower part of the Beaver Run Member down through the Epler into the top of the Rickenbach, except for a few short covered zones. The breccia, which varies from locality to locality, consists of angular blocks of laminated dolomite and rounded cobbles, very large, slightly tilted blocks of laminated dolomite, or a zone of small fragments of slightly rotated laminated dolomite.

At some localities the breccia has filled tube-like channels in the rock. Generally, the breccia/wall-rock contact shows no evidence of faulting. The clasts within the breccia commonly consist of a heterogeneous assemblage derived from the overlying units as well as the unit containing the breccia. The interstitial material is commonly a red to greenish silt, resembling that found in present-day karst deposits.

Some beds of dolomite contain a peculiar crackle breccia which consists of angular fragments measuring from 1/4 inch to 4 or more inches in size; the individual fragments show little to no rotation. This breccia commonly occurs in a 50- to 200-foot-thick zone, which extends from the lower part of the Branchville Member of the Epler down into the Hope Member of the Rickenbach in the dense, finely crystalline dark beds. The crackling may be absent within a few tens of feet horizontally and vertically. Within this zone of crackling, the breccia is largely confined to the finer grained beds; little crackling appears in the coarser interbeds. The filling material between the fragments typically consists of a white- to light-gray crystalline calcite and/or dolomite. In some areas such as Friedensville, Pennsylvania, and Andover, New Jersey the filling material is a light, honey-colored sphalerite.

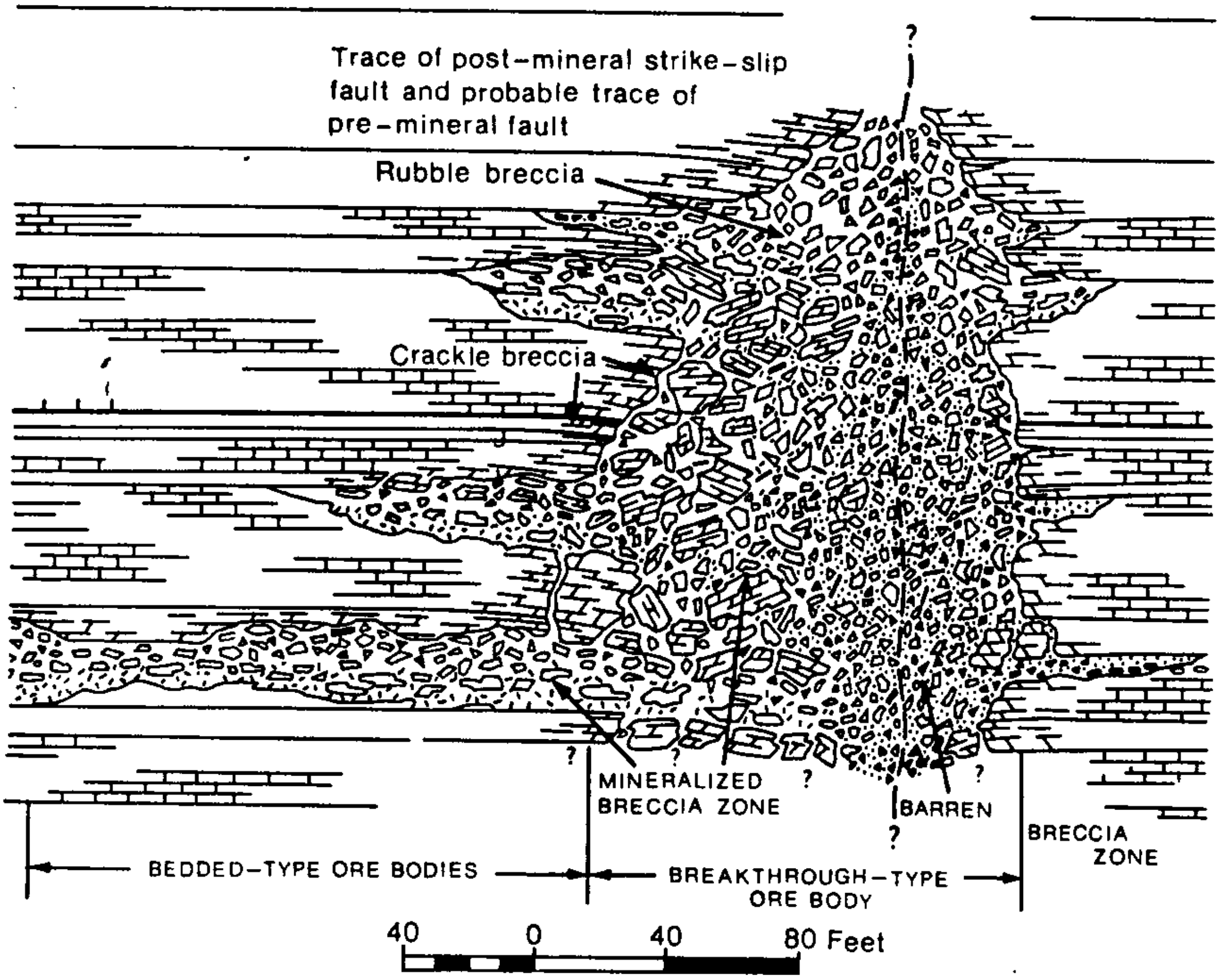

Figure 3. Relationship between crackle breccia and rubble breccia (modified from Hardeman , and others, 1969, figure 4.)

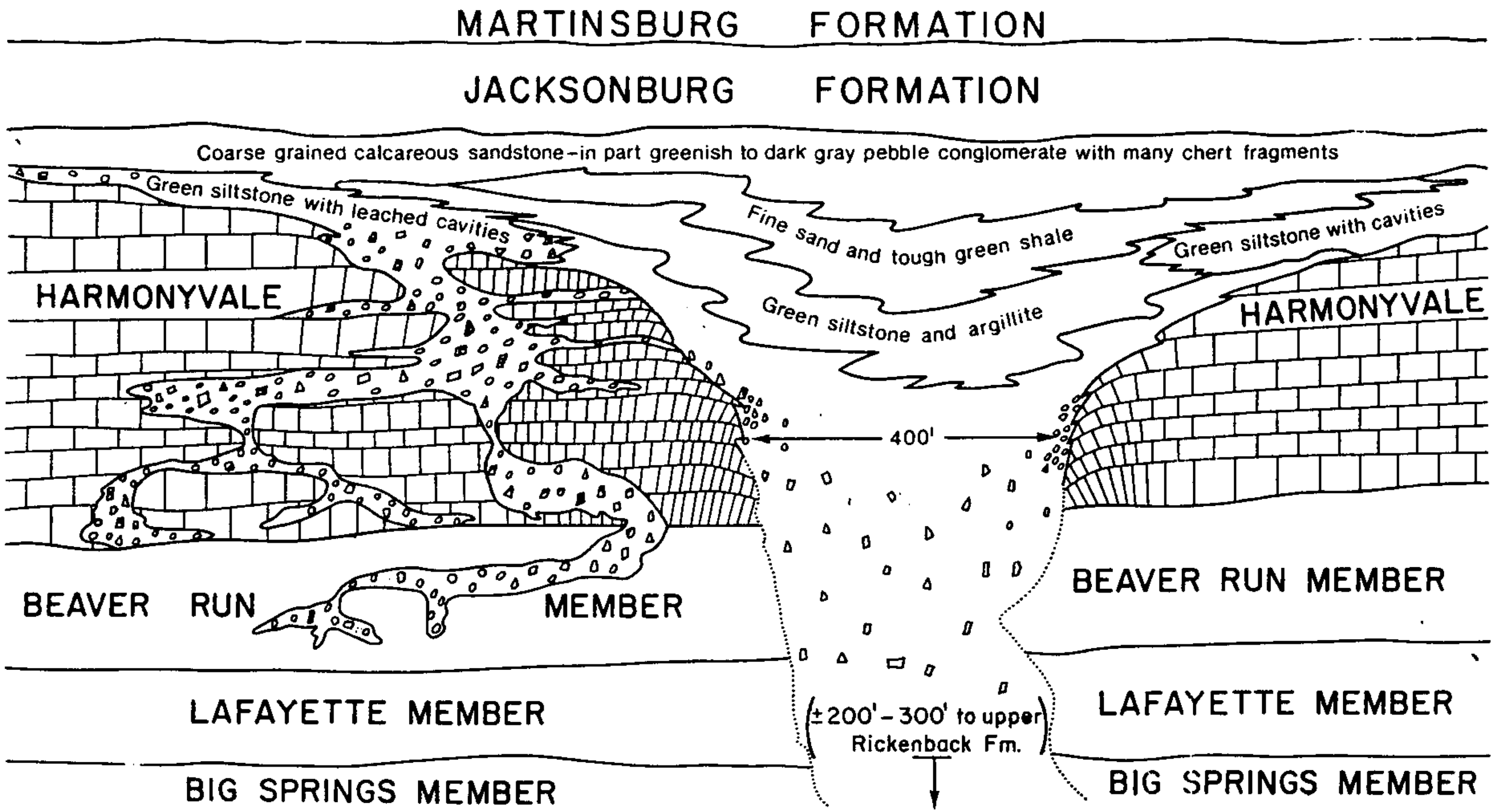

Figure 4. Generalized section showing paleokarst system south of Hamburg (from Markewicz and Dalton, 1977)

The crackle breccia is important because it is a possible guide to sphalerite mineralization and it may help in stratigraphic interpretation. At several localities in New Jersey, sphalerite occurs in the crackle breccia. Its similarity with the Friedensville crackle breccia is striking.

These breccias formed by karstification of the upper parts of the Kittatinny during the erosional period prior to Jacksonburg deposition (the Knox-Beekmantown unconformity). The relationship of the crackle breccia to the massive breccias (rubble breccia) is shown in Figure 3. The crackling probably originated from tension release fractures similar to those associated with present day cave passages.

The most important paleokarst-breccia occurrence is near Beaver Run, Sussex County (Figure 4). Here, 1.9 miles west of Route 94 on Beaver Run Road, a breccia 300 to 400 feet wide can be traced downward for several hundred feet perpendicular to bedding. It is postulated that this breccia was 3,000 to 4,000 feet long before erosion. A few hundred feet to the south, and slightly uphill, occurs one of the most unusual stratigraphic units in the region. It occupies the interval between the Ontelaunee and Jacksonburg Formations. This unit consists of green siltstone with leached cavities and shards of chert, green siltsone and argillite, shale and calcareous sandstone grading to pebble conglomerate. The green siltstone with cavities is in contact with the lower part of the Harmonyvale. The green unit is about 200 feet thick and has a strike length of about 3,000 feet. It thins rapidly, to the north and to the south, and is overlain by typical Jacksonburg. The relationships suggest that the green unit here is filling a paleo-sinkhole. Figure 5 relates the development of the breccia and the land surface karstification.

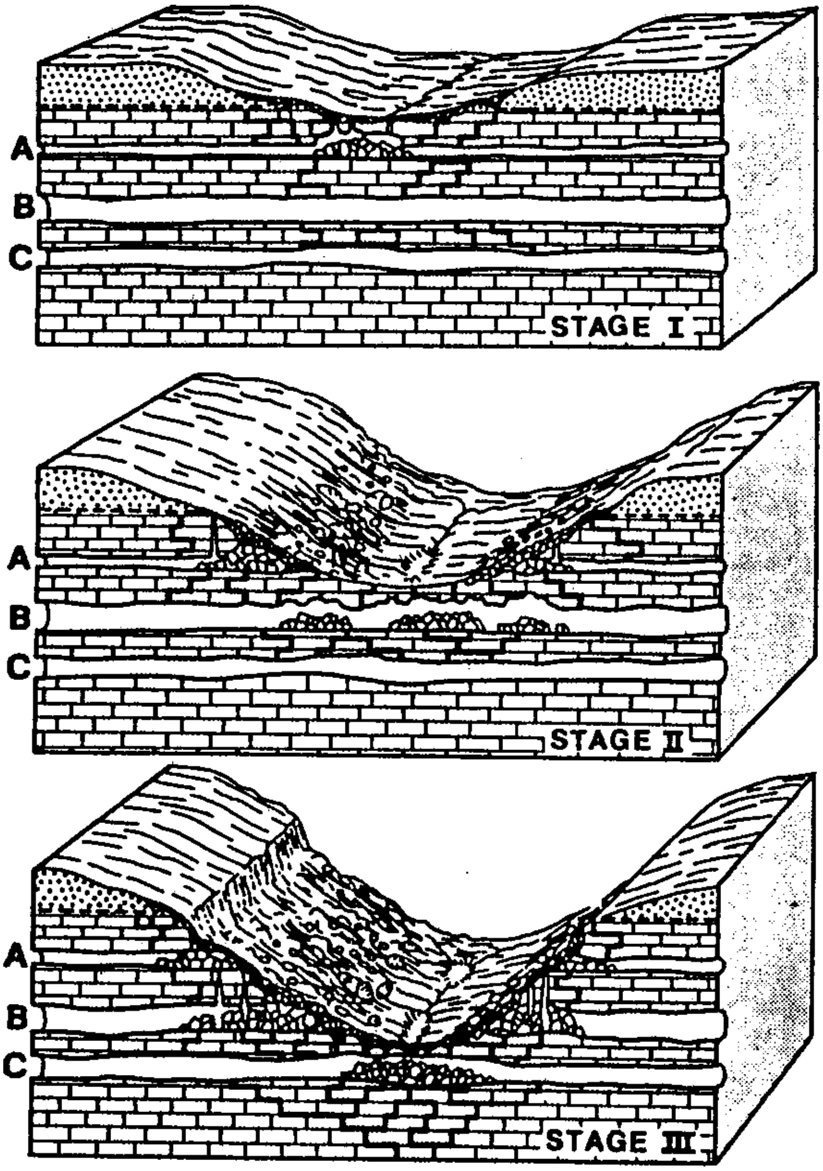

Figure 5. Relationship between downcutting, karsification, and development of breccias (breakdown)(from Bruckner, 1966, fig. 2)

AGE RELATIONSHIPS

Various attempts have been made at correlating the New Jersey Beekmantown sequence to the type areas of the Richenbach, Epler, and Ontelaunee and to the Stonehenge as found in the Reading area of Pennyslvania. The works of Hobson (1963), Drake (1965) and Markewicz and Dalton (1977) were based mainly on lithology because macrofossils are extremely rare in the Beekmantown of New Jersey. Karklins and Repetski (1989) list most of conodont samples collected by the United States Geological Survey (USGS) or the New Jersey Geological Survey (NJGS). Many of the samples were collected for the ongoing New Jersey-USGS COGEOMAP program. Based on conodonts Lyttle & Epstein (1987) and Drake and others (1985) extended the Stonehenge limestone into New Jersey as a mappable unit. They based their correlation on the occurrence in the rocks of New Jersey of the same conodont zones as occur in the Stonehenge of Pennsylvania.

For the Reading area, Karlins and Repetski (1989) indicate that the conodont fauna zones are: for the Stonehenge, A through C; for the Rickenbach, C to low D; the Epler, low D through E; and for the Ontelaunee, highest E through 5. The finding of occasional limestone lenses in the Beekmantown of New Jersey which have a "C" fauna has led Drake to map the Stonehenge Limestone in New Jersey.

The samples, which were obtained by the NJGS, were collected from the various members and some of the USGS samples were field checked to verify the member. The data obtained during the COGEOMAP program and presented in Karklins and Repetski (1989) have been used in Figure 6 to show the relationships of the formations and members as defined by Markewicz and Dalton (1977). The lower member of the Rickenbach was sampled once and no conodonts were found. The Hope Member has been sampled at Andover just above the "7 cherts" marker bed. It contains a fauna indicative of *Cordylodus proavus* Zone. The Crooked Swamp Dolomite was sampled at Walnut Valley from two zones about 50 to 75 feet apart. The lower sample was listed latest Late Cambrian or, more likely, earliest Early Ordovician. The upper sample was identified as the *Clavohamulus elongatus*, the *C.hintzeis proavus* Zone (middle or upper Fauna A).

The Branchville Member of the Epler was sampled near Lake Iliff, Newton and Walnut Valley. The Lake Iliff sample was obtained from the lower part of the member and contained an Upper Cordylodus Zone (conodont Fauna A). The Big Springs Member was sampled near Beaver Run, Newton, Lake Iliff, and Johnsonburg and all samples yielded a Fauna C. The Lafayette Member was sampled near Lake Iliff and also yield a Fauna C.

The Beaver Run Member was sampled near Sussex, Lake Iliff, Jacksonburg, and Phillipsburg. The Sussex, Lake Iliff and Phillipsburg samples yielded a Fauna C to low Fauna D from the lower part of the member. A sample from upper part of the member at Phillipsburg had a Fauna D and the top of the member or base of

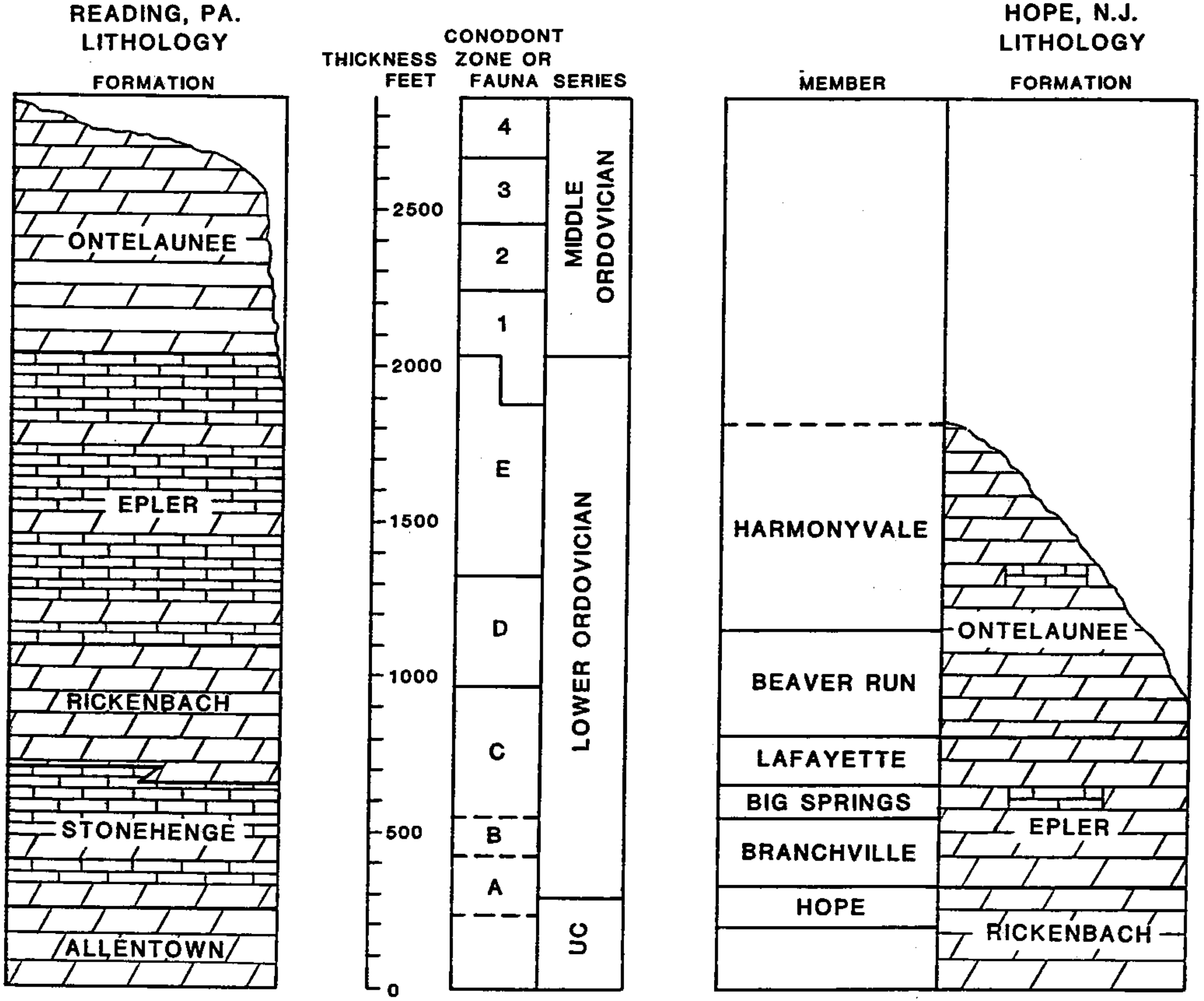

Figure 6. Comparison of Pennsylvania and New Jersey conodont zonation (modified from Lash and others, 1984)

the Harmonyvale Member at Jacksonburg yielded conodont Fauna D to *epikodus communio* Zone. The Harmonyvale Member was sampled at the type section near Beaver Run, at Phillipsburg, and from several horizons at Sarepta. A limestone lens at both the type section and Sarepta yielded a low Fauna D. At Sarepta two dolomite samples were obtained from below the limestone lens. The upper sample was about halfway up the quarry face and had a conodont Fauna D to E. Another sample was obtained from about 30 feet below the previous one and it indicated a Fauna D to low E. The Harmonyvale at Phillipsburg had a Fauna D to E.

The sample data indicate that the Lower Ordovician carbonates are fairly consistent in age along strike in New Jersey and if they were similar in lithology to the rocks of the corresponding age in the Reading area of Pennsylvania the correlation would be simple. In the Reading area the Stonehenge is a limestone and the Epler is an interbedded limestone and dolomite. The Rickenbach and Ontelaunee are dolomites. The top of the Ontelaunee may also contain some limestone. In New Jersey the sequence is mostly dolomite with very little limestone, that generally occurs at two horizons. The Big Springs can contain a limestone which varies from a shaly interbedded limestone to a shaly interbedded dolomite, within the same outcrop. The lithology of this unit is very similar to the middle part of the Epler in the Reading area, although it does not have the same conodont fauna. The other limestone occurs in the Harmonyvale and has been found at only two exposures. The limestone occurs as a lens 5 feet thick which is only 30 to 50 feet long at the type section of the Harmonyvale and at Sarepta it is a questionable outcrop.

Hobson (1963) felt that the Rickenbach, Epler and Ontelaunee Formations were northeastern equivalents of the Stonehenge and Rockdale Run in Franklin County, some 75 miles southwest of the Reading area. The rocks in the New Jersey area are 50 to 75 miles northeast of the Reading area. These distances are more than enough to allow for facies/time transgressions. This seems to be born out by statements in Karklins and Repetski (1989) that there is an increase in dolomite in the Stonehenge in the Delaware Valley. That is exactly what Hobson (1963) indicates and he calls that dolomite unit the Rickenbach Formation. By Hobson's interpretation, the Rickenbach to the northeast of Reading should include rocks which are the same age as the Stonehenge in the Reading area. This fact is borne out by the conodont data.

To understand the facies relationship in the Beekmantown of eastern Pennsylvania and New Jersey it would be desirable to systematically sample across the Beekmantown at several locations from Reading into New Jersey. Examination of the lithologic and biostratigraphic relations of the the "Beekmantown" formations from southwest to the northeast, should make it be possible to determine whether the units are time-transgressive from northeast to southwest.

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Lower Paleozoic environments of deposition and the discontinuous sedimentary deposits atop the Middle Ordovician unconformity surface in New Jersey

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Abstract

Depositional environments of the Lower Paleozoic rocks of New Jersey indicate an evolving orogenic period. The Kittatinny Supergroup portrays a quiescent period of stable platform sedimentation. Regional uplift, erosion with concomitant broad open folding accompanied the initiation of the Taconic orogeny. On this regional unconformity surface, fluvial and paleokarst sediments were deposited. A lower clastic-argillite sequence characterizes this fluvial deposit. Locally it is capped by an upper carbonate sequence of shallow marine origin. Together these two rock sequences comprise the informally named "Wantage Formation." Paleokarst deposits related to the "Wantage" include infilled sinkholes and dolines along with cave collapse breccias and intraformational breccias.

A marine transgression in Trenton time preserved part of the "Wantage" in depressions as wave action winnowed away other signs of the subaerial erosion. The Jacksonburg Limestone was deposited during this transgressive event. Then as a foreland basin developed and deepened, a change in the type of sediment influx occurred as shown by a variation in the regional lithologic character of the Jacksonburg (crystalline limestone to an argillaceous limestone) and deposition of the overlying Martinsburg Formation. Deposition in the foreland basin culminated in a second regional uplift in Upper Ordovician to Lower Silurian time, producing the Taconic unconformity.

Introduction

Recent mapping of the Lower Paleozoic rocks in the Kittatinny Valley and the Highlands province of New Jersey (fig. 1) has delineated a sequence of localized and discontinuous alluvial and shallow-marine sedimentary rocks resting on the unconformity surface at the top of the Beekmantown Group. This rock sequence is here informally introduced as the "Wantage Formation." Paleokarst deposits beneath the unconformity surface are related to the newly-recognized unit but are not mappable at the 1:24,000 scale. A subsequent manuscript will formalize the "Wantage" for the revised Geologic Map of New Jersey to be published at the 1:100,000 scale in conjunction with the United States Geological Survey.

Field data suggest that the candidate formation was deposited in valleys extending along open synclinal troughs and on the flanks of the related arches. These structures formed in the Cambrian - Ordovician miogeoclinal prism as a result of the Taconic orogeny. The Cambrian - Ordovician tectonic environment of deposition is summarized to describe the sequence of events that led to deposition and subsequent burial of this highly variable unit.

Delineation of the "Wantage Formation" and related paleokarst deposits in New Jersey is important because comparable units from the southern and central Appalachians as well as the midcontinent region and Canada are of economic importance. Some paleokarst units have been hosts for economical, secondary base metal mineralization (Callahan, 1968; Sangster, 1988; De Voto, 1988; Haynes and Kesler, 1989). Mussman and Read (1986) note that deposits along the Knox unconformity are possible hydrocarbon reservoirs in the Eastern Overthrust Belt in the Appalachians. Haynes and Kesler (1989) show that hydrocarbons can accumulate in erosional highs which can be outlined by valley deposits. Paleovalley fills have already been exploited for hydrocarbons in the midcontinent (Howard and Whitaker, 1988).

Lower Paleozoic Rocks and Environments of Deposition

Lower Paleozoic rocks of New Jersey crop out in the Kittatinny Valley and as outliers in the Highlands province (fig. 1). The Kittatinny Valley comprises the southeastern part of the Valley and Ridge province, also known as the Great Valley. The northwestern part of the Valley and Ridge province contains Silurian molasse and younger marine-trangressive rocks of Silurian through Devonian age, which are described in detail by Epstein and Epstein (1969) and Epstein and Lyttle (1987). The Highlands province borders the Kittatinny Valley on the southeast and includes the New Jersey part of the Middle and Upper Proterozoic rocks of the Reading Prong (Drake, 1969). Cambrian and Ordovician carbonates within the Highlands are generally restricted to infolded and faulted intermontaine valleys in the southwest Highlands area (Kummel, 1940; Herman

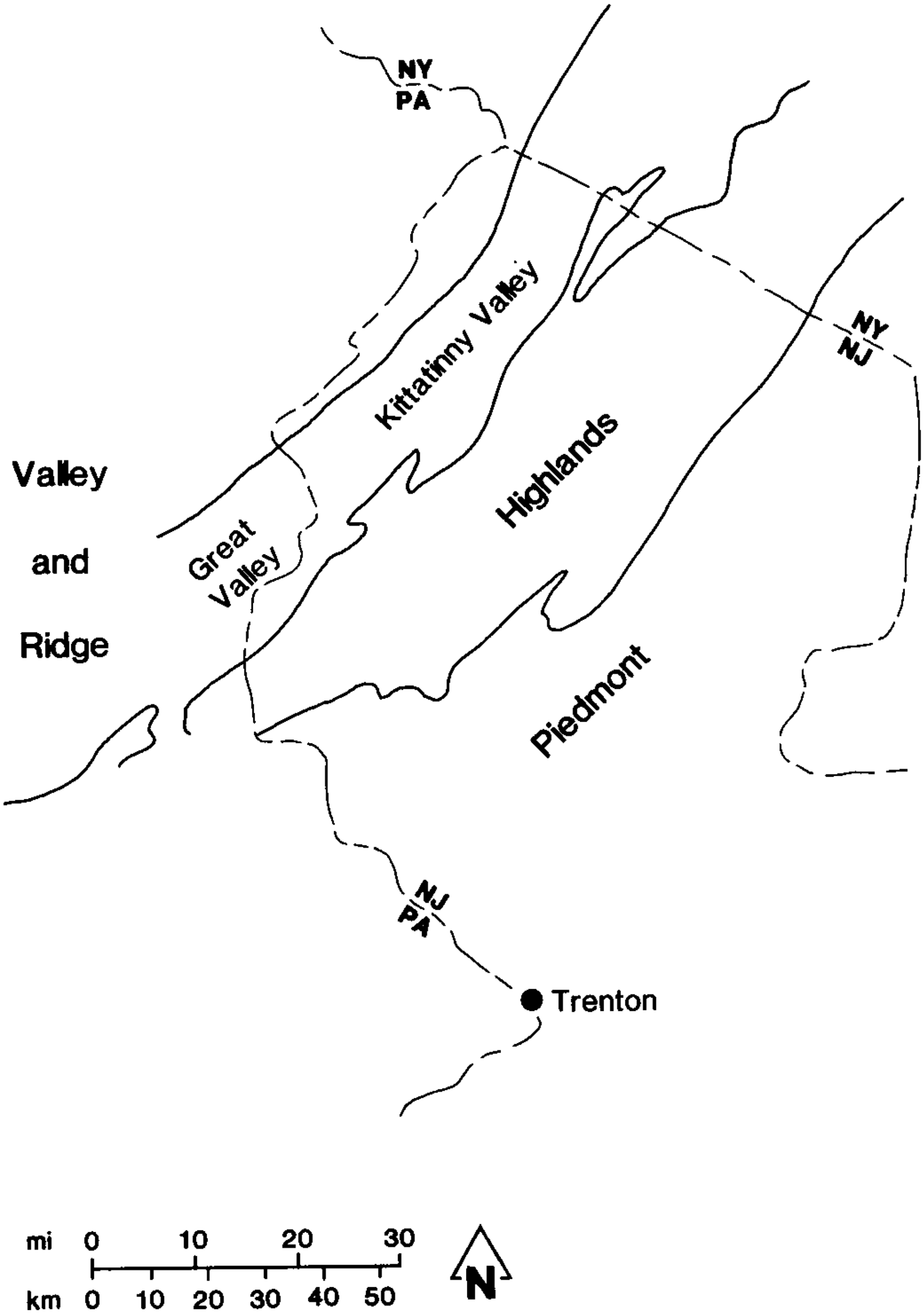

Figure 1. Kittatinny Valley and its setting among the provinces of northern New Jersey.

and Monteverde, this volume, pl. 2a). These carbonate valleys pinch out along strike to the northeast, and also farther to the southeast along the Newark Basin Border Fault System.

The Lower Paleozoic stratigraphy of New Jersey reflects the tectonic evolution from a drift facies, passive margin contintental edge to a convergent foreland margin of the Taconic orogeny. The environments of deposition reflect the tectonic evolution of an initial supratidal and shallow marine environment to a deeper neritic-flysch basin at the foreland of a convergent margin (Epstein and Epstein, 1969). This change included uplift and subaerial erosion of parts of the passive margin sequence caused by foreland migration of a peripheral bulge in front of an eastward dipping subduction zone (Jacobi, 1981; Shanmugam and Lash, 1982, 1983). A subsequent marine submergence of the eroded shelf in a foreland basin setting resulted in the mantling of limestone and flysch sediments over the Cambrian and Lower Ordovician rocks. A later uplift of the filled foreland basin caused subaerial erosion of the Middle and Upper Ordovician flysch deposits before blanketing by a Silurian molasse sequence. The uppermost Lower Ordovician through Upper Ordovician rocks record a continuous deformational event with synchronous sedimentation that culminated in the folding and faulting of all pre-Silurian rocks. A generalized stratigraphic column can be seen in figure 2.

The Hardyston Quartzite and the Kittatinny Supergroup of Drake and Lyttle (1980) represent the passive-margin stratigraphy. The Lower Cambrian Hardyston Quartzite is composed of arkosic sandstone, quartz sandstone and conglomerate resting nonconformably on Middle and Upper Proterozoic granites and gneisses of the Reading Prong (Aaron, 1969). This basal transgressive clastic sequence provides the base upon which the predominently dolomite of the Kittatinny Supergroup was deposited. The Kittatinny Supergroup includes in ascending order, the Lower Cambrian Leithsville Formation, the Middle Cambrian to Lowest Ordovician Allentown Dolomite and the Lower Ordovician Beekmantown Group. The Beekmantown Group is divided into a lower and an upper part.

The Leithsville Formation and Allentown Dolomite are predominantly dolomite with minor interbeds of quartz sandstone and shale. Sedimentary structures include mudcracks, hardgrounds, stromatolites, graded beds, cross-bedded clastics and dolomites, oolites and flat-pebble conglomerate. These features indicate minor eustatic flucuations in an environment varing from supratidal to intertidal (Drake, 1969). The lower part of the Beekmantown Group is also dominantly dolomitic, but contains minor limestone and quartz sand lenses. These lithologies and features indicate a continued subtidal-neritic depositional environment extending into the Lower Ordovician. However, water circulation was restricted during deposition of the fetid dolomite in the basal sequences of

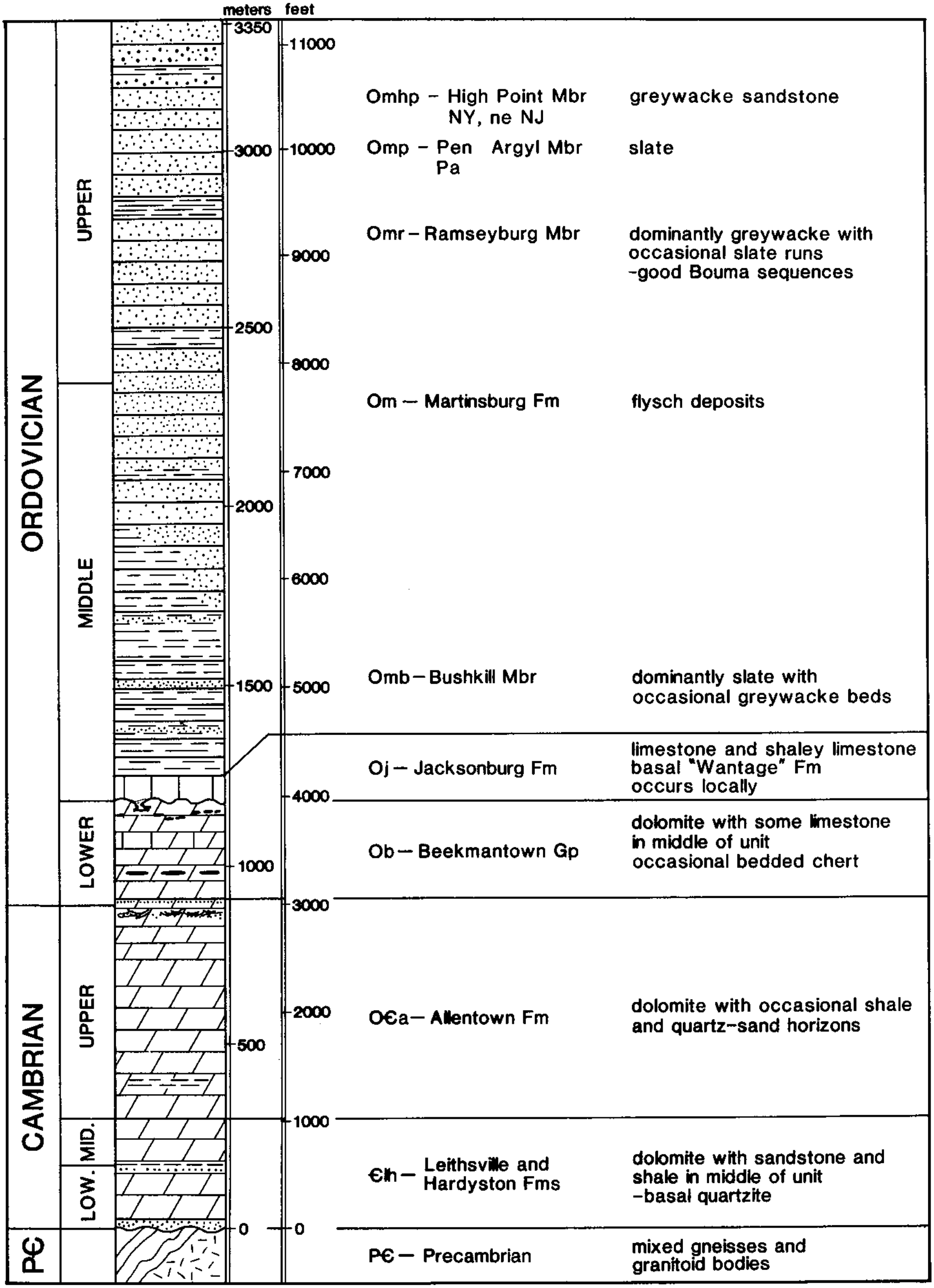

Figure 2. Generalized stratigraphic column for the Kittatinny Valley and southwest Highlands area

the upper part of the Beekmantown Group (Hobson, 1963). The overlying sequence of non- fetid dolomite suggests a subsequent return to a more open circulation. A few local beds of limestone also occur in the uppermost part of the Beekmantown Group in places where erosion was minimal before subsequent mantling by the Jacksonburg Limestone. No noticeable carbonate-platform tilting can be seen between beds in the Kittatinny Supergroup (Kummel 1940).

Savoy (1981) suggests that deposition of the carbonate platform continued at least into the Whiterock Stage before it was disturbed by a regional uplift and concomitant erosion forming the unconformity surface at the top of the Beekmantown. The Whiterockian age is based on faunas obtained from dolomite cobbles originating from the eroded Beekmantown and deposited in the Jacksonburg Limestone. The pebbles are from outcrops near Hope, New Jersey (Savoy, 1981). The unconformity at the top of the Beekmantown thus records the first major sign of the Taconic orogeny. Kummel (1915) suggests that at least 800 feet of the Beekmantown was locally eroded. Erosion generally decreases along strike from the northeast, just over the state boundary into New York, to the southwest into Pennsylvania (Savoy, 1981; Savoy and others, 1981). Savoy and others (1981) suggest that the Beekmantown unconformity in the Great Valley of New Jersey requires stratigraphic relief of 900 feet, near the Pennsylvania border, to 1300 feet, near New York and that a minor regional tilting can account for this relief. However, in southeastern New York, local structural complexities need to be invoked (Savoy, 1981; Savoy and others, 1981). This study shows that a simple platform tilt with paleokarstification cannot account for the degree of local erosion into the Beekmantown Group. Nor can it explain the diversity and distribution of sediments of pre- Trenton and Trenton age deposited on the unconformity surface. Rather, it is suggested that a more undulose carbonate platform surface, marked by broad, low amplitude, longitudinal folds eaxisted during subaerial ersosion and karstification during the uppermost Lower to Middle Ordovician (Herman and Monteverde, this volume).

A strong cross-strike variation in the degree of pre-Silurian erosion of the Kittatinny Supergroup was first recorded by Kummel and Weller (1902). They noted that the unconformity in the Green Pond outlier represents much deeper erosion into lower parts of the Kittatinny dolomite and locally extends to basement, in contrast to the Beekmantown unconformity in the northwest Highlands and Kittatinny Valley. They also suggested that erosion of the Beekmantown Group in the Green Pond area could have continued until deposition of the Silurian Green Pond Conglomerate, with only local deposition of parts of the Middle Ordovician Martinsburg Formation. However, field relations suggest that erosion of the Kittatinny Supergroup in the Green Pond Outlier stems from an Upper Ordovician - Lower Silurian regional unconformity of Taconic time (Rodgers, 1971). This erosional event probably beveled low enough to remove all signs of the older Beekmantown unconformity in areas hindward of the Kittatinny Valley.

The first post-Beekantown unconformity deposit in New Jersey is the "Wantage Formation". The lower "Wantage" is a clastic-to- argillaceous sequence which grades upward into a shallow marine carbonate sequence that is suggested as conformable with the overlying Jacksonburg Limestone. Markewicz and Dalton (1977) described several occurrences of this unit and interpreted them as paleokarst infillings. They noted that the contact between the "Wantage Formation" and the Beekmantown Group varied from an angular unconformity to a disconformity, depending on its position in the karst valley. The clastic-argillaceous and carbonate sequences need not occur together in any single outcrop. The discontinous character and compositional variability of the unit is affected by structural relief and variable source rocks as described in the "Wantage Formation" section below.

The Jacksonburg Limestone consists of a lower, fossiliferious, fine to coarsely crystalline limestone with some dolomite, chert and limestone cobble conglomerate (Cement Limestone Member) that grades upward into a more argillaceous limestone (Cement Rock Member) (Drake, 1969). The formation represents a major marine- transgressive event in the early development of a foreland basin. The Cement Limestone Member contains some cobble-conglomerate beds both on the unconformity surface and higher in the sequence (Kummel, 1901; Miller, 1937). The conglomerate beds have rounded to subrounded cobbles which are eroded pieces of the underlying Beekmantown Group (Markewicz and Dalton, 1977; Savoy, 1981). Kummel (1901) suggests moderate transport of these cobbles. Savoy (1981) differentiates rounded cobbles associated with stream deposits from angular clasts of paleokarst infill deposits. Elsewhere in the central Appalachians, angular blocks of weathered rocks of the Beekmantown Group occur as surface deposits on erosional highs (Mussman and Read, 1986). They are not sinkhole deposits but are composed of the eroded and bisected surface rubble related to overlying soil profiles which were reworked and mantled during subsequent marine transgression. Stream-deposited cobbles that occur above the base of the limestone sequence suggest that initial deposition of this unit occurred in restricted lows, and that as the depositional basin became more submerged due to continuing compression, erosional highs were inundated and their loose rubble was either covered in situ, or susequently reworked and deposited into lows over earlier laid Jacksonburg limestone beds.

Weller (1903) and Miller (1937) report a hiatus in sedimentation towards the base of the Jacksonburg Limestone at the type section in Warren County, NJ. This feature records a fluctuating shoreline before final submergence of the irregular terrane and subsequent deposition of the remaining portions of the Jacksonburg. The Cement Rock Member increases in thickness and volume compared to the Cement Limestone Member in both the Highlands and Kittatinny Valley towards southwestern New Jersey and eastern Pennsylvania (Miller, 1937; Sherwood, 1964; Drake, 1967; Davis and others, 1967; Drake and others, 1969). This implies that regional basin subsidence was more pronounced southwest and southeast of the present-day Kittatinny Valley during the Middle Ordovician. Regionally, the Jacksonburg Limestone grades upward into the basal claystone shale/slate of the Martinsburg Formation (Kummel, 1940; Drake and Epstein, 1967; Drake, 1969).

The Martinsburg Formation in eastern Pennsylvania and western New Jersey has been subdivided into three members. In ascending order they are the Bushkill, Ramseyburg and Pen Argyl Members (Drake and Epstein, 1967). The lithology of the Bushkill and Ramseyburg Members is indicative of flysch sedimentation (Drake, 1969). The Bushkill Member is mostly claystone slate with lesser amounts of graywacke siltstone and carbonaceous slate; its mean grain size increases upward. The Ramseyburg Member is mostly graywacke sandstone and siltstone with a calcareous matrix, but it contains some interbedded shale sequences. Drake (1969) suggests that the Ramseyburg Member was deposited during the peak of Taconic tectonism. The Pen Argyl Member crops out almost entirely in Pennsylvania. It extends eastward across the Delaware River into Warren County, N.J. and pinches out at the surface along Kittatinny Mountain (Drake and others 1969). This upper member contains thick-bedded slate and is thought to represents post-peak-stage Taconic tectonism (Drake, 1969). Drake also proposes that the restriction of the Pen Argyl largely to this area in Pennsylvania is related to the Martinsburg basin morphology.

Another upper member of the Martinsburg Formation which has recently been identified in the northeast part of the Kittatinny Valley continues northeastward into New York. It consists of a thick-bedded graywacke sandstone with a siliceous matrix. Thinner-bedded, planar-laminated to massive shales are interbedded with the coarse clastics, which also contain ellipsoidal rip-up clasts of shale. Drake (in press) has designated this sequence the High Point Member. In this area, the Ramseyburg Member is also coarser and more siliceous than it is to the southwest. These facies relations indicate more proximal deposits to the northeast and more distal, finer- grained flysch concentrations to the southwest.

Taconic tectonism continued with flysch deposition into a foreland basin centering in the current Valley and Ridge province and extending hindward into the Highlands province. The foreland basin was subsequently uplifted in Late Ordovician to Early Silurian time (Rodgers, 1971; Epstein and Epstein, 1969; Epstein and Lyttle, 1987) which locally resulted in a regional unconformity of Taconic age. The angular discordance between the Ordovician Martinsburg and the Silurian Shawangunk Formation varies along strike. Epstein and Lyttle (1987) describe the Taconic unconformity along a 120 mile strike length from eastern

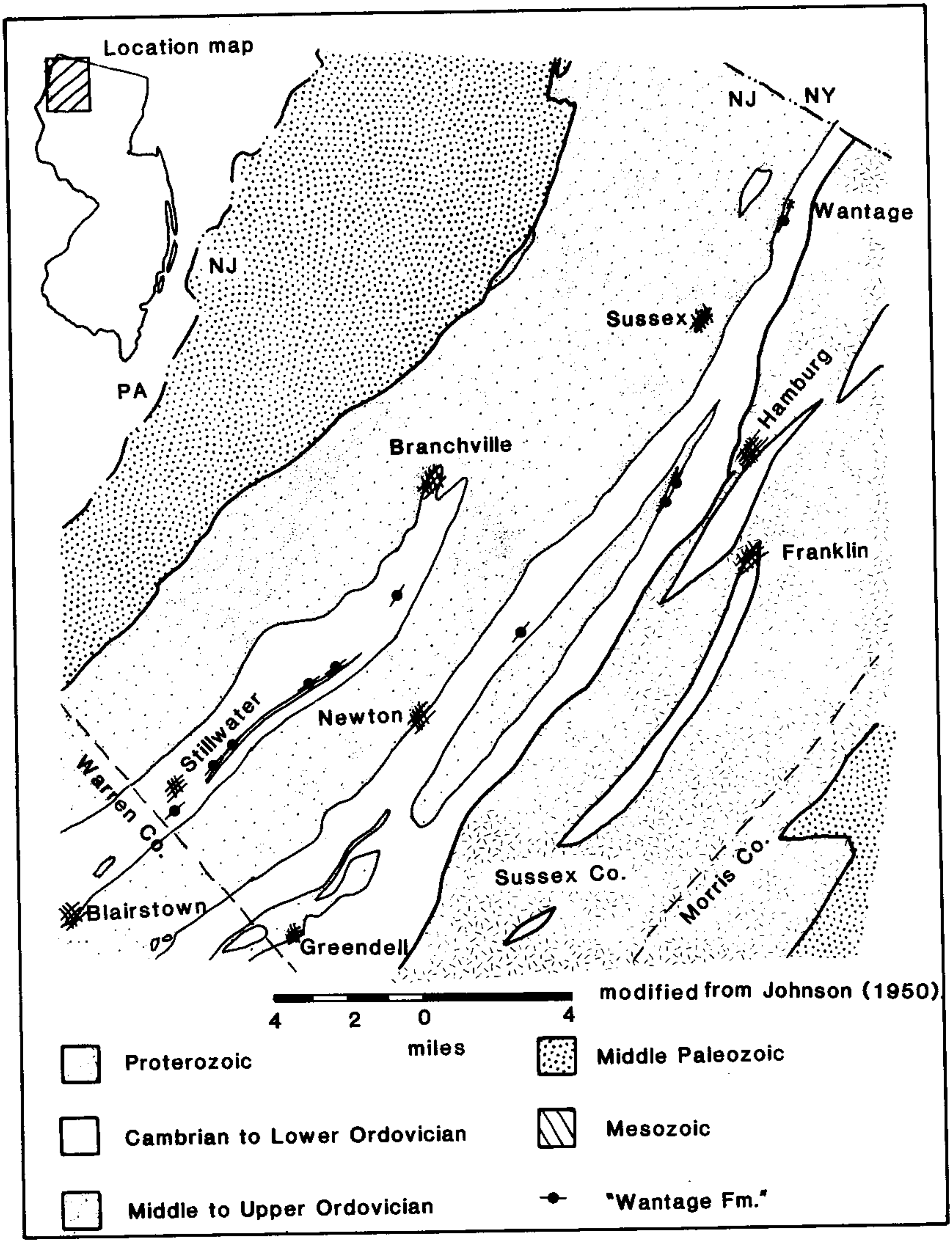

Figure 3. Outcrop locations of the "Wantage Formation" in northeastern Kittatinny Valley.

Pennsylvania through New Jersey and into southern New York where the angular discordance ranges from negligible to a maximum of 15 degrees. In eastern Pennsylvania both an angular unconformity and disharmonic folding occur in the units at the unconformity surface (Epstein and Lyttle, 1987; Herman and Monteverde, this volume). At these locations a detachment surface along the unconformity surface is necessary to explain the disjunctive fold patterns. This detachment has been named the Blue Mountain decollement by Drake and others (1969), and Epstein (1973). Taconic folds in the Martinsburg Formation are described by Epstein and Lyttle (1987) as mostly broad and open except north of Ellenville, New York where deformation and the angular unconformity are intense. Epstein and Lyttle (1987) describe a dimictite on the unconformity surface in southwestern New York State that is generally 1 foot (31 cm) thick. They suggest that this 'weird unit' is colluvium from a totally eroded source rock which could relate to rocks currently cropping out to the east of the exposed unconformity. Subsequent shearing masked much of the original fabric of this unusual diamictite. The folding and faulting related to the Taconic orogenic event are described by Herman and Monteverde (this volume).

The "Wantage Formation"

Recognition of the areal extent of the "Wantage Formation" has been greatly increased since several exposures were first described by Markewicz and Dalton (1977). They did not map these rocks as a separate unit or delineate their regional extent. Recent mapping shows that the "Wantage Formation" is widely distributed thoughout the northwestern Highlands and Kittatinny Valley in each of the major Paleozoic belts containing Ordovician carbonate rocks (figures 1, 3 and 4). Except where modified by structural complexities, the formation rests in depressions on the unconformity surface at the top of the Beekmantown Group and, where the carbonate sequence is present, grades upward into the Jacksonburg Limestone. It commonly occurs as isolated, elongated, lense shaped bodies having a maximum estimated thickness of 150 feet (46 m) and a maximum length of 20,000 feet (6.1 km). A semicircular outcrop pattern occurs where sediments infill doline-like depressions on the unconformity. The longer, narrow outcrop patterns suggest alluvial deposition in paleovalleys. Similar types of deposits have been described in the central and southern Appalachians (Cooper and Prouty, 1943; Cooper, 1944; Miller and Brosge, 1954; Harris, 1960, 1969; Lowry and others, 1972; Mussman and Read, 1986; Haynes and Kesler, 1989; Mussman and others, 1988) and in Canada (Johnson and Rong, 1989; Kerans and Donaldson, 1988; Desrochers and James, 1988).

Regionally, the "Wantage Formation" consists of a lower clastic-argillite sequence which grades upward into an upper carbonate sequence. The argillite's color varies between grayish olive (10Y 4/2), grayish red (5R 4/2 - 10R 4/2) and medium gray (N5). It contains disseminated, subangular to subrounded sand- to

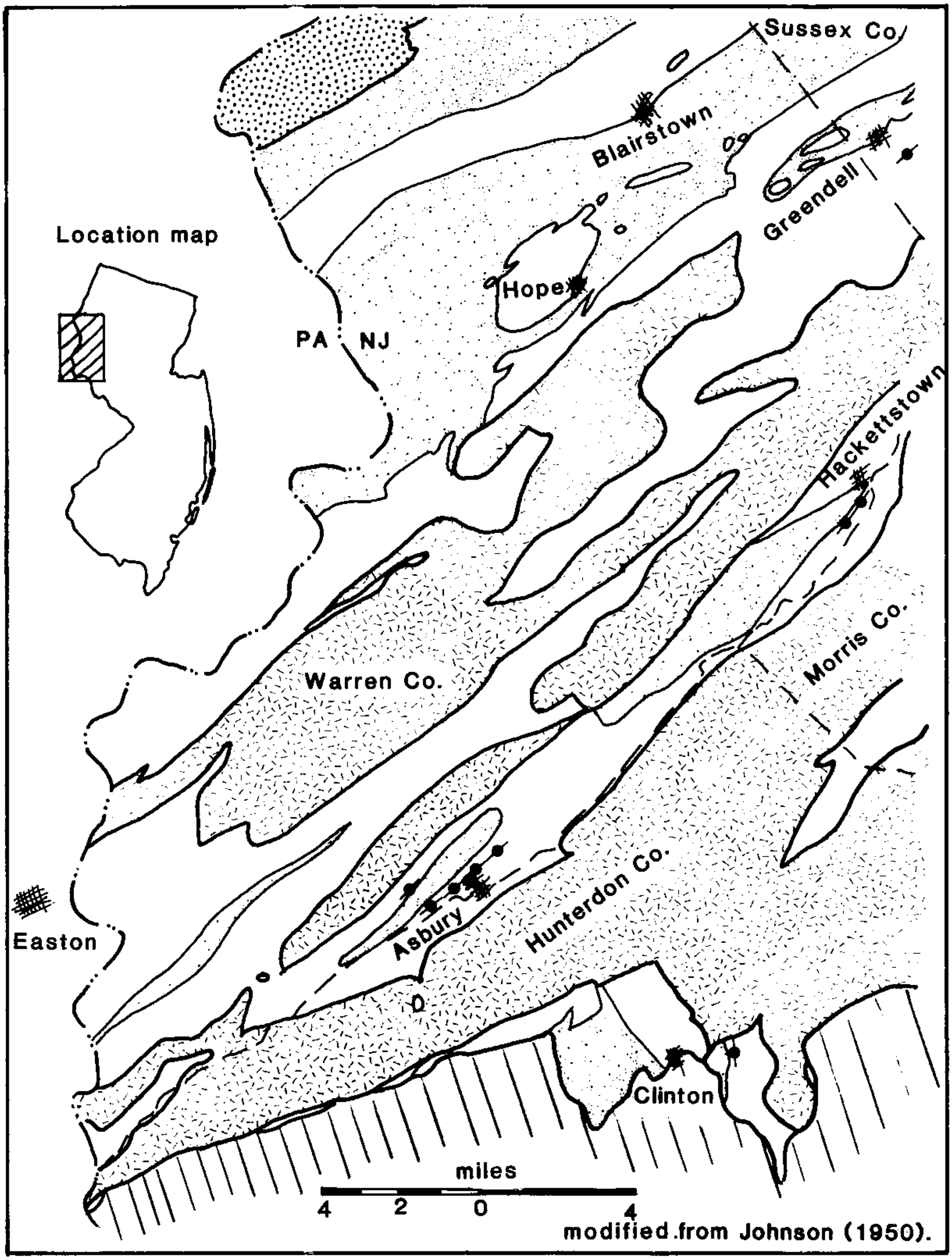

Figure 4. Outcrop locations of the "Wantage Formation" in southwestern Kittatinny Valley and the southwest Highlands area. Note symbols same as in figure 3.

pebble-sized chert clasts. At most outcrops interbeds and lenses of subangular quartz sand are evenly distributed throughout the argillite. Trough cross-bedding, edgewise conglomerate and convolute bedding are common. Near the base, subrounded dolomite and chert cobble-to-pebble conglomerates can recur; they commonly lense out and vary from matrix- to clast-supported. The conglomerate beds have a scoured basal contact and the cobbles are generally aligned along bedding or are slightly imbricated. As suggested by Harms and others (1982), imbrication of conglomerate clasts and trough cross-bedding suggest a fluvial environment of deposition. Matrix material consists of fine quartz sand, chert gravel, argillite and dolomite; the quartz sand and chert gravel are mainly in the lower conglomerate beds. The argillaceous material, along with the subangular chert fragments suggests a reworked soil material (Markewicz and Dalton, 1977) deposited in a fluvial environment. A similar unit has been reported by Harris (1960) in the southern Appalachian region. In New Jersey the chert fragments and frosted quartz sand grains are the relatively insoluble material which would resist weathering in a soil profile to a greater extent than the host dolomite or limestone. The lack of well developed roundness of the chert gravel supports limited transport and a local source terrain. Further evidence for limited transport and reworking is that the chert does not commonly occur concentrated into a lag deposits but is usually "floating" in argillite. Preliminary anaylsis of the argillite shows the presence of kaolinite with lesser amounts of illite. This chemistry may indicate a well- weathered source terrain or could solely be inherited from the parental carbonate. Clearly more work is needed to decipher this.

A generalized carbonate sequence contains interbedded medium light- to medium dark-gray, fine- to medium-bedded, fine-grained limestone and dolomite. The beds are massive to locally laminated. The upper contact with the basal calcarenite of the Jacksonburg Limestone is thought to be conformable. The carbonates were deposited in a shallow marine environment which marks the first evidence of a post-unconformity marine transgression. Generally the lower clastic-argillite sequence is thicker than the upper carbonate sequence.

The ratio between the clastic-argillite and carbonate components varies considerably between different occurrences of the "Wantage Formation" (fig. 5). The type section just south of Beaver Run Road, 1.7 miles west of the town of Hamburg, best represents the generalized regional sequence; it has both the lower clastic- argillite and upper carbonate sequences. The lower clastic- argillite section is dominated by a grayish olive (10Y 4/2) fine- to medium-bedded argillite with disseminated subangular chert sand and chert pebbles. Small (less than 2 inches (5 centimeters) long) lenticular pods of limestone occur within quartz sand lenses in the lower part of the sequence along with several very thin to thin interbeds of rounded to subrounded quartz and chert sand having basal scour and fill structures. The carbonate sequence contains medium light to medium dark-gray (N4 to N6), thin-bedded dolomite, limey dolomite and limestone. These fine-grained carbonates are massive to wavy-laminated. Both the upper and lower contacts are covered. Markewicz and Dalton (1977) describe a contact between the "Wantage Formation" and the Beekmantown Group at this type section. They suggest that a small soil-like zone between the two is apparently a disconformable contact.

In the section near Stillwater, Sussex County, the clastic- argillite sequence is repeatedly interbedded with the carbonate sequence (fig. 5). The sequence contains interbedded sequences of silty to shaley dolomite, suggested as detrital in origin, a few very thin beds of quartz sand, and thick-bedded chert cobble conglomerate with mostly a dolomite matrix. The cobbles range from dolomite to chert with a higher proportion of chert cobbles in the lower conglomerate beds than the upper conglomerate beds. The matrix also appears to have a higher quartz sand content in the lower conglomerates. A basal scour marks the lower contact with the detrital silt-sized dolomites. Fine laminations can be seen in the dolomite interbeds. No argillite is seen. However along strike, there are outcrops of a thin bed of medium light- gray, silty argillite which contains trough cross-bedding and convoluted bedding. Several other longitudinal lenses of the cobble conglomerate also occur along strike. The elongated character of these different outcrops, their compositions, and their sedimentary structure suggest that a fluvial environment existed during "Wantage" emplacement before deposition of the Jacksonburg Limestone.

In the Asbury, Warren County section no carbonate has been noted. This could simply be a structural complication inasmuch as a fault apparently cuts the upper contact of the "Wantage" with the unexposed Jacksonburg Limestone. Grayish olive, argillite to silty argillite with dissemenated pebbles of subrounded to subangular chert and quartz are common here. Fine laminations occur in the siltier beds. A dolomite-and-chert pebble conglomerate and a medium-grained quartz sandstone overlie the argillaceous beds. Dolomite pebbles are subrounded and highly weathered. The chert pebbles are subangular to subrounded and mostly white. The source rock for the chert can be seen along strike where the Beekmantown Group has not been extensively eroded. Matrix material contains green argillite, frosted quartz-sand grains and detrital dolomite. The sandstone resembles the conglomerate matrix in composition. Cross- and planar-bedding can be seen in the sandstone.

In the Hackettstown section in Morris and Warren Counties, there is an abrupt contact between the grayish-olive argillite and the basal Jacksonburg, with no apparent change in strike and dip between units. Immediately along strike to the northeast, the entire sequence thins and the argillite grades upwards into a siltstone. Sedimentary structures include trough and planar cross-bedding, graded bedding, and edgewise conglomerate with shale rip-up clasts. Farther along strike

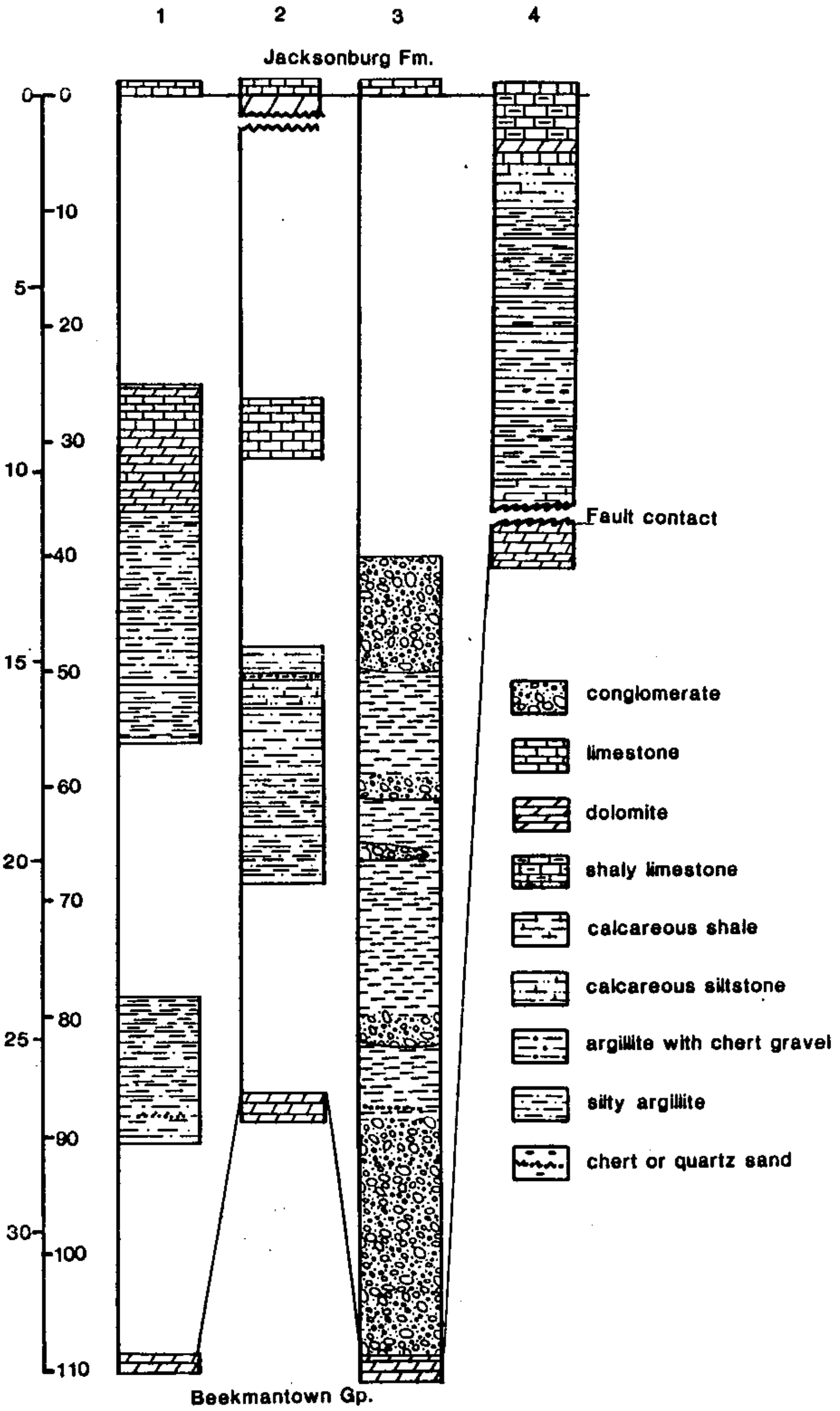

Figure 5. Lithology and correlation of four measured sections of the "Wantage Formation". (1),(2) west of Hamburg, (3) Stillwater, (4) Wantage.

a sequence of a grayish-olive argillaceous siltstone and a thin black shale grades into a limestone. All the beds are thought to belong to the "Wantage Formation" although the limestone could be the basal Jacksonburg Limestone.

Fossils have been ineffective in dating the "Wantage Formation". A slightly abraded conodont assemblage of Canadian age has been reported by Karlins and Repetski (1989) from the Stillwater section. This fauna yielded a spurious age because it represents a reworked fauna liberated from rocks of the Beekmantown Group. Repetski (1985) reports similar relations from northeastern Tennessee where abraded, slightly weathered conodont assemblages were obtained from reworked chert gravel and clay material representing eroded carbonate deposits on the Knox unconformity. Like the fauna recovered in New Jersey, the Tennessee conodont assemblage is much older than the basal unconformity deposits can be. The most reliable estimate of the age of the "Wantage" is bracketed by the youngest dolomite or limestone cobble in the Jacksonburg Limestone as identified by Savoy (1981)(early Whiterockian) and the oldest age represented in the Jacksonburg Limestone, which is either latest Blackriverian (Weller, 1903) or earliest Trenton (Miller, 1937). Therefore the age of the "Wantage" is Whiterockian to early Trenton. Further work is necessary to more closely date the "Wantage". Patchen and others (1985) correlates the "Wantage" with the "Pamelia Formation, green unit" of New York, thereby assigning a lower Blackriver age. This leaves a major time span of nondeposition or deposition and subsequent erosion between the "Wantage" and the Jacksonburg Limestone. As the Pamelia only outcrops in northcentral New York and has not been traced into New Jersey, a direct correlation seems inappropiate. Therefore introduction of a new formation is warranted.

The "Wantage Formation" commonly crops out in narrow, longitudinal bodies. Lithologic composition and sedimentary structures point to a fluvial depositional environment for the clastic-argillite components. The carbonate sequence is probably a shallow marine deposit. An interesting question relating to the shape of these bodies is: how did fold forms of Taconic age affect the deposition of the "Wantage" components. In order to reconstruct the Taconic geomorphology, the structural complexities of younger deformation events must first be removed from the encompassing rock bodies. These procedures are presented in detail by Herman and Monteverde (this volume). However restoration of the original fold and stratigraphic relations, is hampered by the common occurrence of shearing associated with Alleghanian thrust faulting along the contact between the "Wantage Formation" and the surrounding, more competent rocks. This is due to the competency contrast between the dolomites of the Kittatinny Supergroup and the argillites and limestones of the "Wantage Formation" and Jacksonburg Limestone. With the deformation effects of the Alleghanian orogeny removed, the "Wantage Formation" commonly retrodeforms to keels in synclinal troughs of Taconic age and as wedge-shaped deposits shed on the flanks of related arches. It is therefore assumed that open, broad folds on the platform shelf formed at an early time during the Taconic orogeny and coincided with the regional arching associated with the unconformity above the Beekmantown Group. During this erosional period karstification and a well developed soil profile formed on the subaerially exposed carbonates. Erosional lows formed along the flanks of arches and in the keels of synforms. With further erosion, longitudinal alluvial channels were cut into these troughs, and the "Wantage Formation" was deposited. As the seas of Blackriver to Trenton age rose, transgressive wave action may have winnowed away some fluvial beds before laying down the upper Wantage carbonate sequence or the basal beds of the Jacksonburg Limestone. This same wave action would have eroded the soil material from the weathered carbonates. This could explain the limited distribution of the preserved bodies of the "Wantage Formation". The "Wantage" also occurs as depression (doline) and sinkhole infills. Here the outcrop pattern is smaller and more wedge-shaped with more draping of beds on the depressions. A block diagram depicting the proposed depositional environment for the "Wantage Formation" is shown in figure 6.

Related Paleokarst Deposits

Paleokarst deposits both on the unconformity surface and those within the Beekmantown Group which are found in New Jersey are similar to those described elsewhere in the central and southern Appalachians by Callahan (1968), Fagan (1969), Harris (1969), Smith (1980), Mussman and Read (1986), and Mussman and others (1988). Similar deposits are also reported in Canada by Desrochers and James (1988), Kearns and Donaldson (1988), and in the Leadville district of Colorado by De Voto (1988). These deposits are mostly paleosolution breccias in sinkholes and caves, and intraformational breccias (fig. 7).

Sinkholes and dolines are characterized by sharp and irregular contacts between the infilled material and the host rock although gradational contacts can be seen. The solution breccia may grade laterally through rotated block breccia, into open-network breccia and fitted "crackle" breccia until competent rock is reached (Choquette and James, 1988). Markewicz and Dalton (1977) describe an occurrence of a solution breccia 300 to 400 feet (91-122 m) wide and several hundred feet deep with this type of gradational wall rock contact. Angular to subangular blocks from the host beds and from collapsed overlying units are the major clast constituents. Matrix material ranges from a medium- to dark-gray, fine- to medium-grained dolomite, and the cement can range from a white, medium- to coarse-grained calcite to a green argillite depending on the location. The green argillaceous material is considered an infilling of a collapsed soil horizon. Sorting is extremely poor. The contacts are generally perpendicular to bedding but can branch out and become horizontal at depth. When contacts are

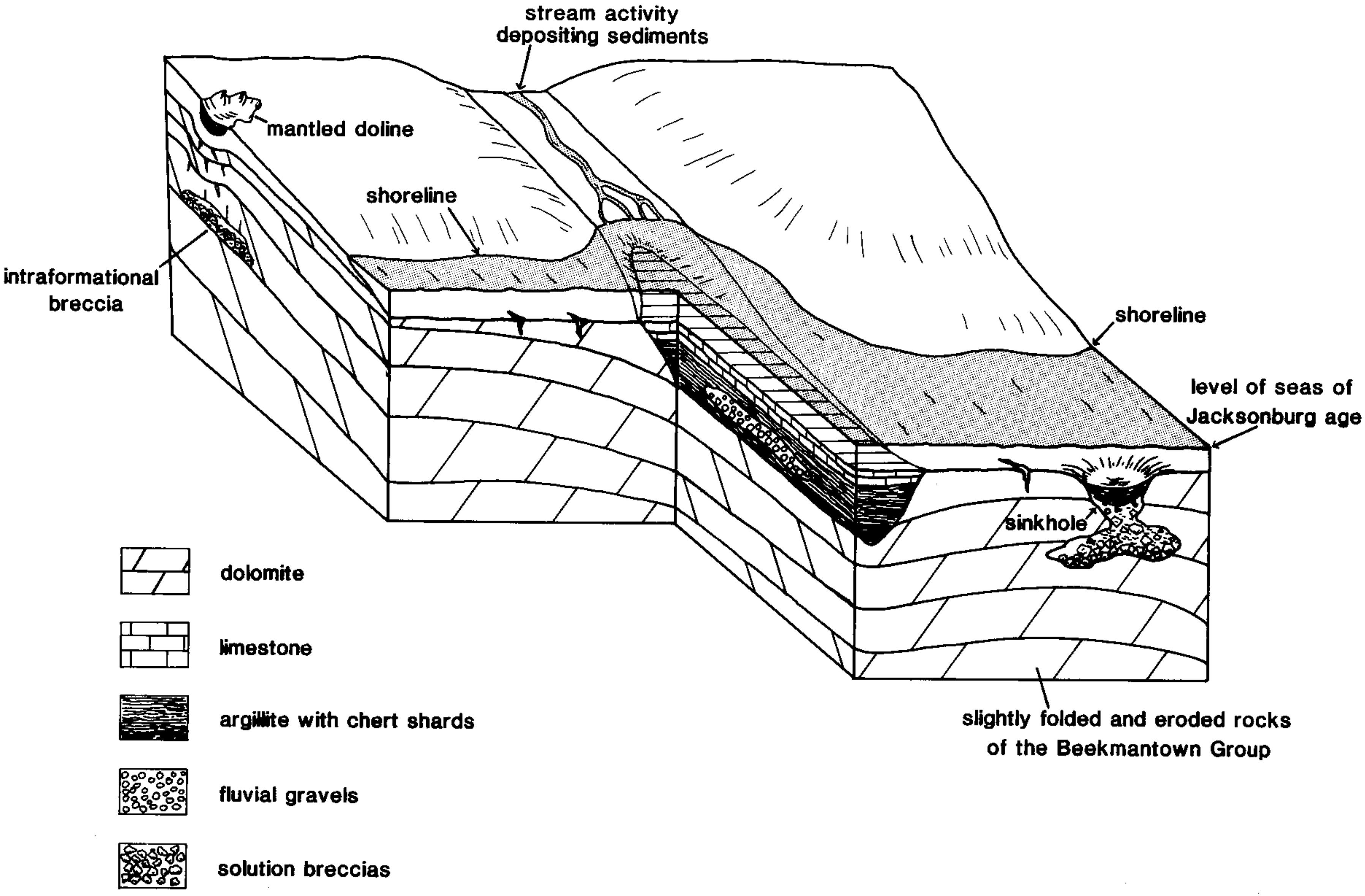

Figure 6. Block diagram showing proposed environment of deposition for the "Wantage Formation".

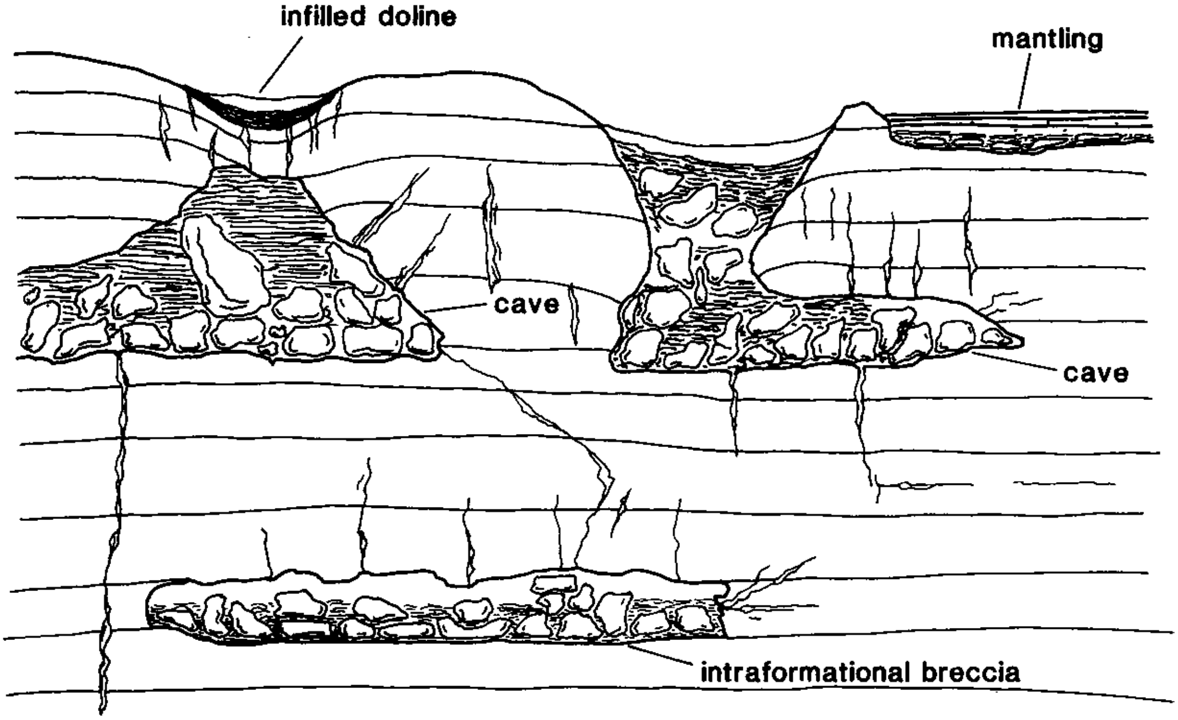

Figure 7. Generalized sketch of types of paleokarst deposits.

Figure 8. Line drawing (from photograph) showing paleosinkhole in Alpha, NJ. Infilling of eroded area interrupts bedding dipping from upper left to lower right.

horizontal a roof commonly occurs and the body is classified a cave. Figure 8 shows a small infilled sinkhole of Lower Paleozoic age exposed in a railroad cut in the town of Alpha, Warren County.

Caves described by Mussman and Read (1986) for the central Appalachians are thin, sheet-like to irregular bodies, both perpendicular and parallel to bedding. They have sharp and irregular contacts with the host rock. In New Jersey, caves contain angular blocks of the host unit in a clast- to matrix-supported breccia. The matrix can range from a fine- grained detrital dolomite to a white, medium- to coarse-grained calcite or dolomite cement. Matrix material may be well sorted as seen elsewhere in the central Appalachians (Mussman and Read, 1986). Caves are usually not visibly connected to the unconformity surface.

Intraformational breccias are the host horizons of some common secondary ore deposits in the central Appalachains. Mussman and Read (1986) suggest that this type of breccia has a regular basal contact and irregular lateral and upper contacts. The main breccia can grade into a rubble breccia, into a crackle breccia, and finally into the host rock (Keating, 1983). All breccia clasts are angular and unsorted. Matrix material is dominated by medium- to coarsely-crystalline calcite and dolomite. Frequently the cement can be mineralized as in the Friedensville zinc deposit in Friedensville, Pennsylvania where a honey-colored sphalerite occurs (Callahan, 1968). Markewicz and Dalton (1977) describe a breccia of this type with a light-gray crystalline calcite and/or dolomite cement as common in the middle of the lower part of the Beekmantown Group.

Conclusions

In summary, the "Wantage Formation" is a paleokarst deposit as described by Choquette and James (1988). As suggested by Markewicz and Dalton (1977) it can directly fill sinkholes and dolines which occurred as lows on the erosion surface. Field data also suggests that the "Wantage" occurs as a fluvial deposit in erosional valleys related to the unconformity surface on top of rocks of the Beekmantown Group. It is suggested that these valleys formed in synclinal troughs and are on the flanks of neighboring arches, both consequences of Taconic orogenesis. Other paleokarst features related to the "Wantage Formation" include sinkholes, caves and intraformational breccias, all of Middle Ordovician age. These other features occur as isolated wedge-shaped lenses and as elongated bodies. Generally the "Wantage Formation" consists of a thicker, lower, clastic- argillite sequence which locally grades upward into a carbonate sequence. Both components can however be interbedded throughout the formation. Locally the carbonate sequence is absent, due to either nondeposition or structural complexities. Source rocks for the "Wantage Formation" are local and contain carbonate soil material, resistant quartz sand and chert fragments;

locally subrounded dolomite cobbles and pebbles are preserved. The upper carbonate component is shallow marine in origin.

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Guide to field stops and road log for the Cambrian and Ordovician rocks of the Phillipsburg,NJ-Easton,PA area

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Guide to field stops and road log for the Cambrian and Ordovician rocks of the Phillipsburg-Easton area.

The following road log is for the Sixth Annual Meeting of the Geological Association of New Jersey. The trip begins at Lafayette College in Easton, Pennsylvania and proceeds with six field trip stops within the Lower Paleozoic carbonate units around the Phillipsburg, NJ-Easton, PA area. All the field trip stops are within the USGS Easton, NJ-PA 7-1/2' topographic sheet (Fig. 1). At each stop, a description of the lithostratigraphy will be given along with a scenario of the local structural relationship.

Stops 1 and 2, led by Gregory Herman, are located at newly exposed road cuts and give a good look at the structural features which formed during the Taconic and Alleghany orogenies. Donald Monteverde leads stops 3 and 5 which show the distinctive lithologic characteristics of the Allentown Dolomite through the upper part of the Beekmantown Group, including some paleokarst deposits. Stops 4 and 6 will be led by Richard Dalton and show both stratigraphic attributes of the Beekmantown Group and Jacksonburg Limestone and the structural relations, including a small horse related to some large-scale overthrust faults.

Please question us on any ideas you might have, as this will only help to further elucidate the geological synthesis of the region.

Mileage

0.0 Begin road log in front of the John Markle Administration Building and college parking deck at Lafayette College, Easton, PA. From the parking lot exit ramp, turn left onto High Street.

0.2 Turn right onto McCartney Street.

0.4 Turn right onto College Avenue and descend hill.

0.5 Outcrop of Allentown Dolomite on right side of road.

0.7 Stop light. Go under the Route 22 overpass.

0.73 At stoplight turn left onto Route 248 east.

0.9 Turn left onto the Route 22 eastbound entrance ramp.

1.0 Cross the Delaware River.

1.3 Outcrop on right is the last stop of the field trip.

1.5 Outcrop of the Beaver Run Member of the Ontelaunee Formation.

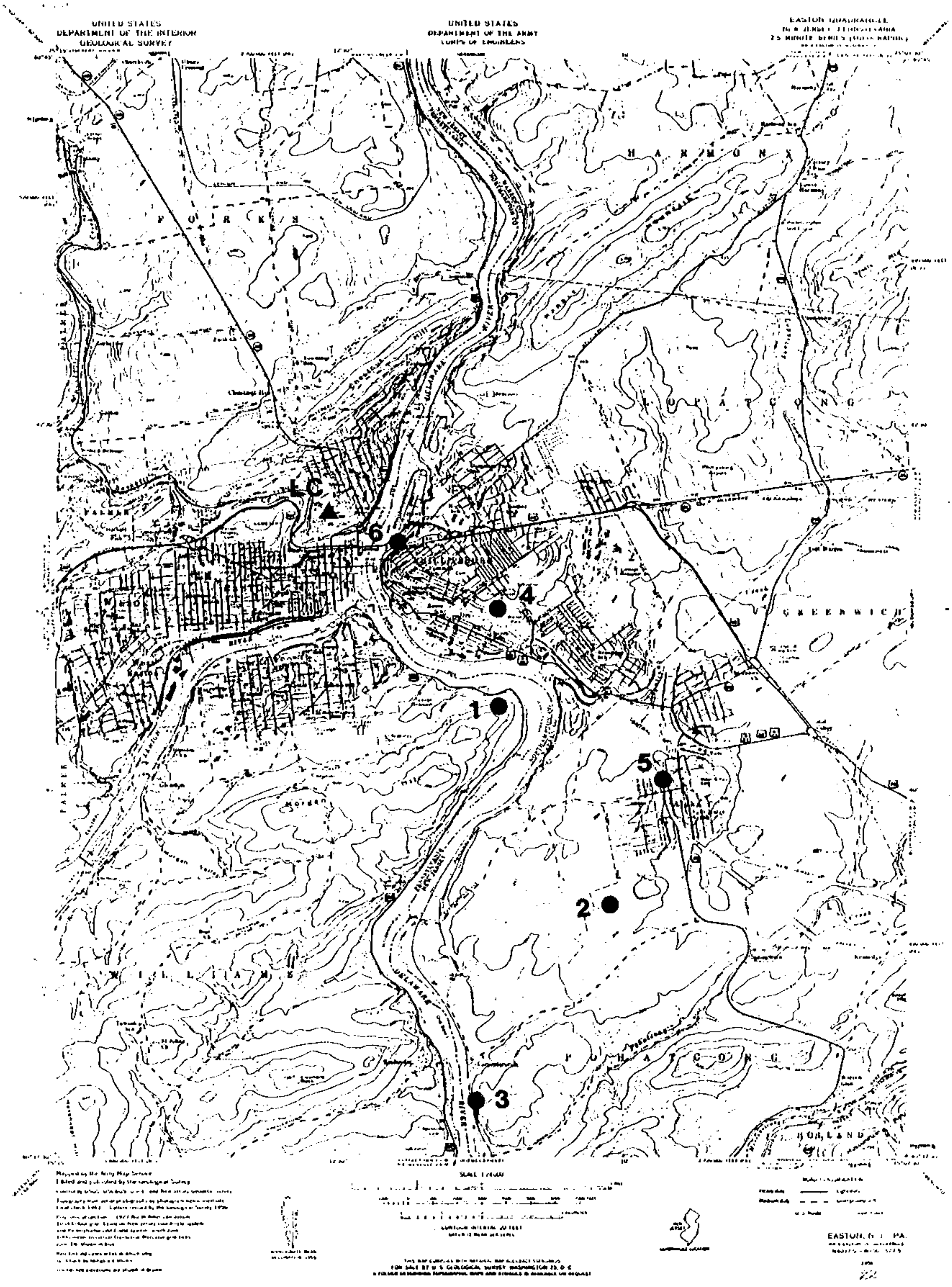


Figure 1. Location map of the field trip starting point, Lafayette College (LC), and the 6 field trip stops.

2.6 Continue straight through intersection and stay in the two right lanes.

3.2 Bear right at "Y" intersection and continue on Route 22 east.

4.1 Passing over route of the old Morris Canal.

4.5 Vista of Scotts Mountain on the left side.

4.9 Turn right at the traffic light onto Route 519 south.

5.7 At red blinker light turn right onto New Brunswick Avenue. This is still Route 519 south, and is also Alternate Route 22 east.

5.9 At traffic light, leave Alternate Route 22 east and turn right onto Third Avenue. This is still Route 519 south.

7.4 At small "Y" intersection bear right off Route 519 and onto small dead-end road (old Snydersville Road before Route 78 construction). This leads to the Route 78 new construction entrance.

7.5 Follow road to the right.

7.6 Turn left and proceed through the construction gate onto Route 78. Follow Route 78 to the west.

8.1 Pass outcrops of Jacksonburg Fm. which will be STOP 2.

8.9 Outcrops of Allentown Dolomite.

9.1 Passing over the covered continuation of the Brass Castle thrust fault.

9.5 Exposures of the Allentown Dolomite.

9.7 Begin crossing the Delaware River.

10.1 STOP 1

Leader - Greg Herman

Location - Morgan Hill, Pennsylvania; Route I-78 roadcut directly south of Easton and west of the Delaware River.

Geologic Setting - Morgan Hill is the Proterozoic core of a large anticlinorium flanked by Lower Paleozoic cover-layer rock (Pl.2a). The core of the anticlinorium is breached by the current land surface and shows the Morgan Hill shear zone (Drake, 1967). The Lower Paleozoic rocks dip off the northeast-plunging termination of Morgan Hill. The recently completed Route I-78 roadcut trends across strike through the northeast end of the hill and exposes a cross-sectional view of the shear-zone tip- line and cover-fold relations.

Geologic Features - This roadcut exposes the basal Paleozoic stratigraphic sequence and makes it possible to observe how the geometry and mineralogy of basement deformation zones result in tip-line cover-layer folds (Tip line -- A line showing the perimeter of a solitary thrust (fault) surface in a three- dimensional view (Boyer and Elliot, 1978)). The basement deformation zones are brittle-ductile shear zones that also cut the Hardyston Quartzite and Leithsville Formations and are therefore Paleozoic (or younger) in age. The stratigraphic and structural relations in the roadcut are depicted in Figure 2.

The nonconformity between the Paleozoic rocks and the underlying Middle Proterozoic basement rocks is exposed at three locations along the upper-level cut (eastbound traffic lane) and two in the lower cut (westbound lane). Three of the five basement-cover contacts are modified by shear strain. The remaining two contacts appear to be relatively unstrained and clearly show the Proterozoic/Paleozoic nonconformable contact. The lower one of these two exposures (in the westbound, lower cut) contains a complete section of Hardsyston Quartzite with both upper and lower contacts. The Hardyston Quartzite is a brown, silty, very fine grained sandstone that grades upward to a medium- to thick-bedded, quartz-pebble conglomerate and medium- grained quartzite. The lower silty facies also contains disseminated angular grains of medium- to coarse-grained quartz sand and pebbles as much as 2 cm. wide, abundant zircon, and dark greenish-gray, chloritic cleavage selvages. In the lower roadcut the upper Hardyston is in abrupt contact with the overlying Leithsville Formation. A pebble-conglomerate quartzite grades sharply upward into thin- to medium-bedded dolomite mudstone with lenses of disseminated quartz sand. The Hardyston is generally coarser and more strongly cemented higher in this lower sequence.

The nonconformable basement-cover contact is also preserved in the northernmost cut of the eastbound lane where only the basal Hardyston bed is exposed in contact with basement. Large detrital pebbles of radioactive monazite were identified here along with abundant zircon (Karl Muessig, N. J. Geol. Survey, oral communication, September 1, 1989). The remaining basement- cover contacts are modified by chlorite-grade cleavage shear zones with abundant sulfide minerals and slip lineations. The sulfide mineral veins and slickensided shear planes are common in the lower level Hardsyston-Leithsville sequence.

The Proterozoic geology is varied. The basement was mapped by Drake (1967) as microperthite alaskite that locally contains unmappable bodies of amphibolite, hornblende granite, and potassic feldspar gneiss. The roadcut, which was unavailable during Drake's earlier study, shows abundant quartz-feldspar gneiss with localized biotite-rich facies. Later geologic features include cross-cutting pegmatites and abundant evidence of a ductile-brittle deformation event. The evidence includes country-rock brecciation, shearing, assimilation, and matrix recrystallization involving microcrystalline bitotite, quartz, hematite, microcline feldspar and sulfides.

The upper-level roadcut shows a conjugate set of broadly curving, brittle-ductile shear-zone structures in the basement core of the overlying cover-layer folds that plunge northeastward at the end of the hill (Pl.2a). The basement shear zones consist of swarms of slip cleavage and crushed basement rock. Abundant cross-strike slip lineations occur on the slip planes. Pale greenish-gray slip-cleavage selvages contain microcrystalline muscovite and quartz identified by X-ray diffraction analysis (Karl Muessig, N. J. Geol. Survey, written communication, September 1, 1989). Chloritic, iron-stained shear fractures systematically separate the rock between shear zones. Mineral lineations consisting of stretched quartz and feldspar are restricted to the cores of the larger shear zones, indicating limited mylonitization. In thin section, the brittle-ductile shear zones show mainly grain fracturing of quartz and feldspar porphyroclasts with tails consisting of mica and lesser quartz. Dynamic recrystallization of quartz and mica also occurs along brittle grain partings. Quartz porphyroclasts show undulatory extinction and subgrain boundaries. Micaceous tails also occur on biotite porphyroclasts.

The set of shear zones shows a conjugate geometry in the roadcut cross section (Fig. 2). The dominant shear zone strikes northeast and dips southeast (Figs. 2, 3); it shows reverse slip by cleavage drag, and by slickensided shear-plane relations. Subordinate, antithetic shear-zone sets dip east-northeast at low angles and show normal slip components. Other subordinate shear zones display synthetic, undulatory, high-angle dips with both normal and reverse slip components (Fig. 2). The primary, synthetic shear zones commonly splay into antithetic footwall shear zones or rotate upward into cross-strike and northest- dipping shear zones. Stereographic projection of a set of shear- zone compass readings and cover-fold relations (Fig. 3) illustrates the structural link between the basement shear zones and cover folding. The cover-layer fold-axis orientation is close to the dip orientation of the subordinate shear-zone set, whereas the strike of the dominant, conjugate shear set is close to the fold trend.

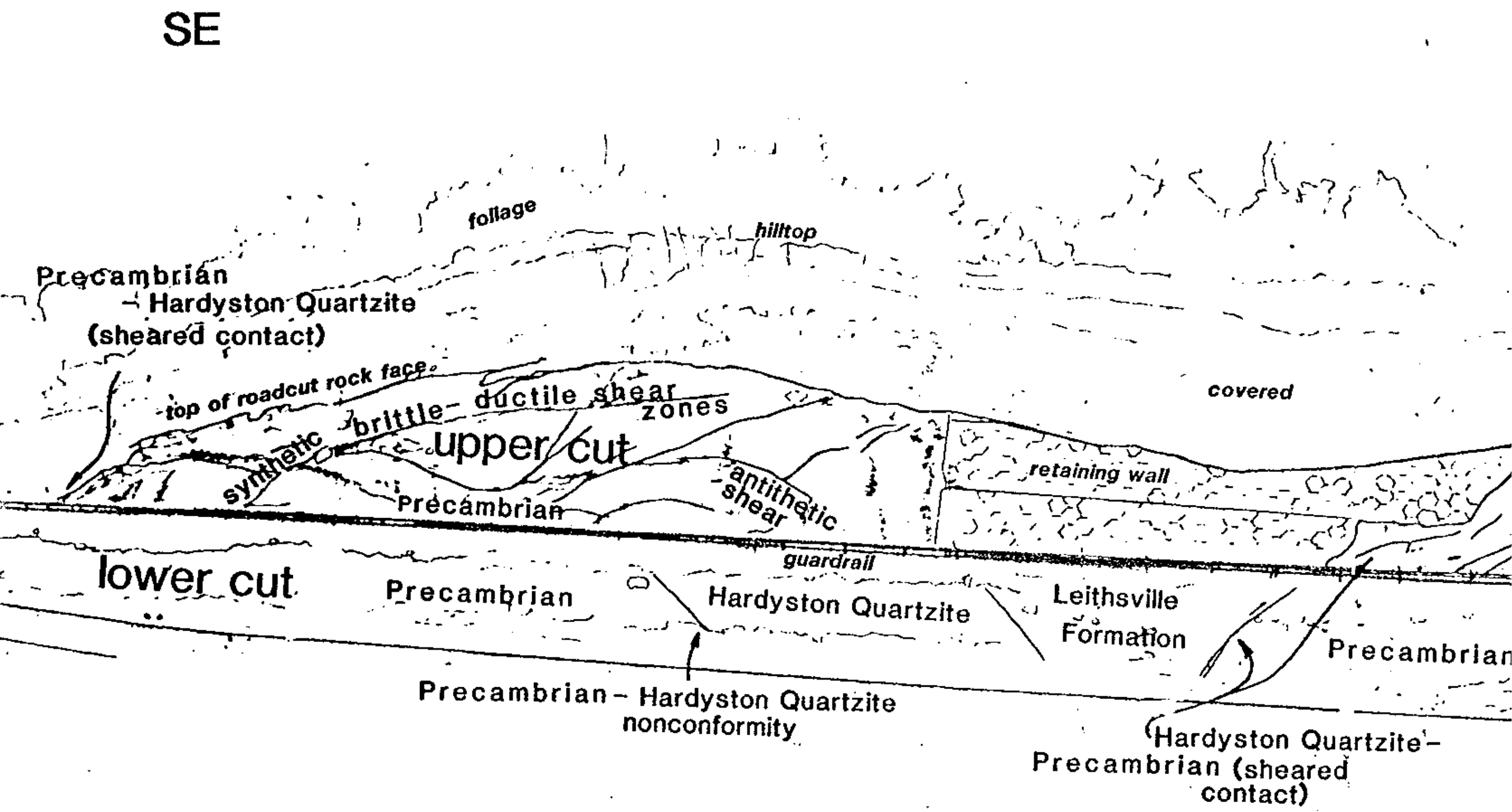
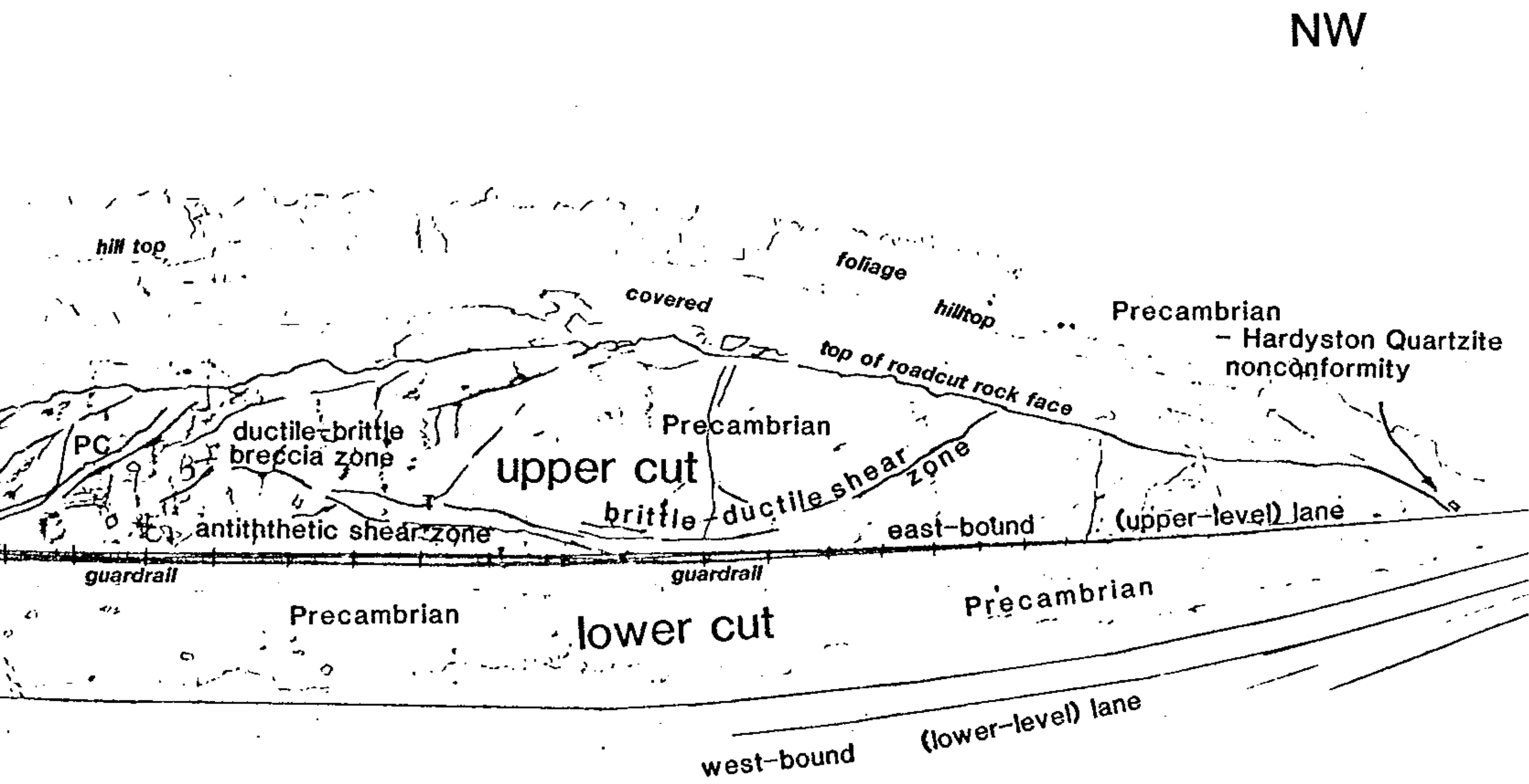


Figure 2 - Sketch of the Morgan Hill I-78 roadcut facing west-southwest. Guardrail posts are approximately 5 meters apart (for scale). The basement - Hardyston Quartzite is shown at three locations in the upper cut and two in the lower, respectively.



SCALE: guardrail posts are set approximately 5 meters apart.

The primary brittle-ductile deformation zones in the basement rocks are shown in the upper cut. They are shown cutting the earlier ductile-brittle deformation zone indicated in the northwest block.

Figure 3a

Figure 3b

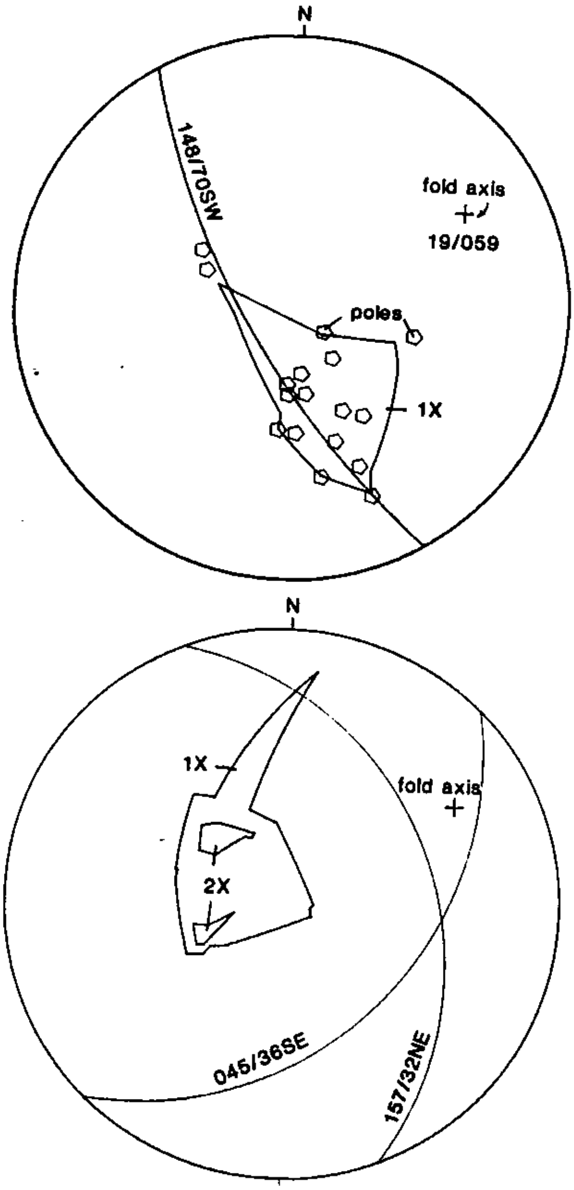


Figure 3 - Lower hemisphere, equal-angle stereographic projections showing the structural link between the conjugate basement shear zones and the cover-layer fold plunging northeast from the I-78 Morgan Hill roadcut. Diagram (a) illustrates the derivation of the cover-layer fold axis orientation plunging northeast away from Morgan Hill. The cover-layer fold axis is the pole to the great circle fit to 17 bedding readings that envelope the northeast termination of Morgan Hill. Diagram (b) shows the fold-axis orientation relative to the most common brittle-ductile shear zones in the I-78 roadcut. The svoronoi contouring method was used to derive the contoured maximums for both plots. The most common shear zones are the great circles corresponding to the 6X maximums for a plot of 18 shear zones randomly sampled from the upper roadcut (Fig. 2). The structural link between the conjugate shear zones and the cover fold is illustrated by the close agreement of 1) the orientation of the cover-layer fold axis with the dip orientation of the cross- strike shear-zone set, and 2) the close agreement between the strike of the southeast-dipping shear-zone set and the trend of the fold axis.

Some smaller, synthetic shear zones cut and offset earlier antithetic shears. Brittle, en echelon quartz-vein arrays also cut all earlier fabrics in the basement rock. These structures could result either from progressive imbricate processes in the footwall or from structural overprinting of separate tectonic events. The relative timing of structures at Morgan Hill is evident but the absolute age of the Paleozoic brittle and brittle-ductile deformation has not been established. We believe that the basement shear zones and attendant cover folds are strain features of the Taconic orogeny. This is based on the following observations: 1) The cover-layer folds are similar in geometry to other F1 folds in the Kittatinny Valley (Herman and Monteverde, this volume), 2) the chlorite-grade, brittle-ductile shear zones are comparable in deformation grade to other faults assigned to the Taconic orogeny in the Highlands-Kittatinny Valley (Herman and Monteverde, this volume), 3) the Morgan Hill shear zone lies in an intermediate position between the traces of two Alleghany thrust faults. However, localized reactivation or tectonic overprinting may be associated with reconnecting or isolated splay faults originating from the bounding regional thrust faults.

Reboard buses and continue with field trip.

10.2 Returning across the Delaware River on Route 78.

12.1 STOP 2

Leader - Greg Herman

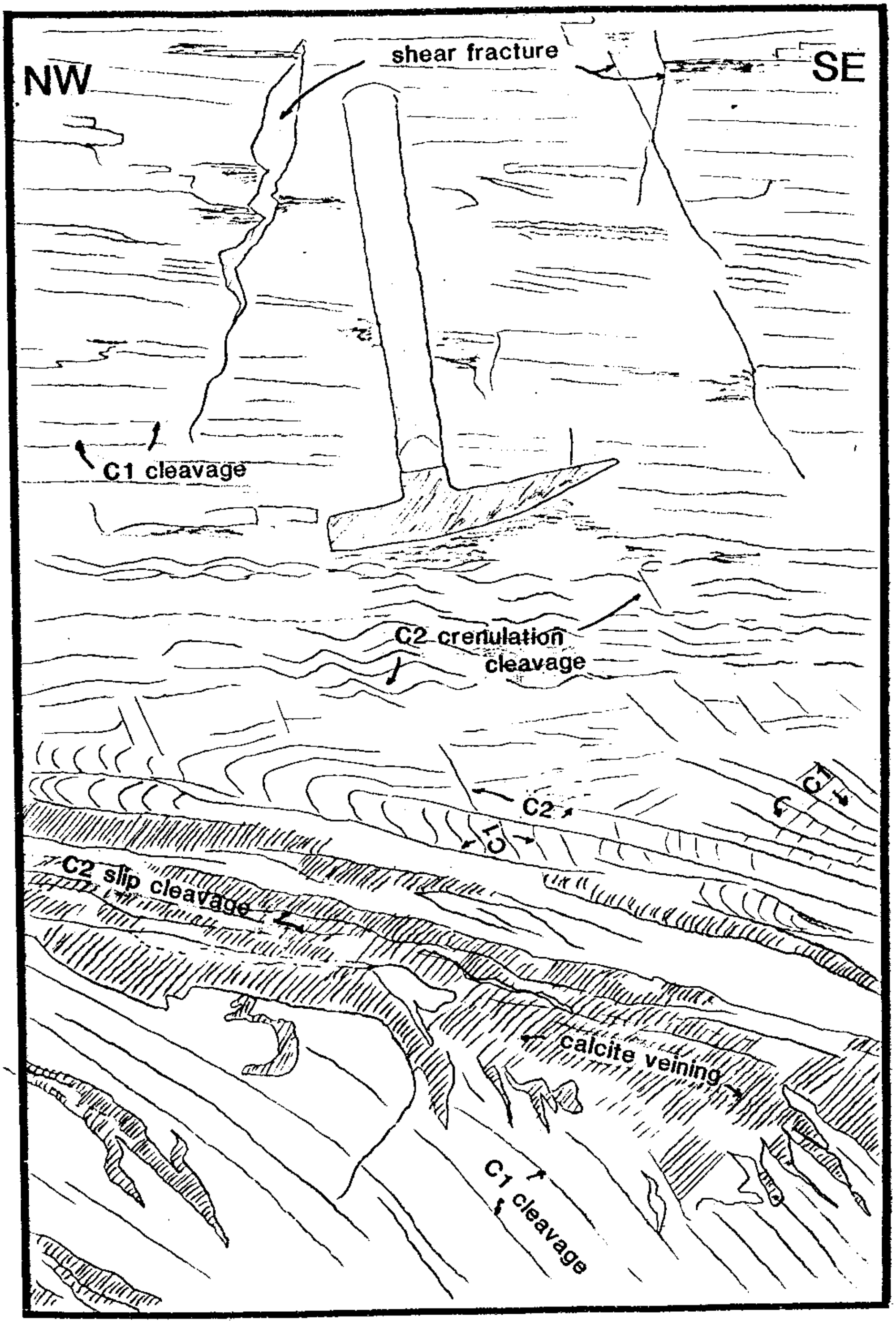
Location - Route 78 west-bound lane roadcut 0.5 mile west of the I-78 entrance from relocated Snydersville road (Fig. 1, Herman and Monteverde, this volume, Pl. 2a).

Geologic Setting - This roadcut exposes the Jacksonburg Cement Rock Member (Drake, 1967) in the hinge area of the Alpha syncline (Pl.2a). The Jacksonburg Limestone is the youngest Ordovician Limestone and caps the Kittatinny Supergroup. The syncline was previously exposed directly northeast (Pl. 2a) in two large quarries from which high calcium (70 - 82 percent $CaCO_3$) limestone was quarried near the turn of the century (H. B. Kummel, 1900, recorded permanent notes, on file at the N. J. Geol. Survey, Trenton, New Jersey). In general, these cement beds form a synclinal structure that is locally overturned. Subsequent to the folding it was crushed and crumpled by overthrusting. The Jacksonburg is sparsely fossiliferous and the most apparent fossils (crinoid columnals) are severly stretched and thinned by pervasive cleavage.

Geologic Features - Both limbs of the overturned syncline are exposed here. The northwest limb dips regularly southeastward at angles of 20° - 40°, subparallel to the early (C1) slaty cleavage. The C1 cleavage fabric is the most apparent parting surface and is easily mistaken for bedding. Bedding is marked by brownish-gray laminas within mostly dark-gray shaly limestone beds. The hinge area of the regional syncline is tight, and occurs midway in the cut where a thick saprolite interval dips moderately southeastward and extends from the top of the cut down to the road level. The C1 cleavage is subparallel to the fold axial surface. The southeast limb is more severly crumpled, crushed, and sheared than the northwest one, and contains very steeply-dipping bedding traces that are locally southeast-dipping and overturned.

The mesostructures in this outcrop are very complex. Besides the C1 cleavage, C2 cleavage sets also occur (Fig. 4) together with multiple bedding and C1 cleavage folds, slip lineations, and mineralized veins and vein arrays. In general, an early synclinal fold structure (F1) and attendant C1 cleavage have been strained by subsequent thrust faulting that produced the C2 cleavage and locally reactivated C1 cleavage planes (Fig. 5). This later deformation involved the interaction of the C1 and C2 cleavages and vein arrays in conjugate shear zones that stretched and thinned the overall sequence. The geometry of the conjugate shear sets involves a dominant northwest-verging, synthetic shear zone set with intervening antithetic conjugate sets showing normal dip-slip components (Fig. 6). The thrust faults that produced these strain features are probably the Kennedys or Musconetcong overthrusts located to the southeast (Pl. 2a). However, local overthrust shearing may also occur along the axis of the regional syncline as noted by H. B. Kummel in 1900 (recorded permanent notes, N. J. Geol. Survey, Trenton, New Jersey) from inspection of the afforementioned quarries.

Figure 4 - Sketch of mesostructure details in the Cement Rock Member of the Jacksonburg Limestone from the Alpha syncline (Plate 2a). The sketch illustrates the relation between C1 and C2 cleavage, calcite veining and shear fractures from the upright, northwest fold limb. A synthetic (southeast dipping) shear zone is marked by the abundant calcite veining and C2 slip cleavage in the lower third of the sketch. The C1 cleavage that bounds the shear zone shows drag indicative of overthrust shearing. The C2 slip cleavage in the shear zone dissipates upward towards the middle of the sketch into C2 crenulation cleavage which shows a sense of rotation compatable with the adjacent shear zone. Shear fracture joints are developed at the outer margin of the lower shear zone, which emphasizes the complex evolution of a shear zone and the diversity of accompanying mesostructures.


NW
shear fracture
SE
C1 cleavage
C2 crenulation cleavage
C2
C1
C1
C2 slip cleavage
calcite veining
C1 cleavage

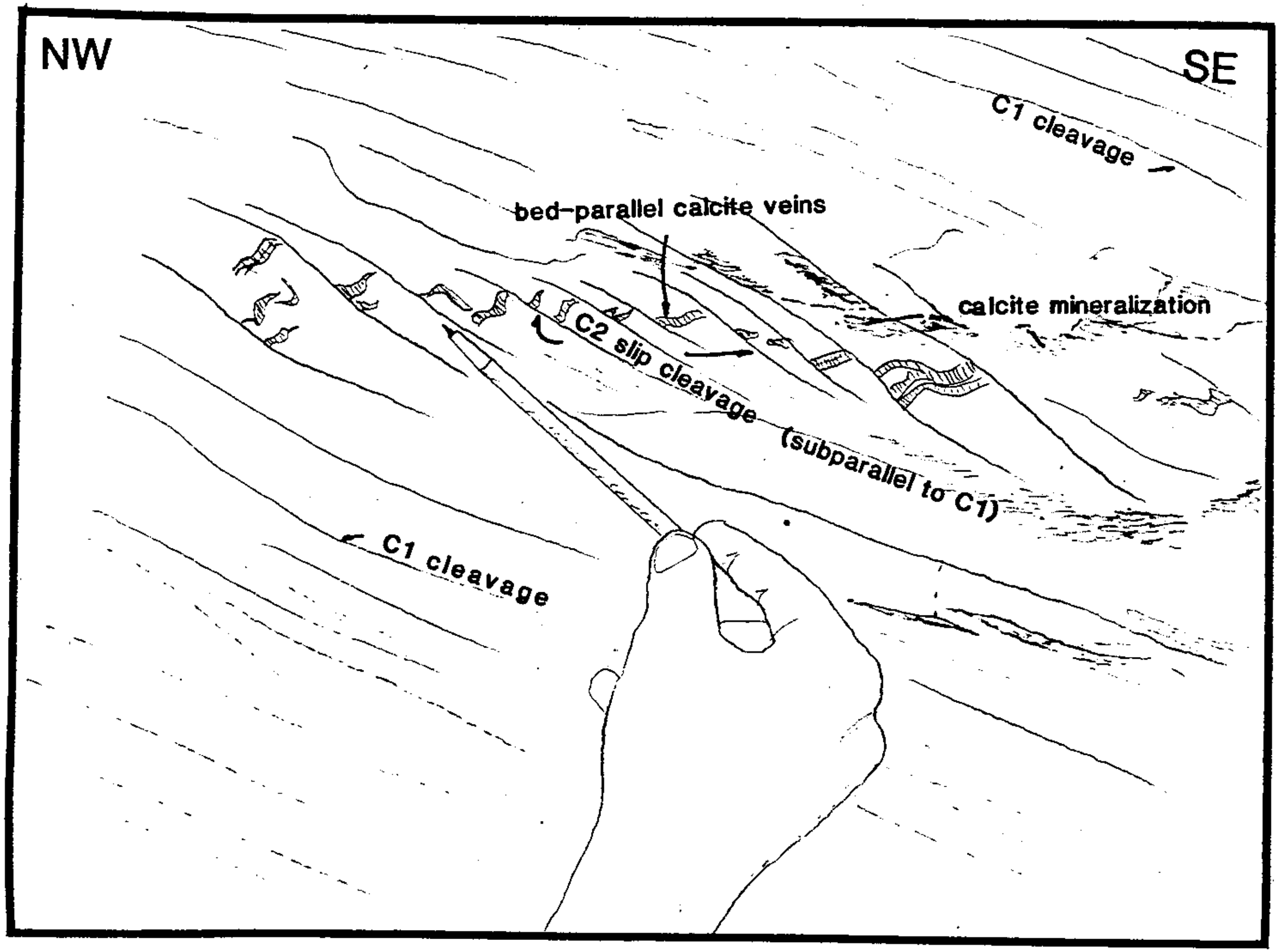


Figure 5 - Sketch of normal-slip C2 cleavage in the Cement Rock Member of the Jacksonburg Limestone from the southeast fold limb of the Alpha syncline (Plate 2a). The normal-slip cleavage is most apparent where an earlier set of calcite veins acts as strain markers. The early vein set is subparallel to bedding and probably originated as mineralized, slickensided bedding planes related to flexural slip folding processes accompanying the development of the Alpha syncline; a probable F1 regional structure. Subsequent regional overthrusting redeforms these F1 structures. This normal-slip C2 cleavage shows that the early C1 cleavage is locally reactivated. The strain effect is flattening and stretching of the interval between bounding shear zones having opposite sense of shear (overthrusting). This relation has been reported from microscopic to megascopic scales in other tectonic environments (see discussion in Herman and Monteverde, this volume).

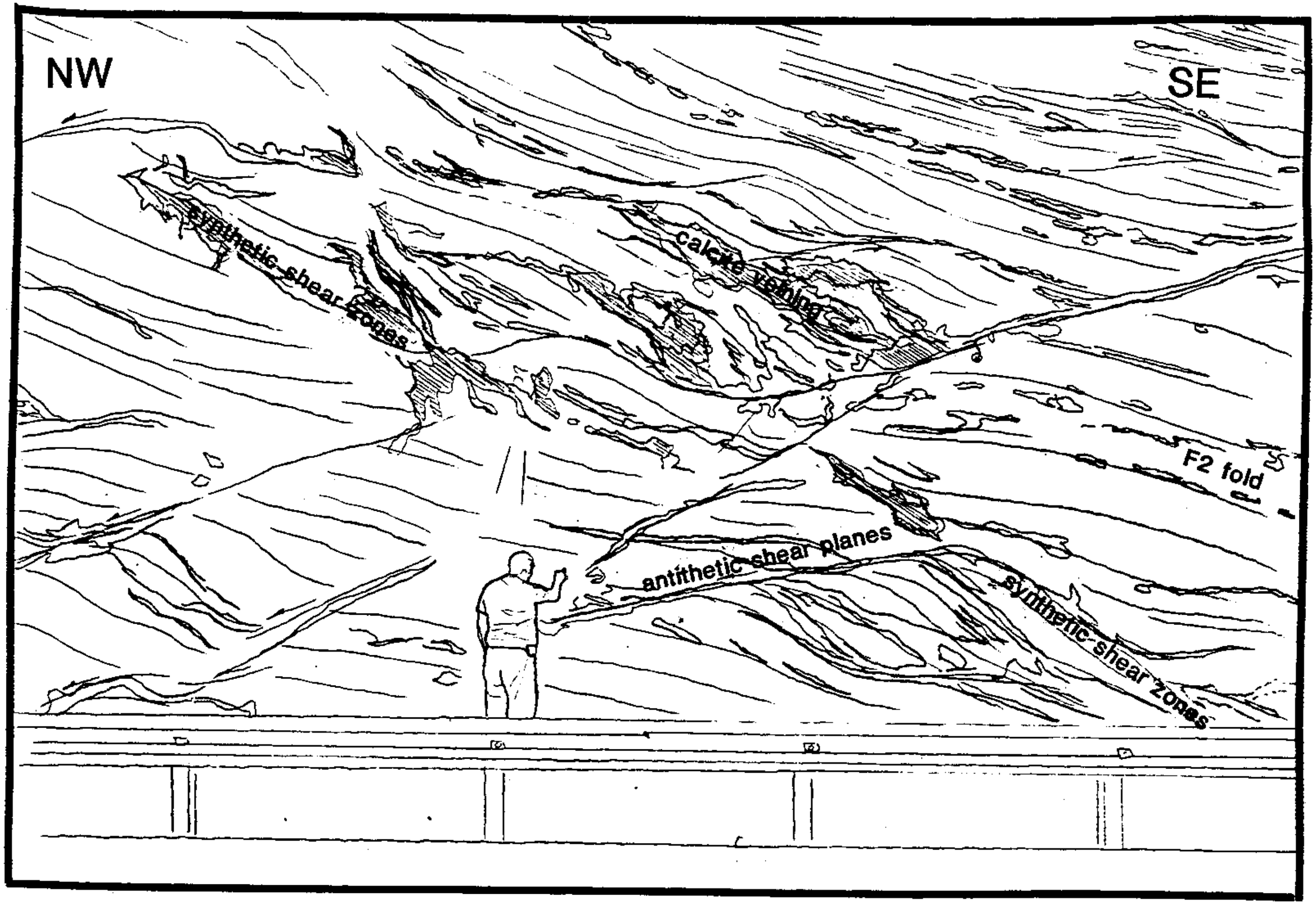


Figure 6 - Sketch of conjugate C2 cleavage relations and mineral vein arrays in the Cement Rock Member of the Jacksonburg Limestone from the northwest limb of the Alpha syncline (Plate 2a). The antithetic (northest-dipping), normal-slip shear zones dip moderately to the left and form an acute angle with the synthetic (southeast-dipping) shear zones. The synthetic shear zones are marked by the calcite veins, vein arrays, and C2 slip-cleavage shear zones shown in detail in Figure 4.

Reboard buses and continue with trip.

12.6 Turn left from Route 78 and go through the construction gate. Turn left again.

12.8 Follow road to the left.

12.9 At stop sign turn right and follow Route 519 south.

12.0 Proceed under the Route 78 overpass.

13.2 Turn right onto Snydersville Road (Warren County Route 635).

14.3 Small ridge to right is a continuation of the Jacksonburg Limestone seen at STOP 2.

14.6 At stop sign turn left onto Carpentersville Road.

14.7 Cross over small stream; a privately owned fish hatchery is on the right.

14.9 STOP 3.

Leader - Donald Monteverde

Location - This stop is located on Carpentersville Road, just south of the town of Carpentersville in Warren County (Herman and Monteverde, this volume, Plate 2a). The road parallels the Delaware River.

Geological Setting - In this region, south of the Wisconsin terminal moraine, outcrops are scarce. This makes a location such as this, with more than one thousand feet of almost continuous outcrop exposing the Allentown Dolomite and the Beekmantown Group, exceedingly important. Various geologists (Kummel, unpublished field notes and map, beginning about 1900, Zadnick, 1960, Hobson, 1963) have selected this series of outcrops for study in attempts to characterize the Kittatinny Supergroup. Drake (1967) has previously mapped this area. Still recognizable red paint markings from an unknown scientist measure the footage northwestward from the stratigraphically highest observed stromatolite colony, the Allentown-Beekmantown contact of Hobson (1963), which extends to the end of the exposure delineating the thickness of the Beekmantown Group.

Structurally, this belt of carbonates forms the overturned southeast dipping limb of the northeast trending Alpha syncline (Herman and Monteverde, this volume, Plate 2a). Evidence of the overturned nature of the rocks includes graded and cross bedding, stromatolites, bedding scour marks, the direction of stratigraphically younger rocks, and bedding-cleavage relationships. STOP 2 is within the core of the Alpha syncline.

Geologic Features - The distinctive features of the Allentown Dolomite observed here include: cross bedding, stromatolites, edgewise conglomerate, oolites, floating quartz sand in a fine- grained dolomite, and the medium-bedded quartzite layers occurring at the Allentown-Beekmantown contact. The dolomites of the Allentown near the contact are predominantly medium to thick bedded with local zones of fine laminations, fine to medium grained, and medium- to dark-gray. The actual contact of the Allentown with the Beekmantown is marked by a distinctive resistent bed of quartzite, approximately 6 inches thick. The quartzite is the matrix of a conglomerate bed which contains dolomite rip-up clasts. This contact can be seen on the south wall of the third quarry from the north. It is near the red paint mark labeled "100".

The rocks of the Beekmantown Group exposed here include the Rickenbach and Epler Formations. As stated by Dalton (this volume) the Beekmantown terminology used by the U.S. Geological Survey differs from that used by the N.J. Geological Survey. The Beekmantown Group formational designations described here are those currently used by the NJGS. The Rickenbach Formation, which directly overlies the Allentown, is thin to medium bedded, fine to coarse grained, light- to dark-gray. In the lower member (Hope Member) several zones of thin, quartz sand stringers occur. Oolites, where present commonly are recrystallized. They can be identified on a polished surface but are masked in thin section and appear as an interlocking network of dolomite crystals. One bed of irregularly formed oolites can be seen in the middle of the third quarry. Above the quartzites, a thick-bedded, coarse- grained, light- to dark-gray sequence of dolomites occurs. These beds may be slightly fetid. Two series of black chert beds, which mark the Rickenbach-Epler transition as described by Markewicz and Dalton (1977) are located along the road on either side of the second quarry. The actual contact between these two formations occurs along the road just north of the second quarry near the red paint mark labeled "385". Based on the red paint marks, the approximate thickness for the Rickenbach Formation at this location is 285 feet (87 meters). The dolomite just below the contact is medium to thick bedded, fine to medium grained, medium- to dark-gray.

The overlying Epler Formation crops out along the road and up into the hillside across from the fish hatchery. The lower beds are thin to medium bedded, generally fine grained and medium- to dark-gray. Straight planar laminations are a distinctive characteristic of this lower sequence. A dolomite sequence which overlies the laminated sequence contains thin to thick bedded, medium grained, medium- to dark-gray, reticulate mottled beds, locally with quartz sand lenses interbedded with thin to medium bedded, locally laminated, fine grained, medium- to dark-gray beds. Elsewhere in New Jersey the reticulate mottled beds may grade laterally into limestone. Similar lithologic characteristics occur between the limestone and the dolomite with the addition of a green shale forming thin, discontinuous lenses in the limestone. The Epler Formation forms the remaining outcrops along this road cut. The contact with the overlying Ontelaunee Formation is not exposed here. Calculated thickness of the exposed Epler at this location is 327 feet (100 meters).

Structural features include spaced cleavage, bedding-plane slip, dolomite veins, dolomite-filled tension-gash arrays, and bedding-parallel stylolites.

15.1 Buses continue across tracks to small parking lot and turn around to retrace steps.

Reboard buses and continue with trip.

15.6 Turn right onto Snydersville Road.

16.6 Turn left onto Oberly Road.

18.2 Turn right onto Carpentersville Road.

18.35 At stop sign, turn left. This is still Carpentersville Road.

19.15 Train overpass.

19.2 Turn left at traffic light. This is South Main Street, also called Alternate Route 22 west.

19.4 Outcrop on right of Allentown Dolomite

20.0 At traffic light, turn right onto Center Street.

20.1 Train overpass.

20.2 Bear to the left onto Lime Kiln Road. There is a train overpass at this same spot.

20.25 Turn left onto Richard Road. This is the entrance to Walter Park.

20.45 LUNCH AND STOP 4

Leader - Richard Dalton

Location - Long exposure in cuts along the Delaware Lackawanna and Western Railroad in Phillipsburg, New Jersey.

Geologic Setting - (Figure 7)
Drake (1967, section C-C') mapped a tightly folded thrust fault here. Erosion of the overturned core has exposed the Epler Formation and Jacksonburg Limestone.

The Epler is exposed at the extreme western end of the cuts and the Ontelaunee is in contact with the Jacksonburg in the central part of the cut. The Knox-Beekmantown unconformity is exposed and is marked by many small-scale irregularities.

The green unit (Wantage) does not occur here; the Jacksonburg "cement limestone" was deposited directly on the Harmonyvale Member of the Ontelaunee.

Geologic Features -

1. The Knox-Beekmantown unconformity.

2. the thin wispy carbonaceous lines in the Harmonyvale, below the unconformity.

3. Fossils in both the Harmonyvale and the Jacksonburg.

Reboard buses and continue with trip.

20.6	Parking lot on right has an overview of the Morgan Hill road cut seen at STOP 1.
20.9	Turn right back onto Richard Road.
21.0	Turn left onto Lime Kiln Road.
21.05	Bear right onto Center Street.
21.1	Bear to the left and proceed under the train overpass. This is still Center Street.
21.2	At the traffic light, turn left back onto South Main Street (Alternate Route 22 east).
22.0	Turn right onto Carpentersville Road.
22.85	Continue straight but the road is now High Street.
23.65	Turn right onto First Avenue.

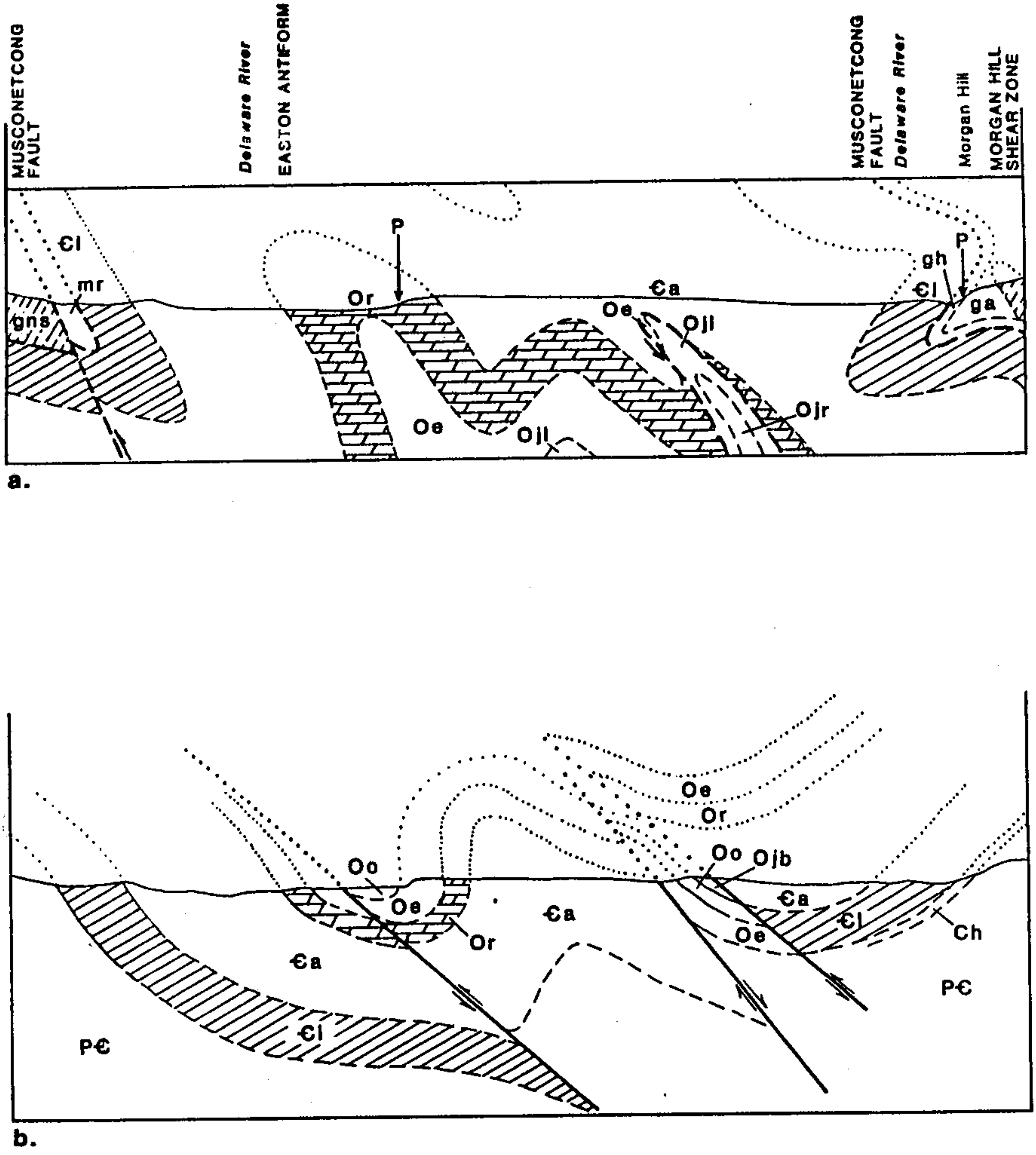


Figure 7. Cross-section **a.**(Drake, 1967), compared to cross-section **b.**(Dalton, 1989) (modified from Dalton and Markewicz, 1976) within cross-section C-C'.

Ojb - Jacksonburg undivided, Ojr - Jacksonburg cement rock, Ojl - Jacksonburg cement limestone, Oo - Ontelaunee Formation, Oe - Epler Formation, Or - Rickenbach Formation, Ca - Allentown Dolomite, Cl - Leithsville Formation, Ch - Hardyston Quartzite, ga - microperthite alaskite, gh - Hornblende granite, gns - sillimanite bearing gneiss, mr - dolomite and calcite marble

23.7 STOP 5

Leader - Donald Monteverde

Location - This stop is located on the Conrail train line which passes through the town of Alpha, Warren County. The exposure is north of the High Street overpass and south of the town baseball field, which is accessible from Francie Street (see Herman and Monteverde, this volume, Plate 2a).

CAUTION: THIS STOP IS ALONG A HIGH-SPEED CONRAIL TRAIN LINE ON A HEAVILY USED TRACK. WE ONLY HAVE A SHORT TIME FOR THIS STOP. THEREFORE PLEASE FOLLOW INSTRUCTIONS AND DON'T PROCRASTINATE WHEN YOU ARE ASKED TO RETURN TO THE BUSES.

Geological Setting - This belt of carbonates forms the fold limb between an anticline to the south and a syncline to the northeast (Herman and Monteverde, this volume, Plate 2a). Due north of this exposure is the Brass Castle thrust fault of Alleghanian age.

Geologic Features - The rocks exposed along the train grade constitute part of the youngest units of the Beekmantown Group in New Jersey. They consist of the two members of the Ontelaunee Formation: the Beaver Run Member and the conformably overlying Harmonyvale Member.

The representative dolomites of the Beaver Run which occur along this train grade are massive, medium to thick bedded, medium to coarse grained, and medium- to light-dark-gray. Two distinctive characteristics are the strongly fetid nature of the coarse- grained dolomites and thick-bedded anastomosing, rugose black cherts. The black cherts occur in the middle of the member. They grade upward into medium to thick bedded, medium to coarse grained, dark-gray to black, fetid dolomite with a few black chert lenses. The contact with the overlying Harmonyvale Member is gradational, extending over a 20-foot (6-meter) interval where a medium to thick bedded, medium to coarse grained, dark-gray dolomite and medium bedded, fine to medium grained, medium-gray dolomite with wavy laminations is visible on weathered surfaces. The contact is placed where the volume of fine-grained, laminated dolomite is equal to, or predominates over, the medium to thick- bedded, coarse-grained, fetid dolomite. The calculated thickness for the exposed Beaver Run along the train grade is 103 feet (31 meters).

The rocks of the Harmonyvale Member at this location are dominantly medium to thick bedded, laminated, fine to medium grained, medium- to dark-gray dolomite. A few lenses of black chert and frosted quartz sand grains are interbedded with the dolomite. In addition a single 2-inch (5-centimeter)-thick bed of white porcelain chert occurs in the middle of the member. This chert bed is a zone of bedding slip which, it is suggested, formed synchronously with a thrust fault located 0.75 mile (1.2 kilometers) to the north of this stop. The dolomite locally contains small cross-bedded lenses which indicate right-side up. The calculated thickness of the exposed section of Harmonyvale along the train grade is 134 feet (41 meters).

In the northern section of the train grade several zones of paleokarst crop out (Fig. 8). These sinkhole deposits contain rotated blocks from the overlying beds which have slumped and fallen into the sinkhole opening. The dolomite collapse-breccia clasts are subangular to subrounded and unsorted. The matrix is unsorted and contains a mixture of quartz sand, dolomite and a well ordered mica, muscovite 2M (Karl Muessig, personal communication, 1989). This paleokarst deposit predates the previously mentioned thrust fault which occurs to the north of this stop. Deformational features attributed to this thrust event include the widespread occurrence of dolomite-filled veins which are prominent in this outcrop and increase in intensity towards the north; also localized spaced cleavage and crenulation cleavage. The veining has a consistent preferred orientation with respect to the bedding. In the paleokarst deposit this same veining can be seen to locally cut through a clast and enter into the matrix material. The lack of pervasive veining in the matrix is probably due to a difference in rheology between it and the host rock which consists of interlocking dolomite grains. The veining within the rotated collapse-breccia clasts maintains the same orientation as the veining in the host dolomite regardless of the orientation of the bedding laminations in the collapsed block. The matrix contains localized zones of cleavage, which is crenulated. This crenulation cleavage is related to the same thrust fault located to the north. The shiny cleavage surface is predominently composed of the same ordered mica found in the matrix, except that there is a larger component of the mica in the cleavage surface than the matrix (Karl Muessig, oral communication, 1989). Several grains of euhedral pyrite also occur on the cleavage plane. This dates the paleokarst deposit as older than the Alleghanian thrusting event (Herman and Monteverde, this volume).

Reboard buses and proceed with trip.

23.75 Turn left onto Morris Street.

23.8 Turn left onto Third Avenue. This, as before, is Route 519 north.

24.3 At traffic light, turn left back onto New Brunswick Avenue (still Rt 519 north).

24.6 At yellow blinker light bear to the left onto South Main Street.

25.2 Crossing trace of the old Morris Canal, Lock 10.

27.0 Crossing over the Con Rail train underpass.

Figure 8. Line drawing (from photograph) showing paleosinkhole in Alpha, New Jersey. Infilling of eroded area interrupts bedding dipping from upper left to lower right.

27.5 Turn right into the entrance to the Delaware Bridge Commission building.

27.6 STOP 6

Leader - Richard Dalton

Location - The large exposure just south of the Delaware River Bridge Commission office on Route 22 at Phillipsburg, NJ.

Geologic Setting - (Figure 7)
Drake (1967) mapped the rocks here as the Rickenbach and Allentown Formations and located the axis of his Easton antiform about 700 feet north of the exposures. Markewicz and Dalton (1977) subdivided these rocks into the Rickenbach, Epler and Ontelaunee Formations.

The contact between the Rickenbach and the Allentown is exposed about 1,000 feet south of the Bridge Commission office. From this point, almost continuous exposures lead to the Beaver Run Member of the Ontelaunee. A swarm of pegmatite dikelets has intruded the Rickenbach and the Epler. The relationship of the pegmatite orientation within the regional structural framework is shown in figure 9. The pegmatite is dominated by quartz and microperthite feldspar, with minor amounts of apatite, tourmaline and magnetite or hematite (Markewicz and Dalton, 1977).

Geologic Features -

A. Rickenbach Formation

1. Occasional dikelets
2. Relationship of dikelets to bedding

B. Epler Formation

1. Increase in number of dikelets as the Big Springs is approached
2. Cross-cutting nature of the dikelets
3. Contacts of the pegmatite
4. Highly altered nature of the Big Springs
5. Limestone bed

27.7 Turn left onto South Main Street.

27.85 At traffic light turn right onto the free bridge and cross the Delaware River again.

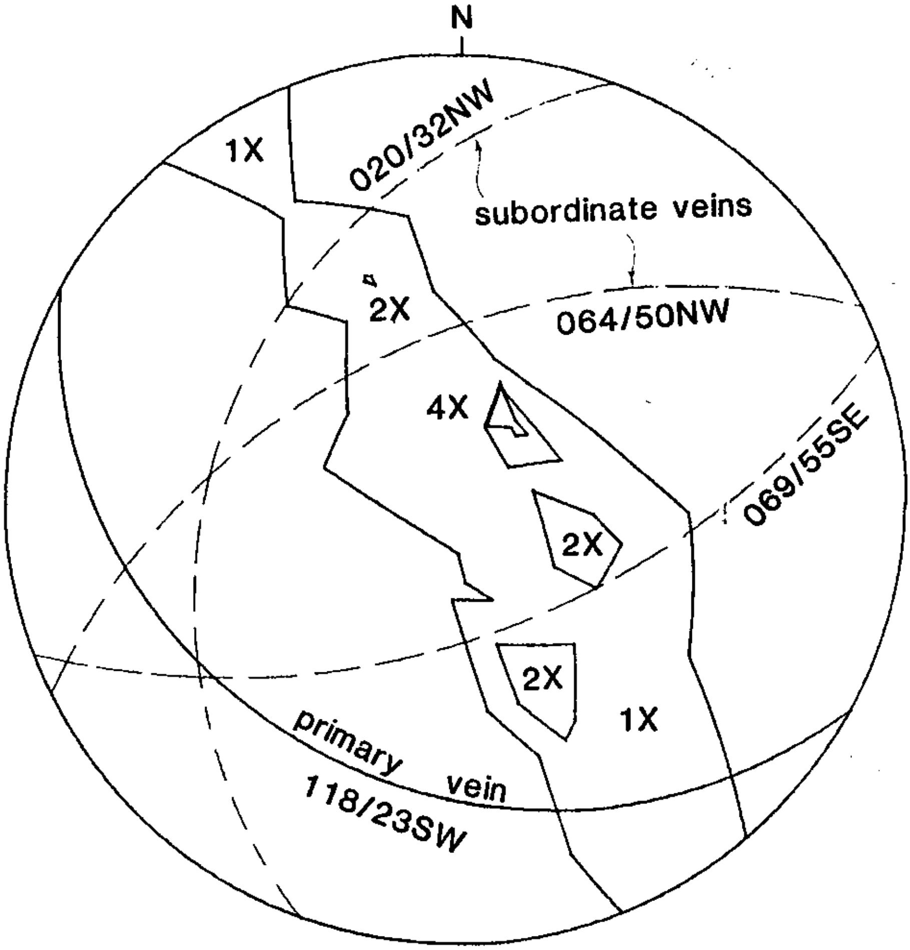


Figure 9 - Lower hemisphere, equal-angle stereographic projection of pegmatite veins in the Beekmantown Group (Ordovician age) in Phillispburg, New Jersey. The systematic orientation of the veins is shown by the contoured maximums of 22 vein readings taken over an outcrop span of approximately 200 meters. The 2X and 4X vein maximums are plotted as great circles. The contoured set of poles-to-veins defines a cross-strike girdle with a pole that plunges gently southwest, subparallel to the fold axes. These relations show compatable structural strain relations and suggest a kinematic link between cover layer folding and synchronous pegmatite development.

27.9 Welcome back into Pennsylvania.

28.2 At traffic light as you face the Easton monument, turn right onto the circle (Pompret Street). This is the only way you can go.

28.25 At the first light on the circle, turn right onto North Third Street.

28.4 Go under Route 22 ovepass.

28.5 Ascend College Avenue towards Lafayette College.

28.9 Turn left at first crossroad, McCartney Street.

29.1 Turn left onto High Street and enter Lafayette College.

29.3 Return to starting point and end of the field trip.

THANK YOU FOR COMING

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Glossary

For Sixth Annual Geologic Association of New Jersey Meeting

Arête - What the police will do to you if you try to drive home from the meeting while under the influence.

Col - A respiratory disease you can catch if someone at the meeting sneezes or coughs on you.

Concealed fault - The sneaky geologist who slinks away and melts into the crowd just as the tab arrives for those 17 beers and 11 highballs.

Glaciolackadaisical - A cold response to your paper by people who don't recognize its immense importance.

Infrared - What the early draft of your paper looks like after editors and so-called colleagues have a go at it.

Hogback - Somebody in the back seat of the car driving to or from the meeting who is too big or rude to give you enough room to sit.

Hot spot - We refuse to define this one on grounds of possible self-incrimination.

Isometric - Said of a geologist who has been behind a desk too long and is spreading out in all directions.

Miogeocline - My interpretation of the geologic history of the area; obviously a major contribution to earth science.

Eugeocline - Your interpretation; obviously invalid.

Morainic - A theory of another geologist which differs from yours.

Pahoehoe - A kind of Hawaiian extrusive that got cold and old but managed to get a song written about it anyway "Lava come back to me."

Palynomorph - What your body feels like after you stayed up too late and then had to get up too early.

Saturated medium - The less said about what happened after the welcoming party, the better.

Scanning electron microscope - A camera-mounted device that must have made the slides you are trying to read from the back of the room.

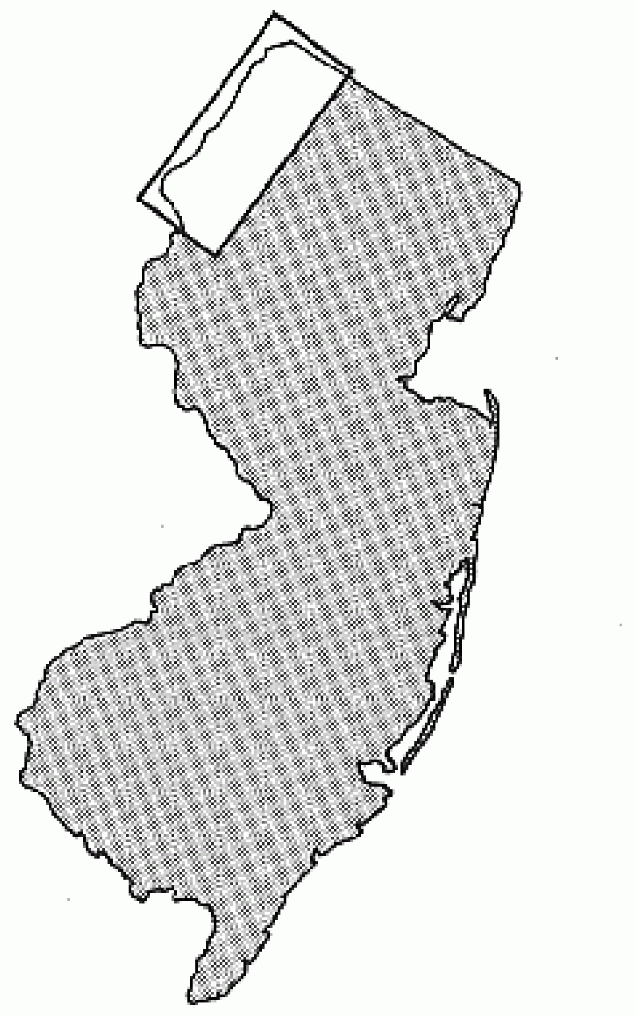
Tetragonal - A geologist who is not symmetrical on his vertical axis but is okay in the right direction.

PLATE 1

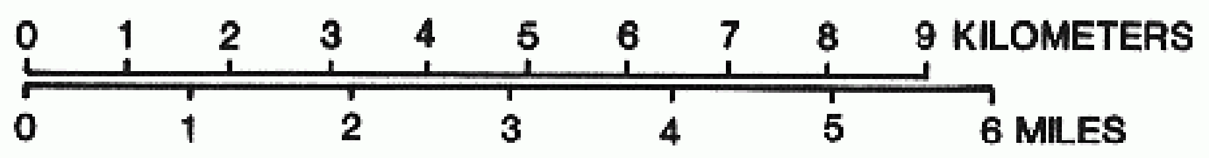
Tectonic Map of Kittatinny Valley and Kittatinny Mountain, New Jersey

by

Gregory C. Herman and Donald H. Monteverde



SCALE 1:100,000



Description of Map Units

12	**Poxono Island Formation through Marcellus Shale undivided (Upper Silurian through Middle Devonian)** - Thin- to thick-bedded and interbedded clastic and carbonate rocks. Lower part of unit is medium-grained limestone, fine- grained limestone, and aphanitic dolomite which grades upwards into an argillaceous shale, a calcareous silty shale, and a silty limestone. Upper part is a coarse-grained quartz sandstone, siltstone, a silty limestone and a shale. New Jersey part of the unit reaches a thickness of 854 m. (2800 ft.).
11	**Bloombsburg Red Beds (Upper Silurian)** - Thin- to thick-bedded shale, siltstone, and sandstone with sparse quartz-pebble conglomerate. Unit is about 442 m. (1500 ft.) thick.
10	**Shawangunk Formation (Middle Silurian)** - Thin- to thick-bedded quartzite, quartz sandstone and quartz pebble conglomerate commonly including some chert and shale clasts. Less abundant siltstone and shale interbeds occur near middle of unit. Unit is about 427 m. (1400 ft.) thick.
Oibc O(?)d	**Igneous rocks (Ordovician)** - Calc-alkalic dikes, sills, diatremes, and stocks of the Beemerville intrusive complex (Oibc), and diabase and lamprophyre dikes undivided (O(?)d).
9 8 7	**Martinsburg Formation (Upper and Middle Ordovician)** - Interbedded, thinly- laminated to medium-bedded slate, siltstone and graywacke where undivided (9). Lower member (Bushkill -7) is laminated to thick-bedded slaty shale and less abundant laminated to thin-bedded siltstone. Thin dolomite beds occur locally in its basal section. Unit is about 457 m. (1500 ft.) thick. Upper member (Ramseyburg - 8) is thin- to very thick-bedded graywacke, laminated to medium bedded siltstone, and less abundant laminated- to thin-bedded shale and slate. Ramseyburg generally coarsens upwards and northeastward. Unit varies from 732 m. (2400 ft.) to 1829 m. (6000 ft.).
6	**Jacksonburg Limestone (Middle Ordovician)** - Fossiliferous, very thin- to medium-bedded, fine- to coarse-grained crystalline limestone with pebble conglomerate, grading upward into a thin sequence of laminated- to thin-bedded, dark shaly limestone. Unit varies from 41 m. (135 ft.) to 92 m. (300 ft.).
Ow	**"Wantage sequence" (Middle (?) Ordovician)** - A discontinuous post-Beekmantown veneer of very thin- to thick-bedded limestone, dolomite, siltstone, and shale. Unit varies from 0 to 46 m. (150 ft.).
5 4	**Beekmantown Group (Lower Ordovician)** - The lower part (4) is laminated- to medium-bedded dolomite and minor interbedded limestone. Silty dolomite laminas and reticulate mottling are common. Fine- to very coarse-grained dolomite occurs in thin to very thick beds at the base. Unit is about 183 m. (600 ft.) thick. The upper part (5) is an aphanitic- to coarse-grained, fetid dolomite that commonly occurs with lenses and beds of dark-gray to black chert. Unit varies from 0 to 69 m. (200 ft.).
3	**Allentown Dolomite (Lowermost Ordovician and Cambrian)** - Very thin- to very thick-bedded dolomite with minor clastics. The lower part contains rhythmically- bedded dolomite with abun dant ooid grainstone, cryptalgal beds, and laminated interbeds of shaly dolomite. Upper part is generally fine-grained, thin- to very thick-bedded, with thin-bedded quartzite sequences and discontinuous dark gray chert lenses occurring directly below the upper contact. Unit is about 610 m. (2000 ft.) thick.
2	**Leithsville Formation and Hardyston Quartzite undivided (Cambrian)** - The Hardyston Quartzite is a basal quartzite and quaetz-pebble conglomerate that coarsens locally into a cobble conglomerate. The Hardyston grades upward into interbedded dolomite and quartz ite. The Leithsville Formation grades upward from interbedded dolomite and quartzite into dolomite with interbedded sandstone and shale. An upper dolomitic facies contains minor clastics. Shaly dolomite and varicolored quartz sandstone, siltstone, and shale are distributed throughout but are most abundant in middle of unit. Unit varies from 244 m. (800 ft.) to 259 m. (850 ft.).
ЄOk	**Kittatinny Supergroup undivided (Lower Ordovician - Cambrian)** - Hardyston Quartzite, Leithsville Formation, Allentown Dolomite, and Beekmantown Group.
1	**Upper and Middle Proterozoic metasedimentary, metaigneous and plutonic rocks undivided**

Explanation Of Map Symbols

- - - -	**unit contact**
─┬──┬─	**thrust fault** - solid where known, dashed where inferred, teeth on upper plate
─┴────	**high-angle fault** - solid where known, dashed where inferred, stick and ball on downthrown side
←────	**fold axial trace** - where indicated, arrow shows direction of plunge
──⧗──	**cleavage fold trough**
─·─·─	**igneous dike**

SOURCES - Kittatinny Valley, Jenny Jump Mt. dikes, and northeast part of Silurian-Devonian rocks mapped by authors 1985-1989. Other geologic data compiled and modifed from:

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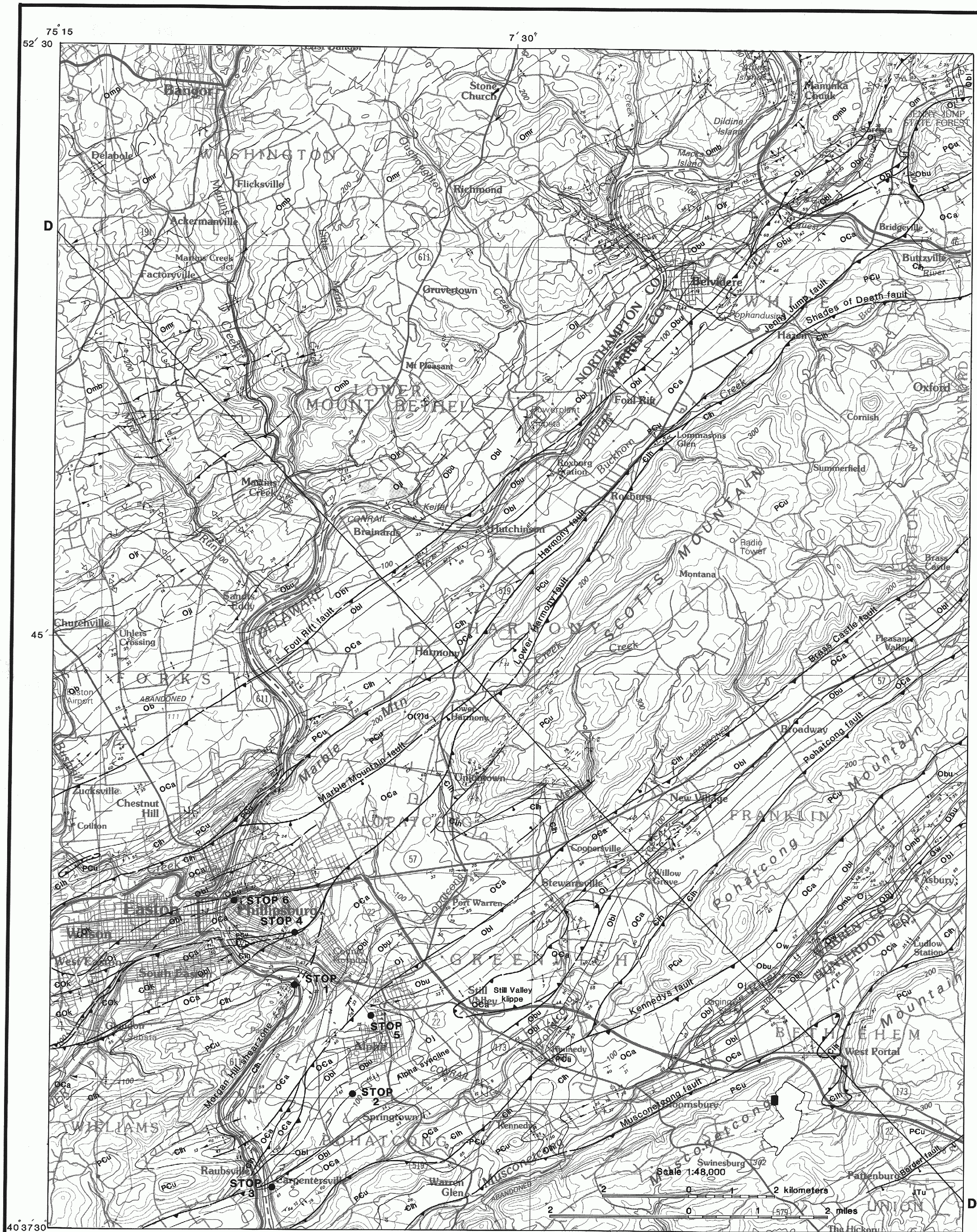

PLATE 2a

Geologic map of southwest Highlands area showing field trip stops in northern New Jersey and eastern Pennsylvania

by

Gregory C. Herman and Donald H. Monteverde

Geology modified from Lewis and Kummel 1910-1912, Davis and others 1967, Drake 1967a, 1967b, and Drake and others 1969. New Jersey geology mapped by authors 1985-1989.

Base modified from U.S.G.S. 30 x 60 Minute Series Maps, Allentown, PA;NJ, and Newark, NJ;NY sheets. Contours shown in 20 meter intervals.

EXPLANATION OF MAP SYMBOLS

All data lines are solid for known relations, long-dashed for inferred relations, and queried where relations are concealed. Short dashed lines represent compiled data. Lithologic contacts and faults shown with tick marks to indicate direction and angle of dip. Fold traces with arrows show direction of dip of limbs and plunge of folds. Dip of limbs and plunge of fold angle indicated in degrees.

Description of map units shown on Plate 2b

Contact - Straight tick mark shows local dip direction and dip angle of inclined contact, curled tick mark denotes overturned contact.

Bedding - strike and dip

- Inclined
- Overturned

Slaty or spaced pressure-solution cleavage - strike and dip

Crenulation cleavage - strike and dip. Includes all spaced cleavage varieties that cross-cut an earlier cleavage set.

Cleavage shear zone - swarms of spaced slip cleavage with attendant quartz, calcite, and minor chlorite veins and shear fractures. Tick mark shows direction and angle of dip.

Thrust fault - sawteeth on upper plate.

High-angle fault - ball and bar on downthrown block.

Basement shear zone: zone of chlorite-, epidote-, muscovite-, and quartz-mineralized shear planes and veins. Cataclastic brecciation indicated by open triangles. Tick mark shows local direction and angle of dip.

Anticline

Syncline

Overturned anticline

Overturned syncline

Steeply-inclined anticline, arrow tail shows direction of dip of upper limb.

Steeply-inclined syncline, arrow tail shows direction of dip of upper limb.

Cleavge fold arch

Cleavage fold trough

Minor bedding fold fold axis (FA)- showing bearing and plunge

Minor cleavage fold axis (CF) - showing bearing and plunge

Lineations

- Intersection of bedding and cleavage - showing bearing and plunge
- Intersection of cross-cutting cleavages - showing bearing and plunge
- Slip lineation - showing bearing and plunge

Ordovician (?) lamprophyre or diabase dike

● Field stop location

Location of cross section on Plate 2a

PLATE 2b

Regional Cross-section D-D' of the southwest Highlands Area

by

Gregory C. Herman and Donald H. Monteverde

Description of Map Units (Plates 2a, 2b)

JTu **Jurassic and Triassic rocks undivided**

O(?)d **Diabase and lamprophyre dikes undivided (Upper Ordovician ?)**

Om (Omr, Omb) **Martinsburg Formation (Upper and Middle Ordovician)** - Coarsening-upward sequence of interbedded thinly-laminated to medium- bedded slate, siltstone and graywacke where undivided (Om). The lower member (Bushkill, Omb) consists of laminated to thick- bedded slaty shale and less abundant laminated to thin-bedded siltstone. Member is about 1250 m. (4100 ft.) thick. The upper member (Ramseyburg, Omr) has thin- to very thick-bedded graywacke, laminated to medium-bedded siltstone, and less abundant laminated to thin-bedded shale and slate. In map area, member is about 976 m. (3200 ft.) thick.

Oj (Ojr, Ojl) **Jacksonburg Limestone (Middle Ordovician)** - The undivided sequence (Oj) consists of locally fossiliferous fine- to coarse-grained limestone grading upward into shaly limestone. Where divided, a lower Cement Limestone Member (Ojl) is commonly fossiliferous, very thin- to medium-bedded, fine- to coarse-grained crystalline limestone with some pebble conglomer ate. Unit varies from less than 15 m. (50 ft.) to about 122 m. (400 ft.) thick. Upper Cement Rock Member (Ojr) is laminated to thin-bedded, dark shaly limestone. In map area, member varies from less than 15 m. (50 ft.) to about 305 m. (1000 ft.) thick.

Ow **"Wantage sequence" (Middle (?) Ordovician)** - A discontinuous post-Beekmantown veneer of very thin- to thick-bedded limestone, dolomite, siltstone, and shale. Unit varies from 0 m. (0 ft.) to about 46 m. (150 ft.) thick.

Ob (Obu, Obl) **Beekmantown Group (Lower Ordovician)** - The undivided sequence (Ob) consists chiefly of laminated- to thick-bedded dolomite with subordinate limestone and interbedded clastics. The lower part (Obl) is laminated- to medium-bedded dolomite and minor interbedded limestone. Silty dolomite laminas and reticulate mottling are common. Fine- to very coarse-grained dolomite occurs in thin to very thick beds at the base. Unit is about 243 m. (800 ft.) feet thick. The upper part (Obu) is aphanitic- to coarse- grained, fetid dolomite that commonly occurs with lenses and beds of dark-gray to black chert. Thin-bedded limestone lenses can occur. Unit thickness varies from about 92 m. (300 ft.) to 243 m. (800 ft.), depending on degree of erosion.

O€a **Allentown Dolomite (Lowermost Ordovician and Cambrian)** - Very thin- to very thick-bedded dolomite with minor clastics. The lower part contains rhythmically-bedded dolomite with abundant ooid lenses, cryptalgal beds, and laminated interbeds of shaly dolomite. Upper part is generally fine-grained, thin- to very thick-bedded, with thin-bedded quartzite sequences and discontinuous dark gray chert lenses occurring directly below the upper contact. Unit is about 671 m. (2200 ft.) thick.

€lh **Leithsville Formation and Hardyston Quartzite undivided (Cambri an)** - The Hardyston Quartzite is a basal quartzite and quartz-pebble conglomerate that coarsens locally into a cobble conglomerate. The Hardyston grades upwards into interbedded dolomite and quartzite. The Leithsville Formation grades upward from interbedded dolomite and quartzite into dolomite with inter bedded sandstone and shale. An upper dolomitic facies contains minor clastics. Shaly dolomite and varicolored quartz sandstone, siltstone, and shale are distributed throughout but are most abundant in the middle of the formation. The combined unit is 244 m. (800 ft.) thick.

€Ok **Kittatinny Supergroup undivided (Lower Ordovician - Cambrian)** - Includes Beekmantown Group, Allentown Dolomite, Leithsville Formation, and Hardyston Quartzite.

P€u **Upper and Middle Proterozoic metasedimentary, metaigneous and plutonic rocks undivided**

Explanation of Cross-section Symbols

Cleavage - slaty variety in Bushkill Member of Martinsburg Formation, spaced solution variety in Ramseyburg Member of Martinsburg Formation, Jacksonburg Limestone, and Kittatinny Supergroup.

Cleavage shear zone - defined on plate 2a

Brittle-ductile basement shear zone - defined on plate 2a