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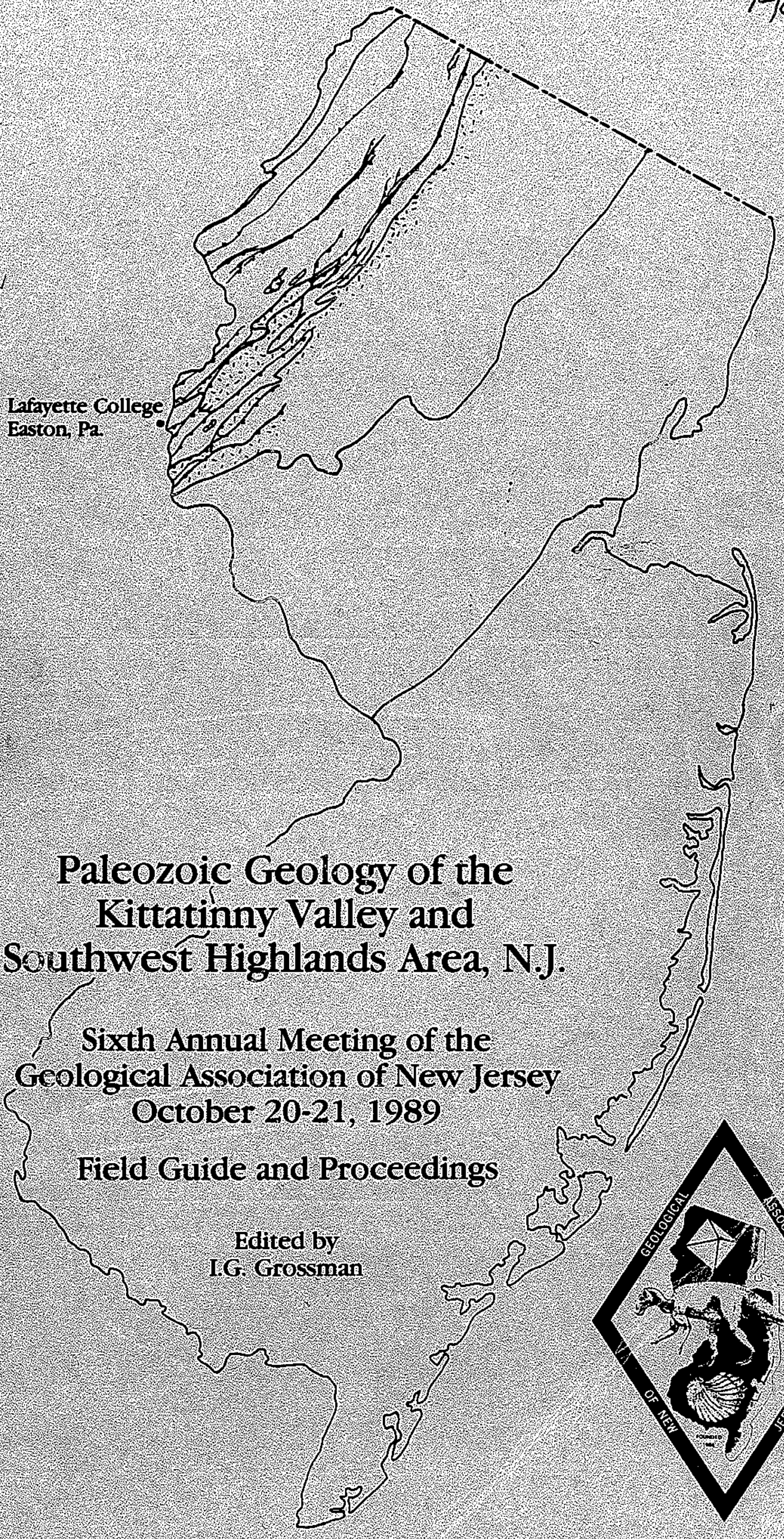

Paleozoic Geology of the Kittatinny Valley and Southwest Highlands Area, N.J.

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

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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.

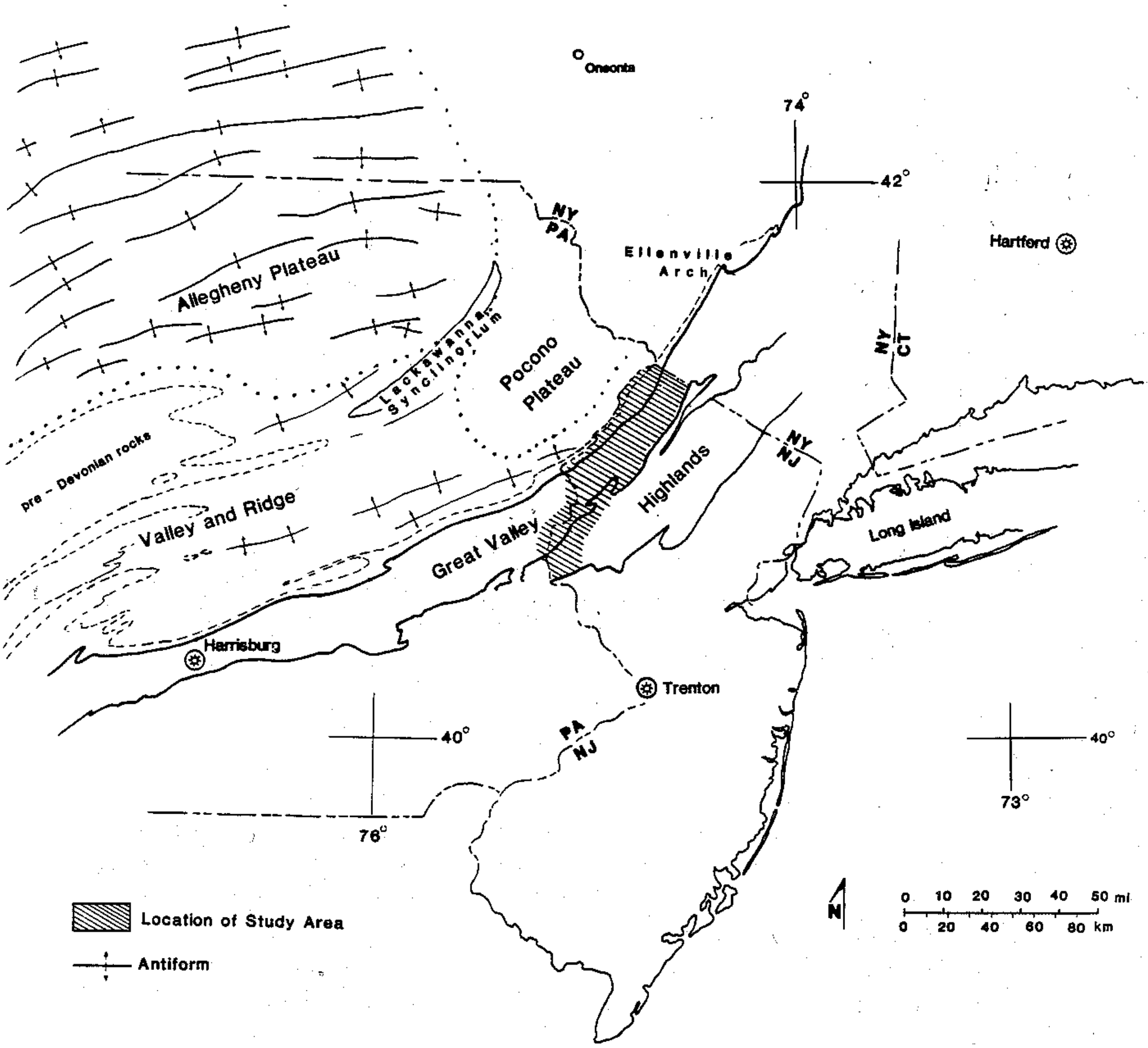


Figure 1 - Regional map of study area and northern tectonic provinces of the northeast central Appalachians, New Jersey and Pennsylvania. Modified from Wood and Bergin (1970) and from the tectonic map of the mid-Atlantic region, Bennison, A. P., compiler, 1976, U. S. Geologic Highway Map Ser., Map no.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

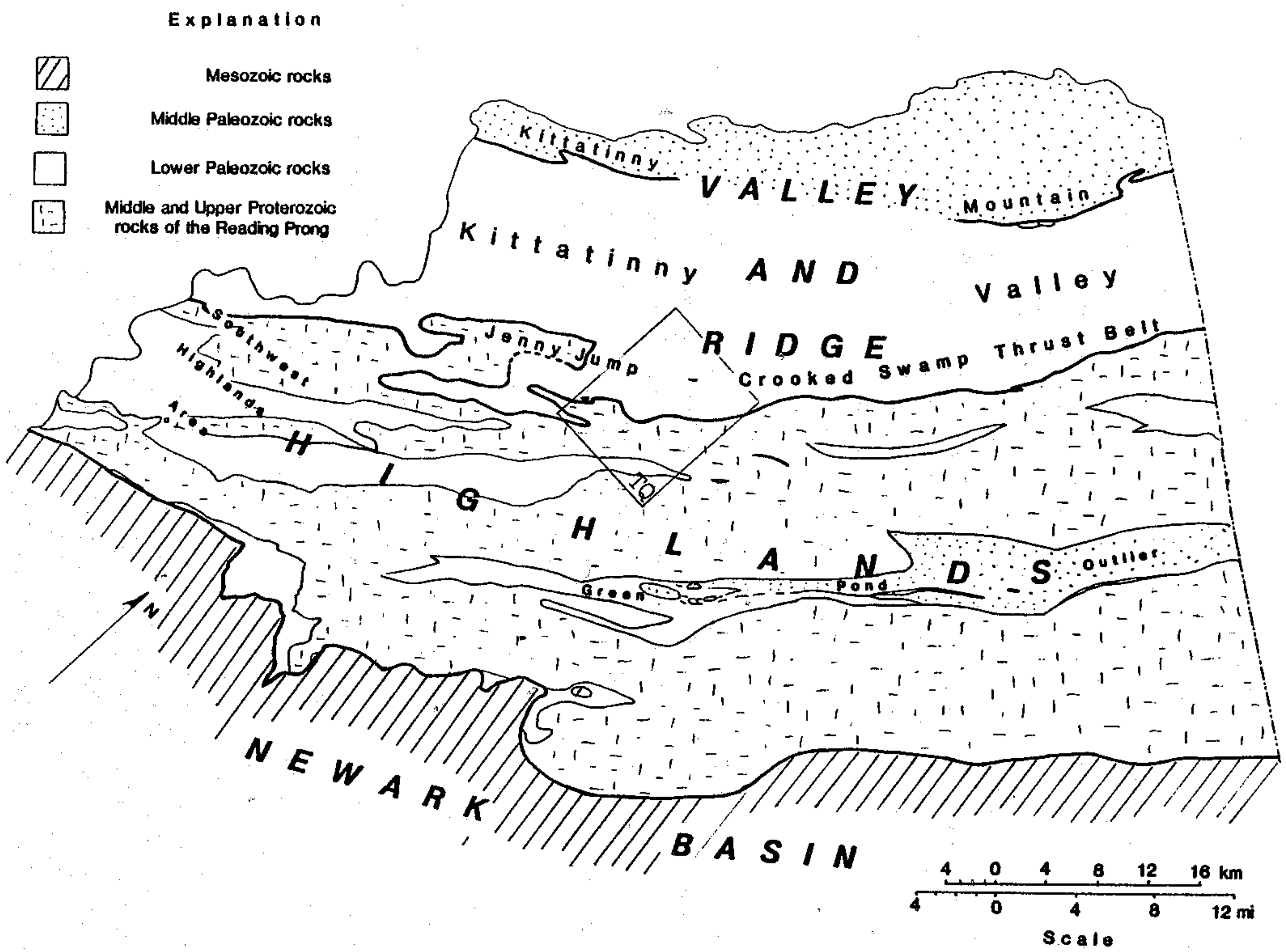


Figure 2 - Generalized geology of the Highlands and Valley and Ridge provinces of New Jersey. Modified from Lewis and Kummel (1910 -1912). Tranquility 7 1/2' quadrangle.

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

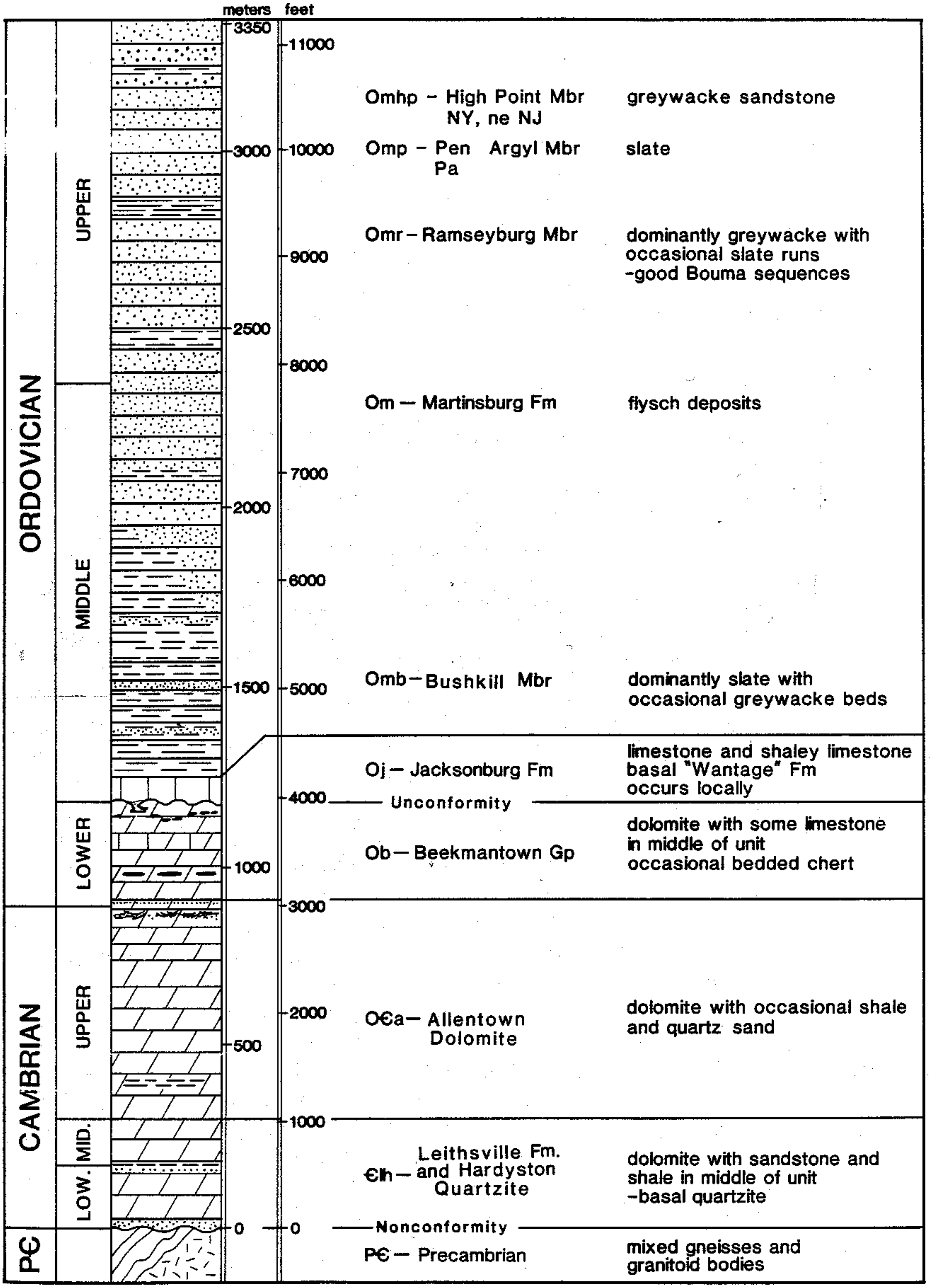


Figure 3. Generalized stratigraphic column for the Kittatinny Valley and southwest Highlands area

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.

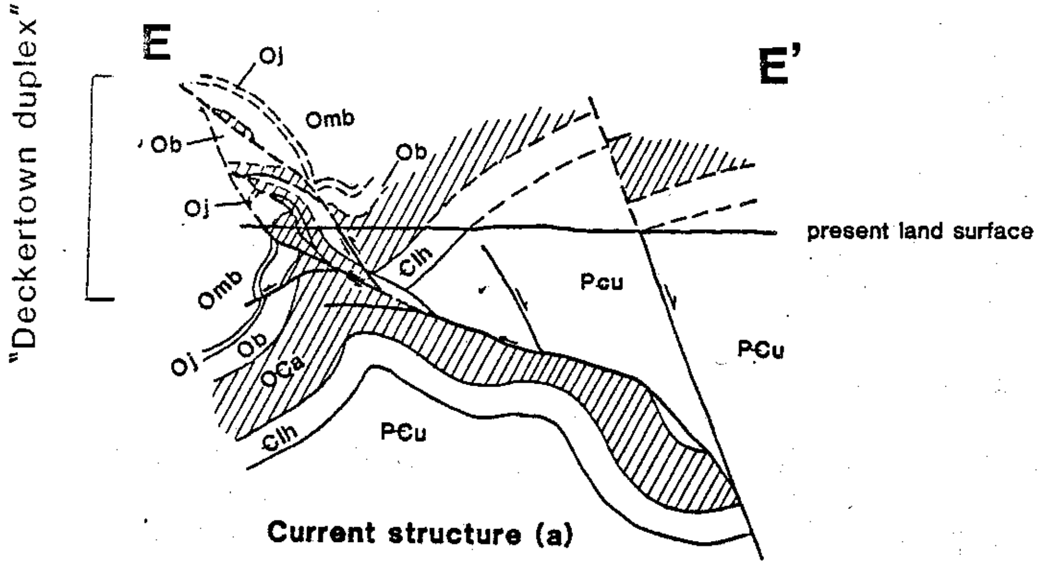
The Ridge and Valley Thrust System is illustrated by maps and cross sections that clarify its structure. The map components are subdivided into emergent-thrust and blind-thrust terranes. The emergent-thrust terrane includes two thrust belts that crop out in the Valley and Ridge province (Pl. 1) and the 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

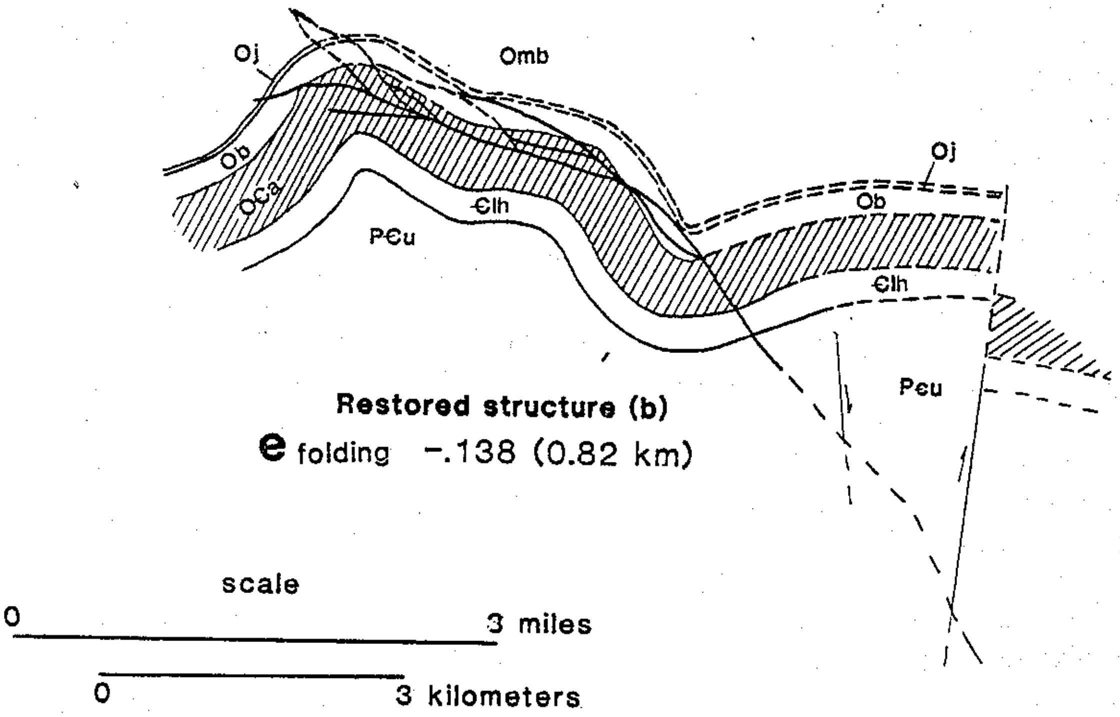
The emergent-thrust terrane of the southwest Highlands area (Pl. 2a) consists of redeformed basement and cover-layer rocks. The delineation of thrust faults in this area differs from the those of Drake (1967a, 1967b), Davis and others (1967), Drake and others (1969), and Lyttle and Epstein, (1987). The 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.

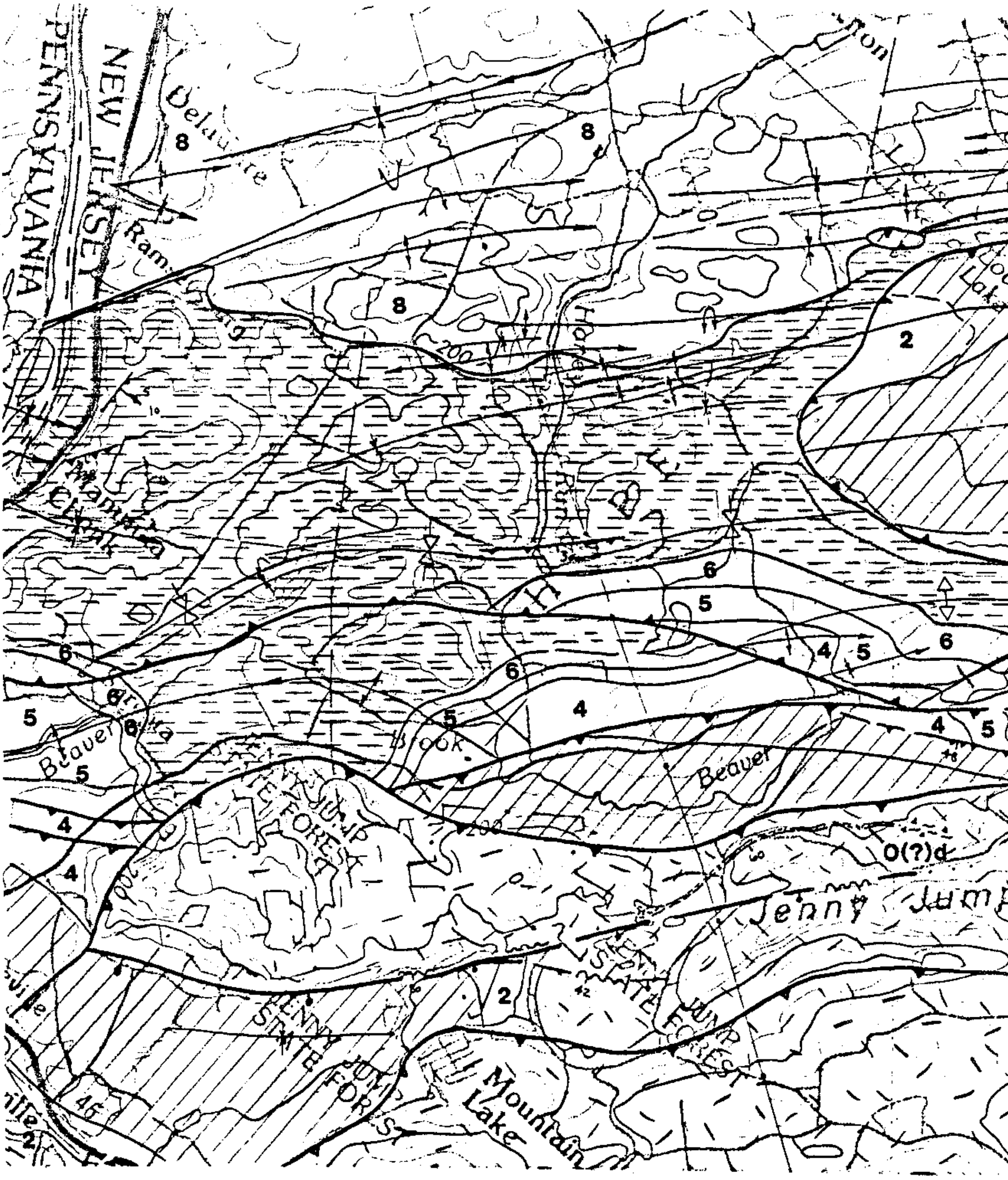
by the later thrust faults. They were restored into their pre-thrust fault form with balanced cross sections delineating the northeast part of the JJCS around the "Deckertown duplex" (Pl. 1). As shown in figure 4, the duplex retrodeforms into a pre-thust anticlinorium. The methods and assumptions on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

ZZZ 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)

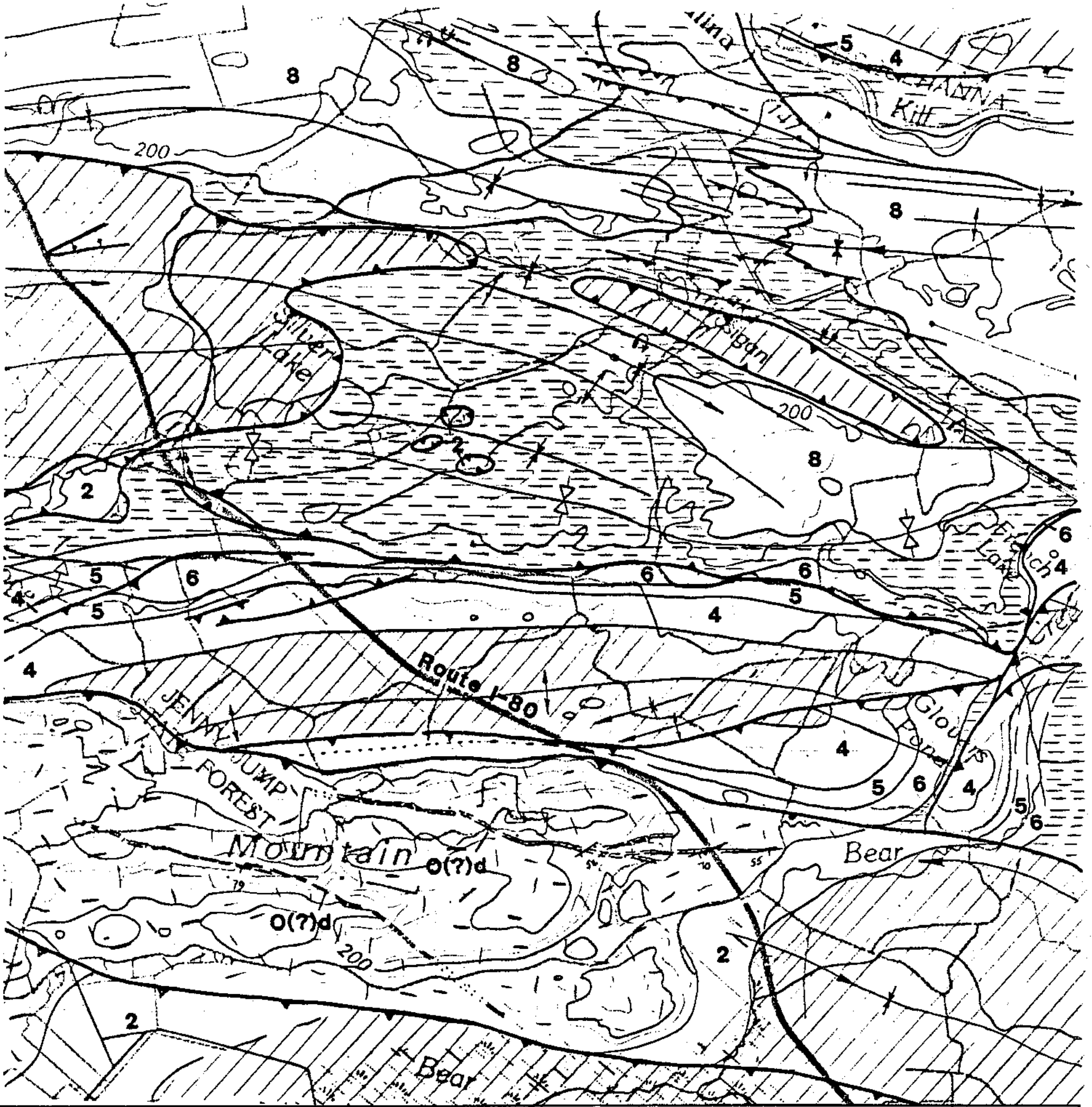
4 Obl - Lower part of the Beekmantown Group (
Ordovician)

▨ O-Ꞓa - Allentown Dolomite (Uppermost Ordov
Cambrian)

2 -Ꞓlh - Leithsville Formation and Hardyston Qua
undivided (Cambrian)

⋰ P-Ꞓu - Upper and Middle Proterozoic metasedi
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
interval 20 m. Geology from 1:24,000 unpublished maps by the authors, on file at the New Jersey Geologic Survey, Trenton



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).

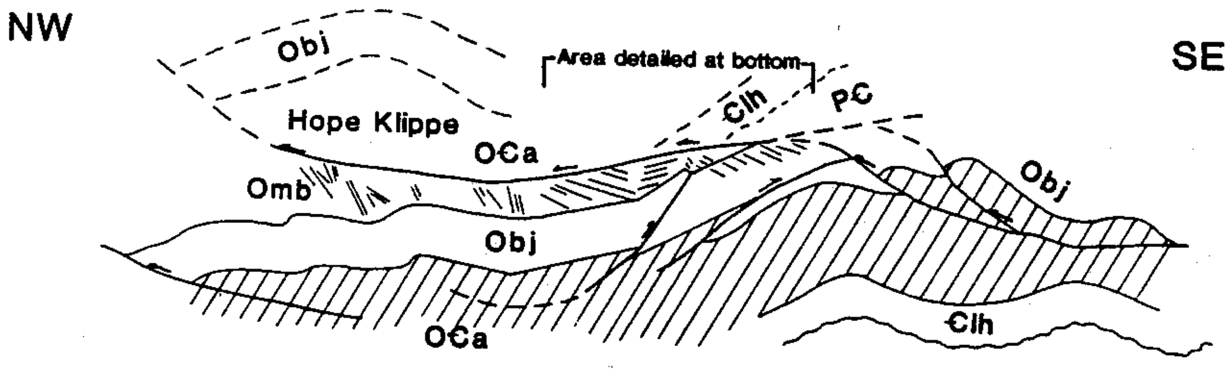
High-angle block faults occur along the southeast margin of the JJCS that are similar to the previously - described ones in the southwest Highlands area. These include the Mountain Lake fault southeast of Jenny Jump Mountain, and a series of faults in the northeast along the margin of the Highlands and 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.

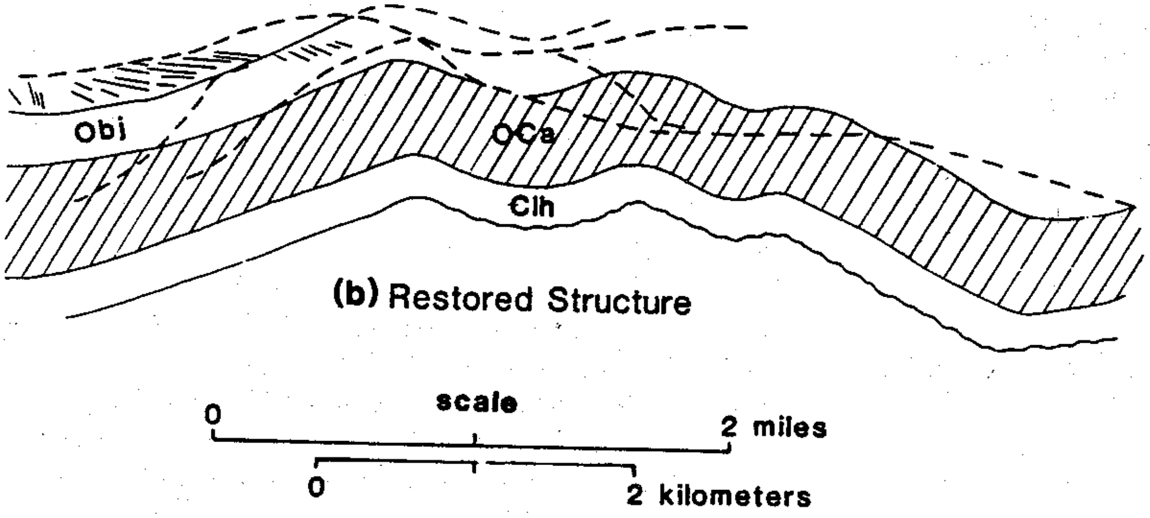
The imbricate thrust sheets that comprise the JJCS and occur in the southwest Highlands are generally northeast-plunging so that successively higher thrust sheets are visable on the map in a progressive northeast direction. In contrast, the Paulins Kill thrust belt is doubly-plunging away from the central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

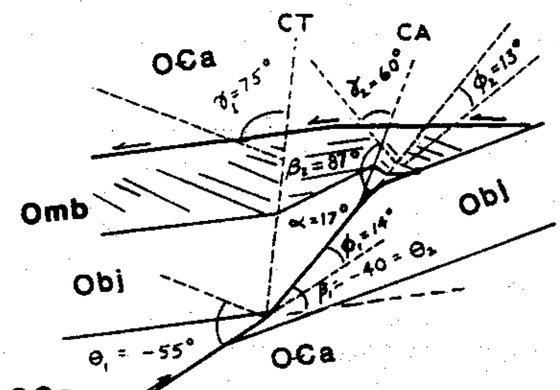


(a) Current Structure



(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

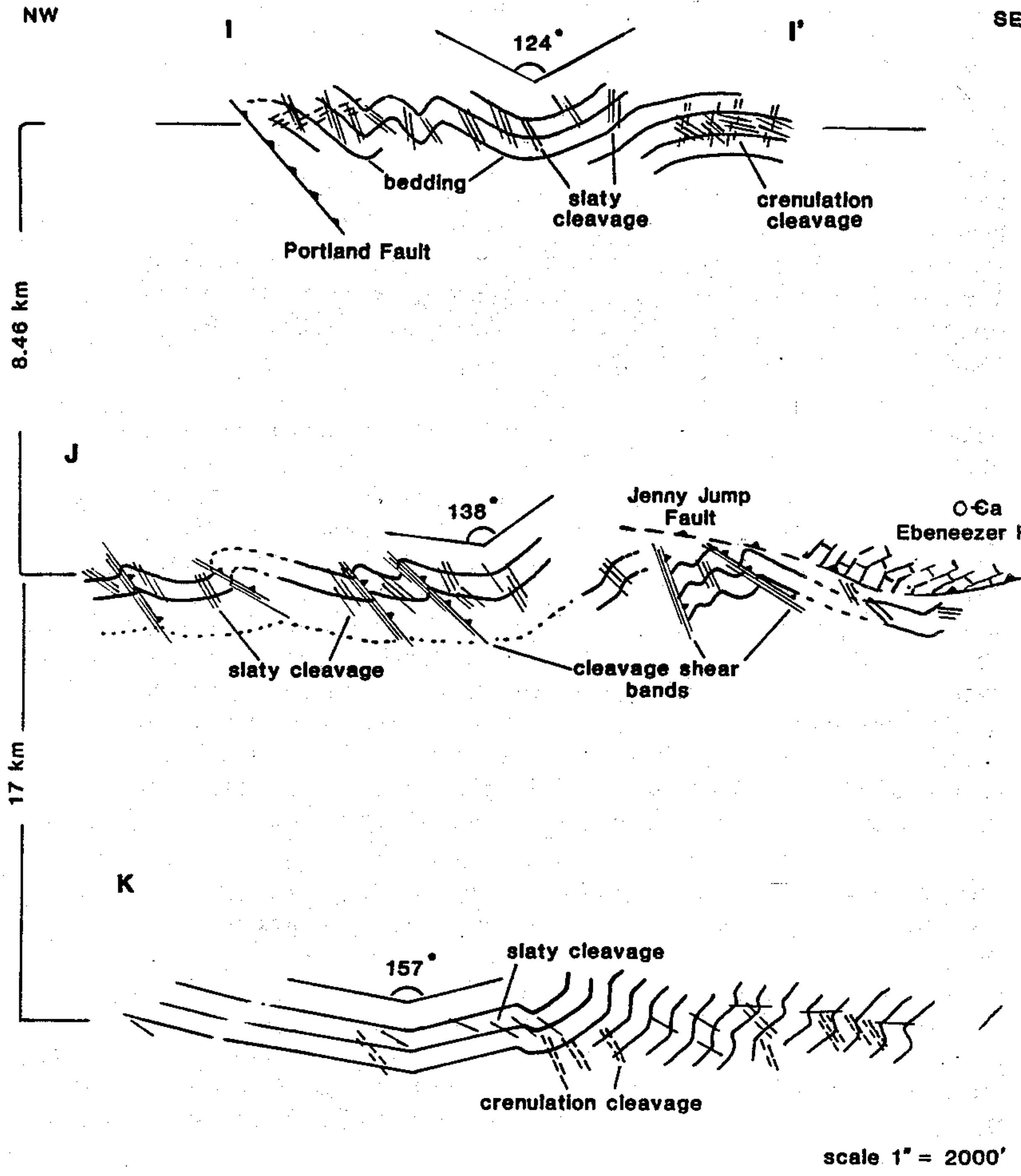


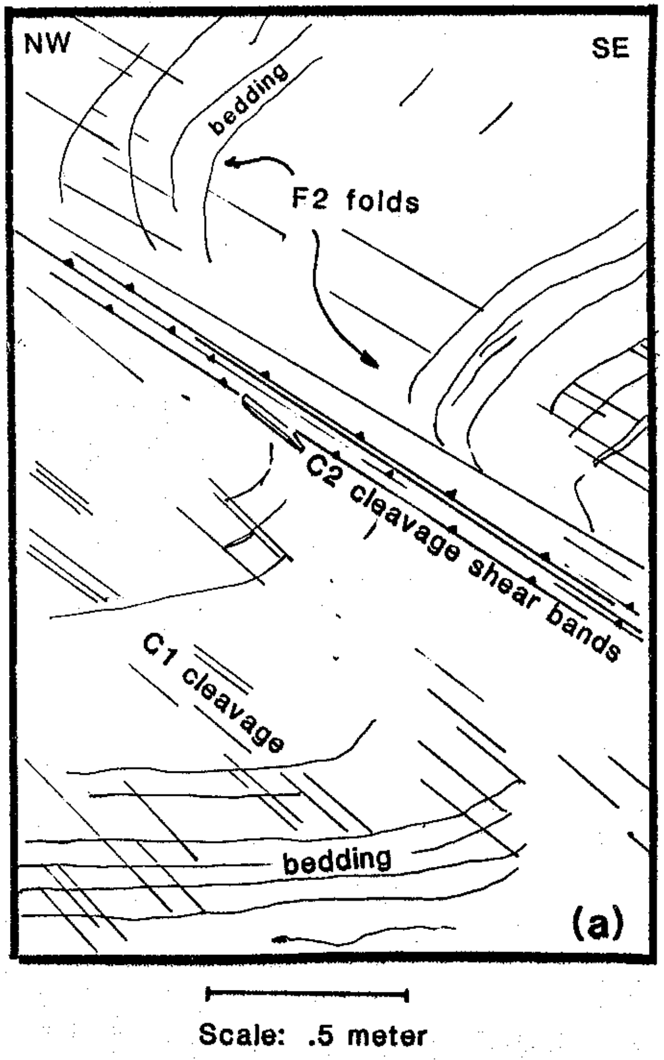
Figure 7 - Halsey synclinorium, cross-section details along three transects. Location of transects shown on Plate 1.

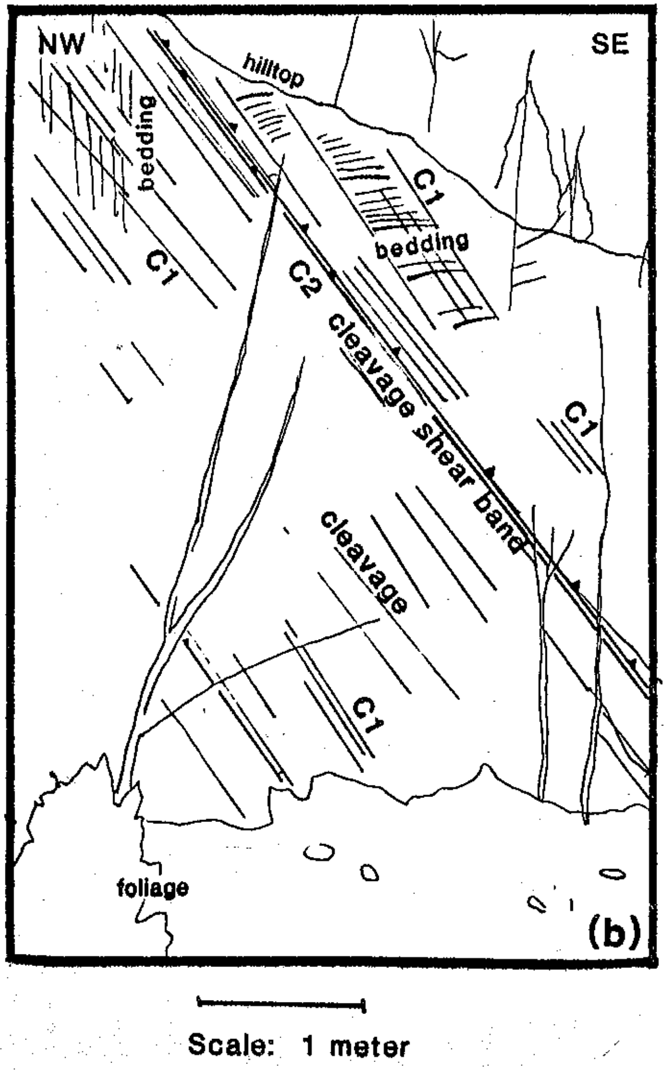
fault processes. The northwest limb of the synclinorium has probably been rotated upward in a clockwise direction because of ramping up the backlimb of the hindward thrust sheet of the Paulins Kill thrust belt. The southeast limb of the synclinorium has probably rotated upward in a counterclockwise direction 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


NW
SE
bedding
F2 folds
C2 cleavage shear bands
C1 cleavage
bedding
(a)
Scale: .5 meter

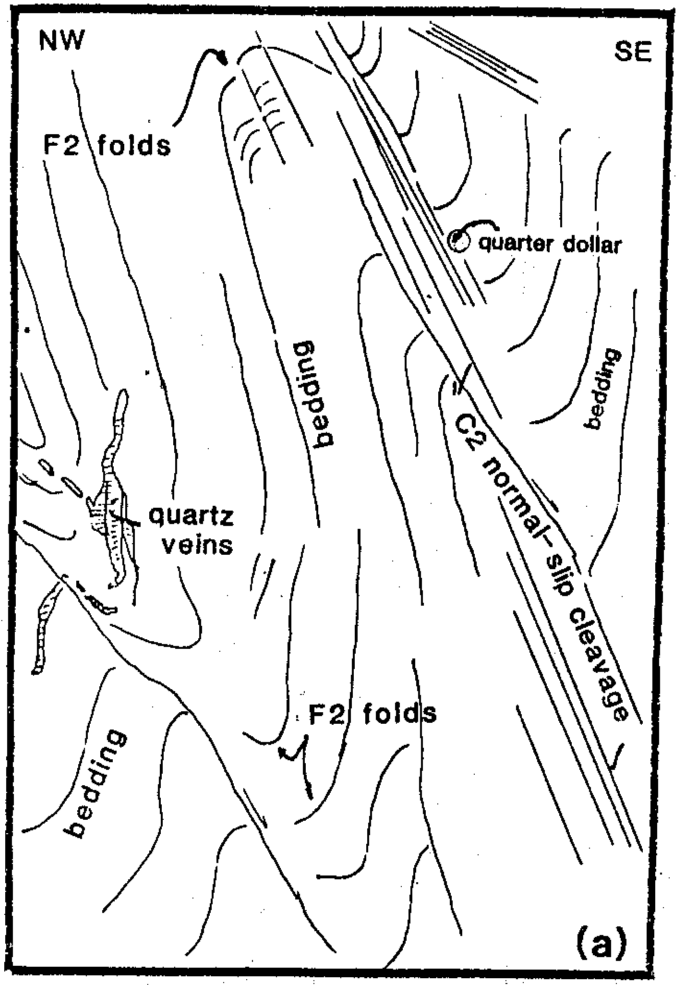

NW
SE
hilltop
bedding
C1
C1
bedding
C2 cleavage shear band
C1
cleavage
C1
foliage
(b)
Scale: 1 meter

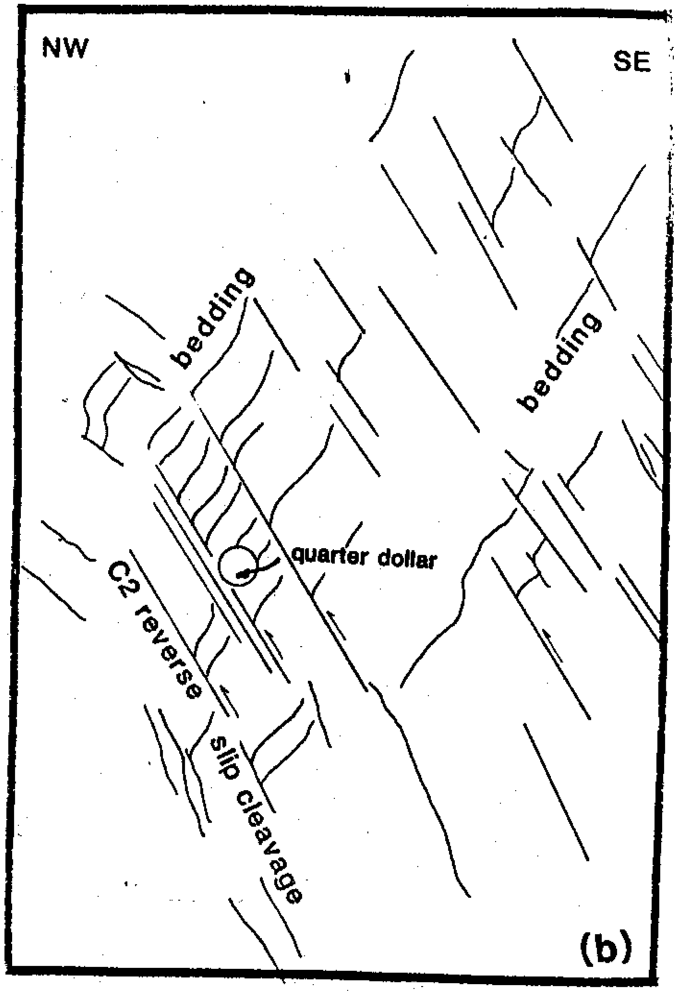
Bushkill Member of the Martinsburg Formation. These folds are most abundant northeast of the Paulins Kill Valley where they accomodate the gradual loss of dip-slip displacement from the Paulins Kill thrust belt along a northeastly trend (Pl. 1).

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


NW
SE
F2 folds
quarter dollar
bedding
bedding
C2 normal- slip cleavage
quartz
veins
F2 folds
bedding
(a)


NW
SE
bedding
bedding
quarter dollar
C2 reverse
slip cleavage
(b)

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.

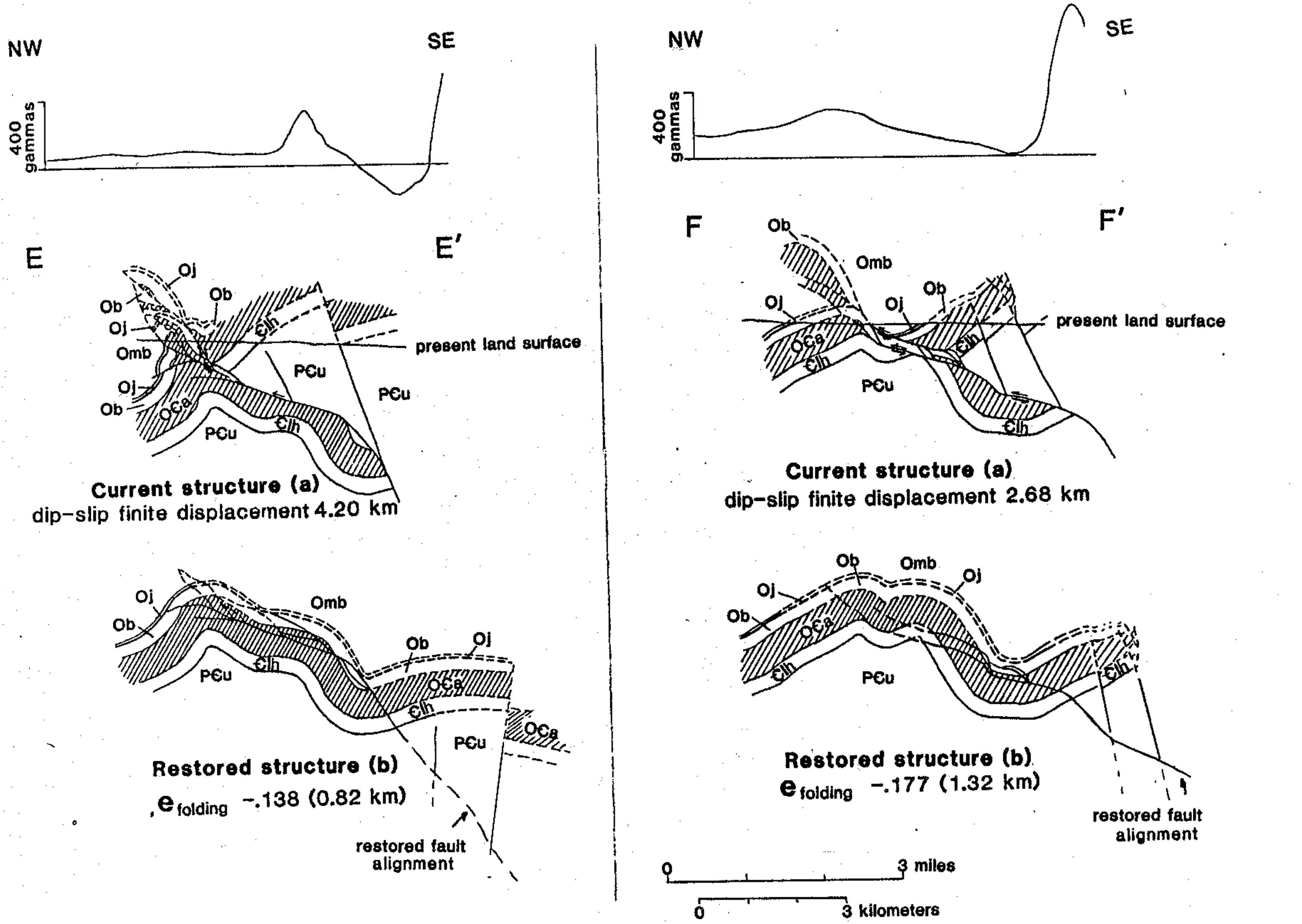


Figure 10 - Cross sections E-E' and F-F' for the northeast Jenny Jump - Crooked Swamp thrust belt. (a) Current sections and corresponding NURE aeromagnetic profiles (LKB Resources, 1980). (b) Restored sections showing pre-thrust cover layer, thrust propagation, and block-fault alignments. Location of sections and description of units shown on Plate 1. of Martinsburg Fm., Omb - Bushkill Member of Martinsburg Fm., Oj - Jacksonburg

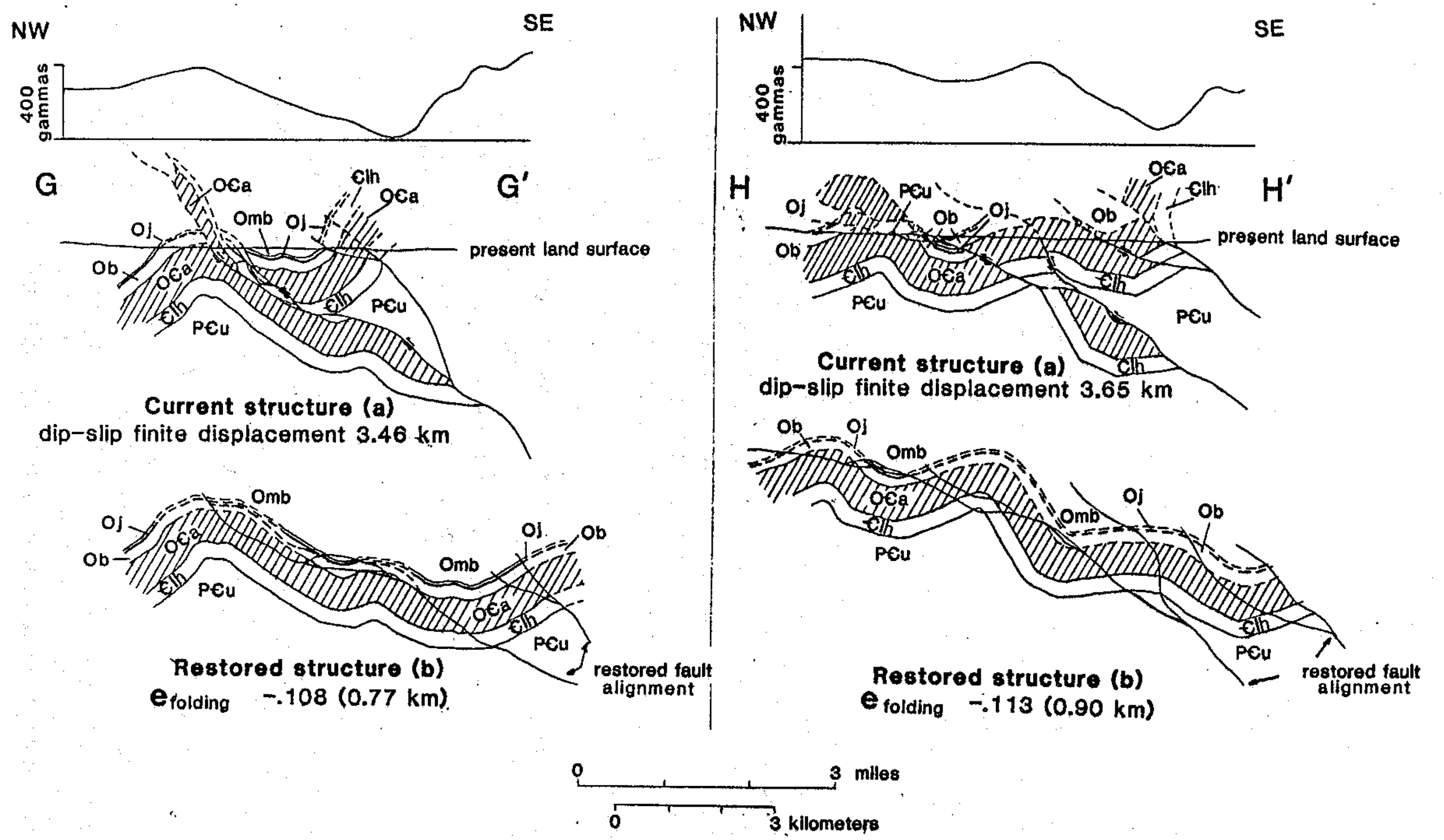


Figure 11 - Cross sections G-G' and H-H' showing the central Jenny Jump - Crooked Swamp thrust belt. (a) Current sections and corresponding NURE aeromagnetic profiles (LKB Resources, 1980). (b) Restored sections showing pre-thrust cover layer and thrust propagation alignments. Location of sections and 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~~6, 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

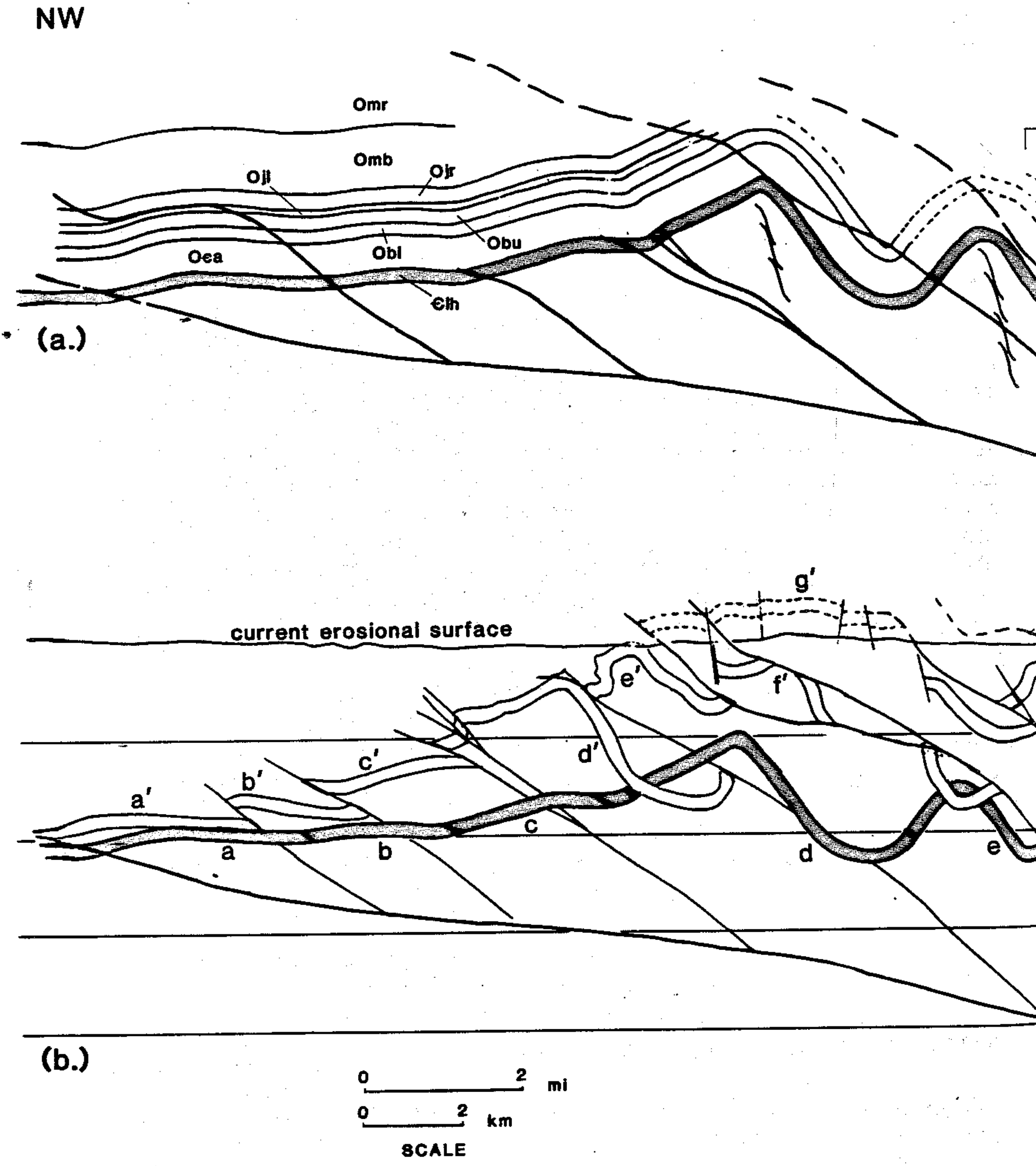
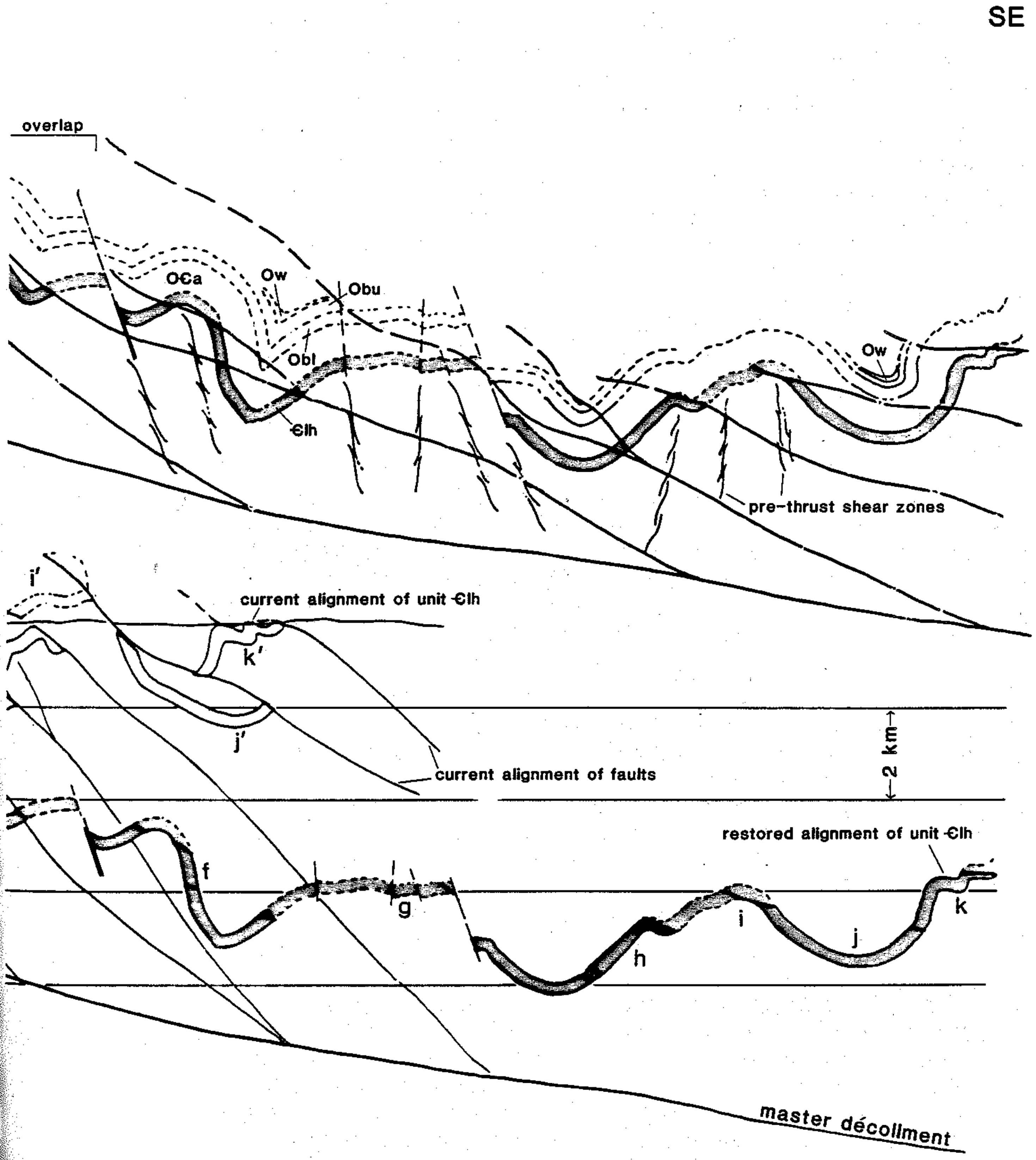


Figure 12 (a.) Restored structure of cross-section D-D′ (Plate 2b)
(b.) Structural relief diagram comparing Ꞓlh unit for current and restored alignments

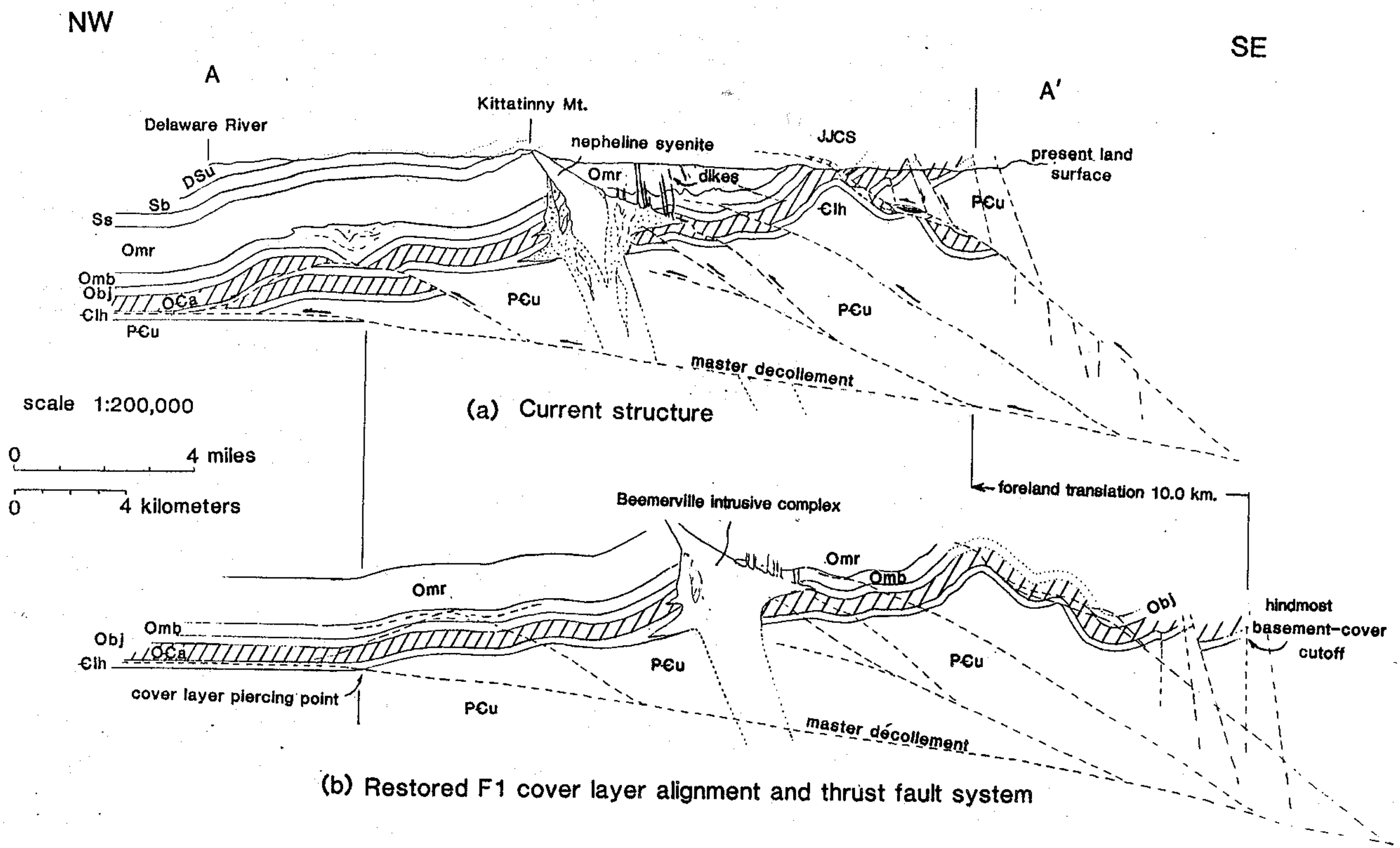

SE
overlap
OЄa
Ow
Obu
Obl
Єlh
Ow
pre-thrust shear zones
i′
current alignment of unit Єlh
k′
j′
current alignment of faults
←2 km→
restored alignment of unit Єlh
f
g
h
i
j
k
master décollment

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.

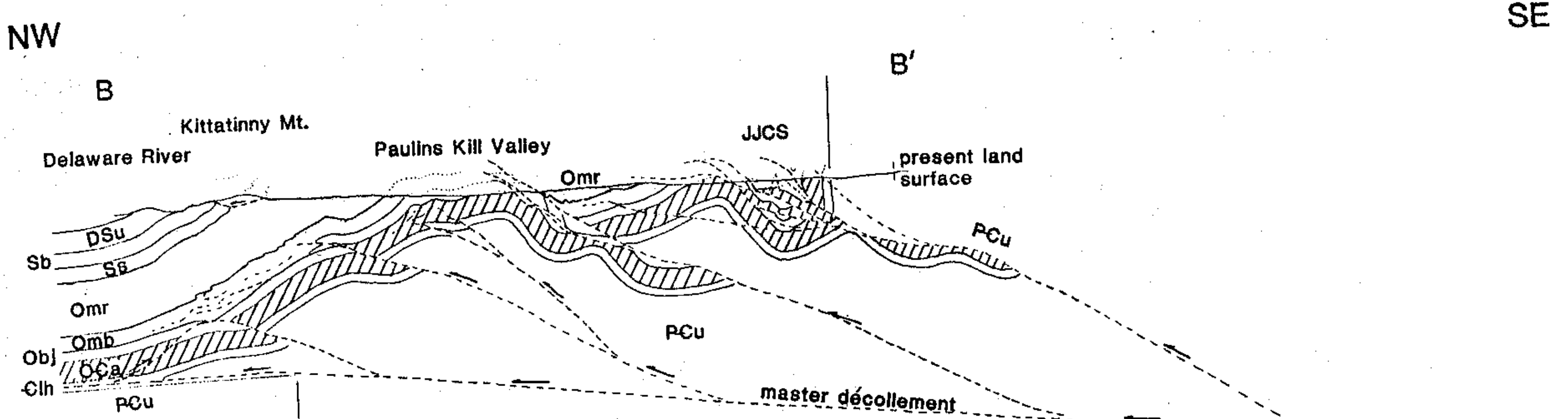
The limited extent of the Blue Mountain décollement shown on Plate 1 is attributed to the location of the emergent thrust faulting in the Paulins Kill Valley relative to the location of the Shawangunk Formation underlying Kittatinny Mountain. Apparently, where the emergent thrust faults in the Paulins 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



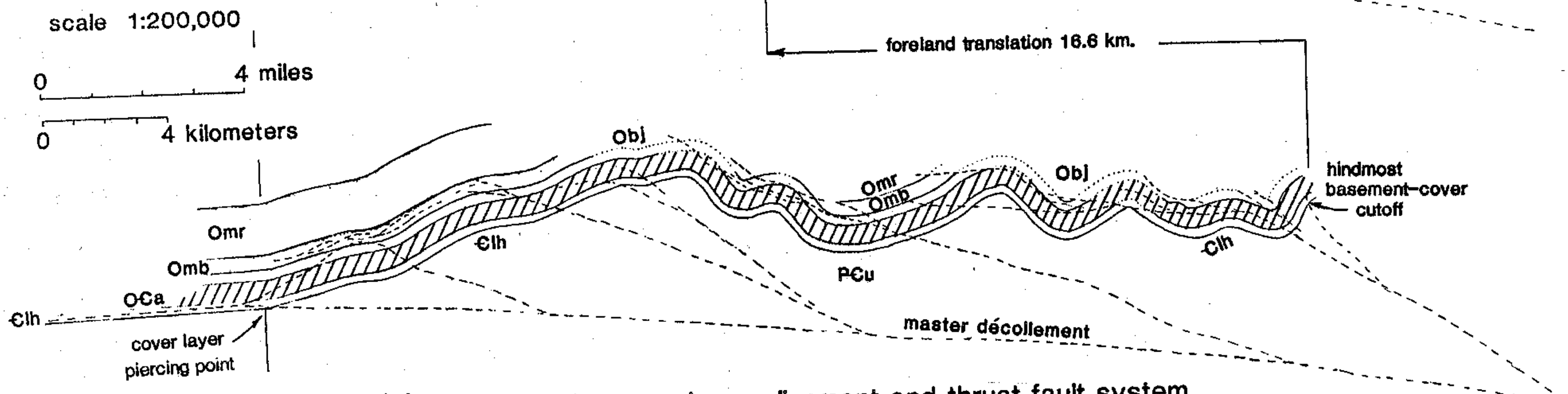
(a) Current structure

(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, O€a - Allentown Dolomite, Ꞓlh - Leithsville Fm. and Hardyston Quartzite undivided, P€u - Precambrian undivided.

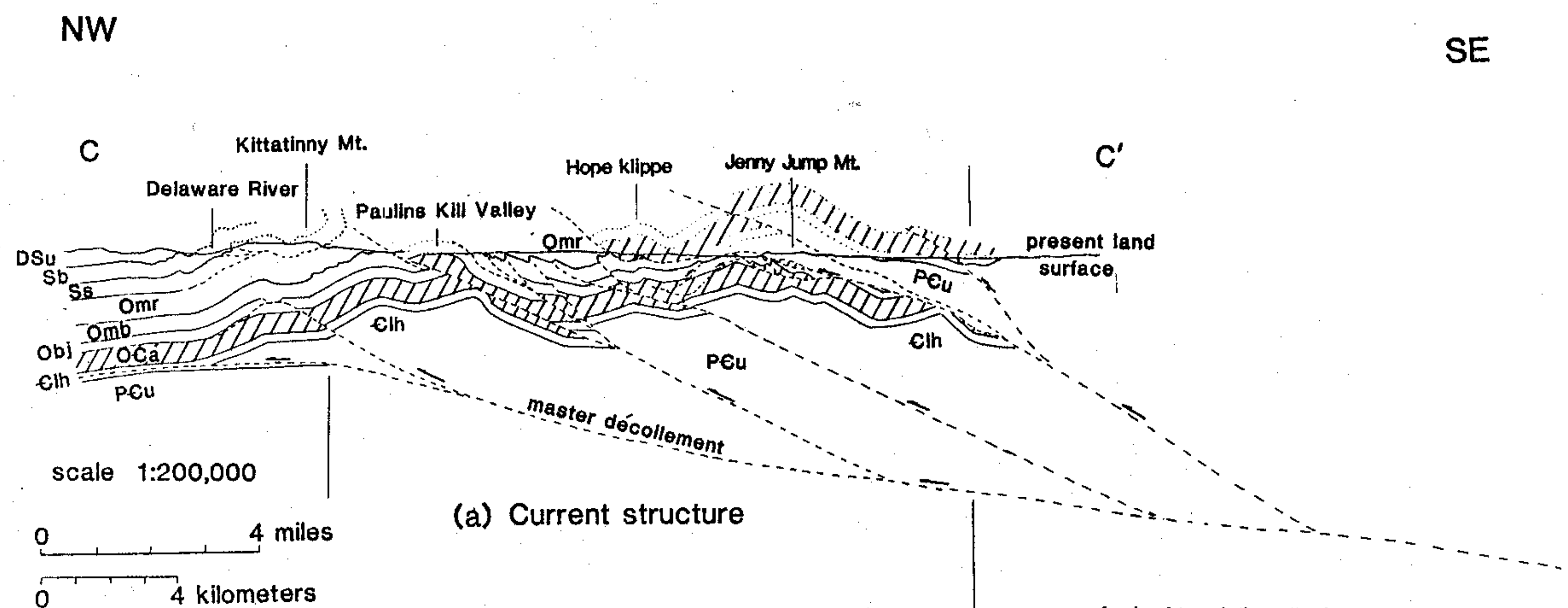


(a) Current structure

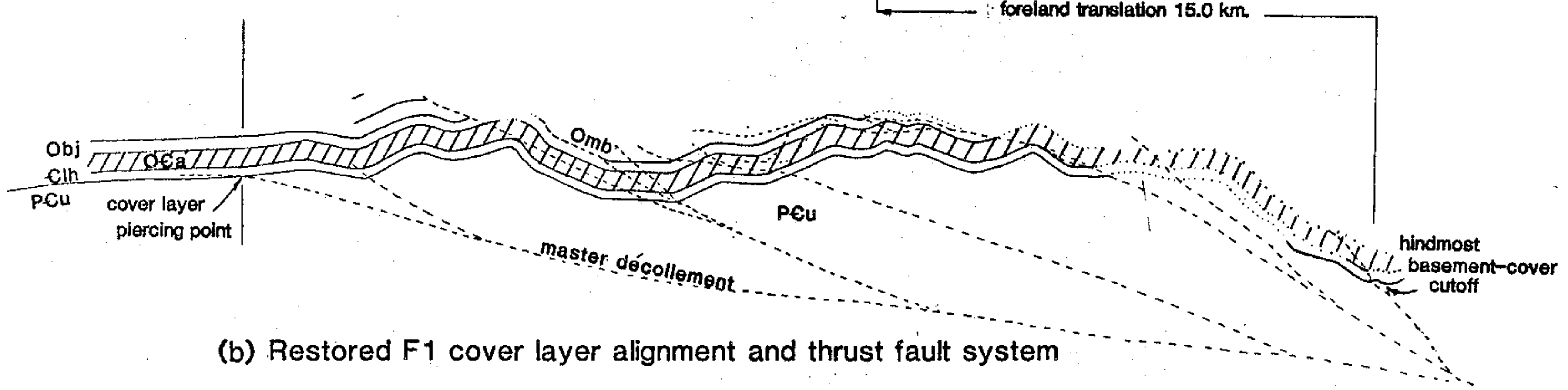


(b) Restored F1 cover layer alignment and thrust fault system

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,



(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, OЄa - Allentown Dolomite, Єlh - Leithsville Fm. and Hardyston Quartzite undivided, PЄu - 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-ta 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 lengt

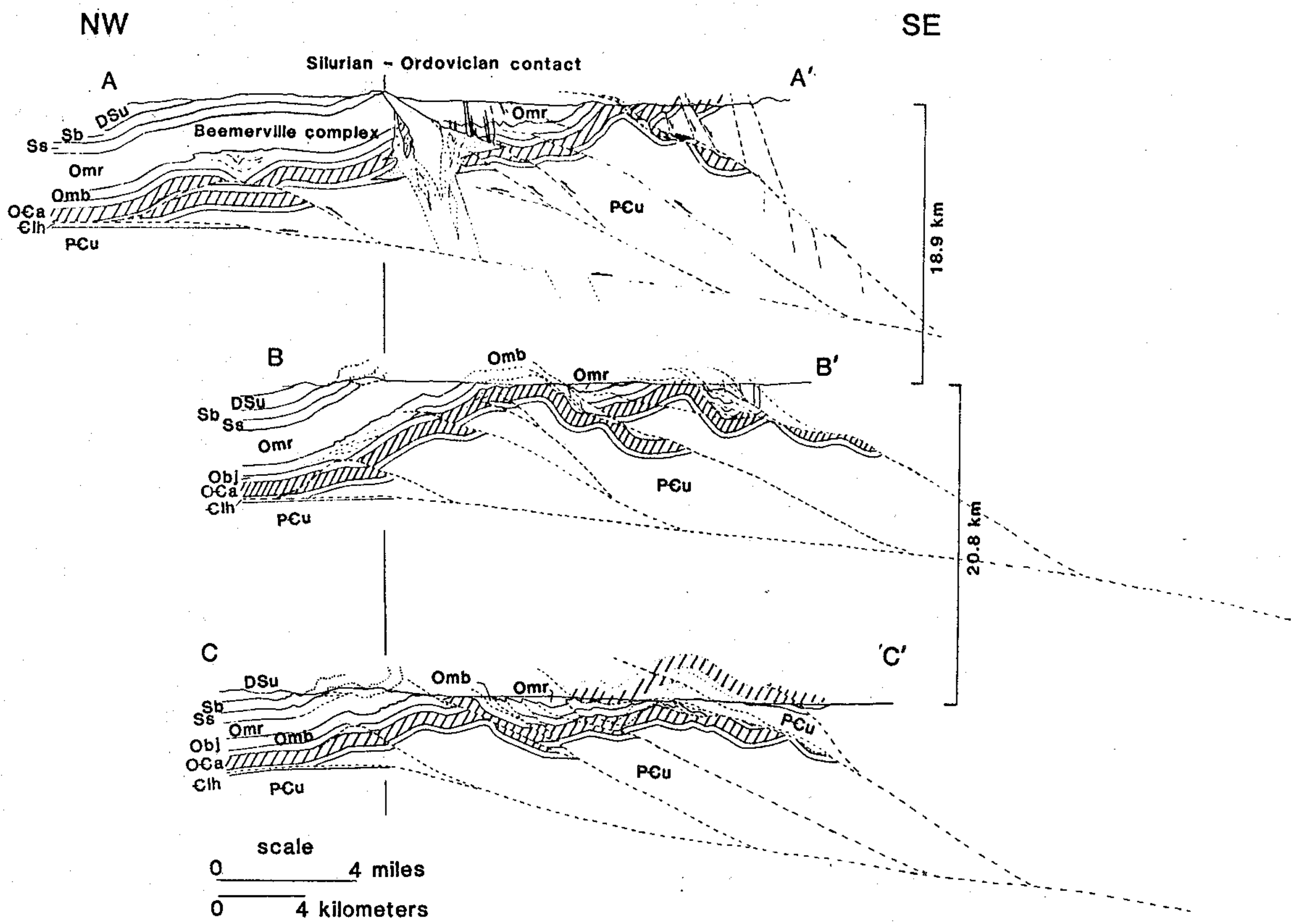


Figure 16 - Series showing current regional cross sections A-A', B-B',and C-C'relative to the Ordovician-Silurian map contact. Location and description of units given on plate 1. DSu - Devonian rocks through Poxono Island Fm. undivided, Sb - Bloomsburg Red Beds, Ss - Shawangunk Fm., Omr - Ramseyburg 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.

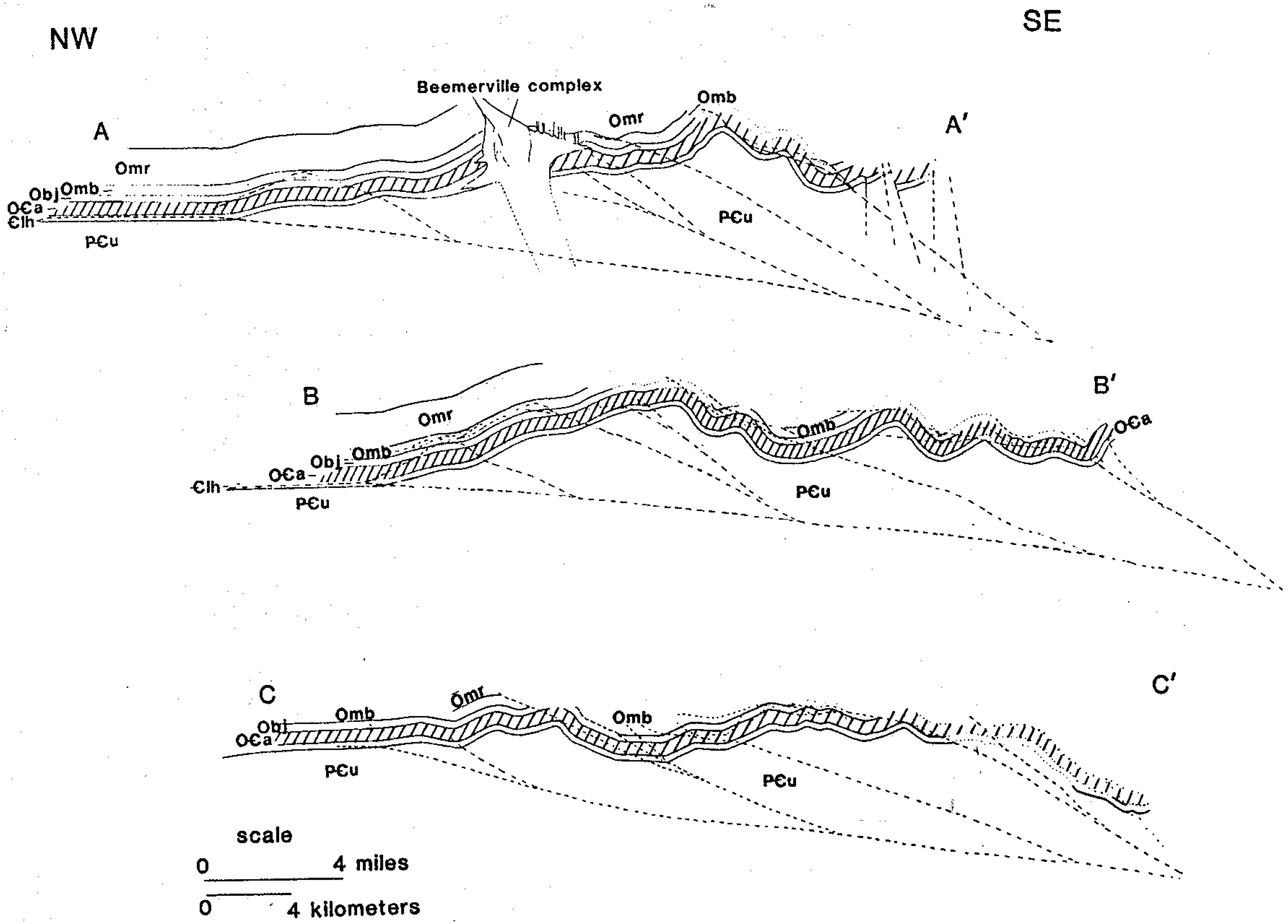


Figure 17 - Series showing pre-thrust restored regional cross sections A-A', B-B',and C-C'relative to current Ordovician- Silurian map contact. Section location and description of units given on plate 1. DSu - Devonian rocks through Poxono Island Fm.

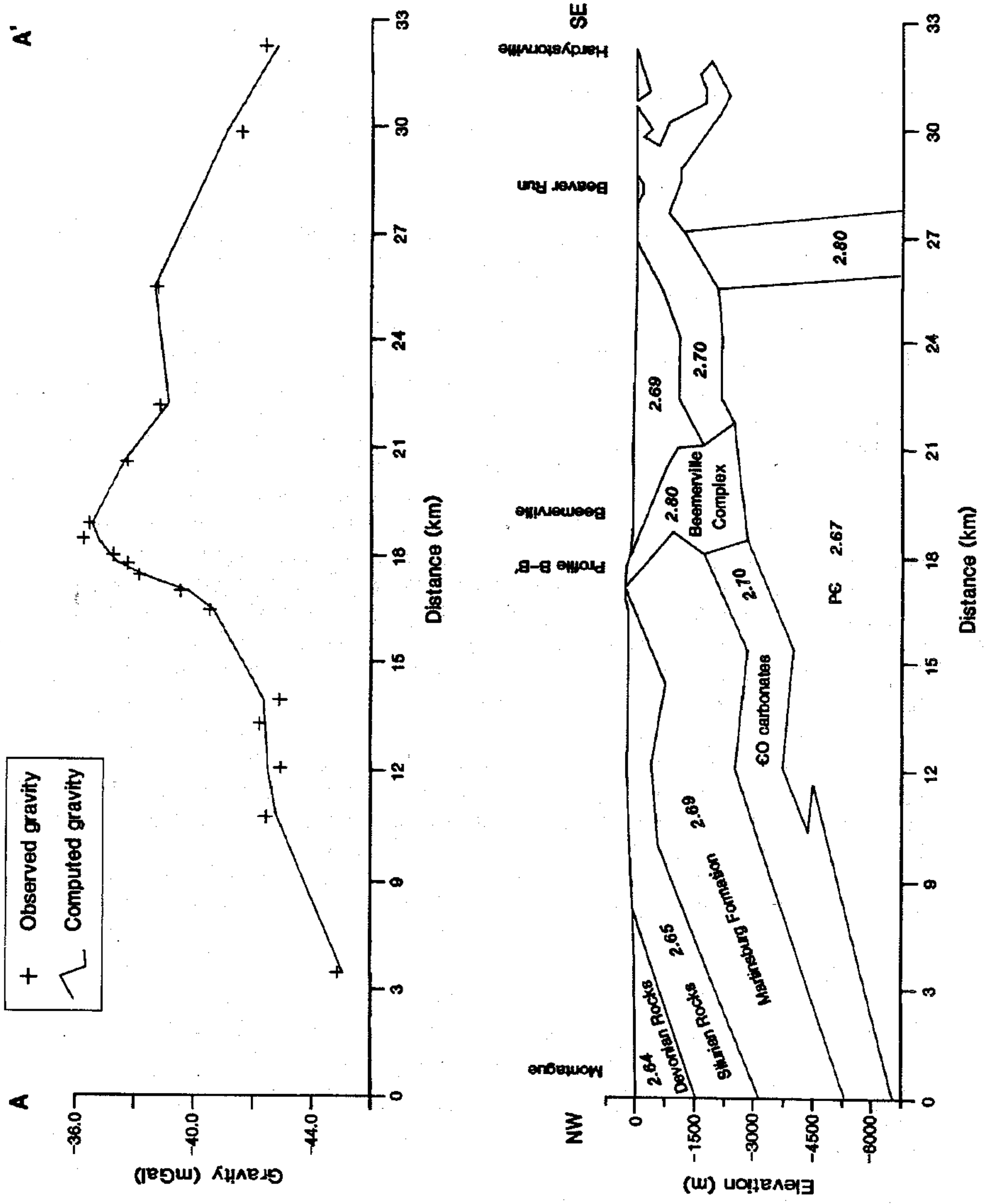


Figure 18. Gravity profile A-A' and interpreted cross-section from Ghatke and others (in press)

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).

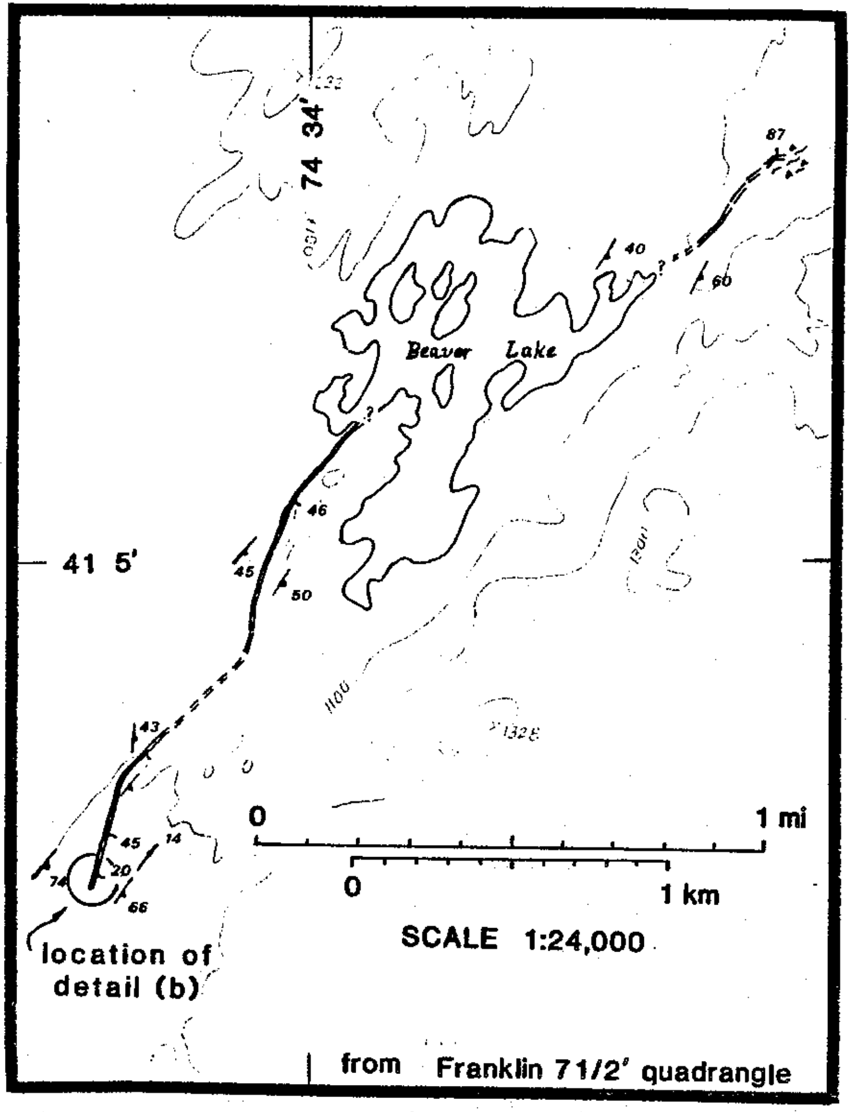
Beginning as early as the uppermost Early Ordovician (Arenigian), the carbonate platform was developing a foreland-migrating peripheral bulge, possibly as shown for the Appalachian margin by Jacobi (1981) and Shanmugam and Lash (1982). Foreland lithospheric block faulting and associated cover layer folding 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, 19~~84~~69). 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.

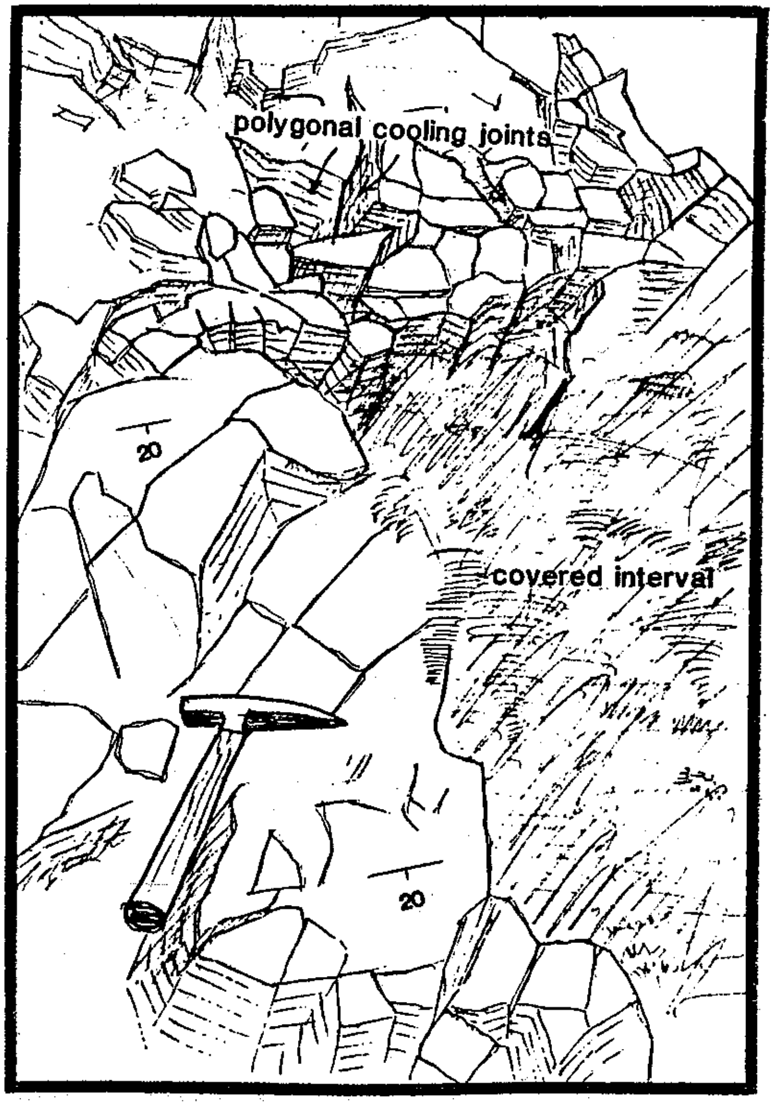
Recent mapping (this paper) supports the proposed Ordovician age of these dikes. Additional support stems from the spatial relation of the dikes to the block faults that locally offset and fold the Cambrian-Ordovican cover rocks, and from limited mesostructural data. For example, a dike that crops out 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.



from Franklin 71/2' quadrangle

(a)



(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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