The Richmond and Greenwich Slices of the Hamburg Klippe In Eastern Pennsylvania—Stratigraphy, Sedimentology, Structure, and Plate Tectonic Implications

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By GARY G. LASH *and* AVERY ALA DRAKE, JR.

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A stratigraphic, sedimentologic, and structural study of a major Taconic-type allochthon in the Great Valley of eastern Pennsylvania

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CONTENTS

ILLUSTRATIONS

TABLE

THE RICHMOND AND GREENWICH SLICES OF THE HAMBURG KLIPPE IN EASTERN PENNSYLVANIA—STRATIGRAPHY, SEDIMENTOLOGY, STRUCTURE, AND PLATE TECTONIC IMPLICATIONS

By GARY G. LASH[1] and AVERY ALA DRAKE, JR.

ABSTRACT

Taconic-type klippen, such as those in the northern and maritime Appalachians, are also characteristic of the Taconides of the central Appalachians. One such body of rock, the Hamburg klippe, anomalous with respect to the age and lithology of its surroundings, has long been recognized in the Great Valley of east-central Pennsylvania.

The Hamburg klippe is bounded on the southeast by the parautochthonous rocks of the Lehigh Valley sequence of Cambrian and Ordovician age. The carbonate rocks of this sequence were deposited on the southeast-facing shelf of the North American Continent and, with the underlying Proterozoic Y basement, were deformed into the Musconetcong nappe system during the Taconic orogeny. Rocks of the parautochthonous nappe system were thrust onto the klippe during the Alleghanian orogeny. To the north, the klippe is in fault contact with both the Shochary Ridge sequence of Ordovician age and the Shawangunk Formation of Late Ordovician(?) or younger age.

Recent detailed mapping at the eastern end of this klippe, between the Schuylkill River and Kutztown in eastern Pennsylvania, has led to the recognition of two stratigraphically and structurally different slices. The lower Greenwich slice consists of rocks of the Windsor Township Formation. The Windsor Township is a Middle Ordovician flysch sequence that contains various-sized bodies of Lower Ordovician chert, deepwater limestone, and variegated shale. The Windsor Township (about 6,215 m thick) consists of three members: (1) the Weisenberg (1,740 m thick), a gray-green shale unit that contains local conglomerate beds; (2) the Switzer Creek (815 m thick), a graywacke–gray-green shale unit that contains local pebble conglomerate; and (3) the Dreibelbis (3,660 m thick), a graywacke–gray-green shale unit. The sedimentology and stratigraphy of these rocks suggest that the graywacke units (Dreibelbis and Switzer Creek) were deposited as channel-axis grain-flow and turbidite sediments and as interchannel turbidite sediments, whereas rocks of the Weisenberg (the shale unit) were deposited as levee and open-fan muds adjacent to the channels. The rocks of the Windsor Township Formation were deposited in the middle-fan area of a large submarine fan, which had a continental source to the southeast. The older lenticular bodies of chert, deepwater limestone, and variegated shale are not restricted to any particular member but are found throughout the Windsor Township. These rocks probably were deposited in an abyssal environment that received periodic influxes of terrigenous material. They were emplaced later into the younger fan deposits.

The upper Richmond slice contains rocks of the Virginville Formation of Late Cambrian and Early Ordovician age. This unit is divided into three members: (1) the Sacony (245 m thick), consisting of olive-green siltstone and shale; (2) the Onyx Cave (90 m thick), consisting of massive to laminated calcarenite, ribbon limestone, massive carbonate-clast conglomerate, and interlaminated black shale and orange dolostone; and (3) the Moselem (230 m thick), consisting of well-cleaved black and green argillite and mudstone and lesser proportions of ribbon limestone and carbonate-clast conglomerate. The Onyx Cave conformably overlies the Sacony, and both tectonically overlie the Moselem. The sedimentology and stratigraphy of these rocks suggest that (1) they were deposited near the base of a northwest-facing slope and (2) the Moselem is a distal equivalent of the Onyx Cave and was deposited to the northwest of it. We suggest that the rocks of the Virginville were deposited on a northwest-dipping slope adjacent to a shallow-water carbonate shelf. Subsequent to deposition, northwest-directed thrust faulting brought the Sacony and Onyx Cave over the Moselem.

The rocks of the Hamburg klippe record the effects of three phases of deformation. Folds related to the first and third phases trend east-northeast to east-southeast and, generally speaking, are differentiated only where overprinting is recognized. The second deformation phase produced folds that trend northeast. Faults within the Greenwich and Richmond slices range from steeply to moderately dipping upthrusts to subhorizontal thrust faults and typically are not well exposed. The contact between the Richmond and Greenwich slices is a thrust fault marked by slivers of Greenwich slice rocks tectonically mixed into the lower part of the Richmond slice.

Rocks in the Richmond slice and the parautochthon deformed differently than those in the Greenwich slice. The less competent rocks of the Richmond slice and surrounding parautochthon contain a slaty cleavage that is axially planar to folds formed during the first deformation (D_1). The rocks of the Greenwich slice generally lack this cleavage but exhibit a scaly cleavage or a poorly developed fracture cleavage consisting of a group of intersecting fracture planes generally subparallel to bedding that formed prior to D_1. The fabric of these rocks is similar to that of tectonic mélanges formed by mechanical fragmentation and mixing.

Results obtained in the present study, combined with data from other investigations within the Pennsylvania Great Valley, are consistent with a plate tectonic model that involves late Proterozoic rifting leading to the development of a marginal basin separating the North American craton from a microcontinent to the southeast. In Cambrian to early Middle Ordovician time, carbonate shelves developed on both the craton and microcontinent. The Virginville Formation was deposited on the lower slope adjacent to the shelf of the microcontinent. Southeast-dipping subduction of the North American craton, as well as any oceanic crust that may have lain to the southeast of it, beneath the microcontinent began in late Early Ordovician to early Middle Ordovician (Chazyan) time. Subduction was accompanied by (1) trench sedimentation of the flyschoid rocks of the Windsor Township Formation, (2) off-scraping and gravity

[1] Department of Geology, State University of New York College at Fredonia, Fredonia, NY 14063.

emplacement of the approaching older abyssal sediments, and (3) subduction-related deformation of all rocks of the Greenwich slice. The marginal basin was essentially closed by late Blackriveran to early Rocklandian time. Because the thick, buoyant continental crust of North America was unable to subduct beneath the microcontinent, the eastern margin of the North American craton was uplifted, exposing the miogeoclinal cover (Black River hiatus). At this time, deposition of the Jacksonburg Limestone and Martinsburg Formation exogeoclinal sequences began in response to uplift to the southeast. Stress continued to build up along the contact of the two plates during Rocklandian to Kirkfieldian time. Consequently, slices of continental basement from the eastern margin of North America were detached along southeasterly dipping ductile shear zones and were thrust into the overlying miogeoclinal sediments, resulting in the formation of a nappe system. The Richmond slice probably was thrust onto the Greenwich slice, and both were superposed on the forming nappe pile at this time of extreme crustal convergence. Continued northwest-directed movement of the nappes and Hamburg klippe during Shermanian time was followed by detachment of the allochthon from the advancing nappe pile and, finally, by its emplacement into the developing Martinsburg foredeep to the northwest.

INTRODUCTION

A large klippe consisting of several stacked slices is a major tectonic feature of the Taconide zone in the northern Appalachians (Zen, 1972). Taconic-type klippen are characteristic also of the Great Valley of the central Appalachians in New Jersey and especially eastern Pennsylvania (Drake, 1980). The eastern end of the largest klippe in Pennsylvania, the Hamburg klippe (Stose, 1946), was studied in the Kutztown and Hamburg 7½-minute quadrangles and surrounding areas (fig. 1).

These quadrangles lie along the northern side of the Great Valley of eastern Pennsylvania. There, the Great Valley is bounded on the north by quartzites of Late Ordovician(?) to Silurian age that hold up Blue Mountain of the Appalachian Valley and Ridge. On the south, the Great Valley is bounded by the Proterozoic Y rocks of the Reading Prong.

This paper describes, in detail, the stratigraphy, sedimentology, and structure of the rocks of the eastern end of the Hamburg klippe and speculates on the depositional environments and the plate tectonic implications of these rocks.

PREVIOUS WORK

Allochthonous rocks in the Great Valley of Pennsylvania were recognized by Stose (1946, 1950a, b), Stose and Jonas (1927), and Kay (1941). These noted similarities between these rocks and rocks of the Taconic sequence of New York and New England. Stose (1946) referred to these rocks as the "Hamburg klippe." Proponents of the Hamburg klippe maintained that the rocks are lithologically different and older than the surrounding Martinsburg Formation.

Despite the arguments of Stose, Kay, and other geologists, Gray and Willard (1955) asserted that the variegated shale and associated rocks are facies equivalents of the parauthochthonous Martinsburg Formation and are not allochthonous. In addition, McBride (1962) in his study of the Martinsburg in New Jersey, Pennsylvania, and Virginia, recognized no allochthonous rocks.

In the late 1960's and early 1970's, several geologists studied the Hamburg klippe. Field studies by Myers (1969) and Platt and others (1972) showed that there are, indeed, allochthonous elements within the Great Valley. These studies, supported by faunal evidence, have shown that the rocks of the Hamburg klippe are older than the surrounding Martinsburg Formation. An Early Ordovician age for the klippe rocks was indicated.

Root (1977) and Root and MacLachlan (1978) discussed the stratigraphy and structure of the western end of the Hamburg klippe. Recently, Lash (1980a, b) and Kodama and Lash (1980) have described a plate tectonic model for the emplacement of the Hamburg klippe.

GEOLOGIC FRAMEWORK

In the Kutztown quadrangle, the rocks of the Hamburg klippe are thrust to the north onto the Shochary Ridge sequence (Lyttle and Drake, 1979) of interbedded graywacke and shale of Middle to Late Ordovician age (Wright and others, 1978, 1979). The allochthonous rocks in the Hamburg quadrangle are in fault contact with the clastic Upper Ordovician(?) and Lower and Middle Silurian rocks of the Shawangunk Formation and Upper Ordovician and Lower Silurian(?) rocks of the Spitzenberg Conglomerate of Whitcomb and Engel (1934). These rocks mark the southern boundary of the Valley and Ridge in the area of study. The allochthonous rocks are bounded to the south by parautochthonous rocks of the Lehigh Valley sequence, the contact being the Kutztown thrust, a gently southeast-dipping fault.

The Lehigh Valley sequence (MacLachlan, 1967) consists of the Allentown Dolomite, Beekmantown Group, Jacksonburg Limestone, and Martinsburg Formation (fig. 2). These rocks form the cover sequence of some of the nappes of the Reading Prong nappe megasystem of Drake (1978), a system of crystalline-cored, stacked nappes in the Great Valley of east-central Pennsylvania and western New Jersey. The Lehigh Valley sequence, therefore, is considered a parautochthonous sequence in the Alpine sense.

TERMINOLOGY

Some mention of terminology employed in this paper should be made. Bouma sequences (fig. 3) are used in a descriptive and nongenetic sense in discussions of the clastic rocks. The rock color chart (Goddard and others, 1948) is used to describe rock colors on fresh surfaces except where otherwise noted. Bedding parameters cited in the lithologic descriptions are from McKee and Weir (1953).

STRATIGRAPHY AND SEDIMENTATION

Field mapping, which led to this paper, indicates that the allochthonous rocks at the eastern end of the Hamburg klippe occur in two tectonic slices or lithotectonic units (fig. 1*B*). These slices are in fault contact and probably are bounded above by a thrust fault. The lower Greenwich slice, named for Greenwich Township in Berks County, Pa., is overlain by the Richmond slice, named for Richmond Township, Berks County, Pa.

Rocks within the Richmond slice of the Hamburg klippe comprise a sequence of quartzose rocks, carbonate rocks, and black and green shale and mudstone that is herein named the Virginville Formation. The tectonically underlying, but younger, Greenwich slice consists primarily of graywacke and shale and lesser amounts of limestone, chert, and conglomerate and is here named the Windsor Township Formation.

WINDSOR TOWNSHIP FORMATION

The Windsor Township Formation is here named for exposures along the east and west banks of Maiden Creek in Windsor Township, Berks County, between the towns of Dreibelbis and Kempton in the Kutztown and Hamburg 7½-minute quadrangles (fig. 1*B*). The formation is predominantly a graywacke-shale unit that locally contains boulder conglomerate and slivers of limestone, chert, and variegated shale and mudstone. The Windsor Township Formation is divided into three mappable members, here named (1) Weisenberg, (2) Switzer Creek, and (3) Dreibelbis. The Weisenberg is predominantly a shale, siltstone, and mudstone unit, and the Switzer and Dreibelbis are graywacke-shale sequences.

The Windsor Township Formation was mapped as "Lithotectonic Unit A" by Alterman (1972). She demonstrated that rocks of the Hamburg klippe and the Martinsburg Formation are different and should not be treated as lithologic equivalents. Our detailed mapping substantiates Alterman's contention that the Windsor Township is a distinct lithotectonic and rock-stratigraphic unit.

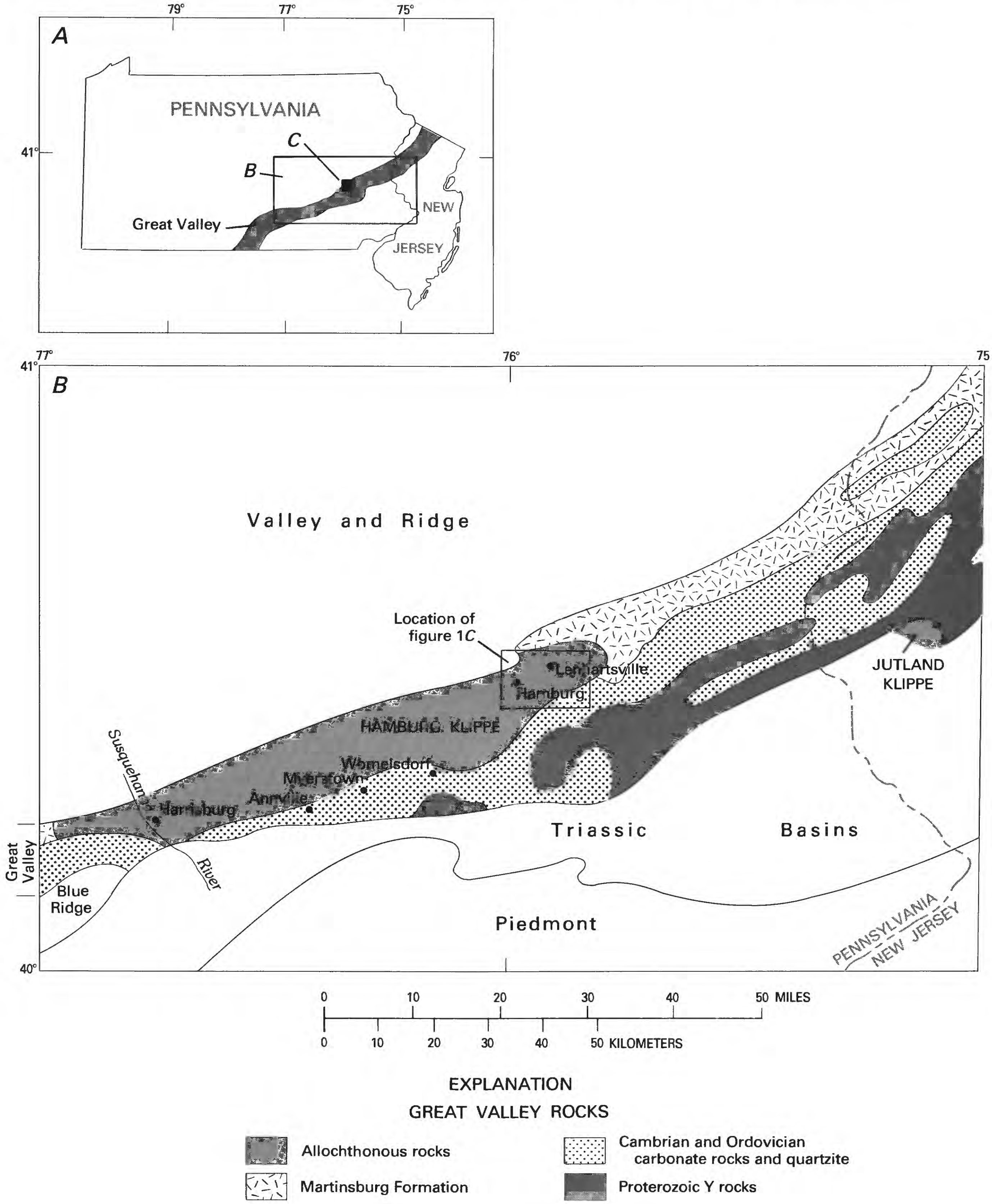
Intraformational faulting and the lack of marker beds preclude an accurate thickness determination, but the unit has a minimum thickness of 6,215 m, calculated on the basis of cross sections constructed for the Kutztown quadrangle (Lash, in press). This thickness may be somewhat high because of internal deformation.

WEISENBERG MEMBER

The rocks within the Weisenberg Member of the Windsor Township Formation consist of poorly cleaved to fissile, light-olive-gray (5*Y* 5/2) to olive-gray (5*Y* 3/2) and grayish-olive (10*Y* 4/2) shale, mudstone, and claystone to micaceous siltstone, containing local interbeds of medium-dark-gray (*N*4) to dark-greenish-gray (5*GY* 4/1) slightly silicified shale and mudstone. Locally associated with the pelitic rocks are well-sorted, parallel to cross laminated pale-brown (5*YR* 5/2) and yellowish-gray (5*Y* 7/2) thin-bedded siltstone, showing well-developed slump folds. The member also contains minor amounts of graywacke and chert. Polymict conglomerate deposits, here called the Werleys conglomerate and informally used to identify lenticular channel fill deposits in the Weisenberg Member, contain clasts of carbonate rock, silicified mudstone, and chert that are locally conspicuous. They are interpreted to be debris flows.

The Werleys conglomerate is best exposed in outcrops about 1,070 m east of Werleys Corner in the Slatedale 7½-minute quadrangle (fig. 1*B*). The conglomerate is a poorly sorted, polymict lenticular channel fill that contains clasts of limestone, shale, and sparse volcanic rocks. Clasts are as much as 7.5 cm in diameter. Weathering of the limestone clasts gives the rock a characteristic pitted appearance. Although outcrops are sparse, Werleys conglomerate is abundant in the Topton and Slatedale quadrangles and, to a lesser extent, in the New Ringgold and Kutztown quadrangles.

The Weisenberg Member is named for a series of exposures located about 1 km south of Weisenberg Church in the Slatedale quadrangle (fig. 1*B*). It varies in thickness from one area to another, depending on the presence or absence of the graywacke members discussed above. The thickest sequence of the Weisenberg in the area studied is 1,740 m, an estimate based


A
79°
77°
75°
41°
PENNSYLVANIA
C
B
Great Valley
NEW
JERSEY
B
77°
76°
75
41°
40°
Valley and Ridge
Location of figure 1C
Lenhartsville
Hamburg
HAMBURG KLIPPE
Womelsdorf
Myerstown
Annville
Harrisburg
Susquehanna River
JUTLAND KLIPPE
Triassic Basins
Great Valley
Blue Ridge
Piedmont
PENNSYLVANIA
NEW JERSEY
0 10 20 30 40 50 MILES
0 10 20 30 40 50 KILOMETERS
EXPLANATION
GREAT VALLEY ROCKS
Allochthonous rocks
Martinsburg Formation
Cambrian and Ordovician carbonate rocks and quartzite
Proterozoic Y rocks

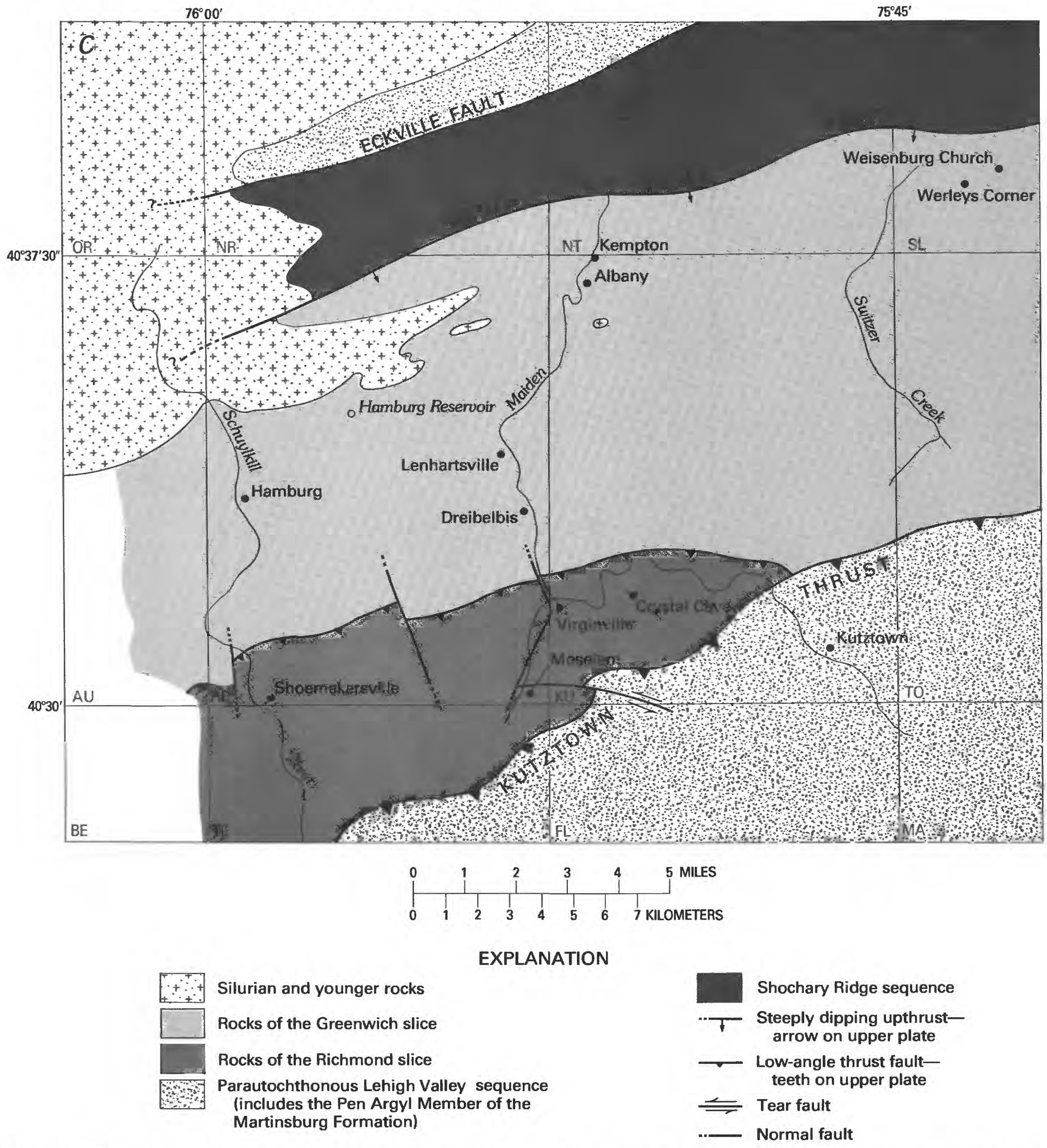


FIGURE 1.—Maps of eastern Pennsylvania. *A*. Map showing location of study area. *B*. Generalized geologic map of part of eastern Pennsylvania and western New Jersey. After Root and MacLachlan (1978). *C*. Generalized geologic map of the Kutztown and Hamburg 7½-minute quadrangles and surrounding areas. Geology of the Temple quadrangle modified from Wood and MacLachlan (1978). Geology of the New Ringgold, New Tripoli, and Slatedale quadrangles from Lyttle and Drake (1979). Quadrangles are Orwigsburg, OR; New Ringgold, NR; New Tripoli, NT; Slatedale, SL; Auburn, AU; Hamburg, HB; Kutztown, KU; Topton, TO; Bernville, BE; Temple, TE; Fleetwood, FL; and Maxatawny, MA.

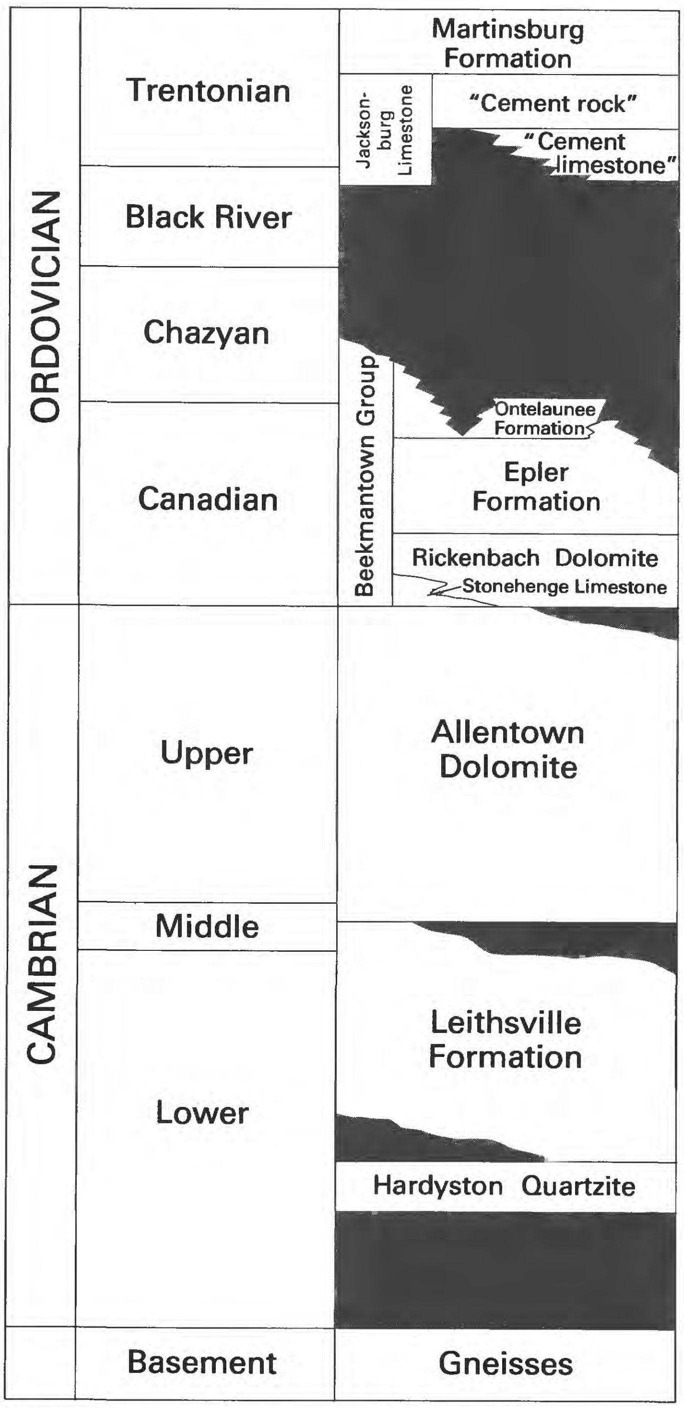


FIGURE 2.—Stratigraphic diagram of the Lehigh Valley sequence. Modified from MacLachlan (1967).

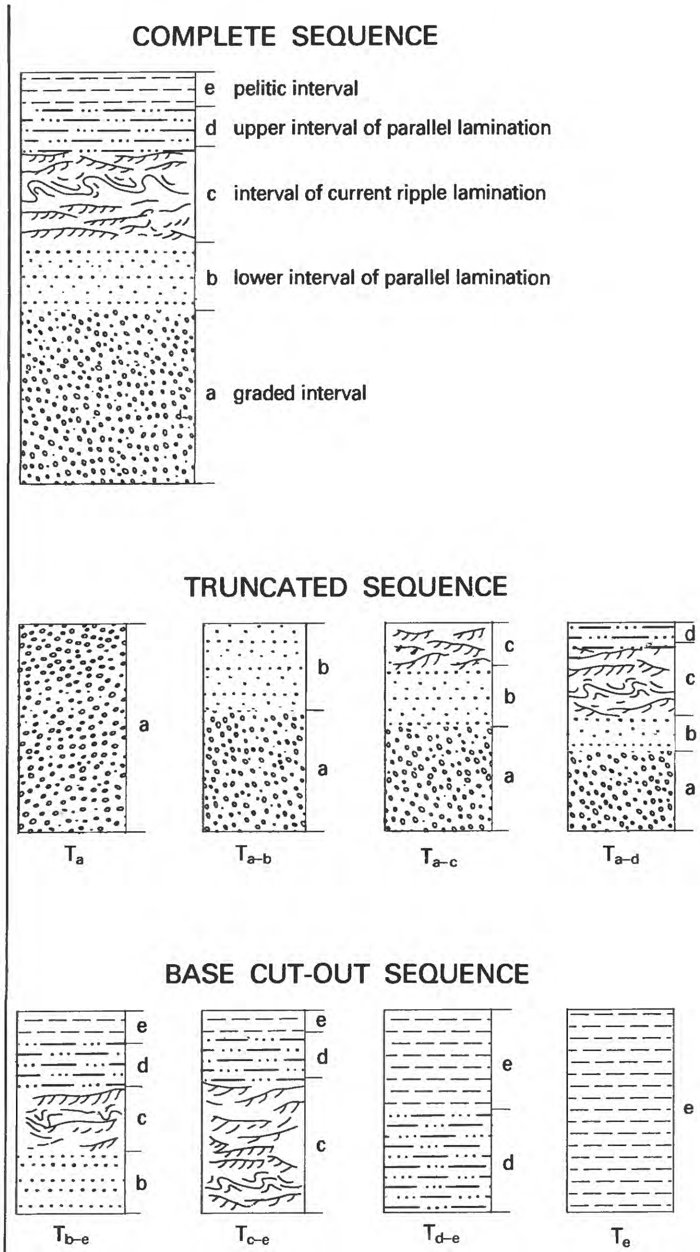


FIGURE 3.—Bouma sequence and variations. T indicates turbidite; small letters indicate the Bouma interval. From Bouma (1962).

upon the construction of geologic cross sections in the Kutztown quadrangle (Lash, in press).

Contorted bedding is the only sedimentary structure in the pelitic rocks other than bedding. These folds are best seen in the light-brown siltstone. The individual laminations have moved relative to each other, resulting in small-scale recumbent folds and faults (fig. 4).

SWITZER CREEK MEMBER

The Switzer Creek Member is named for exposures of interbedded calcareous graywacke and shale along Switzer Creek in the Topton and Kutztown quadrangles (fig. 1*B*). This member is characterized by thick-bedded, medium- to coarse-grained graywacke that contains local conglomerate beds that contain shale and limestone clasts. Graywacke sequences,

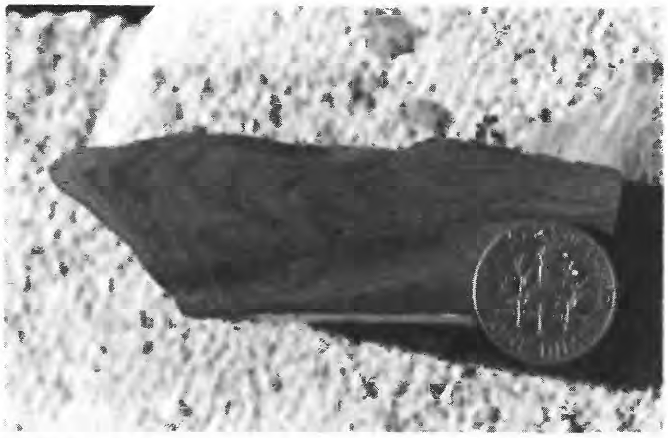


FIGURE 4.—Contorted beds and faults in siltstone of the Weisenberg Member. Coin for scale.

not amalgamated, contain interbedded dark-greenish-gray (5*GY* 4/1) to light-olive-gray (5*Y* 5/2) micaceous siltstone to mudstone. The Switzer Creek has a minimum thickness of 815 m, an estimate based on the construction of geologic cross sections in the Kutztown quadrangle (Lash, in press).

The high porosity of the graywackes of the Switzer Creek differentiates them from graywackes of the Dreibelbis Member. The porosity results from the weathering of the high proportion of limestone clasts and calcite cement in the sandstone. As a result of the weathering, the sandstone takes on a limonite-stained, rotten, pitted appearance.

Bedding in the Switzer Creek is thick to massive; locally, sequences of graywacke beds are amalgamated. In general, the rocks of the Switzer Creek contain a higher proportion of conglomeratic beds and T_a and $T_{a\text{-}e}$ partial Bouma sequences than the Dreibelbis Member.

DREIBELBIS MEMBER

The rocks herein named the Dreibelbis Member of the Windsor Township Formation constitute a sequence of interbedded graywacke and greenish-gray siltstone, mudstone, and shale best exposed along the west bank of Maiden Creek just north of Dreibelbis in the Hamburg 7½-minute quadrangle (fig. 1*B*). The lack of marker beds precludes an accurate thickness determination; however, the Dreibelbis has an apparent thickness of 3,660 m, as based on cross sections constructed for the Kutztown quadrangle (Lash, in press).

The rocks of the Dreibelbis Member were mapped as Martinsburg Formation by Willard (1943) and reported as such on the 1960 Geologic Map of Pennsylvania (Gray and others, 1960). More recently, Alterman (1972) named it the "Berks Formation."

The Dreibelbis Member is made up of three main rock associations. These rock types are not mutually exclusive and appear to be intercalated on all scales. These rocks, particularly the more coarse grained units, appear to form lens-shaped bodies, but, because of the poor exposure, formation of lens-shaped bodies cannot be proven.

The first rock association is typified by laminated to thin- to very thick bedded, medium- to coarse-grained calcareous graywacke interbedded with fine- to medium-grained, thin- to medium-bedded graywacke in $T_{c\text{-}e}$ partial Bouma sequences and very thin beds of siltstone and mudstone (fig. 5). The graywacke is associated with thick sequences of dark-greenish-gray (5*GY* 4/1) to grayish-olive-green (5*GY* 3/2) to light-olive-gray (5*Y* 5/2) fissile to poorly cleaved silty shale. These rocks are only locally exposed, the best exposures being along Route 143 approximately 370 m west of Albany in the northwest corner of the Kutztown quadrangle (fig. 1*B*).

Graywacke beds attain a maximum thickness of about 3 m. Bottom and top contacts are always sharp. Sole marks indicative of erosion (for example, groove casts as much as 20 cm in width) are common (fig. 6). Shale clast conglomerates occur locally. Thick graywacke beds are massive except for sparse parallel and long-wave-length ripple laminations. Sequences of amalgamated graywacke beds are locally conspicuous. Grading is uncommon.

Few of the thinner graywacke beds exceed 9 cm in thickness. These rocks are finer grained than the thicker graywackes. Most of these beds are not laterally continuous and may pinch out within the length of an outcrop. The partial Bouma sequence $T_{c\text{-}e}$ is common, although $T_{b\text{-}e}$ sequences occur in some outcrops. Well-developed parallel and ripple laminations, con-

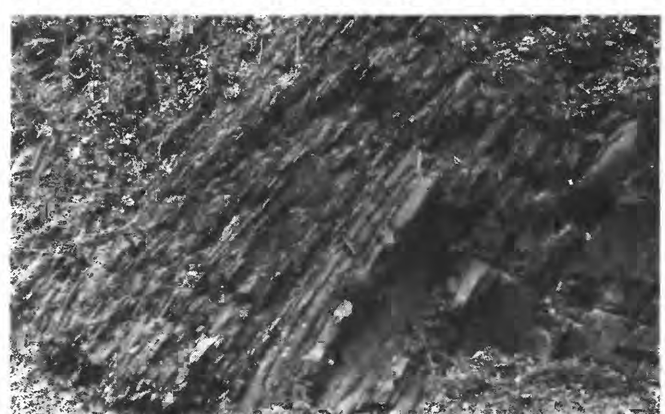


FIGURE 5.—Sequences of thick-bedded graywacke, siltstone, and mudstone of the Dreibelbis Member. Hammer lies along the contact of the graywacke beds (to the right of the hammer) and a thick sequence of mudstone and siltstone. Roadcut along Route 143 approximately 370 m west of Albany. Kutztown quadrangle.

FIGURE 6.—Groove casts on the sole of a thick graywacke bed. Roadcut along Route 143 approximately 370 m west of Albany, Kutztown quadrangle. Brunton compass for scale.

volute bedding, and graded bedding are conspicuous in these graywackes, whereas sole marks are sparse.

The second rock association is characterized by sequences of thick- to very thick bedded, massive to parallel and long-wave-length ripple laminated, medium- to coarse-grained and locally conglomeratic, somewhat calcareous graywacke sandstone and lesser proportions of interbedded light-olive-gray (5 *Y* 5/2) to dark-greenish-gray (5*GY* 4/1) fissile siltstone and mudstone (fig. 7). The graywackes are poorly to well graded, and the partial Bouma sequence $T_{a\text{-}e}$ is common, although $T_{a\text{-}b}$ and sparse $T_{b\text{-}e}$ and $T_{c\text{-}e}$ sequences are known. Individual graywacke beds as thick as 3 m were measured, but the average thickness is between 0.5 and 1 m. Pelitic intercalations range from thin, discontinuous lenses to individual beds with an average thickness of approximately 12 cm.

FIGURE 7.—Predominantly thin- to thick-bedded graywacke with thin pelitic intercalations. Roadcut along Route 143 approximately 610 m north of Dreibelbis, Hamburg quadrangle. Hammer for scale.

Bedding is flat and parallel, and individual beds appear to be laterally continuous in outcrop. Most sole marks are scours, although lesser load and flute casts (fig. 8) are known. Some outcrops have flame structures along the contacts of massive graywacke beds with underlying pelitic intervals. Contorted beds suggestive of slump folds also are present in these rocks (fig. 9).

The third rock association of the Dreibelbis Member is characterized by medium to thick beds of fine-grained, locally calcareous sandstone interbedded with greenish-gray (5*GY* 4/1) fissile siltstone, mudstone, and claystone-shale. The $T_{c\text{-}e}$ partial Bouma sequence containing well-developed convolute bedding, and ripple lamination is extremely common. Both $T_{b\text{-}e}$ and $T_{d\text{-}e}$ partial Bouma sequences are known but are not common. Sole marks are sparse and consist mainly of load casts and lesser groove and flute casts.

FIGURE 8.—Flute casts on the sole of a thin $T_{c\text{-}e}$ turbidite. Current direction is from right to left (northeast). Rock is associated with thick channel-axis turbidite and grain-flow sandstones. Exposure approximately 2.4 km north of Lenhartsville, Hamburg quadrangle. Coin for scale.

FIGURE 9.—Contorted graywacke beds. Note the lack of folding in overlying mudstone and siltstone. Roadcut approximately 2.4 km northeast of Windsor Castle, Hamburg quadrangle. Shovel for scale.

These rocks are best seen in a series of exposures along the west bank of the Schuylkill River about 1.5 km south of Hamburg in the Hamburg quadrangle and in exposures along a secondary road approximately 1.2 km southeast of the Hamburg reservoir, also in the Hamburg quadrangle (fig. 1*B*).

MISCELLANEOUS UNITS

Lenticular to tabular bodies of poorly cleaved to fissile, red and light-green mudstone and shale interbedded with limestone and chert are ubiquitous within the Windsor Township Formation. They are randomly distributed and are not restricted to a specific member. As a result, these rocks have only local stratigraphic significance. Individual bodies of the variegated shale and associated rocks are as much as 240 m thick but are generally thinner.

These rocks consist of dusky-red (5*R* 3/4) to very dusky red (10*R* 4/2) and grayish-red (5*R* 4/2) mottled mudstone and argillite to micaceous shale that is locally interbedded with laminated to thin-bedded siltstone. Associated with the red shale and mudstone are roughly equal amounts of grayish-yellow (5*Y* 8/4) and pale-green (10*G* 6/2) to light-green (5*G* 7/4) mudstone and micaceous siltstone. At some places, thin-bedded, well-sorted siltstone is interbedded with the shale and mudstone.

Green and, less commonly, white chert and quartzite are interbedded with the mudstone and shale. Preliminary petrographic examination of the chert shows variable amounts of detrital quartz in a cryptocrystalline matrix. Millimeter-scale laminae of dolomite rhombs alternate with more quartzose laminae in some sections. Chert beds are as thick as 25 cm (fig. 10), but most are less than 5 cm thick.

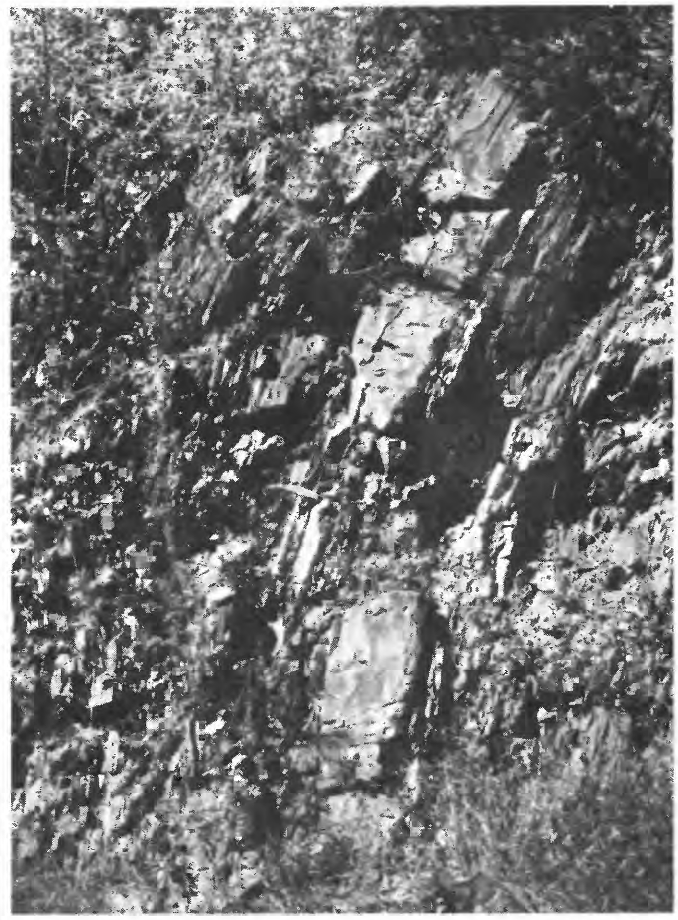


FIGURE 10.—Thick-bedded chert interbedded with red and light green shale and mudstone. The competent chert was boudined by hard rock deformation. Roadcut along Route 143 approximately 360 m west of Albany, Kutztown quadrangle. Hammer for scale.

Parallel lamination is the only sedimentary structure seen. The majority of the chert beds are discontinuous and display pinch-and-swell and pull-apart structures. The development of pinch-and-swell and pull-apart structures appears to be, in part, the result of tectonism, but differential compaction of the chert and mudstone probably was also a factor.

The red and green mudstone is associated with a grayish-black (*N*2) to medium-dark-gray (*N*4) to light-gray (*N*7) weathering, thin-bedded calcilutite (micrite) to calcisiltite. In some exposures, these rock types are separated by thin laminae of black (*N*1) shale. These rocks contain a variable amount of quartz, so that some of the carbonate rocks may be better described as quartzose limestone. Sedimentary structures are limited to parallel lamination and ripple cross lamination including climbing ripples. The laminations are especially well shown on weathered surfaces. Locally, the limestones are extremely distorted, suggesting differential compaction and slumping.

A limestone slide block or megaclast approximately 25 m in length was described by Epstein and others (1972) from an outcrop about 1.5 km east of Lenhartsville in the Kutztown quadrangle. This megaclast is composed of light-gray (*N*7) calcisiltite with starved ripples and climbing ripples surrounded by laminated dark-gray (*N*3) to medium-dark-gray (*N*4) calcareous shale (fig. 11).

Numerous smaller clasts have been found that are lithologically similar to the megaclast. These clasts apparently slumped into the green and red shales that surround them (Epstein and others, 1972). A similar deposit can be seen along the abandoned Reading Railroad grade on the east bank of Maiden Creek approximately 610 m southeast of Dreibelbis in the Hamburg quadrangle.

Contorted beds indicative of slumping (fig. 12) are well exposed in an outcrop of red mudstone and white dolomitic chert about 760 m southwest of Albany on Route 143 in the Kutztown quadrangle. At this locality, a 6.1-m-thick zone of rock has been folded. The folds are generally disharmonic, and, in some cases, an axial plane cleavage has formed. Moore and Geigle (1972) have described similar deformation in Holocene sediments in the Gulf of Mexico in which an incipient cleavage has formed axially planar to folds. Stone (1976) noted a similar phenomenon in glacial sediments in New England.

Polymict boulder conglomerate (figs. 13 and 14) crops out along Route 737 approximately 2 km north of Kutztown in the Kutztown quadrangle in an exposure approximately 1,435 m long. The boulder conglomerate contains clasts and megaclasts of calcareous graywacke, dark-greenish-gray (5*GY* 4/1) mudstone and

FIGURE 11.—Limestone megaclast consisting of starved ripples surrounded by calcareous shale. Exposure located approximately 1.5 km east of Lenhartsville, Kutztown quadrangle. Lens cover for scale.

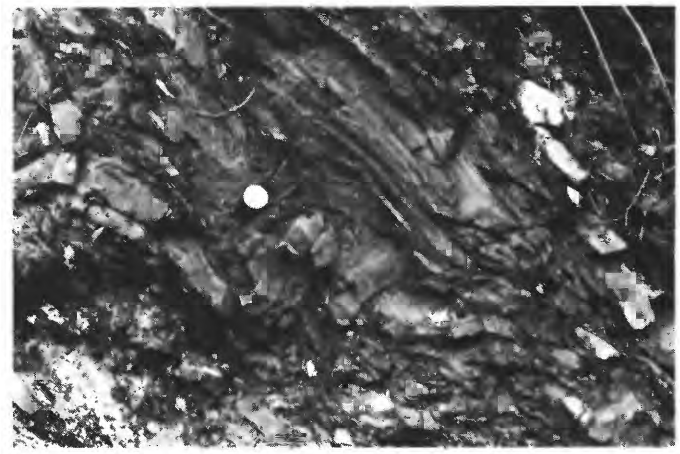


FIGURE 12.—Chaotic slump folds in interbedded red mudstone and white dolomitic chert. Roadcut along Route 143 approximately 760 m southwest of Albany, Kutztown quadrangle. Coin for scale.

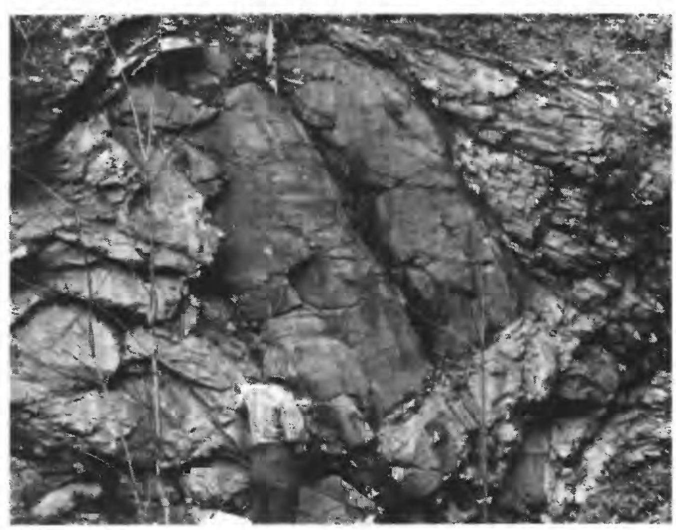


FIGURE 13.—Large graywacke clast (megaclast) in boulder conglomerate. Roadcut along Route 737 approximately 2 km north of Kutztown, Kutztown quadrangle.

FIGURE 14.—Irregularly shaped graywacke megaclast in boulder conglomerate. Note scaly cleavage in the matrix surrounding the clast. Roadcut along Route 737 approximately 2 km north of Kutztown, Kutztown quadrangle.

shale, grayish-black ($N2$) to dark-gray ($N4$) parallel laminated calcilutite and calcisiltite, pale-reddish-brown ($10R$ 5/4) sandstone, and chert, all of which are rock types that occur in the Windsor Township Formation, randomly oriented in a highly contorted matrix of medium-dark-gray ($N4$) to dark-greenish-gray ($5GY$ 4/1) and grayish-olive ($10Y$ 4/2) to pale-green ($10G$ 6/2) shale and mudstone that wraps around the clasts. Graywacke clasts are dominant and range in size from less than 2 cm to 3 m or more in length. Some of the larger blocks are "polished" along their bottom surfaces, indicating that they slid into place.

Detailed study of the exposure along Route 737 indicates that the boulder conglomerate is zoned with respect to clast lithologies and sizes. Moving north along Route 737, the first 305 m of the conglomerate contains clasts of shale, mudstone, reddish-brown siltstone, and limestone. The largest clast is approximately 0.3 m long. This rock type grades into 915 m of conglomerate that contains extremely large clasts or megaclasts of graywacke, mudstone, and limestone. The next 30 m or so of conglomerate contains calcilutite clasts almost to the exclusion of all other types. The matrix for these clasts is the distinctive pale-green ($10G$ 6/2) mudstone that so commonly occurs in the units of chert, limestone, and variegated shale and mudstone. The remaining 185 m of conglomerate contains small clasts of graywacke, shale, and limestone.

All clasts and the matrix of the boulder conglomerate are rock types that occur in the Windsor Township Formation. The graywacke is texturally and mineralogically distinct from the graywacke of the Ramseyburg Member of the parautochthonous Martinsburg Formation to the south. In addition, the pelitic matrix of the boulder conglomerate is not the dark-gray ($N4$) claystone slate that is typical of the Bushkill and Ramseyburg Members of the Martinsburg Formation but is typical of the Windsor Township Formation. This distinction becomes very important in deciding whether or not the boulder conglomerate represents a wildflysch in the Martinsburg.

Alterman (1972) first recognized this conglomerate and described it as a "wildflysch-type" of conglomerate, which heralded the approach of an allochthonous slice into the Martinsburg basin in much the same way as the wildflysch described by Bird (1969) and Zen (1972) heralded the advance of the allochthonous slices during sedimentation in the klippen of New York and New England. Analysis of the clasts in the conglomerate indicates that the clasts were derived from within the Windsor Township depositional basin, not the Martinsburg basin, and suggests a slumped level in the sense of Elter and Trevison (1973) with no input from sources outside the basin. The boulder conglomerate, therefore, should be considered as an intrabasin slump deposit.

GRAYWACKE PETROGRAPHY

Modal analysis of graywackes of the Dreibelbis and several samples of the Switzer Creek Members of the Windsor Township Formation indicates that they can be classified as quartzose to sublabilearenites (fig. 15), according to the classification of Crook (1960). The small amounts of unstable rock fragments and feldspar in the graywackes indicate that the graywacke detrital suite of the Dreibelbis is mature. Limited study of the graywackes of the Switzer Creek indicates that their detrital suite is somewhat less mature and contains slightly more lithic fragments and feldspar.

Quartz is by far the most abundant mineral in the sandstones of the Dreibelbis Member. Plagioclase (albite to sodic oligoclase) is the dominant feldspar and ranges from very clean, angular grains to almost completely sericitized grains. In general, detrital feldspar grains are smaller and more angular than accompanying quartz grains. Lithic fragments include mudstone and shale, limestone, and polycrystalline quartz (quartzite and chert). The mudstone and shale were derived from underlying pelitic intervals. Carbonate is an extremely variable component and occurs as cement, as authigenic rhombohedra of ankerite, and rarely in detrital grains. A few lithic clasts of argillite and possibly slate also were noted. The matrix of the graywacke consists of variable proportions of quartz, sericite, and carbonate.

Analysis of the quartzose-feldspar-lithic fragments (QFL) plot (fig. 15) indicates that the plot cannot differentiate sandstones of the Dreibelbis Member

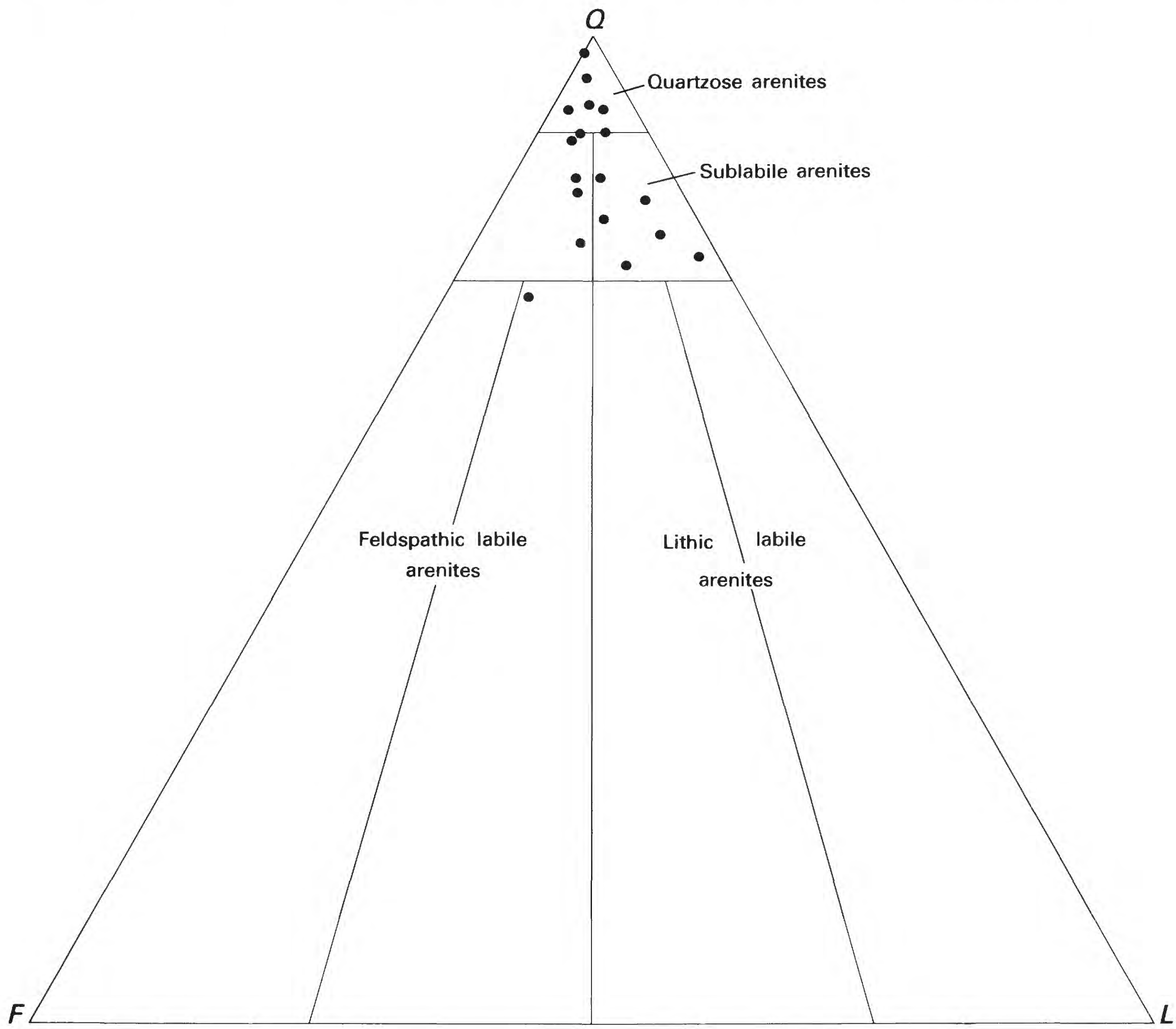


FIGURE 15.—Classification diagram (*QFL* plot) for the graywackes of the Windsor Township Formation. The diagram employs the classification scheme of Crook (1960). *Q*, monocrystalline and polycrystalline quartz; *F*, total feldspar; and *L*, lithic (rock) fragments.

from those of the Switzer Creek Member. In addition, other plots such as $Q_m FL$ (Q_m=monocrystalline quartz) and QFL_t (L_t=lithic grains) yield similar results. The main petrographic difference between the two units is the carbonate content, as can be seen in table 1. The graywackes of the Switzer Creek are obviously much higher in carbonate than those of the Dreibelbis. This difference is reflected in the weathered appearance of the Switzer Creek graywackes.

PROVENANCE

The importance of province studies in understanding the interplay of tectonics and sedimentation of a specific area was stressed by Suttner (1974). In addition, Dickinson (1970, 1971) contributed greatly to our knowledge of the various tectonic settings of graywackes of arc associations of the circum-Pacific region. His work indicates that graywackes derived from volcanic-arc settings are characteristically high in volcanic rock fragments and plagioclase.

Graham and others (1975) studied craton-derived graywackes from the Black Warrior Basin and the Ouachitas. They noted an almost total lack of volcanic detritus and feldspar and an overwhelming predominance of quartz in the detrital suite. The source area for these rocks is characterized by sedimentary rocks,

TABLE 1.—*Modal analyses of graywackes from the Windsor Township Formation*

[3, 9, 12, 13, 14, and 18, Switzer Creek Member; all others, Dreibelbis Member. A minimum of 400 points counted per section]

Constituent	Sample numbers																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Quartz	35.6	39.8	43.6	46.8	49.9	46.1	36.9	26.9	23.0	47.7	38.4	38.6	25.4	43.5	46.6	52.6	36.6	46.7
Plagioclase	3.4	2.2	2.2	3.3	1.7	.9	1.9	2.7	2.0	2.2	7.2	2.5	.5	1.9	4.3	1.7	.2	1.2
Potassium feldspar	.4	.5	0.0	2.0	.5	.7	.9	1.3	.7	2.1	2.9	.5	0.0	1.0	.5	.5	.7	.2
Rock fragments	5.5	2.5	9.6	6.0	4.4	3.8	1.9	4.2	5.5	7.3	6.2	3.4	0.0	.7	3.8	3.6	10.5	.9
Carbonate	0.0	4.7	11.0	2.0	0.0	10.3	6.6	5.1	10.5	6.7	9.3	23.0	2.6	19.0	8.6	7.3	7.6	10.8
Opaques	0.3	1.5	1.3	.2	1.2	1.0	.5	.4	.7	.5	.2	.3	1.0	.5	.3	.4	.8	.2
Accessories	.6	2.2	1.9	2.0	3.6	1.6	2.4	.6	1 6	.6	1.9	.2	1.4	1.0	.7	.7	.7	3.8
Matrix	55.3	47.4	31.4	40.1	39.9	37.2	49.4	57.7	57.2	32.9	36.3	31.5	69.1	32.4	35.9	35.1	43.9	36.2

low-grade metamorphic rocks, and some plutonic rocks.

Crook (1974) suggested a correlation between the framework constituents of graywackes and their tectonic setting. He proposed that the three types of continental margins described by Mitchell and Reading (1969) have distinct compositional varieties of graywackes associated with them. They are (1) quartz-rich modern deep-sea sand and ancient graywacke (greater than 65 percent quartz) that is typical of Atlantic-type continental margins, (2) quartz-intermediate modern sand and ancient graywacke (15 to 65 percent quartz) that typifies trench sediments along Andean-type margins, and (3) quartz-poor modern sand and ancient graywacke (less than 15 percent quartz) that is found along western Pacific margins in trenches external to volcanic-arc systems. This work has been substantiated by Schwab (1975) who included more data from modern and ancient sands.

The graywacke of the Windsor Township Formation falls within the quartz-rich field of Crook (1974) (fig. 16). Graywackes of this classification probably are derived from a predominantly sedimentary province containing minor plutonic and low-grade metamorphic admixtures. The presence of variable amounts of carbonate may reflect some input from a carbonate shelf.

The petrographic data, therefore, are consistent with a cratonic source characterized by sedimentary rocks, low- to medium-grade metamorphic rocks, and some plutonic rocks. The mineralogy of the sandstones suggests an Atlantic-type margin.

AGE AND CORRELATION

The age of the Windsor Township Formation is still an enigma in spite of recent paleontological studies. Wright and others (1978, 1979) report a Middle Ordovician (*Nemagraptus gracilis* zone) age on the basis of graptolite collections from graywacke and gray-green shale. Perissoratis and others (1979) report that graptolites from rocks of the Jutland klippe in New Jersey (see fig. 14), a sequence of rocks lithologically similar to the limestone, chert, and variegated shale units of the Windsor Township, range in age from Early (graptolite zones 2 to 4 of Berry, 1960, 1968) to Middle (graptolite zones 11 to 12 of Berry, 1960, 1968) Ordovician.

Bergstrom and others (1972) collected Early Ordovician conodonts from the limestone megaclast (fig. 11) mentioned in the description of the red and green shale units (p. 10). In addition, these collections contain a Balto-Scandic fauna, as opposed to a North American mid-Continent fauna of the coeval Beekmantown Group (Bergstrom and others, 1972). The Early Ordovician age is similar to some of the graptolite ages of the lithologically similar Jutland klippe but does not agree with the graptolite fauna of the graywacke and gray-green shale sequence of the Windsor Township Formation.

Recent graptolite collections from rocks of the Weisenberg Member (P.T. Lyttle, oral commun., 1978) support a Middle Ordovician age (*Nemagraptus gracilis* zone) for the gray-green shale and graywacke of the Windsor Township. In addition, conodonts collected from limestone associated with several of the chert, limestone, and variegated shale and mudstone units are of Early Ordovician age and constitute a Balto-Scandic fauna. A Middle Ordovician conondont was recovered from a chert, limestone, and variegated shale unit (J. E. Repetski, written commun., 1978), indicating that some of these rocks are coeval with the rocks of the graywacke-gray-green shale sequence.

These recent data support the age discrepancy described above and suggest, therefore, that a majority of the lenticular bodies of limestone, chert, and red and green shale, generally of Ordovician age, are allochthonous with respect to the Middle Ordovician graywacke-gray-green shale sequence of the Windsor Township Formation (fig. 17).

Recently, detailed stratigraphic studies at the western limit of the Hamburg klippe (Root, 1977; Root and MacLachlan, 1978) have shown that two allochthonous slices are in that area—the Enola allochthon and the structurally overlying Summerdale allochthon. Rocks of the Enola allochthon, of uncertain age,

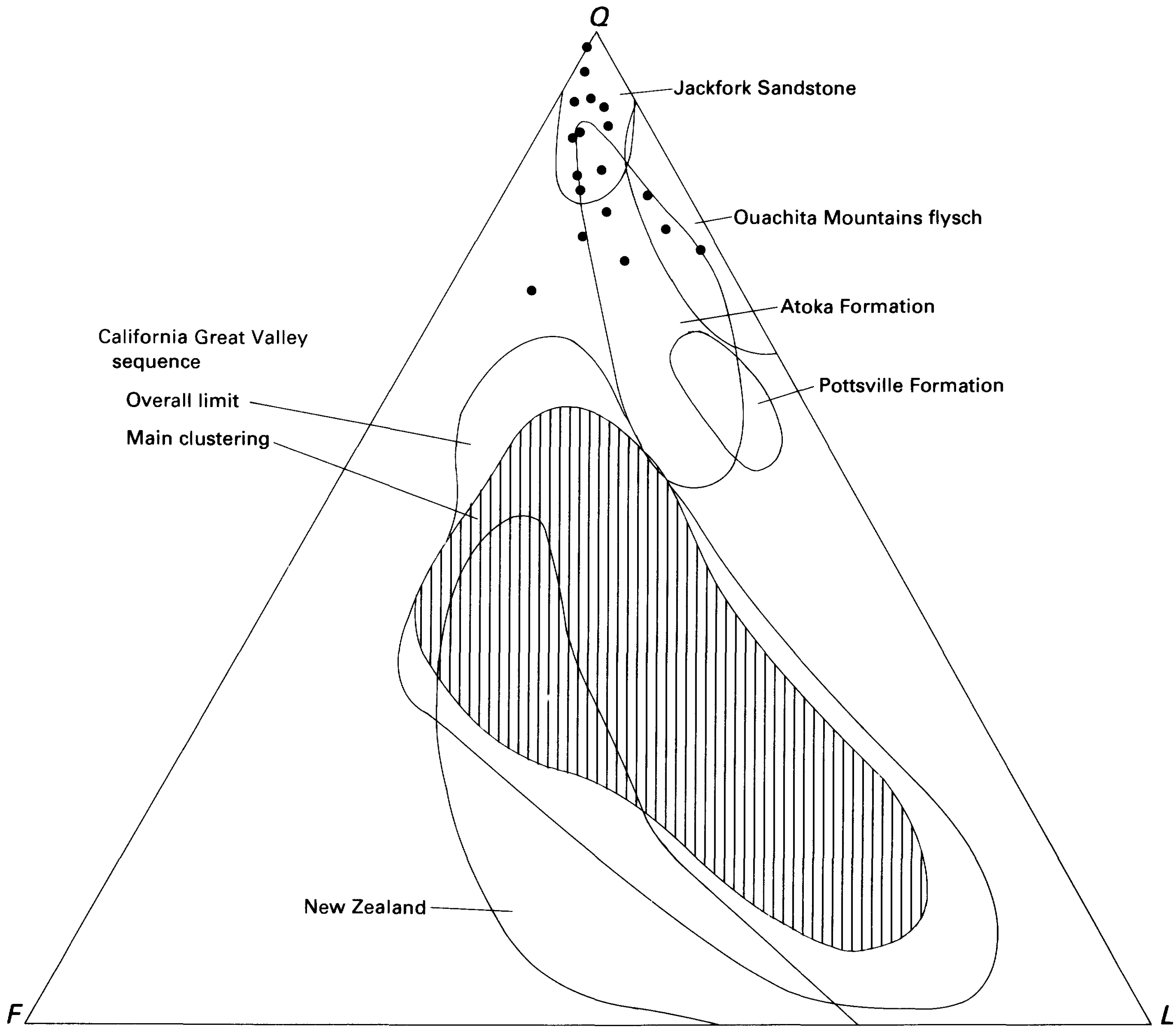


FIGURE 16.—Triangular (*QFL*) plot comparing detrital modes for the New Zealand graywackes, California Great Valley sequence, Black Warrior Basin (Jackfork Sandstone, Atoka Formation, and Pottsville Formation), and Ouachita Mountains flysch (Graham and others, 1975) and those of the present study (black dots). New Zealand and California Great Valley sequence graywackes are derived from a magmatic arc. The other graywacke suites are cratonic derived. *Q*, mono- and polycrystalline quartz; *F*, total feldspar; and *L*, lithic (rock) fragments.

are characterized by chert, limestone, and variegated shale and are quite similar, lithologically, to the variegated shale and mudstone units of the Windsor Township Formation. The Summerdale allochthon, also of uncertain age, consists of "greenish to medium-gray shales containing interbeds of calcareous graywacke 5 to 60 cm thick" and "arenaceous conglomeratic limestones and subordinate platy limestone" (Root and MacLachlan, 1978, p. 1521). Root and MacLachlan recognized the lithologic similarity of the carbonate rocks of the Summerdale allochthon to the carbonate rocks associated with the chert and variegated shale units of the Windsor Township. Therefore, the rocks of the Summerdale allochthon at the western end of the Hamburg klippe can be correlated with the rocks of the Windsor Township of the Greenwich slice.

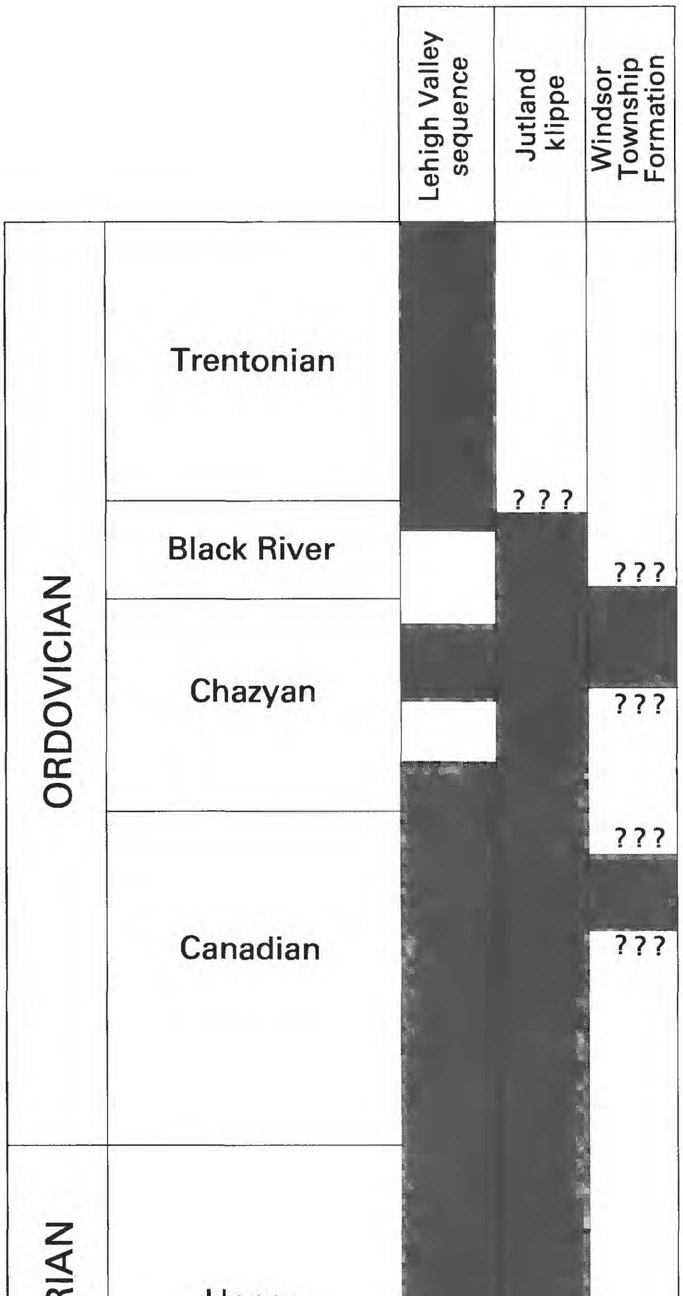


FIGURE 17.—Relations between the Lehigh Valley sequence, the Jutland klippe, and Windsor Township Formation. Age data from Bergstrom and others (1972), Epstein and Berry (1973), Wright and others (1978), Perissoratis and others (1979), and J. E. Repetski (written commun., 1978, 1979, 1980).

ENVIRONMENT OF DEPOSITION

Field and laboratory studies of the flyschoid rocks of the Windsor Township Formation suggest that the rocks represent middle-fan deposits of a large submarine fan. The submarine fan model and facies relations and terminology of the flysch deposits of the Hecho Group in the Spanish Pyrenees, as described by Mutti (1977) (fig. 18), have been adopted and somewhat modified for the study of the Windsor Township. The Dreibelbis Member is divided into three principal channel facies by using the classification of Mutti (1977): (1) the channel-margin facies, (2) channel-axis facies, and (3) interchannel facies. Detailed field mapping indicates that these facies are intercalated and suggests that the channel margin was shifting laterally with time.

The channel-margin facies is characterized by the thick- to very thick bedded, coarse-grained graywacke that is interbedded with fine- to medium-grained, thin bedded $T_{c\text{-}e}$ graywacke and siltstone and mudstone described on p. 8. The thick graywacke beds were probably deposited as grain flows. Mutti and Ricci-Lucchi (1978) maintain that deposits of this type are limited to the infilling of submarine valleys and channels. The thin-bedded $T_{c\text{-}e}$ beds are probably the result of dilute turbidity currents associated with deposition of the thick beds. Nelson and others (1974) and Mutti and Ricci-Lucchi (1978) proposed that these "distal" deposits can be interpreted as thin levee and overbank deposits related to the emplacement of the thick graywackes and, therefore, are deposited in a "proximal" environment.

The channel-axis facies is characterized by the monotonous sequences of thick-bedded, calcareous graywacke sandstone that contains lesser proportions of intercalated mudstone and siltstone. The thick sequences of graywacke so characteristic of the Switzer Creek Member of the Windsor Township Formation are probably channel-axis facies rocks. The channel-axis facies can be subdivided into two subfacies on the basis of somewhat different sedimentary structures. Channel-axis subfacies I is characterized by thick- to very thick bedded massive graywacke sandstone. Scour marks are common on the soles of these beds. This subfacies is similar to "Facies A" of Mutti and Ricci-Lucchi (1978) and appears to have been deposited as grain flows or fluidized flows or a combination of both. The channel-axis subfacies II is characterized by medium- to thick-bedded, parallel- and long-wavelength ripple laminated graywacke beds. These rocks were apparently deposited as grain flows that had tractive action during deposition (Mutti and Ricci-Lucchi, 1978). This subfacies is similar to "Facies B" of

Mutti and Ricci-Lucchi (1978).

The interchannel facies is characterized by the bundles of T_{c-e} partial Bouma sequences that are probably the result of dilute overbank turbidity currents associated with deposition of the thick graywackes of the channel-axis facies.

Rocks of the Weisenberg Member of the Windsor Township Formation are interpreted to be open-fan or levee mudstones and siltstones associated with the channel and interchannel facies rocks (see fig. 18) and as such resemble "Facies G" of Mutti and Ricci-Lucchi's (1978) classification. These sediments are apparently the product of deposition from dilute turbidity currents and nepheloid layers. In addition, the planar- to ripple-laminated siltstones present in the Weisenberg may be "fossil contourites" (Bouma, 1972a, b) and the product of redistribution of material by bottom-following contour currents. Evidence supporting this theory includes the presence of distinct upper and lower bedding planes, a low matrix content, and the well-sorted nature of the siltstones. Heezen and Hollister (1964) have described evidence indicating the presence of these relatively fast-moving, contour-following currents along continental rises.

The spatial distribution and intercalation of the various channel facies of the Dreibelbis Member suggest that interchannel and channel deposits are not mutually exclusive. Nelson and Nilson (1974) have shown that thick-bedded, coarse-grained sandstones can be found in interchannel environments and vice versa. They and other geologists (Shepard, 1966; Normark, 1970) maintain that modern fans and associated channels meander and migrate laterally, resulting in the intermixing of facies. The spatial arrangement of facies in the Windsor Township Formation illustrates this migration of channels in an ancient fan deposit.

As stated at the beginning of this section, the flyschoid rocks of the Windsor Township Formation were deposited in the middle-fan area (supra fan?) of a

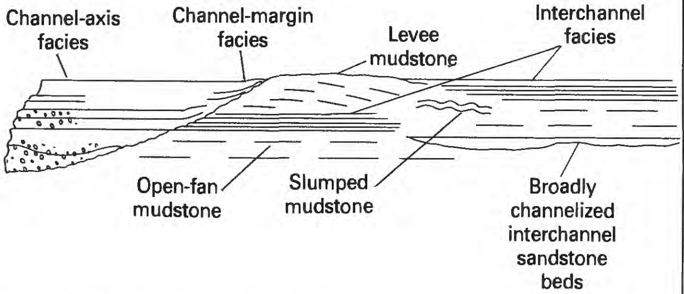


FIGURE 18.—Depositional model for the flysch facies of the Windsor Township Formation excluding the units of variegated mudstone and shale, limestone, and chert and the boulder conglomerate. From Mutti (1977).

large submarine fan. Evidence for this environment of deposition includes the (1) predominance of coarse-grained, thick graywacke beds that appear to represent channel fills flanked by fine-grained sandstone, siltstone, and mudstone in probable levee and interchannel areas, (2) abrupt vertical and lateral variation and distribution of rocks thought to be of the channel-axis and interchannel facies, (3) the predominance of T_a and T_{a-e} partial Bouma sequences, and (4) the lack of the conglomeratic facies that is indicative of an inner fan environment. The Dreibelbis and Switzer Creek Members, therefore, are thought to be sequences of turbidite and grain-flow deposits that were incised into the underlying levee and open-fan mudstone and siltstone of the Weisenberg Member. The graywacke units may have a lenticular geometry, but this geometry is impossible to prove at present. Small lenticular bodies of conglomerate deposits, informally called the Werleys conglomerate, are channel fills (see p. 3) that have cut into the underlying mudstone and siltstone of the Weisenberg Member.

Middle-fan channels in the Windsor Township Formation are characterized as shallow, braided, and depositional as opposed to relatively straight and deep erosional channels more typical of inner fan deposits (Ingersoll, 1978).

The assemblage of thin-bedded chert, limestone, and variegated shale and mudstone within the Windsor Township represents a "starved sequence" deposited in deep water; this interpretation, however, was not always accepted. These rocks have, in the past, been interpreted to be shallow-water continental sediments (Willard, 1939, 1943), although McBride (1962), somewhat later, maintained that they were deepwater marine muds. The carbonate rocks interbedded with the chert and variegated shale of the Windsor Township lends further support to a deepwater, bathyal or abyssal environment of deposition. Wilson (1969), Cook and Taylor (1977), and Scholle (1978) presented criteria elsewhere to distinguish deepwater limestone, deposited below wave base, from shallow-water limestone. The dominance of micrite and lesser amounts of calcisiltite, the lack of shallow-water structures, the presence of millimeter-scale planar and ripple laminations, and the dark color of the limestone within the Windsor Township suggest deposition in an environment below wave base. In addition, the Balto-Scandic conodont fauna present in these rocks, a cold-water fauna, is also suggestive of great depths of deposition. Studies of Holocene sediments by Bouma and Hollister (1973) indicate that red and brown clays are presently accumulating as deep-sea sediments at depths greater than 5,000 m. Although the carbonate rocks of the Windsor Township are deepwater limestones, the depth of the basin could not have exceeded the carbonate compensation depth of 4,000 to 5,000 m on the basis of average depths for modern ocean basins.

Most of the lenticular to tabular bodies of variegated shale and associated rocks are allochthonous with respect to the graywacke and gray-green shale of the Windsor Township Formation. One body contains a Middle Ordovician conodont (equivalent to the *Nemagraptus gracilis* graptolite zone, J. E. Repetski, written commun., 1978) and is, therefore, coeval with the graywacke and gray-green shale sequence of the Windsor Township. This occurrence may indicate intertonguing relations between the two rock types.

Petrographic studies of the graywacke and siltstone of the Windsor Township Formation point to a cratonic source area. The few volcanic clasts in the Werleys conglomerate of the Weisenberg Member may be older rift volcanics related to opening of the proto-Atlantic ocean. Although provenance is difficult to prove, slump folds in the graywacke suggest a paleoslope dipping to the northwest and, therefore, a southeastern source.

In summary, the rocks of the Windsor Township Formation were deposited in the middle-fan area of a submarine fan that had a probable source area to the southeast. The fan was active, as evidenced by the irregular spatial arrangement of the various turbidite facies that indicates the lateral migration and meandering of the channels. Limestone, chert, and red and green shale and mudstone represent bathyal to abyssal sediments. Apparent age discrepancies of the graptolite-bearing graywacke–gray-green shale sequence and the majority of the conodont-bearing red and green shale units indicate that the latter were deposited as pelagic sediments and later incorporated into the younger fan flysch.

VIRGINVILLE FORMATION

The Virginville Formation, named for the town of Virginville in the southeastern part of the Kutztown quadrangle, is herein defined as the 565-m-thick sequence of quartzose rocks, micrite, calcarenite, peloidal limestone, carbonate-clast conglomerate, and black shale and mudstone structurally overlying the Windsor Township Formation. Miller (1937) referred to these rocks as "Martinsburg Shale" and "Martinsburg Limestone." More recently, Alterman (1972) recognized the exotic character of these rocks and established that they were allochthonous. Neither the limestone nor the siliciclastic rocks have any known counterparts in the Lehigh Valley sequence.

The Virginville Formation crops out in the southwest corner of the Kutztown quadrangle and the southern part of the Hamburg quadrangle. Alterman (1972) mapped rocks resembling those of the Virginville in the Temple quadrangle south of the Hamburg quadrangle and west of the Schuylkill River as "Lithotectonic Unit A." Wood and MacLachlan (1978) showed that the Virginville probably extends well into western Berks County. They referred to these rocks as "Lithotectonic Unit 2" and "Lithotectonic Unit 4."

The Virginville Formation is divided into three members—the Sacony, the Onyx Cave, and the Moselem. The Moselem is tectonically overlain by the Sacony and Onyx Cave.

SACONY MEMBER

The Sacony Member is herein named for exposures of siliciclastic rocks along Sacony Creek 1.6 km northeast of Virginville in the Kutztown quadrangle. The Sacony was described as "Martinsburg Shale" by Miller (1937). Alterman (1972) referred to these rocks as the "Virginville Formation." The Sacony has a minimum thickness of about 245 m, an estimate based upon the construction of geologic cross sections in the Kutztown quadrangle (Lash, in press).

The rocks of the Sacony are typically massive, grayish-olive-green (5*GY* 3/2) to pale-blue-green (5*BG* 7/2) and locally grayish-red (10*R* 4/2) micaceous siltstone to sandstone containing intercalations of grayish-green (10*GY* 7/2) to pale-blue-green (5*BG* 7/2) micaceous shale and mudstone. They weather to a distinctive rust color, quite evident in the soil, which aids in mapping in areas of poor exposure. Bedding is marked by lithologic and color contrasts, as well as by planar surfaces having a micaceous sheen. Discontinuous layers of quartz and dolomite also delineate bedding.

A distinctive feature of the Sacony Member is the lenticular or ovoid masses of the rock seen in outcrop (fig. 19). These were noted by Alterman (1972) who believed that these masses have a sedimentary origin. A lack of internal structures that support this interpretation suggests that the masses result from weathering.

At places, minor amounts of chert and highly cleaved grayish-black (*N*2) to light-gray (*N*6) and light-green (5*G* 7/4) thinly laminated, silicified shale are interbedded with the sandstone and siltstone. A fissile grayish-black (*N*2) shale also is present at a few localities.

Averaged analyses of the siltstone and sandstone show that quartz is by far the predominant detrital mineral (24.0 percent), followed by plagioclase (2.5 percent), opaque minerals (2.3 percent), brown mica (2.2 percent), white mica (2.0 percent), potassium feldspar (1.1 percent), and lithic fragments (0.5 percent). Lithic fragments, which never exceed 0.8 per-

FIGURE 19.—Ovoid masses of Sacony Member siltstone. Beds dip to the left (south) at about 45°. Exposure is approximately 150 m north of Virginville, along the old Reading Railroad grade, Kutztown quadrangle. Hammer in lower left corner for scale.

cent, are always polycrystalline quartz (chert). Detrital micas as long as 0.27 mm were noted and show complex kinking from compaction. Some of the mica is not detrital and is related to an incipient cleavage. Quartz grains exhibit a medium to low sphericity, range from angular to round, and have slightly to strongly undulose extinction. Matrix constitutes 50 to 74 percent (average is 65 percent) of the rock and consists of chlorite, sericite, microcrystalline quartz, and minor amounts of brown mica.

ONYX CAVE MEMBER

The Onyx Cave Member of the Virginville Formation, herein named for exposures at Onyx Cave in the Hamburg quadrangle, conformably overlies the Sacony Member and is dominated by four distinct rock types: (1) thin- to thick-bedded, granular and quartzose limestone, (2) thin- to medium-bedded, parallel- and cross-laminated black lime mudstone to granular limestone interbedded with very thin to thin-bedded black, very finely crystalline to argillaceous limestone, (3) very thick bedded, massive carbonate-clast conglomerate, and (4) thinly laminated black shale and orange to light-yellow dolostone and fine-grained limestone. Local minor occurrences of thick-bedded quartzite and quartzose dolostone to granular dolostone are also present. All of the rock types can be found within a single outcrop of the Onyx Cave. The minimum thickness of the Onyx Cave, on the basis of geological cross sections constructed in the Kutztown quadrangle, is 90 m (Lash, in press).

Miller (1937) first described the carbonate rocks of the Onyx Cave Member, which he believed were interbedded with shales of the Martinsburg Formation. In his study, he made no distinction between "Martinsburg Shale" and the green siltstone and sandstone of the Sacony Member described herein. On the 1960 Pennsylvania State Geological Map (Gray and others, 1960), the limestones of the Onyx Cave are shown as limestones of the Beekmantown Group. Alterman (1972) referred to these rocks as the "Cave Limestone Member" of the "Virginville Formation" and regarded them as allochthonous.

The Onyx Cave Member conformably overlies the Sacony Member. The contact can be seen in an exposure approximately 1.5 km southeast of Onyx Cave in the Hamburg quadrangle. At this locality, younging directions in the Onyx Cave indicate that the sequence is right side up. The transition from the Sacony to the Onyx Cave is rapid and takes place over a distance of less than 1 m. Miller (1937) noted this exposure and cited a 3-m transition zone, but detailed petrographic studies do not support this. Directly overlying the green siltstone of the Sacony is a sequence of thinly laminated black shale and orange dolostone and calcisiltite. This sequence is in turn overlain and interbedded with ribbon limestones, thick polymict carbonate-clast conglomerate, calcisiltite, and thick quartzose limestone.

The Onyx Cave Member crops out as isolated patches. These patches are erosional remnants from a once larger mass. All of the major caves in the area except one have been formed along faults within the Onyx Cave.

The medium-light-gray (*N*6) calcarenites and quartzose limestones are typically massive. Micrite pebbles are found in several beds. Bedding is typically planar and parallel, although local lenses of quartzose limestone and calcarenite (fig. 20) cut into the underlying shale and argillaceous limestone. These lenses have maximum thicknesses of 18 cm and maximum widths of 1.5 m. These carbonate rocks may have been deposited in channels incised into shale and mudstone.

FIGURE 20.—Peloidal limestone filling channels in black shale and lime mud of the Onyx Cave Member. Roadcut located approximately 640 m north of Virginville, Hamburg quadrangle. Coin for scale.

The greater part of the Onyx Cave Member is made up of thin- to medium-bedded black (*N*1) to dark-gray (*N*3) lime mudstone to pelmicrite interbedded with thinner grayish-black (*N*2) to medium-dark-gray (*N*4) weathering to light-gray (*N*7) argillaceous lime mudstone or ribbon limestone. The limestones are typically parallel to cross laminated, but massive beds can be found. Graded beds are fairly common but are difficult to recognize in the field. Boudinage is common (fig. 21) and, since it does not appear to be tectonic, is apparently related to differential compaction of the mud and carbonate.

Slump folds are common within the ribbon limestones. Soft sediment slumps have been described in similar rocks associated with the Cow Head Breccia of western Newfoundland (Hubert and others, 1977).

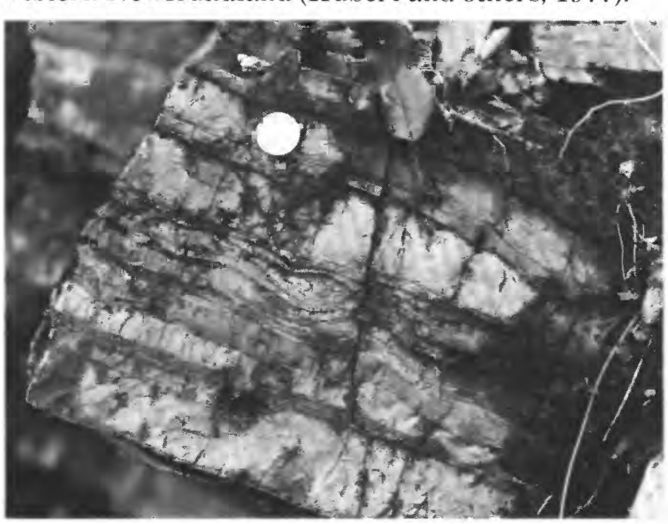


FIGURE 21.—Sedimentary boudinage in ribbon limestones of the Onyx Cave Member. Exposure located approximately 3 km north of Kutztown, Kutztown quadrangle. Coin for scale.

Because of their dark color, millimeter-scale planar and parallel beddng, scarcity of burrows, and lack of wave-produced structures, the limestone and shale are thought to have had a deepwater origin. Such criteria have been used elsewhere (Cook and Taylor, 1977) to connote a deepwater environment.

Polymict carbonate-clast conglomerates or edgewise conglomerates occur throughout the Onyx Cave Member (figs. 22 and 23). Individual beds are massive and range from 0.8 to 1.7 m in thickness. Clasts include micrite (lime mudstone), calcarenite, quartzose limestone, peloidal wackestone, calcisiltite, and locally moderate-yellowish-brown (10*YR* 5/4) dolostone. The clasts are derived from rocks common to the Onyx Cave. The majority of the clasts are tabular, ranging up to 25 cm in length, but well-rounded clasts also are common. Comminuted clasts show that they were of semi-indurated nature prior to deposition. Clasts within individual beds are not graded or sorted,

FIGURE 22.—Polymict carbonate-clast conglomerate of the Onyx Cave Member. The matrix is arenaceous. Variation in size and angularity of clasts is great. Bedding is irregular and has cut into underlying beds. Exposure is about 3 km north of Kutztown, Kutztown quadrangle. Mallet for scale.

FIGURE 23.—Polymict carbonate-clast conglomerate in the Onyx Cave Member containing clasts oriented perpendicular to bedding. Bedding is parallel to the bottom of the photograph. Exposure is located near the Sacony Bridge, Kutztown quadrangle. Mallet for scale.

although a few beds are capped by planar-laminated beds of graded sand-sized quartz and limestone grains.

The conglomerate matrix typically consists of well-rounded, in some cases frosted, quartz grains and peloids. Two of the beds studied, however, have a mudstone matrix. In these rocks, the clast-matrix ratio is much higher than that of the conglomerates having a sandy matrix. Clast fabric ranges from slightly imbricated to randomly oriented. In several examples, clasts are perpendicular to bedding (see fig. 23). Generally speaking, the clast-matrix ratio, clast size, and clast lithology do not vary systematically in vertical sections of beds, although the clast-matrix ratio decreases slightly up section in a few beds. The upper surface of individual conglomerate beds is planar to irregular and in some exposures is characterized by scour-and-fill structures.

Conglomerates in the Onyx Cave Member lack grading and stratification, and only a few are inbricated. Similar conglomerates have been described in detail by numerous geologists (Walker, 1970, 1975; Cook and others, 1972; Cook and Taylor, 1977; Cook, 1979; Krause and Oldershaw, 1979). Walker (1975) proposed descriptive models for conglomerates of turbidite associations on the basis of the presence or absence of grading (reverse or normal), stratification, and imbrication of clasts. Conglomerates in the Onyx Cave Member best fit Walker's disorganized bed model.

The conglomerates are associated with rocks interpreted to be turbidites. They may be channel fills, but no conglomerate bed was seen to pinch out within a single outcrop, and the lateral extent of the conglomerate beds is not known. Therefore, whether the conglomerates are sheet flows or channel flows cannot be determined.

Sequences of thinly laminated to laminated black and current-ripple-laminated (*N*1) to dark-gray (*N*3) and dark-yellowish-orange (10*YR* 6/6) to pale-yellowish-orange (10*YR* 8/6) dolostone and calcisiltite occur throughout the Onyx Cave Member. These sequences commonly show evidence of syndepositional deformation in the form of small folds and pinch-and-swell structures.

Thick-bedded, massive quartzite and quartzose dolostone to dolarenite occur locally. Scarcity of exposures precluded any detailed investigation of these rocks.

MOSELEM MEMBER

The Moselem Member of the Virginville Formation is herein defined as the 230-m-thick sequence of cleaved black and green mudstone and shale and variable amounts of carbonate rock best exposed along Maiden Creek north of Moselem and in the southern half of the Hamburg quadrangle. The Moselem is tectonically overlain by the Sacony and Onyx Cave Members. The unit differs from the Onyx Cave in that it contains more shale and mudstone and less carbonate rock. The carbonate rocks within the Moselem are grossly similar to those of the Onyx Cave. Alterman (1972) referred to the rocks of the Moselem as the "Black-Slate" unit, although she placed them in the same lithotectonic unit as the Windsor Township Formation of the present study.

In addition to the shale and mudstone described in more detail below, the unit also contains very thin to thinly bedded lime mudstone and micrite interbedded with argillaceous limestone to shale. The ribbon limestone of the Moselem Member, like that of the Onyx Cave Member, displays parallel to ripple lamination in some beds, whereas other beds show only sparse graded bedding. Slumped horizons are common and suggest a lower slope environment.

Sequences of thinly interlaminated black (*N*1) to dark-gray (*N*3) graphitic shale and dark-yellowish-orange (10*YR* 6/6) to pale-yellowish-orange (10*YR* 8/6) dolostone and calcisiltite are locally present. These sequences are, in some places, highly contorted and suggest some type of soft sediment deformation (fig. 24).

Carbonate-clast conglomerates within the Moselem Member are generally thinner than those in the Onyx Cave Member. In addition, the average clast-matrix ratio is somewhat lower in the conglomerates of the Moselem than that in the Onyx Cave.

Mudstone and shale, locally well cleaved, are the dominant rocks of the Moselem Member (fig. 25). Alterman (1972) noted the extreme variability of these rocks and attempted to divide them into mappable units. In the western part of the Kutztown quadrangle and the eastern part of the Hamburg quadrangle, the Moselem consists of thin- to thick-bedded, graphitic, grayish-black (*N*2) mudstone and shale interbedded with dusky-brown (5*YR* 2/2) mudstone or claystone and locally ribbon limestone. Lenses rich in pyrite and as much as 18 cm long occur at places. The weathering of the pyrite gives the rock an orange-tan color. Other lithologies within the member include thin- to thick-bedded, grayish-black (*N*2) dolostone interbedded with medium-dark-gray (*N*4) to medium-gray (*N*5) mudstone and light-gray (*N*7) siliceous shale.

FIGURE 24.—Contorted beds in interlaminated black shale and orange dolostone of the Moselem Member. Width of field is approximately 7 cm. Roadcut approximately 640 m north of Virginville, Hamburg quadrangle.

FIGURE 25.—Well-bedded, dark-gray mudstone and shale of the Moselem Member. Exposed in a quarry approximately 915 m northwest of Virginville, Hamburg quadrangle. Hammer for scale.

In the western part of the Hamburg quadrangle, the dominant rock type is dark-gray (*N*3) to dark-greenish-gray (5*G* 4/1) siliceous argillite, which contains lenses and discontinuous beds of chert. Thin-bedded, very light gray (*N*8) quartzite is interbedded with mudstone and shale locally. Pyrite nodules are extremely common in this rock and discolor it upon weathering.

The stratigraphic complexity of the Moselem Member probably results from the intertonguing of the different shales, mudstones, and carbonate rocks. Carbonate rocks are not restricted to any specific shale type but seem to be more commonly associated with the darker shales and mudstones rather than with the green varieties.

AGE AND CORRELATION

The age of the Virginville Formation is not known for certain. Recent conodont collections from the

Moselem and Onyx Cave Members (J. E. Repetski, written commun., 1978, 1979, 1980) suggest a Late Cambrian to late Early Ordovician (Arenigian) age (fig. 26). These rocks, therefore, are coeval with some of the bodies of chert, limestone, and variegated shale of the Windsor Township Formation. They are also coeval with parts of the Allentown Dolomite and Beekmantown Group of the Lehigh Valley sequence.

The Virginville Formation cannot be correlated lithologically with any of the units of the Lehigh Valley sequence. Parts of the Virginville do resemble the Araby Formation and parts of the Frederick Limestone of the Frederick Valley, Md. (Reinhardt, 1974, 1977). More specifically, the Sacony Member resembles the Araby Formation. Reinhardt (1974, p. 7) described the Araby, the Antietam Quartzite of Jonas and Stose (1938), as a "buff to tan or green siliciclastic rock unit" in which "bedding is poorly defined."

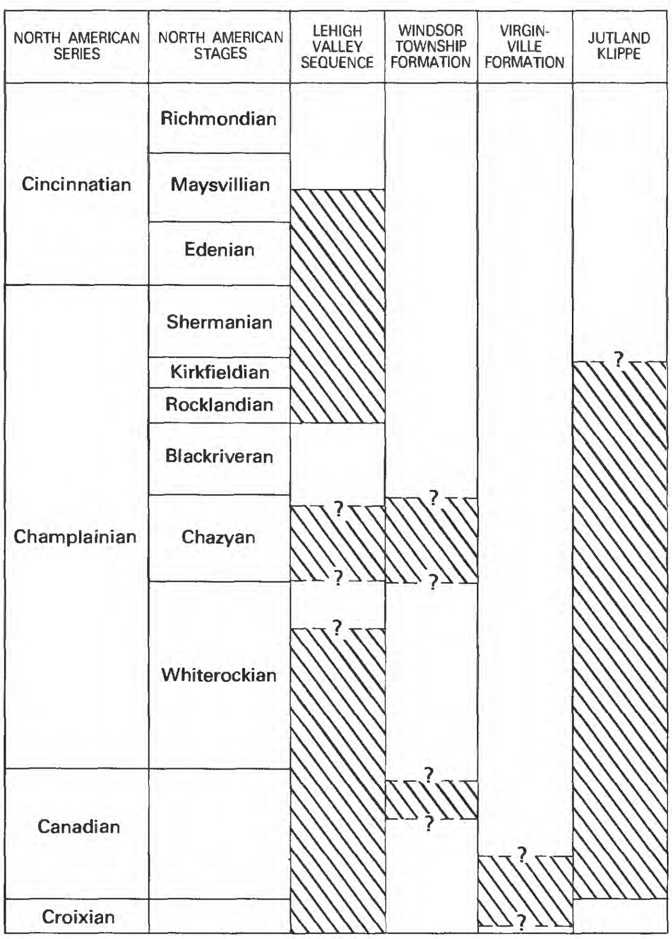


FIGURE 26.—Age relations between the Lehigh Valley sequence, the Windsor Township Formation, the Virginville Formation, and the Jutland klippe. Age data from Bergstrom and others (1972), Epstein and Berry (1973), Wright and others (1978), Perissoratis and others (1979), and J. E. Repetski (written commun., 1978, 1979, 1980).

The Onyx Cave Member is lithologically similar to the lower member of the Frederick Limestone, the Rocky Springs Station Member (Reinhardt, 1974, 1977) that conformably overlies the Araby Formation, whereas the Moselem Member has no lithologic counterparts in the Frederick Valley.

Despite the strong lithologic comparisons of the Frederick Valley sequence and parts of the Virginville Formation, a direct biostratigraphic correlation is lacking. In fact, the limited amount of faunal data collected from the Virginville suggests that the rocks of the Virginville are younger than the rocks of the Frederick Valley sequence.

ENVIRONMENT OF DEPOSITION

Stratigraphic and sedimentologic studies of the Virginville Formation indicate that the formation can be described as a slope and toe-of-slope deposit and probably part of an upward-shallowing sequence. Reinhardt (1974, 1977) envisioned the same paleoenvironment for the Araby Formation and the Frederick Limestone of Maryland. Study of the Sacony Member of the Virginville Formation suggests that the Sacony was deposited in a low-energy clastic basin below wave base, similar to the environment suggested by Reinhardt (1974) for the Araby. The strained quartz and minor, but conspicuous, amounts of microcline and plagioclase as framework constituents are indicative of derivation from a plutonic-metamorphic source, with some input from sedimentary rocks in the form of chert, and not from a volcanic source as suggested by Alterman (1972). Reinhardt (1977), on the basis of geochemical evidence, suggested a westerly cratonic source for the Araby. For reasons explained below, however, a southeasterly cratonic source is proposed for the Sacony Member.

The transition from the siliciclastic rocks of the Sacony Member to the carbonate rocks of the Onyx Cave Member, a slope deposit, is abrupt. The Onyx Cave consists of thin-bedded ribbon limestones and thinly interlaminated black shale and dolostone suggestive of deposition in a quiet slope or toe-of-slope environment below wave base. The carbonate-clast conglomerates and thick, massive calcarenites indicate periodic influxes of material related, in part, to local slumping on the otherwise quiescent slope. Keith and Freidman (1977) have described a similar type of slope and toe-of-slope sequence from the Taconic region of New York.

McIlreath and James (1978) have developed two facies models for carbonate slopes on the basis of the rock record and modern environments. The models are (1) depositional margins typified by slopes that are gentle and decrease in inclination basinward and (2) bypass margins characterized by a margin atop a cliff or submarine escarpment. The main difference between the two models is that, in bypass margins, material is transported directly from the shallow-water shelf to a deepwater environment, thus bypassing a large part of the slope; in the depositional margin, however, shallow-water material may not reach the middle or lower part of the slope because of the gentle inclination. In addition, the nature of the slope sediments are, in part, dependent upon whether the shallow-water margin is formed (1) by lime sands or (2) by reefs and associated reef material. The rock types and sedimentary structures indicate that the rocks of the Onyx Cave Member of the Virginville Formation were deposited on a depositional margin dominated by lime and quartz sand. The lack of reef-derived clasts and fossils and the presence of well-rounded quartz and carbonate grains support the depositional margin model, as opposed to the bypass margin model. Other evidence includes slope-derived carbonate-clast conglomerates, massive to graded calcarenite, parallel- and cross-laminated peloidal calcarenite, and slumped ribbon limestone (fig. 27 and McIlreath and James, 1978).

McIlreath and James (1978) pointed out that none of the slope facies are mutually exclusive, and, as such, the rocks of the Onyx Cave Member may have originated on a depositional margin characterized, in part, by reefs. In this case, the reef-derived material would not have traveled far enough downslope to become incorporated in the rocks of the Onyx Cave or Moselem Members. Nevertheless, the main body of evidence points to a margin characterized by lime and quartz sand and not reefs.

Analysis of the Moselem Member suggests that the Moselem can be interpreted as a toe-of-slope facies and probably a distal equivalent of the Onyx Cave Member (fig. 27), although the Moselem is now in fault contact with the latter. In addition, the Moselem probably interfingers with the Onyx Cave, as suggested by the presence of rock types common to each unit. Local slumped horizons and carbonate-clast conglomerates in the Moselem attest to a lower slope or toe-of-slope environment, although movement can occur on slopes as low as 4° (Lewis, 1971).

The carbonate rocks of the Virginville Formation were deposited by several different depositional mechanisms. Hemipelagic sedimentation and dilute turbidity currents probably resulted in deposition of the ribbon limestone. The rhythmic sequences of lime mudstone and black shale are suggestive of deposition by turbidity currents (Wilson, 1969). The sequences may be overbank levee deposits associated with the emplacement of the thick calcarenites and carbonate-clast conglomerates.

The random orientation of clasts, clasts "floating" in matrix, poor sorting, and lack of grading are suggestive of some type of viscous debric flow mechanism (Johnson, 1970; Cook and Taylor, 1977; Hampton, 1972). In addition, plug flow (Johnson, 1970; Shanmugan and Benedict, 1978) is indicated by the clasts that project through the top of beds.

Recently, Krause and Oldershaw (1979) have developed a two-layer sediment gravity flow model to explain the presence of turbidite caps on conglomerate beds. The few conglomerate beds of the Onyx Cave Member that are capped by turbidites can be classified as stratified disorganized beds and are interpreted to result from deposition farther downslope than the beds that lack the turbidite caps (Krause and Oldershaw, 1979) or the disorganized beds. Hampton (1972) and Krause and Oldershaw (1979) attribute the stratified cap to turbidity currents that develop on top of the main mass of sediment. Material in front of the flow is sheared backwards and on top of the moving mass creating turbulence.

The conglomerates probably result from translational and rotational slides (Cook, 1979). The lack of the turbidite caps on the majority of conglomerates suggests that the sediment mass did not move far from its source. The local origin of the conglomerates is further supported by the clasts being of deepwater rather than shallow-water carbonate rocks. The importance of this relation was noted by Cook and Taylor (1977). Thus, the carbonate-clast conglomerates probably originated in a slumped interval in which the sediment shear strength was exceeded, causing the mass to become mobile, break up, and become a debris flow. Although all clasts are locally derived, no conglomerate could be traced backward to an obvious slump or slide.

The mechanism of deposition of the planar- to current-ripple-laminated black shale and yellow-orange dolostone and calcisiltite is not fully understood but may be the result of contour-following currents that redistributed previously deposited material.

The carbonate rocks were apparently deposited by a continuum of depositional mechanisms that were in operation on the slope. That is, the mechanisms were operating together such as do dilute turbidity currents related to emplacement of massive grain flows, or in opposition, such as do contour currents reworking and redistributing detritus deposited by dilute turbidity currents and debris flows.

In summary, then, the Sacony Member of the Virginville Formation was deposited in a low energy siliciclastic basin below wave base. The transition of the Sacony Member to the Onyx Cave Member, the slope

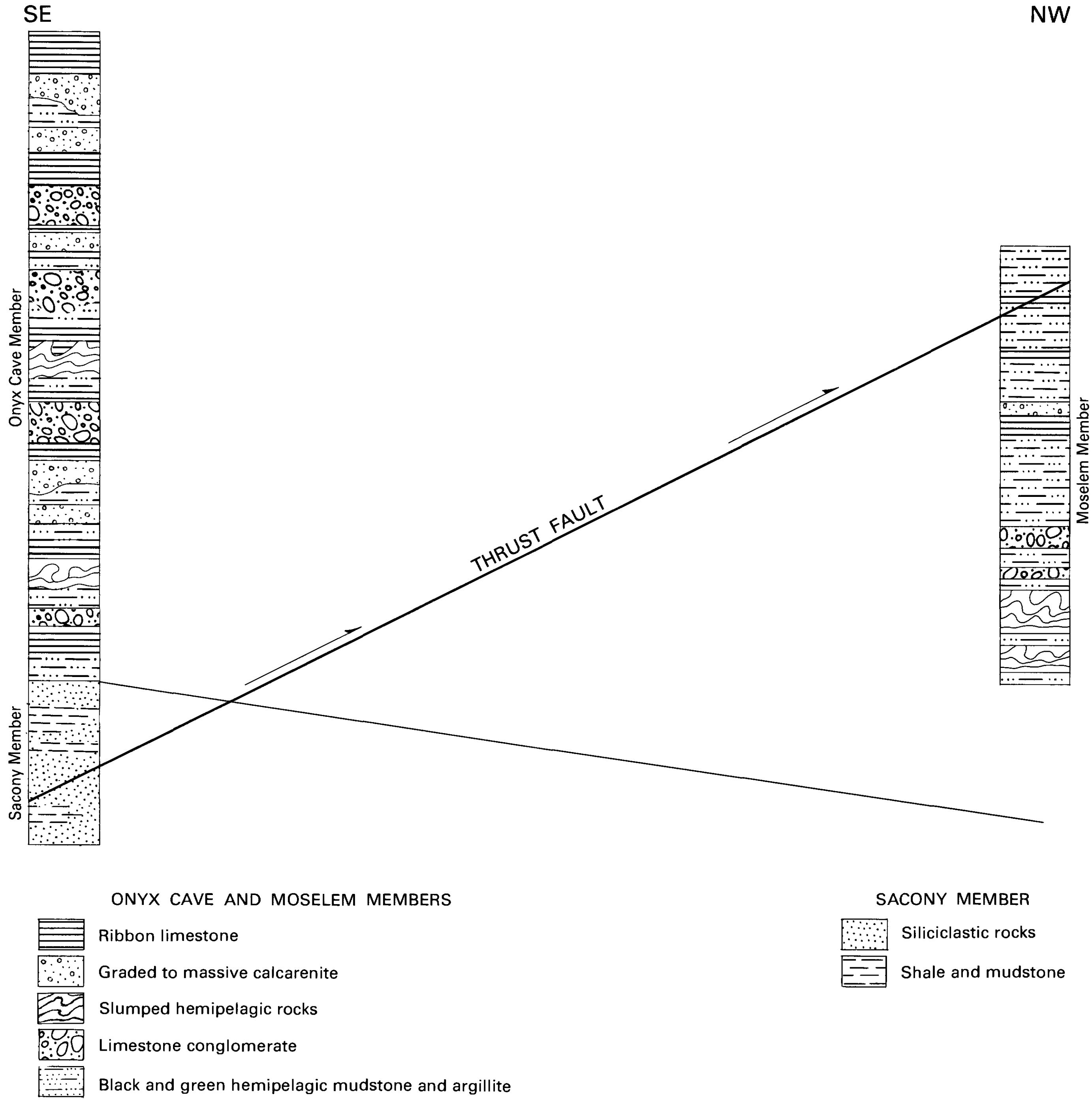


FIGURE 27.—Facies diagram for the Sacony, Onyx Cave, and Moselem Members of the Virginville Formation. Stratigraphy is idealized and is in no way intended to imply specific horizon locations or thickness; the diagram is meant only to illustrate the proposed distribution of rock types.

facies, indicates the development and progradation of a carbonate shelf and slope. This slope is interpreted as a depositional rather than a bypass slope.

PALEOGEOGRAPHY

The facing direction of the slope recorded by the rocks of the Virginville Formation is not known for certain. Some information concerning the direction of slope can be obtained by analysis of slump folds in the Onyx Cave Member and tectonic folds along the fault separating the Onyx Cave and Sacony Members from the Moselem Member.

The orientation of fold axes, axial planes, and bedding in slumped rocks has been used to determine gravity transport direction (Hansen, 1967; Corbett, 1973; Hall, 1973; Stone, 1976). In addition, fold axes and fold vergence have been used to determine movement directions in tectonic folds (Moore and Wheeler, 1978; Wheeler, 1978). All of these studies employed a method of fold analysis developed by Hansen (1967, 1971) in which the slip or slump movement plane and direction of movement within this plane, the slip line, of a slump or tectonic sheet could be obtained by plotting the axes and sense of vergence of asymmetric folds on a stereo net. The investigations cited above and numerous others have shown that this method is useful in paleogeographic reconstructions and, therefore, is suited to the present study.

Excellent exposures of slump folds in the Moselem Member of the Virginville Formation can be found along the Reading Railroad grade approximately 1.2 km southwest of Shoemakersville in the Temple quadrangle (fig. 28). The absence of cleavage and joints that are generally related to tectonic folds of the area, the truncation or beveling of some of the folds by overlying undeformed beds, and the general restriction of deformation to a single bed are suggestive of a soft-sediment origin of the folds. Slip-line analysis of these folds (fig. 29) indicates that mass movement, probably by translational sliding, occurred on slopes that were inclined to the northwest.

Fault-related folds at the contact of the Moselem Member of the Onyx Cave and Sacony Members are characterized by overturned flexural-slip folds. These folds are always associated with an autoclastic melange that is restricted to the fault zone and thereby suggest a tectonic origin for the folds. Although a good amount of azimuthal scatter of the data occurs (fig. 30), analysis of the vergence of these folds indicates northwest transport of the upper plate containing the more "proximal" Onyx Cave Member over the more "distal" Moselem Member. In other words, the rocks of the Onyx Cave Member were deposited to the southeast of the rocks of the Moselem Member.

In summation, analysis of the tectonic and slump folds in the Virginville Formation indicates that (1) extensive remobilization of semiconsolidated to unconsolidated sediments occurred by translational sliding on slopes that were inclined to the northwest and (2) the more proximal carbonate slope rocks (Onyx Cave

FIGURE 28.—Soft-sediment folds in ribbon limestone of the Moselem Member. Folds verge to the northwest (right). The layer of limestone pull-aparts attests to the unconsolidated nature of some of the sediments. Exposure along the Reading Railroad grade approximately 1.2 km southwest of Shoemakersville, Temple quadrangle. Hammer for scale.

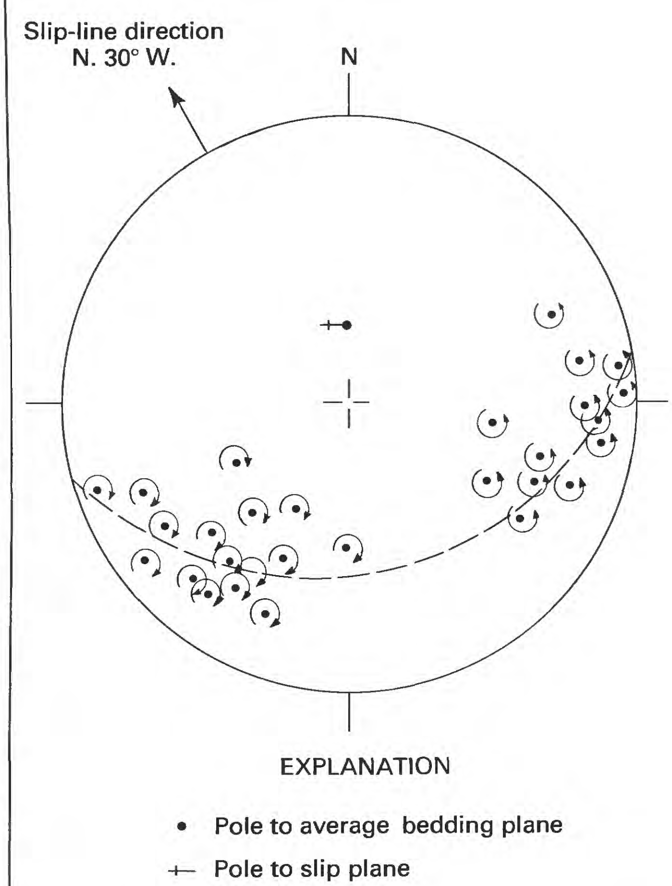


FIGURE 29.—Soft-sediment fold axes (dots), fold vergence (semicircular arrows), calculated slip plane (dashed girdle), and slip-line orientation of slump folds in the Moselem Member along the Reading Railroad grade 1.2 km southwest of Shoemakersville, Temple quadrangle.

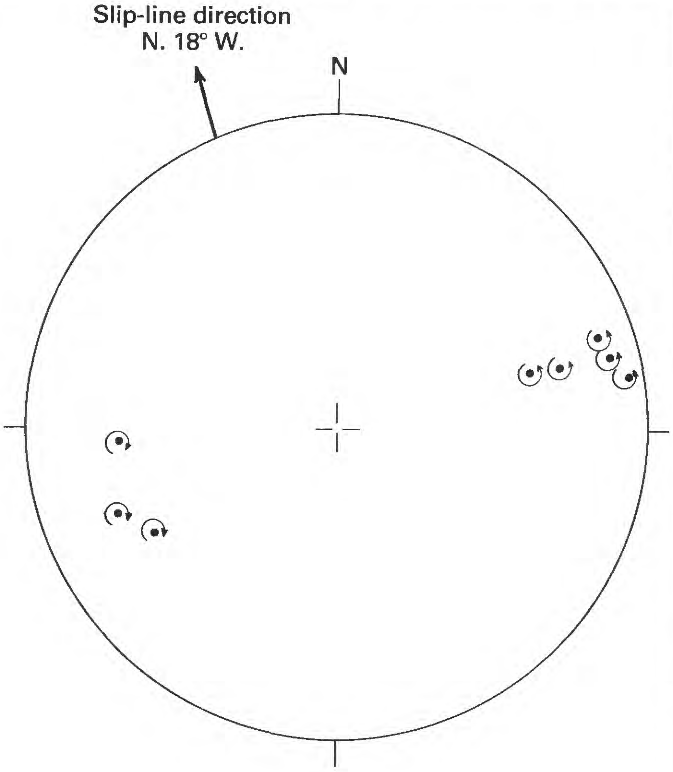


FIGURE 30.—Fold axes (dots), vergence (semicircular arrows), and slip-line orientation of tectonic folds related to thrusting along the fault separating the Onyx Cave and Sacony Members and the Moselem Member.

Member) were thrust to the northwest over their basinal equivalent (Moselem Member), indicating that the rocks of the Onyx Cave Member were deposited to the southeast of the rocks of the Moselem Member

The rocks of the Virginville Formation may be a remnant of a sequence of carbonate slope and rise sediments that were deposited adjacent to a shallow-water carbonate shelf. This shelf may have formed on a topographic high or microcontinent to the southeast of North America. The rocks of the Virginville Formation may have been deposited on the northwest-facing bank of the microcontinent concomitant with shelf sedimentation on the southeast-facing slope of the North America craton. Thus, the Virginville Formation may represent a rock-stratigraphic, if not time-stratigraphic, equivalent of the Frederick Valley sequence, which was deposited on a southeast-facing slope (Reinhardt, 1974, 1977).

STRUCTURE

The part of the central Appalachians of the present study is divisible into three structural terranes, each characterized by a unique sedimentary history and, to a lesser extent, different structural styles. These terranes are the Valley and Ridge province in which the Upper Ordovician(?) to Lower Silurian Shawangunk Formation and younger rocks are exposed, the allochthonous Hamburg klippe consisting of the Greenwich and Richmond slices, and the parautochthonous Lehigh Valley sequence of the Reading Prong nappe megasystem. The latter two are important to the present study, and their deformation is described below.

ROCK FABRIC

The rocks of the Lehigh Valley sequence and of the Hamburg klippe were folded during three main phases. The first fold phase (F_1) is marked by east-northeast-trending isoclinal to open, asymmetric to symmetric folds of various wavelengths and amplitudes. Axial planar slaty cleavage (S_1) is well developed in the rocks of the Lehigh Valley sequence and locally in the less competent rocks of the Richmond slice of the Hamburg klippe. In contrast, the rocks of the Greenwich slice of the Hamburg klippe lack the well-developed slaty cleavage and are, instead, characterized by a "scaly" type of cleavage that is discussed in more detail on page 27.

The second fold phase (F_2) is characterized by northeast-trending, parallel, symmetric to asymmetric, generally open folds of outcrop scale to small crenulations. A well-developed fracture and strain-slip or crenulation cleavage (S_2) has formed in response to folding. In some areas, earlier F_2 parallel folds were flattened, with resultant thickening of the fold hinges and development of a south-dipping fracture cleavage that fans the folds. F_2 structures are well developed in all rocks of the eastern end of the Hamburg klippe.

The latest fold phase (F_3) is only locally developed. It is characterized by east-northeast-trending kink folds, small (meter-scale) open folds, and crenulations.

Detailed structural analysis indicates that the rocks of the Lehigh Valley sequence have been folded by all three fold phases. In contrast, ongoing studies of the Upper Ordovician to Silurian rocks of the Valley and Ridge northeast of Hamburg indicate that only the F_2 and F_3 fold phases are recorded by these rocks. This suggests, then, that the F_1 fold phase is related to a pre-Silurian (Taconic?) orogenic event and the F_2 and F_3 folds are related to post-Silurian (Alleghanian) events. Additional evidence for the pre-Silurian fold phase is (1) the apparent unconformable relations that exist between the steeply dipping allochthonous rocks and the overlying near-horizontal Upper Ordovician Spitzenberg Conglomerate (Whitcomb and Engel, 1934) north of Lenhartsville and (2) the exposed angular unconformity and décollement between the Shawangunk Formation and the Hamburg klippe at Schuylkill gap.

FAULTS

Low-angle thrust faults dominate the complex structure of the eastern part of the Hamburg klippe. The parautochthonous Lehigh Valley sequence is separated from the Hamburg klippe by the Kutztown thrust (fig. 1*B*), a gently southeast-dipping thrust fault that has cut numerous early faults within the Lehigh Valley sequence. MacLachlan (1979), working in the Temple and Fleetwood quadrangles (fig. 1*B*), referred to the Kutztown thrust as the Leinbachs thrust and maintained that it dips gently to the north with the Lehigh Valley sequence thrust beneath the klippe. However, the conspicuous occurrence of north-dipping beds located along the trace of the fault about 3 km southeast of Virginville suggests that the Lehigh Valley sequence moved to the northwest over the allochthon, thereby dragging rocks that originally dipped south into north-dipping attitudes. The evidence suggests that the fault dips south in this area.

The Hamburg klippe is separated from the rocks of the Shochary Ridge sequence by the Kistler Valley fault, a steep southeast-dipping upthrust (Lyttle and Drake, 1979). On the basis of paleontologic evidence, Wright and others (1978, 1979) have questioned the presence of this fault and have, instead, suggested a depositional contact between the two sequences of rocks. This interpretation cannot explain the fault-related deformation along the Kistler Valley fault (Lyttle and Drake, 1979). In addition, mapping in the Shawangunk Formation north of Hamburg (Lash, 1980b) suggests that the Kistler Valley fault continues west into the Silurian clastic rocks north of Lenhartsville where movement on the fault has resulted in bedding discordancies in the rocks.

The fault separating the Richmond slice from the Greenwich slice of the Hamburg klippe is not exposed but is inferred from both the highly contrasting styles of deformation (discussed on p. 26) and the vastly different sedimentologic characteristics of the two slices. Additional evidence in support of the thrust contact of the two allochthonous slices can be found in exposures along the Reading Railroad grade 1.5 km west of Shoemakersville in the Hamburg quadrangle. At this locality, slices of Middle Ordovician (*Nemagraptus gracilis* graptolite zone) rocks of the Windsor Township Formation are found associated with larger slices of Lower Ordovician (Arenigian) ribbon limestones of the Moselem Member of the Virginville Formation. The tectonic slices of the Windsor Township rocks apparently represent slices of underlying rock detached and dragged (tectonically mixed?) into present position during emplacement of the Richmond slice much in the same way as the tectonic slices of the Stockbridge Formation of the Taconic Range were dragged along the sole of the allochthonous Everett Formation (Zen and Ratcliffe, 1966).

STYLE OF DEFORMATION

As described on page 26, the rocks of the Windsor Township Formation in the Greenwich slice lack the well-developed slaty cleavage of the equally incompetent Martinsburg Formation and Jacksonburg Limestone. Instead, they exhibit a "scaly" cleavage characterized by a poorly developed fracture cleavage that consists of a group of intersecting fracture planes. Cowan (1974) has referred to this type of cleavage as a "penetrative shear-fracture fabric" apparently produced by localized losses of resistance at geologically high strain rates (Raymond, 1975a), for example, strain rates typical of subduction complexes.

Without going into the details of mélange nomenclature (for discussion see Berkland and others, 1972; Raymond, 1975a, b; Beutner, 1975), Cowan's (1974) term "tectonic mélange" will be used to describe the rocks of the Greenwich slice. The term "tectonic mélange" as defined by Cowan emphasizes that the mélange records a deformation without regard to types of inclusions or even the presence of inclusions.

The main internal feature typical of tectonic mélanges as described by Cowan is the pervasive, mesoscopic shear fracture. In the Greenwich slice, the shear fractures in the less competent argillaceous rocks result in a scaly appearance in which individual chips are polished and slickensided. Because of relative differences in competency, the rocks take on a very chaotic appearance upon deformation and are characterized by lentils or phacoids of more competent rocks embedded in a sheared matrix of less competent material (fig. 31). This phenomenon is best illustrated in the rocks of the Greenwich slice by zones of intense strain, here referred to as deformation zones, marked by small pull-apart (fig. 32) and small- to large-scale pinch-and-swell (fig. 33) structures.

FIGURE 31.—Large boudin or phacoid of graywacke embedded in a sheared pelitic matrix. Width of boudin is approximately 2.5 m. Roadcut along Route 143 approximately 360 m west of Albany. Kutztown quadrangle.

FIGURE 32.—Small graywacke boudin embedded in a highly sheared pelitic matrix. Note scaly cleavage or "penetrative shear-fracture fabric" (Cowan, 1974) of the pelitic matrix. A late subhorizontal northwest- (right-) dipping fracture cleavage cuts both matrix and boudin. Roadcut along Route 143 approximately 360 m west of Albany, Kutztown quadrangle. Lens cover for scale.

Outside the deformation zones, the less competent mudstone shows the penetrative shear-fracture fabric, and individual sandstone beds are essentially undeformed, although some beds are displaced along fractures at low angles to bedding. Disruption continues to increase in intensity toward the deformation zone until only isolated phacoids of beds surrounded by a completely sheared argillite matrix remain. This progressive style of deformation has been described from the Garzas tectonic mélange of the Franciscan Complex by Cowan (1974). In addition, Hamilton (1979) noted a back-and-forth gradation in disruption, with increasing shearing into a fully developed mélange characterized by abundant lenses and blocks, on Timor Island.

In his study of tectonic mélanges, Cowan (1974) discussed the importance of determining the parentage of the mélange. He noted that, although the position of an inclusion may now be relatable to surfaces of shear, the presence of the inclusion itself may have resulted from chaotic submarine slumps and not from tectonic mixing. Within the Windsor Township Formation, "exotic" inclusions are represented by the Lower Ordovician chert, limestone, and variegated shale units. These inclusions were probably emplaced as subaqueous gravity slides into Middle Ordovician flysch prior to mélange deformation of these rocks. This distinction is a very important point in the final tectonic synthesis.

The development of the tectonic mélange fabric in the rocks of the Greenwich slice occurred prior to F_1 folding of the allochthon and parautochthon. This relation is illustrated in the Albany area and the area south of Dreibelbis, where individual deformation zones have been mapped around F_1 folds.

As noted on page 14, the Greenwich slice is lithologically similar to the Summerdale allochthon of Root and MacLachlan (1978) at the western end of the Hamburg klippe. This correlation is further supported

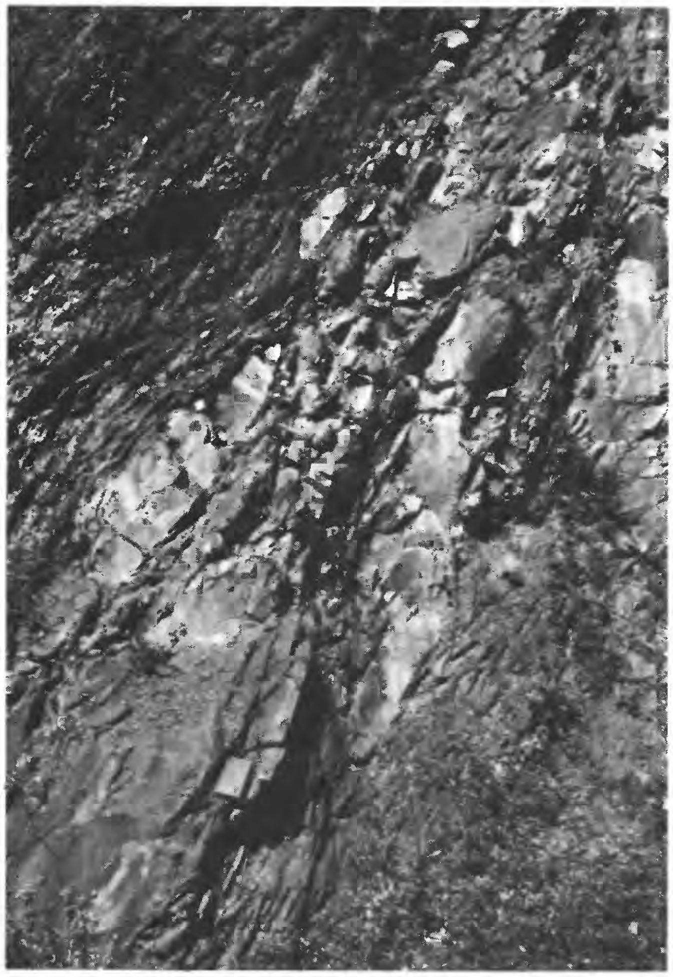


FIGURE 33.—Pinch-and-swell structure. The more competent graywacke has deformed brittlely, whereas the less competent pelite has flowed around the graywacke. Roadcut along Route 143, approximately 360 m west of Albany, Kutztown quadrangle. Notebook in lower left corner for scale.

by the similar deformational styles of the two allochthons. Root and MacLachlan (1978) noted that rocks of the Summerdale allochthon have characteristics of a "highly sheared mélange." The implication of the correlation from the eastern end of the Hamburg klippe to the western end is that the lower lithotectonic units of the Hamburg klippe are characterized by a slice or slices of chert, limestone, and variegated shale. The chert, limestone, and variegated shale slices are tectonically overlain by a highly sheared graywacke-shale slice that contains olistoliths of rocks similar to that in the underlying slice. These slices are in turn tectonically overlain by slices such as the Richmond slice.

PLATE TECTONIC IMPLICATIONS

Many plate tectonic models have been proposed to explain the complex geology of the Appalachian orogen from Newfoundland to Georgia (Bird and Dewey, 1970; Glover and Sinha, 1973; St. Julien and Hubert, 1975; Thomas, 1977; Hatcher, 1978; Osberg, 1978; Schenk, 1978). All of these workers agree upon the closing of a proto-Atlantic ocean and associated subduction and obduction that resulted in the Taconian and Acadian orogenies. From the combined structural, sedimentologic, and stratigraphic data obtained in this study, a conceptual plate tectonic model for the early Paleozoic of this part of the central Appalachians is described below.

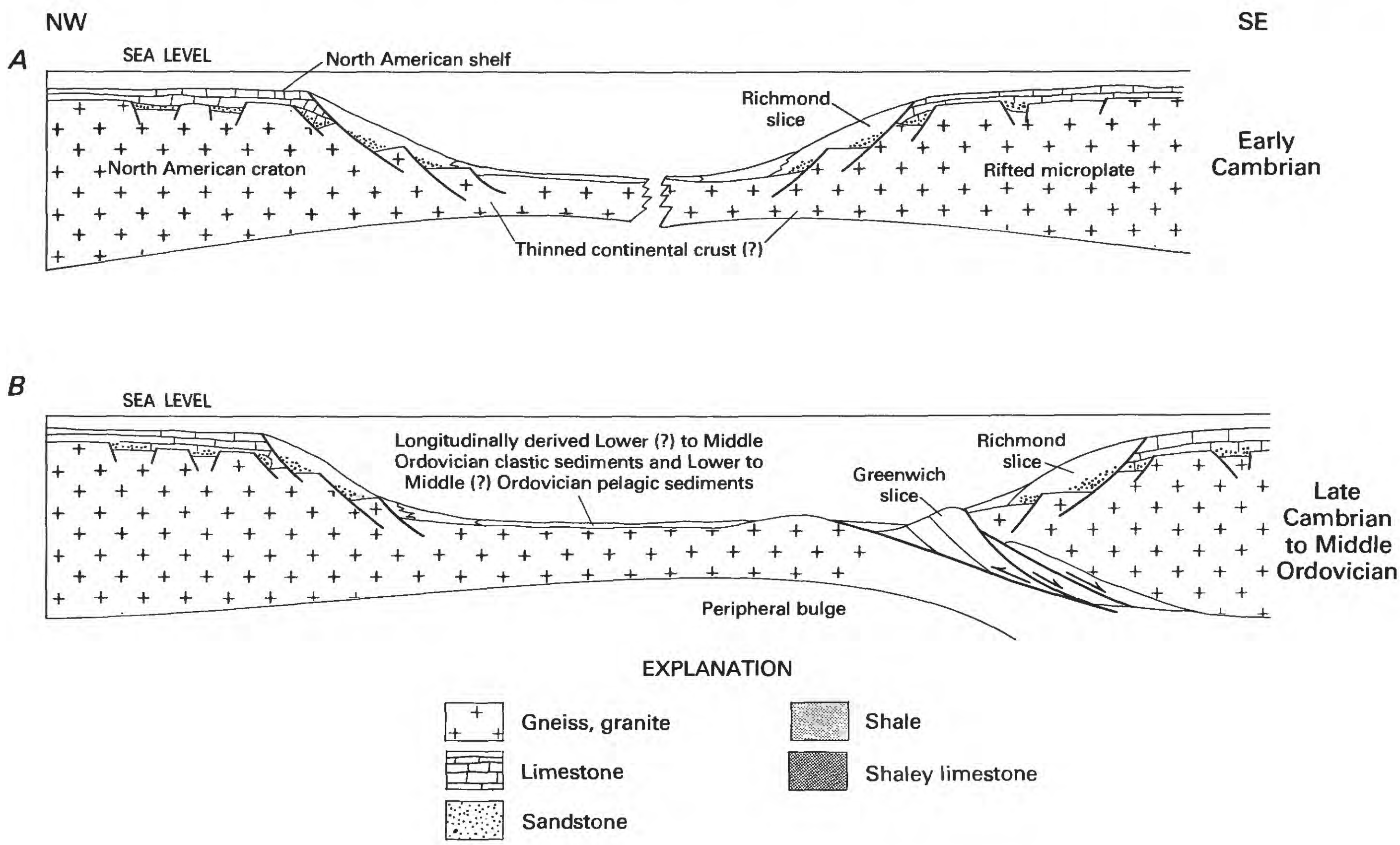
The proposed tectonic model (fig. 34) involves the aborted subduction of the North American Continent beneath a southeastern microcontinent. Tectonic models based on the abortive subduction of the continental margin have been suggested by other geologists for the northern and maritime Appalachians (Chapple, 1973; McBride, 1976; Hiscott, 1978; Stanley and Ratcliffe, 1979).

Late Proterozoic rifting in response to opening of the proto-Atlantic ocean resulted in the formation of a marginal basin separating the North American Continent from a microcontinent to the southeast (fig. 34*A*). The rifted blocks or microcontinents may be represented by such Precambrian complexes as the Fordham Gneiss terrane, Baltimore Gneiss terrane, Pine Mountains, eastern Great Smokey Mountains, and the Sauratown Mountains (Rankin, 1975; Thomas, 1977).

The Early Cambrian of the Appalachians was characterized by the formation of a stable carbonate platform on both the North American Continent (Rodgers, 1968) and the microcontinent (Thomas, 1977) (fig. 34*A*). Development of the shelf on the North American craton is evidenced by the Frederick Valley sequence of Maryland interpreted by Reinhardt (1974, 1977) to be part of the southeast-prograding carbonate shelf. In addition, the Cambrian and Ordovician carbonate rocks of the Pennsylvania Great Valley attest to the vast amount of shallow-water carbonate sedimentation during the lower Paleozoic on the North American Continent. Shallow-water shelf sediments on the microcontinent may be represented by such sequences as the Setters Formation and Cockeysville Marble associated with the Baltimore Gneiss or the lower Inwood Marble associated with the Fordham Gneiss. Carbonate rocks of the Virginville Formation of the present study were deposited on a northwest-facing bank and record maturation of a stable carbonate platform to the southeast, probably a microcontinent.

Shelf deposition and coeval deepwater sedimentation continued into Ordovician time. Some units of the Windsor Township Formation, variegated shale and mudstone and chert and limestone, represent deepwater pelagic sediments deposited concomitant with

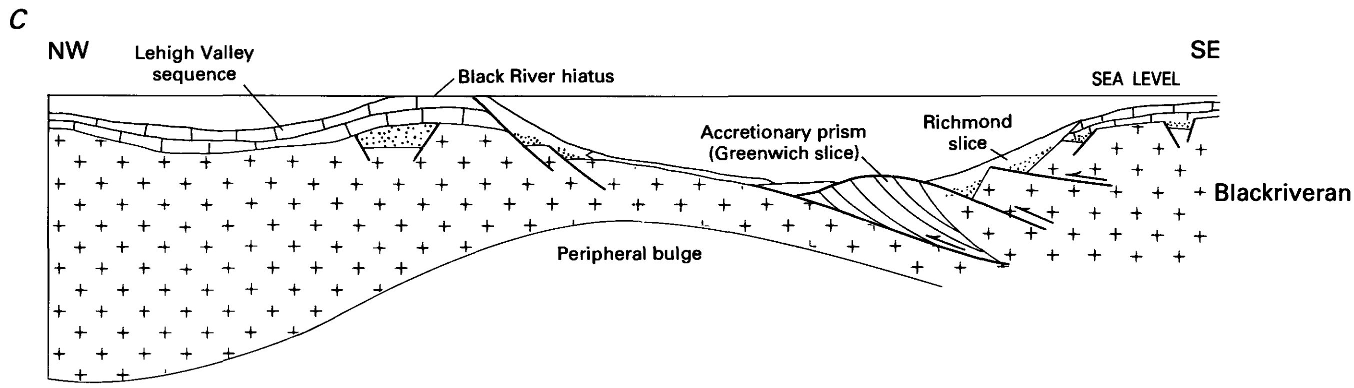
A. Proterozoic Z to Early Cambrian. Rifting resulted in the separation of North America and a microplate located to the southeast, perhaps represented by the Baltimore Gneiss terrane (Thomas, 1977). The separating basin was not very extensive and was probably underlain by thinned continental crust as rifting never progressed beyond the intracontinental phase and the major rift center formed to the east of the microplate. The lack of ophiolite debris in the flysch sequences of the Appalachian Great Valley in Pennsylvania precludes the development of extensive oceanic crust. Rocks of the Richmond slice of the Hamburg klippe were deposited on the northwest-facing lower slope of a passive continental margin on the microplate while coeval carbonate shelf deposits (Allentown Dolomite, Conococheague Group, for example) were deposited on the shelf of the North American craton.

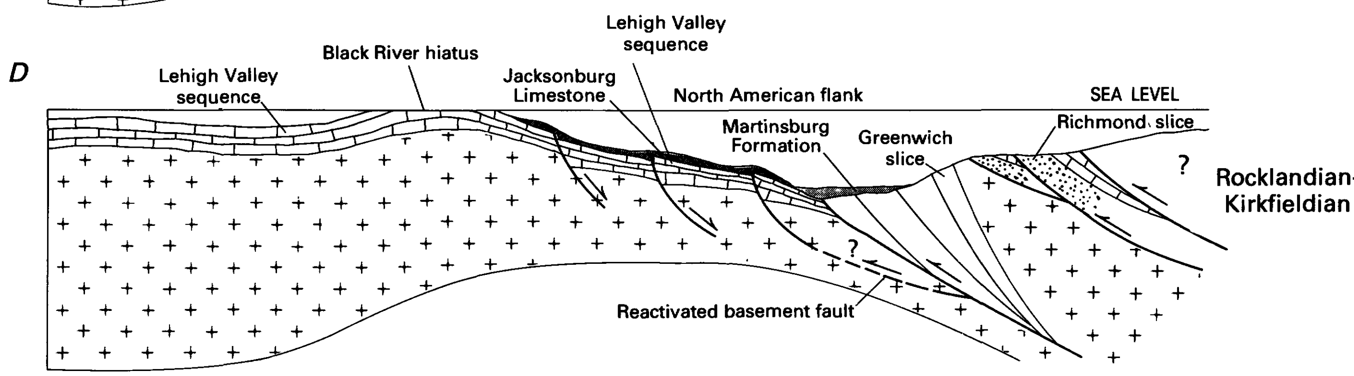


B. Late Cambrian to Middle Ordovician. Subduction was probably initiated by Early Ordovician time. Red and green shale of Early Ordovician age in the Greenwich slice reflects the uplift of a terrigenous source area. This uplift may record a collision at the New York Promontory that resulted in the longitudinal dispersal of pelagite in Early Ordovician time followed by coarse-grained clastic sediment in Middle Ordovician time that was shed longitudinally from an uplifted area to the northeast. These clastic rocks were deposited as abyssal plain turbidites (Stewart, 1976; Dickinson, 1982).

FIGURE 34.—PLATE TECTONIC MODEL FOR THE HAMBURG KLIPPE

C. Blackriveran. As the North American plate approached the trench, it was flexed upward resulting in rapid uplift and erosion of the shelf carbonates at the southeastern margin of the North American craton. Clastic sediments of the Greenwich slice continued to be supplied from a northeasterly source. These sediments (clastic rocks stratigraphically overlying older pelagic sediments) were accreted onto the hanging wall of the trench. The Greenwich slice is part of this accretionary prism.

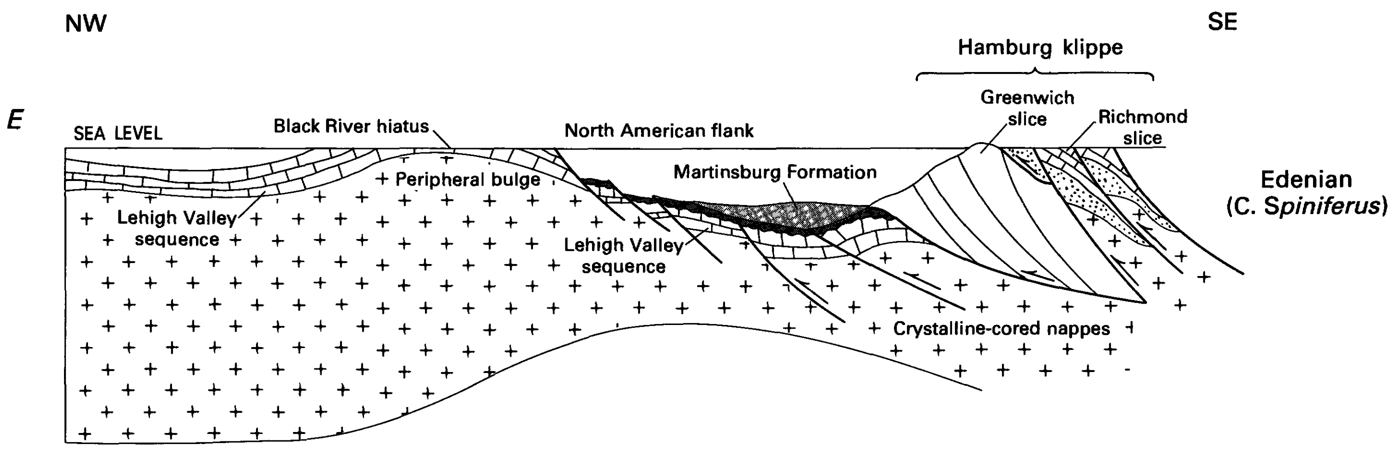


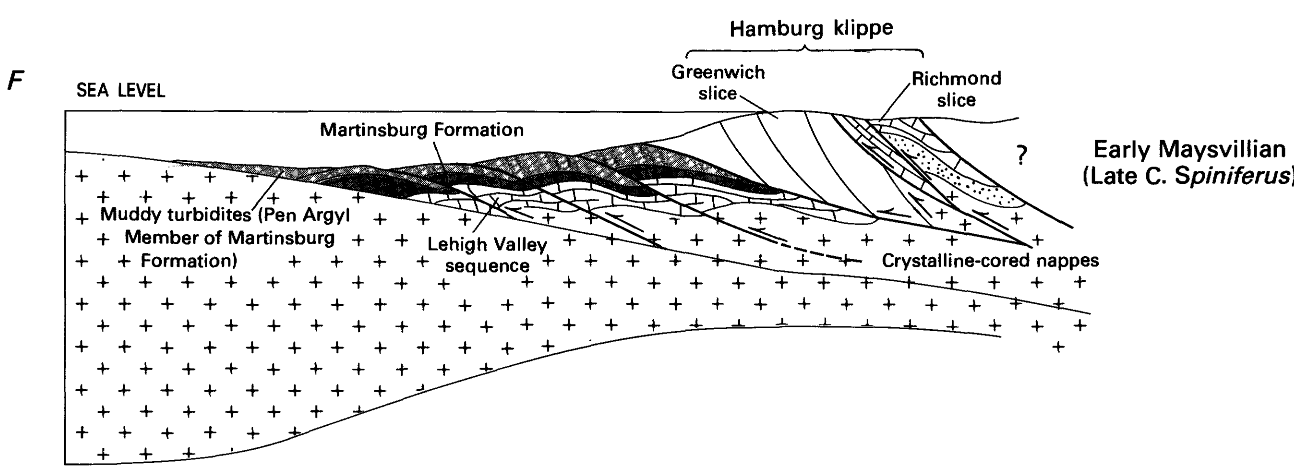


D. Rocklandian-Kirkfieldian. Rocklandian to Kirkfieldian time was characterized by deposition of the Jacksonburg Limestone during rapid basin subsidence. This concept is supported by the lithostratigraphic changes from the "cement-limestone" facies to the "cement-rock" facies of the Jacksonburg and by the transition from the shallow, warm-water North Atlantic province conodont fauna at the base of the Jacksonburg to the deep, cold-water North Atlantic fauna at its top. The basin probably formed by normal faulting in response to "trench suction" (Elsasser, 1971) rather than by tectonic loading at the continental margin. Deposition of the clastic rocks of the Martinsburg Formation was probably initiated at the end of Kirkfieldian time (all contacts are probably time transgressive). By this time, subduction had ended, and the closure of the Jacksonburg-Martinsburg basin was probably accomplished by reactivation of the early formed normal faults into thrust faults. The nappes of the Pennsylvania Great Valley and New Jersey were probably formed in this manner. After the Hamburg klippe was emplaced, it became a passive rider on the stacked nappe sequence. At this time of extreme compression, the Richmond slice was emplaced onto the Greenwich slice.

FIGURE 34.—PLATE TECTONIC MODEL FOR THE HAMBURG KLIPPE—Continued

E. Edenian. By Edenian time, the uplifted area related to the proposed collision at the New York Promontory had migrated laterally and closer to the Martinsburg basin of southeastern Pennsylvania and was now supplying the coarse clastic sediment of the Ramseyburg Member of the Martinsburg Formation. This uplift occurred as the tectonic wave was built up by the accretion of basement rocks and overlying miogeoclinal sequences (nappes). The nappes continued to move by reactivation of the early formed normal faults into thrust faults, and the basin continued to close.





F. Early Maysvillian. By Maysvillian time, tectonic movement had slowed significantly. The source area was now lowered, and the more compositionally mature clastic rocks of the Pen Argyl Member of the Martinsburg Formation were deposited. The Pen Argyl contains structures typical of muddy, slow-moving, low concentrate turbidity current deposits, as described by Stow and Shanmugam (1980), that suggest the progradation of a muddy shoreline.

FIGURE 34.—PLATE TECTONIC MODEL FOR THE HAMBURG KLIPPE—Continued

Early Ordovician shallow-water carbonate rocks of the Beekmantown Group.

Closing of the marginal basin was accomplished by southeast-dipping subduction beneath the microcontinent. Subduction, which was probably initiated in early Early Ordovician time, resulted in the foundering or depressing of the carbonate shelf (fig. 34*B*). Evidence for foundering of the lower Paleozoic North American shelf has been documented in Newfoundland by Stevens (1970) and also may be documented in rocks of the Lebanon Valley sequence of the central Appalachian Great Valley. MacLachlan and others (1975) noted that, in the Lebanon Valley west of Womelsdorf, Pa., the uppermost Ontelaunee Formation is overlain conformably or paraconformably by the Annville limestone, a high-calcium limestone unit, of definite Chazyan age. The change from almost pure dolomite of the Ontelaunee to the high-calcium limestone of the Annville may represent a transgressive period that resulted from foundering of the shelf. Therefore, progradation of the shelf seems to have continued until at least Whiterockian time and probably into Chazyan time. Progradation was followed by a period of transgression that resulted from foundering of the shelf in response to subduction and by deposition of rocks such as the high-calcium Annville Formation.

The style of deformation of the Greenwich slice of the present study and of the Summerdale allochthon of the western end of the klippe suggests that these rocks were deformed in a subduction complex and, therefore, represent trench sediments (fig. 34*B*). Paleogeographic reconstructions based upon the stacking order of thrust sheets have been documented from numerous areas (Williams, 1975; Elliot, 1976) and may be applied to the rocks of the Hamburg klippe. If northwest transport during closing of the marginal basin can be assumed, the stacking order of the slices in the western end of the Hamburg klippe suggests that the abyssal sediments of the Enola allochthon were northwest of the rocks of the Summerdale allochthon and, by correlation, the Greenwich slice. In other words, the abyssal sediments were deposited to the northwest of the subduction zone.

Sparse directional paleocurrent data evince both northwesterly and southeasterly sources, but, as stated earlier, analysis of slump folds supports a predominantly southeasterly source, possibly the microcontinent. Despite this evidence, some of the detritus may represent second-cycle sediments originally deposited as continental slopes and rise sediments adjacent to the southeast-facing shelf.

As subduction continued, the older abyssal sediments, represented by the bodies of red and green shale and accompanying rocks, became detached from the underlying plate and slid into the trench. Moore (1975) maintains that physical properties such as density and yield strength of clastic sediments (that is, hemipelagic and pelagic mud and red and brown clays) and the underlying biogenic sedimentary unit diverge with time; however, the same physical properties of the biogenic unit and the underlying upper basaltic layer of oceanic crust converge. This difference is significant in that the low density of the clastic sediments and resultant relative buoyancy would tend to favor the incorporation of these sediments into the trench sediments at shallow levels, presumably by slumping or sliding along a décollement separating the physically contrasting units (Moore, 1975). As the abyssal sediments approached the trench, the more buoyant red and green mudstone and shale units became detached and were incorporated into the shallow levels of the trench sediments in a manner similar to that described above. The great amount of soft sediment deformation in some of these units attests to slumping and sliding during emplacement. Following emplacement of these units, the rocks were severely sheared and strained resulting in the tectonic mélange style of deformation.

Root and MacLachlan (1978) maintain that the Enola and Summerdale allochthons were closely associated and were likely emplaced together from the same general source. Their assertion appears likely in that during subduction a large mass of pelagic sediments represented by the Enola allochthon became detached from the underlying plate along the décollement separating the younger clastic sediments from the underlying units. This slice was accreted to the trench sediments, and the entire mass moved as a unit. It is possible, but difficult to prove at the present level of erosion, that detachment and accretion occurred several times prior to emplacement of the klippe onto the shelf. The majority of turbidite and grain flow deposits, as well as the olistoliths of pelagic and hemipelagic sediments, were emplaced during Chazyan time, essentially concomitant with foundering of the shelf.

As the North American craton approached the trench, the inability of the buoyant continental crust to subduct beneath the microcontinent resulted in uplift of the continental margin. Erosion of the shelf and continental margin rocks accompanied uplift and is evidenced by the Black River hiatus in the Lehigh Valley sequence (see fig. 2) and the Lebanon Valley sequence that is somewhat different from the tectonically lower Lehigh Valley sequence (MacLachlan and others, 1975). The lack of a well-defined Black River hiatus in the Cumberland Valley sequence (Root, 1977, fig. 2), the tectonically lowest and probably the least traveled sequence in the Pennsylvania Great Valley, indicates that the area of the shelf defined by the carbonate rocks of this sequence was not uplifted but, instead, remained submerged and developed an almost uninterrupted stratigraphic sequence. Therefore, the farther northwest one moves from the tectonic welt or arch, the smaller the unconformity becomes, until conformable or paraconformable relations are realized.

Uplift and erosion of rocks of the Beekmantown Group are evidenced by the presence of dolomite clasts, presumably derived from the Ontelaunee Formation of the Beekmantown Group, within the lower unit, the "cement limestone" facies, of the Jacksonburg Limestone in New Jersey (Drake, 1969) and the Hershey Limestone, a unit which closely resembles the upper "cement rock" facies of the Jacksonburg (MacLachlan, 1967), near Myerstown, Pa. (MacLachlan and others, 1975). The presence of the basal calcirudite unit containing clasts of Beekmantown-type dolomite indicates that uplift of the continental margin was in progress by Rocklandian time, concomitant with deposition of the Jacksonburg Limestone. The change from the relatively shallow-water "cement limestone" facies to the deeper water "cement rock" facies of the Jacksonburg Limestone of the Lehigh Valley sequence indicates that the basin continued to deepen during Rocklandian and Kirkfieldian time. Deposition of the deepwater psammitic-pelitic Martinsburg Shale followed.

The inability of the North American Continent to subduct beneath the microcontinent retarded and eventually stopped subduction and locked the two plates. As stress built up along the contact of the two plates, detachment of wedges or slabs of basement rock and associated miogeoclinal rocks occurred (fig. 34*D*). The detached basement represents the cores of the carbonate nappes of the Pennsylvania Great Valley. Because the Jacksonburg Limestone was involved in nappe formation (Drake, 1978), detachment and imbrication probably started somewhat after deposition of the Jacksonburg, possibly in Late Blackriveran to Kirkfieldian time.

The tectonically telescoped and thickened continental crust resulted from large-scale underthrusting and imbrication of slabs or wedges of cratonic basement on easterly inclined faults or ductile shear zones (fig. 34*D*). Detachment of basement wedges during collisional tectonics has been described from the northern Appalachians by Stanley and Ratcliffe (1979) and Ratcliffe (1979). At this time of extreme telescoping, the Richmond slice (consisting of carbonate-slope rocks of the eastern microcontinent) probably was emplaced upon the Greenwich slice, which had become part of a massive wedge of basement, miogeoclinal, and eugeoclinal rocks.

Following the aborted subduction of the continental margin in late Blackriveran time, southeast-dipping subduction may have started to the southeast of the microcontinent. The continued southeast-dipping subduction probably contributed to the thrust emplacement of the Richmond slice and to further telescoping of the North American continental margin. The amount of time required to close the marginal basin that separated the North American Continent from the microcontinent as determined by the age of the trench sediments of the Windsor Township Formation is approximately two graptolite zones, an amount of time equal to that suggested by Chapple (1973) for a similar model for the northern Appalachians.

Continued convergence drove the wedge of accreted rocks up the basal slope that had been created by subduction of the North American Continent. Elliot (1976) and Wiltscko (1979) maintain that thrust sheets can move up basal slope as long as sufficient surface slope has developed within the thrust sheet itself. The mass will move in the downdip direction of the surface slope even if this means moving up basal slope. Once the wedge of basement, miogeoclinal, and eugeoclinal rocks built up sufficient surface slope, probably by shortening in the back of the wedge, it was able to move up the basal slope.

The massive wedge of thickened continental crust and rocks of the Hamburg klippe continued to move throughout late Middle Ordovician time and caused further depression of the shelf. Rocks of the Martinsburg Formation were deposited in a clastic wedge in a foredeep in front of the wedge of accreted rocks (fig. 34*D*, *E*). The entire Martinsburg appears to have been involved in nappe formation to some extent, which suggests that the nappes continued to "form" into Maysvillian time (see fig. 34*F*). The nappes continued to develop by movement along thrust faults separating each of the basement-cored nappes.

The Hamburg klippe may have become detached from the underlying nappes and may have slid in advance of them into the Martinsburg basin (fig. 34*E*). The mixed allochthonous-autochthonous terrane in the vicinity of Harrisburg, Pa., attests to the subaqueous gravity sliding mechanism for the emplacement of the Hamburg klippe into the Martinsburg basin. The age of the final emplacement of the klippe is not known. The matrix of the wildflysch at the western end of the klippe has not been dated, and there is no wildflysch at the eastern end despite previous reports (Alterman, 1972). If there were wildflysch at the eastern end, it has been removed by faulting or is not exposed at the present level of erosion.

Wright and Stevens (1978) suggest that the allochthons were emplaced during the lower *Diplograptus multidens* graptolite zone. This emplacement seems impossible if the minimum age of the Jacksonburg Limestone is early Rocklandian. Emplacement of the allochthons into the Martinsburg basin during lower *Diplograptus multidens* time would require uplift of the continental margin, detachment of basement and resultant nappe formation, and deposition of the Jacksonburg Limestone and a certain thickness of rocks of the Martinsburg Formation within a very short time. A more likely time of emplacement by analogy with the emplacement of the Normanskill Formation of New York State (Rickard and Fisher, 1973) and the Taconic klippe of New England (Zen, 1967) is the *O. Reudemanni* graptolite zone or late Sherman Falls, although direct evidence is lacking. The true age of the final emplacement of the Hamburg klippe will not be known until datable fossils are obtained from wildflysch associated with the allochthons.

Finally, as motion of the two plates slowed and eventually stopped, post-Maysvillian slow heating and uplift resulted in the unconformity separating the Taconides of the Great Valley and the Alleghanides of the Valley and Ridge (Drake, 1980). Late Alleghanian thrusting, such as that described by Root (1977) and Root and MacLachlan (1978), from the western end of the klippe and the Kutztown thrust of the eastern end continues to move the nappes of the Reading Prong nappe megasystem to the northwest over the klippe rocks.

A modern analogy of the proposed model exists in the vicinity of Timor Island north of Australia. Timor Island, located in the outer Banda Arc (Hamilton, 1977, 1979; Von der Borch, 1979), consists of a chaotic complex of highly deformed and imbricated rocks and was interpreted to be a tectonic mélange by Fitch and Hamilton (1974) and Hamilton (1979). Seismic profiles of the island indicate a wedge-shaped morphology (Von der Borch, 1979) that thins to the south. Deep-sea drilling in the Timor Trough (Hamilton, 1977) south of Timor shows that shallow-water carbonate rocks of the Australian shelf underlie the trench fill and indicates foundering of the shelf. Foundering of the Australian shelf and attendant block faulting has been attributed to subduction of the continental margin beneath the Banda Arc (Crostella, 1977; Hamilton, 1979). The chaotic rocks of Timor Island, therefore, are considered to be part of an accretionary prism of trench, shelf, and crystalline rocks that moved with the upper plate (Hamilton, 1979) during subduction of the Australian shelf and basement.

Although obvious differences exist, the proposal model and the present-day tectonics of the Timor-Tanimbar area are grossly similar. The mélange rocks of the Greenwich slice are similar in style of deformation and stratigraphy to the mélange on Timor Island. In addition, the crystalline cores of the nappes of the Reading Prong nappe megasystem are represented on Timor Island by slabs of what appear to be Australian basement. Future research on the rocks of the Great Valley will undoubtedly clarify certain points of the proposed model and help to refine our ideas of the early Paleozoic plate tectonics of the central Appalachians.

CONCLUSIONS

Taconic-type klippen such as the well-known examples from the northern and maritime Appalachians also have been described from the central Appalachians. The Hamburg klippe of Stose (1946) constitutes one such body in the Great Valley of eastern Pennsylvania. The eastern end of the allochthon was mapped in the Kutztown and Hamburg 7½-minute quadrangles and surrounding areas.

This mapping has led to the recognition of two stratigraphically and structurally different slices. The lower Greenwich slice consists of rocks of the Windsor Township Formation (6,215 m), a flysch sequence that contains various sized bodies of chert, limestone, and variegated shale and boulder conglomerate. The rocks of the Windsor Township are subdivided into three members: (1) the Dreibelbis, a sequence of interbedded graywacke and gray-green shale, siltstone, and mudstone, (2) the Weisenberg, a gray-green shale unit that contains local lenses of polymict conglomerate, and (3) the Switzer Creek, a conglomeratic graywacke-gray-green-shale unit. The lenticular bodies of chert, limestone, and variegated shale and mudstone are not restricted to a particular member but occur throughout the formation and, therefore, have little regional stratigraphic significance. Graptolites collected from the flysch sequence of the Windsor Township yield Middle Ordovician (*Nemagraptus gracilis* zone) ages, whereas conodonts from the carbonate rocks of the bodies of red shale and associated rocks yield Early Ordovician (Arenigian) ages. Therefore, a definite age discrepancy exists between the two types of rock within the Windsor Township Formation.

Sedimentologic analysis of the flyschoid rocks of the Windsor Township Formation suggests that the rocks can be classified into one of four turbidite facies described by Mutti (1977) in his study of a flysch sequence from the Spanish Pyrenees. These are (1) the channel-margin facies characterized by thick, massive (T_a, T_{a-e} partial Bouma sequences) graywacke beds locally interbedded with the T_{c-e} partial Bouma sequence and very thick intervals of siltstone and mudstone, (2) the channel-axis facies characterized by monotonous sequences of thick, massive (T_a, T_{a-e}) graywacke sandstone, (3) the interchannel facies characterized by sequences of bundles of T_{c-e} partial Bouma sequences intercalated with mudstone and siltstone, and (4) levee and overbank deposits characterized by mudstone and shale, locally slumped. The Dreibelbis Member contains rocks of the channel-margin, channel-axis, and interchannel facies, whereas most rocks of the Switzer Creek Member appear to be typical of the channel-axis facies. The Weisenberg Member appears to be a good example of levee and overbank mudstone and siltstone deposits. These rocks were probably deposited in the middle-fan area of a large submarine fan from a source to the southeast. The activity of the channels in the fan is evidenced by the intercalated nature of channel-axis and interchannel facies rocks. This sediment mixing suggests that the channels were meandering freely rather than being incised into the fan mud as would be expected in the upper parts of the fan. The older lenticular bodies of chert, deepwater limestone, and variegated shale were apparently deposited in an abyssal environment that received periodic influxes of terrigenous material. They were later emplaced into the younger fan deposits.

The upper Richmond slice contains rocks of the Virginville Formation (565 m thick) and is divided into three members. (1) The Sacony (245 m thick) consists of olive-green siltstone and shale. (2) The Onyx Cave (90 m thick) consists of massive to laminated calcarenite, ribbon limestone, massive carbonate-clast conglomerate, and interlaminated black shale and orange dolostone. (3) The Moselem (230 m thick) consists of well-cleaved argillite and mudstone and lesser proportions of ribbon limestone and carbonate-clast conglomerate. The limited amount of faunal evidence from these rocks suggests a Late Cambrian to Early Ordovician age. The sedimentology and stratigraphy of these rocks suggest that (1) they were deposited low on a northwest-facing depositional slope and (2) the Moselem Member is a distal equivalent of the Onyx Cave Member. The data suggest that the rocks of the Virginville were deposited on a northwest-dipping depositional slope, probably adjacent to a shallow-water carbonate shelf to the southeast. Subsequent thrusting juxtaposed the Sacony and Onyx Cave on top of the Moselem.

The rocks of the Hamburg klippe have been deformed by three phases of folding. In addition, the Greenwich slice illustrates the effects of an earlier phase of deformation not present in the rocks of the Richmond slice. The rocks of the Greenwich slice exhibit a chaotic style of deformation characterized by pinch-and-swell and pull-apart structures. These rocks lack the well-developed slaty cleavage typical of lithologically similar rocks in the surrounding parautochthonous Lehigh Valley sequence.

First-phase deformation is typified by eastnortheast-eastsoutheast-trending folds. A slaty cleavage is axially planar to these folds in the Lehigh Valley sequence and in the incompetent rocks of the Richmond slice, but slaty cleavage is almost totally absent from rocks of the Greenwich slice. Second-phase deformation is characterized by northeast-trending strain-slip and fracture cleavage and minor folds and is well displayed in all rocks of the allochthon. Finally, third-phase deformation is not well developed, but the structures that appear to be related to this deformation trend eastnortheast. This deformation can be distinguished from the first phase only where cross-cutting relations exist.

A conceptual plate tectonic model for the lower Paleozoic section of the central Appalachians has been developed. The model synthesizes structural, sedimentologic, and stratigraphic data of the present study with interpretations and conclusions of other geologists who have worked in the central Appalachian Great Valley. The proposed model explains the distribution of the allochthonous and parautochthonous rocks in the Great Valley in terms of the present-day tectonics of the Banda Sea north of Australia.

Late Proterozoic rifting resulted in the formation of a basin separating the North American craton and a microcontinent to the southeast. The microcontinent may be represented by such basement complexes as the Fordham Gneiss and Baltimore Gneiss terranes. From Early Cambrian to Early Ordovician time, a stable carbonate platform was established on the North American craton as evidenced by the Frederick Valley sequence of Maryland and the parautochthonous carbonate rocks of the Pennsylvania Great Valley. Formation of a carbonate platform on the microcontinent is illustrated by the Setters Formation and Cockeyville Marble overlying basement rocks of the Baltimore Gneiss (Thomas, 1977). The Virginville Formation, therefore, may represent Upper Cambrian to Lower Ordovician slope and lower slope rocks that were deposited basinward of a carbonate shelf on the microcontinent. Deposition of the deepwater olistoliths of chert, limestone, and variegated shale and mudstone of the Windsor Township Formation occurred concomitant with Early Ordovician shelf deposition of the Beekmantown Group.

Subduction of the North American Continent probably began in early Early Ordovician time. Chazyan foundering of the shelf in response to subduction resulted in transgression characterized by deposition of high-calcium limestone such as the Annville Limestone. The trench sediments of the Windsor Township Formation were deposited in the middle-fan area of a large submarine fan. A southeasterly source for these sediments suggests that the fan was adjacent to the microcontinent. Trench sedimentation and mélange deformation evidenced by the rocks of the Greenwich slice occurred during Chazyan time and was coeval with foundering of the North American shelf. As subduction continued, the chert, limestone, and variegated shale and mudstone units were detached from the subducting plate by the process of selective subduction and incorporated into the progressively deforming trench sediments.

As the North American Continent approached the trench, the continental margin was uplifted as a result of the aborted subduction of the buoyant continental material, and the plates became locked. Erosion of the shelf sediments in response to uplift produced the Black River hiatus. Deposition of the Jacksonburg Limestone to the northwest of the tectonic welt indicates that uplift and erosion were in progress by Rocklandian time. Continued uplift resulted in the transition from the shallow-water "cement limestone" facies to the deeper water "cement rock" facies.

The inability of the North American craton to be subducted beneath the microcontinent resulted in late Blackriveran to Kirkfieldian underthrusting and detachment of slabs of cratonic basement on easterly inclined faults. These slabs of basement and associated miogeoclinal rocks are represented by the carbonate nappes in the Lehigh and Lebanon Valleys. Continued convergence from the southeast, possibly as a result of a shift from southeast-dipping to northwest-dipping subduction southeast of the microcontinent, resulted in the thrust emplacement of the Richmond slice onto the Greenwich slice by Edenian time.

Sediments of the Martinsburg Formation were shed from the northwestward-advancing wedge of basement, miogeoclinal, and eugeoclinal rocks in a foredeep. As the wedge continued to move, the allochthons became detached from the underlying carbonate nappes and slid into the Martinsburg basin in advance of the nappes. This may have occurred in late Shermanian time although direct evidence is lacking. Nappe formation continued into Maysvillian time by thrusting along faults separating each of the basement-cored carbonate nappes.

As motion between the two plates ceased, heating and uplift occurred in Maysvillian and Richmondian time and resulted in the post-Martinsburg deposition (Hudson Valley) unconformity. Later Alleghanian thrust faulting further telescoped the nappes (Drake, 1978) and translated them over the rocks of the Hamburg klippe.

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