THE MIDDLE ORDOVICIAN KNOX UNCONFORMITY, VIRGINIA APPALACHIANS: TRANSITION FROM PASSIVE TO CONVERGENT MARGIN

by

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INTRODUCTION

This paper describes the regional unconformity between Lower/early Middle Ordovician Knox/Beekmantown carbonates and overlying Middle Ordovician limestones, Virginia Appalachians, especially karst features and detrital carbonates associated with the unconformity, and initial post-unconformity sedimentation and facies development. Detailed sedimentologic studies of regional unconformities on shelf carbonates are few. When studied within a regional stratigraphic and tectonic framework, they may provide important information regarding timing of deformation, global sea level change, changes in climate, and post-unconformity sedimentation patterns, including localization of later buildups. Finally, unconformities may be associated with modified porosity characteristics of carbonates below the unconformity surface due to leaching, brecciation and cavern formation.

The Knox/Beekmantown unconformity (Knox unconformity from hereon) of the North American Appalachians marks the transition from Cambro-Ordovician shelf carbonate deposition on a passive (Atlantic-type) margin (Bird and Dewey, 1970) to Middle Ordovician carbonate and clastic deposition in a foreland basin associated with a convergent margin (Read, 1980). This type of unconformity probably represents the initial deformation of a passive margin as it evolves into a foreland thrust-fold belt associated with arc-continent or continent-continent collision. In Virginia, such warping is suggested by early Middle Ordovician folding of post-unconformity carbonates (Lowry, 1957), and Lowry and Tillman (1974) suggested a tectonic rather than eustatic origin for the unconformity. Actively subsiding depocenters in the Appalachians (Colton, 1970; Read, 1980) appear to have controlled unconformity distribution.

Other ancient and modern (evolving) foreland thrust-fold belts also show regional unconformities that separate stable platform sequences from overlying foreland basin sequences, e.g. in the Timor Sea (Veevers, 1971; Crostella and Powell, 1975), Persian Gulf (Murris, 1980), and the Antler Orogenic Belt, western U.S.A. (Poole and Sandberg, 1977; Poole et al., 1977; Wilson and Laule, 1979; Gutschick et al., 1979). Bally and Snelson (1980) suggest that such unconformities form by flexuring of the lithosphere.

Unconformities of this type may be associated with hydrocarbons (e.g. the Knox unconformity in the subsurface of Ohio, Indiana, Kentucky, and southern Ontario; Keller and Abdulkareem, 1980). This may be because source beds associated with the passive margin or the later foreland basin undergo rapid thermal maturation due to high sedimentation and subsidence rates in the foreland basin (Bally and Snelson, 1980). Such unconformities also may be associated with economic deposits of zinc and lead, whose distribution largely is controlled by porosity zones (breccia horizons) developed during unconformity formation. Emplacement of the base metals typically occurs much later, following relatively deep burial of the unconformity by synorogenic clastics.

In this paper, the regional stratigraphic and tectonic setting is outlined. Characteristics of the unconformity such as erosional and structural relief, and paleokarst features and their fills are described in detail, together with post-unconformity breccias and thick, fine detrital dolomite that fill unconformity lows. Eustatic versus tectonic effects during unconformity formation are evaluated. Finally, various unconformities elsewhere that appear to have formed during conversion of passive continental margins into convergent margins are examined.

METHODS

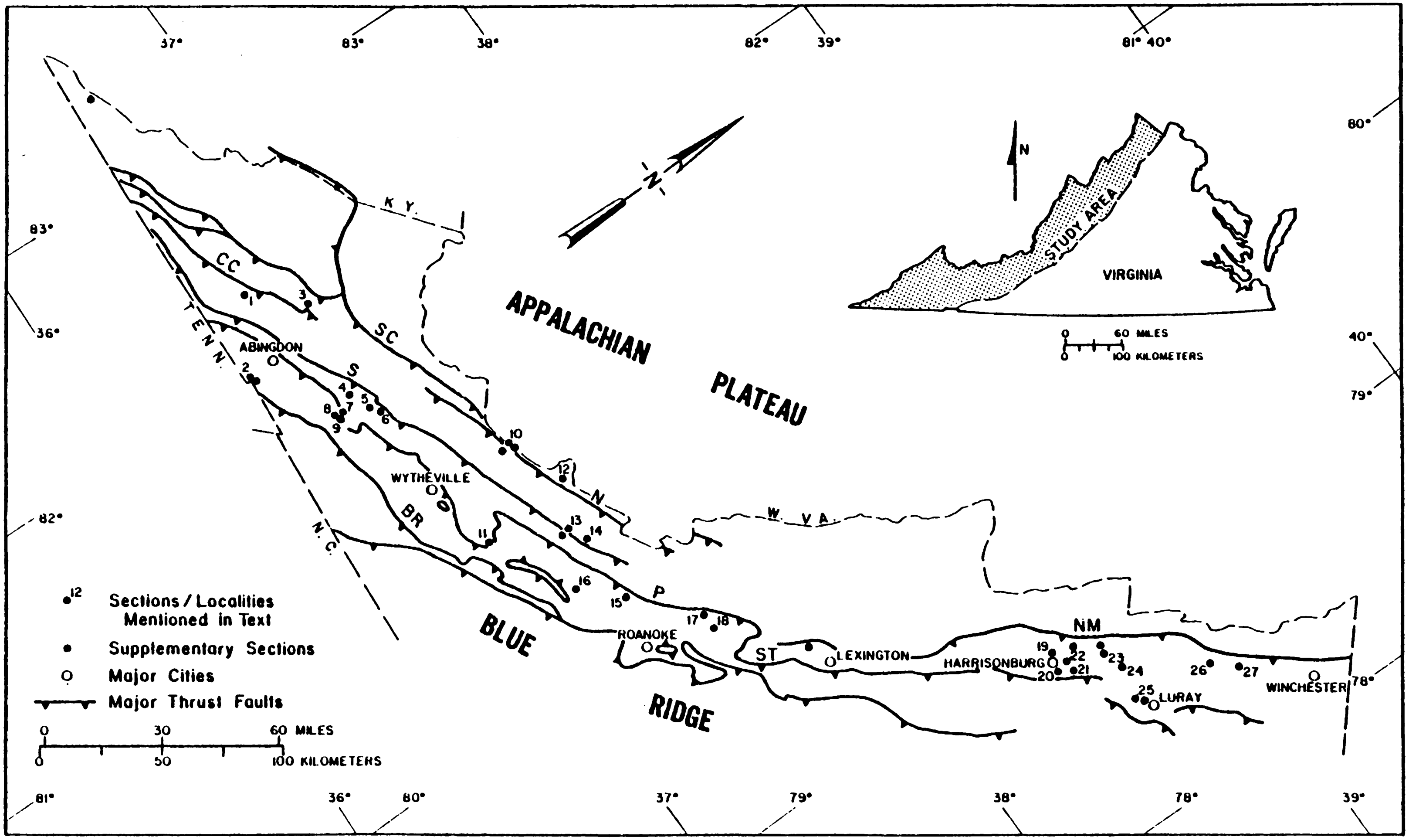
Twenty five stratigraphic sections of Lower-Middle Ordovician upper Knox/Beekmantown carbonates and unconformably overlying Middle Ordovician beds were measured, described and sampled in detail. Some exposures of paleokarst features associated with the unconformity were mapped in detail; Samples were examined using polished slabs and thin sections. thin sections were examined using both plane-polarized and cathodoluminescence.

STRUCTURAL AND STRATIGRAPHIC SETTING

The Middle Ordovician Knox unconformity is exposed within imbricate thrust sheets in the Valley and Ridge Province, Virginia Appalachians. Thrust sheets moved from southeast to northwest, with displacements ranging from a few to 30 km or more. The province lies between overthrust Precambrian and Lower Cambrian igneous and metasedimentary rocks of the Blue Ridge to the southeast, and nearly flat-lying Late Paleozoic sediments of the Appalachian Plateau to the northwest (Fig. 1).

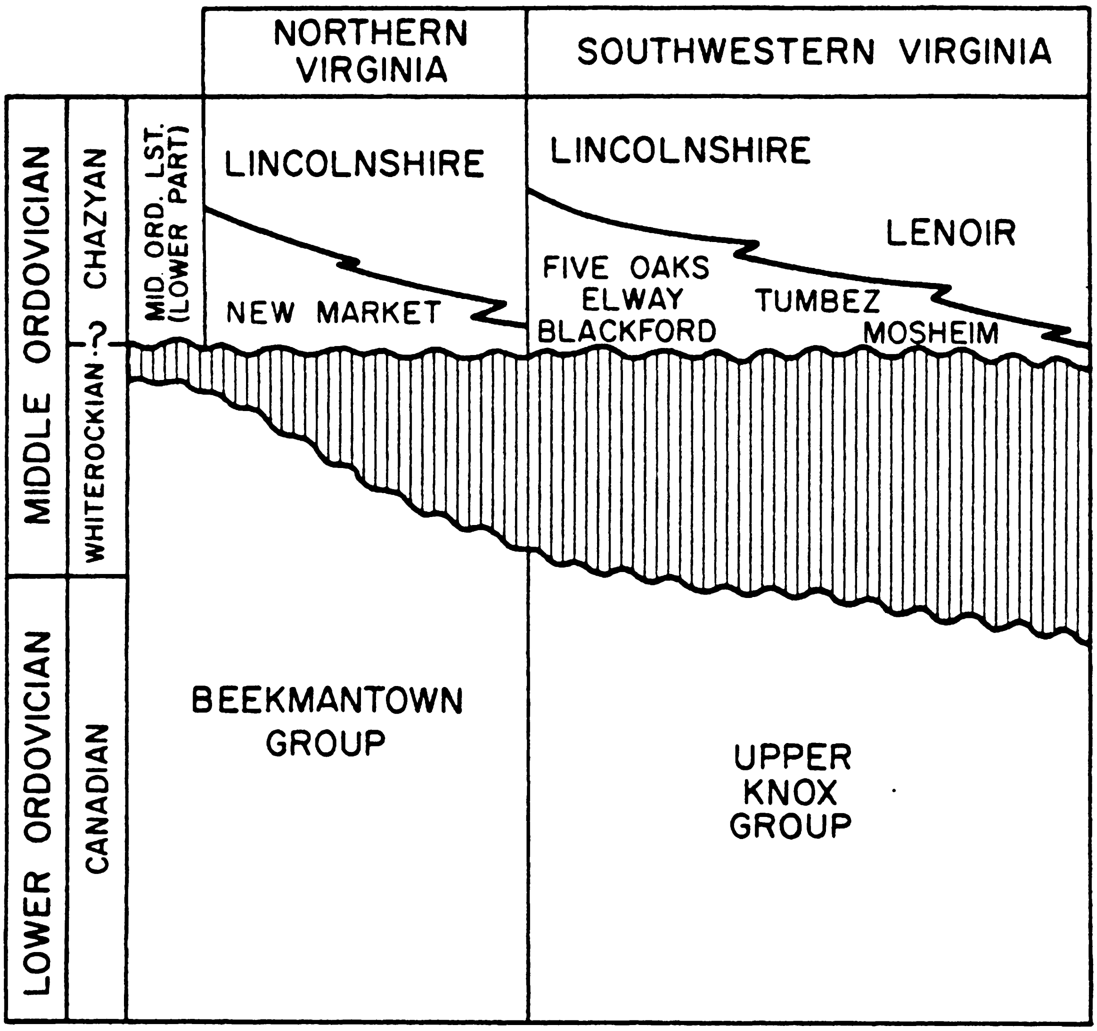
The unconformity is developed on Cambro-Ordovician carbonates referred to as the Knox Group in southwestern Virginia (up to 1000 m thick) and Beekmantown Group in west central and northern Virginia (up to 1200 m thick). The unconformity is overlain in various places by the Middle Ordovician Blackford-Elway-Five Oaks, Tumbez, New Market and Mosheim Formations (locally up to 80 m thick) (Fig. 2). These beds are oldest and thinnest in the south (Tillman, in Markello et al., 1979; Read, 1980). Depocenters centered in Tennessee and Pennsylvania (Colton, 1970; Read, 1980, his Fig. 2) appear to have strongly influenced unconformity development, and thickness and distribution of post-unconformity beds.

Figure 1 : Map of Valley and Ridge Province, Virginia Appalachians, showing distribution of measured sections and major thrust faults; SC=St. Clair, CC=Copper Creek, S=Saltville, P=Pulaski, BR=Blue Ridge, N=Narrows, NM=North Mountain, and ST=Staunton. See Read (1980) for Middle Ordovician outcrop belts.



APPALACHIAN PLATEAU
BLUE RIDGE
VIRGINIA
STUDY AREA
N
0 60 MILES
0 100 KILOMETERS
K Y.
W. V A.
TENN.
N. C.
CC
SC
S
N
BR
P
ST
NM
ABINGDON
WYTHEVILLE
ROANOKE
LEXINGTON
HARRISONBURG
LURAY
WINCHESTER
Sections / Localities Mentioned in Text
Supplementary Sections
Major Cities
Major Thrust Faults
0 30 60 MILES
0 50 100 KILOMETERS
37° 83° 38° 82° 39° 81° 40°
80° 40° 79° 78° 39°
83° 36° 82° 81°
36° 80° 37° 79° 38° 78°

Figure 2 : Simplified stratigraphic chart, Lower and early Middle Ordovician, Virginia.


NORTHERN VIRGINIA
SOUTHWESTERN VIRGINIA
MIDDLE ORDOVICIAN
LOWER ORDOVICIAN
CHAZYAN
?
WHITEROCKIAN
CANADIAN
MID. ORD. LST. (LOWER PART)
LINCOLNSHIRE
NEW MARKET
LINCOLNSHIRE
LENOIR
FIVE OAKS
ELWAY
BLACKFORD
TUMBEZ
MOSHEIM
BEEKMANTOWN GROUP
UPPER KNOX GROUP

Age Relations of Beds Adjacent to the Unconformity

Conodont biostratigraphic studies on beds adjacent to the unconformity in Virginia show that uppermost Knox Group carbonates in southwest Virginia are of Canadian age, and are overlain by limestones of Chazyan age. In northern Virginia, uppermost Beekmantown Group carbonates are of Whiterock age, and are overlain by limestones of latest Whiterock/earliest Chazyan age (Suter and Tillman, 1973; Lowry and Tillman, 1974; Tillman, 1976; Tillman, in Markello et al., 1979).

SUB-UNCONFORMITY KNOX/BEEKMANTOWN LITHOFACIES

Upper Knox/Beekmantown beds consist of cyclic carbonate sequences. Upper units of the Knox Group in southwest Virginia are older than upper beds of the Beekmantown Group in northern Virginia (Fig. 2). Also, Knox beds are mainly dolomite, with abundant bedded and nodular chert and quartz sand stringers, whereas the Beekmantown has many more limestone interbeds (locally up to 50 %). Knox/Beekmantown cycles are 2 to 9 m thick, and consist of, from top to bottom:

4) Cryptalgal laminated dolomite and fenestral limestone: Cryptalgal laminites (0 to 5.5 m thick) are stratiform sheets composed of horizontal, millimeter laminae of dolomite silt and clay size carbonate; locally, there are LLH stromatolites. The cryptalgal laminites commonly have shallow mudcracks, tepees, silicified evaporite nodules, relict fenestrae, and quartz sand stringers. Intraclastic and incipiently brecciated caps may occur within or on top of cryptalgal laminites. Fenestral lime mudstone and pellet intraclast packstone with faint cryptalgal lamination locally are associated with cryptalgal beds in the Beekmantown Group. Cryptalgal and fenestral beds may be underlain (or overlain) by:

3) Thick laminated dolomite: These beds (1 to 4 m thick) contain alternating 0.5-2 cm thick laminae of medium crystalline dolomite (or pellet silt), and finely crystalline dolomite. The coarser laminae are commonly micro-ripple cross-laminated, and have scoured bases with quartz sand lags. Burrow mottling may occur in lower parts of the unit, and deep mud cracks and silicified evaporite nodules are common throughout.

2) Massive and burrow mottled thin bedded dolomite: Massive and burrow mottled dolomites (0.5 to 3 m thick) are medium to coarsely crystalline, and have burrow disrupted,

irregular thin beds or lack internal structure due to burrow homogenization. Recrystallized grainstone or intraclastic beds occur locally, and there is some bedded and nodular chert.

1) Coarsely crystalline dolomite and thrombolites: Coarsely crystalline dolomites (0.5 to 4 m thick) contain relict ooid and skeletal grainstone fabrics and cross-bedding. Nodular chert and basal flat pebble conglomerates are locally associated. Some units have thrombolites (up to 0.5 m high) with undulating tops.

Interpretation: Upper Knox/Beekmantown beds are cyclic, upward-shallowing sequences that resemble Holocene and other ancient tidal flat sequences. They result from rapid transgression and subsequent progradation of shallow subtidal to high intertidal/supratidal facies (Mazzullo and Friedman, 1975; Reinhardt and Hardie, 1976).

Dolomitized basal flat-pebble conglomerate and grainstone are high energy deposits that formed as transgressive lags, or as wave-agitated subtidal shoals. Locally, these areas were sites of thrombolite growth or became sites of low energy deposition of thin-bedded carbonates in which layering was disrupted by burrowers. With shallowing to tidal level and decreasing burrowing, thick laminites and cryptalgal laminites were developed.

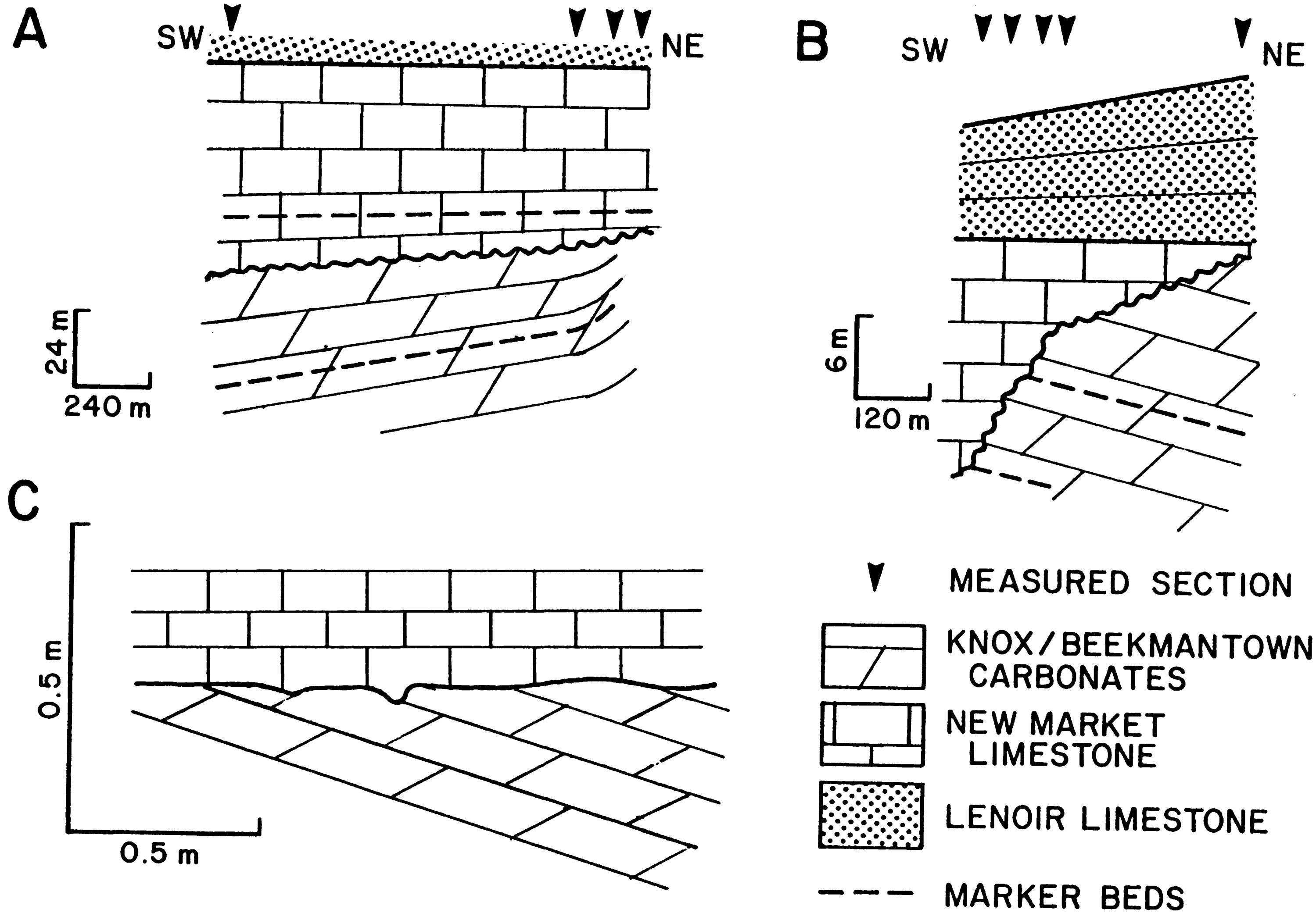
A semi-arid setting and hypersaline conditions are indicated by the association of silicified evaporite nodules, abundant cryptalgal laminites, and thrombolites which reflect lack of browsing of intertidal and subtidal algal mats (Logan et al., 1974; Mazzullo and Friedman, 1975).

POST-KNOX UNCONFORMITY

The post Knox/Beekmantown unconformity is a major stratigraphic break in the Paleozoic sequence of the Appalachians. In most areas in the Valley and Ridge Province of Virginia, the contact is a disconformity (cf. Weller, 1960, p. 391-2), in that beds above and below the unconformity are parallel, and are separated by an erosional surface having relief. However, the contact locally is an angular unconformity, with a discordance of up to 12 degrees (e.g. near Toms Brook, Leaksville, Broadway and Avens Bridge; Locs. 27, 25, 23, and 2, Fig. 1) (Fig. 3a,b,c).

Erosional relief on the unconformity decreases from 140 m or more in southwest Virginia (Webb, 1959) to a few meters or less (rarely up to 20 m) in northern Virginia (Fig. 4a). This corresponds with a decrease in stratigraphic relief along the same line of section (Fig. 4b). Stratigraphic relief also increases across strike from southeast to northwest (Fig. 4c). Neuman (1951) and Lowry (1957) suggested that the contact was locally conformable in northern Virginia. However, in all sections examined, some evidence of an erosional break was found. Such apparently conformable contacts occur where Beekmantown

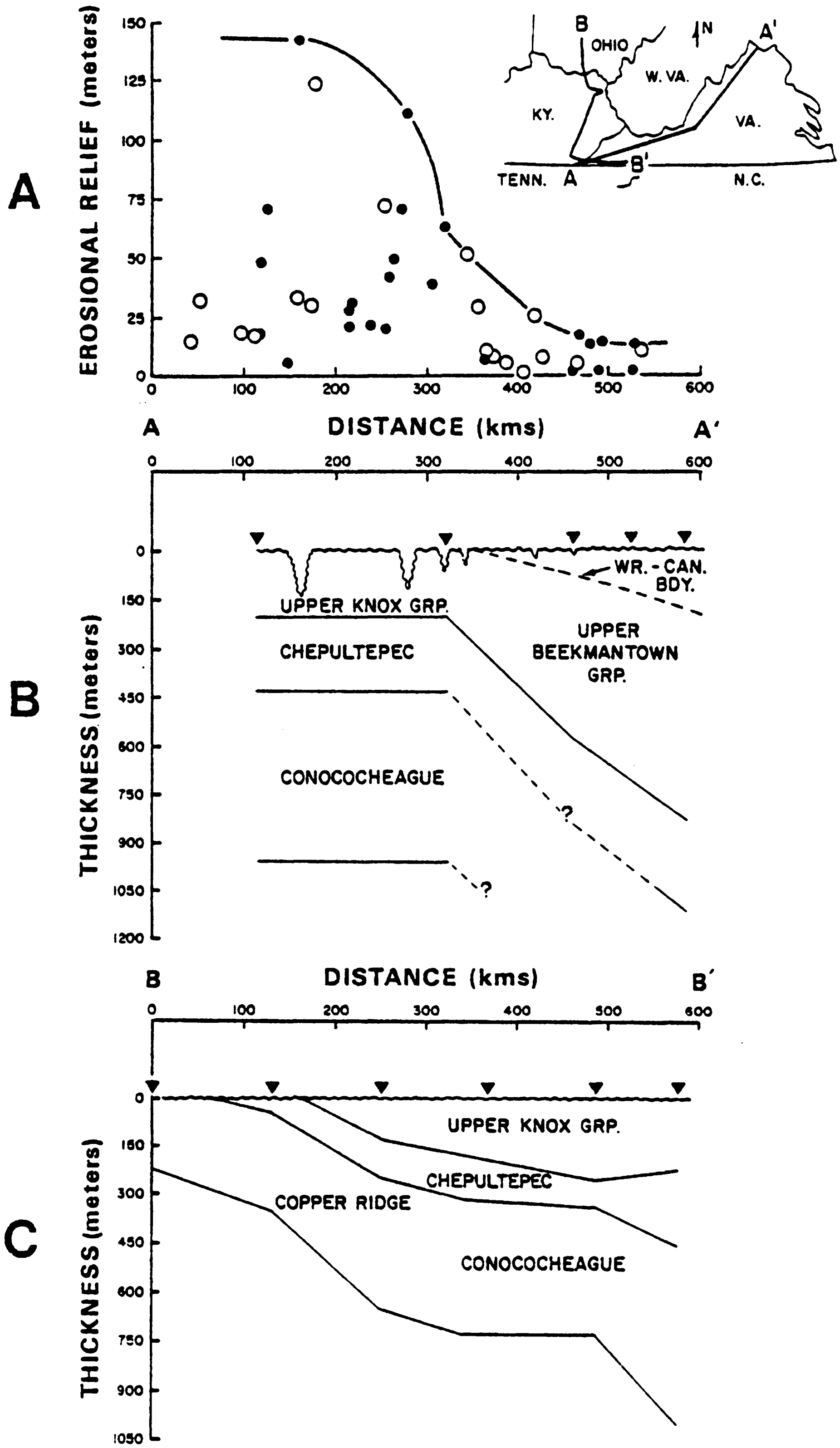
Figure 3 : Angular unconformities. Note exaggerated vertical scale in all diagrams. A, relationships near Broadway, Virginia. B, relationships near Avens Bridge, Virginia. C, relationships near Toms Brook, Virginia.


A
SW
NE
24 m
240 m
B
SW
NE
6 m
120 m
C
0.5 m
0.5 m
MEASURED SECTION
KNOX/BEEKMANTOWN CARBONATES
NEW MARKET LIMESTONE
LENOIR LIMESTONE
MARKER BEDS

dolomites are overlain by fine detrital dolomites (up to 10 m thick), but these can be followed along strike into coarse unconformity breccias (e.g. near Harrisonburg; Locs. 21-22, Fig. 1).

Apparently conformable contacts also occur where limestone beds of the Beekmantown Group are overlain by New Market fenestral limestone (e.g. near Park View; Loc. 19, Fig. 1). Here the unconformity is marked by local limestone breccia sheets. Elsewhere in Virginia, the unconformity has well developed paleokarst features that include paleotopographic highs, and lithoclastic breccias, conglomerates and redbeds that form sheets on the unconformity and fill depressions on the erosional surface. There also are sub-unconformity discordant detrital carbonate bodies and intraformational breccias.

Figure 4 : Erosional and stratigraphic relief on unconformity. A, plot of local erosional relief against distance; strike section, Virginia Valley and Ridge. B, strike section, plot of thicknesses of sub-unconformity formations against distance; stratigraphic relief increases to the southwest. Unconformity used as datum (data from J. Bova, in prep.). C, across-strike section, plot of thicknesses of sub-unconformity formations against distance; stratigraphic relief increases to the northwest. Unconformity used as datum (data from W. Koerschner, in prep.).


A
EROSIONAL RELIEF (meters)
150
125
100
75
50
25
0
0
100
200
300
400
500
600
B
OHIO
N
A'
W. VA.
KY.
VA.
TENN.
A
B'
N.C.
A
DISTANCE (kms)
A'
B
THICKNESS (meters)
0
150
300
450
600
750
900
1050
1200
WR.-CAN. BDY.
UPPER KNOX GRP.
CHEPULTEPEC
UPPER BEEKMANTOWN GRP.
CONOCOCHEAGUE
?
?
B
DISTANCE (kms)
B'
C
THICKNESS (meters)
UPPER KNOX GRP.
CHEPULTEPEC
COPPER RIDGE
CONOCOCHEAGUE

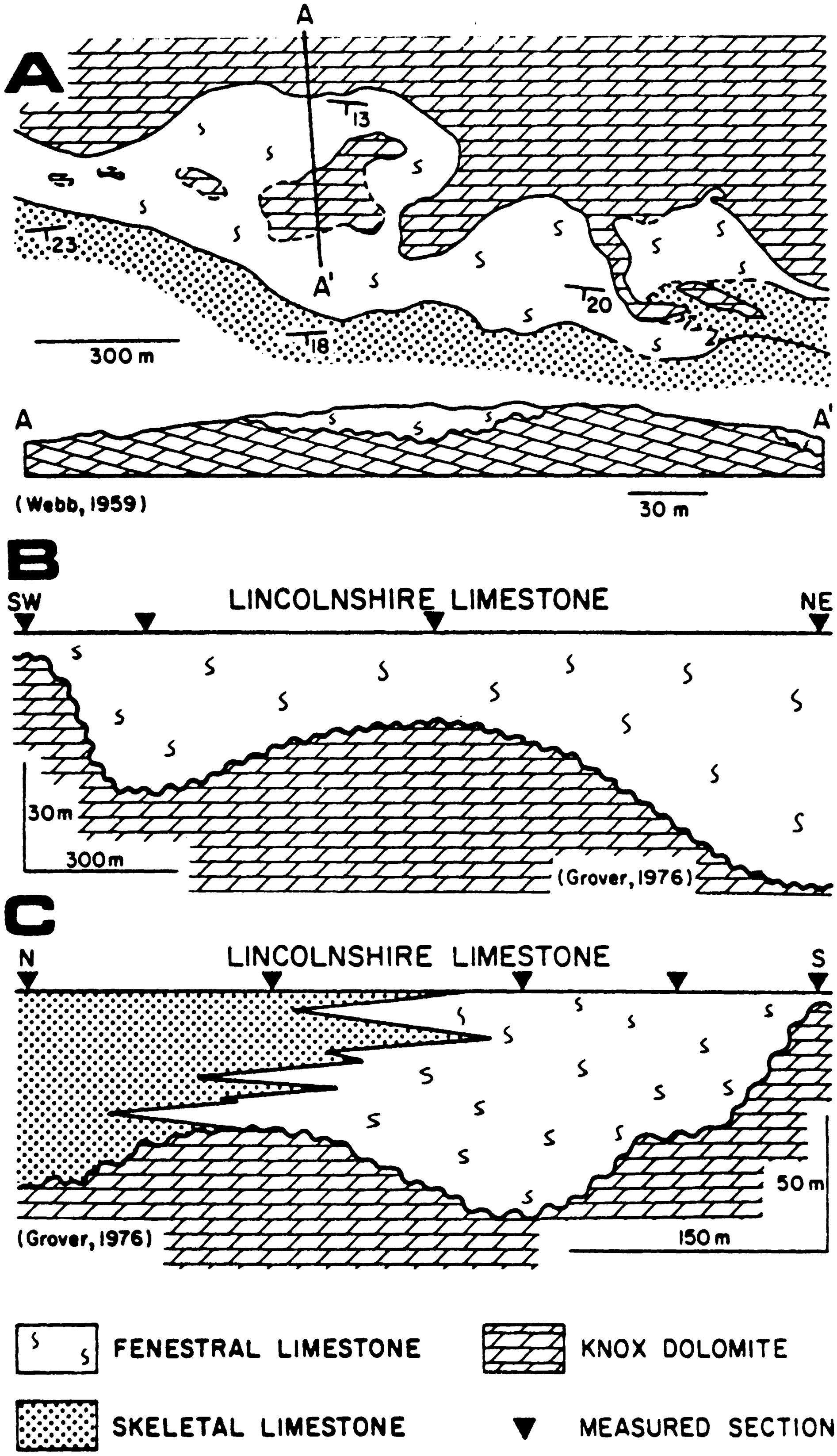
PALEOKARST FEATURES

Paleotopographic Highs

Exposures of paleohighs are present near Lebanon, Harrisonburg, and in Rich Valley (Locs. 3, 22, and 5, Fig. 1). They range from a few meters to 30 m in relief, being highest in southwestern Virginia. They are manifested by the thinning or pinching-out of basal peritidal beds (tens of meters of thinning over a few hundred meters along strike; Fig. 5b,c). They may also be accompanied by a transition from peritidal facies adjacent to the high, into subtidal skeletal beds away from the high (Fig. 5c). In outcrop, unconformity highs may form isolated inliers of Knox dolomite surrounded by peritidal beds (Webb, 1959) (Fig. 5a). The highs commonly are surrounded by a thin veneer (up to 30 cm thick) of mud-supported, chert-dolomite breccia which fines laterally into peritidal beds or fine detrital dolomite.

Origin: Paleotopographic features probably formed by differential chemical and physical weathering of Knox/Beekmantown carbonates during formation of the unconformity. They remained as positive elements during Middle Ordovician transgression, and may have been undercut

Figure 5 : Paleotopographic highs. A, map view showing inliers of Knox dolomite surrounded by fenestral or skeletal limestone, Rich Valley, Virginia (modified from Webb, 1959). B and C, cross-sections showing Knox dolomite overlain by massive fenestral limestone, or fenestral limestone adjacent to high grading into skeletal limestone away from high, Ellett Valley, Virginia (modified from Grover, 1976).


A
A
T13
T23
T20
T18
A'
300 m
A
A'
(Webb, 1959)
30 m
B
SW
LINCOLNSHIRE LIMESTONE
NE
30m
300m
(Grover, 1976)
C
N
LINCOLNSHIRE LIMESTONE
S
50 m
(Grover, 1976)
150 m
FENESTRAL LIMESTONE
KNOX DOLOMITE
SKELETAL LIMESTONE
MEASURED SECTION

by marine erosion. These highs influenced thickness and composition of post-unconformity sediments. They controlled thickness of tidal flat deposits, which pinch out onto the highs or grade away from highs into skeletal beds. Also, highs may have localized Middle Ordovician downslope buildups (Read, 1982).

Similar paleohighs in Indiana (up to 1 km dia. and 50 m high) have been delineated in the subsurface, and many contain hydrocarbons (Patton and Dawson, 1969; Keller and Abdulkareem, 1980). Dawson (1967) suggests that these erosional highs in Indiana formed mainly by physical weathering (deflation), because of the presence of post-unconformity quartz arenites (St. Peter Sandstone), and because their butte-like shapes are characteristic of arid environments. However, lack of post-unconformity sands and corroded clast margins in unconformity breccias in Virginia indicates chemical dissolution was the main weathering process here.

Detrital Carbonate-Filled Depressions

Non-fossiliferous fills: Rare exposures of narrow (3 to 35 m wide, up to 65 m deep) breccia- filled depressions on the unconformity occur near Fincastle (Loc. 17, Fig. 1). They are mainly vertical to bedding, but some extend horizontally at depth. Sides are sub-parallel, and contacts between host beds and fill are sharp and irregular (Fig. 6).

They consist of lithoclast breccia with rare pods and lenses of granule conglomerate in detrital dolomite matrix (Table 1). They lack skeletal remains, are non-graded, and poorly sorted. Breccias are mainly mud-supported, but some are clast-supported. They contain angular, rotated blocks of dolomite/limestone (up to 2 m dia.) and gravel- to cobble-size clasts of chert, dolomite and limestone (up to 25 cm dia.) (Fig. 7a).

Some large blocks show in-place brecciation and fitted fabrics with fractures filled by dolomite mud. Clasts within breccias commonly have scalloped and corroded surfaces (Fig. 7b). Chert clasts are angular whereas limestone and dolomite clasts are poorly rounded. Matrix within breccias is quartzose, fine to medium crystalline dolomite.

Rare granule conglomerates fill scours within dolomite mud (Fig. 7c). Conglomerates are clast-supported, lack grading, and are poorly sorted. Clasts are generally less than 5 mm diameter, and are composed of pellet grainstone, lime mudstone and ripple cross-laminated dolomite. Inter-clast areas are filled by finely crystalline dolomite mud

Figure 6 : Map view of sinkholes on unconformity near Fincastle, Virginia.

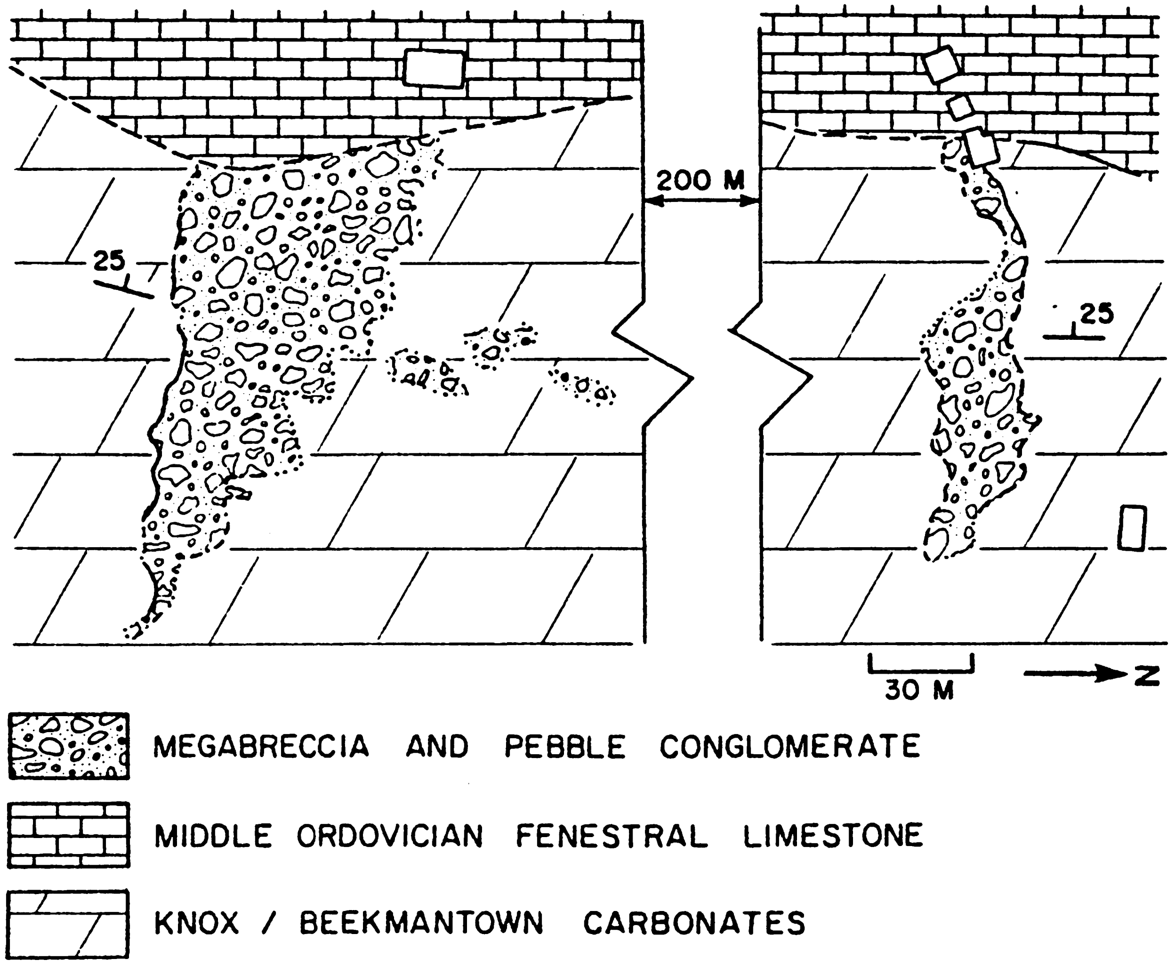
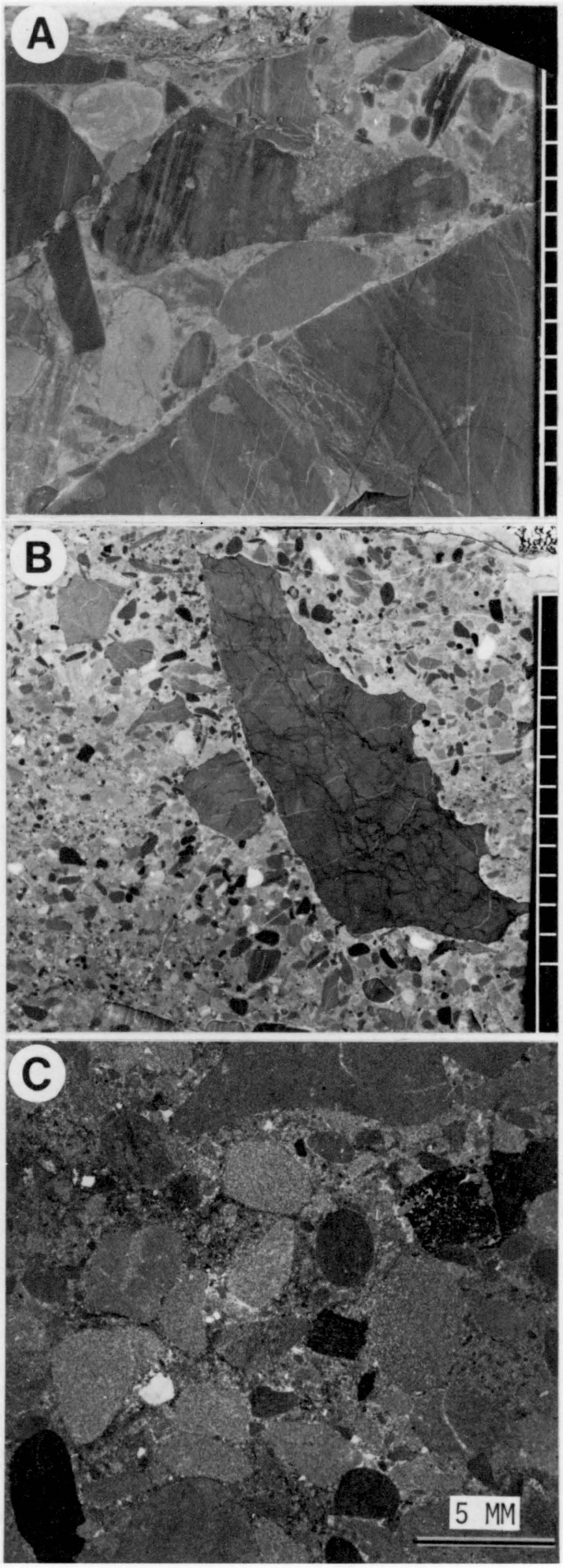

200 M
25
25
30 M
N
MEGABRECCIA AND PEBBLE CONGLOMERATE
MIDDLE ORDOVICIAN FENESTRAL LIMESTONE
KNOX / BEEKMANTOWN CARBONATES

TABLE 1

CHARACTERISTICS OF KARST-RELATED LITHOFACIES

	SUB-UNCONFORMITY			POST-UNCONFORMITY	
	FILLED SINKHOLES	FILLED CAVES	INTRAFORMATIONAL BRECCIAS	BRECCIAS AND CONGLOMERATES	THICK, FINE DETRITAL CARBONATE, BLACKFORD FORMATION
GEOMETRY & THICKNESS	NARROW AND SUBVERTICAL (UP TO 35 M WIDE, 65 M DEEP) OR V-SHAPED (35 M WIDE, 15 M DEEP)	SUBVERTICAL OR PARALLEL TO MOST BEDDING, UP TO 2 M WIDE AND 12 M LONG. NO VISIBLE CONNECTION TO UNCONFORMITY SURFACE	LENTICULAR TO STRATIFORM, UP TO 200 M WIDE AND LONG, AND 35 M THICK IN SUBSURFACE; UP TO 10 M LONG AND 5 M THICK IN OUTCROP	BRECCIAS: THICKEN INTO UNCONFORMITY LOWS, THIN ONTO HIGHS; UP TO 2 M THICK CONGLOMERATES: FILL CHANNEL-FORM DEPRESSIONS ON THE UNCONFORMITY SURFACE; UP TO 6 M THICK	THICKENS INTO DEPRESSIONS, THINS OVER PALEOHIGHS; 0 TO 70 M THICK
DISTRIBUTION	SOUTHWESTERN VIRGINIA	NORTHERN VIRGINIA	THROUGHOUT UPPER KNOX/BEEKMANTOWN BEDS IN VIRGINIA AND TENNESSEE	SOUTHWESTERN VIRGINIA	CONFINED MAINLY TO WESTERN BELTS, SOUTHWESTERN VIRGINIA; OCCURS RARELY IN SOUTHEASTERN BELTS BENEATH PERITIDAL CARBONATES
LITHOLOGY	NON-MARINE FILLS: CHERT/DOLOMITE BRECCIAS (BLOCKS UP TO 2 M DIA) IN FINE DETRITAL DOLOMITE MATRIX; RARE SCOUR-FILLING PEBBLE CONGLOMERATES MARINE FILLS: INTERBEDDED, BLACK, SKELETAL INTRACLAST GRAINSTONE AND LIME MUDSTONE	MAINLY FINELY LAM'D DETRITAL DOLOMITE WITH SCOUR-FILLING PEBBLE CONGLOMERATE, DETRITAL LIMESTONE BLOCKS, AND CHERT-DOLOMITE BRECCIAS IN CAVITIES NEAR UNCONFORMITY	ANGULAR DOLOMITE BRECCIA IN MEDIUM TO COARSE DOLOMITE MATRIX AND/OR COARSE BLOCKY CALCITE OR DOLOMITE CEMENT	CHERT, DOLOMITE AND LIMESTONE CLASTS IN MATRIX OF DETRITAL DOLOMITE, SKELETAL GRAINSTONE, OR FENESTRAL LIME MUDSTONE/PELLET PACKSTONE	MASSIVE FINE DETRITAL DOLOMITE, GRADED LITHOCLASTIC DOLOMITE, QUARTZ SILTSTONE, BENTONITIC SHALE, ALGAL LIMESTONE, RARE ALGAL TUFAS
COLOR	NON-MARINE FILLS: TAN AND BLUE-GRAY CLASTS, LIGHT BROWN OR YELLOW MATRIX MARINE FILLS: DARK GRAY TO BLACK	LIGHT BROWN	CLASTS ARE GRAY TO LIGHT BROWN, MATRIX AND CEMENTS ARE WHITE TO YELLOW	RED, GRAY, OR BEIGE	RED, GRAY OR BEIGE
BEDDING & STRUCTURES	NON-MARINE FILLS: LACK BEDDING AND GRADING, AND ARE POORLY SORTED MARINE FILLS: THIN TO THICK BEDDED; GRAINSTONES CONTAIN SOFT-SEDIMENT FOLDS AND FAULTS	LACK BEDDING BUT ARE FINELY LAMINATED INTERNALLY; CONTAIN SOFT-SEDIMENT SLUMPS, SMALL SCOURS, AND RARE RIPPLE CROSS-LAMINATION	BEDDING AND STRUCTURES ABSENT	BRECCIAS: MEDIUM TO THICK BEDDED, SOME ARE GRADED. CONGLOMERATES: THICK BEDDED AT BASE, THINNING UPWARDS; HARDGROUNDS, CLAST IMBRICATION, RARE RIPPLE CROSS-LAMINATION	THIN TO THICK BEDDED; THIN TO THICK LAMINATION, TEPEES, MUDCRACKS FENESTRAE, CRYPTALGAL LAMINATION, AND BURROW-MOTTLING
BIOTA	NON-MARINE FILLS: BARREN MARINE FILLS: ABUNDANT TRILOBITES, OSTRACODES, AND ECHINODERMS, AND RARE ALGAE, BRACHIOPOD AND BRYOZOAN DEBRIS	BARREN	BARREN	BRECCIAS: DETRITAL DOLOMITE MATRIX - BARREN; SKELETAL MATRIX - OPEN MARINE (ECHINODERM, BRYOZOAN, TRILOBITE, OSTRACODE, AND BRACHIOPOD DEBRIS); FENESTRAL MATRIX - RESTRICTED MARINE (OSTRACODES, ALGAE, DELICATE CORALS). CONGLOMERATES: DETRITAL DOLOMITE OR CHERT/QUARTZ SAND MATRIX - BARREN; LIMESTONE MATRIX - OPEN TO RESTRICTED ASSEMBLAGES (AS ABOVE).	BARREN
DIAGENESIS	COMPACTION AND PRESSURE SOLUTION FEATURES	COMPACTION FEATURES	SILICIFICATION, SADDLE DOLOMITE, SULFIDE ORES, LIQUID HYDROCARBON	ABSENT	DOLOMITIZATION (?), PRESSURE SOLUTION
PRIMARY POROSITY (cement-filled)	MINOR IN PEBBLE CONGLOMERATES, ABUNDANT IN GRAINSTONE BEDS	MINOR IN PEBBLE CONGLOMERATES	TRACE TO 30?	BRECCIAS: TRACE CONGLOMERATES: TRACE TO 5%	TRACE

Figure 7 : Non-fossiliferous sinkhole fills. A, basal lithoclast breccia in dolomite mud matrix, Eggleston, Virginia. Scale in centimeters. B, limestone clasts floating in pebble conglomerate matrix, Fincasltle, Virginia. Note scalloped margins on clasts. Scale in centimeters. C, thin section, pebble conglomerate with dolomite mud matrix and rare calcite cement, Fincastle, Virginia.


A
B
C
5 MM

and rare calcite cements. Some breccia-filled depressions developed on Knox carbonates and below basinal black shale in southeastern belts, southwest Virginia, contain economic deposits of iron sulfide (Cooper and Diggs, 1953).

Fossiliferous fills: Rare depression fills contain fossiliferous lime sands and muds, with only minor breccia (Table 1). Such a depression fill near Leaksville (Loc. 25, Fig. 1), is 35 m wide and 15 m deep, and overlies extensive intraformational breccias within Beekmantown carbonates. Contacts between the fill and Beekmantown beds are sharp. The fill consists of interlayered, black, argillaceous lime mudstone and intraclast packstone/grainstone beds (up to 15 cm thick) that have soft-sediment deformation features; these include small recumbent folds (directed toward the center of the depression) and faults which offset lamination within beds (Fig. 8a,b). The lime mudstones (up to 50 cm thick) are pyritic, argillaceous and slightly fissile, lack lamination, and contain abundant fine quartz sand, rare rounded clasts of dolomitized lime mud (up to 1 mm dia.), and minor ostracode and trilobite debris. Intraclast grainstone layers (up to 10 cm thick) consist of rounded clasts of pelletal mudstone (up to 5 mm dia.) and rare skeletal debris in blocky calcite cement (Fig. 8c).

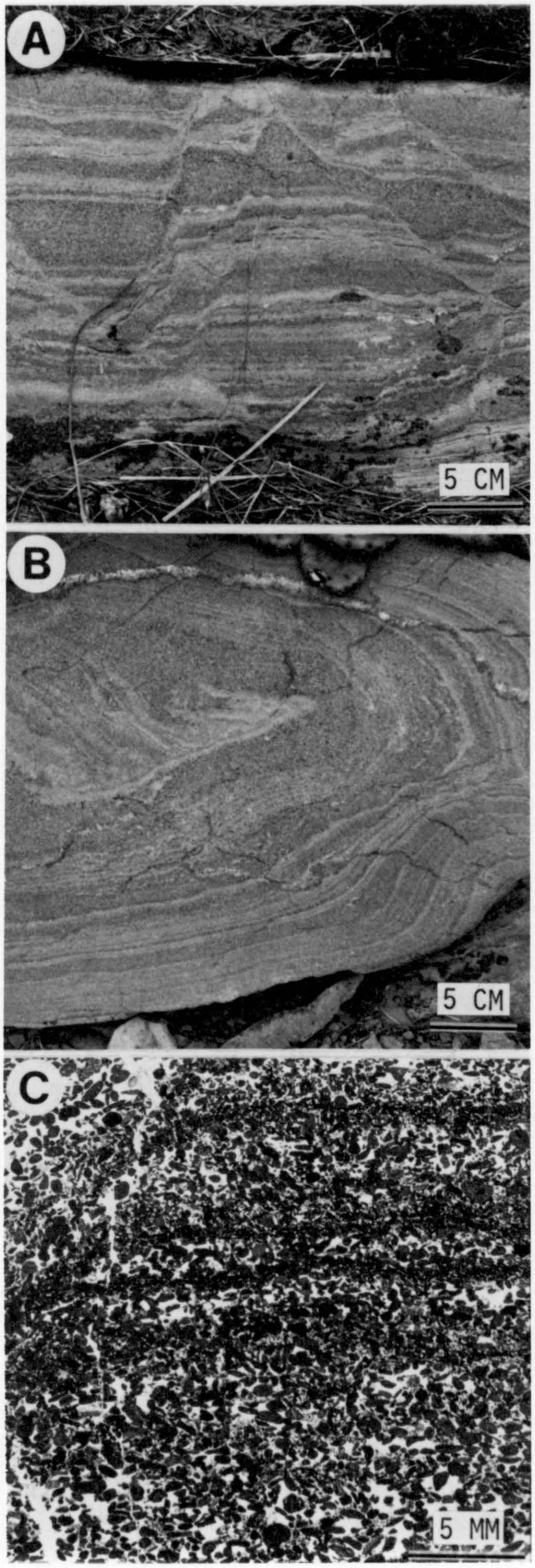
Skeletal grains include trilobite, ostracode and pelmatozoan remains, and rare calcareous algae, brachiopod and bryozoan fragments. Some intraclasts contain skeletal grains that are truncated at clast margins. Grainstones contain seams and stringers of stylolitized packstone in which quartz silt and skeletal grains are concentrated.

Origin: Depression fills of detrital carbonate resemble modern collapse dolines (sinkholes) (Campbell, 1975). Similar filled sinkholes occur on the unconformity in Tennessee (Laurence, 1944; Bridge, 1955), and on the post-Mississippian unconformity, western U.S.A. (Sando, 1974; Maslyn, 1977).

Dolines develop in subaerial settings, primarily by dissolution along joints, fractures, or bedding planes to form depressions, or they form caverns whose roofs collapse. Such dolines are characterized by near vertical sides, high depth to width ratios, and megabreccias (Quinlan, 1972).

Many sinkholes on unconformities occur above intraformational breccias, as in the upper Knox Group of Tennessee (Harris, 1971), the Upper Mississippian of Wyoming (McCaleb and Wayhan, 1969), and in northern Virginia near Leaksville (Loc. 25, Fig. 1). These

Figure 8 : Fossiliferous sinkhole fills. A and B, soft-sediment deformation features in grainstone beds near Leaksville, Virginia. C, thin section showing alternating laminations of skeletal pellet-intraclast grainstone and quartzose, stylolitized pellet-intraclast packstone.


A
5 CM
B
5 CM
C
5 MM

relations suggest that some sinkholes developed as underlying beds became brecciated and collapsed, resulting in local subsidence.

Fills in most sinkholes are non-marine deposits, indicated by lack of marine biotas. They were locally derived by collapse of walls and roofs of cavities, together with boulder- to mud-size detritus from the unconformity surface that was washed into sinkholes during heavy rains, locally forming scour-filling pebble conglomerates. Some blocks were incipiently brecciated after collapse, either by impact or by weathering. Scalloped and corroded margins of clasts reflect chemical dissolution during formation of the sinkholes and their fills.

Fossiliferous sinkhole fills in northern Virginia contain a relatively open marine biota, and probably accumulated during initial Middle Ordovician transgression. Highly reducing conditions in the sediments are suggested by black coloration and abundant pyrite. Such sinkholes may have been connected to the sea by way of subsurface caves, by tidal channels, or may have formed deep ponds surrounded by Middle Ordovician tidal flats. They are similar to sinkholes (up to 75 m wide, 4 m deep) developed on Pleistocene limestone, lower Florida Keys (Dodd and

Siemers, 1971). These sinkholes are presently in water depths of less than 1 m, and contain a fill of black peat and carbonate that is restricted to these depressions.

Middle Ordovician fossiliferous fills contain abraded limestone and dolomite clasts and fine carbonate. Rounding of clasts probably occurred on the unconformity prior to transport into sinkholes; this is suggested by the lack of wave- or current-formed structures in the fills. The clasts were probably transported into sinkholes during storms or high tides, where they accumulated with mud layers deposited during prevailing low energy periods. Soft-sediment deformation features may have been triggered by sinkhole subsidence, or possibly by slumping of sediments deposited on inclined walls of sinkholes.

Discordant Detrital Carbonate Bodies

Thin, sheet-like to irregular bodies (up to 12 m long, and 2 m wide) of detrital dolomite within Knox/Beekmantown carbonates extend down to 35 m below the unconformity near Leaksville and Eggleston (Locs. 25 and 13, Fig. 1). They are horizontal to randomly oriented and lack any connection to the unconformity surface in outcrop (Fig. 9). Contacts between host beds and fill are sharp and highly irregular (Figs. 9,10,11a). Fills are non-fossiliferous, and are dominantly fine dolomite; breccias occur locally, especially in cavities near the unconformity.

Most fine dolomite fills are brown and massive, but some have millimeter to centimeter laminations of alternating fine and medium crystalline dolomite (Table 1). Layering may be inclined toward the interior of the cavity (slopes up to 40 degrees), especially adjacent to walls of host rock, and is commonly truncated by overlying sub-horizontal laminae. Small scours (from a centimeter to a meter across) are common, and are filled with laminated mud in which lamination is conformable to the basal scour surface (Fig. 11b). Small slump masses of laminated dolomite also occur. Other scours are smooth walled, anastomosing and subvertical, and are filled with granule carbonate conglomerate (Figs. 10,11c), which also forms rare sheets (up to 15 cm thick) within or at bases of laminated beds. The conglomerates are clast- to mud-supported, and composed of rounded clasts (up to 8 mm dia.) of dolomite and lime mudstone, with interstitial fine dolomite and sparry calcite cement.

Breccias within these bodies are mainly clast-supported, lack bedding and grading, and are poorly sorted. Clast types are varied and are derived from many Knox/Beekmantown rock types. Clasts (up to 25 cm dia.) are

Figure 9 : Outcrop map of upper Beekmantown Group and New Market Limestone near Leaksville, Virginia, showing relationships between host carbonates, intraformational breccias, and cave fills. Note correspondence between thinned limestone beds and breccias. Unconformity shown by heavy black line. Mapping done by H. Ross and W. Mussman.

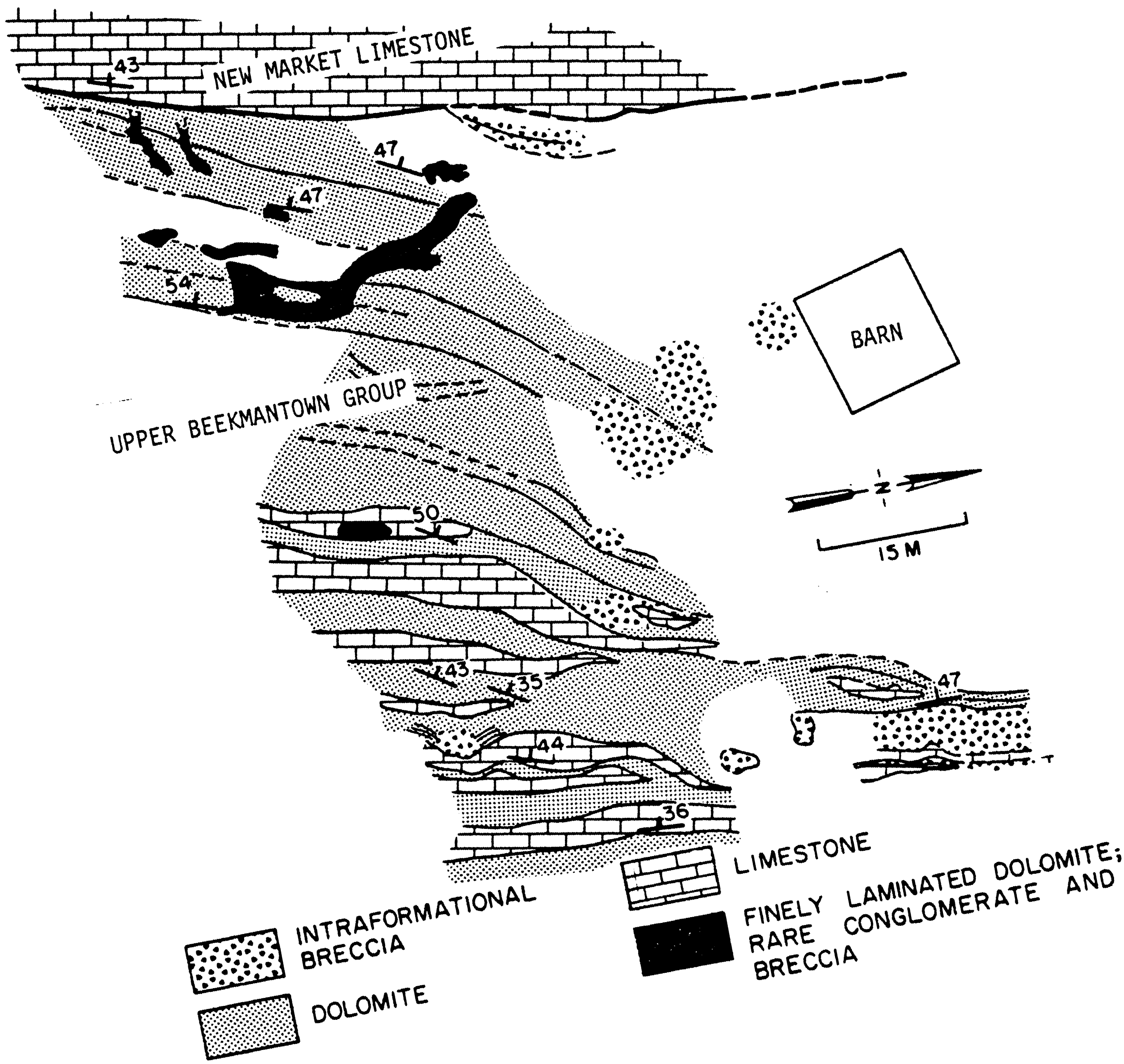

NEW MARKET LIMESTONE
43
47
47
54
BARN
UPPER BEEKMANTOWN GROUP
N
15 M
50
43
35
47
44
36
INTRAFORMATIONAL BRECCIA
DOLOMITE
LIMESTONE
FINELY LAMINATED DOLOMITE; RARE CONGLOMERATE AND BRECCIA

Figure 10 : Cross-section through portion of cave fill within Beekmantown Group, shown on Fig. 9. Note sharp irregular contacts with host rock, bedding which dips toward center of fill, and pebble conglomerates which fill scours or veneer basal contact with host rocks.

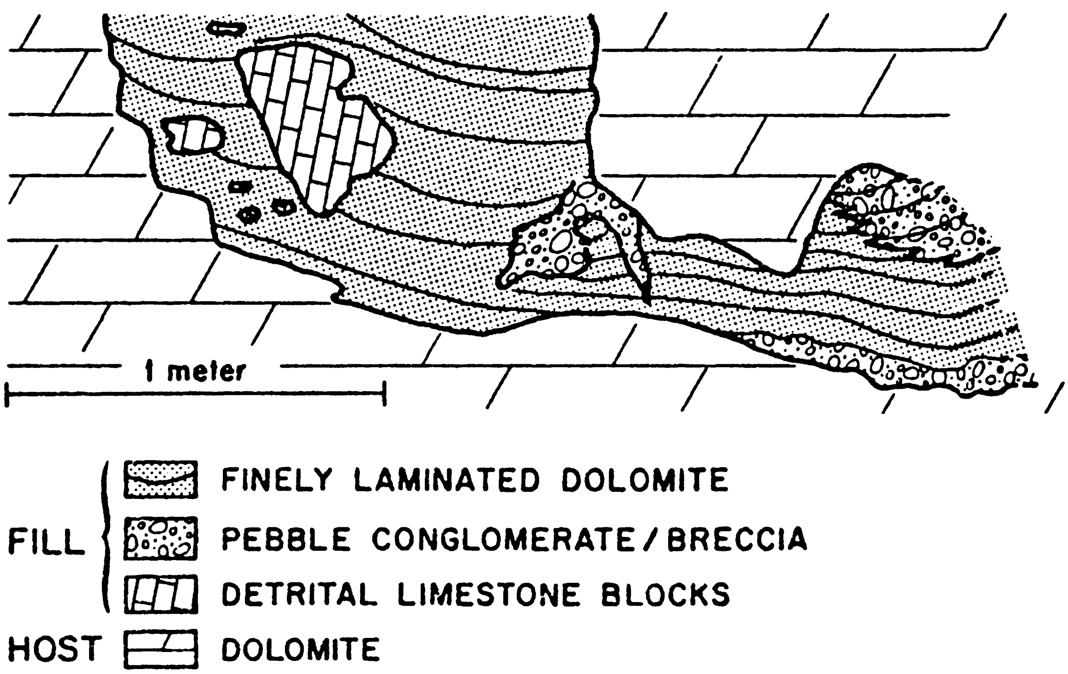
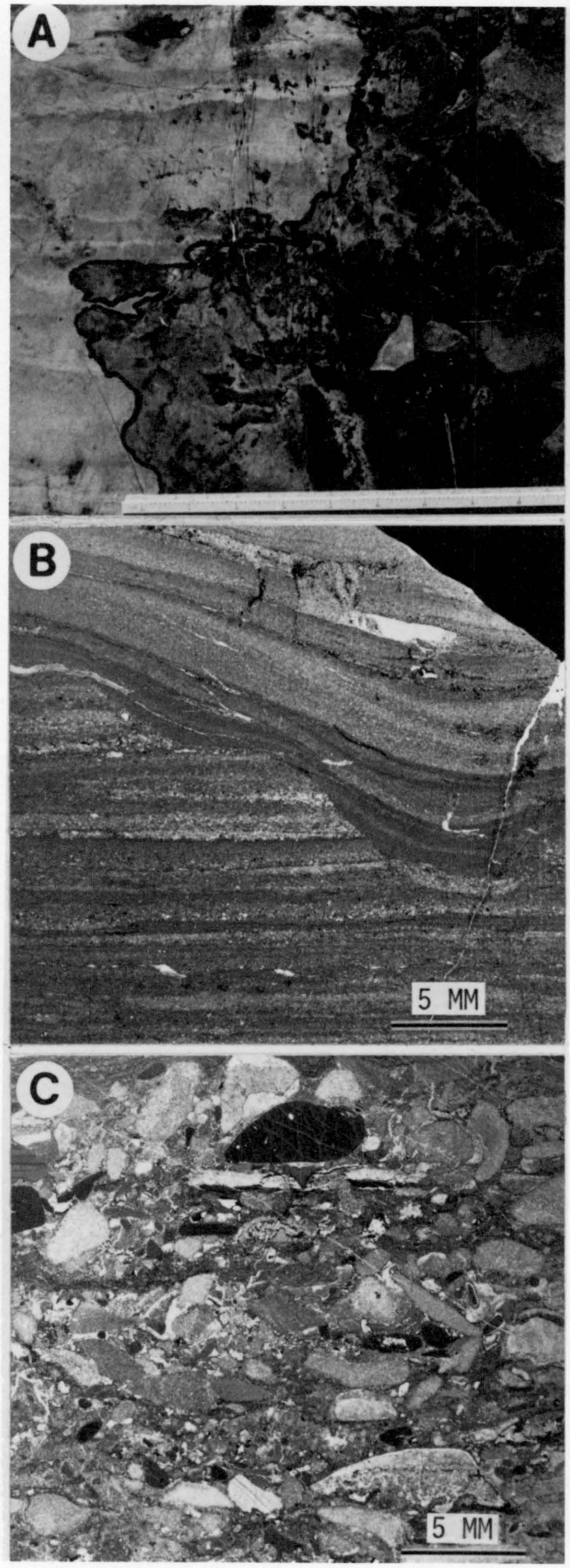

1 meter
FILL
FINELY LAMINATED DOLOMITE
PEBBLE CONGLOMERATE/BRECCIA
DETRITAL LIMESTONE BLOCKS
HOST
DOLOMITE

Figure 11 : Cave fills, Leaksville, Virginia. A, sharp irregular contact (highlighted with felt marking pen) between light-colored host dolomite and brown, fine-grained dolomite of cave fill. Scale in inches. B, thin section showing small scour in finely laminated cave fill. C, thin section of pebble breccia/conglomerate that fills scours within laminated fills or forms basal sheets on host beds.


A
B
5 MM
C
5 MM

subangular to rounded dolomite, limestone and rare angular chert. Some clasts have concentric banding. Matrix in breccias is composed of argillaceous, finely crystalline dolomite with scattered quartz sand.

Origin: Shallow, discordant bodies of detrital carbonate beneath the unconformity surface in Virginia are probably cave fills, although some may be cross-sections of collapse dolines (e.g. near Eggleston; Loc. 13, Fig. 1). Similar features occur below the post-Mississippian unconformity, western U.S.A. (Sando, 1974; Maslyn, 1977).

Caves form by solution along joints, fissures and bedding planes (Sweeting, 1972, p. 130-1). Caves formed along joint planes tend to be high, narrow, winding, to vertical slits; in flat-lying beds, bedding planes commonly control cave shape, and they are generally low and wide (Sweeting, 1972, p. 135-6). Middle Ordovician caves in Virginia are generally narrow slits subvertical to bedding, but there also are large cavities that appear to have formed along bedding planes. When formed in an area of relatively high relief on the unconformity (e.g. near Leaksville; Loc. 25, Fig. 1), caves might be expected to cut down vertically through bedding to the regional water table.

Lack of flowstone or dripstone in ancient cave fills has been used as evidence for a phreatic origin (Sando, 1974); however, contacts between Beekmantown host beds and cave fills in Virginia are highly solutional, which would limit preservation of any locally developed dripstone or flowstone.

Fills in Beekmantown caves are non-marine because they lack skeletal remains and are composed of locally derived detrital carbonate. The dominance of millimeter-laminated fine dolomite containing abundant scours and slump structures is similar to that seen in modern caves, and results from abundant fine material supplied as relatively insoluble residue, and fluctuations in flow (Jennings, 1971, p. 176). Scours in laminated beds that formed during periods of increased flow generally were filled by fine detrital carbonate. However, during periods of flooding when cave waters carried coarse-grained detritus, carbonate gravels were deposited in scours or as upward-fining beds. Fine carbonate, locally deposited on unstable slopes, formed small slump beds. Other laminated fills that are steeply dipping may have been oversteepened during sediment compaction, or subsidence of the cave floor.

Intraformational Breccias

These occur in the upper 200 to 300 m of Knox/Beekmantown beds, within sequences of interbedded limestone and dolomite. They are well exposed near Leaksville, Toms Brook (Rader and Biggs, 1975), and Chatham Hill (F. Webb, pers. comm., 1982) (Locs. 25, 27, and 6, Fig. 1). They are lenticular to stratiform bodies of breccia with irregular lateral and upper contacts with host beds, and relatively sharp, horizontal basal contacts (Figs. 9,12,13b). In outcrop, they are a few centimeters to a few meters thick and up to 10 m long, and may contain base metal deposits (e.g. near Chatham Hill). In the subsurface, ore-bearing breccias are up to 210 m long, 200 m wide, and 35 m thick (Luttrell, 1966). Breccias grade upwards into unaltered host rock through incipiently brecciated (fitted fabric) dolomite (Fig. 13a). Basal contacts have remnants of limestone beds or solution-scalloped limestone clasts (Fig. 12). Laterally, many contacts with unaltered limestone beds are corrosional, but some show soft-sediment deformation adjacent to the breccia.

Breccias are typically clast-supported, poorly sorted, and lack grading (Table 1). Small breccia bodies have few clast types, the clasts being derived mainly from overlying dolomite; however, large breccia bodies contain clasts from various host rocks. Clasts are angular, and are up to 60 cm diameter. Some large clasts appear to have been brecciated _in situ_, and exhibit fitted fabrics. Matrix within breccias is medium to coarsely crystalline dolomite and/or coarse blocky calcite or dolomite cement (Fig. 13c).

Origin: Intraformational breccias in Virginia are similar to those containing base metal deposits in subsurface Knox beds in Tennessee (Kendall, 1960; Harris, 1969; Kyle, 1976).

These intraformational breccias were originally thought to be tectonic breccias related to the late Paleozoic orogeny, but most workers now consider them to be collapse features associated with the dissolution of subsurface limestone beds during the formation of the unconformity, and possibly later (see Harris, 1969 for review). They have been termed interstratal karst (Quinlan, 1972; Sweeting, 1972, p. 298), which forms by subsurface dissolution of carbonate rock.

Dissolution of limestone beds in the subsurface in northwestern belts was probably caused by surface drainage from the unconformity, because there is a close association between sinkholes on the unconformity and intraformational breccias in the subsurface (Harris, 1971). Also,

Figure 12 : Cross-section of intraformational breccia near Leaksville, Virginia (from Fig. 9), showing basal remnant limestone knobs, and lateral transitions from breccia through fitted-fabric into unaltered host dolomite.

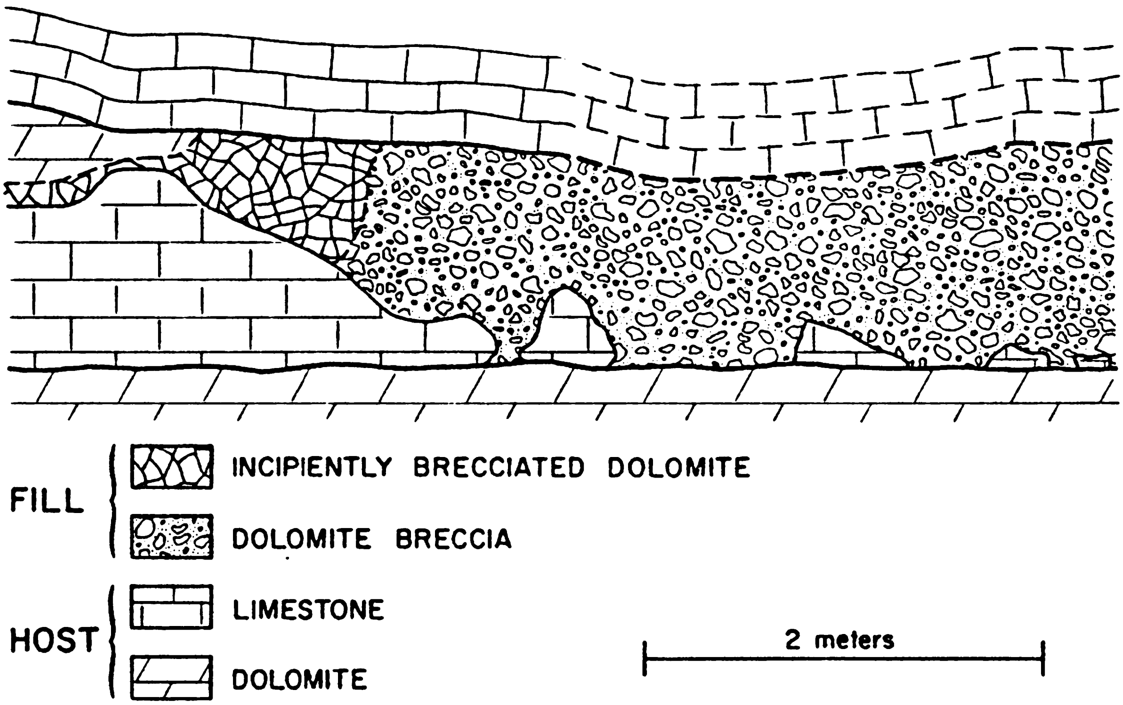
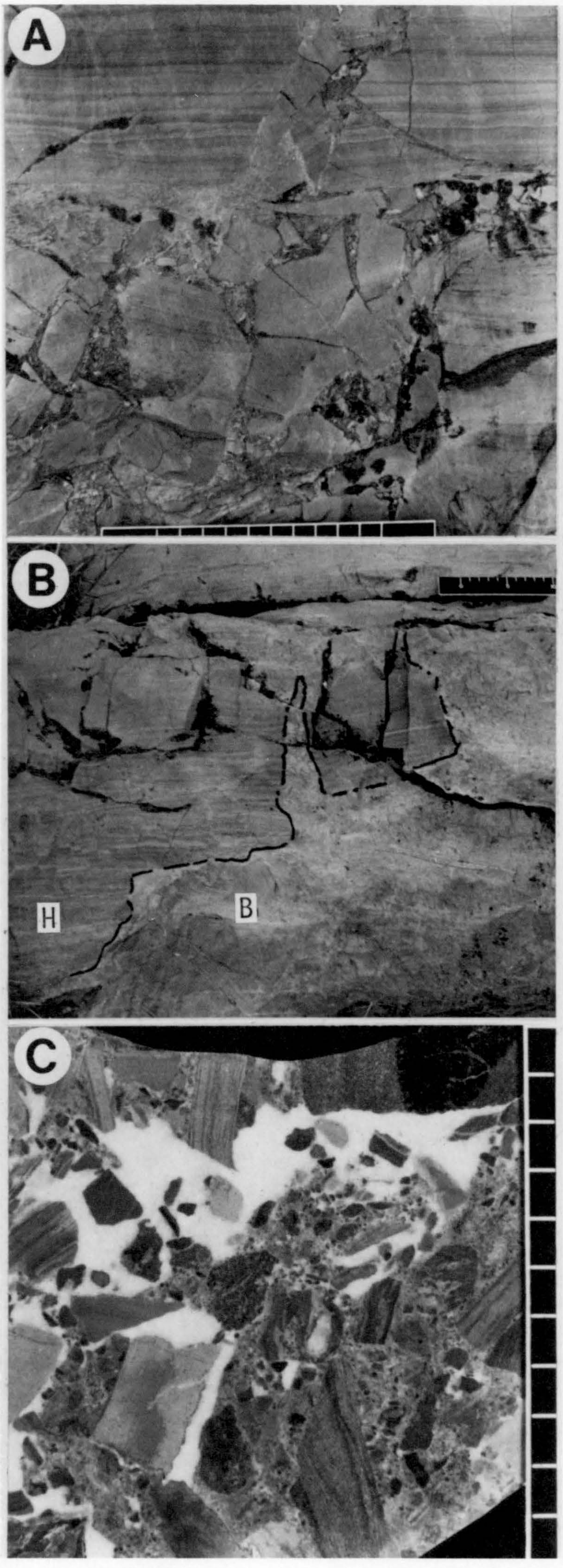

FILL
INCIPIENTLY BRECCIATED DOLOMITE
DOLOMITE BRECCIA
HOST
LIMESTONE
DOLOMITE
2 meters

Figure 13 : Intraformational breccias. Scales in centimeters. A, outcrop photograph showing upward transition from incipiently brecciated fabric into unalterd host dolomite, Leaksville, Virginia. B, outcrop photograph showing transition from breccia (B) to incipiently brecciated/unaltered host dolomite (H), Leaksville, Virginia. Contact highlighted with felt marker. C, Polished slab of breccia showing angular dolomite clasts in white dolomite cement.


A
B
H
B
C

Blackford-type clastics occur in collapse breccias down to 280 m below the unconformity (Harris, 1969,1971; Kyle, 1976). Because there is little correspondence between paleokarst features and collapse breccias in southeastern belts, Harris, (1971) suggests dissolution was caused by the movement of fresh water through a paleoaquifer (Kingsport Formation of Knox Group). Although Harris (1971) believed the recharge area to be to the northwest (cratonward), Grover (1982) suggests that Knox carbonates, exposed in tectonic highlands to the southeast (seaward) during the early Middle Ordovician, provided recharge areas for meteoric waters which would have moved down dip to the northwest. A similar situation occurs in the Black Hills uplift region of South Dakota, where waters collected in an uplifted carbonate terrain move down-dip under artesian conditions causing dissolution of carbonates up to 150 miles away in the subsurface (White, 1969; Swenson, 1968).

Retention of much porosity in the breccias from their time of formation (early Middle Ordovician) to the late Paleozoic is suggested by the intimate association of zinc/lead base metal deposits and hydrocarbons, which were emplaced during the Devonian to Mississippian (cf. Kyle, 1976; Grover, 1982).

POST-UNCONFORMITY LITHOFACIES

Breccia, Conglomerate, and Laminated and Silicified Crusts Veneering the Unconformity

Sheets of angular breccia (regolith) up to 2 m thick commonly veneer the unconformity where it is exposed. They locally pass into broad, lenticular bodies of conglomerate up to 100 m wide and 6 m thick (Campbell, 1975). Laminated micrite crusts or silicified dolomite crusts occur very rarely where breccia and conglomerate are absent.

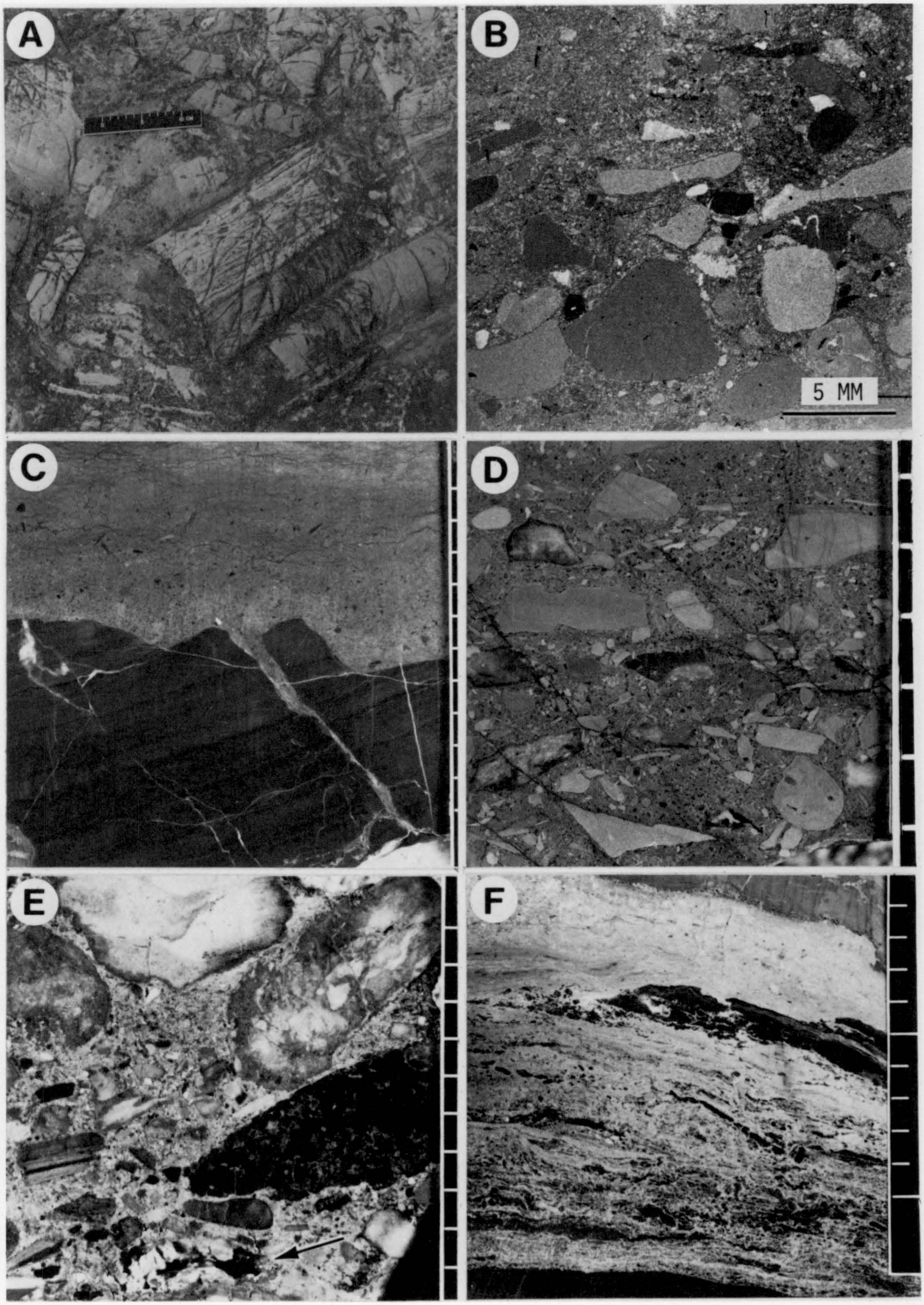
Breccias: Breccias (Fig. 14a) are laterally extensive veneers which thicken into unconformity lows. They consist of lithoclasts of dolomite, lesser limestone and chert (Table 1). Dolomite and chert clasts dominate breccias above Knox beds, whereas dolomite and limestone are the main clast types above Beekmantown beds. They range from clast-supported to matrix supported, and are generally poorly sorted. Clasts range from a few millimeters to 60 cm diameter. Carbonate clasts are angular to rounded, typically have scalloped margins, and many are bored, except for those in basal Blackford breccias (Fig. 14b). In some beds, limestone clasts (up to 1 cm long) are slivers (length to width ratios 40:1) formed by flaking of larger lithoclasts. Chert clasts are angular to subangular and commonly have pitted surfaces. Matrix in breccias is either finely crystalline dolomite, skeletal limestone, or fenestral limestone.

Basal breccias of the Blackford Formation (e.g. near Lebanon and Narrows; Locs. 3 and 12, Fig. 1) consist of clasts of chert and dolomite in fine to coarse dolomite matrix. Dolomite clasts are composed of fine, medium, or coarse interlocking dolomite crystals that lack zonation.

Clast margins are commonly bounded by stylolites; where they are not pressure-solved, finely crystalline clasts have relatively sharp margins, but medium and coarsely crystalline clasts have irregular margins formed by dolomite crystals that extend into the matrix. Dolomite matrix consists of medium and coarse zoned dolomite, much angular sand-size fragments of dolomite, chert, quartz arenite, monocrystalline quartz, silicified detrital ooids, and angular quartz silt. Zoned dolomite crystals in the matrix consist of turbid rhombic to rounded cores and overgrowths of clear dolomite. There also are cements of coarse blocky dolomite, calcite, and fibrous chalcedony.

Basal Tumbez breccias (e.g. near Marion and Draper; Locs. 9 and 11, Fig. 1) are dominated by clasts of chert and minor dolomite and rare vein quartz (Sautter, 1981)

Figure 14 : Post-unconformity breccia, conglomerate and laminated crust. Scales in centimeters. A, dolomite megabreccia in fine dolomite matrix, Marion, Virginia. B, thin section of chert and dolomite breccia in fine dolomite matrix, basal Blackford Formation. C, polished slab showing angular unconformity between Beekmantown dolomite and overlying New Market Limestone near Toms Brook, Virginia. Note lack of breccia, and fractures filled by limestone. D, polished slab of chert and dolomite breccia in fenestral limestone matrix, Goodwins Ferry, Virginia. Note borings (?) in dolomite clast at lower right. E, polished slab of chert conglomerate with chert and quartz sand matrix, Newport, Virginia. Note cavity formed by leaching of carbonate clast (arrow). F, laminated crust (caliche?) developed on or within uppermost Beekmantown carbonates near New Market, Virginia.


A
B
5 MM
C
D
E
F

that float in pinkish-gray to white, sandy skeletal intraclast grainstone containing platy pellet limestone clasts (up to 3 mm dia.) and bryozoan, pelmatozoan, trilobite, ostracode, brachiopod, gastropod and algal fragments. Some of the mollusc grains appear to have been leached. Cements include calcite overgrowths (on pelmatozoans), pendant bladed calcite (on undersides of skeletal fragments), and fine to coarse equant calcite. Rare hardgrounds in Tumbez breccias occur beneath some dolomitic wackestone/ packstone layers.

Basal Mosheim/New Market breccias (e.g. in Rich Valley and near Harrisonburg; Locs. 4 and 21, Fig. 1) consist of clasts of dolomite and lesser limestone in a tan to blue-gray, argillaceous fine dolomite or fenestral lime mudstone/pellet intraclast packstone (Fig. 14d).

Origin: Breccia sheets probably are paleosols and reworked regolith on exposed Knox/ Beekmantown beds, because they veneer the unconformity, they contain angular, locally derived material, and grade upwards into peritidal carbonate and clastic facies (Blackford, Tumbez, New Market and Mosheim Formations). Breccias beneath Blackford sequences in northwestern belts are restricted, non-marine deposits because inter-clast muds lack skeletal debris, and are commonly oxidized to red colors. The breccias lack marine sedimentary structures, and some clasts have been weathered, forming concentric bands that parallel clast margins, whereas others have scalloped margins suggesting dissolution by chemical weathering.

Breccias beneath Tumbez, Mosheim and New Market sequences are peritidal marine deposits because they contain matrix similar to overlying tidal flat carbonates. In many beds, argillaceous dolomitic matrix associated with the original regolith was probably winnowed during marine transgression to form mud free breccias, whereas in others, breccias were infiltrated with peritidal sediment.

Conglomerates: Conglomerates occur as lenticular bodies which fill depressions on the unconformity and thin laterally into breccia veneers (Table 1).

Chert-dominated conglomerates (up to 2 m thick) occur below Blackford sequences near Newport (Gambill, 1975), Tumbez sequences near Marion (Sautter, 1981), and New Market sequences near Lusters Gate (W.D. Lowry, pers. comm., 1982) (Locs. 14, 9, and 15, Fig. 1). Those below Blackford beds consist of interbeds (up to 70 cm thick) of chert conglomerate and sandstone. Most conglomerate beds are clast-supported, but some have clasts (up to 11 cm dia.) which float in a matrix of chert and quartz sandstone (Fig. 14e). They are poorly sorted, non-graded, and clasts are angular to well rounded with orientations generally parallel to bedding. Sandstone beds are poorly sorted, very coarse, and consist of rounded monocrystalline quartz and sand- to pebble-size chert. Sandstones and conglomerates are silica cemented, and contain numerous spherical voids resulting from leaching of carbonate clasts (Fig. 14e).

Conglomerates below Tumbez beds contain abundant clasts of chert as well as dolomite. Clasts are up to 3 cm long, are subangular to rounded, oriented subparallel to bedding, and occur in yellow, finely crystalline dolomite with abundant sand-size fragments of chert, dolomite, and quartz grains. Those below New Market sequences consist of well-rounded and locally imbricated chert and rare dolomite clasts (up to 2 cm dia.) in dark gray, skeletal, pellet-intraclast grainstone that contains abundant ostracode, echinoderm, and trilobite fragments, lesser bryozoan and brachiopod debris, rare hardgrounds, and meniscus cements (at clast contacts) and pendant cements (beneath skeletal grains and clasts).

Carbonate-dominated conglomerates (up to 6 m thick) occur beneath the New Market Limestone near Fincastle

(Campbell, 1975) (Loc. 18, Fig. 1). Basal units are thick bedded, clast-supported, and contain subangular to well rounded clasts (up to 50 cm dia.) of cryptalgal laminated, massive and ripple cross-laminated dolomite and pelletal and skeletal limestone, together with rare pelmatozoan grains, and pendant, neomorphosed bladed and fibrous cement. Numerous micritized hardgrounds truncate cemented sediment and are draped by infiltrated lime mud. Basal conglomerates fine upward into medium-bedded conglomerates (up to 30 cm thick) interlayered with beds of argillaceous dolomite (up to a few centimeters thick) with rare scours. These beds contain well sorted, subrounded and imbricated clasts (up to 3 cm dia.) and interstitial dolomite mud. Conglomerates are capped by interlayered fenestral lime mudstone (up to 3 cm thick), scoured and ripple cross-laminated argillaceous dolomite mud (up to 5 cm thick), and rare lithoclastic sheets of mud-supported, granule conglomerate (up to 2 cm thick).

Origin: Chert-dominated conglomerates (basal Blackford-Tumbez beds) are similar to much thicker (up to 60 m) conglomerates (interpreted as fluvial) that fill depressions on Knox beds in Tennessee (Rodgers and Kent, 1948; Harris, 1971). Basal Blackford-Tumbez conglomerates are considered to be fluvial deposits because they are channel-form, clasts are well rounded, they are interbedded with coarse sandstone that lacks skeletal debris, and they grade into non-marine or shallow tidal flat carbonates. Chert-dominated conglomerates with skeletal matrix (basal New Market beds) probably had an origin similar to carbonate-dominated conglomerates (described below).

Carbonate-dominated conglomerates near Fincastle were considered to be fluvial deposits by Campbell (1975) on the basis of well rounded clasts, their local imbrication, the lack of inter-clast mud in basal beds, and because they fill topographic lows on the unconformity surface. However, the presence of skeletal debris admixed with the clasts, interbedding of the deposits with peritidal facies, and the presence of interstitial mud (at least in upper parts of conglomerates) suggests that they are marine-reworked deposits rather than fluvial. Rounding of clasts may have occurred under fluvial conditions, but much probably occurred by wave-reworking of unconformity detritus into shoreline conglomerates during marine transgression. Hardgrounds in these conglomerates suggest that deposition of finer, interstitial conglomerates was intermittent, with the deposits being cemented in shoreline environments (possibly indicated by pendant fibrous cements).

Laminated Crusts: These are up to 1 m thick, occurring locally on the unconformity beneath New Market Limestone near New Market (Loc. 24, Fig. 1). They are composed mainly of yellow to gray laminated carbonate and interlayered dark gray, massive and intraclastic carbonate (Fig. 14f).

Laminated layers (up to 11 cm thick) encrust host limestone beds, contain rare intraclasts, and consist of alternating dolomite-rich laminae (locally pressure solved) and microspar laminae (less than 0.5 mm thick). Dolomite-rich laminae contain abundant rhombic crystals (0.1 to 0.2 mm dia.) which are commonly partially to completely dedolomitized, with dedolomitization occurring on the outer margins of crystals and extending inwards along cleavage planes.

Massive micrite layers (up to 7 cm thick) that occur between laminated layers are yellow-brown mottled, and have highly irregular, sharp boundaries. Intraclastic layers (clasts up to 1 cm dia.) consist of incipiently brecciated stringers and rounded clasts of host micrite. Laminated layers pinch and swell around intraclastic layers, and clast margins are commonly embayed by rhombic dolomite/dedolomite crystals. Dolomite also occurs as replacive rhombs within clasts.

<u>Origin</u>: Laminated crusts may be caliches that developed locally on exposed Beekmantown beds. This is suggested by some similarities of the crusts to Recent and other ancient caliches (although much of the primary fabric of the Ordovician crusts has been destroyed by dolomitization/dedolomitization), the intimate association of the crusts with the unconformity surface, and the lack of skeletal remains and wave- or current-generated structures. Both modern and ancient caliches (James, 1972; Harrison and Steinen, 1978) have horizontal, incipiently brecciated stringers of host carbonate interlayered with laminated crusts. Recrystallization of host carbonate to microspar is a common feature of caliches (James, 1972; Kahle, 1977). Most lamination in Quaternary caliches is caused by the concentration of organic material or opaque oxides in laminae rather than compositional layering (Multer and Hoffmeister, 1968; Harrison and Steinen, 1978). However, much of the lamination in the Ordovician caliches is diagenetic and related to dolomitization, with some faint lamination in micrite layers caused by iron staining. Finally, abundant dedolomite, which is commonly associated with near-surface diagenetic processes at unconformities (Evamy, 1967; Braun and Friedman, 1970; Chafetz, 1972), also is compatible with a subaerial (caliche) origin.

Silicified Crusts: These are partially to completely silicified, massive to thick laminated dolomite (some relict pellet grainstone fabric) that occur between Beekmantown carbonates and overlying New Market Limestone near Harrisonburg (Loc. 22, Fig. 1). They contain numerous pseudomorphs of a cubic mineral (up to 1.5 cm across), and horizontal to wavy, millimeter laminations of reddish-brown pigment. Samples were not found in-place.

Origin: Silicified crusts may be silcretes developed on exposed Beekmantown carbonates. Because they occur only at one location, are poorly exposed, and could not be found in-place, their origin is uncertain.

Thick, Fine Detrital Facies; Blackford Formation

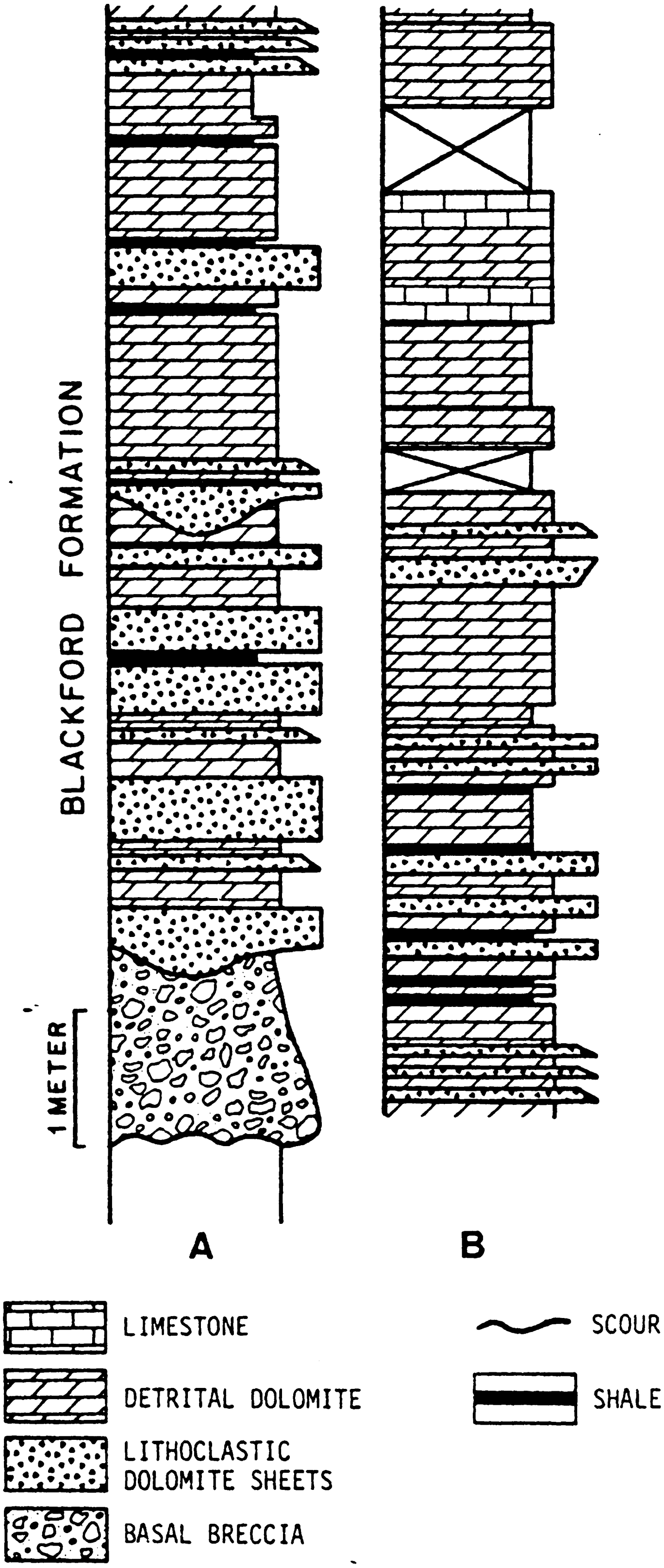
Relatively fine-grained detrital facies of the Blackford Formation (0 to 70 m thick) overlie basal unconformity breccias. Blackford beds consist of red and gray, sandy to silty dolomite, quartz siltstone, and thin, graded lithoclastic dolomites (Fig. 15) (Table 1); these pass upwards into limestone and local gray shale (Heyman, 1970). They typically occur in western belts of southwestern Virginia (e.g. near Lebanon, Eggleston, and Narrows; Locs.

3, 13, and 12, Fig. 1), but also occur beneath tidal flat carbonates (New Market, Mosheim, Tumbez Formations) in eastern belts (e.g. near Ellett and Cedar Grove; Locs. 16 and 20, Fig. 1). They are thickest in unconformity lows, grading into breccias adjacent to highs.

Lithoclastic Dolomite: Thin beds of lithoclastic dolomite (1.5 to 15 cm thick and a few centimeters to 5 m apart) occur interbedded with fine dolomite in the Blackford Formation. They consist of a basal, poorly sorted, clast- or mud-supported layer of angular breccia (clasts up to 5 cm long) which fines upward through a sand-supported layer into a mud-supported cap with rare clasts up to 3 mm long. Only one sample contained fenestrae (vertical tubular, horizontal laminoid, and irregular types) in the basal lithoclastic layer. Breccias have indistinct to sharp erosional bases (up to 1 cm relief) and gradational tops. Rare clast-supported lithoclastic dolomites thicken into depressions (up to 30 cm deep, 1 m wide) cut into other lithoclastic beds or massive dolomite.

Many beds are graded (Fig. 16a), but others are reverse graded or non-graded. Clasts are mainly parallel to bedding, but some are vertical to imbricated. Some vertically oriented clasts occur within dewatering

Figure 15 : Partial columnar section of Blackford Formation, Narrows, Virginia. Section A rests on Knox Group, section B joins top of section A.

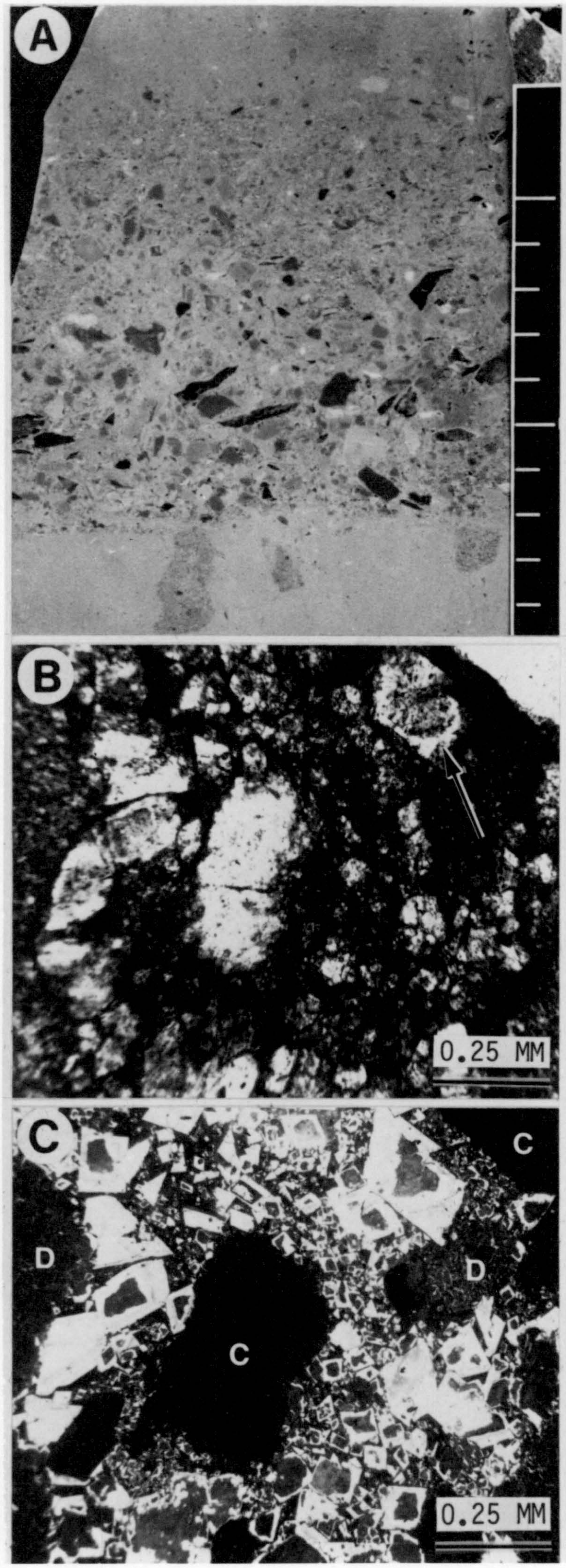

BLACKFORD FORMATION
1 METER
A
B
LIMESTONE
DETRITAL DOLOMITE
LITHOCLASTIC DOLOMITE SHEETS
BASAL BRECCIA
SCOUR
SHALE

structures that are faint, 3 to 15 mm wide fingers of light colored dolomite oriented subvertical to bedding, surrounded by tan to red host dolomite. Lithoclasts are angular to subangular chert and fine to medium dolomite. Where margins are not pressure-solved, dolomite crystals may protrude into enclosing matrix, but more commonly margins are stylolitic. Matrix between clasts is a red to gray, fine to medium dolomite that has silicified ooids, quartz sand and silt. Rare beds have pellet-intraclast packstone matrix.

Basal clast- or mud-supported layers grade upwards into sand-supported layers (ripple cross-lamination seen only in 2 samples) that contain locally abundant lithoclasts (a few millimeters to 1 cm dia.) and discontinuous stringers of quartz sand (a few centimeters thick). Lithoclastic beds are capped by yellow to red, fine dolomite (1 to 3 cm thick) that contains rare lithoclasts and quartz silt. Mud cracks, cryptalgal lamination, and laminoid fenestrae are associated with some mud caps, especially those that are red.

Luminoscope examination shows that dolomite crystals in the matrix of lithoclastic dolomites have nonluminescent (black) subangular to rounded cores (similar to dolomite lithoclasts), surrounded by dull luminescent (orange)

Figure 16 : Blackford lithoclastic dolomite, Lebanon, Virginia. A, upward-fining lithoclastic dolomite. Note mud cracks (?) at base, containing infiltrated sediment from above. Scale in centimeters. B, photomicrograph of lithoclastic dolomite, plane-polarized light. Note dolomite crystal with turbid core and clear overgrowth (arrow). This is characteristic of most dolomite crystals throughout Blackford Formation. C, same area as above, under cathodoluminescence. Dolomite crystals have non-luminescent (black) scalloped and corroded cores, and bright luminescent (orange) overgrowths. Note non-luminescent chert (C) and dolomite (D) lithoclasts.


A
B
0.25 MM
C
C
D
D
C
0.25 MM

overgrowths (Fig. 16b,c). Cements in lithoclastic beds include coarse blocky calcite and dolomite, and chalcedony.

Fine Detrital Facies: Massive fine dolomite that is interbedded with lithoclastic dolomites are light tan to red, medium to thick bedded, argillaceous, and many contain thin shales 2 to 5 cm thick. They have faint, thin cryptalgal and thick lamination (locally mud-cracked) and tubular, laminoid and irregular fenestrae. Some lamination is disrupted by dewatering structures, and others are burrow-mottled. They also have scattered quartz sand and rare angular lithoclasts. Luminoscope examination shows that crystals in the fine dolomites have nonluminescent cores and dull luminescent rims.

Red to gray, mottled quartz siltstone (up to 60 cm thick) occurs locally (Heyman, 1970). In western belts, they are interbedded with massive dolomite. These siltstones are rare in eastern belts, but may be up to 25 m thick in unconformity lows (e.g. near Ellett; Loc. 16, Fig. 1; Gilbert, 1952; Grover, 1976; see Read and Tillman, 1977 for detailed cross-section of Ellett channel).

Shale beds decrease in abundance upwards in the Blackford Formation, whereas limestone beds increase in abundance. Shales contain macroscopic, euhedral biotite, vermiculite and apatite, montmorillonite, mixed-layer chlorite-montmorillonite, and mixed-layer chlorite-vermiculite (Heyman, 1970). Limestone beds are up to 2 m thick, light tan, gray or red, and are composed of lime mudstone that locally contains stromatolitic lamination, abundant fenestrae, and a sparse biota consisting of ostracode, bryozoan, trilobite and algal debris.

Interpretation: Thick Blackford dolomite and siltstone are detrital sediments derived from Knox beds beneath the unconformity. Coarse lithoclastic beds contain dolomite and chert clasts that are readily matched with Knox lithologies. Abundant detrital dolomite in Blackford fine dolomites is indicated by nonluminescent, rounded cores in dolomite rhombs (similar to nonluminescent dolomite crystals in lithoclasts) surrounded by luminescent dolomite overgrowths.

Blackford dolomites are restricted, non-marine to tidal flat deposits that formed between exposed Knox beds to the northwest and tidal flat and subtidal limestones to the southeast (Mosheim, Tumbez, Lenoir/Lincolnshire Formations). Most Blackford beds developed northwest (landward) of an elongate structural or erosional unconformity high (Tazewell Arch; Read, 1980). Blackford-type clastics also occur northwest of a linear high on the unconformity surface in Tennessee (Benedict and Walker, 1978), in Georgia (Chowns and McKinney, 1980), and in Alabama (Birmingham Anticlinorium; Thomas, et al., 1980).

The dominance of non-marine environments is suggested by abundant red (oxidized) colors and rarity of marine fossils. Coarse, basal parts of lithoclastic dolomites resemble thin debris flows on alluvial fans in that they have sheet-like morphologies, indistinct upper and lower contacts, are poorly sorted, generally lack sedimentary structures, and have clasts floating in mud matrix (Bull, 1972; Steel, 1974). Debris flows are promoted by high rainfall of short duration, steep slopes with little vegetation, and a source that provides much mud (Bull, 1972). Erosional highs on the unconformity surface, lack of Ordovician vegetation and abundant fine carbonate detritus may have promoted debris flows. Lithoclastic beds that are graded and have horizontal to imbricated clast orientations probably formed in low viscosity flows, whereas non-graded beds with tabular clasts that locally have vertical orientations formed in high viscosity flows (Bull, 1972).

Clast-supported lithoclasitic dolomites that fill channel-form depressions may be stream-flood or stream deposits that fill channels temporarily entrenched into alluvial fans (Bull, 1972; Steel, 1974). They resemble these deposits in that they are not persistent laterally, are clast supported, and bases are erosional; however, the presence of inter-clast mud, lack of sedimentary structures, and poor sorting is not characteristic of such deposits (cf. Steel, 1974).

Upper parts of lithoclastic beds that are composed of sandy dolomite (rarely ripple cross-laminated) with fine, red to gray mud caps may be water-laid sediments deposited during the waning phase of ephemeral flooding that follows debris flows on fans (Bull, 1972; Steel, 1974).

Fine-grained, detrital red and gray dolomite, red quartz siltstone, and thick shale that lack skeletal remains and are interbedded with lithoclastic dolomites have some similarities to playa mud-flat facies associated with distal fans (cf. Eugster and Hardie, 1975). Characteristics that Blackford dolomites have in common with these include thin layering, fine grain size, mud cracks, abundant quartz silt, and locally abundant fenestrae. Red colors formed by oxidation of sediments when mud flats were exposed.

Upper Blackford fenestral lime mudstone and shale are restricted, shallow subtidal to intertidal facies deposited during marine transgression of the unconformity in western belts (Read, 1980). Heyman (1970) suggests that chemical composition of the shales indicate they are altered volcanic ash.

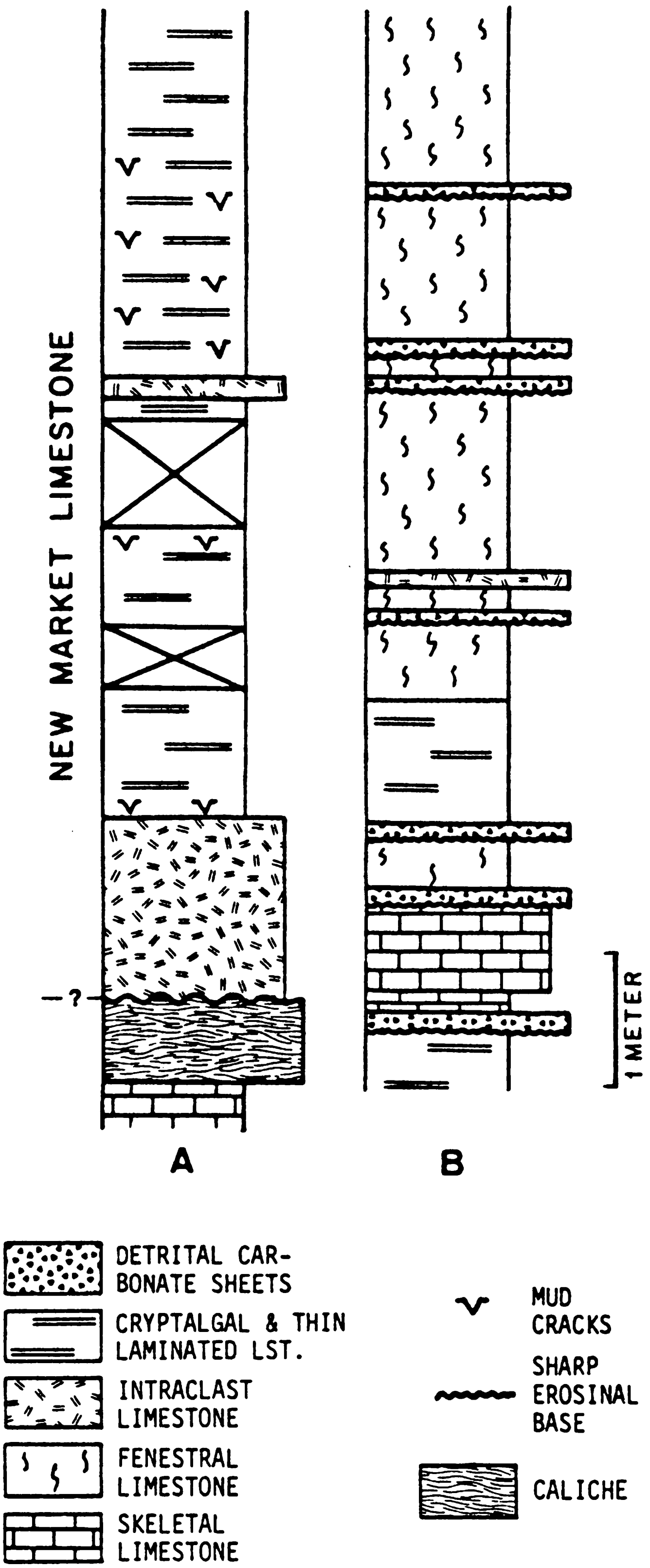
In summary, facies in the Blackford Formation represent a transition from non-marine, playa mud-flat sedimentation in sheltered ponds punctuated by alluvial fan-type debris flows from paleotopographic highs, to restricted, shallow marine tidal flat sedimentation.

Peritidal Carbonates; Mosheim/New Market, Tumbez, Elway-Five Oaks Formations

Middle Ordovician marine peritidal facies rest directly on the unconformity or overlie thin basal breccia/conglomerate or thick detrital carbonates (Blackford Formation). They are overlain by Lenoir/Lincolnshire subtidal cherty skeletal wackestone/packstone (Read, 1980). Various types of erosion surfaces (described later) occur within these formations.

Mosheim/New Market Formations: These occur in eastern belts, southwest Virginia, and throughout northern Virginia. Mosheim sequences in southwest Virginia are thickest in unconformity lows. They mainly consist of fenestral limestone (up to 25 m thick) with minor cryptalgal laminite and skeletal limestone (e.g. in Rich Valley; Locs. 4 and 5, Fig. 1).

Figure 17 : Partial columnar section of New Market Formation, New Market, Virginia. Section A rests on caliche (?) developed on or within uppermost Beekmantown carbonates. Section B joins top of section A.



NEW MARKET LIMESTONE
?
1 METER
A
B
DETRITAL CARBONATE SHEETS
CRYPTALGAL & THIN LAMINATED LST.
INTRACLAST LIMESTONE
FENESTRAL LIMESTONE
SKELETAL LIMESTONE
MUD CRACKS
SHARP EROSINAL BASE
CALICHE

New Market sequences in central and northern Virginia are up to 80 m thick. Locally, New Market beds in northern Virginia (e.g. near New Market; Loc. 24, Fig. 1) contain a lower unit of laminated or dolomitic limestone (10 to 15 m thick) overlain by a fenestral limestone unit (Fig. 17) (Neuman, 1951; Read, 1980). Lower parts of some sequences are cyclic (cycles 1 to 3 m or more thick), that consist of, from top to bottom:

3) Dolomitic Intraclast Limestone: Yellow weathering pellet packstone (1 to 20 cm thick) with abundant rounded limestone intraclasts, rare dolomite and chert lithoclasts, quartz sand grains, common to abundant rhombic dolomite crystals, and clay. Erosional bases common.

2) Laminated Limestone: Gray cryptalgal or thick laminated lime mudstone (0 to 2 m thick). Mud-cracked tops common; fenestrae and skeletal debris rare.

1) Skeletal Limestone: Gray skeletal wackestone/pellet packstone, commonly fenestral; may contain rounded limestone intraclasts (less than 1 cm dia.).

Massive, fenestral, pellet-intraclast packstone overlies the lower laminated unit and comprises the bulk of the New Market Formation (Grover and Read, 1978; Read, 1980). The sediments contain restricted biotas (ostracodes, algae, and the coral Tetradium) and fenestral beds commonly contain vadose diagenetic features.

Tumbez, Elway-Five Oaks Formations: Tumbez beds occur locally in southeastern belts where they rest unconformably on Knox dolomite or erosionally overlie Mosheim beds (e.g. near Marion and Draper; Locs. 8 and 11, Fig. 1). Towards the northwest, the Tumbez becomes thick and cyclic (e.g. near Tumbez; Loc. 1, Fig. 1) and resembles the Elway Formation. Cyclic Elway-Five Oaks beds (Fig. 18) occur in northwestern belts (e.g. near Rocky Gap and Eggleston; Locs. 10 and 13, Fig. 1) and generally rest on Blackford beds. These units are overlain (commonly with erosional contacts) by Lenoir/Lincolnshire beds.

Thin non-cyclic Tumbez sequences (0 to 10 m thick) consist of pink to white, cross-bedded, coarse skeletal intraclast grainstone/packstone that contain bryozoan, echinoderm, trilobite, osracode, and brachiopod debris, and intraclasts of skeletal limestone and lime mudstone.

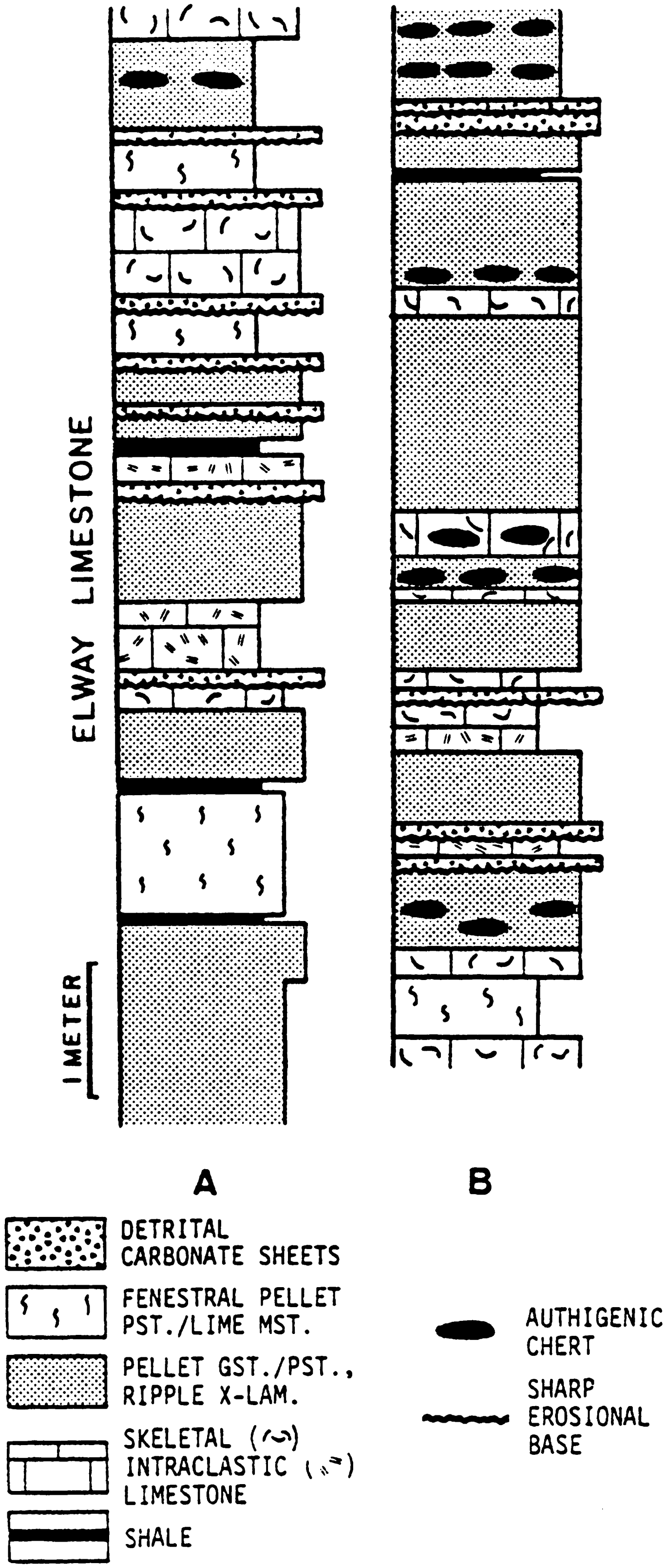
Thick Tumbez and Elway sequences (up to 60 m) have cycles (2 to 20 m thick) that consist of, from top to bottom:

3) Fenestral Limestone, Red Dolomite/Siltstone: Fenestral pellet-intraclast packstone or lime mudstone cap Elway cycles; red, fine to medium dolomite or siltstone cap Tumbez cycles. Rare carbonates contain cryptalgal laminations, mud cracks and algal filament molds.

2) Pelletal Limestone: Cherty, fine, pelmatozoan-pellet grainstone and lenses (few centimeters thick) of coarse skeletal-intraclast grainstone (ripple cross-laminated, plane-laminated, or bioturbated). In some sequences, argillaceous lime mudstone occurs in this position.

1) Skeletal Limestone: Skeletal grainstone (commonly cross-bedded), packstone and wackestone (few centimeters to

Figure 18 : Partial columnar section of Elway Formation, along I-77 near East River Mountain. Section A rests on Blackford Formation. Section B joins top of section A.


ELWAY LIMESTONE
I METER
A
B
DETRITAL
CARBONATE SHEETS
FENESTRAL PELLET
PST./LIME MST.
PELLET GST./PST.,
RIPPLE X-LAM.
SKELETAL
INTRACLASTIC
LIMESTONE
SHALE
AUTHIGENIC
CHERT
SHARP
EROSIONAL
BASE

several meters thick), containing restricted assemblages (ostracodes, calcareous algae and molluscs) to diverse assemblages (bryozoans, pelmatozoans, and brachiopods). They rest on burrowed beds or planar to scalloped erosion surfaces cut into fenestral beds. Skeletal beds may contain detrital chert and dolomite clasts, as well as authigenic chert.

The Five Oaks is a fenestral limestone unit (0 to 10 m thick) that rests on cyclic Elway facies and is overlain with erosional or burrowed contact by Lincolnshire Limestone.

Post-Unconformity Erosion Surfaces

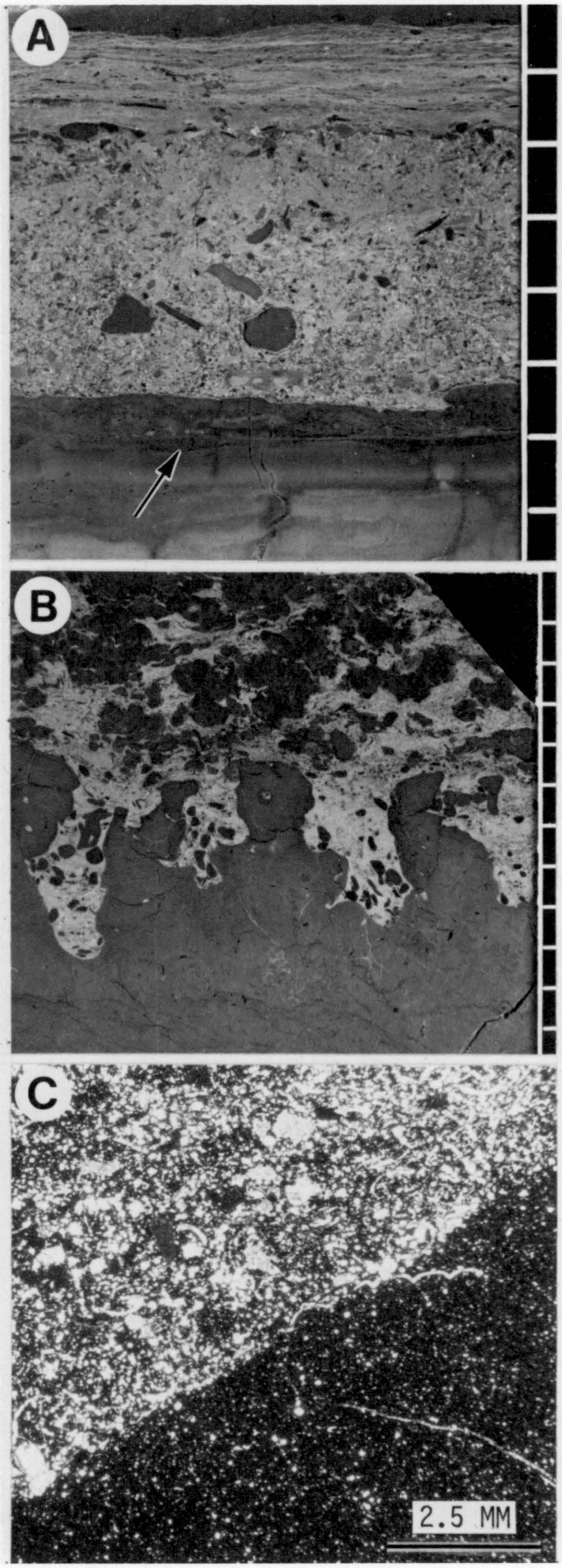
Erosional breaks in the Middle Ordovician limestone sequence may resemble the Knox unconformity in outcrop. They occur within the basal peritidal sequences (commonly at tops of cycles) and at tops of peritidal facies where they are overlain by subtidal skeletal beds (Lenoir/ Lincolnshire, Tumbez Formations).

Scalloped and Planar Erosion Surfaces: These have been described in detail by Read and Grover (1977). They are developed on top of or within sequences of gray, fenestral limestone with rare cryptalgal laminations. They are sharp, planar to scalloped or bored surfaces. Rarely, there are detrital carbonate-filled solution cavities (up to 3 m wide and 1 m deep) in subjacent beds. The fills are composed of argillaceous, dolomitic, alternating thin beds (2 to 4 cm thick) of pellet-intraclast packstone and lime mudstone (locally mud-cracked), that contain locally abundant ostracode debris and lithoclasts of dolomite (up to 1 cm dia.). Also, beds beneath some erosion surfaces have joints (V-shaped, and up to 5 cm wide and 20 cm deep) filled with sediment from overlying beds, or are incipiently brecciated, and may contain multiple sharp erosion surfaces (Fig. 19a).

Scalloped surfaces have smooth, curved basins (10 cm to over 1 m wide) with intervening steep and locally overhanging walls and sharp ridges that have up to 30 cm relief. These pass laterally (within a few meters to tens of meters) into planar contacts that are relatively flat and have little relief. The erosion surfaces truncate grains and cements (Read and Grover, 1977). Planar surfaces are directly overlain by fenestral limestone or thin (up to 20 cm thick) detrital carbonate sheets, whereas scalloped surfaces are generally overlain by dark gray skeletal limestone.

Irregular Erosion Surfaces: These occur in lower parts of Elway sequences and generally are mantled by detrital carbonate sheets. Fingers of detrital dolomitic carbonate

Figure 19 : Erosion surfaces in post-unconformity peritidal carbonates. A, planar erosion surface at cycle top in New Market Limestone, overlain by detrital carbonate sheet, New Market, Virginia. Note multiple, close-spaced erosion surfaces above arrow and beneath detrital carbonate sheet. Also, note thin crust of light-colored dolomite on large gray limestone clast in center. Scale in centimeters. B, irregular erosion surface at cycle top in Elway Formation, overlain by detrital carbonate sheet, Rocky Gap, Virginia. Note borings in pinnacles of fenestral limestone. Scale in centimeters. C, photomicrograph, irregular erosion surface, Elway Formation, along I-77 near East River Mountain. Note trilobite fragment (right of center) that extends from fenestral limestone across erosion surface into detrital carbonate sheet.


A
B
C
2.5 MM

(up to 2 cm wide and 5 cm long) fill irregular depressions on top of, and small cavities within, fenestral limestone (Fig. 19b). Tops of fenestral beds are incipiently brecciated, with fractures filled by fine detrital carbonate, and they also have small burrows/borings (a few millimeters dia.) filled by detrital carbonate (Fig. 19b). Skeletal fragments rarely are truncated by the contacts, but project from fenestral limestone into detrital carbonate.

Detrital Carbonate Sheets: Detrital carbonate sheets that cap cycles in the New Market Limestone are intraclastic dolomitic limestone, whereas those that cap Elway cycles are more skeletal.

They are laterally extensive sheets (1 to 20 cm thick) that generally rest on planar to irregular surfaces, and have sharp or gradational contacts with beds of the overlying cycle. They are yellow to gray weathering, unlayered, non-graded, and (in the New Market) are locally fenestral. They consist of fine, lime mudstone/pellet packstone (New Market) or skeletal wackestone (Elway) that contains intraclasts (lime mudstone, pellet packstone, skeletal wackestone), angular to rounded dolomite lithoclasts and detrital dolomite rhombs, variable amounts of skeletal debris, terrigenous clay, quartz silt/sand, and rare chert clasts. Dolomite rhombs under the Luminoscope have subangular to rounded nonluminescent cores and dull luminescent overgrowths (cf. Fig. 16c). Detrital material is more abundant in sheets near the unconformity and decreases in abundance higher in the sequence. Also, detritus is typically concentrated in basal parts of sheets.

Skeletal material in New Market detrital sheets is mainly fragmented and whole ostracodes, and rare codeacean algae and coral (Tetradium) debris. Skeletal debris in Elway beds is more diverse and includes trilobite, ostracode (some articulated valves), gastropod, bryozoan, echinoderm and algal remains.

Fenestrae (laminoid, tubular and irregular types) in New Market detrital sheets commonly contain crystal silt flooring voids and pendant cements.

Interpretation: Erosion surfaces in New Market and Elway beds formed on fenestral limestones following shoaling of cycles to tidal-supratidal levels.

Irregular erosion surfaces capping cycles appear to have formed on coherent (but not cemented) fenestral beds. The irregular erosional morphology may have formed by physical erosion during emergence (following shoaling to sea level), either subaerially, or by marine erosion during storms when supratidal flats were inundated. Burrowing and boring organisms further modified erosional contacts following marine transgression.

Planar to scalloped erosion surfaces formed on early cemented fenestral limestone, and resemble tidal rock platform and exposed karst formed in coastal zones by dissolution and biological corrosion of emergent lithified limestone (Read and Grover, 1977).

Detrital carbonate sheets that overlie erosion surfaces are composed of intraclasts reworked from subjacent fenestral beds, together with chert and dolomite detritus transported from Knox unconformity highs, and marine sediment and shells carried across tidal flats during storms. The sheets are similar to Recent tidal/supratidal intraclast grainstones that overlie pavements of fenestral carbonate in Shark Bay tidal flats, Western Australia (Brown and Woods, 1974). These are thin sheets (up to 15 cm thick) composed of intraclasts that form by lithification, desiccation, and brecciation of subjacent tidal flat carbonates in dry parts of flats. They differ from Middle Ordovician detrital sheets in that they formed in situ, lack interstitial mud, and largely are composed of locally derived detritus.

Middle Ordovician detrital carbonates more closely resemble Recent incipient soils (developed in supratidal environments) that overlie indurated crusts formed on fenestral carbonates in Edel Province, Shark Bay. These are composed of intraclasts (derived from subjacent beds) in yellow to brown, fine detrital carbonate, together with lithoclasts derived from local Pleistocene unconformity highs.

Middle Ordovician detrital sheets that formed on irregular erosion surfaces were reworked, abraded, and admixed with marine skeletal carbonate to form skeletal-rich detrital sheets; those that formed on planar erosion were early lithified, because they contain clear vadose pendant cements and much infiltrated crystal silt/internal sediment in fenestral pores, and are rarely reworked into beds of the overlying cycle. The general lack of detrital carbonate sheets above scalloped contacts may be due to these erosional surfaces having formed in coastal zones by limestone dissolution in solution basins or potholes (Read and Grover, 1977). Consequently, detrital carbonates rarely accumulated, and these surfaces were overlain by subtidal, skeletal-rich beds. This suggests that scalloped surfaces formed in more seaward locations, or are a less mature form of erosion surface than planar or irregular surfaces that are commonly overlain by supratidal incipient soils.

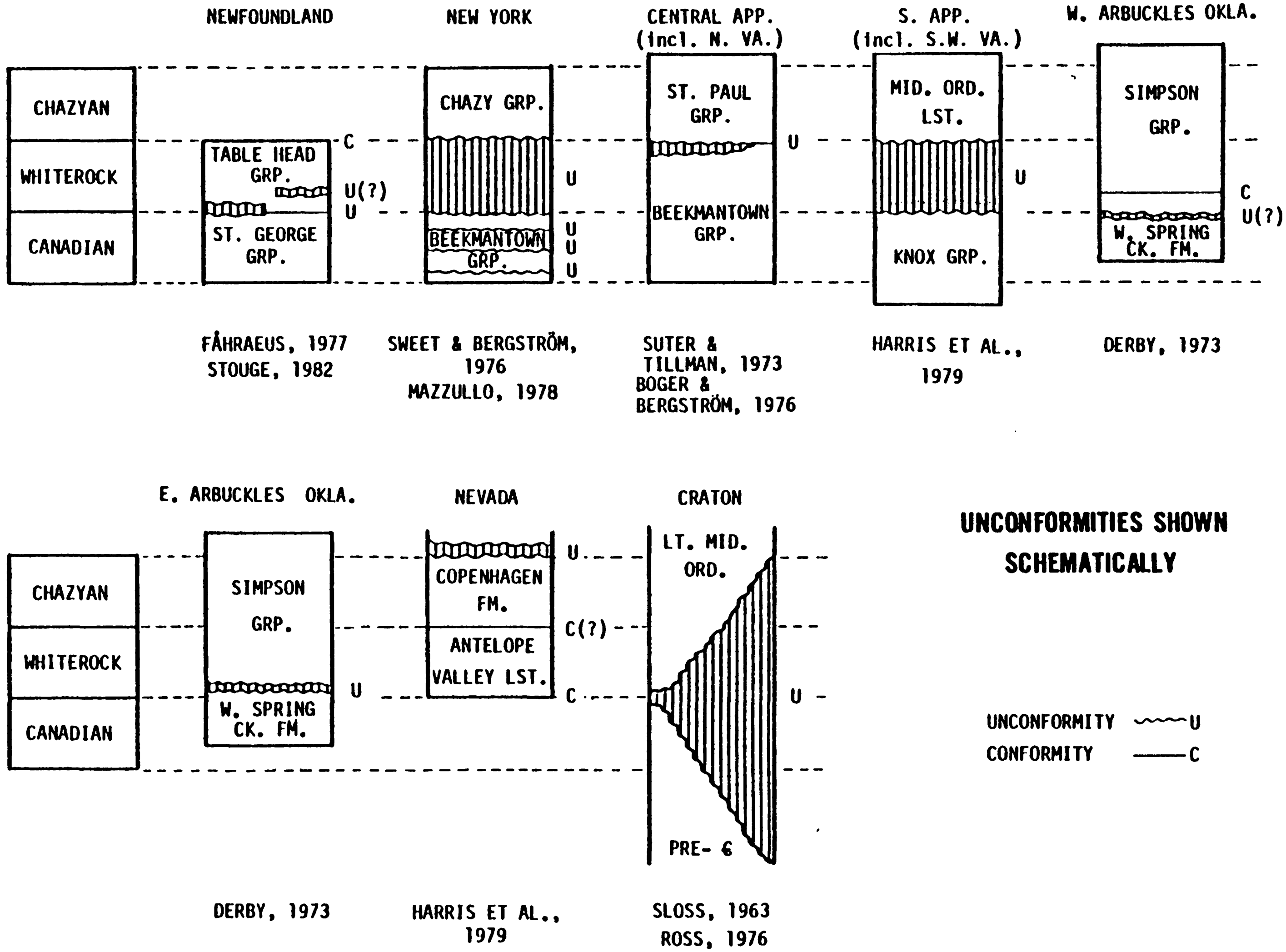
REGIONAL DEVELOPMENT OF THE UNCONFORMITY

One or more regional unconformities have long been recognized at or near the Lower Ordovician-Middle Ordovician boundary in North America and on other continents, associated with Canadian (Early Ordovician), Whiterockian (early Middle Ordovician), and Chazyan age strata (Fig. 20). Biostratigraphic data indicate the unconformity varies significantly in age.

Northern and Canadian Appalachians: In the Canadian Appalachians, Newfoundland, an unconformity separates the St. George Group (mostly Canadian, but may be earliest Whiterock near its top) from the overlying Table Head Group (Whiterock) (Cumming, 1968; Fåhraeus, 1977; Stouge, 1982). In New York, several unconformities have been noted within Canadian age carbonates (Mazzullo, 1978). In the Champlain Valley, New York, the unconformity occurs between Canadian age Beekmantown beds, and the overlying Chazyan beds (Sweet and Bergström, 1976). The unconformity decreases in magnitude southward into Pennsylvania.

Central Appalachians: In the central Appalachians (eastern Pennsylvania-northern Virginia), the Canadian-Whiterock boundary occurs within the Beekmantown Group and is

Figure 20 : Time-rock relationships, Lower-Middle Ordovician boundary, North America. These columns summarize the relationships mentioned in text.



NEWFOUNDLAND
NEW YORK
CENTRAL APP. (incl. N. VA.)
S. APP. (incl. S.W. VA.)
W. ARBUCKLES OKLA.
CHAZYAN
WHITEROCK
CANADIAN
TABLE HEAD GRP.
ST. GEORGE GRP.
C
U(?)
U
CHAZY GRP.
BEEKMANTOWN GRP.
U
U
U
U
ST. PAUL GRP.
BEEKMANTOWN GRP.
U
MID. ORD. LST.
KNOX GRP.
U
SIMPSON GRP.
W. SPRING CK. FM.
C
U(?)
FÅHRAEUS, 1977
STOUGE, 1982
SWEET & BERGSTRÖM, 1976
MAZZULLO, 1978
SUTER & TILLMAN, 1973
BOGER & BERGSTRÖM, 1976
HARRIS ET AL., 1979
DERBY, 1973
E. ARBUCKLES OKLA.
NEVADA
CRATON
CHAZYAN
WHITEROCK
CANADIAN
SIMPSON GRP.
W. SPRING CK. FM.
U
COPENHAGEN FM.
ANTELOPE VALLEY LST.
U
C(?)
C
LT. MID. ORD.
PRE- Є
U
DERBY, 1973
HARRIS ET AL., 1979
SLOSS, 1963
ROSS, 1976
UNCONFORMITIES SHOWN SCHEMATICALLY
UNCONFORMITY U
CONFORMITY C

conformable (Boger and Bergström, 1976). Also, there is little or no break in much of the central Appalachians between the Whiterockian Beekmantown and the overlying, largely Chazyan St. Paul Group (Boger and Bergström, 1976) or the latest Whiterock-earliest Chazyan Beekmantown and overlying Chazyan age Annville Formation (Savoy et al., 1981). In Maryland, the Beekmantown-St. Paul contact is locally unconformable (R. Mitchell and L. Hardie, pers. comm., 1979).

In northern Virginia, the unconformity occurs between Whiterock age Beekmantown and Chazyan age limestones (Suter and Tillman, 1973; Tillman, 1976) or beds that contain a transitional Whiterock-Chazyan fauna (Tillman, in Markello et al., 1979). Smith (1980) suggests there may be a previously unrecognized unconformity within the Beekmantown, although this has not been verified by other workers.

Southern Appalachians: From northern Virginia into southwest Virginia, the unconformity progressively truncates Whiterock age Beekmantown beds until it separates Canadian age Knox beds from overlying Chazyan age limestones (Fig. 2). Associated with this southwestward truncation is increasing erosional and stratigraphic relief

(Fig. 4a,b). Although the unconformity generally lies between Canadian age Knox beds and overlying Chazyan beds throughout much of the southern Appalachians, beds above the unconformity in parts of Alabama, Georgia and Tennessee may be as old as latest Whiterock age (Ross, 1970; Bergström, 1973; Repetski, 1982). Possible overlap between latest Whiterock-earliest Chazyan zones have inhibited more precise dating (Harris et al., 1979). Tillman (in Markello et al, 1979) suggests that post-unconformity Chazyan beds are oldest in southwest Virginia (where they overlie Canadian age beds), becoming younger to the northeast (where they overlie progressively younger Beekmantown beds) (see also Read, 1980).

Unconformity Relations Between Miogeoclinal and Cratonic Sequences: Toward the craton the unconformity bevels progressively older beds from Virginia into West Virginia and Kentucky, removing much or all of the Canadian (and Whiterock) sequence, locally cutting into the upper Cambrian (Fig. 4c) (McGuire and Howell, 1963); the overlying Chazyan beds also young to the west.

On the craton, the pre-Middle Ordovician unconformity is overlain by transgressive quartz arenites (including the St. Peter), ranging in age from early Middle Ordovician to

Late Ordovician age (Sloss, 1963; Ross, 1976). These beds overlie rocks of Lower Ordovician to Precambrian age.

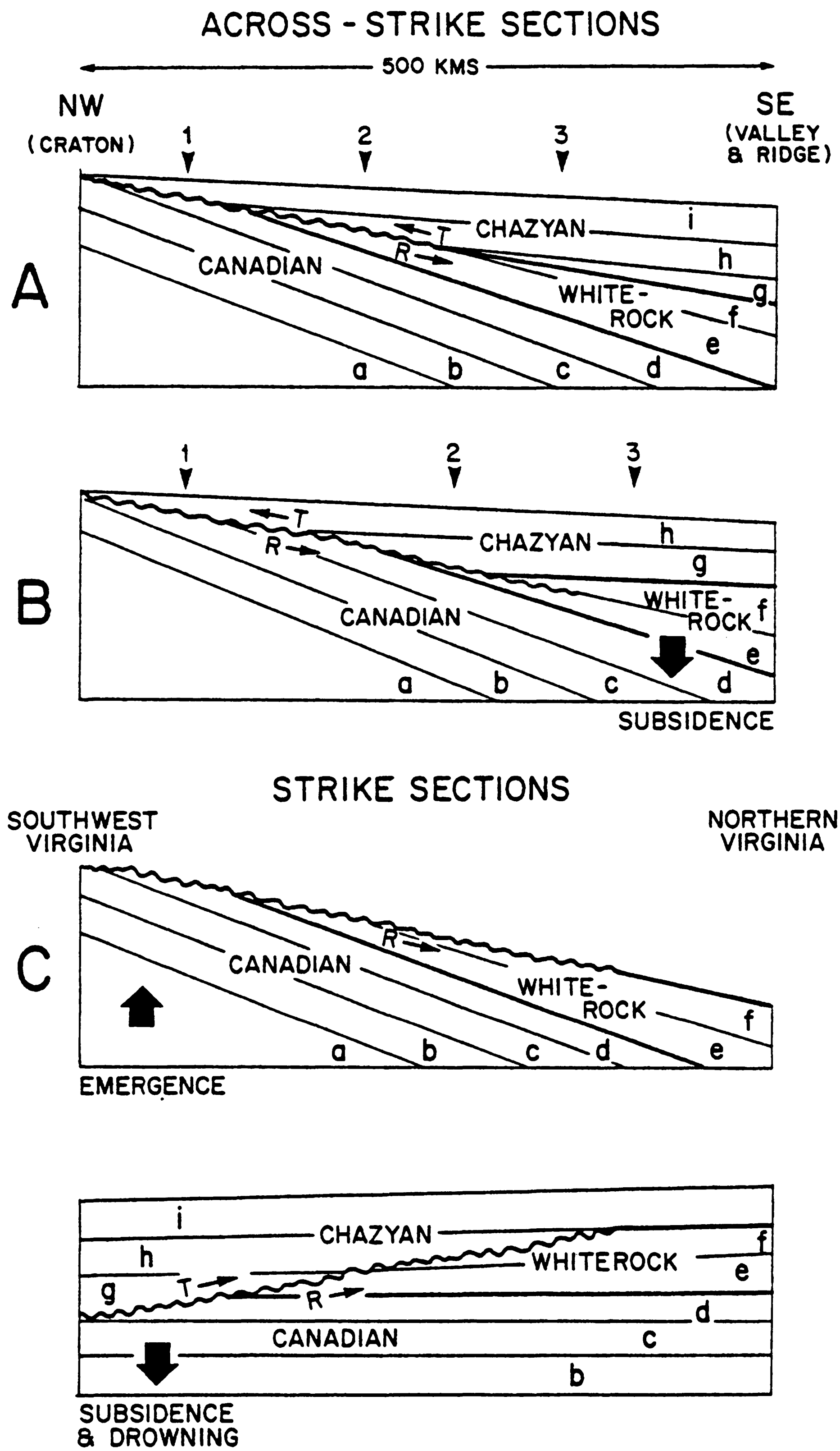
Arbuckle Mountains, Oklahoma, and Western U.S.A.: In the western Arbuckle Mountains, Oklahoma, there is a faunal break at the Canadian-Whiterock boundary, 30 m below the top of the West Spring Creek Formation (Derby, 1973; Ross, 1976). In the eastern Arbuckles, there is an unconformity between the Whiterock age West Spring Creek Formation and the overlying Whiterock/Chazyan Simpson Group (Derby, 1973; Bergström, 1971). A Whiterock-Chazyan unconformity was also considered to occur in the Toquima Range of Nevada, between the Antelope Valley Limestone and the overlying Caesar Canyon Limestone (Ross, 1976). However, Harris et al. (1979) consider deposition in this region to have been continuous from the Whiterock into the Chazyan, and possibly into the Late Ordovician.

Age Relations, Eustasy, and Uplift/Subsidence: The above discussion indicates that in some areas there is more than one unconformity, the unconformities differ widely in age throughout North America, and locally there is no unconformity. However, the regional break in sedimentation between the Canadian and Chazyan sequences of the craton suggest widespread sea level lowering at this time (Sloss, 1963). Regional relationships in the Appalachians cannot be explained by sea level lowering alone, but also require differential warping (Lowry and Tillman, 1974).

Regression, initiated during the Canadian or Whiterockian, caused the sea to retreat gradually from the craton, exposing earlier deposited beds to erosion (Fig. 4, 21a). As sea level dropped, successively younger beds continued to be deposited in miogeoclinal areas, especially those that were undergoing subsidence that roughly equalled sedimentation (e.g. Pennsylvania depocenter). In these subsiding areas, sedimentation was relatively continuous, and Canadian, Whiterock and Chazyan deposition was virtually uninterrupted (Fig. 21a, column 3). With westward transgression during the Middle Ordovician, successively younger Chazyan beds were deposited on progressively older Cambro-Ordovician beds (Fig. 4, 21a). If transgression was initiated in earliest Chazyan time, then progressively younger Chazyan beds would overlie the unconformity. However, locally increased subsidence of the margin could have caused transgression to occur earlier than in less-rapidly subsiding areas, and Whiterock beds could be deposited on the unconformity (Fig. 21b, column 3).

In the southern Appalachians, rate of subsidence was exceeded by sea level lowering, and the sea retreated

Figure 21 : Schematic diagrams showing effects of subsidence and uplift on unconformity formation and sedimentation. Beds a to i used to show relative ages. T is transgression, R is regression. A, regression to southeast (across strike), followed by transgression onto craton to northwest. Note how various stratigraphic relationships can characterize a single unconformity (columns 1, 2, 3.). B, similar to A, but increased subsidence has caused regression and ensuing transgression within the Whiterock, and unconformity is characterized by different stratigraphic relationships (columns 1, 2, 3). C, these diagrams show how relationships along strike in Virginia probably developed. The sea regressed into northern Virginia in the upper diagram, allowing thick sequences of early Middle Ordovician beds to accumulate. Later, southwest Virginia was rapidly downwarped, while northern Virginia remained at about sea level, and transgression took place from southwest to northeast. Note in this diagram that transgression is in the same direction as the earlier regression.



ACROSS - STRIKE SECTIONS
500 KMS
NW
(CRATON)
SE
(VALLEY & RIDGE)
1
2
3
A
CHAZYAN
T
R
CANADIAN
WHITE-ROCK
a
b
c
d
e
f
g
h
i
B
CHAZYAN
CANADIAN
WHITE-ROCK
SUBSIDENCE
STRIKE SECTIONS
SOUTHWEST VIRGINIA
NORTHERN VIRGINIA
C
CANADIAN
WHITE-ROCK
EMERGENCE
CHAZYAN
WHITEROCK
CANADIAN
SUBSIDENCE & DROWNING

northeastward (along present strike) into the depocenter in Pennsylvania (Fig. 21c). Consequently, successively more complete sequences were deposited to the northeast (northern Virginia-Pennsylvania), whereas to the southwest, Whiterock beds were eroded (or were never deposited), and Canadian age Knox beds were subjected to deep dissection (Fig. 4). This appears to have been followed by rapid downwarping (Fig. 21c), causing Chazyan transgression from southwest to northeast, and deposition of successively younger Chazyan beds into northern Virginia.

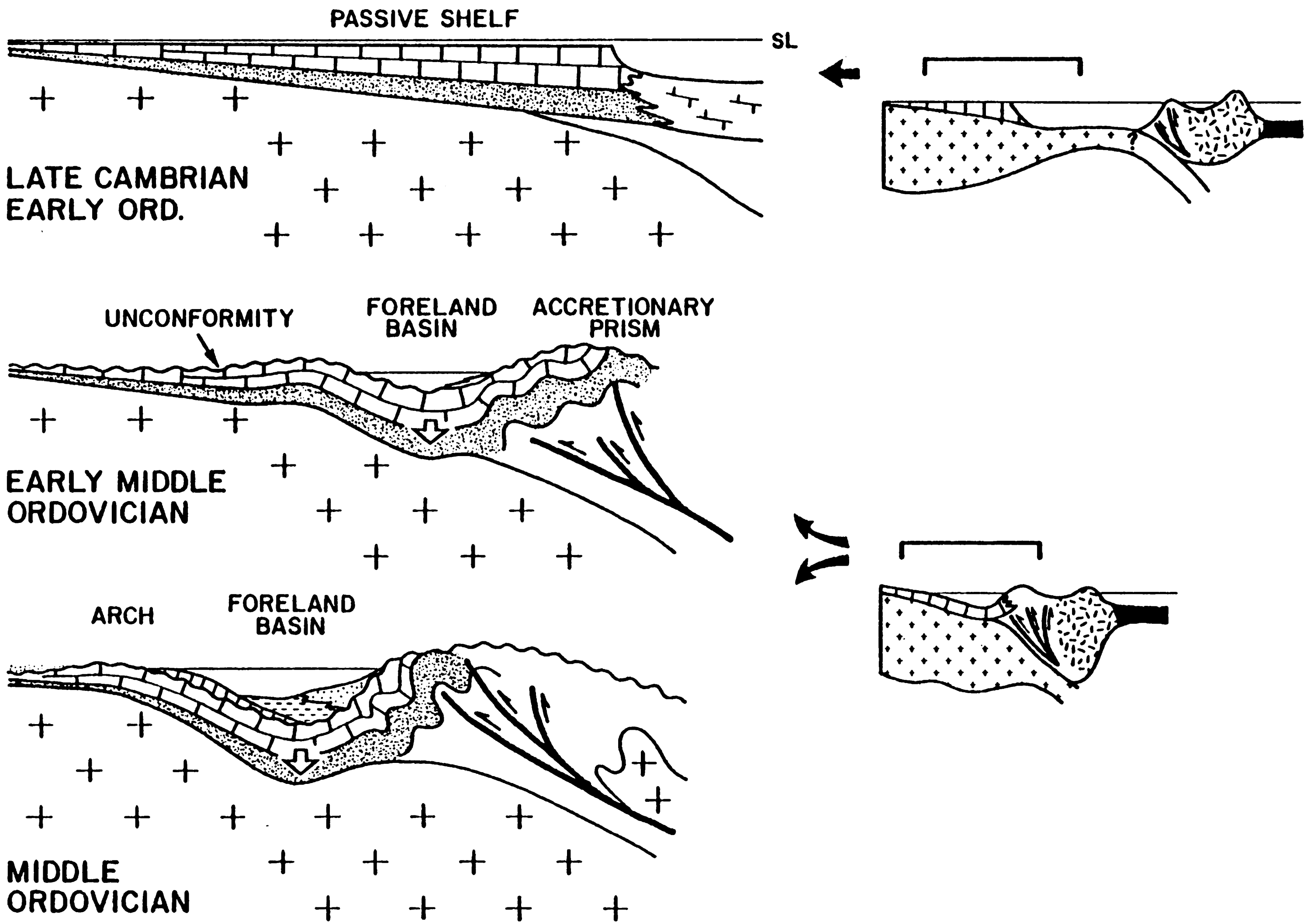
It is possible that Knox beds were increasingly bevelled toward the embryonic Blue Ridge (tectonic highlands). This is indicated by reworked Knox detritus in later Middle Ordovician conglomerates derived from the southeast (Kellberg and Grant, 1956; Lowry et al., 1972; Karpa, 1974). Similar relationships occur in New Jersey, where Middle Ordovician beds above the unconformity contain lithoclasts derived from all the Lower Ordovician units of the Beekmantown Group, suggesting a source that exposed a complete section of these rocks, possibly to the east (Savoy et al., 1981). Also, in Alabama Shaw and Rodgers (1963) suggest the unconformity truncates progressively older Cambro-Ordovician carbonates to the southeast, although Carrington (1973) argues that this contact is a fault.

TECTONIC FRAMEWORK

The Knox unconformity marks the change from Cambro-Ordovician deposition on a passive margin to Middle Ordovician deposition in a foreland basin behind a convergent margin (Fig. 22) (Neuman, 1976; Shanmugam and Walker, 1978, 1980; Read, 1980). In the southern Appalachians, this appears to have resulted from collision between a magmatic arc (Piedmont and/or Carolina Slate Belt) and the North American continental shelf, possibly associated with east-dipping subduction (cf. Hatcher, 1978; Slaymaker and Watkins, 1978; Shanmugam and Walker, 1980). This event is evidenced by a metamorphic peak in the Virginia and North Carolina Piedmont between 438 and 475 m.y., coincident plutonic activity, and pre-metamorphic faulting in the Blue Ridge (Hatcher, 1972, 1978; Tull, 1980), and the presence of volcanic ash beds (bentonites) on the Knox unconformity, and throughout the Middle Ordovician sequence (Laurence, 1944; Cooper and Cooper, 1946; Heyman, 1970).

During initial collision, the Cambro-Ordovician shelf was gently warped, producing open folds (Lowry, 1957; Woodward, 1961; McGuire and Howell, 1963; Finlayson and Swingle, 1963; Thomas et al., 1980). In the Northern U.S.

Figure 22 : Schematic diagram showing tectonic evolution of the Virginia Appalachians, Late Cambrian-Middle Ordovician. Smaller diagrams at right place evolutionary sequence in probable regional tectonic setting.


PASSIVE SHELF
SL
LATE CAMBRIAN
EARLY ORD.
UNCONFORMITY
FORELAND
BASIN
ACCRETIONARY
PRISM
EARLY MIDDLE
ORDOVICIAN
ARCH
FORELAND
BASIN
MIDDLE
ORDOVICIAN

and Canadian Appalachians, the shelf was block-faulted and subjected to regional uplift and unconformity development (Zen, 1968; Rodgers, 1971; Klappa et al., 1980). With continued collision, the leading edge of the continental shelf was deformed, uplifted and incorporated into the accretionary wedge (outer sedimentary arc) to form the embryonic Blue Ridge.

Deposition on the previously passive Cambro-Ordovician margin apparently was influenced by rapidly subsiding depocenters centered in Tennessee and Pennsylvania. In the southern Appalachians, convergence probably occurred in the early Middle Ordovician (Whiterockian), when the shelf may have been uplifted (possibly while the leading edge of the margin was downwarped). This caused deep erosion on the Knox Group in the southern Appalachians. This swell may have been analogous to the swell or rise common to many convergent zones (Bally and Snelson, 1980). However, the central Appalachians at this time were not being affected by the collisional event (Rodgers, 1971), and the depocenter here continued to subside, receiving thick (1200 m) sequences of Canadian-Whiterock age peritidal carbonates, in contrast to 500 m of Canadian age beds in southwest Virginia (Fig. 4b).

During Middle Ordovician (Chazyan) time, continued underthrusting and loading by synorogenic clastics occurred in the southern Appalachians. This caused downwarping of the previously emergent shelf, and peritidal conditions to be rapidly succeeded by basinal environments that migrated northwest and northeast, possibly accompanied by northwestward migration of the swell (perhaps to form the Tazewell Arch and Birmingham Anticlinorium highs). In northern Virginia, subsidence during the Chazyan decreased relative to areas to the southwest, as evidenced by regional thinning of the Middle Ordovician sequence into northern Virginia (Read, 1980). However, in later Ordovician time, subsidence in the southern depocenter slowed following cessation of collision, while increasing convergence in the central Appalachians caused rapid downwarping in the northern depocenter in Pennsylvania, which filled with 2000 m of synorogenic clastics.

UNCONFORMITIES AT PASSIVE MARGIN-CONVERGENT MARGIN TRANSITIONS

The formation of regional unconformities above passive margin sequences as they become convergent is common in developing foreland thrust-fold belts (Bally and Snelson, 1980). In the Antler Orogenic Belt, western U.S.A., a regional latest Devonian unconformity (Poole et al., 1977; Wilson and Laule, 1979) marks the change from Devonian shelf carbonate deposition on a passive margin to Mississippian foreland basin deposition (Poole and Sandberg, 1977; Gutschick et al., 1979). The foreland basin was bordered on the west by uplifted pre-Mississippian platform carbonates (Antler tectonic highlands) which supplied abundant clastics to the basin. Eastward, the basin was bordered by a broad carbonate platform. Paleohighs on the unconformity apparently influenced regional distribution of basal Mississippian facies (cf. Wilson and Laule, 1979).

In the Persian Gulf area, a middle Late Cretaceous unconformity separates stable shelf carbonates from overlying platform carbonates-foreland basin clastics (cf. Murris, 1980). Post-unconformity deposition was influenced by broad, regional paleohighs and deep-seated anticlinal flexures associated with a carbonate platform that passed northeastward into a foreland basin (Murris, 1980). From the Late Cretaceous to present, the foreland basin was a site of rapid clastic deposition, with synorogenic sediments derived primarily from pre-Late Cretaceous shelf carbonates exposed in the rising Zagros Mountains.

In the Timor-Australia region, a Late Miocene-Early Pliocene unconformity separates folded and block-faulted shelf carbonates from the overlying platform carbonates and foreland basin clastics (Veevers, 1971). The unconformity formed during warping and uplift of the pre-Late Miocene passive shelf as the margin became convergent during the Late Miocene. The convergent margin sequence (Middle Pliocene-Recent) consists of shallow water carbonates of the Australian platform that pass northwestward into foreland basin flysch deposits derived from pre-Late Miocene platform carbonates exposed in tectonic highlands of Timor (cf. Veevers, 1971; Crostella and Powell, 1975).

Features of Unconformities Developed During Transition from Passive to Convergent Margin Settings

1) These unconformities develop on uplifted shelf carbonates (passive margin sequence) that may be gently folded or block-faulted.

2) The unconformities are characterized by erosional and commonly structural relief in the form of paleohighs and elongate anticlinal flexures, which may affect facies distribution, composition and thickness of overlying formations.

3) Post-unconformity clastics and carbonates are deposited in platform and foreland basin settings cratonward of the earlier (passive) shelf margin.

4) Carbonate ramps appear to be the most common type of platform to border foreland basins. Ramps may dominate over rimmed shelves because of the inability of reefal biotas to establish and build upward to form a rim. This may be due to rapid subsidence of the platform which outstrips carbonate production, or because the growth of biotas may be hindered by anoxic waters and by synorogenic clastics entering the foreland basin.

CONCLUSIONS

1) The Middle Ordovician Knox unconformity formed on exposed Cambro-Ordovician shelf carbonates as the passive margin became convergent during Middle Ordovician arc-continent collision, possibly during a time of global sea level lowering.

2) Karst features on the unconformity surface in Virginia include paleohighs that extend up to 30 m into overlying Middle Ordovician peritidal beds, sinkholes and caves that extend down to 65 m below the unconformity surface and are filled with carbonate boulder breccias, pebble conglomerates, and finely laminated detrital dolomite (rare fills are marine carbonates), and sub-unconformity dolomite breccia bodies (up to 200 m long and wide, 35 m thick) that formed by collapse after dissolution of limestone interbeds. Coarse detritus on the unconformity surface formed thin to thick veneers of regolith; locally this material was reworked by fluvial and marine processes. Much fine dolomite detritus was reworked from highs and deposited as alluvial fan and playa mud-flat sediments in lows.

3) Erosional relief is greatest in southwest Virginia, decreasing into northern Virginia. This is paralleled by decreasing preservation (or non-deposition) of early Middle Ordovician (Whiterock) beds in southwest Virginia, compared to northern Virginia where an additional 600 m of pre-unconformity (Canadian and Whiterock) beds were depositied. These relations are due to active subsidence of a shelf depocenter (centered in Pennsylvania) which was kept filled by deposition of peritidal Beekmantown beds, while Knox beds in southwest Virginia were undergoing deep dissection in subaerial environments.

4) Post-unconformity marine sedimentation was initiated by south to north transgression. Erosion surfaces in cyclic Middle Ordovician tidal flat sequences resemble exposed karst or tidal rock platforms. The planar to irregular surfaces formed during subaerial exposure after aggradation of peritidal facies to sea level. Following formation of erosion surfaces, supratidal sheets (composed partly of detritus derived from remnant unconformity highs) prograded seaward over the erosion surfaces. These erosion surfaces and associated dertrital carbonate sheets suggest unconformity influence on peritidal sedimentation over 100 m above the unconformity. Later Middle Ordovician buildups appear to be localized over unconformity highs.

5) Unconformities that mark the transition from passive margin to convergent margin sedimentation in foreland zones are common throughout the Phanerozoic, occurring in the Late Paleozoic of the Western U.S.A., Late Mesozoic of the the Middle East, and Tertiary of the Australia-Timor region. These are important because they are associated with faulting, folding, and breccia development (above and below the unconformity), with its attendant potential porosity increase.

6) Unconformities of this type are important because they may form porous zones that act as paleoaquifers carrying meteoric waters from tectonic highlands down deep into the foreland basin sequence, thus influencing diagenesis. Also, these unconformities may localize Pb-Zn base metals or hydrocarbons in breccia zones above and below the unconformity, following migration of fluids from deeply buried foreland basin deposits.

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APPENDIX

Twenty-five stratigraphic sections of uppermost Knox/Beekmantown carbonates and unconformably overlying Middle Ordovician formations (Blackford-Elway-Five Oaks, Tumbez, Mosheim/New Market) were measured for this study, together with 11 spot localities at which paleokarst features or important stratigraphic relationships are exposed. Because many of the measured sections are very similar in thickness and composition, only six representative sections are described in detail below. Symbols used in columnar sections are defined in legend (below). All other sections are described briefly; location, formations present, and thicknesses. Exposures of paleokarst features and other key locations are listed as SPOT LOCALITIES along with GEOLOGIC SECTIONS. Numbers correspond to those on location map (below). Detailed columnar sections and field notes for all sections are on file in the Sedimentology Lab (Room 1047) Derring Hall, Virginia Polytechnic Institute and State University.

List of Geologic Sections

Because the geologic sections are arranged in chronologic order according to their location number on the map, they are not divided into groups of similar sections. The following list groups the geologic sections into categories based on the formation which rests directly on the unconformity.

BLACKFORD FORMATION (many include portions of overlying Elway Formation)

12 Narrows (detailed)

10 East River Mountain South (detailed; includes part of Elway Formation)

30 East River Mountain North

28 Rose Hill

3 Lebanon

31 Rocky Gap

13 Eggleston

MOSHEIM AND NEW MARKET FORMATIONS

Mosheim

4 Rich Valley (detailed)

2 Avens Bridge South

3 Avens Bridge North

New Market

24 Madden Quarry (type section - detailed)

27 Tumbling Run

36 Leaksville North

25 Leaksville South

20 Cedar Grove Church

19 Park View

26 Woodstock

34 Edom

33 Collierstown

23 Broadway East

35 Broadway West

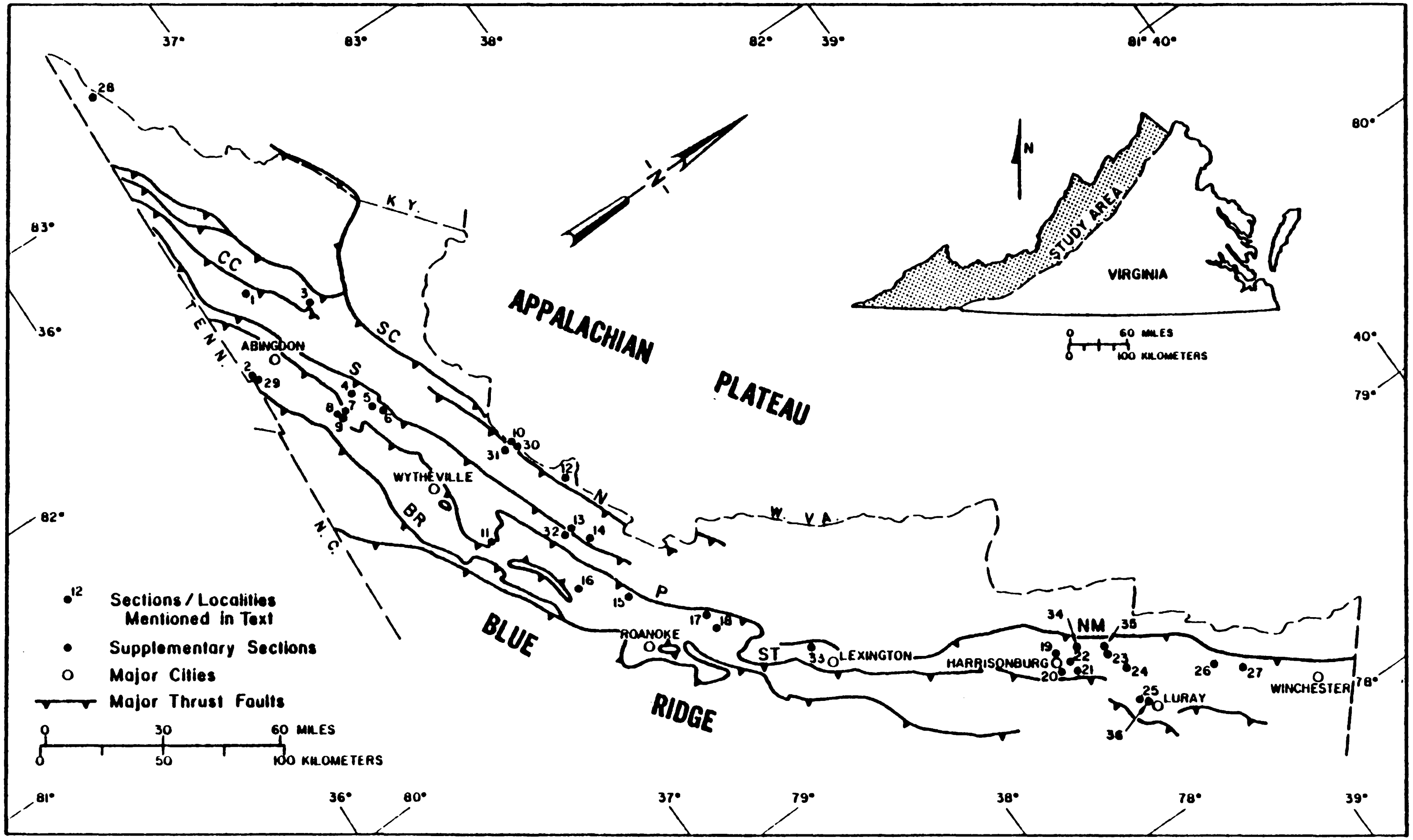
32 Goodwins Ferry

TUMBEZ FORMATION

1 Tumbez (type section - detailed)

9 Marion (detailed)

11 Draper


APPALACHIAN
PLATEAU
BLUE
RIDGE
VIRGINIA
STUDY AREA
N
0 60 MILES
0 100 KILOMETERS
ABINGDON
WYTHEVILLE
ROANOKE
LEXINGTON
HARRISONBURG
LURAY
WINCHESTER
K Y.
W. V A.
TENN.
N. C.
CC
SC
S
N
BR
P
ST
NM
Sections / Localities Mentioned in Text
Supplementary Sections
Major Cities
Major Thrust Faults
0 30 60 MILES
0 50 100 KILOMETERS

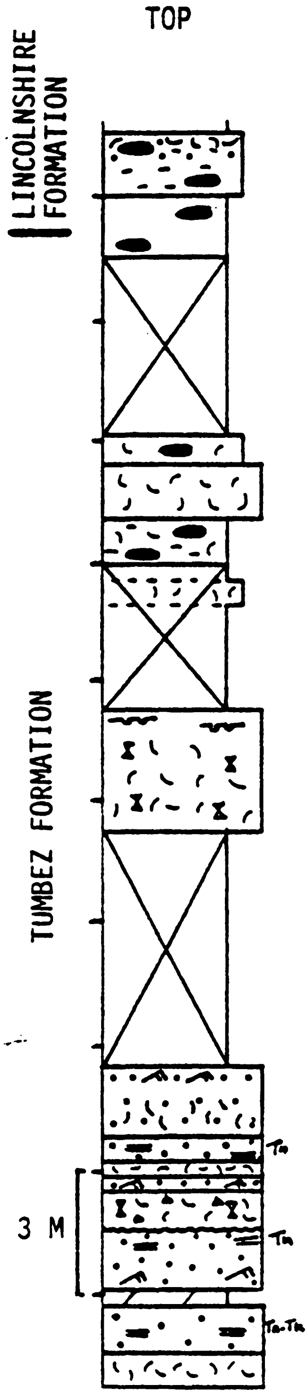
LEGEND

△	LITHOCLASTS
	SKELETAL FRAGMENTS
✱	FENESTRAE
═	LAMINATION Tk= thick Tn= thin
	CRYPTALGAL LAMINATION
B B B	BURROWS OR BURROW-MOTTLING
	AUTHIGENIC CHERT
• • •	PELLETS
	HARDGROUNDS
	INTRACLASTS
	CROSS-BEDDING
	GASTROPODS
Lime Mst.	LIME MUDSTONE
Wst.	WACKESTONE
Pst.	PACKSTONE
Gst.	GRAINSTONE
	ALGAL STRUCTURES
	<u>TETRADIUM</u> (coral)
	MUD CRACKS
·······Q	QUARTZ SAND STRINGERS
	TEPEES
	RIPPLE CROSS-LAMINATION
	ARGILLACEOUS
	SHARP EROSIONAL BASE

1. GEOLOGIC SECTION, TUMBEZ FORMATION, TUMBEZ (measured by J.F. Read)

Base of section exposed on southeast bank of Big Mocassin Creek, approximately 0.5 mi. south-southwest of Tumbez; Moll Creek, Va. 7.5-minute quadrangle, Russel County. Section was measured from base of Tumbez Formation to basal Lincolnshire Formation.

TUMBEZ FORMATION, TUMBEZ



Brachiopod wst., dark gray, shaly, cherty, grades into cherty pellet gst.

Skeletal wst./mst., dark gray, cherty, some encrusting bryozoans, grades into dark gray lime mst.

Skeletal wst., med. gray, contains bryozoans and brachiopods, cherty.

Bryozoan/echinoderm pst./gst., med. gray, very coarse grained.

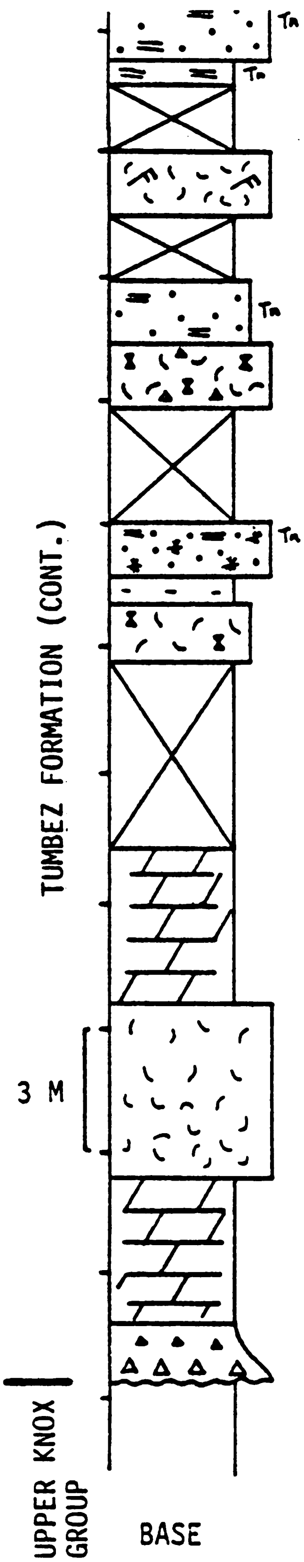
Lime mst., dark gray, cherty, some brachiopods, black shale partings.

Covered, some rare skeletal pst. beds.

Mst., skeletal, intraclastic, algal nodules(Hedstroemia), hardgrounds

Gst., skeletal, pelletal, grades into pellet gst.

Pellet gst., thin lam'd.
Skeletal gst.
Pellet gst.
Erosional base followed by med. to coarse intraclastic, skeletal gst. with algal nodules (Hedstroemia), rare chert lithoclasts.
Pellet gst., cherty, grades into thin lam'd pell gst. cap.
Dolomottled gst., grades into burrowed dolomite.
Pellet gst., thin-thick lam'd.
Skeletal gst., contains algal nodules of Hedstroemia, med. to coarse grained, med. gray.



Pellet gst., thin-thick lam'd.

Lime mst., white weathering, argillaceous, thin-thick lam'd.

Skeletal intra. gst., algal nodules of <u>Hedstroemia</u> up to 1cm dia., glauconite.

Pellet gst., med. grained, thin lam'd.

Skeletal intraclast gst., reddish brown, med.-coarse grained, grades into med. gray gst. at top, rare scattered chert lithoclasts, some nodules of <u>Hedstroemia</u>.

Mostly covered, some exposures of red siltstone.

Pellet pst./gst., fenestral, grades into thin lam'd-cryptalgal lam'd pellet gst. at top, shale partings.

Lime mst., argillaceous.

Skeletal pst./gst., intraclastic, whole skeletal grains.

Dolomite, massive.

Skeletal gst., very coarse, brachiopods concentrated at base.

Dolomite, massive.

Basal boulder dolomite/chert conglomerate, grades into chert breccia.

2. GEOLOGIC SECTION, MOSHEIM AND LENOIR FORMATIONS, AVENS BRIDGE SOUTH

Base of section exposed along southeast side of South Holston Lake, approximately 0.9 mi. south-southeast of Parks Mill, 1 mi. northeast of Avens Bridge, and 0.1 mi. northwest of Bench Mark SHSR 23 (reset); Abingdon, Va. 7.5-minute quadrangle, Washington County. Section was measured from upper Knox Group to base of Paperville Shale.

PAPERVILLE SHALE (1 m; full thickness not measured)

LENOIR FORMATION (12.5 m)

MOSHEIM FORMATION (1.3 m)

KNOX GROUP (2.3 m; full thickness not measured)

3. GEOLOGIC SECTION, BLACKFORD FORMATION, LEBANON

Base of section exposed along gravel road off Va. Rt. 640 approximately 1.1 mi. north-northwest of intersection of U.S. Rt. 19 and Va. Rt. 82 at Lebanon, Va.; Lebanon Va. 7.5-minute quadrangle, Russell County. Section was measured from uppermost Knox Group to top (?) of Blackford Formation. Duplicates section 8a of Heyman, 1970.

BLACKFORD FORMATION (49.7 m; top not exposed)

KNOX GROUP (4.8 m; full thickness not exposed)

4. GEOLOGIC SECTION, MOSHEIM LIMESTONE, RICH VALLEY

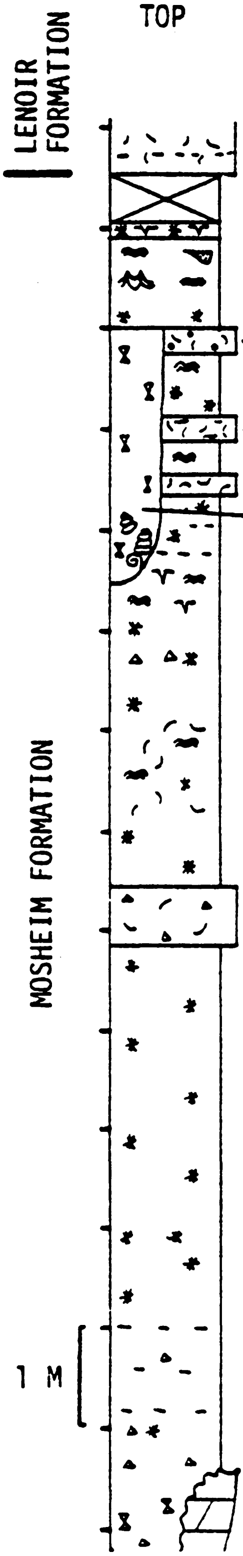
Base of section exposed in field 200 yards southeast of Va. Rt. 610, approximately 2.7 mi. S. 25 E. of Broadford; Broadford, Va. 7.5-minute quadrangle, Smyth County. Section was measured from upper Knox Group dolomites to basal Lenoir Limestone. Duplicates section 2 of Webb, 1959.

LENOIR FORMATION (0.5 m; full thickness not measured)

MOSHEIM FORMATION (12.7 m)

KNOX GROUP (4.2 m; full thickness not measured)

MOSHEIM FORMATION, RICH VALLEY



Skeletal wst., dark gray, argillaceous.

Lime mst., light gray, fenestral, cryptalgal lam'd, mud cracks.

Lime mst./pellet-intraclast pst., cryptalgal, fenestral at base.

Lime mst./pellet-intra. pst., dark gray, massive, rare cryptalgal layering, fenestral.

Skeletal wst., dark gray-black, argillaceous.

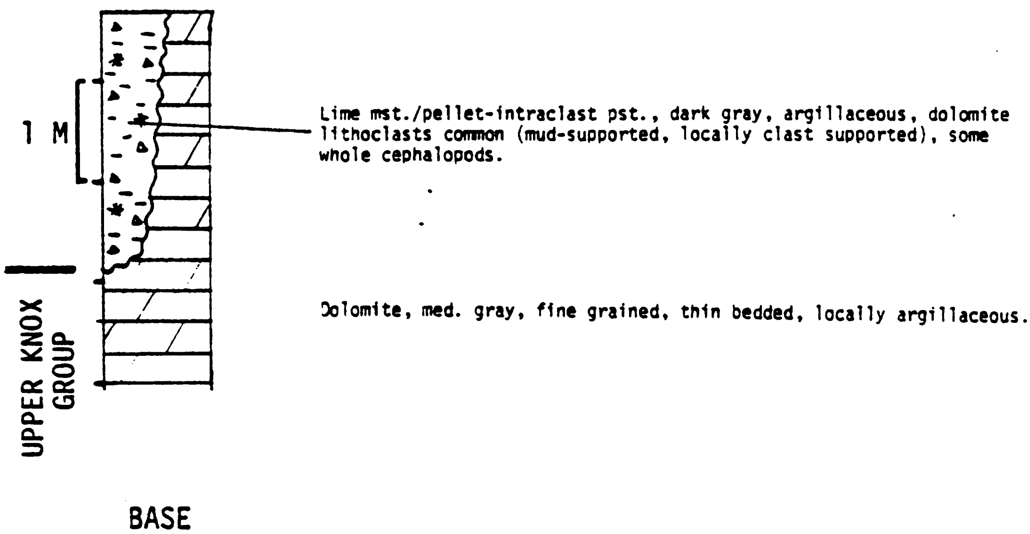
Probable tidal channel fill, consists of basal whole skeleton gastropods and cephalopods, intraclast conglomerate, all in a shaly fenestral lime mst./pell. intraclast pst. matrix. Clasts are dark gray-black skeletal wst. and light gray fenestral lst., up to 3cm long; grades into intraclast conglomerate at top; some chert and dolomite lithoclasts present.

Lime mst./pellet intraclast pst., lt. gray-brownish gray, intraclasts, lithoclasts, fenestrae, oncolites, slightly skeletal, some cryptalgal lamination.

Dolomitic intraclast limestone, mud-supported, many whole cephalopods, some lithoclasts.

Lime mst., dark gray, thin bedded, becomes massive at top, slightly skeletal.

Lime mst./pellet-intraclast pst., light-dark gray, fenestral, locally argillaceous, scattered chert/dolomite lithoclasts. Very coarsely fenestral near top.


1 M
UPPER KNOX GROUP
Lime mst./pellet-intraclast pst., dark gray, argillaceous, dolomite lithoclasts common (mud-supported, locally clast supported), some whole cephalopods.
Dolomite, med. gray, fine grained, thin bedded, locally argillaceous.
BASE

5. <u>SPOT LOCALITY, PALEOTOPOGRAPHIC HIGHS, RICH VALLEY</u>

Paleohighs exposed in field 200 yds. southwest of Va. Rt. 610, approximately 0.9 mi. west of intersection of Va. Rtes. 630 and 610; Broadford Virginia 7.5 minute quadrangle, Smyth County (see also Webb, 1959).

6. <u>SPOT LOCALITY, INTRAFORMATIONAL BRECCIA, CHATHAM HILL</u>

Breccia exposed in roadcut along Va. Rt. 16 approximately 1.1 mi. south-southeast of Chatham Hill; Chatham Hill, Va. 7.5-minute quadrangle, Smyth County.

7. <u>SPOT LOCALITY, BASAL BRECCIA, MARION</u>

Dolomite megabreccia exposed in field 100 yds. southwest of old prison camp near Marion, Va. (see Sautter, 1981).

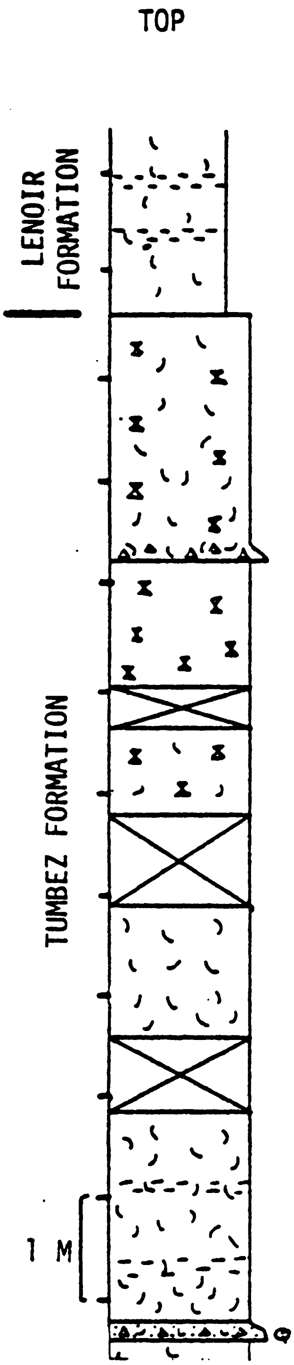
8. <u>SPOT LOCALITY, EROSIONAL CONTACT, MOSHEIM AND TUMBEZ FORMATIONS, MARION</u>

Contact between Mosheim and Tumbez Limestones exposed in median along U.S. Rt. 11 (southbound lane) approximately 2 mi. south of Marion Va.; Marion, Va. 7.5-minute quadrangle, Smyth County (see Sautter, 1981).

9. <u>GEOLOGIC SECTION, TUMBEZ FORMATION, MARION.</u>

Base of section exposed on side of hill in field approximately 0.3 mi. northwest of intersection of U.S. Rt. 11 and I-81 at McMullin and 3.4 mi. west-southwest of Marion; Marion, Va. 7.5-minute quadrangle, Washington County. Section was measured from upper Knox Group to basal Lenoir Formation. Duplicates Gardner section of Sautter, 1981.

TUMBEZ FORMATION, MARION



Skeletal wst., dark gray, pinkish argillaceous partings, darkens upwards, contains coiled cephalopods up to 8cm dia., sharp planar base.

Pellet-intraclast pst/gst., med. gray, skeletal, local thin beds of shaly lst.

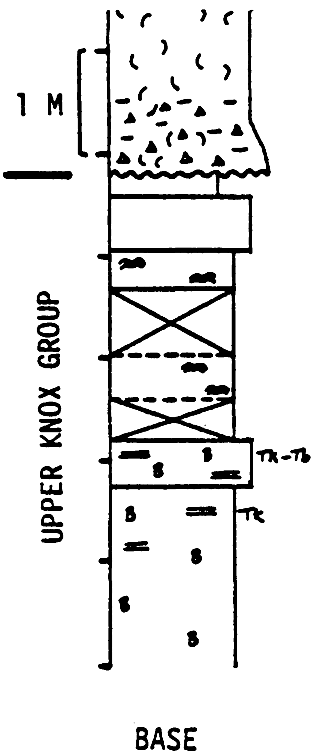
Basal chert breccia, white clasts, mud supported, angular.

Intraclast gst., skeletal, med. gray-pinkish gray, shaly.

Intraclast gst., med. gray-pinkish gray, slightly skeletal, shaly locally.

Skeletal gst., pinkish gray-med. gray, well indurated to poorly indurated, locally shaly, contains echinoderms, brachiopods, and bryozoans.

Chert conglomerate, red, sandy, clasts subangular to rounded, and up to 2cm dia., skeletal lst. matrix.



Basal argillaceous/dolomitic skeletal pst./gst., pinkish gray to gray, chert and dolomite lithoclasts up to 2cm dia., contains whole bryozoans and brachiopods, and also large crinoid columnals, grades into clean skeletal gst.

Interlayered gray fine dolomite and thin-thick lam'd pell gst./lime mst., gst. lenses fill scours.

Dolomie, white, coarse grained, massive.

Dolomite, white, fine-grained to med. grained, cryptalgal lam'd.

Mostly covered, scattered beds of light gray, med.-coarse grained dolomite, massive, rare faint cryptalgal lamination.

Dolomite, gray-brown, coarse grained, thick lam'd-thin bedded, burrowed.

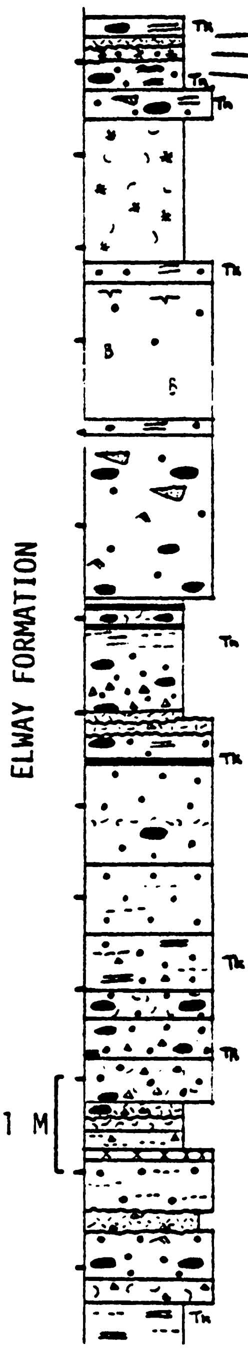
Dolomite, light gray, med. grained, burrowed, thick lam'd at top.

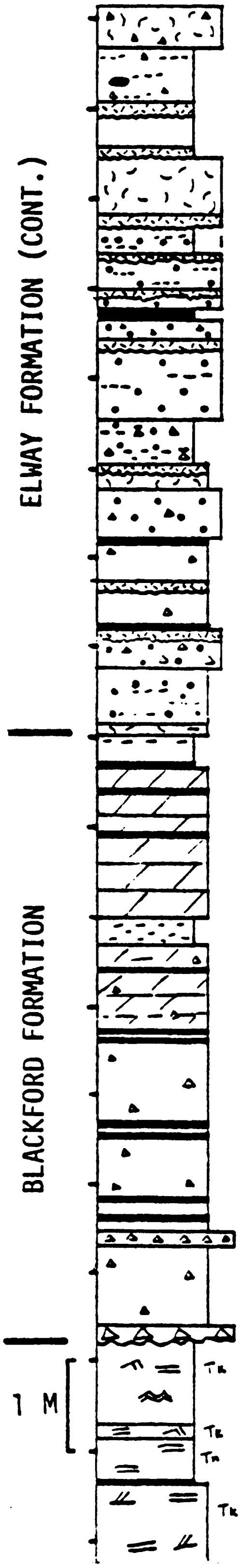
10. GEOLOGIC SECTION, BLACKFORD AND ELWAY FORMATIONS, EAST RIVER MOUNTAIN SOUTH

Base of section is exposed in roadcut along I-77 (westbound lane) approximately 200 yds. northwest of East River Mountain Tunnel and 5 mi. east of Bluefield W. Va; Bluefield Va.-W. Va. 7.5-minute quadrangle, Mercer County, W. Va. Section was measured from uppermost Knox Group to middle of Elway Formation.

BLACKFORD AND ELWAY FORMATIONS, E. RIVER MTN.

TOP





Ostracod/gastropod pst., chert lithoclasts.

Interbedded lithoclastic lst. and limy shale.

Erosional base followed by lithoclastic/intraclastic dolomite, grade into nodular bedded lime mst., erosionally overlain by lithoclastic/intraclastic dolomite.

Erosional base followed by lithoclastic breccia, grades into nodular bedded gastropod/ostracod pst./gst.

Lime mst., shaly, pellet pst. interbeds.

Pellet pst., shaly, irregular erosional base overlain by lithoclastic/intraclastic dolomite.

Irregular erosional base followed by lithoclastic/intraclastic dolomite, grades into pellet pst. with rare lithoclasts, capped by shale.

Pellet pst., shaly.

Lime mst., intraclastic/lithoclastic, pelletal.

Skeletal wst., capped by irregular erosion surface; overlain by lithoclastic/intraclastic dolomite.

Pellet pst., dolomitic, rare chert lithoclasts.

Lime mst/wst., dolomitic, intraclastic and lithoclastic, thin lam'd near center.

Pellet pst./gst., chert lithoclasts.

Pellet wst., shaly.

Ostracode/trilobite wst.

Lime mst., blue-gray, grades into shaly dolomite.

Dolomite, med. grained, massive, shale interbeds.

Marl.

Dolomite , med. grained, massive, detrital chert, shale.

Dolomite, med. grained, chert/dolomite lithoclasts, massive.

Dolomite, gray, med. grained, scattered detrital chert, mud support lithoclast breccia in middle of unit.

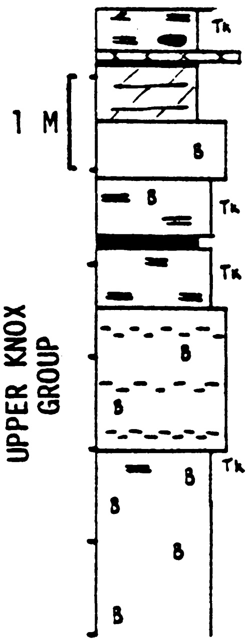
Unconformity breccia, clasts up to 25cm dia., up to 0.7m locally.

Dolomite, fine grained, thick lam'd, scours.

Dolomite, fine grained.

Dolomite, thin lam'd, fine grained, massive.

Dolomite, med. grained, faint irregular thick lam'd, mottled.



Dolomite, fine grained, mottled.

Dolomite, fine grained, massive, shale cap.

Dolomite, coarse grained, massive, burrowed.

Dolomite, med. grained, irregular thick lam'd, burrowed.

Dolomite, med. grained, thick lam'd.

Dolomite, blue-gray, fine-med. grained, massive, burrowed.

Dolomite, gray, med. grained, massive, faint laminations at top, burrowed at base.

BASE

11. GEOLOGIC SECTION, TUMBEZ FORMATION, DRAPER (measured by J.F. Read)

Base of section exposed on southeast side of hill approximately 0.15 mi. northwest of intersection of Va. Rtes. 100 and 658 at Draper and 0.1 mi. southeast of I-81; Dublin, Va. 7.5-minute quadrangle, Pulaski County. Section was measured from base to top (?) of Tumbez Formation.

LINCOLNSHIRE FORMATION (not exposed)

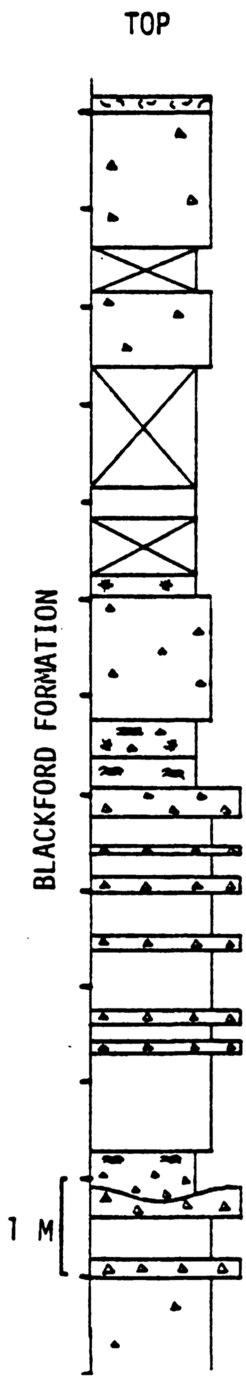
TUMBEZ FORMATION (54 m)

KNOX GROUP (not exposed)

12. GEOLOGIC SECTION, BLACKFORD FORMATION, NARROWS

Base of section is exposed in median along U.S. Rt. 460 (eastbound lane) approximately 2 mi. northwest of intersection of Rt. 460 and Va. Rt. 61 at Narrows; Narrows, Va.-W.Va. 7.5-minute quadrangle, Giles County. Section was measured from uppermost Knox Group to top (?) of Blackford Formation.

BLACKFORD FORMATION, NARROWS



Skeletal wst., rare dolomite lithoclasts.

Dolomite, fine grained, brown-gray, fenestral, rare lithoclasts, thick bedded.

Partly covered, dolomite, gray to pink, med. grained, chert lithoclasts scattered.

Dolomitic lime mst., fenestral, nodular bedded, skeletal.

Lime mst., med. gray, fenestral.

Dolomite, med. gray, thick bedded, scattered lithoclasts, some dolomitic limestone near top.

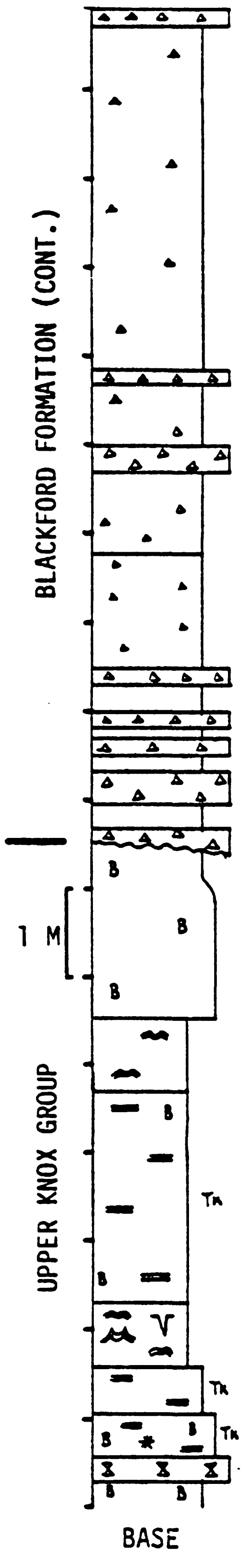
Lime mst., med.-dark gray, fenestral, thin lam'd at top, rare chert lithoclasts, interbedded skeletal intraclast wst./mst.

Dolomite, med. gray, fine grained, cryptalgal lam'd, slightly skeletal, intraclastic.

Dolomite, med. gray, thick bedded, with many mud-supported lithoclastic dolomite interbeds.

Scoured base, followed by thin lithoclastic dolomite, cryptalgal lam'd at top.

Dolomite, med. grained, med. gray, lithoclastic dolomite interbeds (mud-supported).



Dolomite, med. gray, med. grained, massive, many mud-supported lithoclastic dolomite interbeds.

Dolomite, med. gray, med. grained, lithoclastic, capped by mud-supported lithoclastic dolomite.

Dolomite, med. grained, lithoclastic.

Dolomite, med. gray, med. grained, massive, with multiple lithoclastic dolomite interbeds (mud-supported) except for basal unconformity breccia which is clast supported. Clasts are chert/dolomite, up to 8cm dia., angular.

Dolomite, med. gray, coarse grained, burrowed, med. grained near top.

Dolomite, med. gray, fine grained, thin lam'd to cryptalgal lam'd, sharp basal contact.

Dolomite, med. gray, fine grained, irregularly thick lam'd, burrowed.

Dolomite, med. gray, fine grained, cryptalgal lam'd.

Dolomite, med. gray, thick lam'd, rare fenestrae.

Dolomite, med.-dark gray, thick lam'd-thin bedded, slightly fenestral, top of unit burrowed.

Intraclastic dolomite, clasts rounded and up to 3cm in length.

Dolomite, med. gray, med. grained, faintly burrowed.

13. GEOLOGIC SECTION, BLACKFORD FORMATION, EGGLESTON

Base of section is exposed in railroad cut east of, and parallel to, New River, approximately 0.5 mi. south-southeast of intersection of Va. Rtes. 622 and 730 at Eggleston; Eggleston, Va. 7.5-minute quadrangle, Giles County. Section was measured from uppermost Knox Group to basal Elway Formation.

ELWAY FORMATION (1.8; full thickness not measured)
BLACKFORD FORMATION (26 m; top not exposed)
KNOX GROUP (16.4 m; full thickness not measured)

14. SPOT LOCALITY, CHERT CONGLOMERATE (BLACKFORD), NEWPORT

See Gambill, 1975 for location

15. SPOT LOCALITY, CHERT CONGLOMERATE (NEW MARKET), LUSTERS GATE

Conglomerate exposed in roadcut along Va. Rt. 785, 1 mi. northeast of McDonalds Mill; McDonalds Mill, Va. 7.5-minute quadrangle, Montgomery-Roanoke County line.

16. SPOT LOCALITY, ELLETT RED BEDS, ELLETT

See Gilbert, 1952 or Grover, 1976 for location and description.

17. SPOT LOCALITY, SINKHOLES, FINCASTLE

See Campbell, 1975 for location

18. SPOT LOCALITY, CARBONATE CONGLOMERATES (NEW MARKET), FINCASTLE

See Campbell, 1975 for location

19. GEOLOGIC SECTION, UPPER BEEKMABNTOWN GROUP AND NEW MARKET FORMATION, PARK VIEW

Base of section exposed on east side of hill, northeast of Va. Rt. 763, approximately 0.3 mi. northwest Eastern Mennonite College in Park View; Bridgewater, Va. 7.5-minute quadrangle, Rockingham County. Section was measured from upper Beekmantown carbonates to basal New Market Formation. Duplicates Park View section of Suter, 1973).

NEW MARKET FORMATION (13.2 m; full thickness not measured)

BEEKMANTOWN GROUP (23.5 m; full thickness not measured)

20. GEOLOGIC SECTION, NEW MARKET FORMATION, CEDAR GROVE CHURCH

Base of section exposed in field north of Va. Rt. 718, approximately 0.6 mi. east-northeast of intersection of Va. Rtes. 718 and 720, and 1.9 mi. northeast of of Interstate 81 - U.S. Rt. 33 cloverleaf; Harrisonburg, Va. 7.5-minute quadrangle, Rockingham County. Section was measured from uppermost Beekmantown carbonates to middle (?) of New Market Formation.

NEW MARKET FORMATION (11.8 m; full thickness not measured)

LOWER DETRITAL DOLOMITE MEMBER (8.8 m)

BEEKMANTOWN GROUP (4.4 m; full thickness not measured)

21. SPOT LOCALITY, CARBONATE BRECCIA (NEW MARKET), HARRISONBURG

Breccia exposed in field and along dirt road, approximately 0.75 mi. east of Melrose and 0.4 mi. northeast of Va. Rt. 724, Harrisonburg, Va. 7.5-minute quadrangle, Rockingham County.

22. SPOT LOCALITY, PALEOTOPOGRAPHIC HIGHS, HARRISONBURG

22.7 m of relief on unconformity. Unconformity exposed near edge of pond on farm 50 yds. west of Va. Rt. 753, approximately 3.1 mi. north-northwest of Court House at Harrisonburg; Harrisonburg, Va. 7.5-minute quadrangle, Rockingham County.

23. GEOLOGIC SECTION, UPPER BEEKMANTOWN GROUP AND NEW MARKET FORMATION, BROADWAY EAST

Base of section exposed in field behind Broadway Motor Co., 200 yds. northwest of intersection of Va. Rtes. 259 and 42 at Broadway; Broadway, Va. 7.5-minute quadrangle, Rockingham County. Section was measured from upper Beekmantown carbonates to upper New Market Formation.

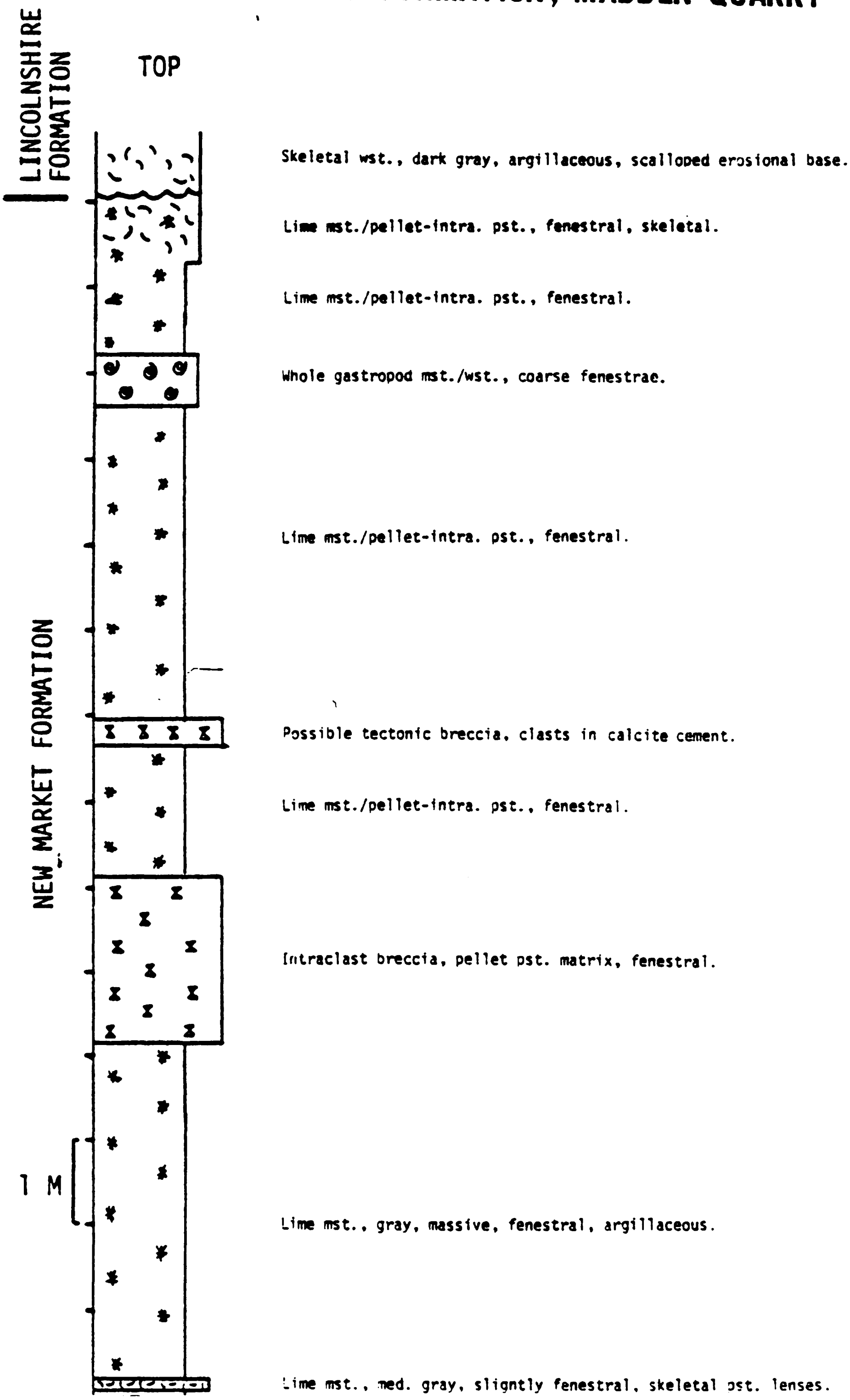
NEW MARKET FORMATION (17.3; full thickness not measured)

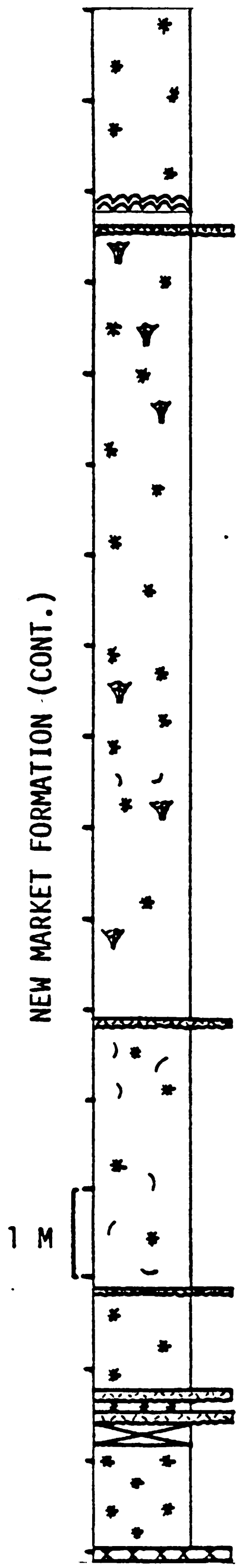
BEEKMANTOWN GROUP (23.3 m; full thickness not measured)

24. GEOLOGIC SECTION, NEW MARKET FORMATION, MADDEN QUARRY

Base of section exposed at entrance to Madden Quarry, located on west side of hill approximately 0.4 mi. southwest of intersection of Va. Rt. 260 and Interstate 81 at New Market; New Market, Va. 7.5-minute quadrangle, Shenandoah County. Section was measured from uppermost Beekmantown to basal Lincolnshire Formation.

NEW MARKET FORMATION, MADDEN QUARRY





Lime mst./pellet-intra. pst., fenestral, LLH stromatolites locally.

Planar erosional base followed by intraclastic pellet-intra. pst.

Lime mst./pellet-intra. pst., dark gray, fenestral, Tetradium (coral).

Planar erosional base followed by yellow weathering, intraclastic pellet-intra. pst., dolomitic, overlain by calcarenite.

Lime mst./pellet intra. pst., slightly fenestral, skeletal.

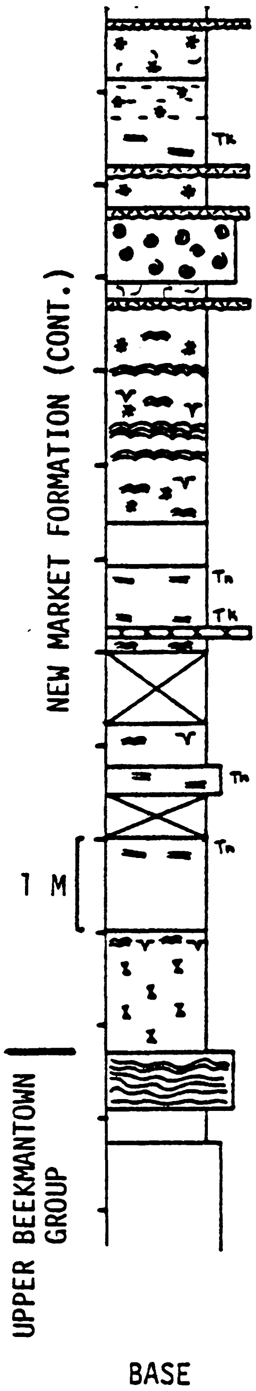
Lime mst./pellet intra. pst., med. gray.

Planar erosion surface overlain by dolomitic intraclastic pellet pst.

Lime mst./pellet intra. pst., med. gray, massive.

Two dolomitic intraclast pellet pst. beds, both with planar erosional bases, separated by fenestral limestone interbed.

Planar erosional base followed by dolomitic intraclast limestone, yellow-weathering, grades into fenestral lime mst., gray.



Planar erosional base followed by dolomitic intraclastic lst., yellow-weathering, grades into fenestral lime mst. with incipiently brecciated fabric.

Lime mst., fenestral, slightly skeletal.

Planar erosional base followed by dolomitic intraclast lst., yellow-weathering, grades into irregular thick lam'd lime mst. that becomes shaly upwards.

Planar erosional base followed by dolomitic intraclast lst., grades into gray fenestral lime mst.

Whole gastropod pst./wst., med. gray, also contains ostracodes, trilobites, and brachiopods.

Planar erosional base followed by dolomitic intraclast lst., yellow-weathering, grades into med. gray skeletal lime mst./wst.

Cryptalgal lam'd fenestral lime mst., LLH's locally.

Lime mst., med. gray, thin bedded.

Lime mst. at base(cryptalgal lam'd), followed by intraclastic lst. breccia (possibly tectonic), overlain by thick to thin lam'd lime mst.

Lime mst./wst., thin to thick lam's, mostly cryptalgal.

Dolomite, med. gray, med. grained, thin lam'd.

Lime mst., dark gray, thin lam'd, dolomitic at top, erosional contact at top.

Intraclast breccia, clast-supported, pinkish-brown clasts, has cryptalgal lam'd and mud-cracked top.

Caliche (?), yellow and gold banded, mostly lime mst., abundant dolomite rhombs concentrated along laminae.

Lime mst., med. gray, massive.

Dolomite, med. gray, med. grained, limy, thin bedded.

25. GEOLOGIC SECTION, NEW MARKET FORMATION, LEAKSVILLE SOUTH

Base of section exposed in field west of Va. Rt. 618, approximately 2.6 mi. north-northeast of Alma and 0.4 mi. southwest of Leaksville; Stanley, Va. 7.5-minute quadrangle, Page County. Section was measured from uppermost Beekmantown Group to basal Lincolnshire Formation.

LINCOLNSHIRE FORMATION (1 m; full thickness not measured)

NEW MARKET FORMATION (15.3 m)

BEEKMANTOWN GROUP (3.6 m; full thickness not measured)

26. GEOLOGIC SECTION, NEW MARKET FORMATION, WOODSTOCK

Base of section exposed on east bank of Puhs Run, approximately 3.8 mi. southwest of Maurertown, Va., and 0.1 mi. southeast of U.S. Rt. 11; Toms Brook, Va. 7.5-minute quadrangle, Shenandoah County. Section was measured from uppermost Beekmantown carbonates to upper New Market Formation.

NEW MARKET FORMATION (10.6 m; full thickness not measured)

BEEKMANTOWN GROUP (2 m; full thickness not measured)

27. GEOLOGIC SECTION, NEW MARKET FORMATION, TUMBLING RUN

Base of section is exposed on east bank of Tumbling Run (section continues in roadcut) where it passes under Va. Rt. 757, approximately 0.3 mi. northwest of Toms Brook; Toms Brook, Va. 7.5-minute quadrangle, Shenandoah County. Section was measured from uppermost Beekmantown Group to basal Lincolnshire Formation.

LINCOLNSHIRE FORMATION (3 m; full thickness not measured)

NEW MARKET FORMATION (67.5 m)

BEEKMANTOWN GROUP (4.4 m; full thickness not measured)

28. GEOLOGIC SECTION, BLACKFORD AND ELWAY FORMATIONS, ROSE HILL

Base of section is exposed in roadcut along northeast side of va. Rt. 667, approximately 3.75 mi. southeast of intersection of U.S. Rt. 58 and Rt. 667, and 4.6 mi. southeast of Rose Hill; Rose Hill, Va. 7.5-minute quadrangle, Lee County. Section was measured from uppermost Knox Group to lower Elway Formation.

ELWAY FORMATION (5 m; full thickness not exposed)

BLACKFORD FORMATION (40.9 m)

KNOX GROUP (9 m; full thickness not measured)

29. GEOLOGIC SECTION, MOSHEIM AND LENOIR FORMATIONS, AVENS BRIDGE NORTH

Approximately 400 yds. northward and along strike from geologic section 2.

PAPERVILLE SHALE (2 m; full thickness not measured)

LENOIR FORMATION (8.4 m)

MOSHEIM FORMATION (17.4 m)

KNOX GROUP (3 m; full thickness not measured)

30. GEOLOGIC SECTION, BLACKFORD FORMATION, EAST RIVER MOUNTAIN NORTH

Base of section exposed in roadcut along curved exit ramp 100 yds. north of Geologic Section 10. Section was measured from uppermost Knox Group to basal Elway Formation.

ELWAY FORMATION (6.3 m; full thickness not measured)

BLACKFORD FORMATION (18.6 m)

KNOX GROUP (4.5 m; full thickness not measured)

31. GEOLOGIC SECTION, BLACKFORD AND ELWAY FORMATIONS, ROCKY GAP

Base of section exposed in roadcut along service road southwest of and parallel to I-77, approximately 1 mi. southeast of Rocky Gap; Rocky Gap, Va. 7.5-minute quadrangle, Bland County. Section was measured from uppermost Knox Group dolomite to basal Elway Formation.

ELWAY FORMATION (5.4 m; full thickness not measured)

BLACKFORD FORMATION (21.8 m)

KNOX GROUP (9 m; full thickness not measured)

32. GEOLOGIC SECTION, NEW MARKET FORMATION, GOODWINS FERRY

Base of section exposed in railroad cut east of and parallel to New River, approximately 1.1 mi. south-southeast of intersection of Va. Rtes. 605 and 625 at Goodwins Ferry; Eggleston, Va. 7.5-minute quadrangle, Giles County. Section was measured from upper Knox Group dolomites to top of New Market Formation.

NEW MARKET FORMATION (17.9 m; top not exposed)

KNOX GROUP (9.4 m; full thickness not measured)

33. GEOLOGIC SECTION, NEW MARKET FORMATION, COLLIERSTOWN

Base of section exposed in roadcut along Va. Rt. 676 (north side), approximately 0.1 mi. southeast of intersection of Va. Rtes. 644 and 676, and 1.7 mi. southeast of Collierstown; Collierstown, Va. 7.5-minute quadrangle, Rockbridge County. Section was measured from upper Beekmantown carbonates to base of Lincolnshire Formation.

LINCOLNSHIRE FORMATION (1 m; full thickness not measured)

NEW MARKET FORMATION (16.8 m)

BEEKMANTOWN GROUP (2.2 m; full thickness not measured)

34. GEOLOGIC SECTION, NEW MARKET FORMATION, EDOM

Base of section exposed in roadcut along Va. Rt. 753 approximately 1.7 mi. northwest of intersection of Va. Rtes. 753 and 42, and 3.3 mi. northwest of Linville; Broadway, Va. 7.5-minute quadrangle, Rockingham County. Section was measured from upper Beekmantown carbonates to top of New Market Formation.

NEW MARKET FORMATION (24.2 m; top not exposed)

BEEKMANTOWN GROUP (13.3 m; full thickness not measured)

35. GEOLOGIC SECTION, NEW MARKET FORMATION, BROADWAY WEST

(measured by J.F. Read)

Base of section in roadcut along Va. Rt. 259, approximately 1.9 mi. west of intersection of Va. rts. 259 and 42, near Broadway; Broadway, Va. 7.5-minute quadrangle, Rockingham County. Section was measured from base to middle of New Market Formation.

NEW MARKET FORMATION (12 m; full thickness not measured)

36. GEOLOGIC SECTION, FOSSILIFEROUS SINKHOLE FILL, LEAKSVILLE NORTH

Base of section is exposed 100 yds. north of Geologic Section 25. Section was measured from base of sinkhole fill to basal Lincolnshire Formation.

LINCOLNSHIRE FORMATION (1 m; full thickness not measured)

NEW MARKET FORMATION (9.7 m)

SINKHOLE FILL (15.5 m)

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THE MIDDLE ORDOVICIAN KNOX UNCONFORMITY, VIRGINIA APPALACHIANS: TRANSITION FROM PASSIVE TO CONVERGENT MARGIN

by

William J. Mussman

(ABSTRACT)

The Knox unconformity in the central and southern Appalachians is developed on Lower to early Middle Ordovician Knox/Beekmantown carbonates. The unconformity marks the transition from Cambro-Ordovician shelf carbonate deposition on a passive margin to carbonate and clastic deposition in a foreland basin associated with a convergent margin, possibly during a time of global sea level lowering.

Erosional relief on the unconformity decreases from over 140 m in southwest Virginia to 20 m or less in northern Virginia. This corresponds with a marked decrease in stratigraphic relief in the same direction. Paleokarst features that formed on the unconformity include topographic highs that extend up to 30 m into overlying Middle Ordovician peritidal carbonates, sinkholes and caves that extend down to 65 m below the unconformity and are filled with detritus from the unconformity and breccia from host carbonates, and sub-unconformity dolomite breccia bodies that formed by collapse after dissolution of limestone interbeds. Coarse detritus on the unconformity

surface formed thin to thick veneers of regolith; locally this material was reworked by fluvial and marine processes. Much fine dolomite detritus was reworked and deposited as alluvial fan and playa mud-flat sediments in lows on the unconformity surface.

The unconformity influenced the regional distribution, composition and thickness of some post-unconformity peritidal carbonates. This is evidenced by lithoclastic supratidal sheets that cap cycles in these beds up to 100 m above the unconformity. Unconformity highs also may have controlled later Middle Ordovician buildup distribution in Virginia.

Development of regional unconformities on shelf sequences of passive margins immediately beneath foreland basin sequences is common in other orogens, reflecting gentle warping of the shelf prior to foundering beneath synorogenic clastics. Such unconformities may localize hydrocarbons and base metal deposits (Pb-Zn), by controlling the distribution of permeable horizons adjacent to the unconformity.