High Resolution Sequence Stratigraphy of Late Mississippian Carbonates in the Appalachian Basin

by

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(ABSTRACT)

The late Mississippian carbonates in the Appalachian Basin, U.S.A., were deposited on a huge, south-facing ramp during long-term Mississippian transgression that formed the Mississippian supersequence. The St. Louis- to Glen Dean interval consists of up to twelve fourth-order depositional sequences (300 to 400 k.y. average duration). The sequences (a few meters to over a hundred meters thick) consist of eolianites, lagoonal carbonate muds, ooid shoals, and skeletal banks, and open marine skeletal wackestone and basinal marl on the ramp-slope and basin margin. Sequence boundaries are at the top of prograding red-beds, eolianites, and shoal water facies on the ramp, and beneath lowstand sand bodies and quartzose calcisiltite wedges on the ramp margin and slope. Maximum flooding surfaces are difficult to map regionally, therefore it is difficult to separate the TST from the HST of these fourth-order sequences.

Up-dip in eastern Kentucky, along the Cincinnati Arch and Pine Mountain belts, sequences are defined by their regionally-traceable, bounding disconformities, which have paleosols with exposure features varying from incipient quartz peloid paleosols, breccias, tepees, caliches and rare vertisols in red-beds. However, down-dip, where subsidence rates were higher, sequences are conformable and are transgressive to regressive upward shallowing units. In Kentucky, parasequences (less than 10 m thick) are upward shallowing units of grainstone to mudstone typically. These are best developed down-dip on the Pine Mountain belt; up-dip, they tend to be locally developed.

The northward and counterclockwise movement of the North American plate progressively moved the Appalachian Basin toward the equator from the Devonian through Carboniferous, resulting in a gradual shift from semi-arid to more humid climate, which affected the types of disconformities produced, and may have limited widespread ooid shoals to low in the section. Rapid thickening into the basin was due to thrust-loading. It is synchronous with differential subsidence on the distal foreland, where fault-blocks were reactivated. The development of regionally traceable, disconformity-bounded, grainstone-dominated sequences is coincident with the onset of the Carboniferous Gondwana glaciation, which caused repeated flooding of the ramp to depths favorable for widespread grainstone deposition. Backstepping of ooid reservoirs was controlled by the long-term transgression. Lateral partitioning of these reservoirs likely reflects strong tidal influence. Vertical partitioning of reservoirs by shoal water carbonate muds and tight calichified exposure surfaces was due to repeated fourth-order, moderate amplitude sea-level changes.

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CHAPTER ONE

INTRODUCTION

This study presents a detailed basin-wide sequence stratigraphic study of the Mississippian carbonates of the Appalachian foreland basin (Figs. 1 and 3), during a phase of active subsidence, onset of the southern hemisphere Gondwana glaciation, and long term climatic shift. Previous work on the Late Mississippian (Meramecian-to Early Chesterian) St. Louis to Glen Dean interval in the Appalachian Basin (Fig. 3) included regional surface mapping and biostratigraphy by Butts (1922, 1940, 1941), Reger (1926), Wells (1950), Mc Farlan and Walker (1956) and Bartlett and Webb (1971), and detailed studies on a local-to sub-regional scale to define synsedimentary tectonics by Dever (1973, 1986 and 1995), Ettensohn (1975, 1980), MacQuown and Pear (1983), and Yeilding and Dennison (1986). Carney (1993) identified the Greenbrier Limestone in northeastern West Virginia as a long-term transgressive succession. Limited published subsurface work includes regional mapping of the Greenbrier (Big Lime) on well-logs (Flowers, 1956) and detailed local mapping of ooid reservoirs (Kelleher and Smosna, 1993) in West Virginia.

This dissertation attempts to provide the first detailed, high-resolution sequence stratigraphic study of the Mississippian Chesterian carbonates from the sections on the distal foreland, Kentucky, into the very thick basin-fill of the foredeep of the Appalachian Basin, West Virginia/Virginia, this is based on regional lithologic cross-sections, incorporating detailed logs from 32 outcrop sections, 4 shallow long cores, and drill-cuttings from 5 oil/gas wells. This was done by tracing disconformities and correlative conformities, previously thought by most workers to be relatively local in extent, across the basin, along with distinctive lithologic markers.

Chapter 2 is a summary of the regional geologic setting in the Appalachian Basin, and Chapter 3 is a detailed description of the sedimentary facies within the interval of study. Chapter 4 presents the regional sequence stratigraphy and tectonic history of the actively subsiding basin during the deposition of the St. Louis (Hillsdale) to Glen Dean (Glen Ray) interval in West Virginia/Virginia. This data set includes some outcrop sections, one core and well cuttings.

Chapter 5 presents the high-resolution sequence stratigraphy of the St. Louis-to Glen Dean interval of the distal foreland, Cincinnati Arch and Pine Mountain area in eastern Kentucky. The data set is based on outcrop sections and shallow cores, and thus is of high quality.

The study shows that fourth-order sequences in the Mississippian likely formed by moderate amplitude fourth-order glacio-Eustasy in the actively subsiding Appalachian foreland basin, during a long term climatic shift from semi-arid to slightly humid conditions. It documents how the rapid thickness variation in the sequences reflects deformation of the faulted foreland, coupled with regional subsidence related to thrust-loading. Finally, it illustrates the strong control that fourth-order eustasy during buildup of the Gondwana ice-sheet had on the development of widespread oolitic reservoir facies, and lowstand bank and sand units.

CHAPTER TWO

GEOLOGIC SETTING

Paleogeographic Setting

During the Late Mississippian, the Appalachian Basin lay in a sub-equatorial, arid, desert belt within approximately 25 degrees south of the equator (de Witt and Mc Grew, 1979; Scotese and McKerrow,1990). By the Pennsylvanian, northward drift of the North American plate carried the basin into the equatorial belt (de Witt and Mc Grew (1979) and Scotese and McKerrow (1990). Sedimentologic evidence from the study interval indicates a gradual change from an arid to semi-arid climate during the Late Meramecian-Early Chesterian to a wetter climate by the mid to Late Chesterian (Ettensohn et. al., 1988).

Regional Structural Setting

The study area includes the eastern Kentucky, West Virginia, and southwestern Virginia portions of the central Appalachian Basin of the eastern U.S.A. (Figs. 1 and 2). The basin is an elongate foreland basin, filled by Middle Ordovician to early Permian sediments (Colton, 1970; de Witt and McGrew, 1979). In the western part of the study area (Appalachian Plateau), the Paleozoic rocks are undeformed to gently folded. The Cincinnati Arch forms the western margin of the basin, and separates it from the Illinois Basin. The eastern portion of the basin comprises the folded and thrusted Valley-and-Ridge Province, bordered on the further east by Pre-cambrian and Cambrian

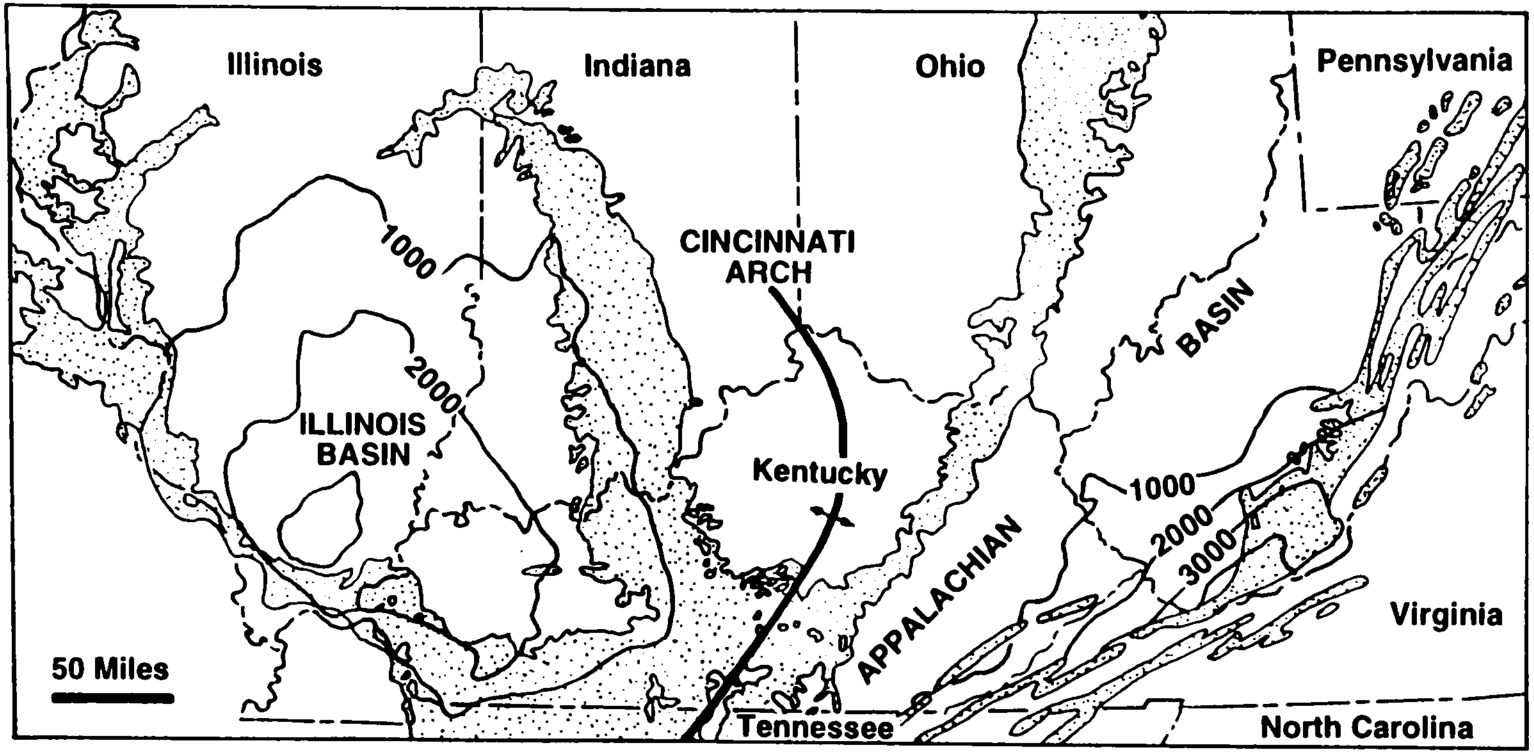


Fig.1 Outcrop map of Mississippian rocks in the Appalachian and Illinois Basins of eastern North America (stippled pattern). Contours are Mississippian isopachs in feet. The Cincinnati Arch was a broad positive element that separated the two basins in the Mississippian. The study area of this project is in the Appalachian Basin. The time equivalent interval in the Illinois Basin (Ste. Genevieve to Glen Dean) has been studied by Smith (1996).

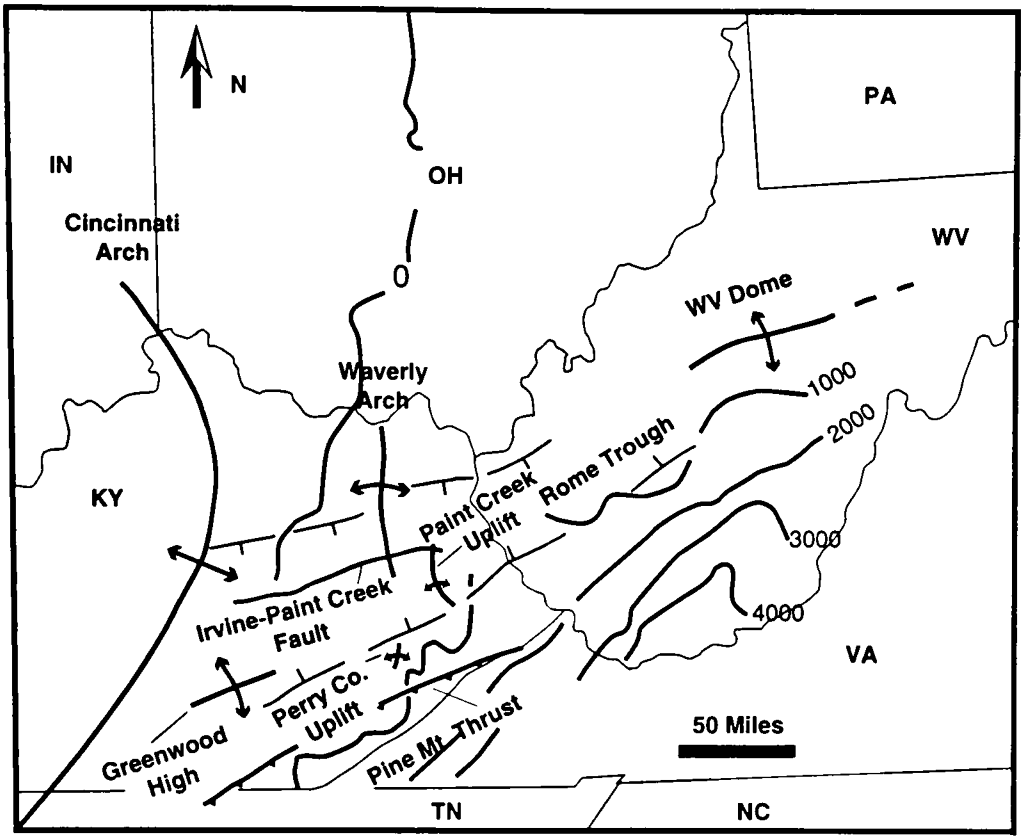


Fig. 2A Tectonic map of the Appalachian Basin, eastern Kentucky, West Virginia, and Virginia. Contours are isopachs (in feet) for the Mississippian rocks in (Modified from Pryor and Sable, 1974; MacQuown and Pear, 1980; Yeilding and Dennison, 1986; Dever, 1986, 1995; Sable and Dever, 1990, Dever et. al., 1990)

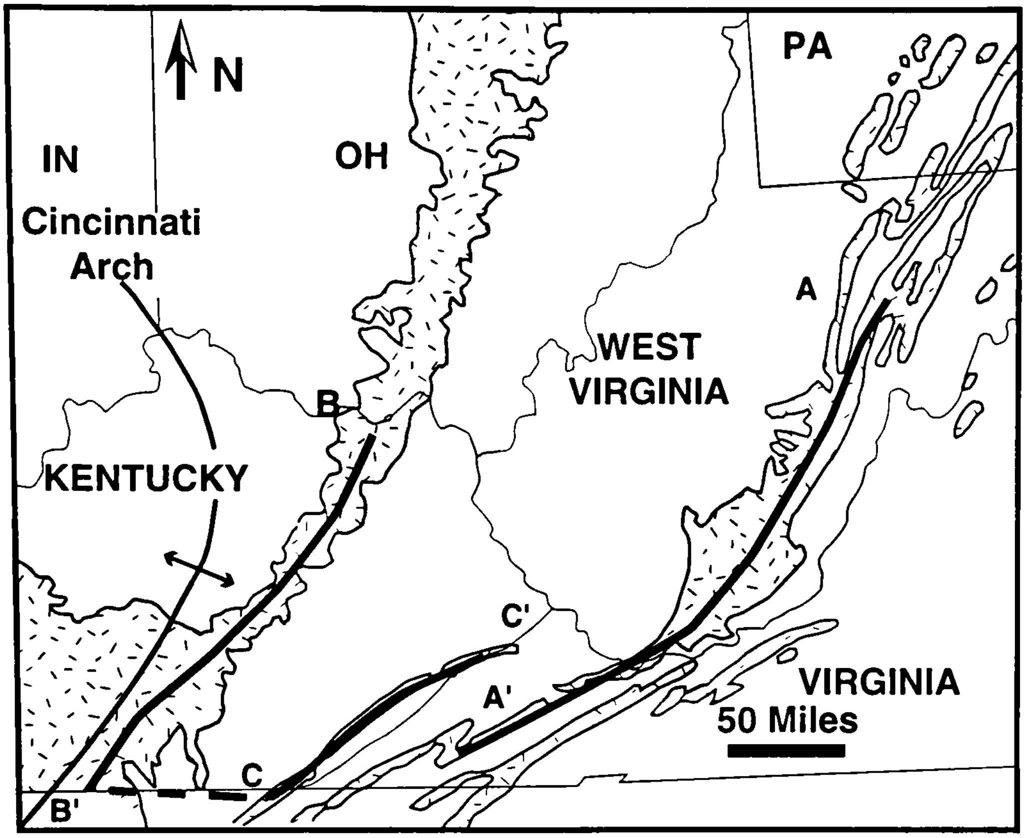


Fig. 2B Location map of Mississippian outcrop belts (stippled pattern) in the Appalachian Basin, eastern Kentucky, West Virginia, and Virginia. A-A' is the traverse in eastern West Virginia used to generate the detailed cross-section of Figure 5. B-B' is the traverse along the Cincinnati Arch, and C-C' is the traverse along the Pine Mountain thrust in eastern Kentucky (see Fig. 6).

crystalline and metasedimentary rocks of the Blue Ridge Province (Colton, 1970, de Witt and McGrew, 1979).

The Late Mississippian carbonates are exposed in a narrow northeast-southwest outcrop belt in eastern Kentucky along the eastern margin of the Cincinnati Arch (Figs. 1 and 2). The units thicken and dip southeastward beneath the overlying Late Carboniferous siliciclastics, and are exposed again in narrow, northeast-southwest trending outcrop belts in the eastern Appalachian Plateau and Valley-and-Ridge Provinces.

The Appalachian foreland basin was tectonically active during the deposition of these Late Mississippian carbonates. This is evident by the rapid thickening of the Mississippian rocks into the foredeep in southwestern Virginia and Tennessee (Figs. 1 and 2). The depocenter of the Late Mississippian carbonate ramp is located in the Greendale Syncline, southwestern Virginia, where Mississippian units thicken to over 2000 meters of basinal, slope, and ramp-margin facies, and is one of the best preserved, and most fossiliferous exposed Mississippian successions in North America (Cooper, 1948; Bartlett and Webb, 1971).

Several synsedimentary positive structures occur in West Virginia and eastern Kentucky (Yeilding and Dennison, 1986; Dever et. al., 1990; Sable and Dever, 1990; Dever, 1995). Faults, arches and domes active during the Mississippian resulted in rapid thickness changes across downdropped blocks, and thinning and erosion over highs.

The Irvine-Paint Creek Fault System (Fig. 2A) separates a southern down-dropped block from a northern block which resisted subsidence (Dever, 1986, 1995). The southern down-dropped block is marked by an abrupt thickening of the Ste. Genevieve to "Warix Run" interval southward across the extended west-to-east trend of the Irvine-Paint Creek fault system (Dever, 1986, 1995).

The Perry County uplift in eastern Kentucky (Mac Quown and Pear, 1983) is associated with a gravity anomaly interpreted as a basement high (Fig. 2A), and the Paint Creek uplift of Dohm (1963) is east of the southern extension of the Early Paleozoic Waverly Arch of Woodward (1961) (Fig. 2A).

The Cincinnati Arch (Figs. 1 and 2A), which borders the western edge of the basin, resisted subsidence in Mississippian Chesterian time, to form a broad arch between the Appalachian and the Illinois Basins. The Jessamine (Lexington) Dome in central Kentucky and the Nashville Dome in central Tennesse are separated by the Cumberland Saddle in south-central Kentucky along the trend of the Cincinnati Arch (Pryor and Sable, 1974; deWitt and McGrew, 1979; Whitehead, 1984; Sable and Dever, 1990; Dever, 1995; Smith, 1996; Khetani, 1997). The Cumberland Saddle was a passageway between the Appalachian and Illinois Basins during the Chesterian. A smaller arch, the Waverly Arch in northeastern Kentucky (Woodward, 1961; Ettensohn 1975, 1980) also was active in the Mississippian (Fig. 2A). The study interval is eroded on the flanks of the Waverly Arch and absent over the axis of this structure (the "Apical Island" of Ettensohn, 1975).

The Greenwood Anomaly is a gravity anomaly over a possible basement high in southeastern Kentucky (Fig. 2A) (Dever et. al., 1990). The area of the Greenwood anomaly resisted subsidence in Early Chesterian time to form a local disconformity. The West Virginia Dome was a positive structure along the 38th parallel lineament in northeastern West Virginia, which was active during Early Chesterian time (Yeilding and Dennison, 1986).

Stratigraphy

The regional stratigraphy of the Mississippian in the study area is given in Butts (1922, 1940, 1941), Reger (1926), Wells (1950), McFarlan & Walker (1956), Pryor and Sable (1974), de Witt & McGrew (1979), Rice et. al. (1979), Maples and Waters (1987), and Sable and Dever (1990) (Figs. 3A and 3B). The top of the Devonian-Early Mississippian black shale forms a regional basal marker to the Mississippian interval, that is distinctive on well-logs and in outcrop. The Mississippian/ Pennsylvanian unconformity defines the top of the Mississippian interval at the base of the Pennsylvanian siliciclastics. The black shales are overlain by the Price/Borden delta system, whose seaward shelf margin forms the northeast-southwest trending Borden front bounded by the 20 to 200 m Borden isopachs (Whitehead, 1984, Sable and Dever, 1990). The Price/Borden siliciclastics are unconformably overlain down-dip by the Ft. Payne-Salem carbonates, which pinch out onto the Borden delta (Sable and

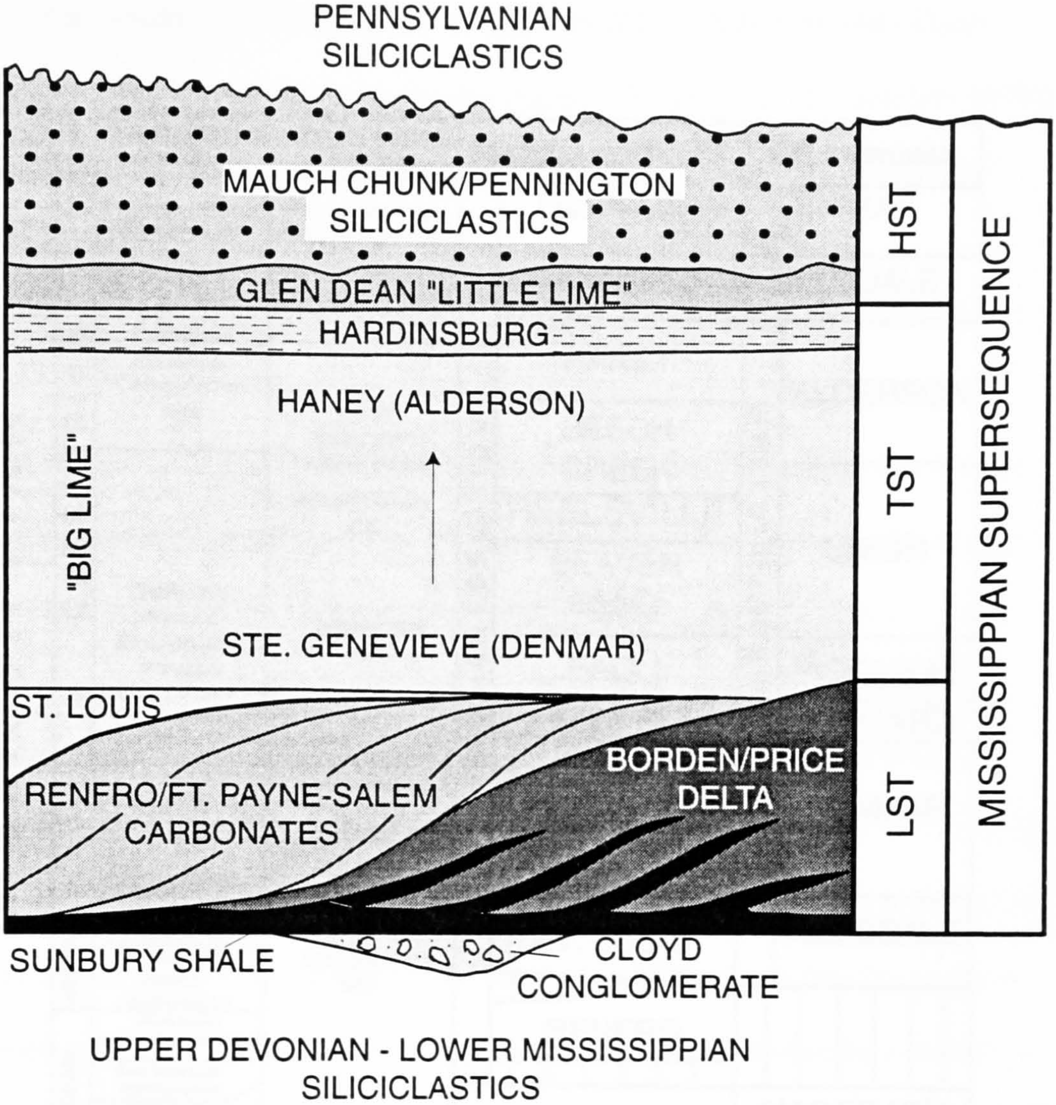


Fig. 3A Generalized diagram of the Mississippian supersequence showing the Cloyd-to Salem lowstand interval, overlain by the St. Louis-to Glen Dean transgressive units (study interval). The late Mississippian Mauch Chunk siliciclastics are the prograding highstand of the super-sequence.

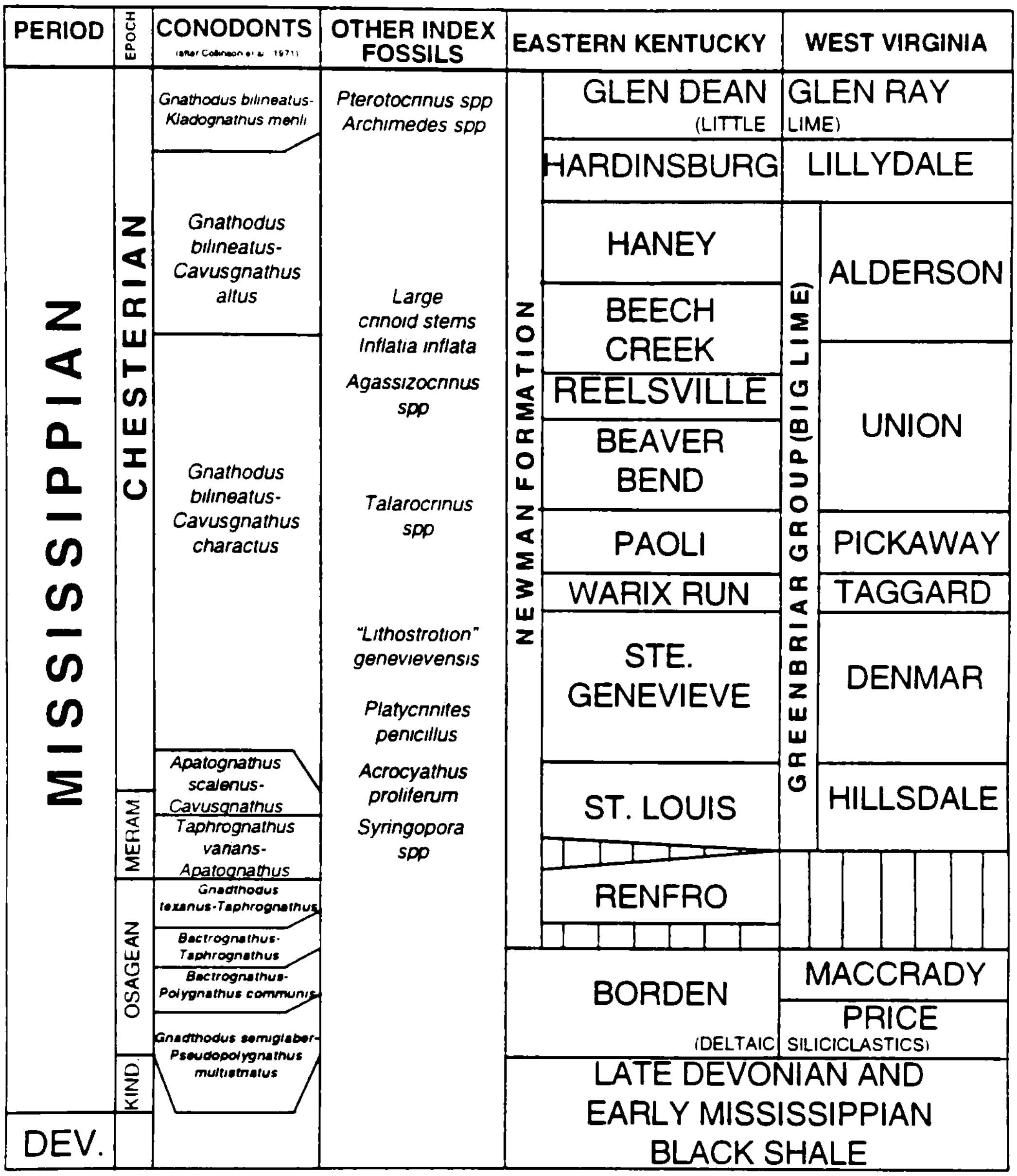


Fig. 3B Biostratigraphy and correlation chart of Mississippian rocks (modified from de Witt and McGrew, 1979; Ettensohn et. al., 1984; Sable and Dever, 1990).

Dever, 1990; Khetani, 1997). This is overlain by the St. Louis to Glen Dean interval (0 to 1000 m thick) studied in this paper. These units are overlain by the Late Mississippian Pennington/Mauch Chunk siliciclastics, whose top is the major Mississippian-Pennsylvanian unconformity.

St. Louis/Hillsdale Formations: The St. Louis Formation (Butts, 1922, 1940, 1941; Swann, 1963; Reger, 1926; Wells, 1950) generally is a very cherty, pelletal/peloidal and skeletal packstone/wackestone with the distinctive corals Syringopora and Acrocyathus proliferus (Lithostrotionella); oolitic units locally may develop in the unit in eastern Kentucky. In the up-dip area, the St. Louis Formation onlaps and overlies the Borden Delta. Further south, the St. Louis Formation unconformably overlies the Renfro/Salem Formations. In West Virginia, the St. Louis equivalent is the Hillsdale Limestone, which unconformably overlies the Maccrady red-beds. The St. Louis Limestone is overlain by the Ste. Genevieve/Denmar Formation. The top of the St. Louis Formation in northern Kentucky is a major disconformity, marked by caliche breccia and paleo-sinkholes (Ettensohn, 1975, 1980; Ettensohn et. Al., 1988). In southern Kentucky, the top of the St. Louis Formation generally is conformable with the oolitic Ste. Genevieve Formation. The St. Louis Formation is onlapped by successively younger formations (Ste. Genevieve, "Warix Run", Paoli, and Cave Branch Formations) from south to north. The St. Louis Formation is generally absent east of the Waverly Arch in northeastern

Kentucky (Ettensohn 1975,1980) and in northeastern West Virginia (Reger, 1926; Wells, 1950).

The top of the St. Louis/Hillsdale Formation is paraconformable with the overlying Ste. Genevieve/Denmar formations, and is marked biostratigraphically by the last appearance Acrocyathus (Lithostrotionella), the conodont Aptognathus sclanus. The conodont Gnathodus bilineatus first appear in the Ste. Genevieve Formation.

Ste. Genevieve/Denmar Formation: This unit consists of oolitic grainstone, thin-bedded skeletal wackestone/mudstone, and minor quartz-peloidal grainstone, with numerous exposure surfaces marked by caliche and lithoclastic breccia, that die out down-dip. Down-dip, it has abundant skeletal packstone and grainstone along with thick units (up to 8 m) of dolomitized laminated carbonate mudstone. It is dominated by thick, evenly and thinly laminated-to rippled marl (up to 80 m) and thinner skeletal grainstone tongues (3 m) along the seaward basin margin. The base of the Ste. Genevieve/Denmar Formations is placed at the base of the first oolitic unit above muddy carbonates of the St. Louis interval. The top of the Ste. Genevieve is a disconformity that is coincident with the last appearance of the crinoid Platycrinites penicillus (Butts 1922, 1940, 1941; Mc Farlan & Walker, 1956; Dever et al., 1990). This post Ste. Genevieve disconformity is overlain by eolianites along the Cincinnati Arch in Kentucky. In West Virginia, the top of the Ste. Genevieve/Denmar interval is marked by the widespread Taggard red-beds. The Ste. Genevieve Formation is absent in the northern upthrown block (north of the Irvine-Paint Creek Fault System) in eastern Kentucky (Butts, 1922). The Ste. Genevieve is relatively thin along the Cincinnati Arch in eastern Kentucky (0 to 20 m), but thickens to over 300 m in the Appalachian Basin.

"Warix Run" and Taggard Formations: The Warix Run Formation (Ettensohn et. al., 1984) is a cross-bedded quartzose peloidal grainstone that generally lacks whole, in-situ fossils, and contains several paleosol horizons. The upper quartz peloidal (eolianite) facies of the Ste. Genevieve on the southern block has been named "Warix Run" (Dever et. al., 1990, Dever, 1995). However, this facies is older than the type Warix Run, and the name thus should not be used for the upper Ste. Genevieve units (Dever, pers. Com., 1998). The "Warix Run" Formation is restricted to the southern block along the Cincinnati Arch in eastern Kentucky, where it rests unconformably on the Ste. Genevieve Formation and is unconformably overlain by the Paoli Formation.

The correlative Taggard Fm. is a thin red shale and siltstone 0 to 30 m thick unit in eastern West Virginia and Pine Mountain, eastern Kentucky. It rests on the Denmar (Ste. Genevieve) Formation (Reger, 1926; Wells, 1950) and pinches-out downdip into marine carbonates, quartz peloidal grainstone (eolianites), and quartz sandstone.

Paoli to Haney/Gasper: This interval consists of oolite and skeletal limestone rich units (and subordinate carbonate mudstone). In Kentucky, this interval overlies the Warix Run Member and includes the Paoli Formation (with the crinoid index fossil Talarocrinus); the Beaver Bend Formation; Reelsvile-to-Beech Creek Formations (with distinctive unidentified large crinoid columnals; Mc Farlan and Walker, 1956); and the Haney Formation. In Virginia, this interval is named the Gasper (Butts, 1940, 1941), and in West Virginia it is subdivided into the Pickaway, Union, and Alderson Formations (Reger, 1926).

In Kentucky, the Paoli to Haney interval contains regionally traceable disconformities. In West Virginia and Virginia, the disconformities are limited to up-dip areas, while down-dip, semi-regional red-beds, fine-grained quartz sandstone, and thin marine shales bound the carbonate units. Along the deeper basin margin, dark gray skeletal wackestone interfingers with tongues of laminated marl.

Hardinsburg/Lillydale Formations: The Hardinsburg Formation is a gray shale with minor brachiopods and bryozoans along the Cincinnati Arch and the Pine Mountain belt, where it forms the regionally traceable marker (up to 3 meters thick). In West Virginia, this unit is the Lillydale Shale (Reger, 1926), which thickens to up to 40 meters in the south. In the basin, the Lillydale Shale includes the Fido Sandstone and the overlying deep water laminated carbonate muds of the basal Cove Creek Formation (Butts, 1940, 1941).

Glen Dean/Glen Ray Formations: In Kentucky, a regionally traceable argillaceous skeletal limestone, the Glen Dean Formation (up to 10 meters thick) outcrops both along the Cincinnati Arch, and in the Pine Mountain thrust belt. Disconformities within the unit are restricted to the Pine Mountain belt, where they are associated with minor oolite and eolianite quartz peloidal grainstone. In West Virginia, the correlative unit is the Glen Ray Limestone (Reger, 1926), which is a relatively discontinous unit up to 15 m thick of cross-bedded oolitic grainstone, skeletal limestone, and local boundstone units above the Lillydale shale.

Paragon-to Pennington Formations/lower Mauch Chunk Group: Siliciclastic sandstone, gray shale, and minor limestone of the Paragon-to Pennington Formation overlie the Glen Dean Formation in Kentucky. In West Virginia, the equivalent units are the lower Mauch Chunk Group (Bluefield Formation), which contains abundant red siltstone and mudrock. The top of the Pennington-Mauch Chunk is the major Mississippian-Pennsylvanian unconformity.

CHAPTER THREE

MISSISSIPPIAN FACIES

Late Mississippian carbonate platform in the Appalachian Basin formed a gradual transition from shallow to deep marine facies without a marked break in slope to form a homoclinal ramp (Ahr, 1973; Read, 1985). The facies developed are shown on an idealized ramp model (Fig. 4). The regional distribution of facies in West Virginia and Kentucky are shown in Figures 5 and 6. Facies comprising the Mid to Late Mississippian succession of the Appalachian Basin are summarized in Tables 1 and 2. These ramp carbonates consist of a complex mosaic of facies, in which individual facies are laterally discontinuous. Up-dip, sections are dominated by shallow water facies whereas down-dip sections are dominated by deeper water facies, but minor shallow water units are developed even on the ramp-margin. The ramp margin in southeastern West Virginia (sections 9 and 10, Fig. 5) is defined based on the drastic thickening southward into the foredeep in Virginia (section 11, Fig. 5), and based on the transition from shallow-ramp and skeletal bank facies into deep marine skeletal wackestones and basinal marls (Figs. 4 and 5). Sequences in the succession are disconformable and bounded by paleosols in up-dip areas, and are conformable down-dip, where they are bounded by flooding surfaces.

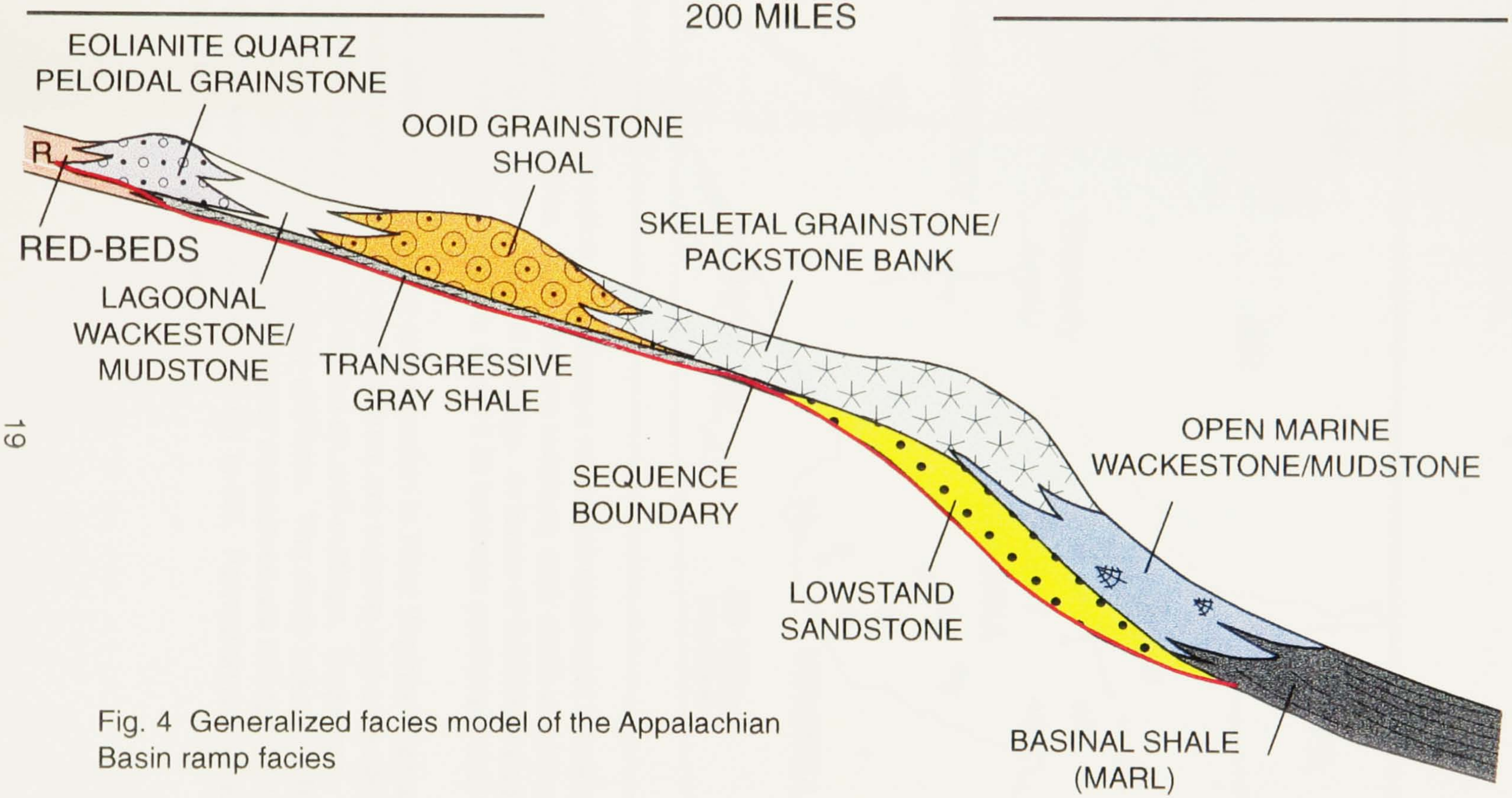


Fig. 4 Generalized facies model of the Appalachian Basin ramp facies

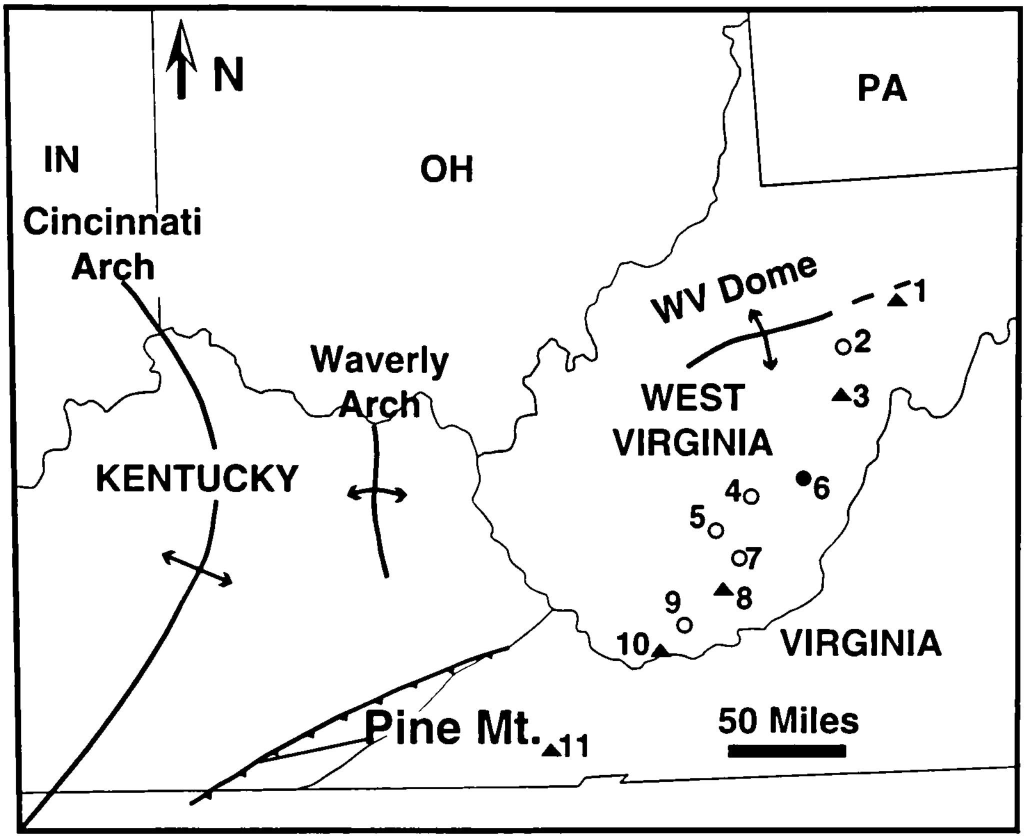


Fig. 5A Section location map along a northeast-southwest traverse, West Virginia/Virginia. Triangles are outctops, dark circle is a biscuited core, and open circles are well cuttings. In terms of thickness and position on the ramp, sections 4 and 5 lie between sections 3 and 6.

Fig. 5B Detailed interpretive cross-section in West Virginia/Virgina (on following page). Heavy vertical lines are outcrop and core sections, thin vertical lines are sections based on well-cuttings. Sequence boundaries are marked by heavy red lines. The study interval is from the Hillsdale to Glen Ray, the Denmar sequences are labeled D1 to D5, the Gasper sequences are labeled G1 to G5. Formation names are shown within the cross-section.

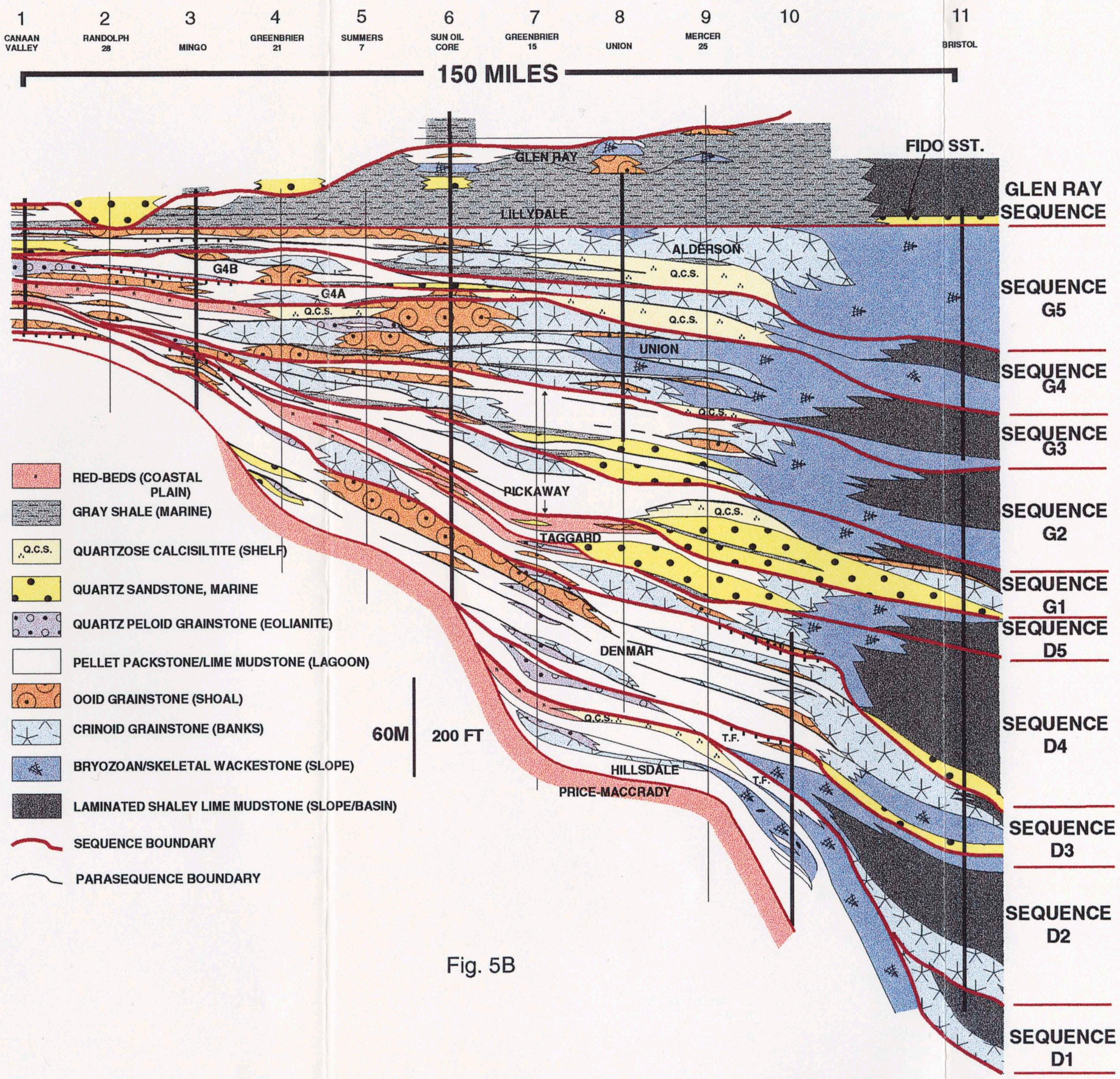

1
CANAAN VALLEY
2
RANDOLPH 28
3
MINGO
4
GREENBRIER 21
5
SUMMERS 7
6
SUN OIL CORE
7
GREENBRIER 15
8
UNION
9
MERCER 25
10
11
BRISTOL
150 MILES
FIDO SST.
GLEN RAY
LILLYDALE
ALDERSON
Q.C.S.
G4B
G4A
UNION
PICKAWAY
TAGGARD
DENMAR
HILLSDALE
PRICE-MACCRADY
T.F.
GLEN RAY SEQUENCE
SEQUENCE G5
SEQUENCE G4
SEQUENCE G3
SEQUENCE G2
SEQUENCE G1
SEQUENCE D5
SEQUENCE D4
SEQUENCE D3
SEQUENCE D2
SEQUENCE D1
60M
200 FT
RED-BEDS (COASTAL PLAIN)
GRAY SHALE (MARINE)
QUARTZOSE CALCISILTITE (SHELF)
QUARTZ SANDSTONE, MARINE
QUARTZ PELOID GRAINSTONE (EOLIANITE)
PELLET PACKSTONE/LIME MUDSTONE (LAGOON)
OOID GRAINSTONE (SHOAL)
CRINOID GRAINSTONE (BANKS)
BRYOZOAN/SKELETAL WACKESTONE (SLOPE)
LAMINATED SHALEY LIME MUDSTONE (SLOPE/BASIN)
SEQUENCE BOUNDARY
PARASEQUENCE BOUNDARY

Fig. 5B

Table 1. Paleosol and Siliciclastic Facies

Facies & Dep. Env.	**Coated peloidal pkstn. (Subaerial)**	**Laminar caliche (Subaerial)**	**Fitted fabric breccia & lithoclasts (Subaerial)**	**Siliciclastic paleosols and red-beds (Subaerial to Shallow Marine)**	**Gray shale (Shallow Marine)**	**Quartz sandstone (Shore -face)**	**Quartzose calcisiltite (open shelf)**	**Calcareous quartz sandstone (Deep marine)**
Lithology	Quartzose peloid packstone	Laminar carbonate crust (Caliche)	Granule to pebble breccia	Mudrock	Shale	Calcareous medium-to fine quartz sandstone	Quartzose calcisiltite	Fine-grained calcareous quartz sandstone
Color	Dirty gray-to brown	Light gray to brown	Gray to dirty gray	Red, maroon and green mottled	Gray	Tan-to light gray	Tan	Light gray-to tan
Texture	Poorly sorted, rounded, medium-grained	Rooted fabric in laminar calcite crusts and joint/fracture fills	Angular-to subangular (less commonly rounded), poorly sorted granule-to pebble and fitted fabric breccia	Clay and silt	Clay and silt	Well-sorted medium-to fine-grained	Well-sorted silt-size quartz and silt-size carbonate mud	Mostly fine, subangular, well sorted quartz, and lesser fine rounded carbonates
Composition	Quartz and peloids	Calcite, commonly silicified	Carbonate and siliciclastic grains and clasts from the host or underlying lithology	Siliciclastic muds	Siliciclastic muds	Mostly quartz and lesser peloids	Quartz and carbonate silt	Quartz (> 50 %) and pellets/peloids
Sedimentary Structures	Structureless	Wavy lamination, rootlet casts, incipient brecciation	Structureless to fitted fabric breccias	Rare wave ripples in red-beds. Slickensides, teepee structures, and rooted fabrics in paleosols	Poorly fissile, laminated	Cross-bedded to structureless	Festoon cross-bedded and wave- rippled, to thinly bedded to structureless	Commonly structureless, rarely thinly laminated
Fossils	None	Rootlet traces	None	Root burrow traces in paleosols	Scarce brachiopods and bryozoa	None	None	None
Diagnostic features	Dirty gray to brown to green color, coated grains	Brown to gray laminar calcite crusts rooted fabrics, silicification	Breccia from underlying beds	Red-beds, rare wave-ripples, paleosols with rooted fabric, slickensides.	Sparcely fossiliferous gray shale	Cross-bedded calcareous quartz sandstone	Cross-beeded, rippled and flat- bedded quartzose calcisiltite	Structureless, fine-grained calcareous quartz sandstone associated with basinal facies

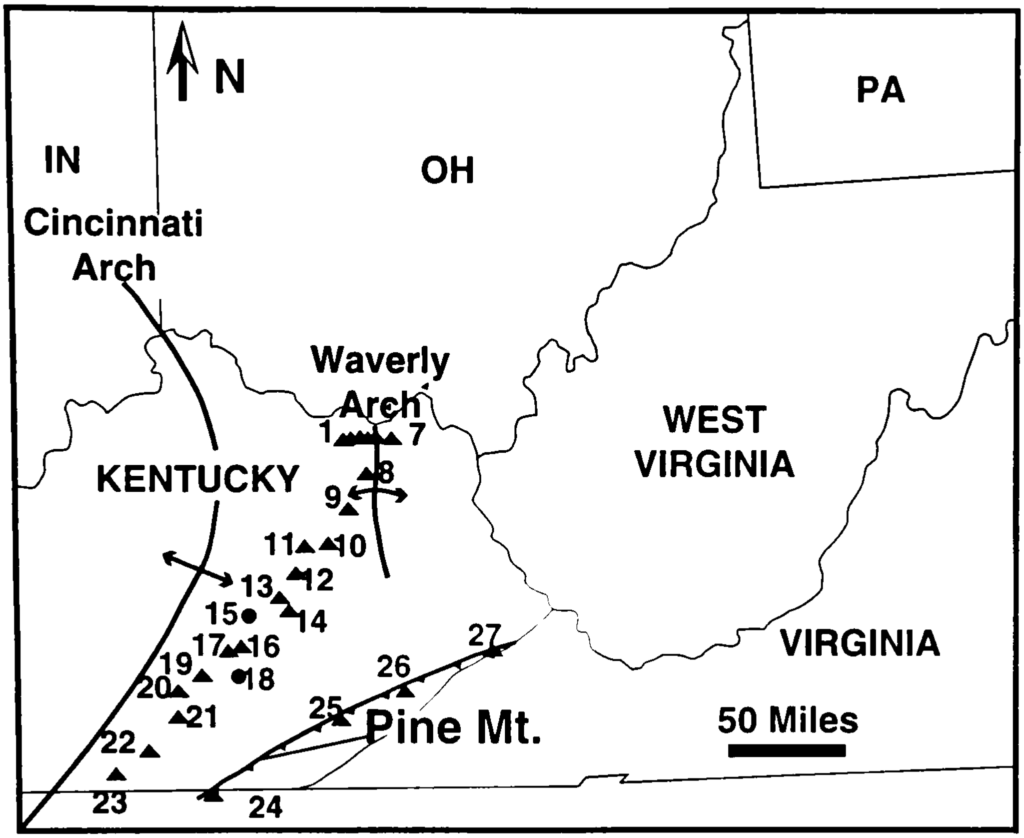


Fig. 6A Section location map in eastern Kentucky. Triangles are outcrop sections, dark circles are cores. Sections 1 to 7 form an west-east traverse across the Waverly Arch. Sections 7 to 23 form a northeast-southwest traverse along the Cincinnati Arch, and sections 24 to 27 form a southwest-northeast traverse along the Pine Mountain Thrust.

Fig. 6B Detiled interpretive cross-section in eastern Kentucky (On following page). Vertical lines are section locations, heavy red lines are sequence boundaries, which are mapped over hundreds of miles in the basin. The interval of study is the St. Louis to Glen Dean, sequences are assigned names same as the formation names.

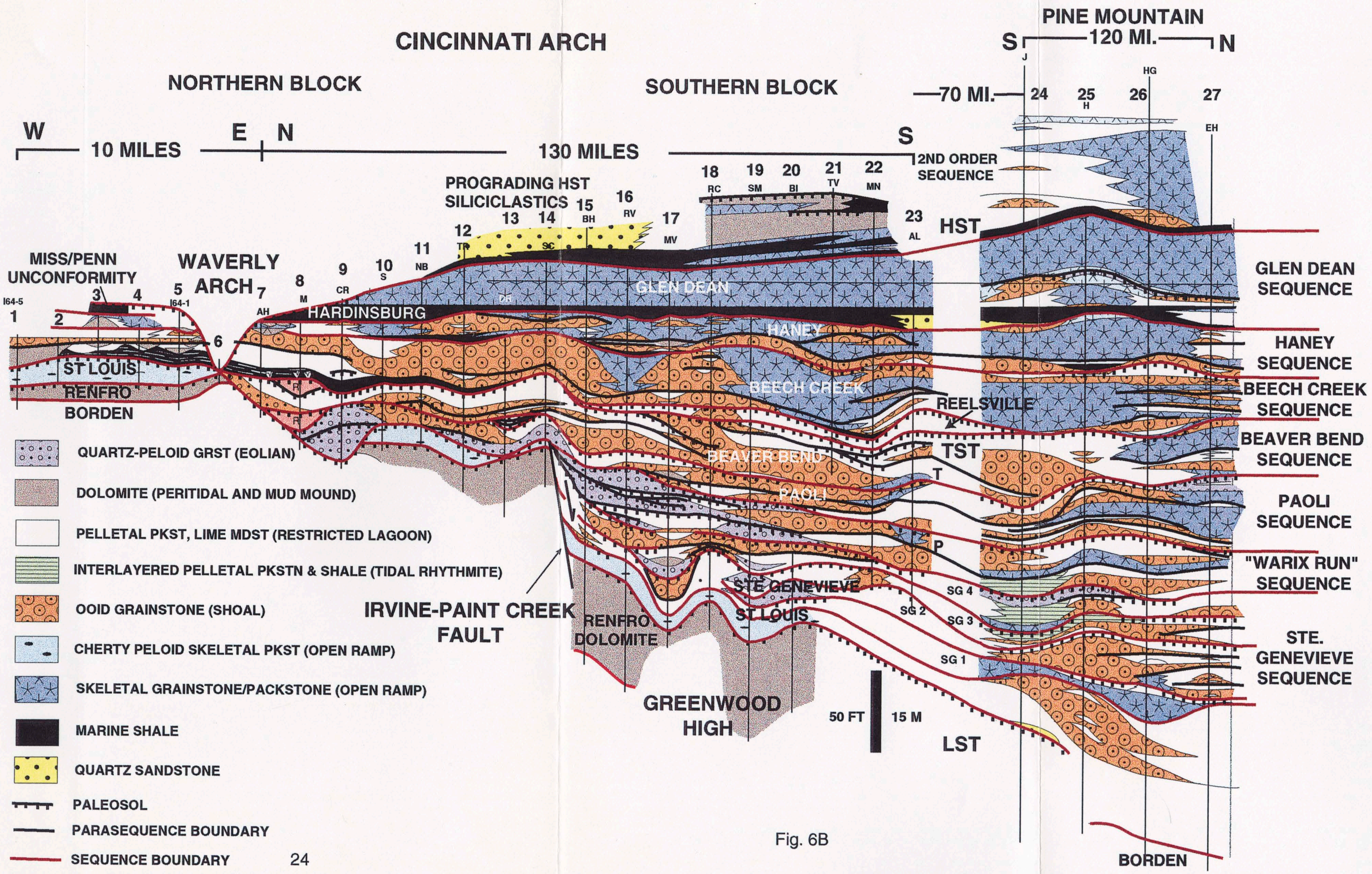

CINCINNATI ARCH
NORTHERN BLOCK
SOUTHERN BLOCK
PINE MOUNTAIN
S
120 MI.
N
W
10 MILES
E
N
130 MILES
S
70 MI.
2ND ORDER SEQUENCE
PROGRADING HST SILICICLASTICS
MISS/PENN UNCONFORMITY
WAVERLY ARCH
1 I64-5
2
3
4
5 I64-1
6
7 AH
8 M
9 CR
10 S
11 NB
12 TR
13
14 SC
15 BH
16 RV
17 MV
18 RC
19 SM
20 BI
21 TV
22 MN
23 AL
24 J
25 H
26 HG
27 EH
HST
TST
T
P
LST
GLEN DEAN
HARDINSBURG
DB
HANEY
BEECH CREEK
REELSVILLE
BEAVER BEND
PAOLI
STE GENEVIEVE
ST LOUIS
RENFRO
BORDEN
RENFRO DOLOMITE
GREENWOOD HIGH
IRVINE-PAINT CREEK FAULT
SG 1
SG 2
SG 3
SG 4
50 FT
15 M
GLEN DEAN SEQUENCE
HANEY SEQUENCE
BEECH CREEK SEQUENCE
BEAVER BEND SEQUENCE
PAOLI SEQUENCE
"WARIX RUN" SEQUENCE
STE. GENEVIEVE SEQUENCE
BORDEN
QUARTZ-PELOID GRST (EOLIAN)
DOLOMITE (PERITIDAL AND MUD MOUND)
PELLETAL PKST, LIME MDST (RESTRICTED LAGOON)
INTERLAYERED PELLETAL PKSTN & SHALE (TIDAL RHYTHMITE)
OOID GRAINSTONE (SHOAL)
CHERTY PELOID SKELETAL PKST (OPEN RAMP)
SKELETAL GRAINSTONE/PACKSTONE (OPEN RAMP)
MARINE SHALE
QUARTZ SANDSTONE
PALEOSOL
PARASEQUENCE BOUNDARY
SEQUENCE BOUNDARY

Fig. 6B

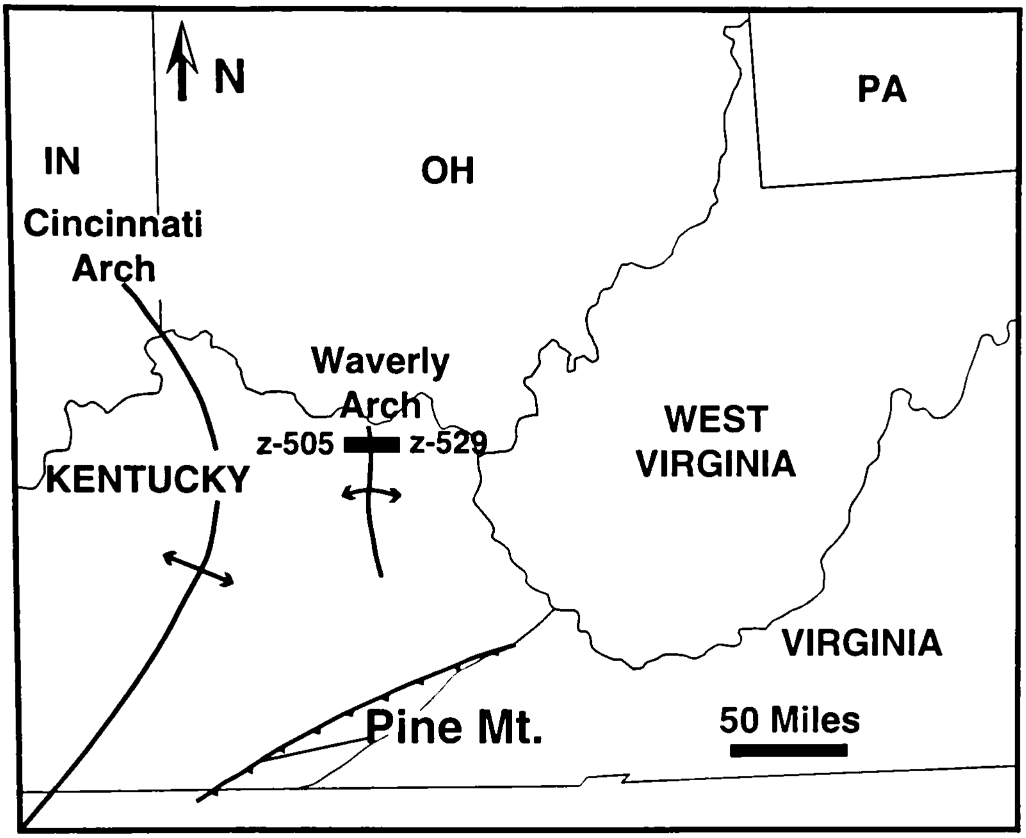


Fig. 6C Location map for the west-east traverse across the Waverly Arch. Original detailed stratigraphic study done by Ettinsohn (1975, 1980), section numbers z-505 to z-529 are those of Ettensohn (1975).

Detailed interpretive cross-section of the west-east traverse across the Waverly Arch, eastern Kentucky (on following page). Vertical lines are outcrop section locations. Sections labeled 1 to 7 are the same as those in Figure 6. Section 7 is also known as the Armstrong Hill section.

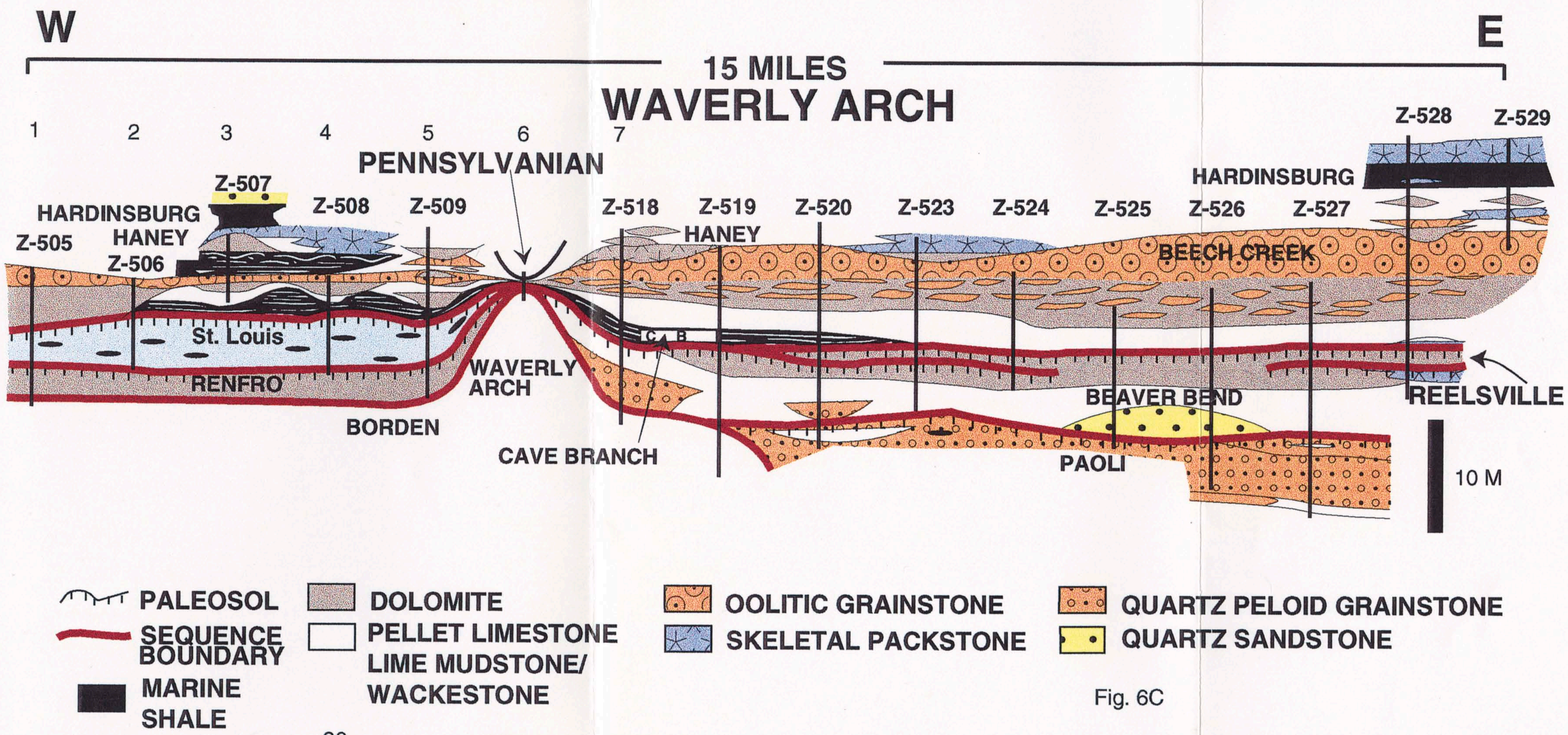

W
E
15 MILES
WAVERLY ARCH
1
2
3
4
5
6
7
PENNSYLVANIAN
Z-505
Z-506
Z-507
Z-508
Z-509
Z-518
Z-519
Z-520
Z-523
Z-524
Z-525
Z-526
Z-527
Z-528
Z-529
HARDINSBURG
HANEY
HANEY
HARDINSBURG
BEECH CREEK
St. Louis
RENFRO
BORDEN
WAVERLY ARCH
CAVE BRANCH
C
B
BEAVER BEND
PAOLI
REELSVILLE
10 M
PALEOSOL
SEQUENCE BOUNDARY
MARINE SHALE
DOLOMITE
PELLET LIMESTONE
LIME MUDSTONE/ WACKESTONE
OOLITIC GRAINSTONE
SKELETAL PACKSTONE
QUARTZ PELOID GRAINSTONE
QUARTZ SANDSTONE

Fig. 6C

Paleosols

In the Appalachian basin, carbonate paleosols (Table 1) mark disconformity-bounded sequences and up-dip parts of parasequences, and have been described by Dever (1973), Ettensohn (1975), Harrison and Steinen (1978), Niemann and Read (1987), Ettensohn et al. (1988), and Dever et al. (1990). They include incipient, coated-grain packstone paleosols, laminar caliches, breccias, and tepeed horizons.

Coated Peloidal Packstone: Poorly sorted, quartzose, gray to brown, coated grained peloid packstones form thin paleosol horizons at exposure surfaces. They are relatively subtle features, highlighted by a pale brownish color, and coated-grain packstone fabrics, along with small carbonate nodules and scattered lithoclasts. They resemble incipient soils on carbonate grainstones from seasonally wet-dry climate settings (Read, 1974).

Laminar Caliche (Calcrete): These form brown laminar caliche crusts (Fig. 7a) on host rock and fissure-fills, which are composed of cryptocrystalline calcite, and they commonly show rootlet fabrics. Sediments beneath caliche horizons commonly are silicified. Well developed, mature paleosols, which are common up-dip, have multiple, subhorizontal millimeter-to decimeter crusts that extend downward up to a meter below the exposure surface. Such mature profiles are especially common on the St. Louis unconformity on the northern block, eastern Kentucky (Ettensohn et. al., 1988). Down-dip, soils have thin decimeter-to centimeter laminar crusts at or just below the exposure surface. Crusts may be associated with fitted-fabric breccia, tepees, lithoclasts, residual clay units, and a brown-to-dirty gray discoloration of the host rock.

Laminar caliche crusts form in semi-arid or seasonally wet-dry climate. The aquifer was recharged during the humid season, and the water underwent capillary rise toward the exposure surface during the dry season (Price, 1925; Chilinger et. al., 1967; Reeves, 1976; Harrison and Steinen, 1978; Ettensohn et. al. 1988). The caliche calcite was precipitated beneath thin soils and along joints and fractures in the cemented host to form the laminar crusts. Many of these thin soils commonly were stripped during the subsequent transgression.

Breccias and Reworked Lithoclastic Sheets: In-situ pedogenic breccias with fitted fabrics (Fig. 7a) are developed on a variety of host carbonates including wackestone/mudstone, pelletal mudstone, and laminated caliches. The breccias occur in zones up to a meter thick, and commonly are discontinuous. They commonly are associated with laminar caliche crusts, tepees, lithoclasts, and residual clay. This type of brecciation is due to the pedogenic break-up of the host rock below the surface of exposure.

Reworked Lithoclastic Units: These consist of yellow-to-brown lithoclastic carbonates eroded from the exposed host rock beneath the disconformity surface, to form a basal sheet of angular to rounded clasts, and variable amounts of quartz grains, at the base of the overlying marine unit. Reworked units overlie caliche crusts, breccia, and tepees and occur within or cap residual

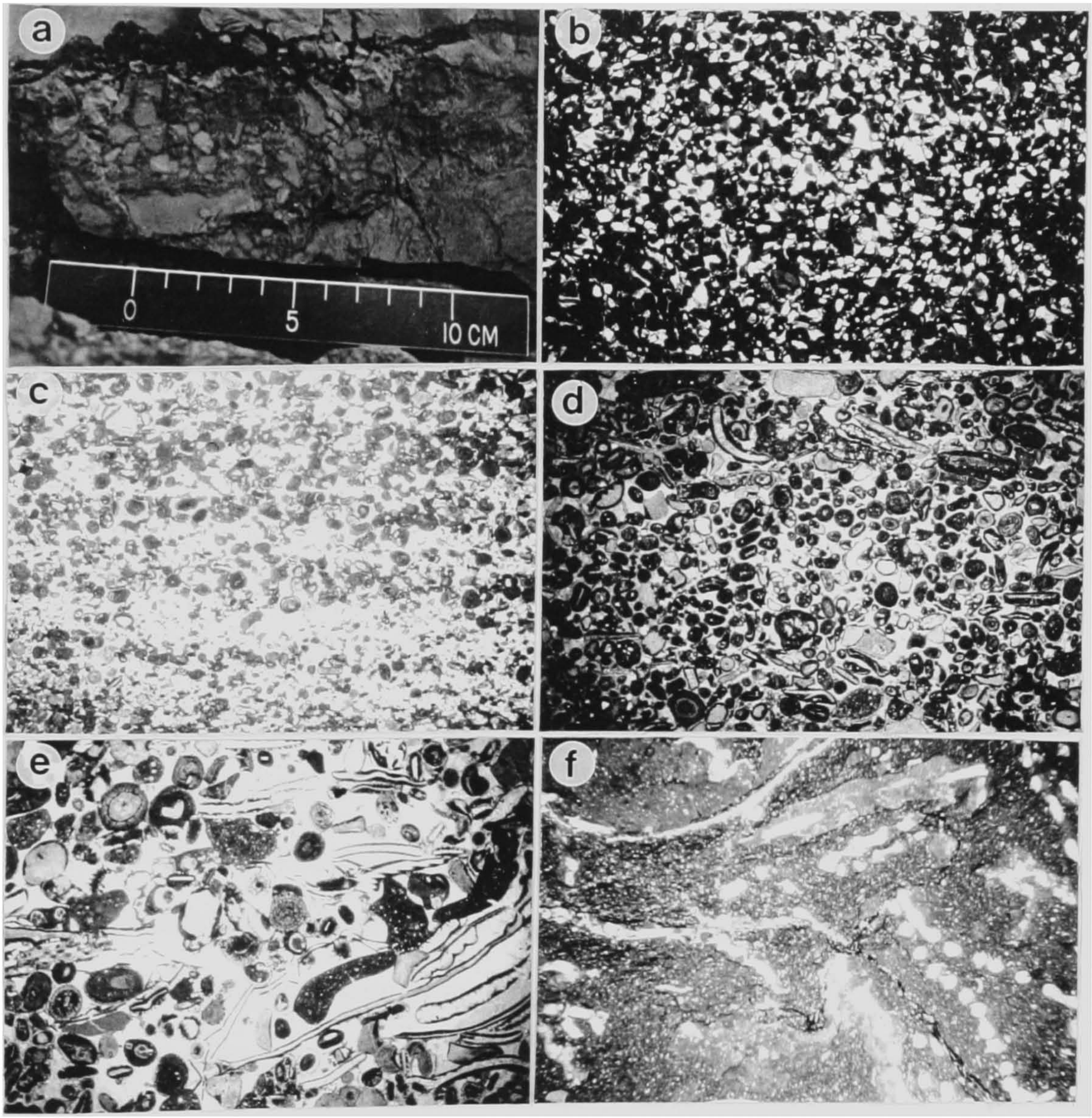


Fig. 7 Photomicrographs of main rock types. a) Rooted caliche with fitted fabric breccia (disconformity/sequence boundary); b) fine calcareous quartz sandstone (lowstand sand) ; c) quartz peloid grainstone (eolianite); d) ooid grainstone (shoal); e) skeletal grainstone (high energy bank); f) skeletal (bryozoan) wackestone (slope to basin carbonates).

green clay units. Lithoclastic units define reworked tops of exposure profiles, which may contain multiple caliche and breccia horizons.

Karst Surfaces and Residual Clay Sheets: The karst surfaces are irregular; locally scalloped surfaces with sinkholes that may be filled by green clays and commonly are developed above laminar/brecciated units (Ettensohn et. al., 1988). Sinkholes may be up to a few decimeters wide and deep, but generally relief is a few centimeters. Exposure surfaces commonly are overlain by a thin, green to gray, unfossiliferous, centimeter-to-decimeter thick clay veneer, which may include lenses of lithoclastic breccia. These overlie, and are infiltrated into the underlying unit, and may be capped by a lithoclastic breccia at the base of the overlying marine unit. These karst surfaces were formed due to the dissolution of the host marine limestone under humid climate. These were developed on exposure surfaces that lack semi-arid climatic indicators as on the top Beech Creek disconformity on the northern block in Eastern Kentucky. Other karstic surfaces overprinted previously formed semi-arid paleosols as on the top St. Louis unconformity on the northern block of eastern Kentucky (Ettensohn, 1975, 1980; Ettensohn et. al, 1988). The residual clay veneers formed by accumulation of in-situ or transported residual clays weathered from the host carbonates, and carried to the site of deposition by sheet-wash during floods.

Siliciclastic Paleosols: These are red, maroon and green mottled and nodular mudrock, with slickensides, tepee structures up to a few meters wide, and rooted fabrics. Siliciclastic paleosols occur in up-dip areas associated with marginal marine, red-beds that fill incised valleys on the upper bounding unconformities of the Paoli and Beaver Bend Sequences on the northern, upthrown block, Kentucky (Fig., 5; Section 8).

Siliciclastic Units

Red-Beds (Marginal-Marine): These are red, commonly structureless, unfossiliferous, fine siliciclastic, mudrocks and laminated shale (Table 1). Up-dip in West Virginia, ripple-and wave-laminations and mud-cracks are common, but burrows are rare. Some red-beds have rooted paleosol burrows. The red-beds are common in up-dip areas, where they are associated with eolianites, restricted lagoonal and shoal water grainstones. In Kentucky, these fill incised valleys in up-dip areas. These up-dip facies are marginal marine to intertidal-supratidal red-beds, which formed as highstand, basinward shifting facies at the same time as the disconformities along the Cincinnati Arch in eastern Kentucky.

Gray Shale, Quartz Sandstone and Quartzose Calcisiltite (Tidally Influenced Open Siliciclastic Shelf): Regionally traceable dark gray, poorly fissile, limy shale with sparse small productid brachiopods and rare bryozoa (Table 1) overlie pyritized bedding planes showing abundant lacy bryozoans at the top Haney/Alderson and the Glen Dean Formations. They range from a few centimeter thick units that pinch out laterally, thickening into extensive sheets up to 30 m thick (e.g. Lillydale Shale) on the ramp margin in West Virginia, where they grade up into argillaceous, skeletal limestones. These shales are quiet water, fine siliciclastics, that formed shoreward of open marine limestone during basinward shifts of siliciclastics. High siliciclastic influx may have been due to more humid climate, perhaps coupled with short-term sea-level lowering. This increased turbidity suppressed the carbonate productivity on the ramp, generating wide-spread shale deposits.

Quartz sandstone units (Fig. 7b) up to four meter thick occur locally in the lower Hartselle/Hardinsburg Shale of southeastern Kentucky. The sandstone units show even-to irregular flaser, lenticular-and wavy bedding with mud-drapes. Such sands are rare in south-central Kentucky, but are more abundant west of the Cincinnati Arch (Smith, 1996). The sands contain sedimentary structures indicative of deposition in tidal channels or bars under tidal-current influence, below storm wave-base. The sands likely were sourced from the north or northeast, or they could have entered from the Illinois Basin across the Cumberland Saddle.

Cross-bedded, quartzose calcisiltite are festoon cross-bedded-to wave-ripple cross laminated, unfossiliferous units (Table 1). These form units up to 10 meters thick along the ramp margin in West Virginia. The quartzose calcisiltites contain sedimentary structures which suggest a high energy wave and current influenced setting on the outer ramp, where there was a high fine siliclastic influx and where suppressed carbonate productivity was limited to deposition of carbonate silt from nearby shallow areas of the platform.

Eolianites and Beach Facies

Quartzose Peloidal Grainstone (Coastal Eolianites): These generally are very fine to fine (and less commonly medium) quartzose peloidal grainstone composed of well rounded grains that include peloids, rare ooids, skeletal fragments, along with finer grained subangular quartz grains concentrated in razor sharp layers (Fig. 7c). They lack in-situ biota (Table 2).

They are cross-stratified, with foresets of extremely planar to curved, paper thin, millimeter laminae. Laminae, commonly are inversely graded (from very fine-to-fine sand), and form a characteristic pin-stripe pattern on the outcrop or in core. Where inverse grading is absent, laminae form couplets of alternating very fine-and-fine sand. Quartz-peloidal grainstones commonly are bounded by paleosols, or are interbedded with lagoonal muds and ooid grainstone, in Kentucky. Up-dip in West Virginia, they are interbedded with red-beds, lagoonal and ooid shoal facies.

These facies are interpreted as coastal eolianites on the basis of abundant quartz peloid grainstone lithology; the well rounded carbonate grain shapes; planar to curved foresets with inverse grading and very fine-to-fine sand couplets, pin-stripe lamination; and lack of in-situ fossils or burrow (Hunter 1993; Dodd et. al., 1993; Smith, 1996).

Low-Angle, Cross-bedded Grainstone (Beach Facies): These commonly make up thin (about 0.5 meter thick), poorly fossiliferous, oolitic or quartzose-peloidal grainstone, with low angle planar and slightly curved cross-beds. Foreset

Table 2. Carbonate Facies

Facies & Dep. Env.	**Coated peloidal pkstn. (Subaerial)**	**Laminar caliche (Subaerial)**	**Fitted fabric breccia & lithoclasts (Subaerial)**	**Siliciclastic paleosols and red-beds (Subaerial to Shallow Marine)**	**Gray shale (Shallow Marine)**	**Quartz sandstone (Shore -face)**	**Quartzose calcisiltite (open shelf)**	**Calcareous quartz sandstone (Deep marine)**
Lithology	Quartzose peloid packstone	Laminar carbonate crust (Caliche)	Granule to pebble breccia	Mudrock	Shale	Calcareous medium-to fine quartz sandstone	Quartzose calcisiltite	Fine-grained calcareous quartz sandstone
Color	Dirty gray-to brown	Light gray to brown	Gray to dirty gray	Red, maroon and green mottled	Gray	Tan-to light gray	Tan	Light gray-to tan
Texture	Poorly sorted, rounded, medium-grained	Rooted fabric in laminar calcite crusts and joint/fracture fills	Angular-to subangular (less commonly rounded), poorly sorted granule-to pebble and fitted fabric breccia	Clay and silt	Clay and silt	Well-sorted medium-to fine-grained	Well-sorted silt-size quartz and silt-size carbonate mud	Mostly fine, subangular, well sorted quartz, and lesser fine rounded carbonates
Composition	Quartz and peloids	Calcite, commonly silicified	Carbonate and siliciclastic grains and clasts from the host or underlying lithology	Siliciclastic muds	Siliciclastic muds	Mostly quartz and lesser peloids	Quartz and carbonate silt	Quartz (> 50 %) and pellets/peloids
Sedimentary Structures	Structureless	Wavy lamination, rootlet casts, incipient brecciation	Structureless to fitted fabric breccias	Rare wave ripples in red-beds. Slickensides, teepee structures, and rooted fabrics in paleosols	Poorly fissile, laminated	Cross-bedded to structureless	Festoon cross-bedded and wave- rippled, to thinly bedded to structureless	Commonly structureless, rarely thinly laminated
Fossils	None	Rootlet traces	None	Root burrow traces in paleosols	Scarce brachiopods and bryozoa	None	None	None
Diagnostic features	Dirty gray to brown to green color, coated grains	Brown to gray laminar calcite crusts rooted fabrics, silicification	Breccia from underlying beds	Red-beds, rare wave-ripples, paleosols with rooted fabric, slickensides.	Sparcely fossiliferous gray shale	Cross-bedded calcareous quartz sandstone	Cross-beeded, rippled and flat- bedded quartzose calcisiltite	Structureless, fine-grained calcareous quartz sandstone associated with basinal facies

laminae are a centimeter thick, commonly well sorted and of medium-to-coarse sand size grains. These are interpreted as beach facies, because they overlie subtidal facies and grade up into eolianites. Compared to the eolianites, they have slightly thicker foresets and coarser grain size, and they lack the characteristic eolianite pin-strip lamination.

Marine Facies

Fine-Grained Peritidal Carbonates (Tidal-Flat and Lagoon): These include laminated to massive muddy carbonate units (Table 2). The up-dip laminated units consist of dolomitized, millimeter laminae of alternating fine pellet/quartz silt and lime-mud, that are crinkled and disrupted by mud-cracks, and generally are unfossiliferous. This lithology is rare and mainly occurs as units up to 1.5 meters thick up-dip, which contain thin interbeds of burrowed, dolomitized pelletal packstone. Thicker-laminated, lime-mudstone/pellet packstone is common in down-dip areas. It is centimeter-layered and composed of interlayered dolomite and limestone; laminae are unfossiliferous and rarely mud-cracked. This facies forms units from 1 to 8 meters thick, interlayered with eolianite quartzose peloidal grainstones and shallow subtidal facies (lagoonal carbonate muds, shoal water oolites, and skeletal bank facies, and rare erosional exposure surfaces.

Millimeter-laminated carbonates were formed in intertidal settings beneath microbial mats (laminites) on the inner ramp. Thick-laminated dolomitized tidal-flat facies down-dip on the ramp, probably were formed by deposition of relatively thick sediment layers transported into late high-stand tidal-flats during storms reflecting high sediment supply in these areas.

Massive, fine-grained carbonate units are composed of thin-to medium-bedded, light gray pelletal packstone/lime-mudstone and skeletal wackestone with common gastropods, ostracodes, and rare small fragments of echinoderms and brachiopods (Table 2). Bedding planes locally contain abundant trace fossils.

The massive fine-grained carbonates, formed behind grainstone barriers in low energy lagoonal settings. Lack of open marine fossils, association with shallow marine facies and exposure surfaces indicate a relatively restricted, possibly hypersaline lagoonal setting. Patchily developed fine dolomitization of the laminated and massive units appear to have occurred early in peritidal settings under evaporative conditions (Niemann and Read, 1988).

Peloidal/Skeletal Packstone (Open Lagoon and Foreshoal): These facies are thin to thick bedded, light to medium gray, cherty pelletal packstone and peloid-skeletal packstone (Table 2). They generally are poorly sorted, and consist of fragmented skeletal debris of echinoderms, brachiopods, bryozoans, corals, and mollusks, as well as sand size peloids; or in finer grained facies, silt size pellets in a packstone fabric. The unit locally contains storm layers of upward fining skeletal lags, and in-situ to overturned coral heads (Acrocyathus proliferus and Syringopora sp) are common locally. Up-dip, this facies in the St. Louis Formation is bounded by unconformities, but down-dip, it grades upwards into fine grained pelletal mudstone and laterally into ooid grainstone in the Pine Mountain area. Its stratigraphic occurrence, and peloidal packstone lithology with open marine fauna suggest a foreshoal to very open marine lagoonal setting locally subjected to storms.

Oolitic Grainstone (Oolitic Shoals and Tidal Bars): These are white, cross-bedded well-sorted oolitic grainstone composed of medium sand-size ooids, intraclasts and fragmented echinoderm, bryozoa, brachiopod, and mollusk remains (Fig. 7d). They form shoals from 1 to 12 meters thick, and from a few hundred meters to several tens of kilometers long. In the subsurface, the oolites form dip-oriented northwest-to-southeast trending oolitic sand-ridges over 30 kms long and 1.4 kilometer wide, along the ramp margin (Kelleher and Smosna, 1993).

These oolitic facies (Table 2) are abundant on the inner and mid-ramp, decreasing onto the outer ramp. These units formed on high energy tide-and lesser wave-influenced oolitic shoals (Kelleher and Smosna, 1993).

Skeletal Grainstone (High-Energy, Shelf): These are medium to thick-bedded, cross-bedded to structureless, medium-to coarse-grained units (Fig. 7e). They consist of whole and fragmented crinoid, bryozoan, brachiopod, and lesser mollusk remains (table 2). In down-dip settings, the skeletal beds contain abundant whole columnals and calyxes. Skeletal grainstones in the Ste. Genevieve to Glen Dean interval form extensive sheets seaward of oolitic grainstone shoals, and grade down-dip into open marine skeletal packstone.

Along the basin margin in West Virginia/Virginia, the skeletal grainstones form units up to 16 meter thick, which interfinger with wackestone and deep-water laminated marls.

These facies up-dip are high-energy skeletal banks and sheets deposited between and seaward of ooid shoals, in wave agitated settings. Down-dip, they formed as crinoidal banks on the ramp margin.

<u>Dolomitized Mud Mounds and Bryozoan Reefs:</u> Mud mounds occur in both up-dip and down-dip areas in the St. Genevieve to Haney interval as small mounds and sheet-like bodies. Bryozoan reefs locally occur in down-dip areas in the Haney Formation. The mounds and reefs are a few meters to a few tens of meters in length and width, and up to a few meters thick.

The mud mounds are composed of structureless, dolomitized pellet packstone and skeletal wackestone/mudstone with few-to-abundant fossils, as medium to very coarse grain skeletal fragments and rare whole crinoid and bryozoans. Dolomitized mounds commonly are enclosed in undolomitized thin-bedded lagoonal mudstone/pellet packstone and oolitic shoal facies. In the Haney Formation, they occur in open shelf, thin-bedded argillaceous skeletal pellet packstone.

The bryozoan reefs are small, up to 1.5 meters thick and a few meters across. They have flat bases and mound-like, domal tops with inter-mound channels in the swales. The reefs consist of fenestrate bryozoan rudstone, bafflestone and bindstone, whereas inter-reef channel fills are crinoid-bryozoan grainstone. Bryozoan reef-flanks are made up of centimeter to decimeter interlayers of gray lime-mudstone and fenestrate bryozoan wackestone with sparse spherical to irregular algal/microbial oncoids.

Argillaceous Skeletal Limestone with Storm Beds: These are medium to thick-bedded skeletal packstone and wackestone, with thin shale partings along the bedding planes; they are gray to dark gray, and composed of medium to very coarse grained echinoderm, brachiopod and bryozoan debris with interstitial finely fragmented skeletal debris and argillaceous lime mud and clay stringers (Fig. 7f and Table 2). These skeletal limestone units commonly are decimeter storm-beds of skeletal grainstone/packstone capped by skeletal wackestone. These facies gradually onlap the ramp, and are most abundant along the basin margin in West Virginia and in the Glen Dean Formation in Kentucky. They formed below fair-weather wave-base and above storm wave-base on the open ramp. Siliciclastic mud drapes may have washed out onto the ramp following floods or storms, or they may mark brief cessation in carbonate deposition during short periods of more humid climate.

Laminated Shaly Lime Mudstone (Ramp Slope-To-Basin Marls): These occur as unfossiliferous, dark gray, evenly thin-laminated-to-structureless, shaly lime-mudstone (marl) units up to over 100 meters thick in the Appalachian foredeep, where they periodically shoal up into skeletal banks, off-bank facies, and marine sandstone. They are deep water ramp slope-to-basin floor facies (Table 2), which lack shallow water sedimentary structures and biota. Fine carbonate sediment was brought onto the slope perhaps by storms and tidal currents and mixed with clays derived from the shield and Appalachian highlands to the north and east. Lack of burrowing suggests deposition in anoxic waters well below the photic zone (30 to over 100 m), the photic zone perhaps extended to as little as 30 m depth given the turbid basin waters.

CHAPTER FOUR

SEQUENCE STRATIGRAPHY

The depositional sequence, the fundamental unit of sequence stratigraphy, consists of genetically related strata that are internally conformable (Mitchum and Van Wagoner, 1991). It is bounded by unconformities (surfaces of erosion or nondeposition) and their correlative conformities, (Mitchum and Van Wagoner, 1991). A type 1 sequence boundary is characterized by subaerial erosion resulting from emergence and subaerial exposure, and is the lower boundary of a type 1 sequence (Mitchum and Van Wagoner, 1991). A type 2 sequence boundary is marked by subaerial exposure, but lacks major subaerial erosion. And is the lower boundary of a type 2 sequence (Mitchum and Van Wagoner, 1991).

A sequence consists of systems tracts and their component parasequences and parasequence sets (Mitchum and Van Wagoner, 1991). The lowstand systems tract (LST) lies directly on a type 1 sequence boundary; it is deposited seaward of the shelf break, and commonly is made up of progradational to aggradational parasequence sets. The ramp-margin wedge (RMW) lies on a type 2 sequence boundary on the ramp-margin landward of any break in slope (Mitchum and Van Wagoner, 1991; Sarg, 1988). The transgressive systems tract (TST) is composed of retrogradational parasequence sets and is capped by the maximum flooding surface (mfs), which separates the TST from the overlying highstand systems tract (HST). The highstand systems tract is composed of aggradational to progradational parasequence sets (Mitchum and Van Wagoner, 1991). A parasequence is a relatively conformable succession of genetically related beds bounded by marine-flooding surfaces, across which there is evidence of an abrupt increase in water depth.

MISSISSIPPIAN SEQUENCE STRATIGRAPHY, APPALACHIAN BASIN, WEST VIRGINIA-VIRGINIA

Mississippian Supersequence

The study interval in the Appalachian Basin makes up the transgressive portion of a second order supersequence spanning the Mississippian (Fig. 3A). The lower supersequence boundary is a basal Mississippian, regional erosional unconformity at the base of the Cloyd Conglomerate (Bjerstadt and Kammer, 1988) (Fig. 3A). The lowstand of this supersequence consists of the fluvial-to-estuarine and tidal flat facies of the Cloyd Conglomerate in Virginia/West Virginia and the overlying Price/Borden deltaic complex (Branson, 1912; Butts, 1940, 1941; Bjerstadt and Kammer, 1988). The Price/Borden delta formed a siliciclastic lowstand wedge that prograded out onto black shale of a starved basin. Red-beds and evaporites of the Maccrady Formation (Reger, 1926; Butts, 1940, 1941) overlie the Price/Borden delta and mark the last stage of siliciclastic progradation. Up to six sequences have been recognized within the Price/Borden interval (Bjerstadt and Kammer, 1988). The late lowstand portion of the Mississippian supersequence consists of the Ft. Payne-to-Salem carbonates (Butts, 1940, 1941), which following a short term floodback of the delta top, developed as a series of toplapping 3rd order sequences that prograded out from the Borden paleoshelf margin (Khetani, 1997).

The transgressive portion of the Mississippian supersequence consists of the St. Louis (Hillsdale) to the base of the Glen Dean (Glen Ray) interval (Carney, 1993). Units within this interval generally show a gradual onlap onto the supersequence lowstand units of the Price/Borden-to-Fort Payne-Salem units. The Mississippian supersequence consists of the prograding, late Mississippian, open marine carbonates of the Glen Dean and Glen Ray and the overlying dominantly siliciclastic Mauch Chunk Group (Reger, 1926). The Mississippian/Pennsylvanian unconformity marks the upper boundary of the Mississippian supersequence. The interval studied in this paper thus forms the overall transgressive portion of the Mississippian supersequence.

Fourth-Order Depositional Sequences

The cross-section of the study interval (Fig. 5A and B) is based in part on subsurface cuttings (10 to 15 ft sample intervals) and wire-line logs, with five detailed, measured sections and one “biscuited” core (Sun Oil core). The sequences and their component facies are traceable from the outcrop sections into the subsurface using the cuttings and wireline, especially gamma ray logs, but the subsurface data set does not allow parasequences within sequences to be traced from the outcrop sections into the subsurface. Sequence boundaries down-dip were picked beneath low stand, ramp-margin wedge skeletal banks or marine sand bodies. On the ramp, sequence boundaries were placed at the top of local erosional disconformities, or above regional red-beds or eolianites, shallow marine sands or tidal flat units, where these mark a regional shallowing trend. In general, maximum flooding surfaces could not be picked for the third order sequences and so TSTs and HSTs were not mapped separately. However, important reservoir type facies were assigned to the TST if they occurred low in the sequence and appear to backstep, or to the HST where they occurred high in the sequence and appeared to be progradational. Possible parasequences were picked in the representative stratigraphic logs of the outcrop sections. The relation of the formational stratigraphy to depositional sequences is shown in Figure 8.

The Hillsdale Sequences

This sequence (Figs. 5B and 8) is from the top of the Price-Maccrady red-beds to the top of the lower Denmar red-beds, quartzose calcisiltite and peritidal units, thinning to a featheredge between sections 6 and 7. It is considered to be a composite sequence given its great thickness down-dip, where it is 85 m to over 270 m in foredeep sections in the Greendale Syncline, Virginia; and over 150 m thick in south-central Kentucky (Bartlett and Webb, 1971; Sable and Dever, 1990). It appears to consist of at least two parasequences (or sequences). The lower parasequence (?) has a medial skeletal grainstone, underlain and overlain by peritidal (shallow ramp) carbonates, and capped by

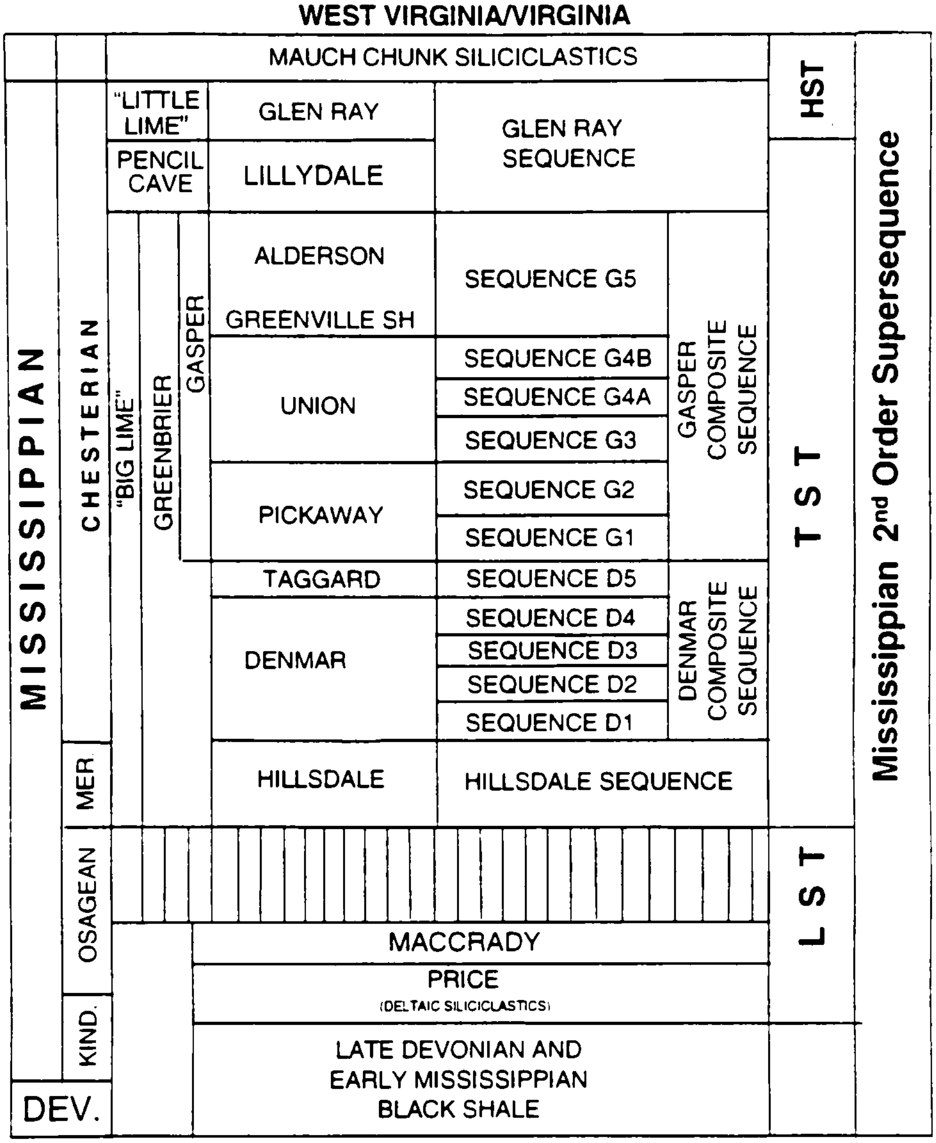


Fig. 8 Chart of sequences in West Virginia/Virginia related to the formational stratigraphy.

quartz peloid grainstone (eolianite) up-dip. The upper parasequence (?) shows a marked basinward shift relative to the underlying sequence, and consists of skeletal grainstone that is overlain by, and passes up-dip into peritidal carbonates, capped by quartz calcisiltite and red-beds.

The Denmar Sequences

Up to five sequences within Denmar-to-Taggard interval, labeled D1 to D5 in the Denmar Formation, possibly comprise a larger scale Denmar composite sequence (Figs. 5B and 8) on the basis of major influx of prograding Taggard red-beds and succeeding down-dip lowstand quartz sands at the top of the interval. The base of the Denmar composite sequence down-dip is at the top of the basal Denmar red-beds/quartzose calcisiltite and peritidal facies on top of the Hillsdale sequence. Up-dip, the top of the Denmar composite sequence is at the top of the Taggard red-beds.

Up-dip, the Price-Denmar unconformity forms the lower boundary of the composite sequence. The lowstand of the composite sequence consists of skeletal grainstone banks at the base of the Denmar sequence D1 and D2 along the ramp margin. The TST of the Denmar composite sequence consists of Denmar sequence D1-to D3, which onlap the lower composite sequence boundary. The maximum flooding interval is placed at the base of Denmar sequence D4, which extends far back onto the ramp, and contains the most landward development of skeletal limestones in the composite sequence. The HST of the Denmar composite sequence includes Denmar sequences D4 and

D5, which show a basinward shift of Taggard red-beds capping sequences D4 and D5, and their lowstand marine sandstone units.

Denmar Sequence D1 and D2: Sequence D1-to D2 (Figs. 5B and 8) is up to 120 m thick in the basin and pinches out at the Price-Maccrady disconformity between sections 6 and 7. The basal sequence boundary is placed at the base of skeletal grainstone bank facies in the basin (section 11), and above peritidal facies, quartzose calcisiltite and red-beds of the underlying Hillsdale sequence (sections 7 to 10).

The lowstand appears to consist of two skeletal grainstone banks separated by a basinal argillaceous mudstone. These may in fact be lowstands of 2 separate sequences, but are lumped together, because the lower sequence D1 is not regionally traceable. Up-dip on the ramp, the sequence D2 consists of peritidal carbonate mudstone capped up-dip by quartzose peloidal grainstone (eolianite) (sections 7, 8 and 9). On the ramp margin, the sequence consists of skeletal wackestone overlain by peritidal carbonates and a thin oolite tongue.

Denmar Sequence D3: Sequence D3 is 40 m thick in the basin, 57 m thick on the ramp margin, and thins almost to a feather-edge at section 1 (Figs. 5B and 8). The lower sequence boundary is placed at the base of a thin marine quartz sandstone in the basin (section 11); on the ramp the lower sequence boundary is the disconformity on peritidal facies at sections 10, 9 and 8, and eolianite on quartz peloidal grainstone in section 7, and on top of Price-Maccrady red-beds (sections 1 to 6). There may be 3 to 4 parasequences present within sequence D2. The lower part of the sequence above the lowstand sands is a 15 m thick succession of skeletal wackestone. This passes up-dip perhaps via subsurface bank margin grainstone (not sampled by any section) into peritidal carbonates with thin skeletal/ooid grainstone units on the outer ramp (sections 7 to 10), interlayered thin quartz peloidal (eolianite) on the mid ramp (section 8) and quartz sandstone at the up-dip pinchout section. The upper part of the sequence on the mid-ramp is dominated by widespread oolite up to 19 m thick (sections 5 to 7), which pinches out up-dip into peritidal carbonates capped by a thin quartz peloidal grainstone (section 4). Peritidal mudstone makes up the sequence up-dip (sections 1 to 3).

Denmar Sequence D4: Sequence D4 (Figs. 5B and 8) is up to 100 m thick in the basin (section 11) and thins up-dip to less than 15 m (section 1). The basal sequence boundary is placed at the base of the quartz sandstone in the basin (section 11), and at the erosional disconformity on peritidal carbonates along the ramp margin (outcrop section 10). On the ramp, it is typically placed at the change from less marine to more marine facies. Thus it is placed above a widespread oolite overlain by skeletal limestone on the mid-ramp (sections 5 to 7), on a thin eolian quartz peloidal grainstone beneath peritidal facies (sections 3 and 4), and at the disconformity capping up-dip peritidal carbonates (section 1). Sequence D3 may contain two or more parasequences that are evident up-dip and down-dip, but are difficult to define on the mid-ramp.

On the outer ramp, sequence D4 is composed of skeletal grainstone (up to 15 m thick) and thin oolite units (1 to 3 m thick) capped by a regional carbonate mudstone (sections 7 to 10). The thin oolite units may backstep between sections 10 to 7. Two stacked thick skeletal grainstones (15 m thick total with a middle shale) reappear up-dip on the ramp in section 5. Up-dip the sequence consists of oolite-to-lime mudstone parasequences. The lower Taggard red-beds cap the upper part of sequence D4, and pinch out up-dip beneath the upper sequence boundary.

Denmar Sequence D5: Sequence D5 (Figs. 5B and 8) is 38 m thick on the ramp margin, pinching out up-dip at section 3. The basal sequence boundary is placed below the sandstone unit of sequence D5 along the ramp margin (sections 8 and 9), and at the top of the lower Taggard red-beds up-dip. Sequence D5 consists of a lower unit of fine grained carbonate with two stacked locally developed oolite units and an intervening red-bed (section 6 and 8). The upper half of the sequence consists of upper unit made up of upper Taggard red-beds.

The Gasper Sequences

This interval includes the Pickaway, Union and Alderson limestone, and consists of Gasper sequences G1 to G5, which possibly are packaged into a longer term composite sequence (Figs. 5B and 8). The lower boundary of the composite sequence is placed beneath thick ramp-margin wedge sandy units of sequence G1. The TST of the Gasper composite consists of Sequences G1 and G2, which onlap the composite sequence boundary, and show backstepping of ramp margin wedge sands and on-ramp grainstones. Maximum flooding of the Gasper composite sequence is marked by onlap of deep water, skeletal wackestone in the Gasper sequence 3 onto skeletal grainstone (sections 9 and 8). The HST of the Gasper composite sequence consists of sequences G3 to G5, and shows progradation of skeletal grainstone bank facies seaward onto ramp margin skeletal wackestone.

Gasper Sequence G1: This sequence includes the lower Pickaway Formation (Figs. 5B and 8). It pinches out up-dip between sections 3 and 2, thickens to 45 meters on the ramp margin, and thins to 30 meters in the basin. Up-dip, the lower boundary of sequence G1 is placed at the top of the Taggard red-beds, and down-dip along the ramp margin, the lower sequence boundary is placed beneath the quartz sandstone of the basal Pickaway Formation (sections 9 and 11).

The ramp margin wedge of sequence G1 consists of a basal unit of fine- to very fine-grained quartz sandstone and fine-grained quartz sandy limestone, which in outcrop show wavy, limy shale partings. The upper part of the ramp margin wedge consists of crinoid banks capped by thin ooid grainstone (1.5 m thick; section 11), and onlaps the quartz sandstone wedge and grades up-dip into quartzose calcisiltite on the ramp margin (section 9).

Sequence G1 (lower Pickaway) is dominated by fine grained carbonates, in which thin oolite and skeletal grainstone units backstep from sections 6 to 4, suggesting that the lower grainstone is within the TST. The HST of sequence G1 consists of the most up-dip, thin grainstone (section 4) and a basinward shifted relatively thick (30 m) skeletal grainstone (highstand bank units ?) capped by quartzose peloid grainstone in the upper part of sequence G1 in sections 6 and 7, which are separated by fine-grained carbonates.

Gasper Sequence G2: Sequence G2 makes up the upper Pickaway Formation (Figs. 5B and 8). It pinches out up-dip (between sections 3 and 2), thickens to 45 m on the ramp margin and to 60 m in the basin. Its lower boundary is placed at the base of quartz sandstone along the ramp margin and beneath marine gray shale further up-dip (section 7). Sequence G2 backsteps slightly relative to sequence G1

Two stacked units of shaly quartz sandstone and an intervening fine grained limestone form the Ramp Margin Wedge. The sandstone bodies pass down-dip into deeper water skeletal wackestone and up-dip into gray marine shale. The upper shale veneers the sequence boundary over the up-dip part of the ramp forming a basal transgressive shale at the base of sequence G2 on the mid-ramp.

On the ramp, skeletal grainstone banks and minor overlying units appear to backstep initially and aggrade to form a thick bank at section 4, backed up-dip by shoal water oolite and eolian quartz peloidal grindstone (section 3), which make up the up-dip pinchout of sequence G2.

This is overlain by an extensive oolite to mudstone parasequence beneath the upper sequence boundary (sections 5 and 6), and then by a major basinward shift in oolite and skeletal grainstone facies to the ramp margin, where they are overlain by fine-grained limestone (section 9).

Gasper Sequence G3: Sequence G3 (Figs. 5B and 8) consists of the lower Union Formation, which is 15 m thick up-dip, where it passes out of the study area, and it thickens to 50 m on the ramp margin, and thins slightly to under 40 m in the basin. The lower boundary of sequence G3 is placed beneath a thin quartzose unit along the ramp margin (section 9), and above peritidal mudstone and up-dip eolianites (section 3) on the inner ramp. The ramp margin wedge of sequence G3 consists of thin quartzose calcisiltite in section 9, which pass down-dip into open ramp skeletal wackestone.

The transgressive part of sequence G3 consists of a single, thin parasequence of skeletal grainstone banks, up-dip ooid grainstone, and peritidal carbonate. The maximum flooding surface appears to be at the base of the next parasequence, which shows a major landward shift in skeletal facies; this parasequence, plus a less regional parasequence on the seaward margin of the ramp, and the topmost regional parasequence make up the highstand systems tract, of oolitic/skeletal grainstone dominated parasequences, in which the major oolite bodies (up to 20 m thick) shift slightly basinward (sections 5 and 6). The upper oolite passes landward into quartzose calcisiltite and extensive up-dip red-beds beneath the upper sequence boundary G3 (sections 1 to 4).

Along the ramp margin, isolated thin bodies of skeletal/ooid grainstone interlayered with deeper water skeletal wackestone (sections 8 and 9) appear to be high-frequency, ramp margin wedge deposits of the middle two parasequences.

Gasper Sequence G4: Sequence G4 (Figs. 5B and 8) consists of the upper Union and lower Alderson Formations, and is over 40 m thick in the basin, 30 m thick on the ramp margin, and thins to 15 m (section 3) at the up-dip limit of the study area. It consists of two higher frequency disconformity bounded sequences G4A and G4B.

The lower boundary of sequence G4A is placed at the top of the extensive red-beds up-dip, and at the base of cross-bedded quartzose calcisiltite and their deep ramp skeletal wackestone equivalent along the ramp margin. This cross-bedded quartzose calcisiltite (15 m thick) and down-dip skeletal wackestone form the ramp margin wedge.

Sequence G4A appears to backstep landward, relative to sequence G3. It thins down-dip and may pinchout onto the quartzose calcisiltite of the ramp margin wedge. On the ramp, it has locally developed oolite sheets (sections 1 to 3 and 6) and small skeletal grainstone banks (sections 4), capped by peritidal carbonates. Eolianites cap sequence G4A up-dip (section 1).

Sequence G4B rests over a local erosional disconformity up-dip at section 3, veneered by quartz peloidal eolianites. Down-dip, sequence G4B contains a basal sandstone (section 6) and shale (section 5) on the mid-ramp.

It may contain two to three parasequences of oolite or skeletal grainstone units capped and surrounded by shallow ramp fine-grained carbonates. The oolites of the middle parasequence backstep_relative to the lower parasequence (sections 3 and 4) and the upper parasequence shows a major basinward shift in bank facies (sections 7 to 9). Sequence G4B is capped by red-beds up-dip (sections 1 and 2).

Gasper Sequence G5: Sequence G5 (Figs. 5B and 8) consists of the upper Alderson Formation, it is 70 m thick in the basin, under 40 m on the ramp margin, and 15 m at the up-dip limit of the study area. The lower sequence boundary of G5 is placed at the base of skeletal wackestone on the ramp-slope (section 11), beneath quartzose calcisiltite units on the ramp-margin (sections 8 and 9) and marine gray shale on the mid-ramp (sections 8 to 6 and section 3), and at the top of up-dip red-beds of sequence G4B (sections 1 and 2).

The ramp margin wedge contains wave-rippled and cross-bedded quartzose calcisiltite (sections 9 and 8) along the ramp margin, grading down-dip into deeper ramp skeletal wackestone (section 11). Up-slope, the marine Greenville shale and its up-dip sandstone equivalent overlie the lower sequence boundary (sections 3 and 6 to 8).

The sequence may contain two parasequences. The lower parasequence consists of shale to skeletal grainstone capped by oolite (sections 6 and 7), which grades up-dip into peritidal carbonate mudstone, basal shale and sandstone, with an erosional disconformity in section 3. The upper parasequence has a quartz calcisiltite ramp margin wedge. On the ramp margin, it is dominated by an extensive ooid grainstone (sections 2 to 6) passing down-dip into a widespread skeletal grainstone bank (sections 6 to 9), with local bryozoan reefs (section 8) and ramp-slope skeletal wackestone. .

The Glen Ray Sequence

The Glen Ray sequence (Figs 5B and 8) consists of the Lillydale Shale to Glen Ray Limestone interval, which is up to 50 m on the ramp margin, thinning to 10 m up-dip. The lower boundary of the Glen Ray sequence is placed at the base of the Fido sandstone in the basin (section 11), and at the base of the regional Lillydale marine gray shale on the ramp, which overlies oolite and skeletal grainstone banks of Sequence G5.

The Fido Sandstone, a thin (less than 10 m) shore-face quartz sandstone forms the ramp margin wedge in the basin (section 11). The Lillydale marine gray shale (0 to 30 m) is the TST of the Glen Ray sequence, where it floods the ramp over the sharp lower Glen Ray sequence boundary, which lacks evidence of emergence. The HST of this sequence consists of local skeletal banks, ooid shoals and bryozoan mounds (sections 1, 3, 6, 8 and 9). The equivalent unit in the basin consists of 360 m of Cove Creek Formation (Bartlett and Webb, 1971) basinal carbonates.

DISCUSSION

Duration of Sequences

The sparse radiometric data and their error bars, and the difficulties in inter-continental correlation between Mississippian brachiopod, conodont, and foraminiferal zones, makes absolute age determination of the study interval difficult. Total duration of the St. Louis to Glen Dean interval (equivalent to the Hillsdale to Glen Ray interval) is poorly constrained, but is estimated by Sando (1984) to be up to 10 m.y. (about 8 m.y. for the post St. Louis to Glen Dean interval). The most recent ages for the Mississippian period in Australia were given by Roberts et. al. (1995), where an estimate of 3 m.y. for the post St. Louis to Glen Dean (Glen Ray) interval was calculated (Smith, 1996) based on correlation to European and North American stratigraphy (Baxter and Brenckler, 1982).

Assigning an upper duration of 8 m.y. for the 10 sequences in the Denmar to Glen Ray interval, the sequences in the Appalachian Basin could be as much as 800 k.y. However, using the lower estimate of 3 m.y. would give 300 k.y. per sequence, which is similar to average duration of 375 m.y. for the sequences in the Illinois Basin (Smith ,1996). Similarly, Miller (pers. comm., 1997) using the total number of sequences in both the carbonate and the overlying siliciclastic sequences of the Mauch Chunk units estimates an average sequence duration of about 400 k.y.

Tectonics and Subsidence Rates

The Late Mississippian carbonate ramp bordered the northern and western margins of the northeast-southwest trending Appalachian Basin (Figs. 1 and 2). Subsidence rates were highest (11 to 29 cm/k.y.) in the basin (section 11) compared to the ramp margin (sections 8 to 10) (5 to 14 cm/K.Y.), subsidence rates were lowest (1 to 3 cm/k.y.) up-dip (sections 1 to 4). Differential subsidence is evident in the gradual thickening from northeast to southwest across the basin margin (Fig. 5B), reaching up to 900 m above the Price/Borden deltaic siliciclastics. Such rapid downwarping of this region over the previously emergent delta in the foreland basin indicates that accommodation space was initiated tectonically, perhaps by thrust loading of the plate margin.

The Denmar Composite Sequence is 280 m in the basin, which is about twice the thickness on the ramp margin (145 m) and over ten times the up-dip thickness (25 m). The Gasper Composite Sequence shows a more gradual up-dip thinning from 245 m in the basin to 207 m at the ramp margin to 45 meters at the up-dip unit. This indicates that there was much higher differential subsidence in the foredeep during deposition of the Denmar Composite Sequence, compared to the Gasper, where subsidence rates increase more gradually towards the foredeep. Even allowing for palinspastic thrust-fold shortening within the fold-thrust belt, the most drastic thickening occurred from the Pine Mountain region in Kentucky into the foreland, where thicknesses rapidly increased almost ten fold over palinspastic distances of less than 100 miles (160 km).

Tectonic instability during Ste. Genevieve (Denmar) deposition extended out onto the foreland in eastern Kentucky, where numerous blocks underwent differential subsidence giving rise to rapid thickness changes (Ettensohn, 1975, 1980; Dever, 1986, Dever et. al., 1990, Mac Quown and Pear, 1983).

Climate

During the early Mississippian, the Appalachian Basin had a humid climate, which favored a great influx of siliciclastics and deposition of the Price/Borden delta complex (Branson, 1912), which prograded southwestward across the foreland basin onto the starved, deep water Sunbury shale (Butts, 1940, 1941; Sable and Dever, 1990; Ausich and Meyer, 1990; Khetani, 1997). Maccrady red-beds and evaporites capping the Price/Borden delta mark the onset of an extremely arid climate, which shut down the supply of siliciclastics to the shelf, and allowed deposition of a prograding wedge of carbonates, evaporites, widespread shoals in the Illinois Basin, minor siliciclastics (Ft. Payne-to Salem interval) in front of the delta, and evaporites in the Renfro-to St. Louis in Kentucky indicate that arid conditions persisted throughout the Middle Mississippian (Sable and Dever, 1990; Ausich and Meyer, 1990, Khetani, 1997).

Climate became semi-arid by early Chesterian time. The Chesterian Denmar to Alderson carbonates show a gradual shift from semi-arid to more humid climate by the latest Mississippian. Semi-arid climate is evident in the lower Chesterian (Denmar to Union interval) by early tidal-flat dolomites, red-beds, widespread oolitic ramps, coastal eolianites, and caliche in Kentucky and in the Illinois Basin (Dever, 1973, 1995; Ettensohn et. al., 1988; Smith, 1996). Similarly, early meteoric cements are absent until the latest Chesterian (Neimann and Read, 1989; Nelson and Read, 1990). As the climate became more humid in the later Chesterian (Alderson to Glen Ray), coarse siliciclastic influx increased, which also is evident in the Illinois Basin (Swann, 1964; Smith, 1996), and oolitic deposits became less common. This upward change from semi-arid to humid climate in the late Mississippian is evident in Kentucky by the change from caliches in the lower part (semi-arid) to paleokarst in the upper part (Ettensohn et al, 1988). By latest Mississippian time, the deposition of the Mauch Chunk red-beds and semi-arid paleosols indicated the persistence of long term semi-arid climate (Caudill et. al., 1996). This gave way finally to the predominantly equatorial humid conditions of the Pennsylvanian in the Appalachian Basin (Cecil, 1990). The large influx of Late Mississippian Mauch Chunk siliciclastics, may reflect sweeping progradation due to the reduced accommodation space following the basin filling by Greenbrier carbonates and does not appear to be due to increasingly humid conditions.

The Mississippian to Pennsylvanian climatic changes are borne out by paleogeographic reconstruction of the Carboniferous (de Witt and Mc Grew, 1979; Scotese and McKerrow, 1990), which show that during the Meramecian to Chesterian, the North American plate was gradually rotating counterclockwise and moving northward from the arid sub-equatorial belt (latitudes of 25 degrees or less) northward toward the equator by Pennsylvanian time.

Eustasy

There are up to twelve probably fourth-order depositional sequences in the study interval (Hillsdale to Glen Ray interval) (Fig. 8). Three composite sequences (Hillsdale, Denmar, and Gasper); composed of bundles of these probably fourth-order sequences can be defined in the basin. Because of the relatively higher subsidence rates in the study area along the axis of the basin and more continuous sedimentation, the sequences are more conformable and lack regional bounding disconformities, when compared to Kentucky (chapter 5) or the Illinois Basin (Smith, 1996). On the ramp margin and basin slope, lowstand sands and high-energy skeletal banks above basin facies overlie the lower sequence boundaries. On the ramp, late highstand prograding shallow water to subaerial facies, that are laterally variable but regionally traceable as shallowing events underlie the upper sequence boundaries.

These sequences are of basin-wide extent (over 150 miles), and can be correlated with disconformity-bounded sequences on the more stable foreland in eastern Kentucky (Chapter 5) and in the Illinois Basin (Smith, 1996) (Fig. 5B). The extent of these sequences suggest that global Eustasy played a major role in their development, rather than tectonics alone, which would operate locally as the basin subsided differentially. However, differential subsidence had a major control on thickening and thinning of sequences within the Appalachian and Illinois basins.

The strong suggestion of ~ 300 to 400 k.y. average duration per sequence falls in the long-term eccentricity band of Milankovitch orbital forcing, which predominates during times of global ice-sheets (Imbrie and Imbrie, 1986; Ruddiman et. al., 1986). This is compatible with the onset of Late Paleozoic, Gondwana glaciation in the southern hemisphere, in the Early Chesterian (Frakes et al., 1992).

Controls on Sequence Development

The Mississippian Supersequence

The supersequence boundary and lowstand (Fig. 3A) appear to have succeeded the last pulse of the Acadian (Late Devonian) thrust loading (Dennison, 1985; Ettensohn, 1994). The waning stage of this tectonic pulse during a relative lowstand of sea-level and humid climate, possibly led to high influx of siliciclastics and sweeping progradation of the Price/Borden deltaic complex. Onset of arid climate (Cecil, 1990) shut down the siliciclastic influx. This allowed Ft. Payne-to-Salem carbonate clinoforms to accrete from the margin of the Price/Borden delta onto the starved, anoxic Sunbury Shale during the later half of the supersequence lowstand (Ausich and Meyer, 1990; Khetani, 1997).

A major increase in differential subsidence in the Chesterian in the foredeep in Virginia, perhaps coupled with global sea-level rise, led to increased accommodation rate. This, coupled with semi-arid climate, gave way to long-term onlap of carbonate sequences onto the earlier Price/Borden delta and Ft. Payne-Salem complex (Fig. 3A and 5B). The eight retrograding sequences within the Hillsdale to Glen Ray interval form the transgressive portion of the Mississippian supersequence (Hillsdale to Gasper sequence G3) (Fig. 5B). As subsidence rates on the ramp slowed in the upper Gasper time, the upper three sequences started to aggrade and slightly prograde (Gasper sequences G3 to G5). A rapid thickening of the succeeding Glen Ray sequence to over 300 m in the foredeep (Butts, 1940, 1941; Bartlett and Webb, 1971) indicates a return to high differential subsidence while the distal foreland remained relatively stable. This episode of possibly renewed thrust-loading resulted in the rapid flooding of the ramp by the Lillydale marine gray shale and Glen Ray carbonates.

The siliciclastic dominated HST of the supersequence (Fig. 3A) formed during sweeping progradation of Mauch Chunk siliciclastics, following decrease in load-induced subsidence and basin filling by the distal shaly equivalents of the transgressive part of the supersequence (Hilsdale-to Gasper sequences).

Sequences and Composite Sequences:

The twelve fourth-order (?) depositional sequences of the Hillsdale to Glen Ray interval, which range from a few tens of meters thick on the ramp to over 100 m thick in the foredeep, reflect relatively higher subsidence rates along the axis of the basin. Relatively continuous sedimentation due to high subsidence rates resulted in generally conformable sequence boundaries, and the relative scarcity of regionally traceable disconformities and incision on the ramp compared to eastern Kentucky. Minor exposure surfaces along sequence and parasequence boundaries up-dip and on the ramp-margin were associated with relative falls of sea level.

Quartz sand bodies and skeletal banks formed the lowstand systems tracts in the depositional sequences D1 to G1 (Fig. 5B). High differential subsidence resulted in higher slopes on the ramp margin. This caused sea-level drops to favor lowstand sand bodies and skeletal banks to form along the ramp-margin on top of slope-to basin facies. In the upper sequences (sequences G2 to Glen Ray), lower differential subsidence formed relatively gentle ramp margin slopes. Therefore, when sea-level fell, lowstand banks, ooid shoals, and quartzose calcisiltites formed ramp-margin wedges and down-dip open marine and basinal facies on the gentle ramp-slope-to basin profile.

Sea-level drops exposed much land peripheral to highland areas, and exposed the ramp so that siliciclastics could be carried out onto the margin. The lowstand units in the Denmar sequences are dominated by skeletal banks, and only minor sands (Fig. 5B). In contrast, the upper sections (sequences D4 to Glen Ray) have better developed lowstand quartz sands and ramp-margin units (Fig. 5B). A slight shift in climate towards more humid conditions upsection may have favored development of more quartzose low-stand systems. Major influx of siliciclastics however, is concentrated at the composite sequence scale, where the regional Taggard red-beds and their lowstand sands, and the Fido sandstone (up to 18 m thick; Bartlett and Webb, 1971) developed during major sea-level drops. The siliciclastics seem to be sourced from the east-to northeast down to the ramp margin, where they were deposited as lowstand sand bodies.

The mfs of each sequence is difficult to recognize in the drill-hole cuttings. However, the data suggests that the sequences seem to undergo rapid stepwise deepening over sequence boundaries. This caused backstepping of facies belts in the transgressive parts of some sequences (e.g. sequences D3, G2 to G4) (Fig. 5B).

Progradation and basinward shift of skeletal banks, shoals, tidal flats and red-beds formed the late HST of the sequences (e.g. sequences D2 to G5) (Fig. 5B). Tidal flat facies are rare, perhaps because sea-level fall caused rapid seaward shift of the shoreline, faster than tidal-flats could prograde. They were best developed locally during late highstand along the ramp margin. The widespread high energy facies along the mid- and outer-ramp also may have inhibited the development of tidal flat facies during sea-level fall.

The mfs of the composite sequence is evident in Gasper sequence G3, where ramp-slope bryozoan wackestone backstep onto the ramp (Fig. 5B). The low relief across the ramp margin, due to relatively low differential subsidence, resulted in widespread flooding of the ramp during eustatic sea level rise. The lack of mfs in the Denmar composite sequence may be due to the higher relief across the margin, which limited deep water facies to the margin of the ramp during the sea level rise.

The coincidence of the study interval with the onset of the southern hemisphere, Gondwana glaciation (Fig. 9) (Frakes et. Al, 1992), and their Milankovitch band of ~400 k.y. periodicities, suggest that fourth-order (?) glacio-Eustasy controlled the formation of these sequences. This is further supported by the duration of the time equivalent depositional sequences in the Illinois Basin (Smith, 1996), and the later Mississippian siliciclastic sequences in the Appalachian Basin (Miller and Eriksson, 1997; Miller, pers. Com., 1997). Thus they herald the onset of the high-amplitude glacio-eustatic Pennsylvanian cyclothems (Heckel, 1986).

Controls on Reservoir Development

Late Mississippian carbonates are major hydrocarbon producers in the Appalachian Basin (Keleher and Smosna, 1993), where the most producing and potential reservoirs are ooid grainstone, dolomites and lowstand quartz sandstone.

Ooid shoals were best developed on the mid-ramp, where they appear to form thick transgressive bodies over sequence and parasequence (?) boundaries within fourth-order sequences. They also formed smaller prograding ooid bodies toward the ramp margin in some parasequence (?)

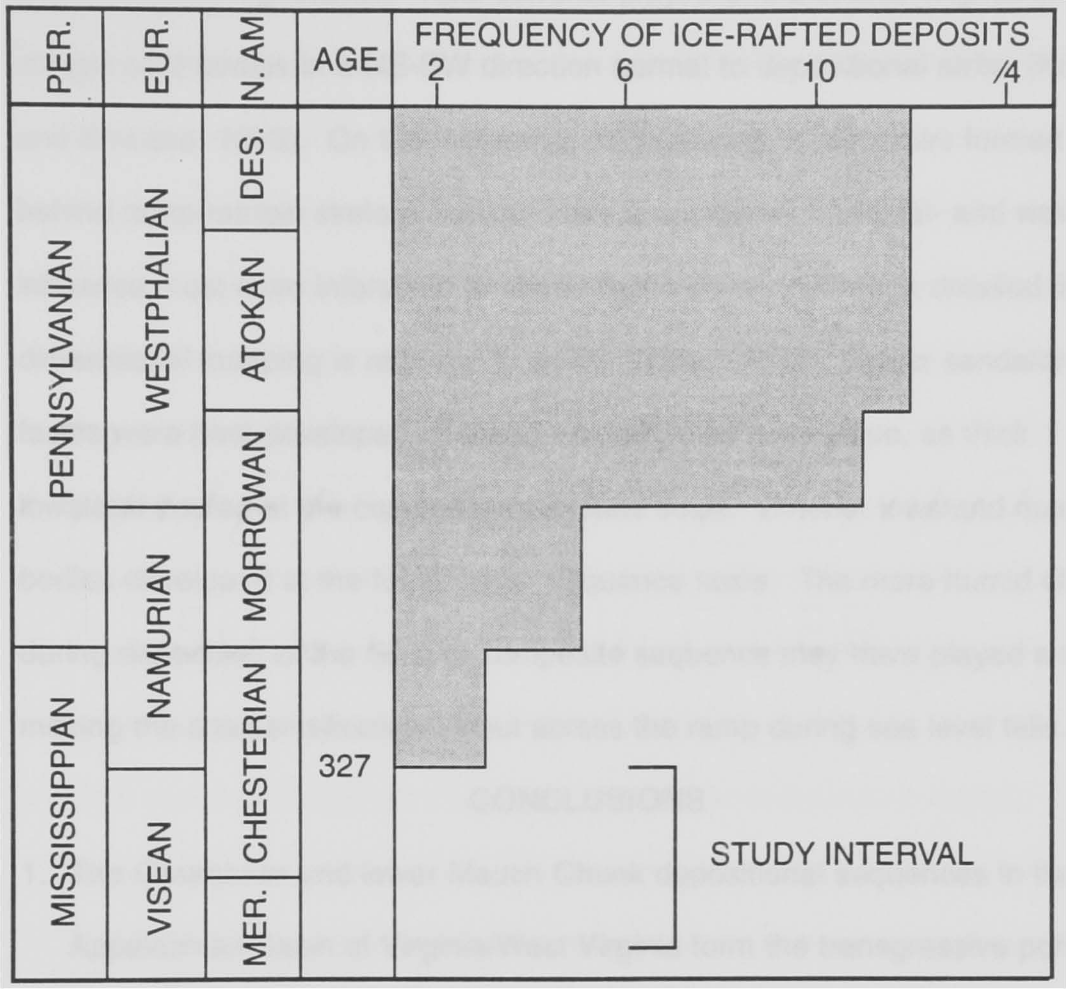


Fig. 9 Global climate setting of Late Mississippian to Pennsylvanian, with increasing number of occurrences of ice-rafted deposits world-wide into the Pennsylvanian, leading to the Late paleozoic Gondwana Glaciation (modified from Frakes et. al, 1992; age from Roberts et. al., 1995). Study interval occurs just below the first recorded glacial deposits. (Smith, 1996)

lowstands and highstands. Tidal currents played a role in orienting ramp-margin ooid bodies in a NE-SW direction normal to depositional strike (Kellehar and Smosna, 1993). On the mid-ramp, ooid grainstone reservoirs formed behind ramp-margin skeletal banks. Here a combination of tidal- and wave-influence must have interacted to shape these shoals, although detailed three-dimensional mapping is required to define these bodies. Quartz sandstone facies were best developed on the ramp margin-to ramp-slope, as thick lowstand bodies at the composite-sequence scale. Smaller lowstand quartzose bodies developed at the fourth-order sequence scale. The more humid climate during deposition of the Gasper composite sequence may have played a role in moving the coarser siliciclastics out across the ramp during sea level falls.

CONCLUSIONS

1. The Greenbrier and lower Mauch Chunk depositional sequences in the Appalachian Basin of Virginia/West Virginia form the transgressive portion of the Mississippian supersequence. The interval formed during the onset of the southern Hemisphere Gondwana glaciation in the Late Mississippian (Early Carboniferous), and consists of up to twelve fourth-order depositional sequences, which appear to fall within the ~400 k.y. long-term, Milankovitch, eccentricity band. Climate gradually shifted from arid to semi-arid to humid throughout the interval of study.

2. Down-dip thickening into the foredeep suggests that differential subsidence of the foredeep during the Late Mississippian (Chesterian) was important, and may mark the early onset of Alleghanian thrust-loading.
3. The lower (Denmar) sequences show onlap onto the Price/Borden delta during a period of high differential subsidence of the foreland basin and initial, long term sea level rise. The upper (Gasper) sequences exhibit aggradation to slight progradation as a result of decreased accommodation during reduced differential subsidence and a slower long-term rise in sea level. Supersequence highstand siliciclastics of the Mauch Chunk Group underwent sweeping progradation during long term sea level highstand, following the filling of the basin by the carbonate sequences.
4. Ooid reservoir facies are thickest on the mid ramp and ramp-margin. These were controlled by tidal and possibly wave-influence during the fourth-order TST to HST. Quartz sandstone reservoirs formed lowstand bodies during fourth-order sea level falls, and were best developed during third order (composite sequence scale) relative falls in sea level.
5. The sequence stratigraphy of this Greenbrier-to Glen Ray interval thus provides an analog for tropical mixed carbonate siliciclastic ramps extending into foreland basins during onset of global continental glaciation.

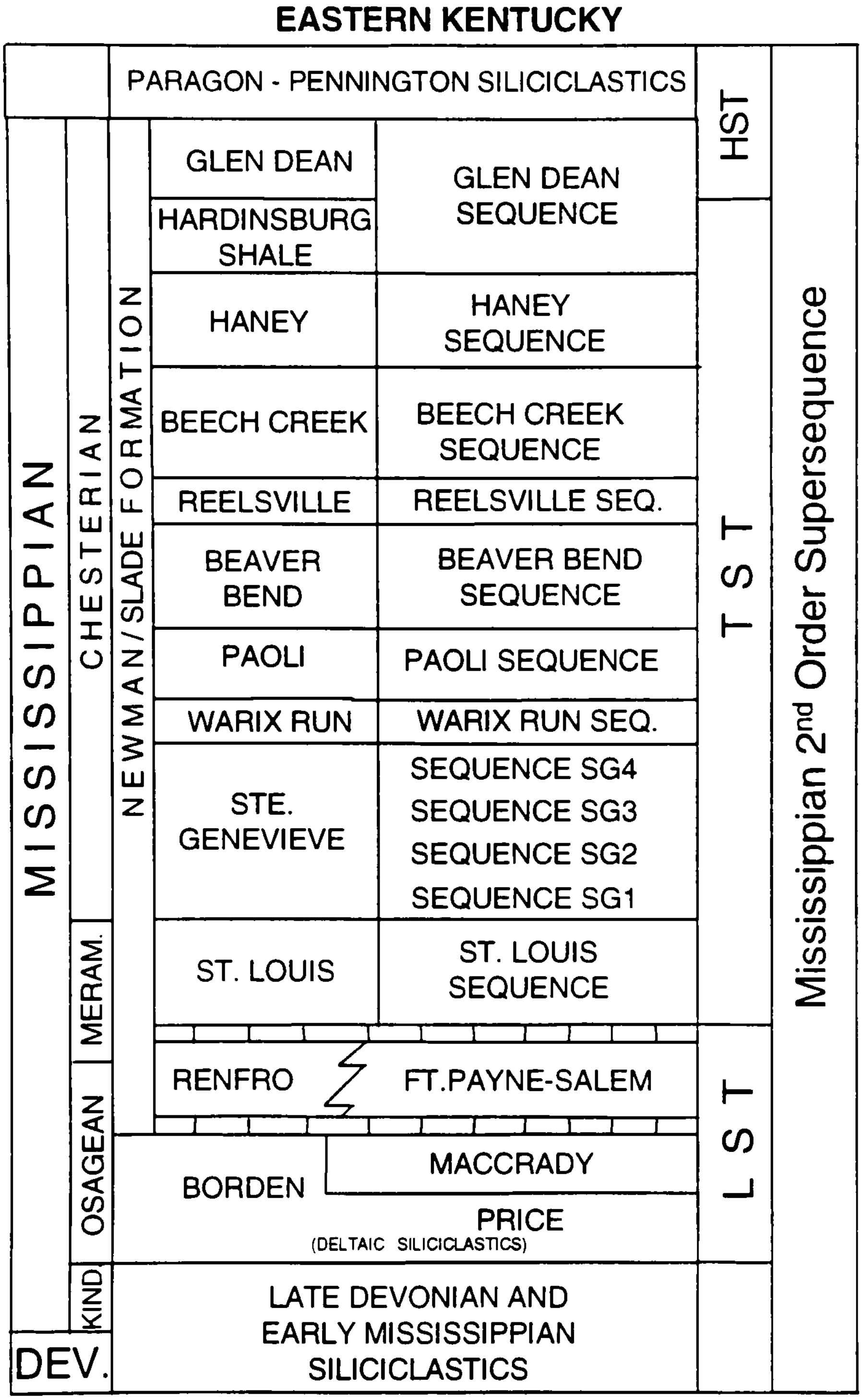
CHAPTER FIVE

SEQUENCE STRATIGRAPHY OF MISSISSIPPIAN STE. GENEVIEVE TO GLEN DEAN INTERVAL, APPALACHIAN BASIN, KENTUCKY

The Kentucky cross-sections (Figs. 6) were based on outcrop sections exposed in road-cuts and quarries, along with shallow stratigraphic cores (Fig. 6A) housed at the Kentucky Geological Survey. Individual disconformities and marker beds were traced regionally using closely-spaced measured sections and cores. The wireline log expression of the succession was defined by tying the outcrop into nearby wells, which contained suites of wireline logs. The regional cross-section (Fig. 6B) was hung on the base of the regional Glen Dean Limestone. The Ste. Genevieve to Glen Dean interval in Kentucky was subdivided on the basis of regionally mappable disconformities into unconformity-bounded depositional sequences (Fig. 10). Some sequences are further subdivided into regionally mappable parasequences which are bounded by marine flooding surfaces and generally shallow upwards.

Ste. Genevieve Sequences

The Ste. Genevieve interval is from the unconformity on top of the St. Louis (and its down-dip conformity) to the base of the “Warix Run” sequence. The Ste. Genevieve contains four disconformity-bounded sequences, which are stacked into a composite sequence (Fig. 6B and 10). The Ste. Genevieve interval is 0 to 20 meters thick. It abuts the Paint Creek fault, and is absent on the northern block (Fig. 6B) (Butts, 1922). The lower sequence boundary in the



EASTERN KENTUCKY

		PARAGON - PENNINGTON SILICICLASTICS			HST	Mississippian 2^{nd} Order Supersequence
MISSISSIPPIAN	CHESTERIAN	NEWMAN/SLADE FORMATION	GLEN DEAN	GLEN DEAN SEQUENCE		
			HARDINSBURG SHALE		TST	
			HANEY	HANEY SEQUENCE		
			BEECH CREEK	BEECH CREEK SEQUENCE		
			REELSVILLE	REELSVILLE SEQ.		
			BEAVER BEND	BEAVER BEND SEQUENCE		
			PAOLI	PAOLI SEQUENCE		
			WARIX RUN	WARIX RUN SEQ.		
			STE. GENEVIEVE	SEQUENCE SG4 SEQUENCE SG3 SEQUENCE SG2 SEQUENCE SG1		
	MERAM.		ST. LOUIS	ST. LOUIS SEQUENCE		
	OSAGEAN		RENFRO	FT.PAYNE-SALEM	LST	
		BORDEN		MACCRADY		
				PRICE (DELTAIC SILICICLASTICS)		
	KIND.	LATE DEVONIAN AND EARLY MISSISSIPPIAN SILICICLASTICS				
DEV.						

Fig. 10 Chart of sequences in eastern Kentucky related to the formational stratigraphy.

north is a type 1 boundary with extensive paleokarst , well developed caliche, fitted fabric and lithoclastic breccia, and tepees. Down-dip the boundary appears to be conformable, and is placed at the base of skeletal grainstone with the common fossil Platycrinites penicillus.

Ste. Genevieve Sequence 1: This sequence down-dip in the Pine Mountain belt (sections 24 to 27) contains a thick basal skeletal grainstone, overlain by and grading up-dip into carbonate mudstone (Fig. 6B).

Ste. Genevieve Sequences 2,3 and 4: These are disconformity-bounded type 2 sequences of oolite to carbonate mudstone, that grade up-dip into carbonate mudstone and eolianite (Fig. 6B). Local thickening of sequences 2 and 3 (?) occurs in section 17 apparently associated with local downwarping. Sequence 4 in the Pine Mountain belt (sections 24 and 25) contains an eolianite beneath the upper sequence boundary (the most southeastern occurrence of this facies), which up-dip to the northwest is underlain by oolite. Regionally traceable parasequences are not evident in the Ste. Genevieve sequences. However, up to four local oolite to mudstone parasequences occur in Ste. Genevieve in sequence 2 in the Pine Mountain belt (section 27).

"Warix Run" Sequence

The "Warix Run" sequence (Figs. 6B and 6C) is 2 to 12 meters thick, pinching out against the northern block (sections 1 to 14). The lower boundary is a regional type 2 disconformity , on local eolianites in Pine Mountain (sections 24 and 25) and on eolianites elsewhere.

Two regional parasequences are developed, the lower parasequence makes up the TST, and is an oolite to carbonate mudstone unit that grades up-dip into tidal flat facies (section 24) or into quartz peloidal eolianites (sections 14 to 19). The upper parasequence makes up the HST with the mfs occurring beneath its basal skeletal grainstone down-dip (sections 23 to 27) and beneath oolite in sections 19 to 22. This upper parasequence contains widespread oolite, that grades up-dip into eolianite with multiple internal disconformities ("Warix Run" Formation, sections 15 to 19). The upper "Warix Run" parasequence (HST) pinches out between sections 15 and 14 on the margin of the northern block.

Paoli Sequence

The Paoli sequence (Figs. 6B and 6C) is 2 to 12 meters thick, but pinches out west of section 7 onto the western flank of the Waverly Arch. The lower boundary of the Paoli sequence in most sections is a regional type 2 disconformity on the "Warix Run" sequence. The Paoli sequence contains up to four parasequences down-dip in the Pine Mountain belt (sections 24 to 27) but only two elsewhere.

The TST consists of two oolite to carbonate mudstone parasequences down-dip (sections 24 to 27), which pinch out onto, and onlap the basal sequence boundary up-dip beyond section 20. The MFS appears to lie at the base of a widespread skeletal grainstone of parasequence 3 down-dip (Pine Mountain belt, sections 25 to 27).

The HST consists of parasequences 3 and 4, which progressively onlap the basal sequence boundary (between sections 20 to 7), but whose skeletal grainstone units show a slight basinward shift (sections 25 to 27), terminating in eolianites below the upper sequence boundary (sections 27).

Beaver Bend Sequence

The Beaver Bend sequence (Figs. 6B and 6C) is 8 to 15 meters thick along the Cincinnati and Pine Mountain belts, pinching out up-dip at section 6 onto the western flank of the Waverly Arch.

The lower boundary is a type 2 sequence-bounding disconformity with regional caliche, a red-bed paleovalley fill (section 8) and multiple incipient soils (section 13) on the northern block; and tepees, caliche anticlines and breccia on the southern block and Pine Mountain area.

The sequence consists of up to 5 parasequences. The lower three show progressive onlap onto the lower sequence boundary between sections 15 to 10. The TST consists of parasequence 1, which pinches out against the northern block, and is composed of a basal, centimeter gray shale, local skeletal grainstone beneath a regional oolite, that passes near the shoreline into quartzose grainstone tidal bars and channel-fills (sections 7 and 8), and a regional widespread carbonate mudstone cap, capped up-dip by a disconformity.

The HST of the Beaver Bend sequence consists of parasequences 2 to 5, that occur as a series of clinoformed wedges that top-lap beneath the upper sequence boundary (beneath the regional Cave Branch Shale). These highstand parasequences consist of ooid grainstone capped by carbonate mudstone, and commonly are disconformity-capped, but merge into a single parasequence in sections 24 to 27.

Reelsville Sequence

This sequence (Figs. 6B and 6C) is a thin disconformity-bounded unit (less than 3 m thick) developed between sections 15 and 23. It is dominated by peritidal carbonate mudstone, with a local oolite at section 18, and probably is the up-dip feather-edge of a sequence that is better developed down-dip.

Beech Creek Sequence

The Beech Creek sequence (Figs. 6B and 6C) is up to 10 meters thick along the Cincinnati Arch and Pine Mountain belts, thinning to a few meters on the northern block (sections 1 to 6). It is bounded at the base by a regional disconformity that is a type 2 sequence boundary. West of the Waverly Arch, the lower boundary is a major amalgamated unconformity that spans the post St. Louis-to- top Beaver Bend interval, and is marked by over a meter of brecciated and calichefied St. Louis Limestone with paleo-sinkholes filled with green shale (Ettensohn et al., 1988). Along the eastern edge of the Waverly Arch, the lower sequence boundary is a regional paleosol with red-bed filled incised valleys (up to 3 meters deep) at section 8. Elsewhere on the southern block and Pine Mountain, the boundary is a regional paleosol with breccia and tepee horizons up to a meter thick locally with centimeter-thick caliche crusts.

Two poorly defined regional parasequences are recognized in the Beech Creek sequence, although up to 4 parasequences are locally developed in the interval (sections 18 and 26 to 27).

The transgressive part of the sequence consists of the basal portion of an open marine skeletal grainstone that grades laterally into ooid grainstone with local carbonate mudstone caps forming a poorly defined basal parasequence. In the north (sections 1 to 5), this parasequence passes up-dip into gray green shale, overlain by thin-bedded shale and lime mudstone (Cave Branch shale) and capped by tidal channel fills and fenestral dolomite.

No regionally traceable mfs is evident, although it probably lies at the base of the upper regional parasequence. The HST of the Beech Creek sequence up-dip consists of the upper regional parasequence. It consists of a thin oolite capped by peritidal mudstone (sections 1 to 15). Further down-dip it consists of thick ooid grainstone units (up to 7 meters thick), that interfinger and grade down-dip into skeletal grainstone capped by a thin regional ooid grainstone sheet (up to 2 meters thick), with a locally developed peritidal mudstone cap (section 10, 24 to 27). The top of the Beech Creek sequence up-dip on the northern block is an irregular dissolution surface. Down-dip (sections 21 to 27), the upper surface contains minor, centimeter-thick caliche crusts and breccia on the uppermost oolite and mudstone.

Haney Sequence

The Haney sequence (Figs. 6B and 6C) is bounded at the base by a disconformity in much of the Pine Mountain belt (sections 24 to 26) and on the southern block along the Cincinnati Arch (sections 20 to 22), where it contains minor caliche horizons and breccia. The basal sequence boundary is a type 2 boundary on the northern block, where it is an irregular low relief karstic (?) surface, whereas elsewhere it appears to be a paraconformity. The Haney sequence is 3 to 10 meters thick along the Cincinnati Arch, thickening to 15 meters in the Pine Mountain belt.

The TST of the Haney sequence is composed of a uniformly thin parasequence with a basal, locally developed thin, gray, unfossiliferous marine shale that fills swales on the underlying sequence and is overlain by a regional, sheet-like oolitic unit, which pinches out up-dip at section 15. The base of the overlying parasequence is the MFS for the sequence, and this parasequence consists of a regional skeletal grainstone which locally shallows up into two local parasequences of skeletal grainstone to oolite at sections 11 to 16 and sections 21 to 22 and perhaps 27. Up-dip, the parasequence grades into shallow water, thin bedded shaly, pelletal skeletal limestone and dolomitized mud-mounds.

Glen Dean Sequence

The Glen Dean sequence (Figs. 6B and 6C) consists of the Hardinsburg Shale and Glen Dean Limestone and is 8 to 25 meters thick. The lower boundary of the Glen Dean sequence is apparently disconformable on the Haney sequence only on the Waverly Arch. Elsewhere, it is a paraconformable, type 2 sequence boundary. The lower boundary of the Glen Dean sequence is a planar topped, cemented, skeletal packstone/grainstone surface on the Haney with Archimedes bryozoa and common pyrite. This is overlain by the sparsely fossiliferous Hardinsburg Shale.

The 0 to 5 m thick, regionally extensive blanket of Hardinsburg marine shale and local sandstone at the southern margin of the outcrop belt (sections 23 and 24) make up the transgressive part of the sequence. The laterally restricted, evenly, medium to thin bedded tidally influenced sandstones (section 23) grade laterally and are overlain by marine shale. The shale grades upwards into the Glen Dean argillaceous, skeletal packstone with storm beds, and diverse open marine fossil assemblages. Parasequences can only be recognized in the Pine Mountain belt. Here the lower parasequence is a skeletal packstone flanked by carbonate muds, shallowing up into a skeletal grainstone bank and flanking ooid shoals, and an eolianite veneer (section 24 to 27) and erosional disconformity (sections 25 and 26). The upper parasequence uniformly drapes the lower parasequence and is up to 15 m thick. It consists of open marine, storm-influenced skeletal packstone. The Glen Dean skeletal limestones gradually thin onto the northern block (sections 27 to 10). The top of the Glen Dean sequence is a paraconformity overlain by marginal marine green and gray shale, peritidal dolomites and paleosols, and siliciclastics of the Late Mississippian Paragon-to Pennington Formation.

Subsurface Correlation:

The study interval, which is an important hydrocarbon producer in the Appalachian Basin (Kelleher and Smosna, 1993), contains oolitic reservoir facies. However, the regional subsurface correlation of the interval is limited to tracing the "Big Lime" (Greenbrier and equivelant units), Pencil Cave (Lillydale/Hardinsburg), and Little Lime (Glen Ray/Glen Dean). This is because the "Big Lime" interval is dominantly a limestone unit lacking regional siliciclastic units that might form markers on the wire-line logs.

This study suggests that the sequence-bounding disconformities are veneered by thin, marine, flood-back clays. These shales (high gamma-ray signal and and low bulk density) show a distinctive signal on the wire-line logs, and can be tied into adjacent outcrops. A traverse of outcrop and core sections, and wire-line logs (showing gamma-ray and density for each well) from adjacent wells along the Cincinnati Arch belt in eastern Kentucky is shown in Plate 5 (Appendix E). The main sequence-bounding disconformities show on the logs. Once the disconformities have been defined on the well-logs by correlating them with the detailed stratigraphy in the outcrop belt, these "markers" can be extended into the subsurface away fron the outcrop. A regional cross-section from the top of the lower Mississippian Black shale to the top of the "Little Lime" (Glen Dean) is shown on Plate 6 (Appendix E). The study interval, which overlies the Price/Borden deltaic complex, contains regional log markers at the top of Paoli, top of Beaver Bend, top of Beech Creek, top of Heny, and top of Glen Dean sequences. This allows these to be mapped regionally in eastern Kentucky and south-central West Virginia.

DISCUSSION

Duration of Sequences and parasequences

As in West Virginia and in the Illinois Basin, the absolute age control on the study interval (Fig. 10) is poorly constrained due to error bars on radiometric data, and the difficulties in inter-continental correlation between Mississippian brachiopod, conodont, and foraminiferal zones. However, the eleven sequences in the study interval in Kentucky (St. Louis to Glen Dean) are estimated to have average durations within the eccentricity band of Milankovitch periodicity (~ 400 k.y.; see Chapter 4 Discussion). These depositional sequences in eastern Kentucky are disconformity-bounded as opposed to the more conformable sequences in West Virginia/Virginia (Chapter 4). It is conceivable that a significant amount of the sequence duration is a hiatus represented by each sequence-bounding disconformity.

There are a maximum of 25 parasequences (Fig. 6B) within the study interval, which given the likely 3 m.y. total duration of the interval (Smith, 1996; Chapter 3, this paper) results in an average parasequence duration of ~120 k.y., which suggests that they lie within or below the eccentricity band of Milankovitch cyclicity.

Tectonics and Subsidence Rates

The Mississippian carbonates in Kentucky were deposited on the distal margin of the actively subsiding Appalachian foreland basin. The Renfro through St. Louis sequence (Fig. 6B) was deposited with no rapid lateral thickening and with little evidence of major differential subsidence (Khetani, 1997). The absence of the Renfro-to St. Louis interval on the eastern side of the Waverly Arch due to erosion (Ettensohn, 1975; 1980) or non-deposition indicates that the eastern side of the Waverly Arch (Ettensohn, 1975, 1980) resisted subsidence at this time (Figs. 6B and 6C). Differential subsidence is evident in the rapid lateral thickening and thinning of the sequences over the several tectonic and structural elements that post-date St. Louis deposition. Differential subsidence is greatest in the lower part of the study interval (St. Louis to "Warix Run" sequences) (Fig. 6B), differential subsidence is still evident, but to a lesser extent up to the Beaver Bend Sequence (Fig. 6B). This marked differential subsidence in Kentucky is synchronous with the pronounced differential subsidence of the ramp nearer to the basin in West Virginia/Virginia.

Reactivation of the Irvine-Paint Creek fault system within the Cambrian Rome Trough began by the end of deposition of the St. Louis sequence (Dever, 1986; 1995), which is evident by soft sediment deformation at sections 13 and 14. Subsidence continued on the southern down-dropped block relative to the northern-block, which remained above sea-level during Ste. Genevieve to "Warix Run" deposition to the south (Fig. 6B). Facies similar to those in the Ste.

Genevieve-to "Warix Run" sequences had been defined on the northern block (Butts, 1922; Dever, 1973; Ettensohn, 1975, 1980). However, the lack of Ste. Genevieve biostratigraphic markers on the northern block (north of the Irvine-Paint Creek fault system) (Butts, 1922; Dever, pers. Com., 1996) and detailed, high-resolution correlation of this study, indicate that the St. Genevieve to "Warix Run" sequences onlap the top St. Louis sequence boundary, but were never deposited on the northern block (Fig. 6B).

During Paoli-to Beaver Bend deposition, the eastern side of the Waverly Arch subsided while the western side remained high (Ettensohn, 1975, 1980; and Fig. 6C). This reversed the formerly southwest paleoslope to the east and is synchronous with relaxation of thrust-loading in the foredeep (see Chapter Four). High-energy, tidal channel fills of quartzose peloidal grainstone (Fig. 6C) were deposited in incised channels on the northern block during the Paoli-to Beaver Bend interval, perhaps during lowered sea-levels.

The basement high marked by the Greenwood Anomaly resisted subsidence during Ste. Genevieve deposition (Dever et al., 1990; and Fig. 6B), synchronous with the subsurface Perry County and Paint Creek uplifts (Dhom, 1963; MacQuown and Pear, 1983) and the West Virginia dome (Yeilding and Dennison, 1986) (Fig. 2A). These active structural elements during the Ste Genevieve-to "Warix Run" deposition may have been local fault-blocks in the foreland, that were reactivated during the onset of thrust-loading of the proximal foreland basin margin.

The younger Paoli-to Reelsville sequences were deposited across the ramp and onto the northern block (Figs. 6B and 6C), perhaps indicating that the foreland started to subside more uniformly. This is consistent with the reduced differential subsidence in the proximal foreland in West Virginia/Virginia at this time. Some differential subsidence across the Waverly Arch persisted through the Beech Creek-to Haney interval, but there was less accommodation on the western side, toward the Cincinnati Arch, causing thinning of the units (Ettensohn, 1975, 1980; and Fig. 6). However, relatively uniform regional subsidence continued during deposition of the Beech Creek-to Glen Dean sequences (Figs. 6B and 6C).

Regional Correlation

Possible regional correlation between the eastern Illinois Basin (Smith, 1996) and the Kentucky and West Virginia portions of the Appalachian Basin are shown in Figure 12. Unconformities in the Illinois Basin are labeled A to Q after Smith (1996). Approximately five sequences occur in the Denmar-Taggard interval, West Virginia/Virginia and the Ste. Genevieve- "Warix Run" interval, Kentucky, although they occur in the same biozone, but it is not certain that these are the same units because they have not been tied together in the subsurface. Although Smith (1996) mapped 2 to 3 sequences in the Illinois Basin in this interval, five regionally traceable, disconformity-bounded units can be traced up-dip onto the margin of the Illinois Basin into the Cincinnati Arch area, and it is possible that these units are the same as those mapped in the Appalachian Basin.

Base of the Paoli and Pickaway appear to be synchronous (Butts, 1922, 1940, 1941; Wells, 1950). Two sequences can be mapped in the Paoli interval in the eastern Illinois Basin and the Pickaway in West Virginia. In Kentucky, the Paoli interval is a disconformity-bounded sequence that contains two regional parasequences that likely are time-equivalent to these two sequences mapped elsewhere.

The Beaver Bend sequence can be mapped regionally from the Illinois Basin (where it locally has a basal lowstand Bethel sandstone) (Smith, 1996), and it appears to be equivalent to the Lower Union sequence G3 in West Virginia (de Witt and McGrew, 1979).

The Reelsville sequence of the Illinois Basin can be mapped into the Kentucky Appalachian basin where it is a thin disconformity-bounded unit. Although de Witt and Mc Grew (1979) equate Reelsville with upper Union, it appears to be equivalent to the thin sequence G4 (middle Union) in the West Virginia Appalachian Basin.

The Beech Creek sequence, which in the Illinois Basin has the basal Cypress Sandstone and upper Big Clifty Sandstone can be mapped into the Kentucky Appalachian Basin, and appears to correlate with sequence 4B (upper Union and perhaps lower Alderson) (de Witt and Mc Grew, 1979).

The Haney sequence is traceable throughout the region, and is sequence G5 (correlative with the bulk of the Alderson limestone) in the Appalachian Basin of West Virginia/Virginia (de Witt and Mc Grew, 1979).

The Glen Dean sequence, which in Kentucky and the Illinois Basin has a basal sand or shale (Hardinsburg), is sequence G6 in the West Virginia Appalachian Basin, composed of the Lillydale shale and overlying Glen Ray limestone of the lower Bluefield Formation (de Witt and Mc Grew, 1979).

Thus most of the sequences can be correlated between the Illinois and Appalachian Basins, and across the intervening Cincinnati Arch. This strongly suggests a eustatic rather than local tectonic origin for the sequences.

Eustasy

The eleven depositional sequences in the St. Louis-to Glen Dean interval in eastern Kentucky are bounded by regionally traceable disconformities in the study area (Fig. 6B and 10). These regional disconformities likely were due to exposure of the ramp during periods of lowered sea-level. The low subsidence rates of the distal foreland of eastern Kentucky promoted the emergence of sequences during lowstands of sea-level. In contrast, more conformable sequences developed bordering the more rapidly subsiding basin in West Virginia/Virginia. Component parasequences are best developed down-dip (on the southern block and Pine Mountain areas) where greater accommodation space formed by higher subsidence rates.

The depositional sequences are traceable into time-equivalent sequences toward the axis of the Appalachian Basin (Chapter 4) and the Illinois Basin (Smith, 1996). The sequences (~ 400 k.y.) and their component parasequences (~ 100 k.y.) are within the eccentricity band of Milankovitch periodicity, which seem to be the overriding signature during times of continental glaciation (Heckel, 1986; Smith, 1996). This is consistent with the study-interval being synchronous with the early Chesterian onset of the southern hemisphere Gondwana glaciation (Frakes et al., 1992; Smith, 1996). It is likely that eccentricity-driven glacio-eustatic sea-level changes associated with Gondwana ice-sheet formed the fourth-order sequences and component parasequences. The regional flooding of the ramp during eustatic rises, the relatively shallow facies developed, and formation of regional disconformities during sea-level falls, suggest sea-level changes of perhaps ten to a few tens of meters (Smith, 1996). This contrasts with green-house cycles, which are capped by regional tidal flat facies, and poorly developed bounding disconformities, and which appear to have formed under sea-level fluctuations of 10 meters or less (Koerschner and Read, 1989; Goldhammer et al., 1990, 1991; Osleger and Read, 1991). Increased amplitude sea-level fluctuations with time may be reflected in the increasingly open marine facies upsection, but this is difficult to separate from the effects of the long term transgression that formed the supersequence TST. The Chesterian interval is transitional into the higher amplitude sea-level fluctuations that formed the Pennsylvanian cyclothems (up to 100 m total rise-fall; Heckel, 1986)

Controls on Supersequence and Sequence Development

Development of the Mississippian Supersequence, Eastern Kentucky:

The study interval in eastern Kentucky forms the retrogradational or transgressive limb of the Mississippian supersequence (Fig. 3A), which is composed of eleven backstepping fourth-order sequences. The lower sequences (St. Louis-to Beaver Bend) are dominated by eolianites, and shallow water lagoonal muds and oolite, and lesser open marine facies, whereas the upper sequences of the Beech Creek- to Glen Dean interval, adjacent to the maximum flooding of the supersequence, contain more open-marine, skeletal grainstone ramp facies (Fig. 6B). Fourth-order sequences in Kentucky do not show obvious stacking into composite, third-order sequences, which are better developed down-dip in West Virginia/Virginia, where siliciclastic units are developed near third order sequence boundaries. However, the abundant eolianites in the Ste. Genevieve-to "Warix Run" sequences appear to correlate with prograding red-beds and lowstand sands at the top of the Denmar composite sequence in West Virginia/Virginia (Chapter 4) (Figs. 5B, 6B and 11).

Following maximum flooding, accommodation started to decrease and the carbonate ramp was covered by Paragon-to Pennington siliciclastics that prograded in from the north and east, which is at a considerable angle to the

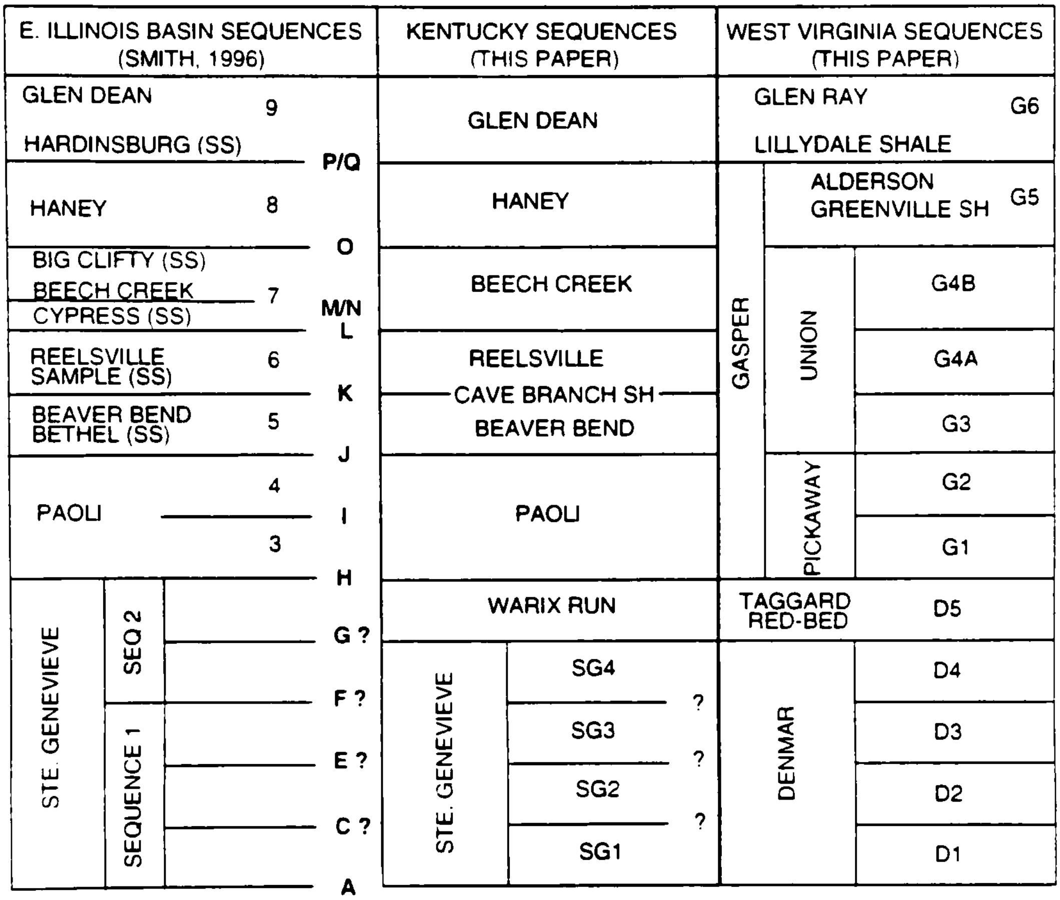


Fig. 11 Regional correlation chart of sequences from the Illinois Basin into the Appalachian Basin of eastern Kentucky and West Virginia/Virginia.

northwest to southwesterly progradation directions of the underlying St. Louis-to Glen Dean carbonates.

The semi-arid climate influenced the widespread development of oolitic reservoir facies on the ramp in generating waters supersaturated in calcium carbonate. As the climate became more humid higher in the section, the development of oolite shoals may have decreased and skeletal banks became widespread, although this effect is difficult to separate from the effects of the long-term transgression that formed the study interval. Semi-arid climate also promoted widespread caliche development on unconformity surfaces. With more humid climate, the disconformities became dominated by karstic features (Ettensohn et al., 1988).

Fourth-order Sequence Development

Local tectonics interacted with Eustasy to control the distribution and development of the fourth-order sequences and parasequences. During fourth-order eustatic sea level lowstands, the ramp on the distal foreland of eastern Kentucky was exposed to form regionally traceable, sequence-bounding disconformities, which amalgamate and stack over local tectonic highs. Correlative lowstand sand bodies and banks were formed down-dip along the ramp margin in the foredeep of West Virginia/Virginia (Chapter 4).

Fourth-order eustatic sea level rises formed depositional sequences that thin and pinch out over tectonic highs. In the Illinois Basin, a thin but clearly recognizable TST is developed in the fourth-order sequences, which are composed of regionally traceable parasequences (Smith, 1996). In contrast, in fourth-order sequences in the Kentucky Appalachian Basin, the TST's and maximum flooding surfaces are only poorly defined, and parasequences are few and rarely can be traced throughout the region. This is due to the limited accommodation in the Kentucky portion of the Appalachian Basin compared to the Illinois Basin and the proximal Appalachian Basin. Consequently, fourth-order sea-level rises of about ten meters formed a broadly submerged tide-and wave-agitated ramp dominated by widespread grainstone shoals. As sea-level fell, grainstone units in up-dip areas and locally down-dip, became capped by lime mudstone, and regional disconformities to form fourth-order sequences a few meters to ten meters thick. Higher in the TST of the supersequence, widespread marine shales and minor tidal sandstones (basal Beech Creek, basal Haney and Hardinsburg) were deposited above sequence boundaries. These fine-grained siliciclastics may have been transported to the shallow shelf as a result of more humid climate in the hinterland. Each subsequent fourth-order sea-level rise shut down this siliciclastic deposition, which was succeeded by regional carbonate deposition.

The St. Louis sequence formed above the post-Renfro sequence boundary (Khetani, 1997) as a back-shoal facies behind a major down-dip ooid shoal (Fig. 6B), during a time of little tectonic activity or differential subsidence. The Ste. Genevieve-to “Warix Run” sequences were formed during long-term sea-level rise, and superimposed fourth-order sea-level changes caused progressive onlap of the distal foreland and northern block during reactivation of differential subsidence along the Irvine-Paint Creek fault system (Dever, 1986, 1995) (Fig. 6B). Eustatic fluctuations influenced the regional extent of the Ste. Genevieve-to "Warix Run" sequences, but the elevated position of the northern block and the Greenwood high, and subsidence of the southern block limited the deposition of this interval to the southern block and Pine Mountain belt. As long-term sea-level rise gradually flooded the ramp, the increasingly open marine Paoli-to Glen Dean sequences (Fig. 6B) were deposited. Reduced differential subsidence at this time caused deposition of sequences of relatively uniform thickness, that lack the marked onlap of the lower units.

Parasequence Development

Regionally mappable parasequences within the fourth-order sequences in Kentucky (as in the "Warix Run") may be due to superimposed higher frequency sea-level changes on fourth-order sea-level fluctuations. The parasequences are dominated by shallow-water facies (Fig. 6B), reflecting the low accommodation on the distal foreland. Rapid flooding of the ramp formed transgressive ooid shoals and tidal ridges (?) over sequence and parasequence boundaries, and skeletal banks and open marine packstones down-dip. Fourth-order eustatic sea-level highstands resulted in the progradation of grainstone units and gradual shallowing of parasequences up into lagoonal carbonate muds and eolianites, especially below sequence boundaries. During the high-frequency sea-level falls, eolianites and disconformities capped the parasequences up-dip or near sequence boundaries. However, down-dip parasequences, or those in the lower parts of the fourth-order sequences tended to be bounded by a flooding surface and were not exposed significantly due to greater accommodation.

The scarcity of regional parasequences within fourth-order sequences when compared with thicker sections in the Illinois Basin (Smith, 1996), suggests that only the parasequence(s) associated with fourth-order maximum flooding were deposited on the relatively slowly subsiding, distal Appalachian foreland. Alternatively, regional parasequences may not have developed because of lower sedimentation rates or high-energy conditions, which inhibited development of muddy caps to grainstone shoals as high frequency sea-level fell. This may be the situation in the Pine Mountain belt, where superimposed high frequency sea-level changes were recorded as parasequences in areas of high accommodation and locally high sedimentation rate (Fig. 6B). But, elsewhere they are represented by monotonous subtidal grainstone units. More local clinoformed parasequences (such as the Beaver Bend) likely reflect higher frequency sea-level changes superimposed on a regressive fourth-order sea-level fall (Fig. 6B). Some locally developed parasequences (as in many of the Pine Mountain sequences) may be autocycles due to localized shoaling due to high sedimentation rates, and may be unrelated to high frequency sea-level changes.

Controls on Reservoir Development

Subsidence related to loading during early onset of the Alleghanian Orogeny coupled with long term second-order sea-level rise, resulted in major backstepping of the oolite facies on the ramp during the long-term transgression of the second-order supersequence. The up-dip position of these oolitic reservoirs on the ramp suggests that low accommodation was needed to maintain the ramp in relative shallow water (maximum of a few meters) favorable for oolite production. Consequently, as the second-order transgression continued, the ramp gradually deepened, and skeletal facies succeeded oolitic reservoir facies, except where higher frequency sea-level changes reduced accommodation for a short time to produce thin oolitic units such as in the lower and upper parts of the down-dip Beech Creek and Haney sequences, and the lower Glen Dean sequence (Fig. 6B). Development of oolite reservoir productivity virtually was shut down following the maximum flooding of the supersequence (top of the Haney sequence). The decrease in oolite facies also was due to a more humid climate, which decreased oolite production. Finally, oolite/skeletal facies were succeeded by prograding marine siliciclastic shale and sandstone during the HST of the second-order sequence.

Vertical partitioning of the reservoirs strongly reflects fourth (and higher) order eustasy. This caused oolite shoals to be capped by low permeability facies such as lagoonal mudstone, calichefied oolites associated with disconformities or quartz peloid eolianite, which compacted to form a tight facies. In a few cases, impermeable shales above sequence boundaries cover the underlying oolite shoals to form a seal. Lateral continuity of the shoals was controlled by tidal currents/waves which molded the grainstones into narrow elongate ridges in the Appalachian basin-margin (Kelleher and Smosna, 1993) and in the Illinois Basin (Smith, 1996).

Lack of regional tidal flat facies on the ramp appear to reflect the dominance of fourth-order moderate amplitude eustasy. Because sea-level fell faster than tidal flats could prograde, disconformities developed, extending out onto all subjacent facies. The general lack of tidal flats generally inhibited regional dolomitization of the oolite shoals to form dolomite reservoirs even though the climate was semi-arid and highly favorable to dolomitization. The moderate amplitude fourth-order eustasy was important in developing abundant stacked oolitic grainstone reservoir facies, because of repeatedly generated water depths and energy conditions favorable to oolite formation.

During greenhouse times, such as the Cambrian-early Ordovician and the Triassic, low-amplitude, high-frequency sea-level changes generated ramps dominated by muddy peritidal upward shallowing cycles, in which grainstones are limited to the deeper outer parts of the ramps (Koerschner and Read, 1989; Goldhammer et al., 1990, 1991; Osleger and Read, 1991). At the other extreme, high amplitude Eustasy leads to rapid deepening, and water depths may become too deep for the formation of extensive oolite shoals except at the tops of cyclothems (Heckel, 1986). It appears that moderate-amplitude, fourth-order

Eustasy generated the most favorable water depths and energy conditions for widespread oolite reservoir development.

CONCLUSIONS

1. The Mississippian St. Louis to Glen Dean interval in the distal foreland of the Appalachian Basin, eastern Kentucky, forms the transgressive portion of the Mississippian supersequence. It consists of a series of onlapping fourth (?) order disconformity-bounded sequences (2 to 15 m thick) dominated by oolite and skeletal grainstone.
2. Relaxation of the Late Devonian-Early Mississippian thrust-load, coupled with topography produced by the Price/Borden delta, appear to have generated a northeast-to-southwest paleoslope. Renewed loading initiated a northwest-to-southeast paleoslope and marked differential subsidence on the foreland. This differential subsidence, associated with fault-bounded basement blocks, resulted in rapid lateral thickening and thinning of the sequences and component parasequences, especially during Ste. Genevieve-to "Warix Run" deposition. This differential subsidence decreased later as relaxation of the load took place.
3. The interval contains eleven fourth-order, disconformity-bounded depositional sequences, with estimated durations of ~ 400 k.y. per sequence, and a total of 25 local to regional parasequences in the interval, averaging ~ 100 k.y. per parasequence. The sequences and their component parasequences appear to fall within the long- and short-term eccentricity

band of Milankovitch orbital forcing, and is compatible with onset of global ice-house conditions on Gondwana in the early Chesterian.

4. The dominance of fourth-order, moderate amplitude eustasy generated a succession of disconformity-bounded, widespread grainstone-dominated sequences, that backstep in response to the long-term relative rise of the Mississippian sea-level supercycle. This fourth-order eustasy generally formed stacked oolitic reservoirs partitioned by regressive muddy carbonates, eolianites and calichefied disconformities.

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APPENDIX A: LOCATIONS OF SECTIONS IN EASTERN WEST VIRGINIA AND SOUTHWESTERN VIRGINIA

Section 1	Canaan Valley Section. Roadcut along Rt. 32, 10 miles south of Davis, just south of entrance to Cannan Valley State Park. Blackwater Falls Quadrangle, Tucker County, West Virginia. (Denmar to Mauch Chunk red-beds avove the Glen Ray)
Section 2	Randolph 28 Well Cuttings. (Cuttings kept at the West Virginia Economic and Geological Survey, Morgantown), Adolph Quadrangle, Randolph County, West Virginia. (Denmar to Lillydale)
Section 3	Mingo Section. Roadcut along Rt. 219 at the intersection with Mingo flats road. Mingo Quadrangle, Randolph County, West Virginia. (Denmar to Glen Ray)
Section 4	Greenbrier 21 Wire-line logs and Cuttings. (Cuttings and wire-line logs kept at the West Virginia Economic and Geological Survey, Morgantown), Cornstalk Quadrangle, Greenbrier County, West Virginia. (Denmar to Lillydale and overlying snadstone [?])
Section 5	Summers 7 Wire-line log and Cuttings. (Cuttings and wire-line logs kept at the West Virginia Economic and Geological Survey, Morgantown), Dawson Quadrangle, Summers County, West Virginia. (Denmar to Lillydale)
Section 6	Sun Oil Core and Gamma-Ray Log. (Core is biscuited and kept, along with the gamma-ray log, at the West Virginia Economic and Geological Survey, Morgantown). Lobelia 15' Quadrangle, Droop 7.5' Quadrangle, Pocahontas County, West Virginia. Top of Price, Hillsdale (?), Denmar to Glen Ray)
Section 7	Greenbrier 15 Well-cuttings. (Cuttings are kept at the West Virginia Economic and Geological Survey, Morgantown), Asbury Quadrangle, Greenbrier County, West Virginia. (Hillsdale to Lillydale)
Section 8	Union Section. Roadcut along Knobs Road, north of the intersection with Rt. 219 at Union, Union Quadrangle, Monroe County, West Virginia. Pickaway to Glen Ray)

Section 9	Mercer 25 Wire-line log and Cuttings. (Cuttings and wire-line logs kept at the West Virginia Economic and Geological Survey, Morgantown), Athens Quadrangle, Mercer County, West Virginia. (Hillsdale to Glen Ray)
Section 10	Ingleside Section. Roadcut along railroad tracks and along I-77 near mile post 5 in overturned beds. Mercer County, West Virginia. (Hillsdale to Denmar)
Section 11	Holston Section (Muddy Hollow Section of Bartlett and Webb, 1971). Roadcut along Muddy Hollow, 0.2 miles south of junction of State Roads 616 and 798, section starts just south of the Holston River North Fork, Greendale Syncline, Wallac Quadrangle, Washington County, Virginia. (St. Louis [Hillsdale to Fido Snadstone and overlying basal Cove Creek Limestone)

APPENDIX B: LOCATIONS OF SECTIONS ALONG THE CINCINNATI ARCH, EASTERN KENTUCKY

Section 1	Roadcut along west bound lane of I-64, 10.2 miles west of intersection with KY Rt. 2 (This is the western most Mississippian carbonate outcrop along I-64 in northeastern Kentucky). Cranston Quadrangle (18-V-74), Rowan County. (Renfro to Haney)
Section 2	Roadcut along west bound lane of I-64. 0.2 miles east of Section 1 Cranston Quadrangle (18-V-74), Rowan County. (Renfro to Haney)
Section 3	Roadcut along west bound lane of I-64. 0.4 miles east of Section 1 Cranston Quadrangle (18-V-74), Rowan County. (Renfro to Hardinsburg, Pennsylvanian Lee Sandstone sits unconformably over the Hardinsburg).
Section 4	Roadcut along west bound lane of I-64. 0.9 miles east of Section 1 Cranston Quadrangle (19-V-74), Rowan County. (Renfro to Hardinsburg)
Section 5	Weigh Station Section. Roadcut along west and east bound lanes of I-64. 1.5 miles east of Section 1, Cranston Quadrangle (20-V-74), Rowan County. (Renfro to Haney)
Section 7	Armstrong Hill Section. Roadcut on KY Rt. 2 at the intersection with I-64. Olive Hill Quadrangle (23-W-76), Carter County. (Beaver Bend to Haney)
Section 8	Morehead Section. Roadcut along KY Hwy 519, 5.2 miles south of Morehead. Rowan County. (Reworked lithoclasts from the underlying St. Louis, ammalgammated paleosols at top of Paoli paleosol, Beaver bend to Hardinsburg)
Section 9	Cave Run Lake Section. Roadcut on KY Hwt 801, the intersection with KY Hwy 1274 is near the top of the section. Bangor Quadrangle (1-S-73), Rowan County. (Paoli to Hardinsburg, Pennsylvanian Lee Sandstone sits unconformably over the Hardinsburg)

Section 10 Slade Section. Roadcut along west bound lanes of Mountain Parkway, 2.5 miles east of the Slade off-ramp, Slade Quadrangle (11-P-70), Powell County. (Renfro to Glen Dean)

Section 11 Natural Bridge Stone Quarry. 1 mile south of Bowen, Stanton Quadrangle, Powell County. (Renfro to Glen Dean)

Section 12 Tipton Ridge. Roadcut along south side of KY Hwy 52, 4.1 miles northeast of junction with KY Hwy 1571. Irvine Quadrangle (14-O-68), Estill County. (Renfro to Haney. Haney to Pennington measured on the back side of the adjacent quarry).

Section 13 Drip Rock Section. Roadcut along south side of KY Hwy 89, 2 miles south of bridge across Station Camp Creek. Leighton Quadrangle (23-N-67), Estill County. (Renfro to Haney).

Section 14 Station Camp Creek. Roadcuts along east side of KY Hwy 1209, 10 miles south of junction with KY Hwy 89, Leighton Quadrangle (15-M-68), Jackson County. (Renfro to Glen Dean).

Section 15 Bighill Core. (Core kept at the Kentucky Highway Department, Frankfort, KY). Bighill Quadrangle (19-M-64), Madison County. (Renfro to Pennington).

Section 16 Renfro Valley Section. Roadcut along Interstate 75 near milepoast 61, Rockcasle County. (Ste. Genevieve to Glen Dean, Renfro to St. Louis measured half a mile north of this section).

Section 17 Mt Vernon Section. Section south of Mt Vernon, section starts at the intersection of KY Hwy 461 with KY Hwy 1326 and continues northward along Hwy 461, Rockcastle County. (Renfro to Glen Dean).

Section 18 Rockcastle Core. (Core kept at the Kentucky Geological Survey, Lexington, KY). Billows Quadrangle (13-I-63), Rockcastle County,. (Renfro to lower Paragon).

Section 19 Somerset Stone Co. Quarry. Sometset, Somerset Quadrangle (16-H-60), Pulaski County. (Warsaw (?), Renfro (?) to Haney).

Section 20	Burnside Island Section. Roadcut along west side of entrance road, General Burnside Island State Park, Burnside Quadrangle (10-F-59), Pulaski County. (Salem-Warsaw, Renfro (?), St. Lois, and lower Ste. Genevieve).
Section 21	Strunk Construction Quarry. Off Rt. 27 a few miles south of Burnside Island, Tateville . (Beaver Bend to lower Paragon).
Section 22	Bassett Stone Co. Quarry. Monticello, Monticello Quadrangle (10-D-56), Wayne County. (upper Ste. Genevieve to lower Paragon).
Section 23	Gaddie Shamrock Quarry. Albany, Albany Quadrangle (6-C-53), Clinton County. (upper Ste. Genevieve to Glen Dean).

APPENDIX C: LOCATIONS OF SECTIONS ALONG PINE MOUNTAIN, EASTERN KENTUCKY AND TENNESSEE

Section 24	Jellico Section. Roadcut along northbound lanes of I-75, just south of the Jelico off-ramp, Jellico, Tennessee. (Floyds Knob Bed, Fort Payne to Pennsylvanian siliciclastics)
Section 25	Harlan Quary. Along south side of u.s. hwy 421, 7.2 miles north of Harlan.Bledsoe Quadrangle (6-E-75), Harlan County, Kentucky. (St. Louis to lower Paragon).
Section 26	Hurricane Gap Section. Along east side of KY Hwy 160, 3.8 miles northwest of Cumberland, 0.8 miles south of Gordon. Louellen Quadrangle (2-F-78), Letcher County, Kentucky. (Renfro (?) Fort Payne (?), St. Louis (?), limestone section above the dolomite measured in the Quarry on the west side of the road)
Section 27	Elk Horn Core. Elkhorn City Quarry, Elkhorn, Elkhorn Quadrangle, Pike County, Kentucky. (Renfro (?) to Glen Dean)

APPENDIX D: LOCATIONS OF SECTIONS ACROSS THE WAVERLY ARCH, NORTHEASTERN KENTUCKY

Sections 1 to 7	See Appendix A
Section Z-519	Roadcut along west bound lanes of I-64, 4.5 miles west of intersection with U. S. 60, Olive Hill Quadrangle (2-V-76), Carter County. (Top Paoli unconformity rests on Borden, interval through Beech Creek)
Section Z-520	Roadcut along west bound lanes of I-64, 0.2 miles east of section Z-519, Olive Hill Quadrangle (2-V-76), Carter County. (Paoli to Beech Creek)
Section Z-523	Roadcut along west bound lanes of I-64, 1.1 miles east of section Z-519, Olive Hill Quadrangle (1-V-76), Carter County. (Beaver Bend to Haney)
Section Z-524	Roadcut along west bound lanes of I-64, 1.3 miles east of section Z-519, Olive Hill Quadrangle (1-V-76), Carter County
Section Z-525	Roadcut along west bound lanes of I-64, 1.4 miles east of section Z-519, Olive Hill Quadrangle (1-V-76), Carter County. (Paoli to Beech Creek)
Section Z-526	Roadcut along west bound lanes of I-64, 1.6 miles east of section Z-519, Olive Hill Quadrangle (1-V-76), Carter County. (Paoli to Beech Creek)
Section Z-527	Roadcut along west bound lanes of I-64, 1.8 miles east of section Z-519, Olive Hill Quadrangle (1-V-76), Carter County. (Paoli to Beech Creek)
Section Z-528	Roadcut along west bound lanes of I-64, 2.5 miles east of section Z-519, Olive Hill Quadrangle (1-V-76), Carter County. (Beaver Bend to Glen Dean)
Section Z-529	Roadcut along west bound lanes of I-64, 3. 8 miles east of section Z-519, 0.7 miles west of intersection with U. S. 60, Olive Hill Quadrangle (2-V-76), Carter County (Beech Creek to Glen Dean)

APPENDIX E: LOCATIONS OF SUBSURFACE WIRE-LINE LOGS

KENTUCKY:

Permit number 78028, Haddix Quadrangle (21-L-74), Brettitt County

Permit number 48370, Martin Quadrangle (16-M-81), Floyd County

Permit number 72514, Tyner Quadrangle (14-J-67), Jackson County

Permit number 66506, Lily Quadrangle (21-G-66), Laurel County

Permit number 71446, Lily Quadrangle (10-H-66), Laurel County

Permit number 62341, (13-N-71), Lee County

Permit number 74982, Kermit Quadrangle (19-Q-85), Martin County

Permit number 29846, Scranton Quadrangle (14-Q-72), Menifee County

Permit number 58705, West Liberty Quadrangle (22-R-75), Morgan County

Permit number 77725, Mistletoe Quadrangle (3-J-72), Perry County

Permit number 48007, Zachariah Quadrangle (8-O-70), Powell County

Permit number 76970, (14-H-63 [?]), Pulaski County

Permit number 16862, Livingston Quadrangle (23-K-64), Rockcastle County

Permit number 51133, Johnetta Quadrangle (11-K-64), Rockcastle County

Permit number 34478, Frakes Quadrangle (16-C-68), Whitley County

WEST VIRGINIA:

Permit number 1074, Madison Quadrangle, Boone County

Permit number 614, Powelton Quadrangle, Fayette County

Permit number 557, Ansted Quadrangle, Fayette County