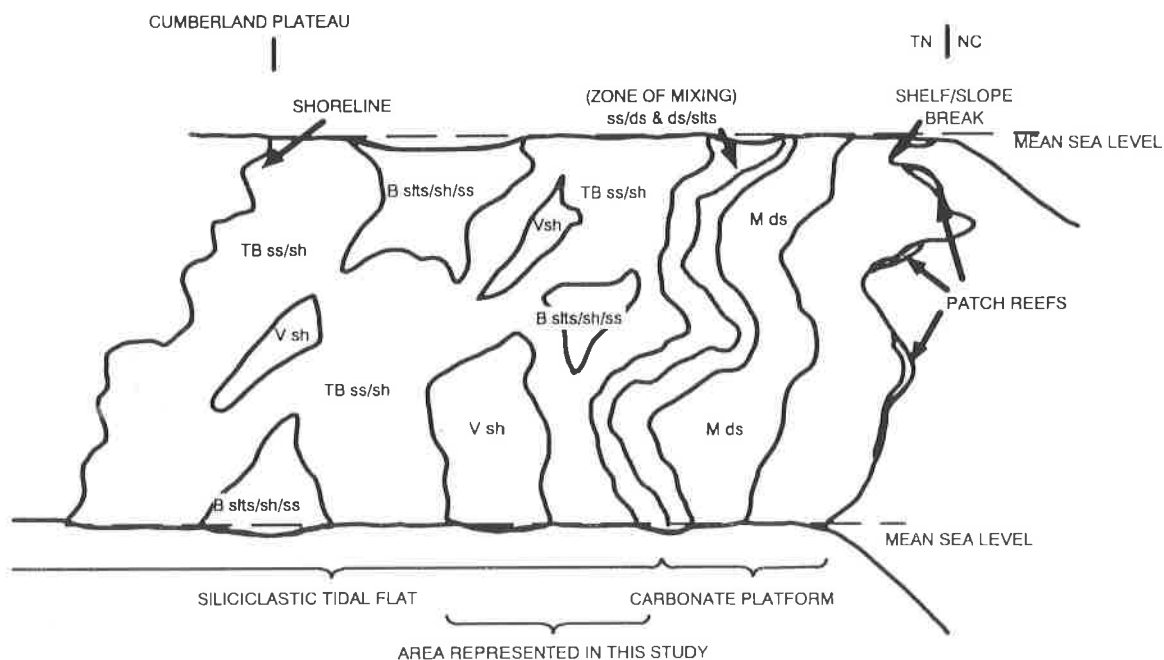


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PALEOENVIRONMENTS AND FACIES RELATIONS OF THE ROME FORMATION (LOWER CAMBRIAN) ALONG HAW RIDGE, ROANE AND ANDERSON COUNTIES, TENNESSEE

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ABSTRACT

The Rome Formation (Lower Cambrian) of East Tennessee is a mixed siliciclastic-carbonate deposit dominated by siltstone, sandstone, and shale with a subordinate dolostone component. We applied a detailed facies analysis to the Rome in a limited area and defined seven lithofacies along a fifteen kilometer segment of Haw Ridge in Anderson and Roane Counties, Tennessee, which contains Rome Formation exposed along strike within the Copper Creek thrust sheet. Three facies: *thin-bedded sandstone*, *variegated shale*, and *bioturbated siltstone* represent pure terrigenous clastic end-members interpreted as sub-environmental of a broad, expansive tidal flat environment that was frequently inundated by storms. Two other facies: *sandstone/dolostone*, and *dolostone/siltstone* are mixed siliciclastic-carbonate deposits, which represent the gradational boundary between pure terrigenous clastic facies and pure carbonate facies. The final two facies are pure carbonate end members: *massive dolostone* and *laminated dolostone* deposited in a quiet-water, back platform environment. Stratigraphic evidence indicates that the Rome inherited a "carbonate platform" type basin constructed during the deposition of underlying Shady Dolomite (or equivalent lowermost Rome carbonate), and that this basinal configuration forced the dominantly siliciclastic sediments of the Rome to take on a mosaic

stratigraphy more typical of carbonate sediments. This conceptual model helps explain the "uncorrelatable" stratigraphy commonly encountered in the Rome, and also accounts more easily for repeated shifts in Rome paleoenvironments through time which otherwise have been attributed solely to relative sea-level changes. The mixed siliciclastic - carbonate model provides an alternate viewpoint for interpreting Rome paleoenvironments and the groundwork for development of an improved regional paleoenvironmental model for the Rome Formation in East Tennessee.

INTRODUCTION

The Rome Formation (late Early Cambrian) of the Valley and Ridge Province in East Tennessee is generally treated as a terrigenous clastic sequence for paleoenvironmental interpretations. Although previous workers (Resser, 1938; Fox, 1943; Harvey and Maher, 1948; Rodgers and Kent, 1948; Spigai, 1963; and Samman, 1975) noted a significant dolostone component within the sandstone, siltstone, and shale dominated Formation, the stratigraphy and paleoenvironments were interpreted within a strictly clastic paradigm. This approach has met with limited success. To date, only a limited paleoenvironmental model for the Rome exists (Samman, 1975). The Rome should not be interpreted as a terrigenous clastic sequence, but instead, as a mixed siliciclastic - carbonate sequence.

The purpose of our study is to re-interpret Rome stratigraphy and paleoenvironments for

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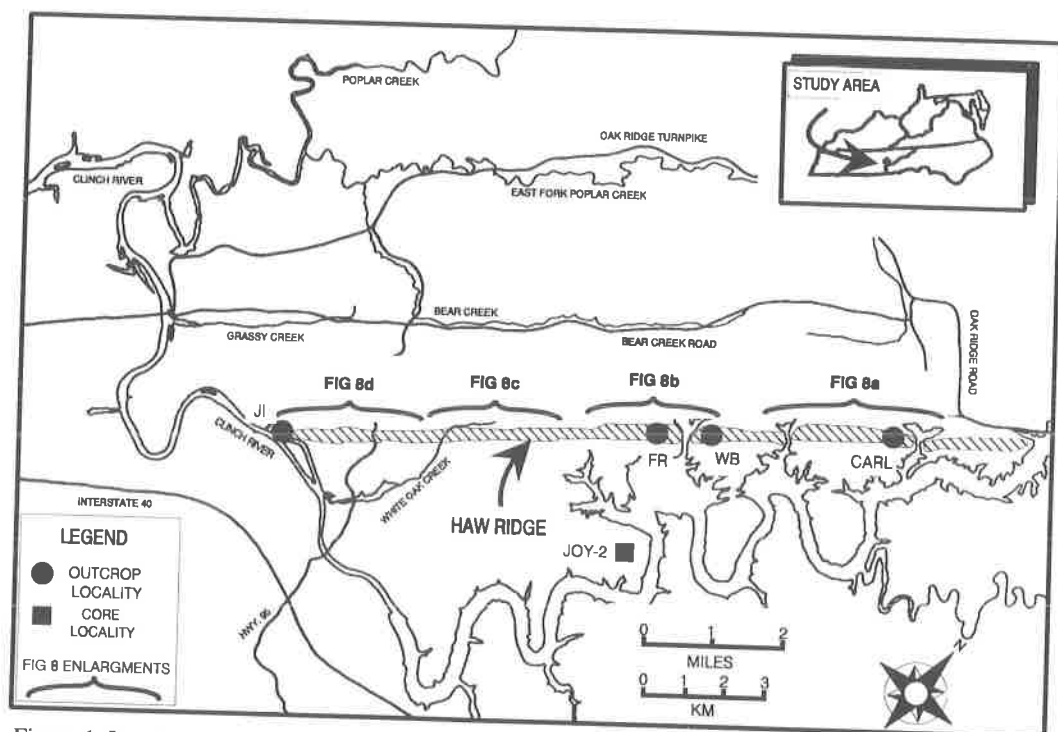


Figure 1. Location map of study area, located at the Oak Ridge National Laboratory near Oak Ridge, Tennessee. JI, FR, WB, and CARL indicate outcrop sections discussed in the text; Joy-2 locates the core utilized in the study. The hatched boxes locate Figures 8a - 8d, enlarged to show study area structure.

a small area in light of a mixed siliciclastic - carbonate paradigm and to determine if this alternate approach might be useful in constructing a better regional depositional and stratigraphic model.

Site and Methods of Study

The study area is on the U.S. Department of Energy Reservation in Oak Ridge, Tennessee (Figure 1). It extends along Haw Ridge from Jones Island on the Clinch River, in the southwest corner of the reservation, to Pumphouse Road behind the Scarboro Facility, in the northeast corner of the reservation. This fifteen kilometer segment of Haw Ridge contains Rome Formation exposed along strike within a single major thrust sheet, namely the Copper Creek thrust sheet. This eliminates any need for major palinspastic restoration of outcrop sections and the problems inherent to the procedure.

Outcrops at Pumphouse Rd. (CARL), Walker Branch (WB), Fuel Recycling (FR), and Jones Island (JI), as well as one drill core (JOY-2), were utilized for stratigraphic and sedimentologic data (Figure 1). The outcrops were measured in detail, and the Joy-2 core was logged on a centimeter-by-centimeter scale. Field mapping was conducted using enlarged 7.5' topographic quadrangles as a map base. Paleocurrent data gathered in the field were restored from structural deformation using the techniques described in Ragan (1973). Thin-section and slabbed hand-specimens were used to supplement and check field descriptions.

Regional Stratigraphy

The Shady Dolomite, Rome Formation, and Conasauga Group form a lithofacies-related and partially time-equivalent relationship across the Valley and Ridge of East Ten-

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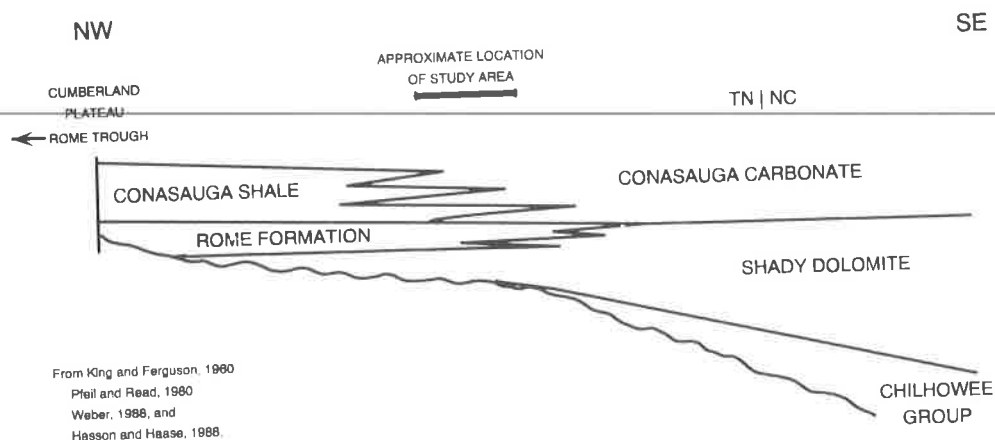


Figure 2. Stratigraphic relations of the Lower to Middle Cambrian sequence of eastern Tennessee. Note the intertonguing relationships of the Shady Dolomite, Rome Formation and Conasauga Group. (modified from King and Ferguson, 1960; Pfeil and Read, 1980; Weber, 1988; Hasson and Haase, 1988).

nessee (Figure 2; King and Ferguson, 1960; Harris, 1964; Samman, 1975; Haase and Hasson, 1988; Barnaby and Read, 1989). In general, the Rome is conformably overlain by the shale and carbonate strata of the Conasauga Group and is commonly fault-bounded at the base (Rodgers and Kent, 1948). Because of the fault-bounded base, the stratigraphic relations of the Rome with underlying units is poorly understood. The Rome is underlain conformably by the Shady Dolomite towards the east, at the boundary of the Valley and Ridge and Blue Ridge Provinces (King and others, 1944; King and Ferguson, 1960). The Formation thins to the northwest and onlaps Precambrian basement beneath the Cumberland Plateau in central Tennessee and eastern Kentucky (Harris, 1964).

The Rome is commonly subdivided into an upper sandy member and a lower shale member (Rodgers, 1953; Rodgers and Kent, 1948), and where basal sections are available, a thin limestone/dolostone unit has been observed at the base (Keith, 1895; Resser, 1938; Cattermole, 1955; Samman, 1975; McReynolds, 1988). Haase and others (1985) interpreted the lower shale member as being comprised of tectonically emplaced slices, whereas the upper member was considered a coherent stratigraphic section. Caution should

be used in dividing the Rome into these two members because entire outcrop belts of the Rome are typically composed of repeating imbricate slices bounded by thrust faults, which therefore invalidates such an upper and lower subdivision. Imbrication was a major problem in the Haw Ridge study area; thus, the two members of the Rome are not distinguishable.

Structural Controls on Stratigraphy

The Rome Formation is the décollement of Alleghanian thrusting in the Valley and Ridge Province of Tennessee and forms the base of numerous southeastward-dipping imbricate thrust sheets (Harris and Milici, 1973). The thrust faults, in addition to removing the base of the Formation, created large outcrop voids between thrust sheets in which no Rome section is exposed at the surface. The net result is that correlation across the basin in a dip direction is almost impossible. Another equally important consequence of this structural pattern is the disturbance of original stratigraphy within the Rome, which creates problems in determining the thicknesses of even partial Rome sections. Entire outcrop belts of the Rome are composed of repeating imbricate slices bounded by thrust faults. If measured

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sections in the Rome are to represent true stratigraphic thicknesses, imbrication and other structural components must be recognized and taken into account. Some previous workers (Samman, 1975; Spigai, 1963) have noted, but not accounted for, structural deformation in the Rome. Thus, their reported stratigraphic thicknesses of 200 to 300 meters in the western Valley and Ridge are undoubtedly exaggerated. We have estimated the thickness of the Rome in the study area of approximately 100 m thick after accounting for structure. This agrees with the 90 to 125 m range for partial thicknesses determined by Haase and others (1985). The Rome section is known to thicken considerably eastward into the basin and estimates up to 550 m have been made for the Rome in the eastern Valley and Ridge (King and Ferguson, 1960).

Geomorphology

The Rome Formation crops out along southwest-to-northeast trending ridges which have a distinct steep slope and "cockscorn" morphology. In our experience, most Rome ridges are held up by thick-bedded, resistant sandstone layers common in the uppermost part of the Formation. The amount and type of tectonic structure in the Rome are also believed to control ridge morphology. Thus, ridge morphology can provide insight into the structures contained in the Rome where outcrops are inconclusive or absent. For example, a single well-formed ridge generally suggests a single, unduplicated, and relatively undeformed Rome section, whereas a broad dissected ridge with several peaks indicates a duplicated Rome stratigraphy that consists of several imbricate slices containing resistant sandstone layers (McReynolds, 1988; Woodward and Beets, 1988).

FACIES ANALYSIS

Lithofacies Description

In the Haw Ridge area, seven lithofacies

were recognized: *thin-bedded sandstone and shale facies* (TB ss/sh), *variegated shale* (Vsh), *bioturbated sandstone/siltstone/shale* (B sh/slts/ss), *sandstone/dolostone* (ss/ds), *dolostone/siltstone* (ds/slts), *massive dolostone* (M ds), and *laminated dolostone* (Lam ds). The facies are summarized in Table 1. The first three lithofacies described are the pure terrigenous clastic end-members of facies observed in the study area. The next two facies are mixed carbonate-terrigenous clastic deposits, and the final two facies are the relatively pure carbonate end-members. The lithofacies were defined from the hand sample- to outcrop-scale for easy recognition in the field, and confirmed with thin-section data. Lithologic composition, grain size, and sedimentary structures were the major criteria used to define lithofacies.

Structural Imprint on Facies

Lithofacies in the study area cannot be easily correlated among the four primary outcrop sections. Similar lithologies occur at all outcrops, but the sequence at each is different. In addition, the total stratigraphic thicknesses at each are markedly dissimilar, with 57 m of Rome at the CARL section (Figure 4), 220 m at the FR section (Figure 5), 200+ m at the WB section (Figure 6), and 95+ m at the JI section (Figure 7). Because of these complications, detailed geologic mapping was undertaken in order to determine whether or not some of the sections are duplicated because of structure (Figures 8a-d: geologic map). Faults in the study area are generally indicated by abrupt changes in lithology, (most involving maroon shale overlying gray dolostone), combined with subtle discordance of bedding strike and dip at the lithologic boundary. Additionally, the topographic expression of Haw Ridge is a guide for noting these faults and their associated stratigraphic duplication.

Haw Ridge is divided into three structural blocks bounded by two tear faults (see Figure 1 for the location of Figures 8a-d, enlarged areas showing structural data). The CARL section is

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Table 1. Summary of Facies in the Rome Formation

FACIES NAME	FACIES DESCRIPTION	PROCESS INTERPR./PALEOENV.	FACIES ASSOCIATION
TB ss/sh (Thin bedded sandstone and shale)	Maroon, thin to medium-bedded fine-grained sandstone interbedded with shale. Micro-hummocky cross-stratification, ripple marks, wavy laminations, horizontal burrows and mudcracks are common.	Occurs across entire tidal flat in an alternating intertidal to subtidal open marine environment dominated by intense storm and normal tidal processes.	Most abundant facies occurs throughout the Rome and in association with B slts/sh/ss and Vsh.
V sh (Variegated shale)	Variegated, dominantly maroon, fissile shale with infrequent discontinuous thin-bedded siltstone.	Occurs on the tidal flat as a low-energy, quiet water, restricted to anoxic marine environment; coarser lenses represent storm beds.	A minor facies abundant in lower portions of the Rome. Ubiquitously associated with TB ss/sh and B slts/sh/ss facies.
B slts/sh/ss (Bioturbated siltstone, shale, and sandstone)	Red to maroon, bioturbated shaly siltstone interbedded with shale and thin discontinuous fine-grained sandstone beds.	Occurs on the tidal flat as open marine, intertidal to shallow subtidal, storm dominated environment in patches where benthic organisms thrived.	Abundant facies normally occurs in the lower portions of the Rome in association with Vsh and B slts/sh/ss facies.
ss/ds (dolomite sandstone to sandy dolostone)	Gray, thin to thick-bedded and massive, recrystallized, gradational dolomitic sandstone to sandy dolostone. Percentage of dolomite ranges from near zero to almost 100%.	Facies mixing environment as siliciclastics on the tidal flat merge with carbonate platform facies in back platform areas; probably intertidal; May contain penecontemporaneous dolomite.	A common facies abundant in the middle portions of the Rome and occurs as transition between TB ss/sh or B slts/sh/ss and Mds facies.
ds/slts (Interlaminated dolostone and siltstone)	Gray to red, interlaminated dolostone and micro-hummocky cross-stratified siltstone.	In Situ mixing in intertidal to supratidal tidal-flat depositional environment. Probably contains penecontemporaneous dolomite.	A rare facies that usually occurs near the base of the Rome in association with underlying Lam ds facies.
M ds (Massive dolostone)	Gray, massive recrystallized dolostone; bedding usually not distinguishable.	Deposited as a carbonate mud in back platform areas far behind the shelf edge reefs.	Common facies that commonly occurs in middle portions of the Rome and associated with ss/ds facies.
Lam ds (Laminated dolostone)	Gray, finely laminated dolostone with chaotic bioturbated intervals.	Underlies entire basin; intertidal to supratidal tidal-flat environment. Probably contains penecontemporaneous dolomite.	Very rare facies that occurs at the base of the Rome (only at J1). Associated with overlying ds/slts.

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COLOR		LITHOLOGY		SEDIMENTARY STRUCTURES	
G	- GRAY		DOLOSTONE		HUMMOCKY CROSS-STRATIFIED
DG	- DARK GRAY		SANDY DOLOSTONE		WAVY LAMINATED
G/G	- GREENISH GRAY		DOLOMITIC SANDSTONE		PLANAR LAMINATED
G/R & G	- GREEN TO RED AND GRAY ALTERNATING		SANDSTONE		FISSILE
M/R	- MAROON TO RED		SILTY SANDSTONE		MASSIVE
M/R & R/G	- MAROON TO RED AND RED TO GREEN ALTERNATING		SANDY SILTSTONE		NO DATA
			SILTSTONE		BIOTURBATED
R	- RED		SILTY SHALE		DESSICATION CRACKS
R/G	- RED TO GREEN		SHALE		CURRENT RIPPLE MARKS
R & G	- MOTTLED RED AND GREEN ALTERNATING		GLAUCONTIC		SALT "HOPPER" CASTS
R/GY	- RED TO GRAY		PHOSPHATIC		THIN-BEDDED
R/T	- RED TO TAN		FELDSPATHIC		MEDIUM-BEDDED
T	- TAN		FAULT		THICK-BEDDED
V	- VARIEGATED		COVERED		DISCONTINUOUSLY BEDDED

Figure 3. Key to symbols used in stratigraphic columns.

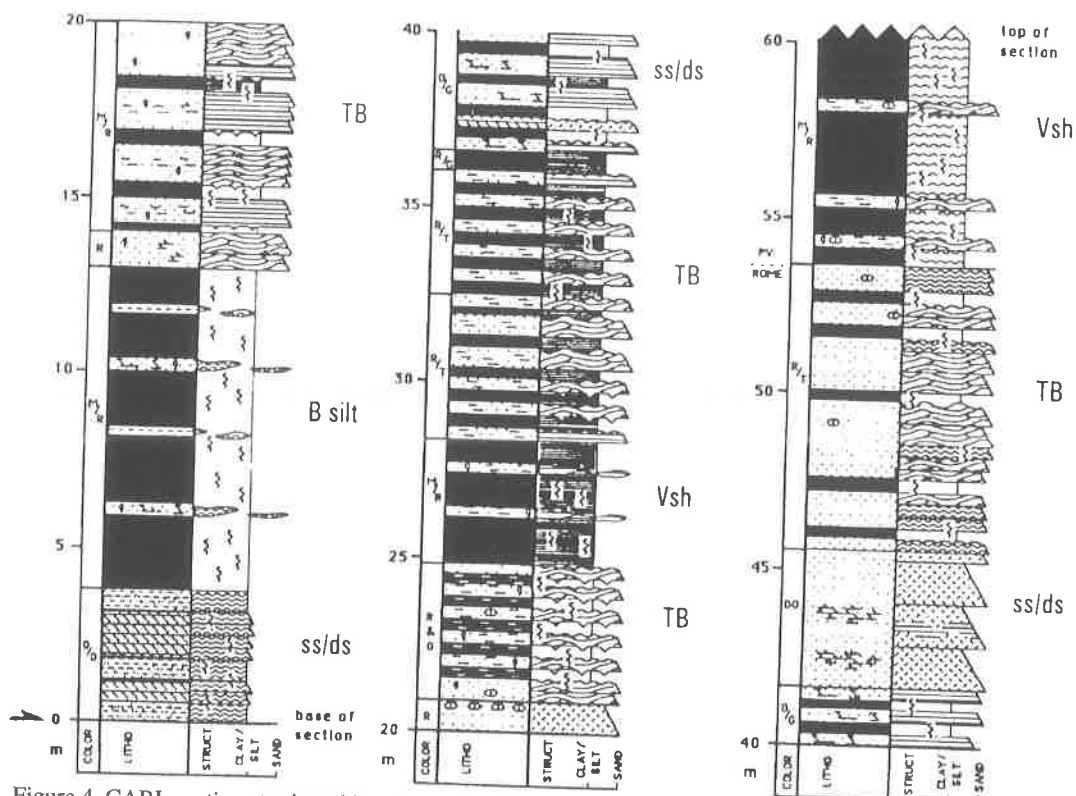


Figure 4. CARL section stratigraphic column. See Figure 3 for key to symbols.

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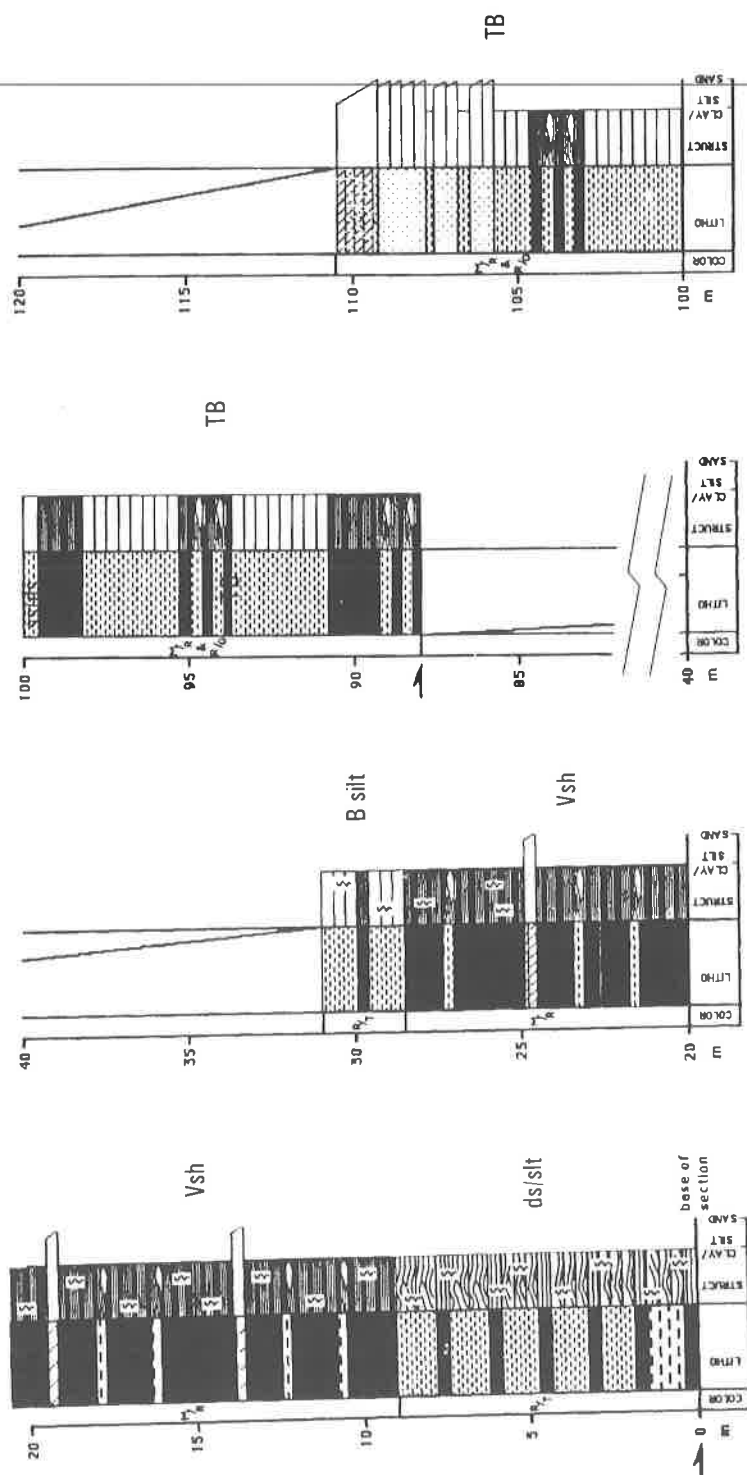


Figure 5. FR section stratigraphic column. See Figure 3 for key to symbols. Continued on next page.

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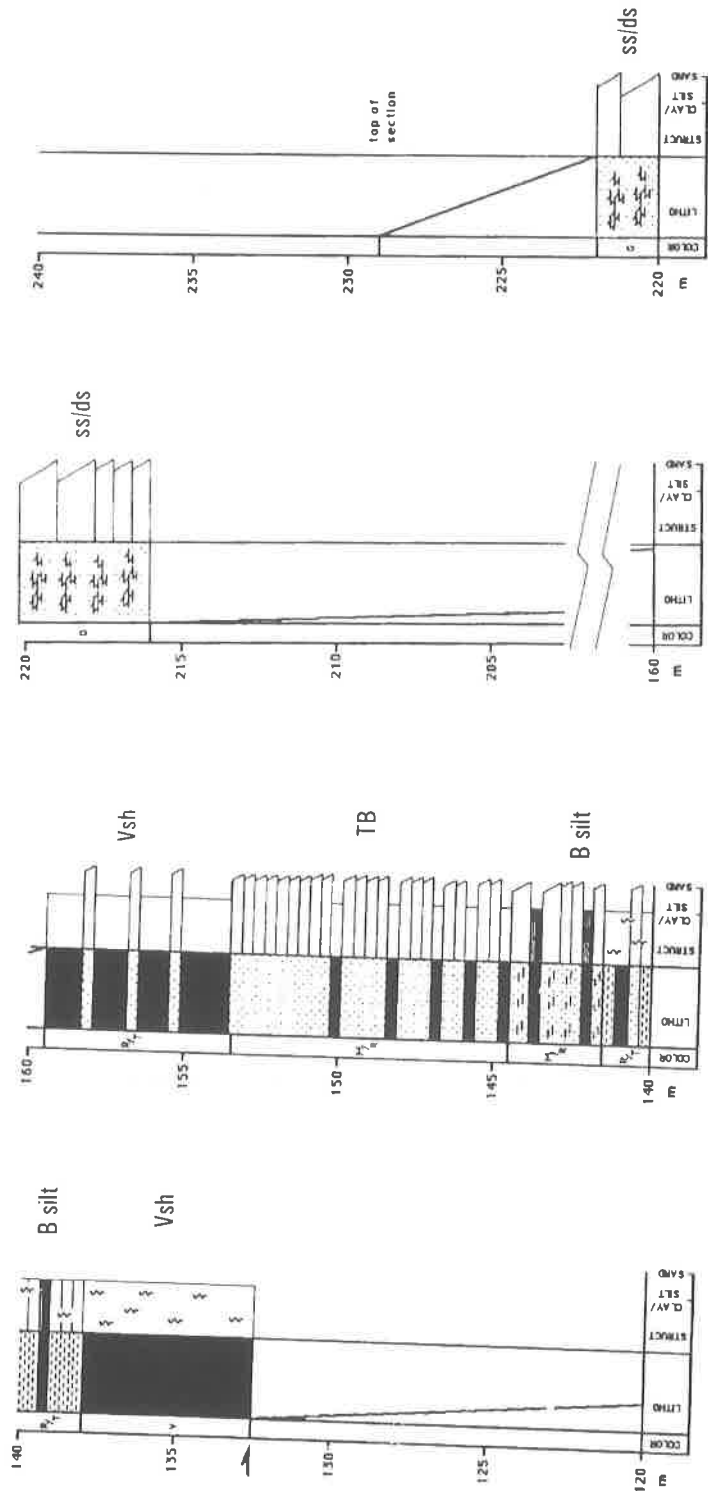


Figure 5. FR section stratigraphic column. See Figure 3 for key to symbols.

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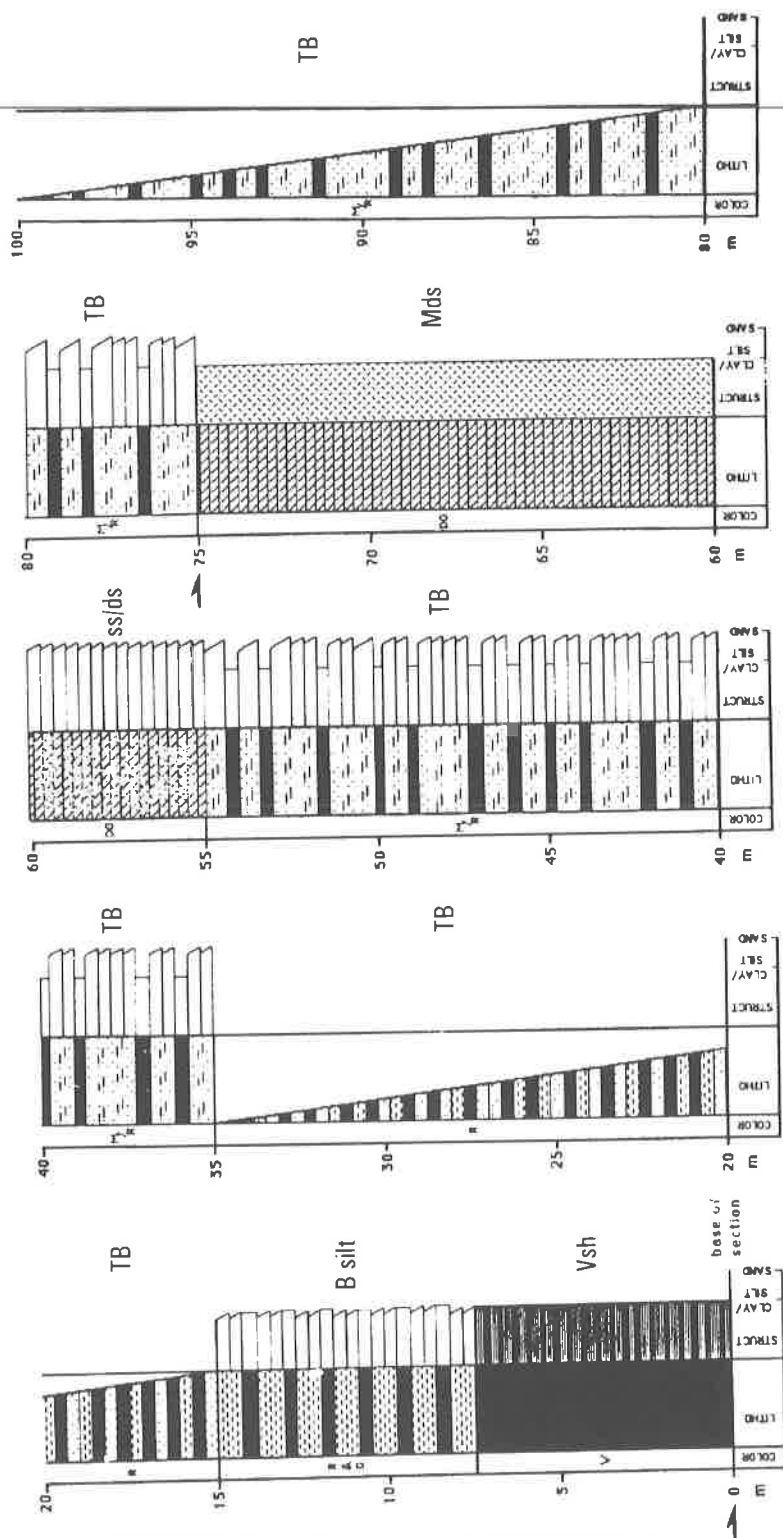


Figure 6. WB section stratigraphic column. See Figure 3 for key to symbols. Continued on next page.

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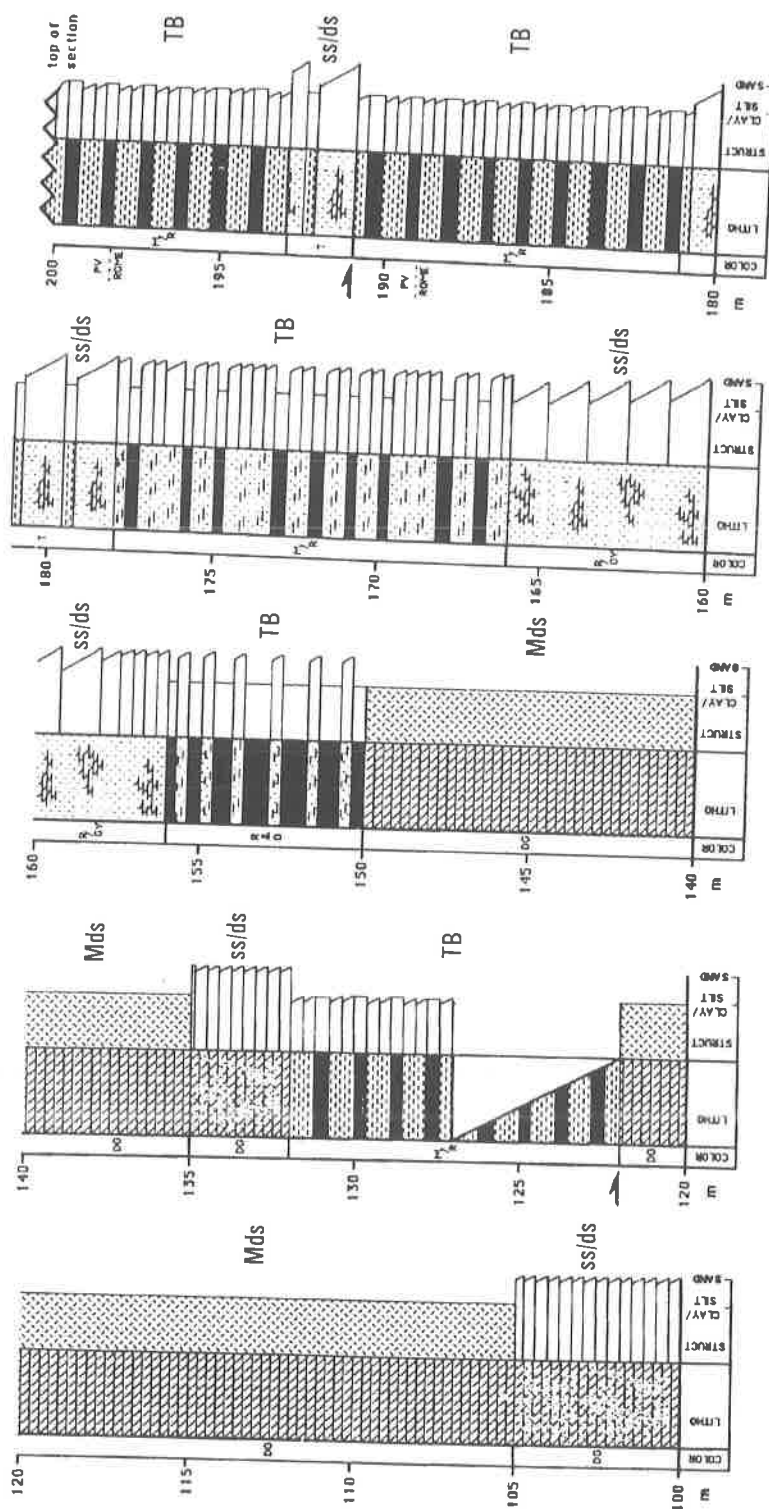


Figure 6. WB section stratigraphic column. See Figure 3 for key to symbols.

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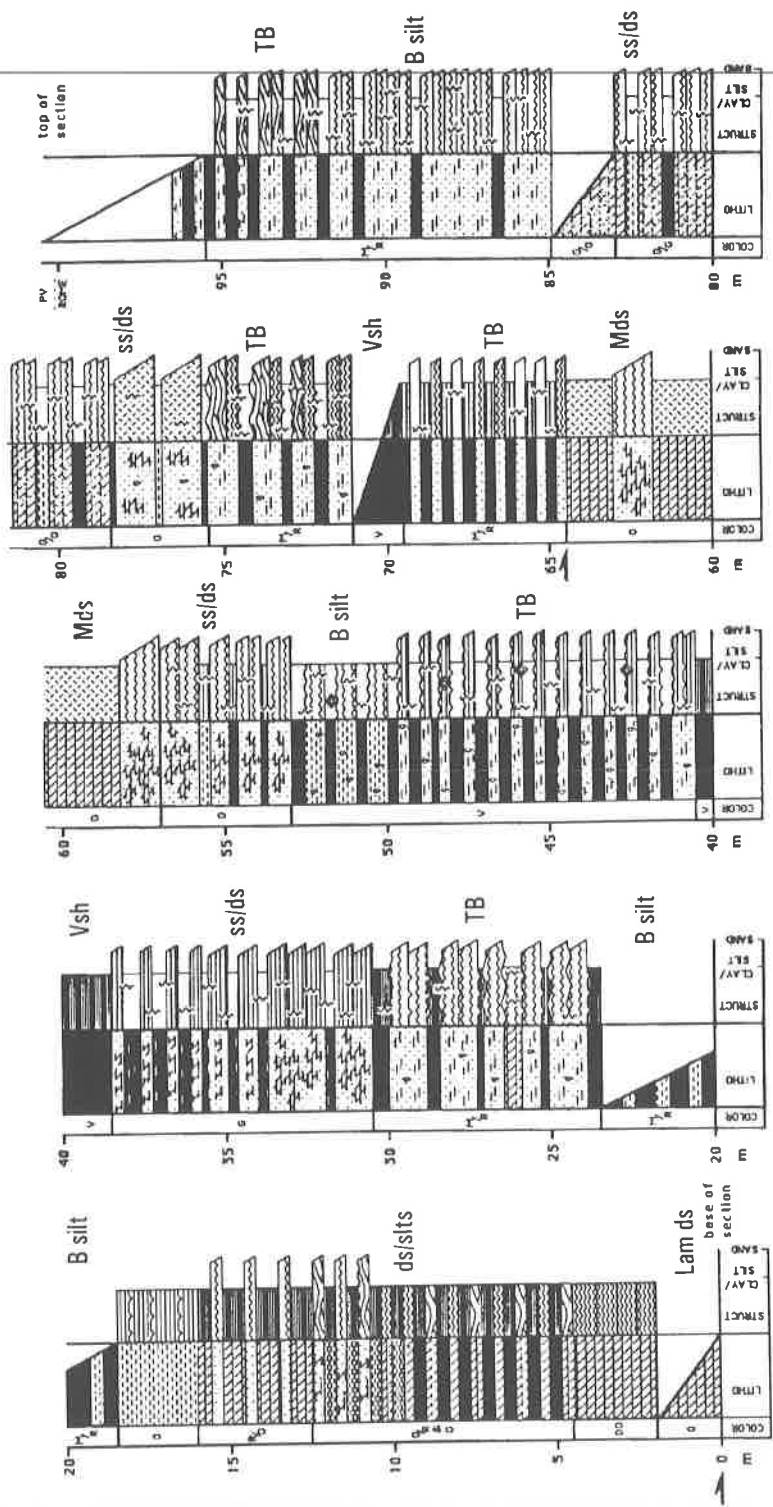
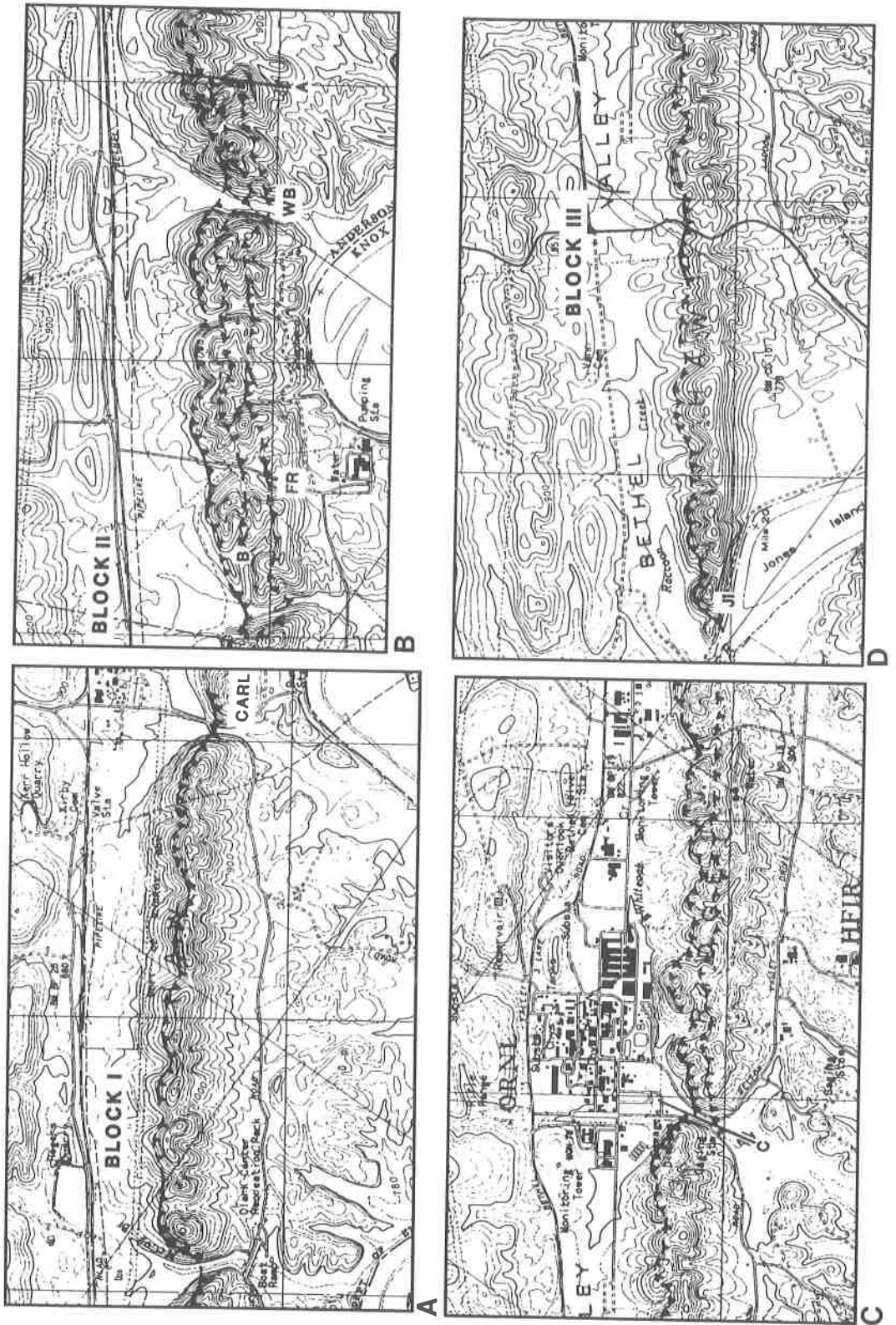


Figure 7. II section stratigraphic column. See Figure 3 for key to symbols.



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the only major outcrop within structural block I (Figure 8a). No imbricates are noted in the measured section, and the presence of a single, well-defined ridge crest suggests no duplication. Traversing southwest along Haw Ridge, the first tear fault (point A, Figure 8a) is indicated by the abrupt change in ridge morphology near the WB section. At this point, massive dolostone beds are found laterally adjacent to a silty sandstone lithology, with highly discordant bedding orientations observed at the interface.

Rome section duplication within structural block II (Figure 8b) is indicated by a repetition of stratigraphic section in a sequence that consists of a basal, red interbedded siltstone and shale, followed by a red sandstone, then a gray dolomitic sandstone, and a massive gray dolostone at the top. Each repetition is marked by a change in the strike and dip of bedding. This sequence is repeated three times at the WB section (Figure 6). The section repetition, combined with bedding orientation changes, suggests the presence of two imbricate faults plus the main thrust fault. Ridge morphology, which consists of three sub-ridges, supports this interpretation (Figure 8b). The apparent thickness of the Rome in block II is further exaggerated by a broad anticline noted at WB, which probably extends throughout the entire block.

The lowermost imbricate dies out just southwest of the FR section, as displacement is transferred into a region of extremely tight folding (point B, Figure 8c). The single remaining imbricate and the main thrust can be traced southwestward to the end of Block II. The second major tear fault is observed in the offset of Haw Ridge across a water gap at point C (Figure 8b). The tear fault has also been observed in seismic surveys (R. Dreier, pers. comm., 1988).

Haw Ridge once again assumes a morphology consisting of a single, well-formed crest within structural Block III (Figure 8d). This suggests that a fairly uninterrupted sequence of Rome is contained in this structural block. The JI section (Figure 7) is in general agreement with this interpretation, with the possible exception of very minor imbrication or duplication of section at the 53 m and 65 m stratigraphic levels.

Once the structural problems were resolved well enough for the purpose of correlation, the thick sandstone and dolostone key beds noted by Rodgers and Kent (1948) were used to correlate the four sections in the study area. The stratigraphy without structural correction is shown in Figure 9. Structurally restored stratigraphy (Figure 10) results in distinctive, patchy or "mosaic" lithofacies patterns, which are more typical of carbonate sequences rather than terrigenous clastic sequences (Wilson, 1975).

Depositional Environments for Individual Facies

The *thin-bedded sandstone and shale facies* (TB ss/sh) represents quite variable and changing environmental conditions. Scattered, shallow mudcracks and small salt "hopper" casts observed on bed tops indicate an intertidal tidal flat environment (Handford, 1981; Reading,

Figure 8 A- An enlarged portion of study area to show tectonic structure. Part 'a' shows the area in structure block I, around the CARL outcrop. Note that faulting manifests as a single major thrust fault in the area. B- An enlarged portion of study area to show tectonic structure. Part 'b' shows the northeastern section of structure block II around the WB and FR outcrop. Point "A" marks the tear fault that separates blocks I and II. Abrupt changes in bedding orientation, lithologies, and ridge trend locate the fault. Point "B" marks an area of intense folding in which one imbricate thrust died out. Note that faulting manifests as a series of first three, and then two imbricate thrust faults southwest of point "A". C - An enlarged portion of study area to show tectonic structure. Part 'c' shows the southwestern section of structure block II. Point "C" marks the tear fault that separates blocks II and III. Abrupt change in ridge trend along with seismic data locate the fault. Note that faulting manifests as a series of imbricate thrust faults southeast of point "B", but becomes a single thrust again in block III. D - An enlarged portion of study area to show tectonic structure. Part 'd' shows the area in structure block III, around the JI outcrop. Note that faulting manifests as a single major thrust fault in the area.

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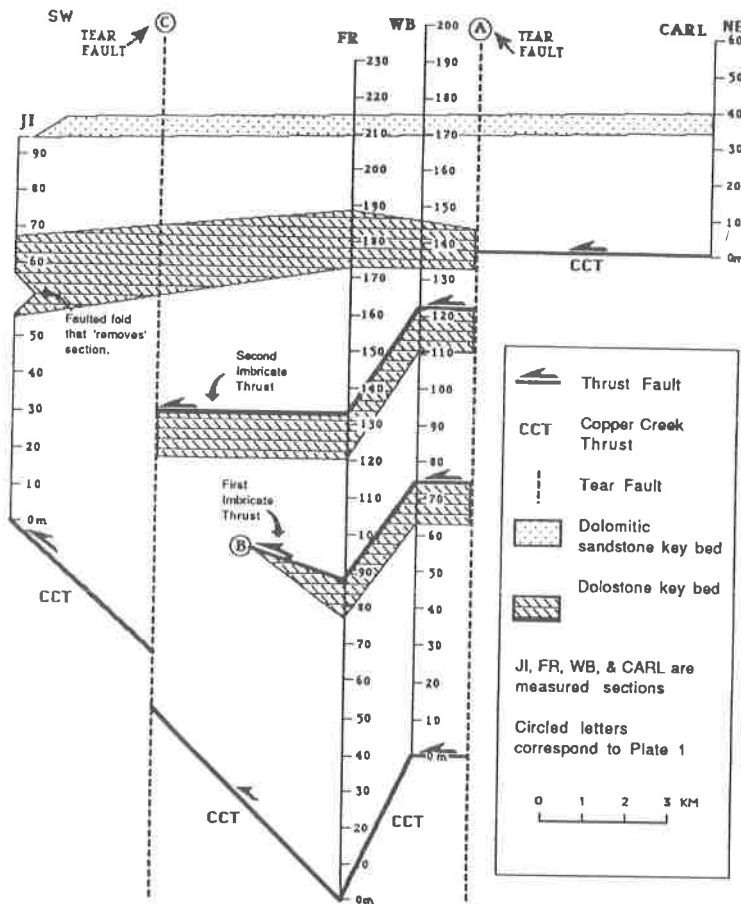


Figure 9. - Stratigraphic cross-section of the study area, showing repetition of strata due to structural deformation. Stratigraphic data are omitted except for marker dolostone and sandstone units.

1986), whereas horizontal burrows on bed bottoms, micro-hummocky and hummocky cross stratification, and planar laminations suggest that a subtidal environment also existed (Harms and others, 1975; 1982; Reading, 1986). The abundant occurrence of *Cruziana*, *Planolites*, and *Rusophycus* traces suggest the presence of a nutrient-rich environment in which benthic organisms thrived (predominantly arthropods, as evidenced by the observed traces) (Frey, 1975). Abroad, open tidal-flat setting could have provided such an environment (Frey, 1975). The TB ss/sh facies is interpreted as an alternating intertidal to shallow subtidal, tidal-flat environment, and the dynamics of the tidal flat were dominated by storm processes as well as normal tidal pro-

cesses. The observation of salt casts in an intertidal environment indicates that a seasonally wet and probably subtropical climate existed (Reading, 1986).

The *variegated fissile shale facies* (Vsh) is interpreted as having been deposited in a low-energy, quiet-water setting which is required for deposition of suspended mud- and silt-sized sediments; the lack of biota and bioturbation further suggest a restricted and at times, anoxic environment (Potter and others, 1980; Byers, 1974; 1977). The occasional lenses of sand (quartz, dolostone, and glauconite) are interpreted as storm wash, an example of "punctuated" mixing (Mount, 1984). The Vsh facies is interpreted to have been deposited in the deeper, more restricted and protected areas of a

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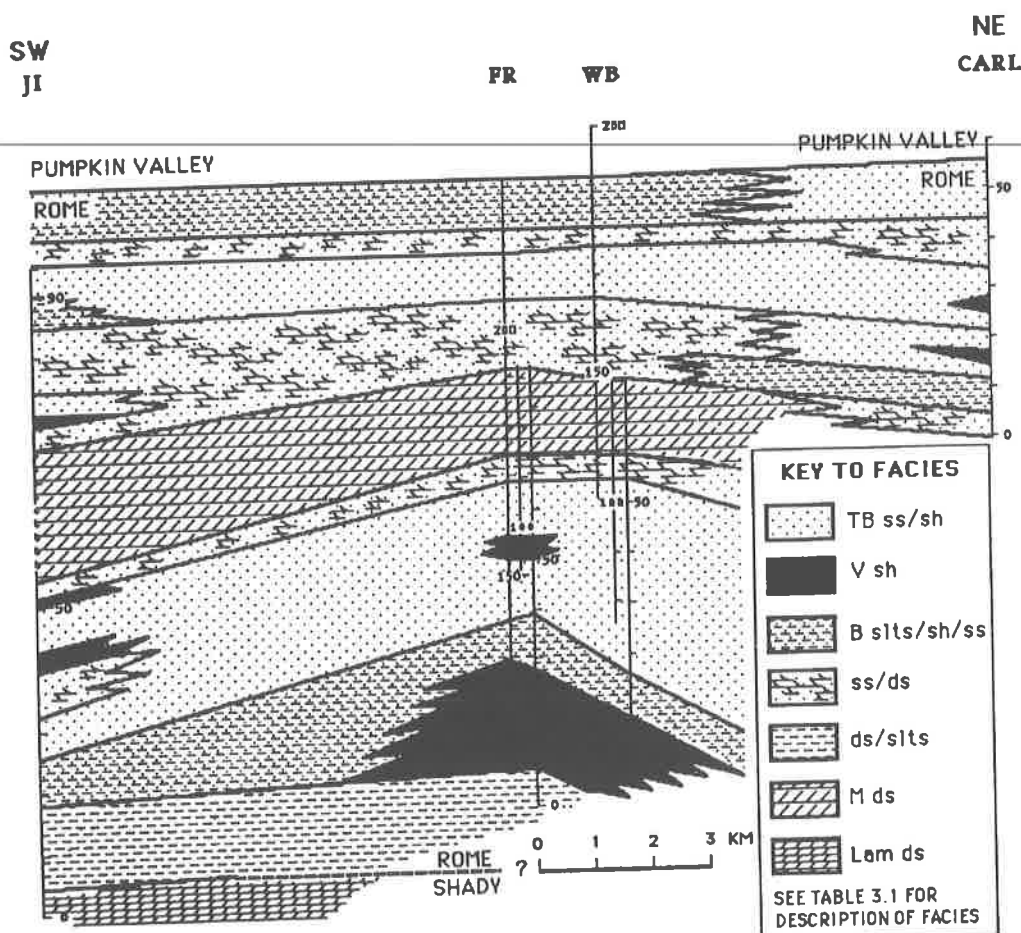


Figure 10. - Interpretive stratigraphic cross-section of the study area, corrected for repetition of strata due to structural deformation. Note patchy "mosaic" pattern of lithofacies. Thickness shown in meters. See Figure 3 for key to symbols used in diagram.

broad, subtidal, tidal flat environment. Siribhadki (1976) interpreted some shale beds in the Rome as metabentonites, but none occurred persistently enough throughout the field area at the same stratigraphic horizon as to be interpreted as bentonites.

The *bioturbated sandstone/siltstone/shale facies* (B sh/slts/ss) shows the homogenizing effects of bioturbation, which leave little evidence of original flow conditions. In this facies, the evidence of abundant biogenic reworking indicated by ubiquitous and disorganized mottling (Frey, 1975) is ambiguous for environmental interpretations. The facies is so intensely bioturbated that distinct ichnofossils could not be identified. Yet, because stratifica-

tion has been completely destroyed, bioturbation is interpreted as very intense, and the facies is assigned to the *Skolithos* ichnofacies, which implies an intertidal to shallow subtidal environment (Frey, 1975). No sedimentary structures indicating subaerial exposure are found in this facies, and the entire unit is mottled by burrowing. These characteristics suggest a subtidal environment. The presence of ubiquitous burrowing suggests an abundance of life which supports the interpretation of an open marine environment with well-circulated and oxygenated water (as opposed to the restricted Vsh facies) (Potter and others, 1980). Furthermore, the lithologic similarity to TB ss/sh and rare preservation of micro- hummocky

cross-stratification suggests the B slts/sh/sh facies had the same depositional environment as the TB ss/sh facies, namely an intertidal to subtidal, tidal flat environment frequently interrupted by storms. The facies occurred in more open, well-circulated, subtidal areas on the flat.

The *mixed dolomitic sandstone to sandy dolostone facies (ss/ds)* represents an ideal case of "facies" mixing (Mount, 1984), a consequence of Walther's Law; ss/ds represents facies mixing gradational between the M ds facies (carbonate platform deposits), and the TB ss/sh facies (a siliciclastic tidal flat deposit). Common occurrences of ss/ds between the TB ss/sh and M ds facies with gradational contacts support this hypothesis. Faint laminations, sometimes present but usually not preserved due to recrystallization, could indicate mixing occurred in an intertidal, sabkha setting such as occurs in Shark's Bay (Logan, 1974), and along the Trucial Coast (Shinn, 1983). It would be reasonable to interpret the dolomite of this facies as forming penecontemporaneously in these sabkha type environments (Shinn, 1983; Logan, 1974), but because the dolomite is mostly ferroan and has been totally recrystallized, a penecontemporaneous interpretation is questionable (Boles, 1978). Ferroan dolomite can be produced by any reducing, iron-rich fluid altering carbonate material. This alteration typically occurs in late diagenetic, deep burial environments, but could also have occurred in the environment of deposition considering the rich organic carbon content and abundant iron observed in other Rome lithologies. Also, the dolomite could be altered carbonate material that replaced original penecontemporaneous dolomite. Tentatively, the facies is interpreted as having been deposited in a supratidal, tidal flat environment.

The *laminated dolomitic mudstone interbedded with siltstone facies (ds/slts)* represents another type of sediment mixing, an example of "in situ" mixing (Mount, 1984), in which thin algally trapped and bound carbonate mud laminations are covered by thin siltstone laminations derived from the siliciclastic tidal-flat

environment (Hardie, 1977; Logan, 1974). The thin interbedded nature of the dolomitic mudstone and siltstone lithologies along with the identification of fenestrae support this interpretation. The faint desiccation cracks, again, indicate that the mixing occurred in an intertidal sabkha environment similar to Shark's Bay (Logan, 1974) and the Trucial Coast (Shinn, 1983). Just as in ss/ds facies, interpreting the dolomite in the ds/slts facies as penecontemporaneously deposited would be reasonable, but because the dolomite in this facies is mostly ferroan and finely recrystallized, the dolomite may be due to processes occurring in a late diagenetic burial environment.

Interpretation of the *massive dolostone facies (M ds)* is most difficult due to almost complete recrystallization and severe tectonic deformation, and the observation of the dolomite as ferroan with a coarse-grained fabric suggests the possibility of a late diagenetic, deep burial origin for the dolomite, but does not preclude a supratidal, intertidal tidal-flat interpretation (Boles, 1978). Although this facies represents the pure carbonate end-member of the facies model, it does contain a small percentage of terrigenous sand. The original sediments are believed to have been carbonate mud (Bathurst, 1975), and the lack of stratification is attributed to intense bioturbation as well as diagenetic and tectonic recrystallization (Bathurst, 1975). The facies is interpreted as a lagoonal back-platform deposit that formed laterally adjacent and shelfward of the tidal flat. It was probably deposited during a lull in siliciclastic input from the source area. Large salt "hopper" casts found by the first author in the same lithology near Sweetwater, Tennessee suggest a subtidal to intertidal environment (McReynolds, 1988).

The cryptalgal structures within the *laminated dolostone facies (Lam ds)* indicate an intertidal to supratidal tidal-flat environment of deposition (Hardie, 1977; Logan, 1974). It may have occurred in a sabkha type environment in which penecontemporaneous dolomite formed; however, evidence is inconclusive because of the large amounts of coarser ferroan dolomite

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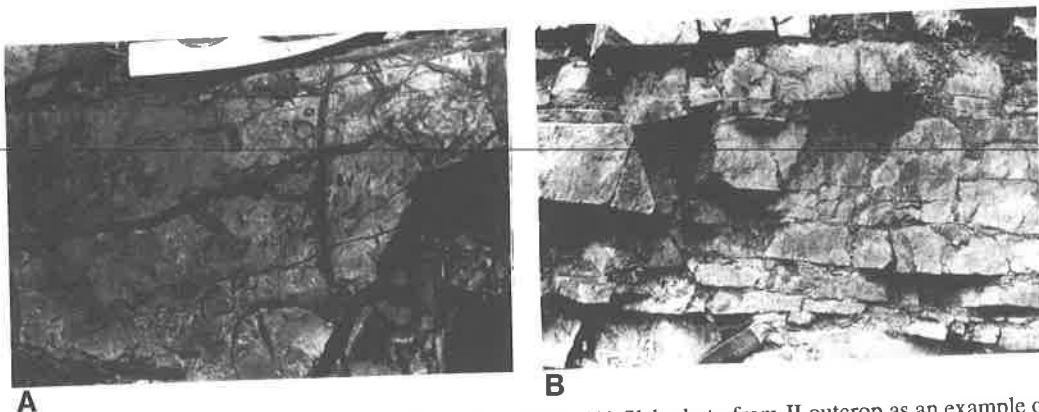


Figure 11. - Outcrop photographs of the Rome Formation. (A) Slab photo from JI outcrop as an example of bedding surface structures. (B) Photo from CARL outcrop to show example of bedding cross section.

now present (Boles, 1978) and the fact that evaporites or their pseudomorphs are not observed (Reading, 1986). Due to the occurrence at the base of JI below what has previously been interpreted the lowermost terrigenous shale and siltstone deposits of the Rome (Samman, 1975; Haase and others, 1985), as well as the striking similarity of the facies to the Ivanhoe and Austinville members of the Shady Dolomite of southwestern Virginia described by Pfeil and Read (1982), the Lam ds facies is tentatively interpreted as a carbonate tongue of the uppermost part of the Shady Dolomite.

Interpretation of Sedimentary Processes

Physical sedimentary structures are observed most commonly in the TB ss/sh facies. The structures in the facies appear to imply contradictory interpretations. Internal bedding structures, chiefly hummocky cross-stratification and micro-hummocky cross-stratification (Table 1) indicate high flow velocities that are typical when storms affect shoreface environments at depth (Harms and others, 1975), whereas bedding top- structures such as desiccation polygons, salt "hopper" casts, and raindrop impact marks, indicate a lack of intense tractional flows and common subaerial exposure (Potter and Pettijohn, 1963; Hardie, 1977). These contradictory structures commonly occur within the same bed (Figure 11), and indicate that deposition of facies TB ss/sh was controlled by two alternating hydrody-

namic regimes. One regime occurred as normal tidal processes prevailed, characterized by traction transport by weak flood and ebb currents, alternating with quiet-water (slack-water) deposition of suspended sediment. Floods may have provided copious quantities of mud to the tidal flats (see for example, Field and others, 1988). Tidal flat exposure during exceptionally low tides produced the array of supratidal indicators. The other hydrodynamic regime occurred during the major storms which episodically affected the tidal flat, vigorously suspending and transporting sediment under pure oscillatory, or possibly a combined-flow, to produce hummocky cross-stratification, as has been suggested by the recent experimental work of Arnott and Southard (1990) and Southard and others (1990). This hydrodynamic interpretation for the Rome requires that either greater water depths were produced by storms setting up water on the tidal flat during deposition, or that hummocky cross-stratification, as a combined-flow phenomenon, can be produced at depths much more shallow than was previously thought.

Sedimentary structures observed in the other six facies give more internally consistent interpretations than do those observed in the TB ss/sh facies. The B slts/sh/ss facies, dominated by ubiquitous bioturbation, is interpreted to have been deposited under the same hydraulic conditions as TB ss/sh, with the exception that bioturbation occurring during normal, non-storm periods reworked the sediment so com-

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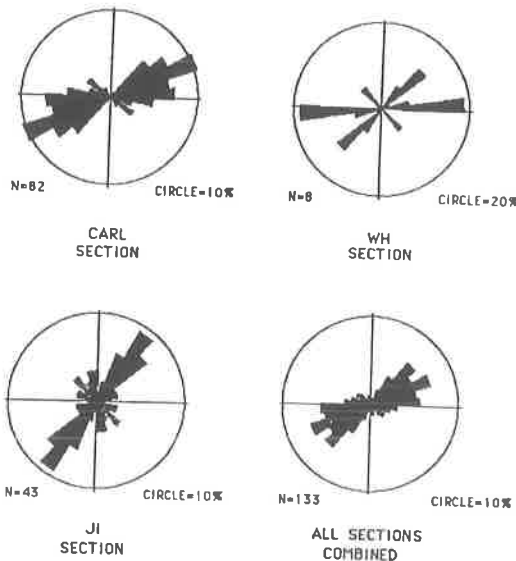


Figure 12. - Paleocurrent data (wave ripple crest orientations) for CARL, WH, and JI sections; also note rose diagram that contains the data for all sections combined. A northeast-southwest trending paleoshoreline is indicated.

pletely as to destroy most original physical sedimentary structures. The V sh facies lacked sedimentary structures on the whole, which would suggest the presence of a weak flow regime and quiet-water conditions characteristic of mud-dominated tidal flats. The mixed facies and carbonate end-member facies are

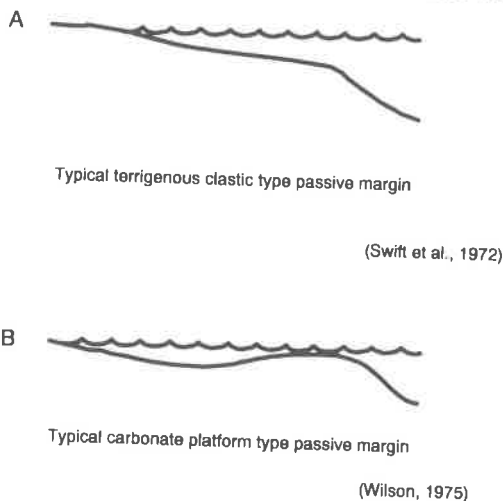


Figure 13. - Fundamental differences in shape between siliciclastic and carbonate margins.

dominated by cryptalgal structures and bioturbation, which together suggest normal tidal processes with frequent subaerial exposure. All of the sedimentary structures taken together indicate that both storm and normal tidal processes were major factors in creating the hydraulic conditions which prevailed during the deposition of the Rome.

Interpretation of Paleocurrents

Paleocurrent analysis was confined to facies TB ss/sh, because only in this facies are there abundant sedimentary structures for which directional properties could be determined. Altogether 133 ripple crest orientations were gathered from the CARL, JI, and WH sections. None were observed at the dominantly soil covered FR section. Rose diagrams of all outcrops individually, as well as combined (Figure 12), show wave ripple crests consistently oriented in a northeast-to-southwest trend (mean trend azimuth approximately 50 degrees). Asymmetrical ripples, although few in number, generally dip to the southeast, indicating unidirectional current flow in that direction.

These paleocurrent data suggest a northeast-southwest trending paleoshoreline, which agrees with the paleoshoreline configuration proposed by Samman (1975) for the Rome. It also agrees with paleoshoreline configurations determined for the Chilhowee Group (Lower Cambrian) in East Tennessee (see Cudzil and Driese, 1987; Walker and others, 1988) as well as for the Shady/Rome interval in southwestern Virginia (Pfeil and Read, 1980; Read, 1989).

Rome Facies Model

Developing a Rome facies model from a mixed siliciclastic - carbonate perspective instead of using strictly terrigenous clastic concepts requires a fundamental change in the underlying framework with which the paleoenvironments of the Rome are interpreted. Instead of using a typical siliciclastic shelf setting (Figure 13), a carbonate-platform basin configuration is hypothesized to have been inherited from the underlying Shady Dolomite

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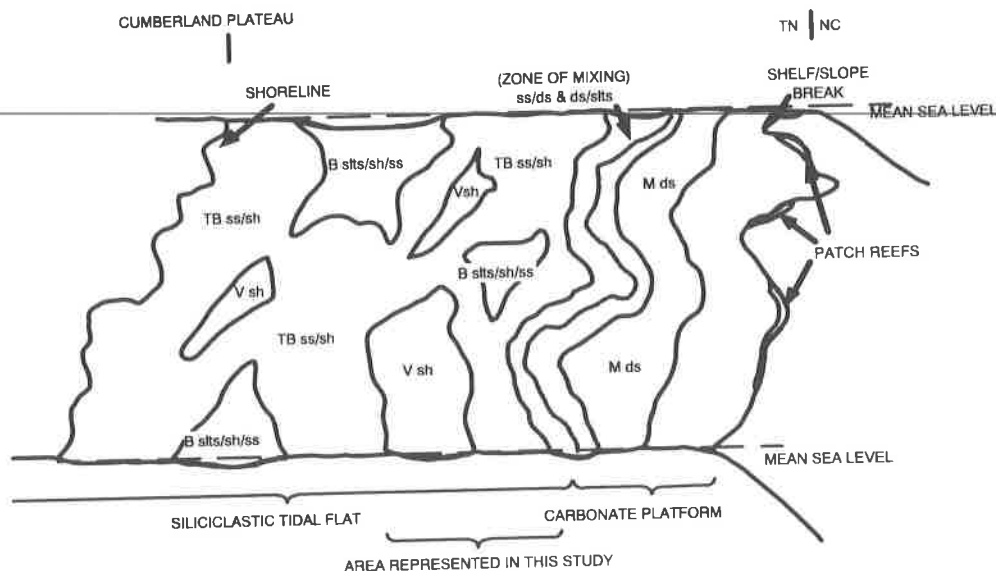


Figure 14. - Conceptual model for mixed siliciclastic and carbonate deposition in the Rome Formation, eastern Tennessee. See Table 1 for description of facies.

and/or basal Rome (Figure 13). The initial basin configuration consisted of a broad, expansive tidal flat between the shoreline and a carbonate platform at the shelf-slope break. The same basic basin configuration has been interpreted for the overlying Conasauga Group (Haase and Hasson, 1988) with the exception that for the Rome Fm. a broad, tidal-flat replaces the Conasauga Group intrashelf basin.

The three siliciclastic facies, TB ss/sh, V sh, and B slts/sh/ss, were deposited on a broad tidal flat that was frequently inundated by storms (Figure 14). The TB ss/sh facies occurred basin wide, possibly in broad, shallow tidal channels, and both fairweather and storm processes are inferred to have controlled tidal-flat deposition. The V sh facies occurred in the subtidal, more restricted and protected "ponds" on the tidal flat. The B slts/sh/ss facies occurred in patches over the entire basin as biota reworked sediment in a subtidal environment. The rare carbonate beds within these facies represent "storm"-type mixing (Mount, 1984), in which storm events episodically moved carbonate mud from the backside of the seaward-adjacent platform onto the tidal flat. Preservation of these storm sequences suggests

high depositional rates and high storm frequencies (Arnott and Southard, 1988).

The ss/ds and ds/slts facies represent the mixed lithologies classified as "facies"-type mixing (Mount, 1984). They formed at the boundary of the tidal flat and platform areas in an intertidal environment and mark the transition between the tidal-flat clastic facies and the platform carbonate facies (Figure 14). The related pure carbonate facies, M ds, is a bioturbated mud deposited in quiet-water landward of patch reefs on the carbonate platform that existed further seaward (southeast) at the shelf edge (Figure 14). The Lam ds facies (not represented in Figure 14) represents the state of the basin prior to the influx of Rome clastics and was deposited in intertidal to supratidal environment. Due to its occurrence at the base of the Rome and striking similarity to the Ivanhoe and Austinville members of the Shady Dolomite of southwestern Virginia described by Pfeil and Read (1980), the Lam ds facies is tentatively interpreted as a carbonate tongue of the uppermost part of the Shady Dolomite.

As craton-derived sediment influx increased into the study area from the northwest, the clastic tidal-flat eventually engulfed

the carbonate platform. Hydraulic conditions for the tidal-flat alternated from normal tidal processes to intense storm flows. The stacking of storm beds and fairweather deposits through time controlled by the original "carbonate platform"-type basin produced the mosaic stratigraphy of the Rome found in the study area (Figures 10, 14).

The Great Barrier Reef Province of northeastern Australia might be a reasonable modern analog for Rome paleoenvironments. This vast area (270,000 km²) is a mixed siliciclastic - carbonate environment that contains a dominantly terrigenous clastic coast and inner shelf, whereas the outer shelf is dominated by a carbonate reef environment (Belperio and Searle, 1988). The mixing of these two environments does not occur as a gradation from one to the other on the intervening shelf area, but instead, is mixed in patchy environments created by the movement of along-shelf currents (Flood and Orome, 1988). Transgression, together with the increasing influx of terrigenous clastic sediment, is slowly drowning the shelf and burying the barrier reefs. Unfortunately, the analogy between the Great Barrier Reef and the Rome Fm. is not perfect. In particular, the small delta environments occurring alongshore of the Great Barrier Reef have not been found in the Rome Formation, nor do the abundant tidal-flat indicators characteristic of the Rome Fm. exist in the Great Barrier Reef area.

REGIONAL IMPLICATIONS OF THE ROME FACIES MODEL

The mixed siliciclastic - carbonate model satisfactorily accommodates regional data. Our model represents a subtle, but significant, modification of the Rome facies model of Samman (1975). Our model incorporates the basic regional observations documented in the Rome by previous workers (Harvey and Maher, 1948; Rodgers 1953; 1968; Woodward, 1961; Spigai, 1963; Harris, 1964; Samman, 1975). The fundamental elements include the interpretation of Rome deposition as occurring on a broad,

expansive tidal flat in which the sediments deposited were derived from a cratonic source area to the northwest. The uplift that created the source area is still believed to have been caused by renewed extensional tectonics in which the eastern craton was broadly flexed prior to the onset of rifting, which would culminate in the Middle Cambrian as the Rome Trough-Rough Creek graben system (Milici and de Witt, 1988). For regional paleogeography, a northeast-to-southwest trending paleoshoreline located in central Tennessee and eastern Kentucky is maintained as the landward side of a shallow, tidal-flat shelf which terminated seaward onto a carbonate platform existing further to the southeast at the shelf-slope break (Samman, 1975). Clastic deposition is still interpreted to have dominated the landward shelf areas and carbonate deposition to have dominated the seaward platform areas (Samman, 1975).

The first major change in regional interpretations involves the lower regional stratigraphic boundary of the Rome. We reinterpret the locations where the Rome ceases to be underlain by the Shady dolomite and onlaps Precambrian basement. Based on only a limited number of cores, previous workers (Woodward, 1961; Harris 1964; and Samman, 1975) confined the Shady to the eastern portions of the Valley and Ridge where it is seen in outcrop, but later workers with more subsurface data (Webb, 1980; Sutton, 1981; Barnaby and Read, 1990) have identified Shady (or equivalent Tomstown) in the Rome Trough, and indicated Shady deposition as far northwest as eastern Kentucky. Also a limestone/dolostone lithology has been noted at the base of the Rome at various localities across the basin (Keith, 1895; Rodgers, 1953; Cattermole, 1955; Milici, 1973; McReynolds, 1988). Whether these carbonate strata are assigned to a basal unit of the Rome or instead, the uppermost part of the Shady Dolomite makes the interpretation of how far west the Shady extends a semantic argument. The important observation is that carbonate deposition extended across most of the basin prior to clas-

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tic deposition in the Rome. The basic assumption in which Rome deposition inherited a carbonate-platform basin configuration from the underlying Shady Dolomite is, therefore, valid in light of this reevaluation of Rome-Shady stratigraphic relations, which is based on more comprehensive data.

The present regional stratigraphic framework within the Rome is based on limited data and is tentative at best. In previous work, Rodgers and Kent (1948) noted that two marker beds, a thick sandstone at the top of the Formation and a distinctive massive dolostone unit in middle of the section, could be used locally to correlate stratigraphy in the Hawkins County, Tennessee area of the western Valley and Ridge. In the first regional Rome study in East Tennessee, Spigai (1963) concluded that no regional marker beds existed across East Tennessee and that more detailed work was needed to produce a reliable regional framework. The most recent model (Samman, 1975) interpreted a regional stratigraphy for the Rome in which bands of outcrop correlate, in "layer-cake" fashion, long distances parallel to strike. Although this work is the most comprehensive depositional model for the Rome to date, the weakest part of the model is its regional approach to correlation of stratigraphy. Because of its regional scope, the study suffered from a lack of a detailed stratigraphy as well as a lack of detailed sedimentological data. Furthermore, tectonic structures within the Rome were observed, but were never incorporated into correlations parallel and perpendicular to depositional strike. Regional correlations across thrust belts (commonly ten to fifteen miles apart when palinspastically restored) were tenuously based on environmentally and areally limited oolite- and *Skolithos*-bearing marker beds, which could not be traced with confidence between all outcrops. Other parts of the regional correlation were based on transgressive/regressive packages constructed from measured sections, which did not account for structural duplication and therefore did not represent a true stratigraphic succession of lithologies. All of these shortcomings com-

bined to render the details of Samman's stratigraphy unsupportable. The stratigraphic and lithologic variability of the sections used by Samman (1975) does, however, demonstrate the difficulty of correlating Rome stratigraphy using a siliciclastic paradigm. In developing our facies model from a mixed siliciclastic - carbonate perspective instead of using strictly terrigenous clastic concepts, we interpret a mosaic Rome stratigraphy in which the basin-controlled dynamics inherited from the underlying Shady Dolomite, a carbonate platform sequence, strongly influenced the terrigenous deposits of the Rome to form "carbonate-like" mosaic patterns.

CONCLUSIONS

The mixed siliciclastic - carbonate paleoenvironmental model is a modification of the presently accepted Rome depositional model of Samman (1975). While maintaining the clearly established interpretations of the present model, it offers an alternate viewpoint for regional stratigraphy. Instead of forcing Rome stratigraphy into linear bands characteristic of many clastic models, the mixed siliciclastic - carbonate model is used to interpret a mosaic "patchwork" stratigraphy for the Rome. This interpretation hinges on the reevaluation of the lower stratigraphic contact between the Rome Formation and the Shady Dolomite. Based on more recent data, the Shady is believed to underlie the Rome across the entire Valley and Ridge, and thus a "carbonate platform"-type basin can be interpreted as the basin configuration prior to the deposition of the Rome.

This conceptual model has several advantages. It helps explain the "uncorrelatable" stratigraphy commonly encountered in the Rome, and accounts more easily for repeated shifts in Rome paleoenvironments through time, which might otherwise be attributed solely to relative sea-level shifts. The model fits well into the present Lower Paleozoic regional framework because it maintains the same basic basin shape which has been better

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documented above and below the Rome in the Valley and Ridge stratigraphy (Read, 1989; Pfeil and Read, 1980; Haase and Hasson, 1988; Walker and others, 1983). Furthermore, the intertonguing nature of the Shady/Rome/Conasauga interval fits what this model would predict.

Previous workers have interpreted Rome paleoenvironments based on siliciclastic depositional paradigms and have met with limited success in developing a coherent stratigraphy and creating a regional depositional model for the Rome. Interpretation as a mixed siliciclastic - carbonate sequence is an alternate viewpoint for interpreting Rome paleoenvironments that we believe can lead to an improved regional depositional environment model for the Rome Formation in East Tennessee.

The model proposed here combines detailed work in the study area and reconnaissance of scattered outcrops across the basin to build our hypothesis. The results from the Haw Ridge study area demonstrate that detailed mapping of the Rome is necessary to separate the structural and stratigraphic components which create the stratigraphy observed in outcrop. If the regional stratigraphy of the Rome is ever to be accurately resolved, this type of detailed mapping will be required across the entire basin. Until such work is completed, any regional model of Rome paleoenvironments, including our mixed siliciclastic - carbonate model, must remain a testable working hypothesis.

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SEQUENCE STRATIGRAPHY OF THE LOWER MISSISSIPPIAN PRICE AND BORDEN FORMATIONS IN SOUTHERN WEST VIRGINIA AND EASTERN KENTUCKY

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ABSTRACT

The Lower Mississippian in the Appalachian Basin of southern West Virginia and eastern Kentucky is a clastic wedge produced by erosion of the Acadian orogen. Previous studies have failed to adequately document the diachronous nature of these sediments caused by their westward progradation. Using the methodology of sequence stratigraphy, combined with biostratigraphic control, it is possible to document in detail the westerly progradational history of the Lower Mississippian. These rocks comprise a single depositional sequence that can be divided into four allostratigraphic units (allo-units) that reflect minor episodes of relative sea level fluctuation. The four allo-units together record at least four separate episodes of progradation and basin filling as sediments were shed westward from the Acadian orogen. Extension of this analysis to Lower Mississippian outcrops in north-central Kentucky and southern Indiana allows recognition of at least two younger allo-units. Thus, a minimum of six episodes of progradation can be recognized as the Early Mississippian clastic wedge prograded from the Appalachian Basin to the Illinois Basin.

opposite sides of the Appalachian Basin in southern West Virginia and eastern Kentucky. Geologists have long considered these rocks to be essentially age equivalent on both sides of the basin; e.g., the COSUNA charts for this region (Patchen and others, 1985a, b). However, several studies have documented that Lower Mississippian rocks comprise a progradational wedge that formed as sediments were shed westward across the Appalachian Basin from the Acadian orogen in the east (e.g.; Weir and others, 1966; Moore and Clark, 1970; Peterson and Kepferle, 1970; Pryor and Sable, 1974; Kepferle, 1977; Rice and others, 1979; Ettensohn, 1987; Bjerstedt and Kammer, 1988; Sable and Dever, 1990). Thus, the Lower Mississippian outcrops in West Virginia, in general, contain beds older than those in Kentucky. The present study was undertaken to document the details of the progradational history of the Lower Mississippian, and also determine the specific age relationships between rocks in West Virginia and Kentucky. To accomplish these goals, subsurface data were used to correlate between outcrops on the eastern and western sides of the Appalachian Basin (Figure 1).

INTRODUCTION

The Lower Mississippian crops out on those rocks contained within the Kinder-

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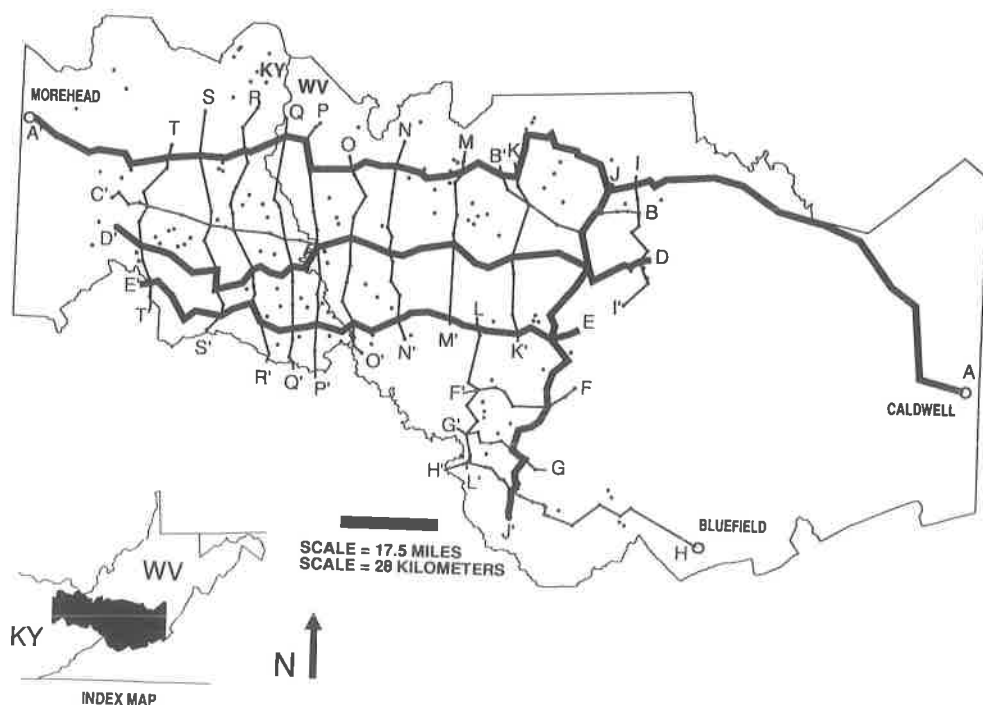


Figure 1. Map of the study area with location of outcrops and cross sections. Outcrops are at Caldwell and Bluefield, West Virginia, and Morehead, Kentucky. Cross sections presented in this paper are indicated by bold lines, all other sections are available in Matchen (1992).

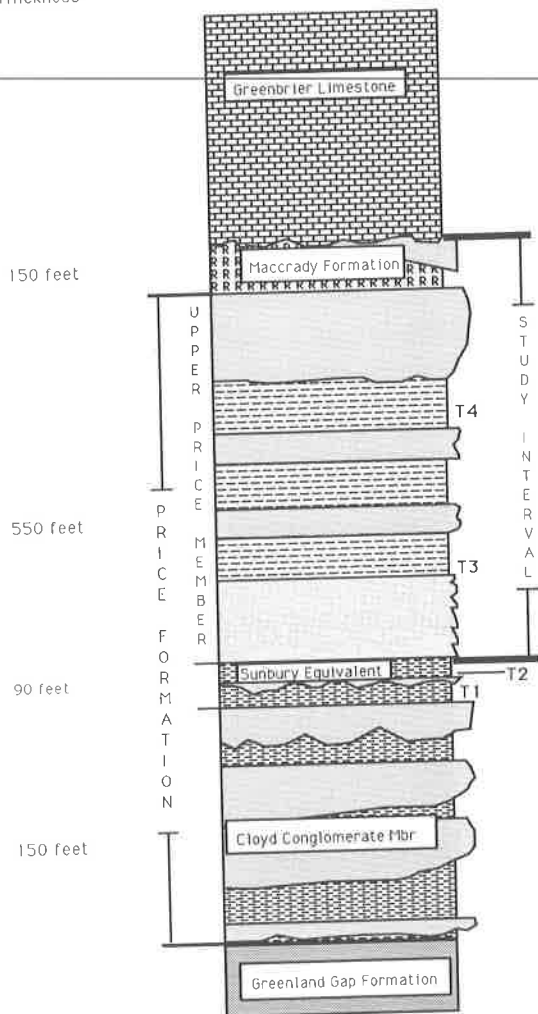
hookian and Osagean stages of the Mississippian System. In the study area, two distinct formations have been defined, the Price Formation of West Virginia and the Borden Formation of Kentucky. The study interval overlies the Sunbury Shale, which marks the base of the Mississippian System in the study area (de Witt, 1970). The top of the study interval is truncated by the sub-Greenbrier unconformity, which causes the thickness of the Lower Mississippian to vary within the study area (Bjerstedt and Kammer, 1988, fig. 4). The study interval includes all rocks from the top of the Sunbury Shale to the base of the Meramecian-age carbonates, which are the Greenbrier Limestone of West Virginia and the Slade Formation of Kentucky (Ettensohn and others, 1984). This interval also includes the red beds of the Maccrady Formation, which range in thickness from zero to a few hundred feet because of pre-Greenbrier erosion.

The Price Formation at Caldwell, West

Virginia, is composed of three major units: the Cloyd Conglomerate Member in the lower part, a middle shale unit, and an informal upper Price member (Figure 2). The Devonian-Mississippian boundary is within the middle shale unit, based on correlation of the upper portion of the shale unit with the Sunbury Shale in the subsurface (Jewell, 1988). Thus the Cloyd is within the Upper Devonian and outside the scope of this project. (Additionally, the Cloyd contains Late Devonian brachiopods [Carter and Kammer, 1990]). The upper part of the Price Formation consists of all rocks from the top of the Sunbury-equivalent shale to the base of the Maccrady Formation, and consists of interbedded sandstones, siltstones, and shales. Shales deposited during marine transgressions served as key beds for correlation. On outcrop these shales contain lag deposits of phosphate nodules and reworked fossil debris indicative of transgressive surfaces of erosion (Bjerstedt and Kammer, 1988). These transgressive shales

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Thickness



Not Drawn to Scale

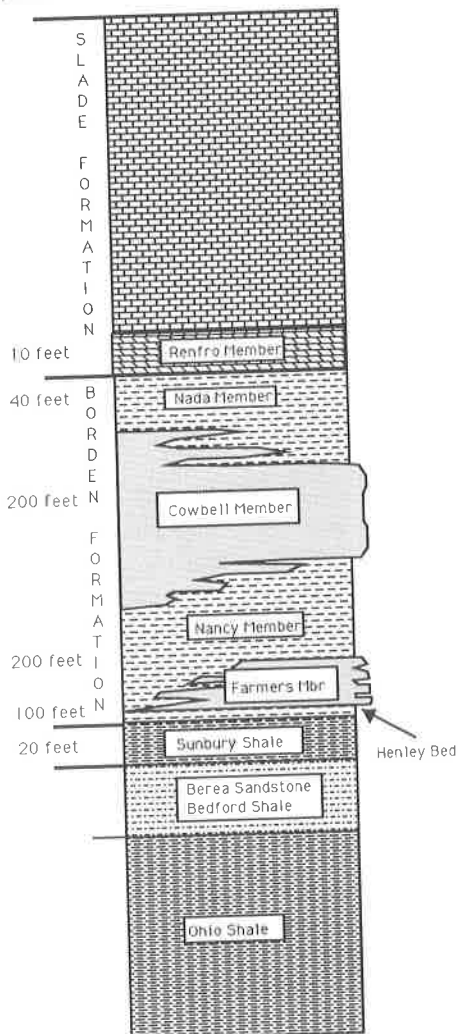
Figure 2. Generalized stratigraphic column for the Price Formation at Caldwell, West Virginia. The Price extends from the top of the Greenland Gap Formation to the base of the Maccrady Formation. Transgressive horizons (e.g., T2) are from Bjerstedt and Kammer (1988, fig. 6B). Diagram not drawn to scale.

were traced into the subsurface and used to separate packages of progradational sediment.

The Maccrady Formation overlies the Price Formation in southern West Virginia. The Maccrady consists of red mudstones and channel-fill sandstones. On outcrop, the Maccrady

is distinguished from the Price by the red color of the shales; however, these two formations cannot be differentiated on wireline logs. Therefore, the Price and Maccrady are included together as one depositional package from the top of the Sunbury Shale to the base of the Greenbrier Limestone.

Thickness



Not Drawn to Scale

Figure 3. Generalized stratigraphic column for the Borden Formation at Morehead, Kentucky based on Chaplin (1980). The Borden extends from the top of the Sunbury Shale to the base of the Renfro Member, which is the basal member of the overlying Slade Formation (Ettensohn and others, 1984). Diagram not to scale.

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At Morehead, Kentucky (Figure 1), the Lower Mississippian is exposed in the Borden Formation as fine-grained sandstones, siltstones, and silty shales. The Borden Formation is divided into the following units in ascending order: the Henley Bed, the Farmers Member, the Nancy Member, the Cowbell Member, and the Nada Member (Figure 3). Contacts between members of the Borden are gradational, indicating slowly changing depositional conditions. The Henley Bed is a gray shale beneath the fine-grained sandstones of the Farmers Member. It represents a time of increased oxygenation of the seafloor relative to the anoxic conditions associated with the deposition of the underlying Sunbury Shale. Thickness of the Henley Bed varies from a maximum of 90 feet at the northeast end of the outcrop belt (Potter and others, 1991) to a minimum of 10 feet in the Morehead area. The overlying Farmers Member varies from 2-270 feet through the same region. The Henley Bed

represents hemipelagic sedimentation prior to the active progradation of the Borden delta (Chaplin, 1980, 1982).

Overlying the Henley Bed are the turbidites of the Farmers Member (Moore and Clark, 1970). The Farmers is described as laterally extensive, parallel bedded, fine grained, moderately well-sorted, texturally mature to sub-mature sandstones (Chaplin 1980). Next is the Nancy Member, which consists of greenish-gray silty shale, with a few turbidites similar in composition to those found in the Farmers Member. Above the Nancy lies the Cowbell Member which is composed of 150-200 feet of siltstones, sandstones, and shales. The siltstones and sandstones are interpreted as delta front sediments, whereas the shales are interpreted as interdistributary bay deposits (Chaplin, 1980). Above the Cowbell lies the Nada Member, which consists of 40 feet of green-gray mudstones and shales, and interbedded calcareous siltstone and sandstone units. The

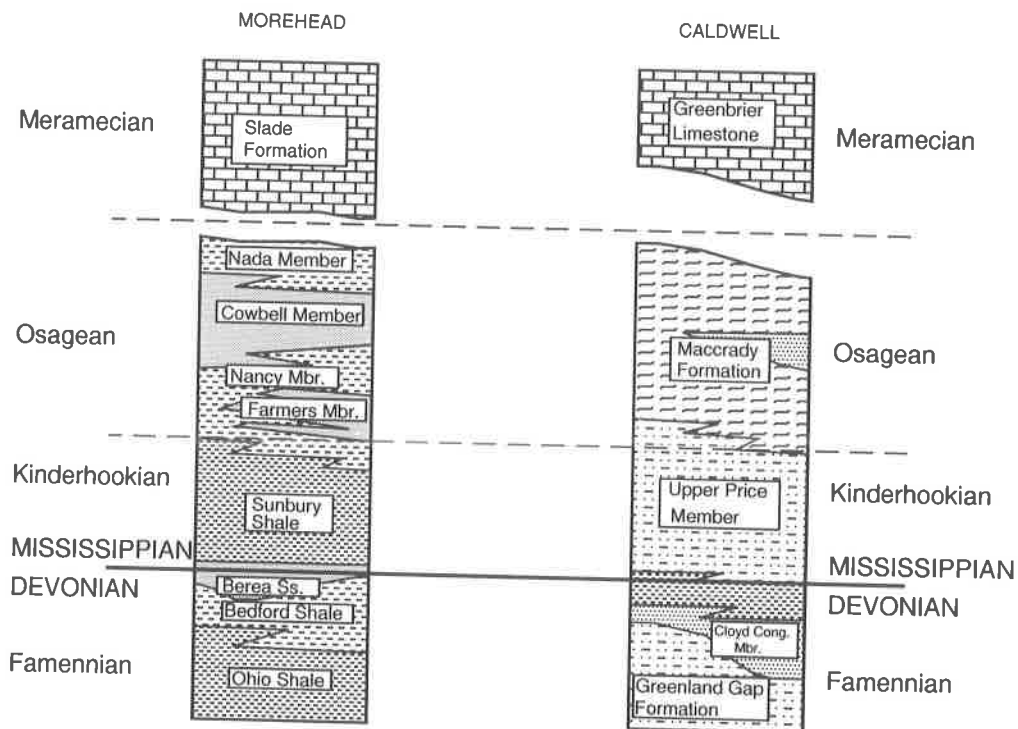


Figure 4. Age relationships between the Price and Borden outcrops. Chronostratigraphic correlations are based on biostratigraphic studies discussed in the text. Note that the Price Formation is almost completely older than the Borden Formation. Not drawn to scale.

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Nada represents the delta platform and is interpreted as a bay or lagoon facies at the top of the Borden Delta (Chaplin, 1980).

The age relationships between the outcrops on opposite sides of the Appalachian Basin are key to documenting the progradational history of the interval. Biostratigraphic work by Kammer and Bjerstedt (1986) and Carter and Kammer (1990) demonstrates that the majority of Price rocks in southern West Virginia are Kinderhookian in age (Figure 4). The Kinderhookian-Osagean boundary is recognized by the occurrence of the ammonoid *Muensteroceras arkansanum* Gordon near the top of the Price at Marlinton, Pocahontas County, West Virginia (Kammer and Bjerstedt,

1986). *Muensteroceras arkansanum* is restricted to a very short time interval from latest Kinderhookian to earliest Osagean time (Ramsbottom and Saunders, 1985). The overlying Maccrady Formation is above the Kinderhookian-Osagean boundary and is thus Osagean in age. There is no evidence that the Maccrady contains rocks younger than Osagean. Only one locality with a marine fauna has been found in the Maccrady (Butts, 1940, p. 353), and this fauna is clearly Osagean based on its brachiopod species. In Kentucky, the Borden is almost entirely Osagean in age (Figure 4). Biostratigraphic work by Chaplin (1982) and Lane and DuBar (1983) shows that the Kinderhookian-Osagean boundary lies in the Henley Bed and

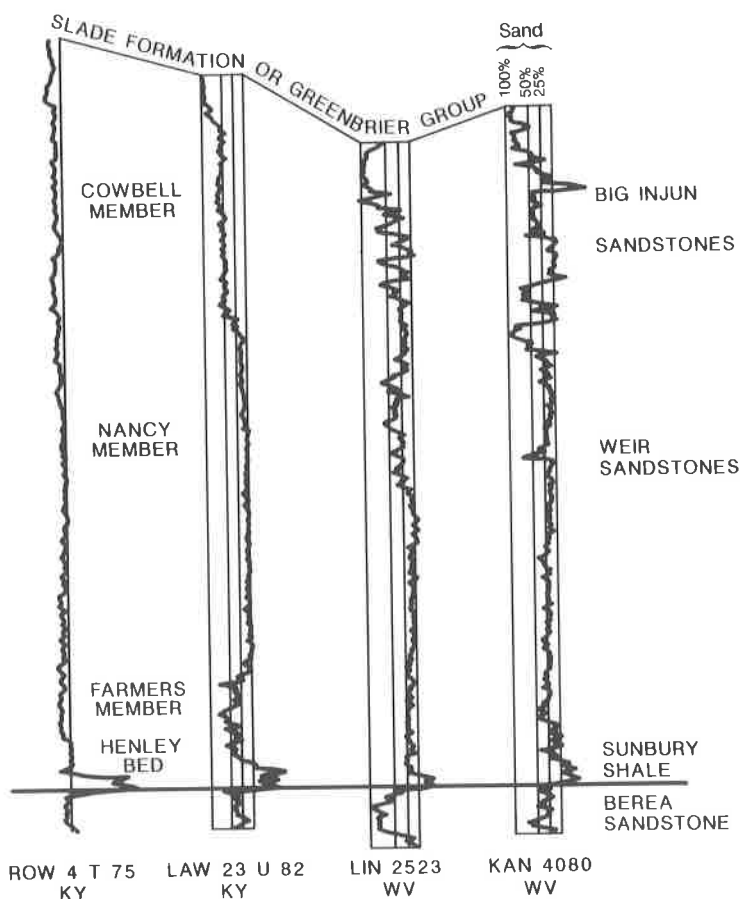


Figure 5. Typical gamma-ray log signatures from the Price and Borden Formations. Signatures are partitioned using the baseline method ranging from 100% shale on the right to 100% sandstone on the left. ROW=Rowan County, LAW=Lawrence County, LIN=Lincoln County, KAN=Kanawha County.

that the Nada Member is no younger than early Osagean. Thus, marine deltaic rocks of the Price Formation on outcrop are almost totally diachronous with respect to the marine deltaic rocks of the Borden Formation on outcrop, although both formations are Early Mississippian in age.

DATA AND METHODS

Three sets of outcrops were used in conjunction with subsurface data (Figure 1). These included outcrops of the Price Formation near Caldwell and Bluefield, West Virginia (Bjerstedt and Kammer, 1988), and outcrops of the Borden Formation near Morehead, Kentucky (Chaplin, 1980).

Subsurface data included 340 gamma-ray well logs (Figure 1; see Matchen, 1992, Plate 1 for detailed locations). Initial correlations were made by correlating gamma-ray patterns on the logs. Creating stratigraphic cross sections required an arbitrary designation to separate sandstones from shales on the logs. Sandstones were recognized by establishing separate base-lines for sandstone and shale signatures on each gamma-ray log. Each log was then partitioned on the basis of percentage of sand (Figure 5). For this study, 25% sand was used as the arbitrary designation for sandstone. In similar studies 50% is the common cut-off (Boswell et al, 1987; Boswell, 1988). The paucity of sands within the study area when the 50% cut-off was used required a lower cut-off in order to place a reasonable number of sand bodies on the cross sections. Many of the sandstones thus recognized would correspond to fine-grained sandstones or siltstones on outcrop. Once all logs were correlated and sandstones identified, cross sections were constructed in a grid across the study area (Figure 1).

Subsurface correlations were tied to the outcrops by using the established lithostratigraphic units defined on outcrop by previous workers (Chaplin, 1980; Lane and DuBar, 1983; Bjerstedt and Kammer, 1988; Potter and others, 1991). Biostratigraphic correlations were based on data presented in Chaplin (1980,

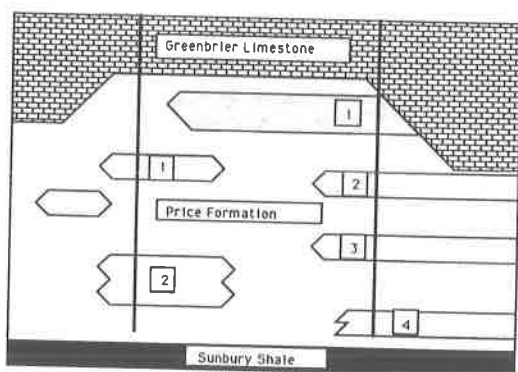


Figure 6. Drillers' terminology for subsurface Lower Mississippian sandstones. Note how the amount of erosion on the sub-Greenbrier unconformity, and the number of sandstones, effects the naming of sandstones. 1) "Big Injun/Squaw"; 2) "Upper Weir" or "Weir"; 3) "Middle Weir"; and 4) "Lower Weir". Vertical lines represent hypothetical wells.

1982), Lane and DuBar (1983), Kammer and Bjerstedt (1986), and Carter and Kammer (1990).

Informal lithostratigraphic terminology currently in use in the Appalachian Basin was a major obstacle to correlation within the study area. A set of names evolved from drillers' usage have been applied to sandstone intervals within the subsurface of the Appalachian Basin (Figure 6). As defined by drillers, the first sandstone encountered below the Greenbrier Group (Big Lime), is named "Big Injun" (Figure 6). A small sandstone below the Big Injun is termed the "Squaw" Sandstone. Below the "Big Injun/Squaw" interval lies the "Weir" sandstones. Depending upon the number of sands found below the "Big Injun/Squaw" there may be an upper, middle, and lower "Weir" sandstone.

When used within the context of a single oil field, or a single county, this terminology is adequate. However, when attempting to extend this terminology over large areas the terms often lose significance, and miscorrelations result. Two common reasons for miscorrelation in the Lower Mississippian interval are facies changes and the sub-Greenbrier Unconformity. The unconformity truncates the Lower Mississippian section, often cutting into and remov-

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ing the "Big Injun" sandstone. In other areas, the unconformity rises over 200 feet in section and preserves portions of the Maccrady Formation. As the Maccrady includes some sandstones, a well drilled in an area with preserved Maccrady sediments may encounter sandstones above the "Big Injun" horizon. Using traditional nomenclature, these sandstones would be named "Big Injun", when the real "Big Injun" interval is lower in the section.

To avoid confusion inherent in the drillers' stratigraphic nomenclature, an approach utilizing the principles of sequence stratigraphy was used to divide the Lower Mississippian into units analogous to parasequence sets (Van Wagoner et al, 1990). In order to comply with the rules of the North American Stratigraphic Code (1983), we used the allostratigraphic approach recommended by Walker (1990). Allostratigraphy divides stratigraphic sections by defining and identifying units of rock on the basis of bounding discontinuities (North American Commission of Stratigraphic Nomenclature, 1983, p. 865). The allostratigraphic scheme does not define the exact nature of bounding discontinuities, therefore unconformities and flooding surfaces are both accepted as bounding discontinuities.

Units defined in this study are informal allostratigraphic units (allo-units) because no formal alloformations are recognized. These allo-units can be considered as genetically-related sediments, identified on the basis of bounding discontinuities. Each of the allo-units probably contains several small parasequences stacked in a regressive pattern. On outcrop it is possible to recognize the smaller-scaled

parasequences that comprise a parasequence set. However, lack of cores, the imprecision of gamma-ray logs, and the thin spatial density of wells, made resolution of individual parasequences impractical, if not impossible on the subsurface cross sections. Flooding surfaces, although represented on the cross sections by a single line between allo-units, are, likewise, probably composed of a set of parasequences stacked in a transgressive pattern.

Depositional geometries defined by allostratigraphy represent various sedimentary facies including turbidite, delta front, delta platform (marine), delta plain (nonmarine), and alluvial plain. Without actual rocks to support detailed facies interpretations in the subsurface, the more generalized facies terminology of Rich (1951, as described by Friedman and others, 1992), undathem, clinothem, and fondothem, was used to describe sedimentary geometries without designating specific depositional environments (Figure 7).

Undaform is the "...flat topographic surface that exists above wavebase". Clinof orm is the "sloping surface extending from wave base to the flat floor of the water body". Fondof orm is the "flat floor of the water body". Rock units formed on each of these surfaces can be referred to as undathem, clinothem, and fondothem.

The undathem includes all sediments deposited near sea level. Based on outcrop studies in West Virginia (Bjerrstedt and Kammer, 1988), this would include marine deposits of the delta platform such as open shelf, shoreface, and foreshore facies, and nonmarine deposits (both red and non-red beds) of the

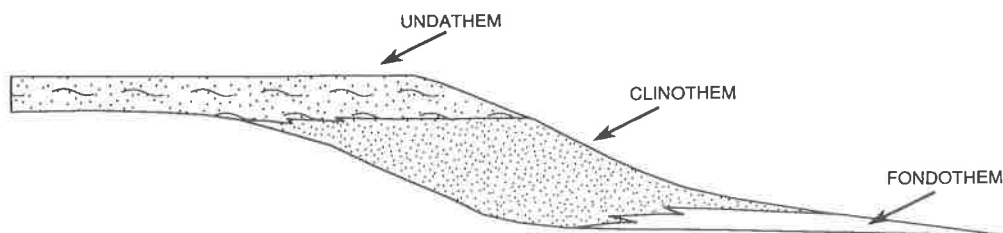


Figure 7. Diagram illustrating the geometries and positions of the undathem, clinothem, and fondothem (based on Rich, 1951). No vertical scale implied.

delta plain and alluvial plain such as distributary channel, bay, coastal plain, coal swamp, and fluvial facies. This complex mosaic of facies was deposited as part of a combined delta complex and prograding shoreline system (Boswell and others, 1987; Bjerstedt and Kammer, 1988). Sandstones at the leading edge of the undathem are interpreted as delta front deposits because they are positioned adjacent to the clinothem.

The clinothem includes sediments deposited on the slope below the undathem. These sediments consist of silts and clays deposited as pelagic sediments, and discrete packages of turbidites formed during maximum progradation. Turbidites are separated by transgressive shales.

These turbidites accumulated in discrete areas that can be correlated to specific clinothems. Turbidites are located in north-south trends with transgressive shales defining the boundaries between specific clinothems. A series of recently exposed roadcuts near the Ohio River in northeastern Kentucky (Potter, et. al., 1991) show the nature of the clinothem in the western part of the study area.

The Henley Bed is the fondothem in the Borden Formation. The fondothem in the Price Formation consists of the thin interval of sediments between the top of the black Sunbury Shale and the base of the clinothem turbidites. The Sunbury Shale is an older fondothem deposit (Ettensohn, 1992, p. 80).

SEQUENCE STRATIGRAPHY

The sequence-stratigraphy approach to stratigraphic subdivision and correlation is based on fluctuations in sea level, either local or eustatic (Van Wagoner and others, 1990). A rise in sea level produces transgressive deposits, which are often fine-grained but may contain reworked basal lag deposits of conglomeratic sandstones, fossil skeletal debris, or phosphate nodules (Weimer, 1992). These transgressive deposits are usually followed by regressive deposits (progradation) of

the highstand systems tract. A major drop in sea level produces a lowstand systems tract in the basin, while the former shelf is subaerially exposed producing a regional unconformity. These unconformities, or their correlative conformities, form the boundaries of a depositional sequence.

The Lower Mississippian of the study area comprises a single depositional sequence bounded by unconformities at both top and bottom. The lower unconformity is beneath the base of the Riddlesburg Shale on outcrop in West Virginia. The shallow-water equivalent of the basinal Sunbury Shale, the Riddlesburg is a transgressive deposit overlying the nonmarine redbeds of the Late Devonian Hampshire Formation in eastern West Virginia and western Maryland (Bjerstedt and Kammer, 1988; Carter and Kammer, 1990). The unconformity at the top of the sequence is the regional sub-Greenbrier unconformity.

Within this depositional sequence, several allostratigraphic units can be recognized. As previously suggested, these are more or less equivalent to the parasequence sets of Exxon terminology (Van Wagoner and others, 1990). These allostratigraphic boundaries can be defined on outcrop and correlated into the subsurface. The outcrop at Caldwell contains transgressive shales with phosphate-nodule lag deposits (Bjerstedt and Kammer, 1988, fig. 6B). Gamma-ray logs occasionally mark the apparent presence of phosphate nodules within the study area by very strong gamma-ray spikes. However, these spikes are restricted to undathem deposits and are not present basinward in clinothem deposits. Without key beds to identify bounding surfaces throughout the study area, other information was needed to identify the flooding surfaces.

Recognition of transgressive horizons in the subsurface was based on the pairing of turbidite and delta front couplets (Figures 8-11). Sandstones at the base of the Price (Figure 8a) are interpreted to be turbidites by analogy with turbidites on outcrop on both sides of the basin. Thick sandstone bodies updip from these turbidites are interpreted as delta fronts (Figure

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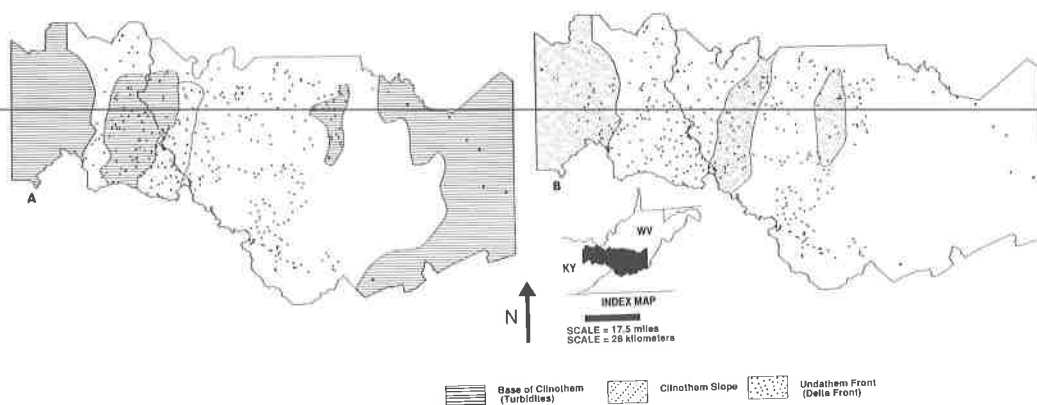


Figure 8. Sandstone distribution maps. A) Turbidites at the base of the study interval, the Lower Weir sandstones of drillers' terminology. B) Delta front accumulations, the Upper Weir sandstones of drillers' terminology.

8b). These distinctive turbidite-delta front couplets were used to define four allostratigraphic units, labeled A-D (Figures 9-11). The spatial separation between turbidites and delta fronts was used to define the undathem-clinotherm boundary on each cross section. Note that for allo-unit A there is no delta front because the front was originally to the east of the Caldwell outcrop. Allo-unit B is unusual in lacking well-developed turbidites, although turbidites are present on Section D-D' (Figure 10). Allo-units C and D both have a well-developed turbidite-delta front couplet.

The geographic separation between turbidite-delta front couplets is assumed to represent a hiatus in progradation caused by transgression. Shales deposited during each transgression can be readily identified on the dip cross sections (Figures 9-11). By tracing transgressive shales from basal turbidite horizons upsection to the top of the delta front accumulation, the transgressive surface can be given an approximate stratigraphic location in the thick undifferentiated siltstones. Additionally, transgressive shales can be located in this manner within the stacked undathems and traced to their outcrop equivalents at Caldwell (Figure 9). Positions of transgressive shales and the corresponding allo-units along strike were determined by correlation between dip sections. Section J-J' is an example of a strike section showing the position of allo-units A-D

(Figure 12).

Paleogeography of undathem and clinotherm deposits for each of the four intervals defined by allo-units A-D, was mapped (Figure 13) by transferring boundaries from the four cross sections presented in this paper (Figures 9-12), plus 16 cross sections (Figure 1) presented in Matchen (1992). These paleogeographic maps show westward progradation during the Early Mississippian in the study area.

DISCUSSION

Sequence stratigraphic analysis of the Lower Mississippian in southern West Virginia and eastern Kentucky shows the progradational history of these rocks. At least four separate episodes of westward progradation can be recognized (allo-units A-D). This progradation is associated with the fourth, and last, tectophase of the Acadian Orogeny (Ettensohn, 1987). Thrust loading (Quinlan and Beaumont, 1984; Tankard, 1986; Beaumont and others, 1988; Flemings and Jordon, 1990) in the Acadian orogen produced the foreland basin occupied by the Sunbury Shale. This basin was filled during the Early Mississippian by a clastic wedge as uplands within the Acadian orogen were eroded. This clastic wedge not only filled the Appalachian Basin, but crossed the Cincin-

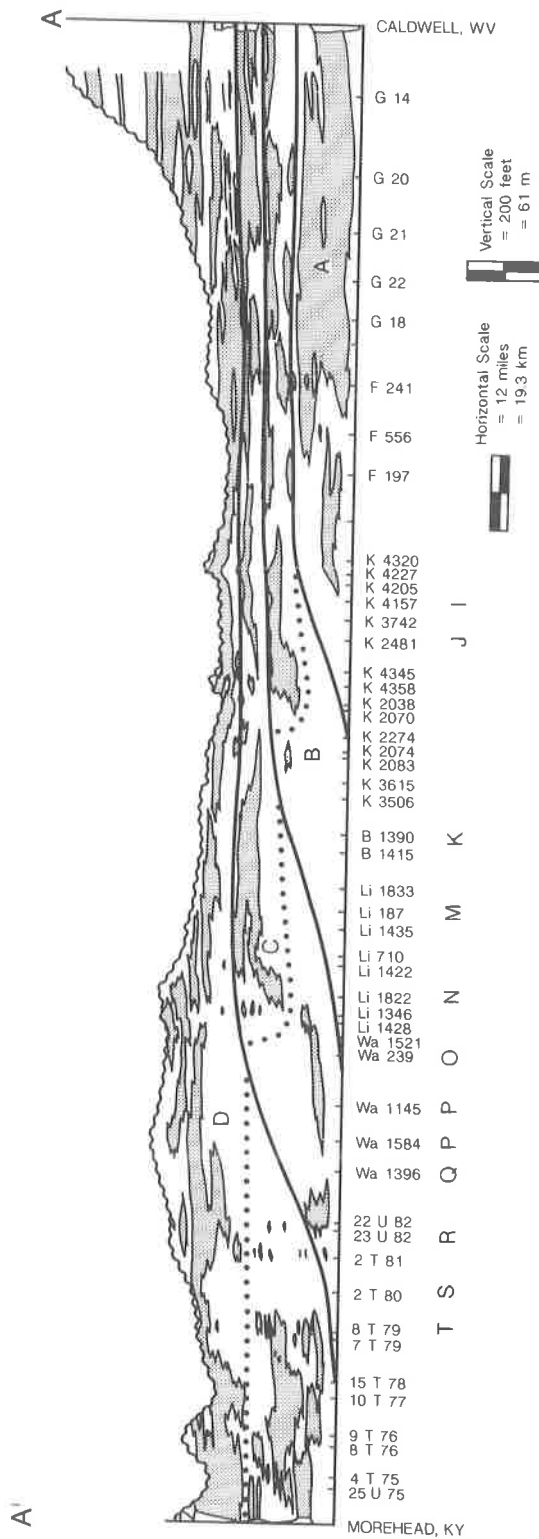


Figure 9. Cross section A-A' (Figure 1) showing allo-units A-D separated by solid lines. Dotted lines mark the approximate boundary between the undathem and clinothem in each allo-unit. The outcrop at Caldwell extends to the top of the Price Formation (Bjerstedt and Kammer, 1988). The overlying Maccrady Formation is shown in the subsurface to the west. The outcrop at Morehead is a complete composite section of the Borden Formation based on Chaplin (1980). Well numbers correspond to the well permit numbers used by the West Virginia Geological Survey and the Carter Coordinate System used by the Kentucky Geological Survey for filing well logs. Letters below well numbers mark tie wells with other cross sections (Figure 1).

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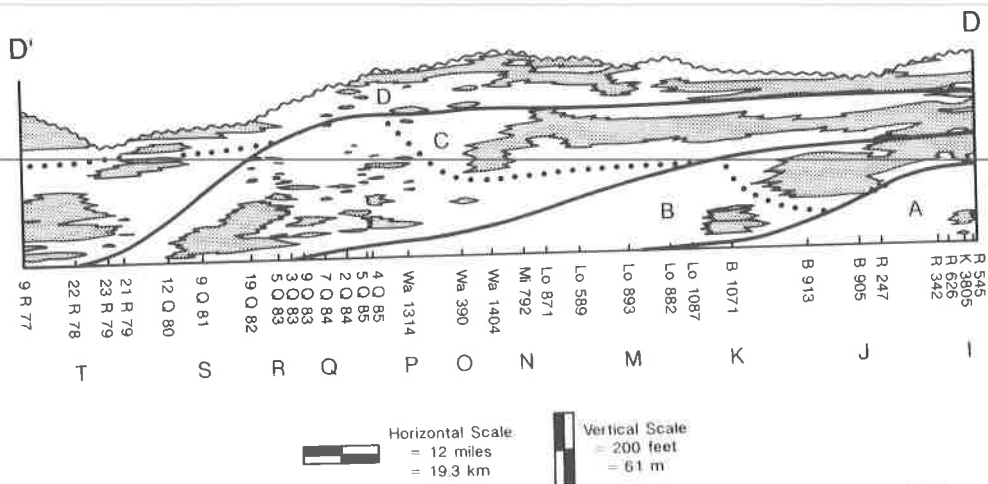


Figure 10. Cross section D-D' (Figure 1) showing allo-units A-D separated by solid lines. Dotted lines mark the approximate boundary between the undathem and clinothem in each allo-unit. Well numbers correspond to well permit numbers used by the West Virginia Geological Survey and the Carter Coordinate System used by the Kentucky Geological Survey for filing well logs. Letters below well numbers mark tie wells with other cross sections (Figure 1).

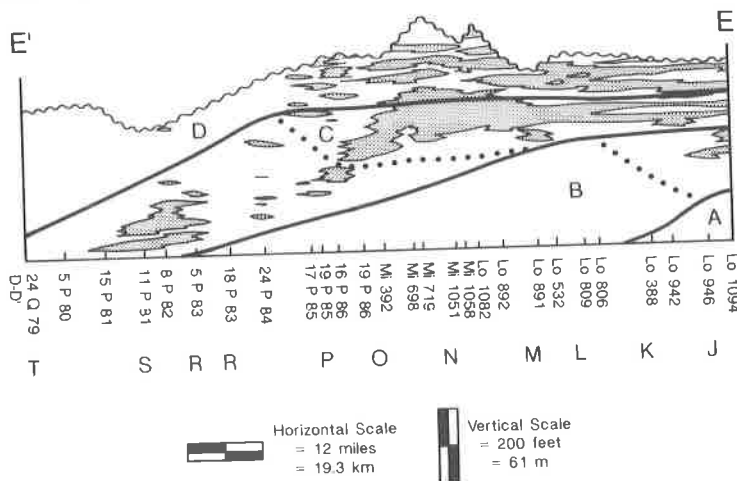


Figure 11. Cross section E-E' (Figure 1) showing allo-units A-D separated by solid lines. Dotted lines mark the approximate boundary between the undathem and clinothem in each allo-unit. Well numbers correspond to well permit numbers used by the West Virginia Geological Survey and the Carter Coordinate System used by the Kentucky Geological Survey for filing well logs. Letters below the well numbers mark tie wells with other cross sections (Figure 1).

nati Arch and the Cumberland Saddle to produce the Borden Formation in the Illinois Basin (Weir and others, 1966; Moore and Clark, 1970; Peterson and Kepferle, 1970; Pryor and Sable, 1974; Kepferle, 1977; Rice and others, 1979; Ettensohn, 1987; Bjerstedt and Kammer, 1988; Sable and Dever, 1990).

The Osagean-Meramecian boundary in the Illinois Basin marks the end of dominantly clastic sedimentation and the beginning of dominantly carbonate sedimentation (Shaver, 1985; Kammer and others, 1990). The Meramecian was a period of tectonic quiescence in the eastern United States as indicated by domi-

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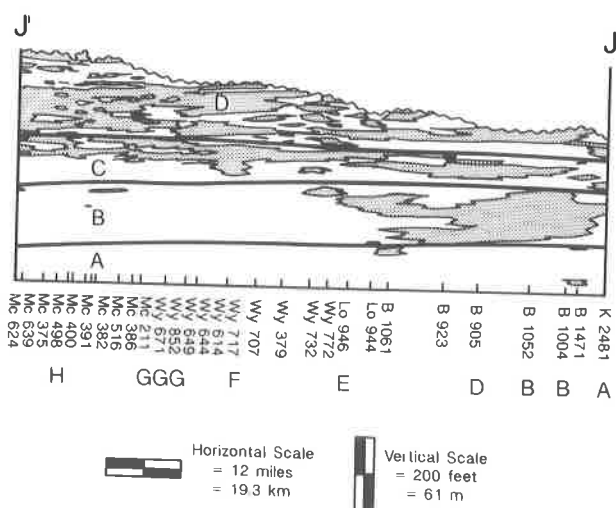


Figure 12. Cross section J-J' (Figure 1) showing allo-units A-D separated by solid lines. Dotted lines mark the approximate boundary between the undathem and clinothem in each allo-unit. Well numbers correspond to well permit numbers used by the West Virginia Geological Survey and the Carter Coordinate System used by the Kentucky Geological Survey for filing well logs. Letters below the well numbers mark tie wells with other cross sections (Figure 1).

nance of carbonate rocks in both the Illinois and Appalachian basins (Tankard, 1986; Carney and Smosna, 1989). During Meramecian time, sea level rose producing a transgression from west to east, with the result that Meramecian-age carbonates encompass more time in the Illinois Basin whereas in the Appalachian Basin only the latest Meramecian is represented (Kammer, 1992). During early Meramecian, and possibly even late Osagean time, the Appalachian Basin was emergent. Hence, the sub-Greenbrier unconformity in West Virginia formed during the time span from the late Osagean to the late Meramecian, after which the Greenbrier sea transgressed across southern West Virginia. Thus, the Lower Mississippian is a sequence bracketed by unconformities that are overlain by transgressive deposits: the Riddlesburg Shale (or Sunbury Shale) and Greenbrier Limestone, respectively.

The four allo-units, A-D, reflect minor episodes of relative sea level fluctuation. Changes in sea level can be caused by a wide variety of processes (Hallam, 1992), including: local tectonism, tectonoeustasy (plate tectonics), and glacioeustasy. The limited scale of the present study prevents determination of the

cause(s) of sea level fluctuation that produced transgressive surfaces separating the allo-units. We can, however, offer the untested hypothesis that transgressions separating the allo-units were the result of minor tectonic loading in the Acadian orogen. Episodes of thrusting may have loaded the edge of the lithosphere producing minor subsidence of the foreland basin (Quinlan and Beaumont, 1984; Beaumont and others, 1988; Flemings and Jordan, 1990). The present study has larger implications regarding the depositional history of the Lower Mississippian of the eastern United States. The Borden Formation in eastern Kentucky is contained entirely within allo-unit D, the last allo-unit to be deposited within the study area. However, the Borden did not stop prograding at Morehead. Rather, there was a northwest-southeast trending shoreline system that prograded across Kentucky, Ohio (Cuyahoga and Logan formations), Indiana, and Illinois in a southwestward direction (Figure 14). To the west in north-central Kentucky, the Borden is comprised of units and lithologies that are younger than, but analogous to, units at Morehead (Figure 15). These include a turbidite deposit, the Kenwood Siltstone, and a delta

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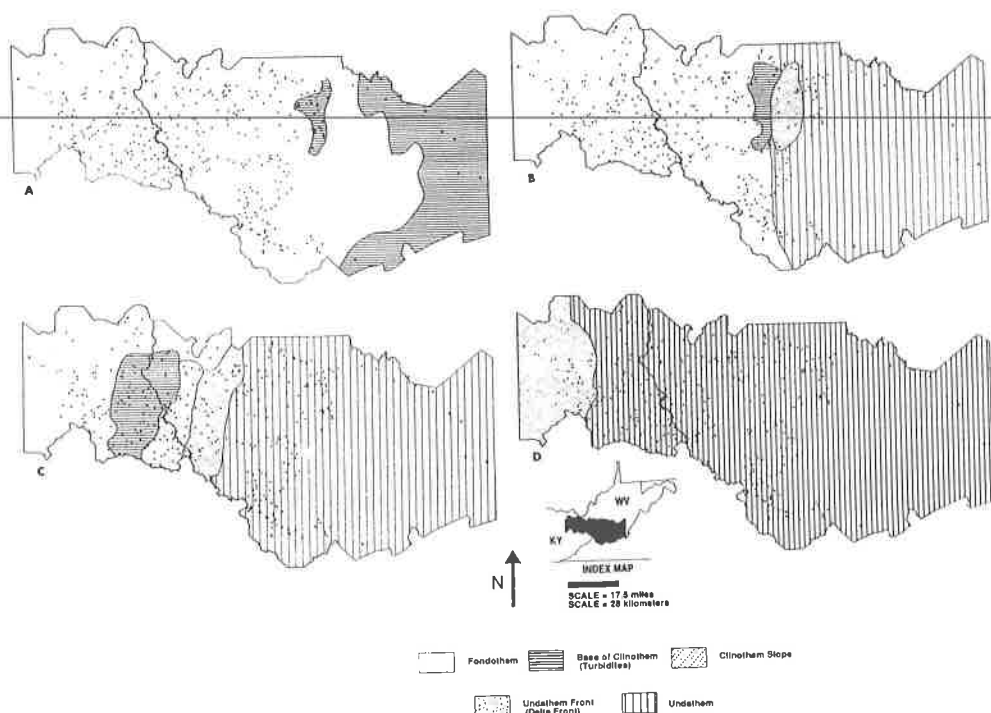


Figure 13. Paleogeographic maps of each allo-unit. A, allo-unit A; B, allo-unit B; C, allo-unit C; D, allo-unit D.

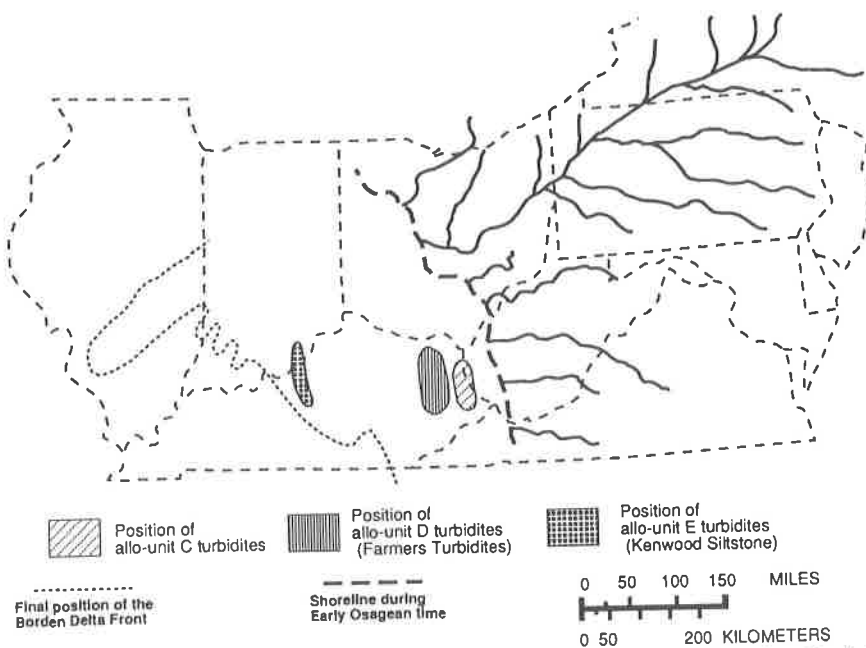


Figure 14. Paleogeography of the Early Mississippian in the eastern United States (based on Kepferle, 1977). Note the westward progradation of turbidites and shorelines. Allo-unit D turbidites are the Farmers Member (Moore and Clark, 1970) of the Borden Formation. The Kenwood Siltstone is the youngest turbidite deposit (Kepferle, 1977) (Figure 15).

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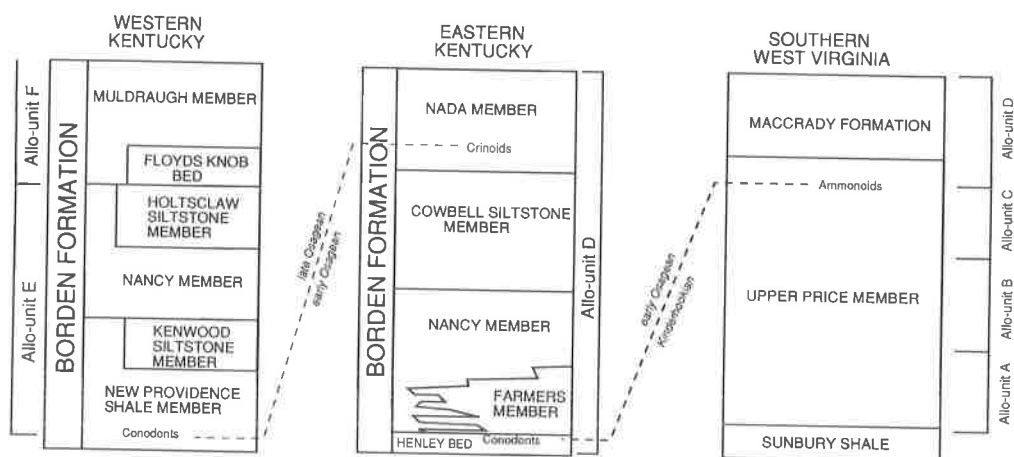


Figure 15. Stratigraphic columns illustrating the geographic and stratigraphic distribution of allo-units A-F from southern West Virginia to western Kentucky. The Kinderhookian-Osagean boundary is based on ammonoids (Kammer and Bjerstedt, 1986), whereas the early Osagean-late Osagean boundary is based on crinoid (Lane and Dubar, 1983; Kammer, 1984) and conodont (Rexroad and Scott, 1964) studies.

front deposit, the Holtsclaw Siltstone (Kepferle, 1977). This younger turbidite-delta front couplet may represent a fifth allo-unit, allo-unit E (Figure 15). The Muldraugh Member at the top of the Borden in north-central Kentucky represents a sixth allo-unit, allo-unit F. The Muldraugh is separated from the rest of the underlying Borden by the Floyds Knob Bed. In Kentucky and adjoining southern Indiana, the Floyds Knob marks an erosional phase and depositional hiatus of terrigenous clastics within the Borden delta (Peterson and Kepferle, 1970; Whitehead, 1978). Layers of glauconite and oolitic limestone indicate a depositional pause caused by transgression across the delta platform. The Floyds Knob Bed can be traced from the delta platform to the prodelta environment (Peterson and Kepferle, 1970). The Floyds Knob Bed defines the final clinoform of the Borden delta and separates the Fort Payne Formation from the majority of the Borden Formation. The Muldraugh Member is laterally equivalent to the Fort Payne Formation (Kepferle, 1977).

Paleontologic studies also justify recognition of allo-units E and F. Lane and Dubar (1983) compared Borden Formation crinoids from the delta platform, or undathem, from eastern Kentucky (Nada Member) and southern Indiana (Edwardsville Shale=Muldraugh).

Nada Member crinoids are early Osagean age, whereas Edwardsville Shale crinoids were late Osagean age, indicating progradation of the Borden delta. The youngest Borden fossils in eastern Kentucky are early Osagean age, as are the oldest Borden fossils in north-central Kentucky (Figure 15). Rexroad and Scott (1964) used conodonts to recognize the boundary between early and late Osagean near the base of the New Providence Shale in north-central Kentucky and southern Indiana. Kammer (1984) recognized late Osagean crinoids in the New Providence Shale. Thus, the Borden in north-central Kentucky and Indiana is almost entirely late Osagean in age. As noted above, these late Osagean rocks can be divided into two allo-units by the Floyds Knob Bed.

In summary, a total of six allo-units are recognized. The Kinderhookian-Osagean boundary is located close to the boundary between allo-units C and D. The first three allo-units, A-C, are mostly Kinderhookian age, whereas the last three allo-units, D-F, are mostly Osagean age (Figure 15).

CONCLUSIONS

Lower Mississippian rocks in southern West Virginia and eastern Kentucky comprise a

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single depositional sequence that can be divided into four allo-units analogous to parasequence sets. These four allo-units define at least four separate episodes of progradation as sediments were shed westward from uplands formed in the last tectophase of the Acadian Orogeny. Extension of this analysis to outcrops in north-central Kentucky and southern Indiana allows recognition of at least two more allo-units. Thus, a minimum of six episodes of progradation can be recognized as the Lower Mississippian clastic wedge prograded from the Appalachian Basin to the Illinois Basin.

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Jim Drahovzal and Brandon Nuttall, Kentucky Geologic Survey, generously made available the well-log data base for eastern Kentucky. Mary Behling, Nora Simcoe, and Pat Johns, West Virginia Geologic and Economic Survey, helped compile the well-log data base for West Virginia. Alison Hanham, West Virginia University, drafted the final versions of the cross sections. Ron McDowell, Ana Vargo, and Michael Hohn, West Virginia Geological and Economic Survey, provided helpful comments on an earlier draft of the manuscript. W. Burleigh Harris, University of North Carolina at Wilmington, and Glen Merrill, University of Houston-Downtown, improved the manuscript with their insightful reviews.

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SEDIMENTATIONAL RESPONSE TO A SERIES OF TECTONIC EVENTS, CUMBERLAND PLATEAU, EASTERN TENNESSEE

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ABSTRACT

Strata ranging in age from Upper Ordovician through Carboniferous under the Cumberland Plateau in Tennessee show different responses to tectonic factors in the northeastern and southwestern plateau areas. The response of the Virginia Promontory and Tennessee Reentrant, which were part of an irregular Paleozoic continental margin, to thrusting produced Paleozoic forebulges like the isostatically repressed Cumberland Plateau Dome.

Silurian through Carboniferous strata in the southwestern portion of the Cumberland Plateau in Tennessee accumulated under conditions of generally steady subsidence over the Cumberland Plateau Dome. This region within the Tennessee reentrant records only localized gaps in the stratigraphic record. However, the northeastern region of the Plateau Dome, which behaved like a forebulge, was uplifted and underwent erosion. The sedimentary record, ranging from Upper Ordovician through Carboniferous atop this forebulge, is marked by gaps (unconformities) caused by vertical oscillations related to thrusting during the Caledonian(?), Acadian, and Alleghenian tectonic events.

INTRODUCTION

In Tennessee, the Cumberland Plateau is capped by Pennsylvanian Coal Measures and underlain by Mississippian platform carbonates. In northeastern Tennessee these carbonates contain a number of secondary porous zones which produce modest amounts of oil and gas in Fentress, Morgan and Scott Coun-

ties (Figure 1.)

This paper compares the Middle and Late Paleozoic strata in the northeastern and southwestern areas of the Cumberland Plateau and presents arguments that these rocks record the interplay of sedimentation and erosion related to tectonic events.

PROMONTORIES AND REENTRANTS

Figure 2 from Williams (1978) shows the major geologic provinces in the southern Appalachians and the irregular Paleozoic continental margin made up of the Alabama and Virginia Promontories and Tennessee Reentrant.

Lash (1988) proposed variations in forebasin evolution as a result of continental collision along an irregular continental margin. He suggested offshore, thrust-faulted complexes impinged on promontories causing loading and flexing of the promontories. Flexing caused gaps (unconformities) in the stratigraphic record of the promontories; whereas, stratigraphic sequences recorded in reentrants were largely continuous. Although Lash developed this model for the Ordovician tectonic event, it is reasonable to expect this model to apply for Caledonian (?) Acadian and Alleghenian events as well.

STRATIGRAPHY WITHIN THE TENNESSEE REENTRANT

The generalized surface stratigraphic sequence in southeastern Tennessee, which is

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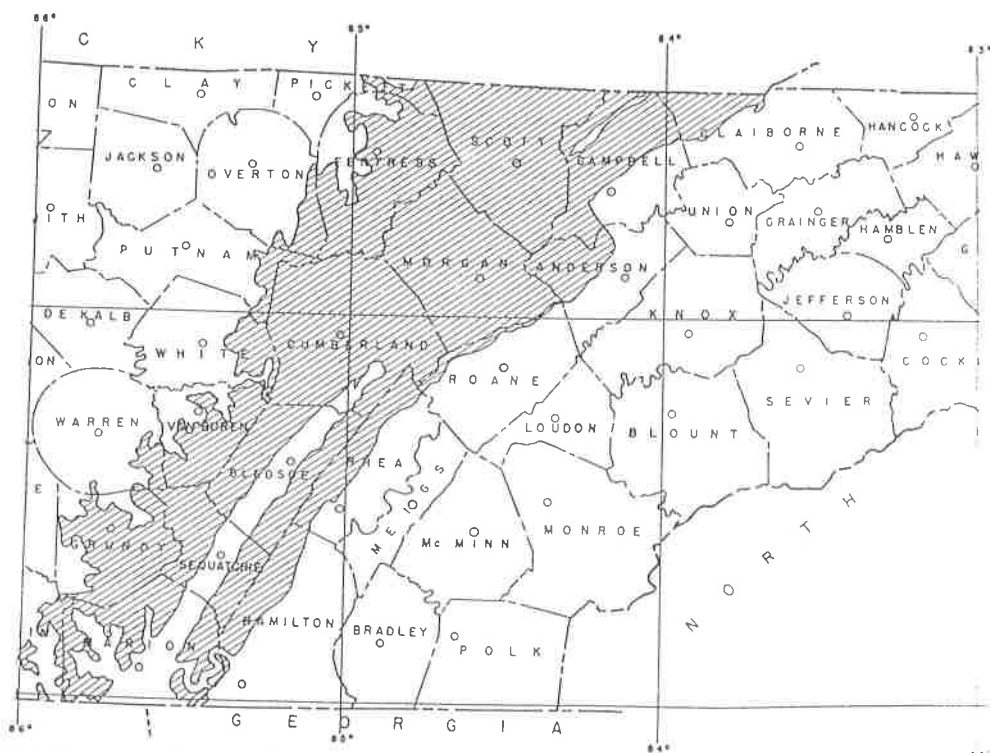


Figure 1. Location of Fentress, Scott and Morgan Counties on the Cumberland Plateau (lined area) in Tennessee.

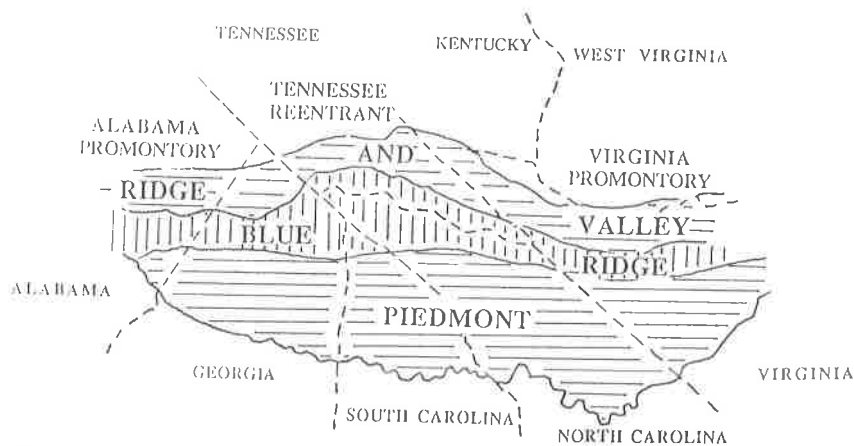


Figure 2. Southern Appalachians, major geologic provinces, Alabama and Virginia promontories and the Tennessee reentrant. After Williams (1978).

located largely in Hamilton and Marion Counties near Chattanooga, is given on Figure 3. See Figure 1 for the location of Hamilton and Marion counties. This stratigraphic sequence is located in the Tennessee Reentrant (Figure 2) and is marked by generally conformable stratigraphic units. At this point it is important to

note that all stratigraphic sequences of Hamilton County are situated in a thrust belt area (Figure 8). This means that these rocks underwent tectonic transport from east to west, and telescoped the facies that were at one time more widely separated.

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Silurian Rockwood and Devonian-Mississippian Chattanooga Shale

The Silurian Rockwood Formation which contains thin-bedded argillaceous sandstones and fragmental carbonates interbedded with thin, green-gray shale comprise the base of the reentrant sequence in this paper. Chowns (1972) reported the Silurian system in north-west Georgia consists of only the Red Mountain Formation. Chowns pointed out that the Silurian sediments in the Appalachian Basin of Georgia and Tennessee had a terrigenous source area to the east that arose as a result of the Taconic orogeny. A large mass, or wedge, of clastic molasse originated in this source area and prograded from east to west. Massive sandstones like the Silurian Clinch Sandstone (Tennessee) predominate in the east and grade westward into the alternating sandstone-shale sequence of the Rockwood Formation (Tennessee).

Rindsberg and Chowns (1986) studied the Early Silurian Red Mountain Formation at Ringgold Gap, Georgia and described and interpreted a shallowing-upward clastic sequence that ranges from turbidites through storm beds to littoral beds. Easthouse and Driese (1988) analyzed siliciclastic systems in a Silurian shelf system (Rockwood Formation, Green gap in White Oak Mountain, Hamilton County, Tennessee) by means of proximity trends and trace-fossil distribution and obtained evidence for three shallowing and four deepening sea level fluctuations. Depositional sequences here formed both below and above fairweather wave base.

Extensive studies of the Devonian-Mississippian black and gray shales in central and eastern Kentucky by Ettensohn and others (1988) have shown these deposits to be cyclic, transgressive-regressive sequences likely related to periods of tectonic activity and quiescence in the Acadian orogen situated to the east. The organic-rich, cyclic black shales are considered to be transgressive and are the result of migration of foreland basins and peripheral bulges (Figure 7) associated with

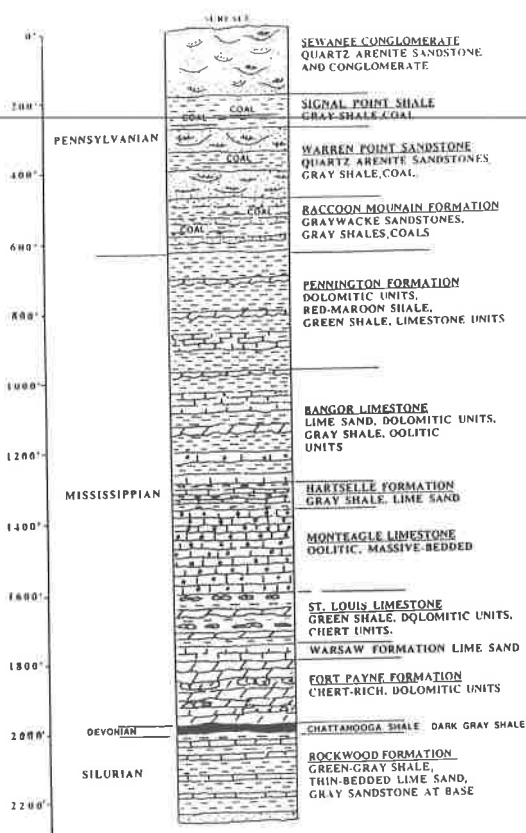


Figure 3. Generalized stratigraphic sequence with transitional formation boundaries. Hamilton and Marion Counties, southeastern Tennessee.

deformational loading in the Acadian orogen. The gray shales in each cycle represent distal area of clastic progradations that formed during times of decreased tectonic activity with attendant cratonic relaxation and upwarping.

Mississippian System

Fort Payne and Warsaw Formations

The Mississippian carbonate sequence begins with the Fort Payne Formation which is a chert-rich, dolomitic with abundant echinoderm fossil clasts. Overlying the Fort Payne is the thin Warsaw Formation which is made up of dolomitic, echinoderm clast-rich calcarenite.

St. Louis Limestone

The St. Louis Limestone overlies the War-

saw. Cooper (1979) identified seven carbonate lithofacies in the St. Louis which he interpreted to have accumulated in an interior platform carbonate setting made up largely of a range of shallow subtidal, intertidal and supratidal environments. Although they are not specifically labeled as such on Figure 3, uppermost units of the St. Louis are chert-rich and may be considered as a separate stratigraphic unit designated as the Lost River Chert zone (Milici and Finlayson, 1967), a zone that separates the overlying Monteagle Limestone from the St. Louis.

Monteagle Limestone

Handford (1978) studied eighteen stratigraphic sections of the Monteagle that crop out in southeastern Tennessee, northwestern Georgia and northeastern Alabama. At least two of these exposures are situated in the Appalachian thrust belt area; namely, the northern tip of Lookout Mountain in the Chattanooga area and a section in Georgia southeast of Trenton.

Hanford recognized six lithofacies within the Monteagle exposures located in the Tennessee Reentrant. An idealized vertical sequence of Monteagle carbonate units begins with massive-to lenticular-bedded, subtidal packstone and grainstone deposits. These basal units are overlain by northeast-southwest trending tidal bars (subtidal to intertidal, oolitic grainstone with large-scale tabular crossbeds) which are capped by emergent tidal-flat deposits.

Exposures of the Monteagle on Lookout Mountain (Figure. 8) consists of thick-bedded to massive-bedded carbonates. Examination of over 100 thin sections of the Monteagle (University of Tennessee at Chattanooga reference collection) from the northern tip of Lookout Mountain, adjacent to Interstate 24, shows numerous dolomitized micrite, packstone and grainstone deposits.

Hartselle Formation

The Hartselle Formation exposed in a roadcut on Interstate 24 on the northern tip of Lookout Mountain, in the thrust belt area, consists of approximately 2.1 meters of shale and approximately 8 centimeters of sandstone in its

middle portion. Bergenback (in press) identified four shale-with dolomicrite horizons that mark the Hartselle Formation.

Rich and Hunter (1980) described 20.4 meters of the Hartselle (dominantly sandstone with 1.5 meters of limestone and 2.4 meters of shale) on Monteagle Mountain west of the thrust belt. They pointed out that the Hartselle is a generally discontinuous, approximately synchronous, sand body occupying the same stratigraphic position throughout its extent in northeastern Alabama and south-central Tennessee. Ten kilometers northwest of the Monteagle Mountain exposure, the underlying Monteagle Limestone is separated from the overlying Bangor Limestone by a fossiliferous, sandy, intraclast-rich limestone. Calcareous foraminifers in this Hartselle interval indicate a Middle Chesterian age. Perhaps these Hartselle exposures on Monteagle Mountain (and to the northwest) mark the western-most extent of the Tennessee Reentrant.

Bangor Limestone

Williams (1980) examined four exposures in southeastern Tennessee and one core of the Bangor from Pigeon Mountain, Georgia (Figure, 8-southeast of Lookout Mountain) and recognized five lithofacies; mudstone, wackestone, packstone, grainstone and gray shale. The Tennessee exposures are situated west of the thrust belt. Williams (1980) states "the Bangor was deposited slightly above, or below, mean sea level on a gently-sloping, shallow marine shelf." Bergenback and others (1980) interpreted the Bangor as a marginal marine, generally lower tidal-flat facies equivalent of the overlying generally high intertidal-supratidal Mississippian Pennington Formation. This tidal-flat complex prograded regionally from east to west and southwest, and likely was the harbinger of a Pennsylvanian terrigenous clastic wedge that also prograded from east to west and southwest over the Mississippian Bangor and Pennington tidal-flat complex. The Bangor in the Pigeon Mountain, Georgia core is composed of high energy, oolitic, shelf-edge carbonates (perhaps on the

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flank of a foredeep located to the southeast).

Vertical distribution of sedimentary structures and texture and composition of the Bangor suggests deposition on a carbonate platform complex with the lowest Bangor containing intertidal units; Middle Bangor composed of an oolitic tidal bar array capped with subaerial units; and Upper Bangor made up of a vertical sequence of subtidal to intertidal to supratidal paleoenvironments.

Pennington Formation

Bergenback and others (1980) report that the Pennington Formation in the Tennessee Reentrant consists of red and green shale, fossiliferous gray shale, fragmental limestone and dolomicrite, all of which have been interpreted as part of a high-intertidal, or supratidal, tidal-flat complex. In a regional sense, the Pennington represents a marginal marine tidal-flat complex encompassing parts of Virginia, Kentucky, Tennessee, Georgia and Alabama

Pennsylvanian System

In the Tennessee Reentrant, the Mississippian-Pennsylvanian systemic boundary is transitional, with the lowermost Pennsylvanian stratigraphic unit, the Raccoon Mountain Formation (Figure 3), transitional with the underlying Mississippian Pennington Formation. In the thrust belt area (Figure 8), especially along the Walden Ridge (Tennessee)-Sand Mountain (Alabama) coextensive trend of the Cumberland Plateau (Figure 9) a number of northwest-southeast oriented mini-basins have been identified and are characterized by localized thickening (over 150 meters in the Raccoon Mountain Basin, Figure 9), of the Pennsylvanian Raccoon Mountain Formation.

In the Monteagle area, west of the thrust belt, the Raccoon Mountain Formation averages only 12 meters thick (Bergenback, in press). Williams and Bergenback (1979) examined core data from the eastern part of the Monteagle Quadrangle and western part of the adjacent White City Quadrangle. The data are located east of the Monteagle Mountain road-

cuts (and west of the thrust belt) described and interpreted by Bergenback (In Press). This core study indicates that, in this area, the Mississippi Pennington Formation shows an irregular upper surface (both local conformities and unconformities) in contact with the overlying Raccoon Mountain. Here there is a low regional dip to the southeast. Evidently the Raccoon Mountain thickens to the southeast, ranging in thickness from 18 meters in the northwest to 56 meters in the southeast. Perhaps these data locate an isolated mini-basin situated west of the thrust belt.

STRATIGRAPHY AT THE SOUTHERN EDGE OF THE VIRGINIA PROMONTORY

Most of the subsurface stratigraphic information indicated on Figure 4 is interpreted from gamma ray, bulk density and porosity geophysical logs. In addition, consulting geologists who work(ed) in this area have prepared

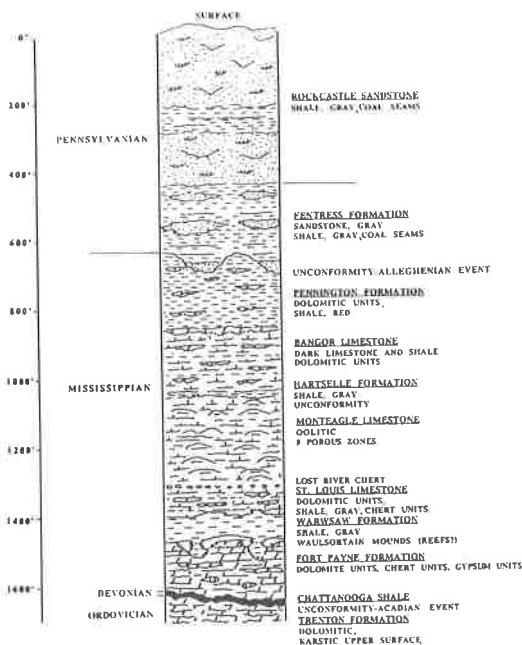


Figure 4. Generalized subsurface stratigraphic sequence bounded by unconformities under the Cumberland Plateau in Fentress, Morgan and Scott Counties, northeastern Tennessee.

sample logs, most of which correlate well with geophysical log interpretations. Further, gamma ray and bulk density logs identify shale sections but do not differentiate sandstone from limestone. It is here that sample logs come into play. Finally, core logs enabled subsurface stratigraphic interpretation in the Stearns, Kentucky region of McCreary County (Figures 6 and 8).

Ordovician Trenton Formation and Devono-Mississippian Chattanooga Shale

A karst surface, formed during subaerial exposure of the Ordovician Trenton Formation, has been preserved in the subsurface of Fentress, Morgan and Scott Counties in Tennessee (Figures 1 and 5). Over much of this area, Silurian rocks are not present and therefore the Chattanooga Shale is draped over an Ordovician karst surface. Thus there is a gap in the stratigraphic record here which may be the result of migration of foreland basins and peripheral bulges (forebulges or foreland bulges) associated with deformational loading in the Acadian orogen (Acadian tectonic event) as suggested by Ettensohn and others (1988).

Mississippian System

Fort Payne and Warsaw Formations

Cores from the lower part of the Fort Payne Formation (Fentress County) contain chert, gypsum and dolomicrite and may indicate that the barren (of oil and gas) lower Fort Payne here is part of an interior platform deposit. MacQuown and Perkins (1982) suggested the productive upper part of the Fort Payne, under Scott and Fentress Counties, produces from porous zones in Waulsortion mounds (reefs?) that formed around topographic highs on the underlying Chattanooga Shale. The Warsaw Formation overlies the Fort Payne and consists largely of dark gray shale and lesser sandstone and fragmental limestone.

St. Louis Limestone

Gray shale, dolomicrite and chert layers

comprise the St. Louis Limestone. A "cherty zone" at the top of the St. Louis is considered by some workers as the Lost River Chert.

Monteagle Limestone

In northeastern Tennessee the Monteagle Limestone is largely oolitic (sample log data) and is best known for its gas reservoirs (consulting geologists reports on individual wells). Porous zones in the Monteagle have been recorded on bulk density and porosity logs. A Monteagle isopach map (Oneida South Quadrangle, see Figure 5 for quadrangle location) shows a number of mound-like build-ups reminiscent of the tidal bars of Handford (1978)] that trend northeast-southwest; have up to 15 to 18 meters of relief; and extend up to 1.6 kilometers in length. Monteagle porous zones, correlated on stratigraphic diagrams, show that most of these zones are confined to the mound-like buildups (i.e., are laterally discontinuous) and occur at eight to ten distinct stratigraphic levels.

Hartselle Formation

Thin, siliciclastic shale and sandstone as well as fragmental carbonates, make up this subsurface Hartselle Formation. The gamma ray log identifies shale units, but sandstone and carbonate layers are differentiated by means of sample logs. As of the date of this paper, the author knows of no published information on the regional thickness variation, nor regional lithologic changes of the subsurface Hartselle. However, the presence of siliciclastic units within a thick carbonate sequence would seem to indicate an unconformity in this part of the stratigraphic record.

Stapor and others (1992) made a thorough outcrop study of the Hartselle along the western margin of the Cumberland Plateau, extending from the northern Alabama to the Tennessee-Kentucky state line. The Hartselle is a regionally prograding (north to south) quartz arenite-rich, wave-dominated deltaic unit made up of onlapping parasequences. Detailed pedogenic studies have identified paleosols (actually their remnants) that formed atop the

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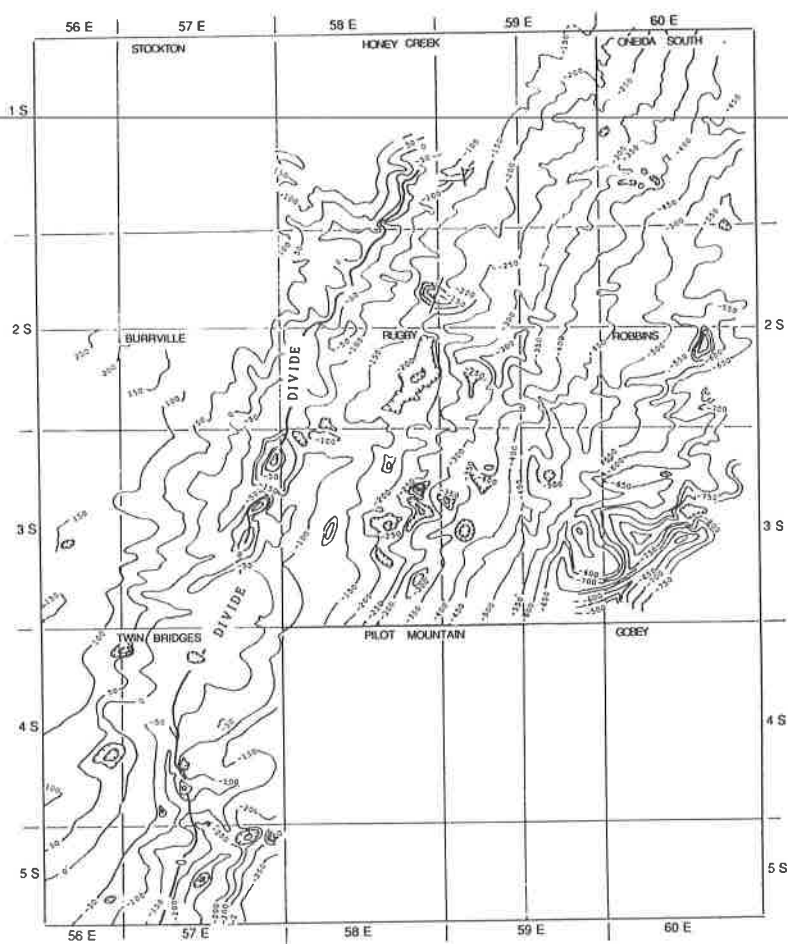


Figure 5. Generalized structure contour map on the Chattanooga Shale.

Monteagle Limestone when it was subaerially exposed by a third order Vail-Exxon sea-level fall. The basal Hartselle-Monteagle has paleosol debris in its sediment. Thus the Hartselle-Monteagle contact is marked by a disconformity that is interpreted as a sequence boundary.

Bangor Limestone and Pennington Formation

The stratigraphy, lithology and interpretation of the Bangor and Pennington in the southern end of the Virginia Promontory are similar to these units in the Tennessee Reentrant.

Pennsylvanian Fentress Formation and Rockcastle Sandstone

Outcrop and core studies, Bergenback and

Wilson (1961), reveal that the upper surface of the Mississippian Pennington Formation in this area has been deeply scoured and displays as much as 60 meters of relief. This significant unconformity may be related to the onset of the Alleghenian tectonic event. Pennsylvanian sedimentary rocks overlying the unconformity on the Pennington encompass the Fentress Formation and Rockcastle Sandstone.

On the Cumberland Plateau in southeastern Tennessee, Lower Pennsylvanian strata are included in the Gizzard and Crab Orchard Mountains Groups. All of these formations in this part of Tennessee, except the Rockcastle Sandstone, when traced northeastward under the Cumberland Plateau, lose their integrity and are considered under the catchall name of Fentress Formation.

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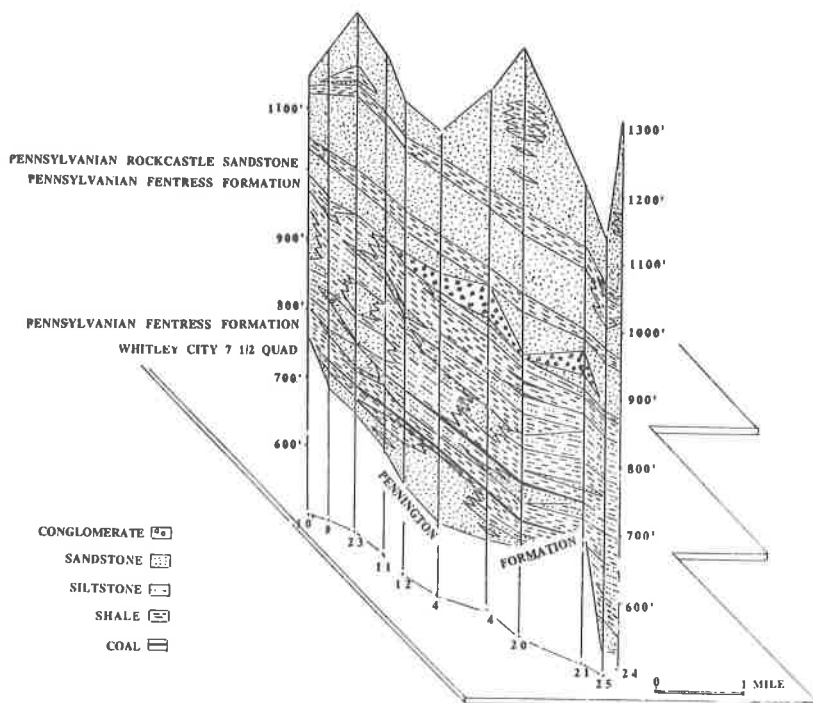


Figure 6. Erosional Mississippian-Pennsylvanian boundary, Whitley City Quadrangle, McCreary County, Kentucky.

Thus, along the southern margin of the Virginia Promontory, in the northeastern portion of the Cumberland Plateau, the Early Paleozoic sequence contains a lower unconformity related to a Caledonian(?) or Acadian tectonic event and an upper unconformity related to the onset of the Alleghenian tectonic event. This is perhaps a classic example of the unconformity-bounded stratigraphic sequence concept pioneered by Sloss (1953).

There may be those who are distressed that these unconformities along the southern margin of the Virginia Promontory are interpreted as wholly related to localized tectonic events (Acadian-Alleghenian) and not to world-wide sea-falls associated with glacial epochs. However, in defense of the localized tectonic interpretation, it must be noted that unconformities of these magnitudes are not present in the area of the Tennessee Reentrant.

Lower Unconformity

Over 1,500 geophysical logs from the Burville, Honey Creek, Oneida South, Robbins,

Rugby and Twin Bridges 7 1/2' quadrangles were examined for Chattanooga Shale "tops". It is understood that not all of the more than 1,500 drill records penetrated the Chattanooga Shale. Nonetheless, these data were used to construct a generalized structure contour map on the Chattanooga Shale (Figure 5).

This map (Figure 5) shows knobs, depressions and buried solution or stream valleys, all of which reflect draping of the relatively thin Chattanooga Shale over an Ordovician karst surface. The dashed "divide" in Figure 5 passes through a sequence of knobs and broadened contour lines that suggest a pre-Chattanooga drainage divide. Buried valleys west of the divide trend west and those to the east trend east. Draping of the Chattanooga over an Ordovician karst surface represents a major unconformity related to a Caledonian(?) or Acadian tectonic event, or a merger of the two.

Upper unconformity

The panel diagram in Figure 6 is based upon logs from cores recovered from the Whit-

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ley City 7 1/2' quadrangle in Kentucky (Bergenback and Wilson, 1961). Although this diagram was used to study the Pennsylvanian stratigraphy of the area, it also shows the unconformity between Mississippian and Pennsylvanian strata.

MAJOR TECTONIC FEATURES

Irregular Continental Margin

Lash's (1988) recognition of the role an irregular continental margin played in controlling Paleozoic sedimentational responses to distinctive tectonic features; i.e., promontories and reentrants, is fundamental to the thesis of this paper.

Foredeeps and Forebulges

Tankard (1986) modeled the deposition of the Carboniferous of eastern Kentucky. He assumed that the lithosphere responded in a viscoelastic manner to the load of the thrust complex to produce an adjacent foredeep and landward forebulge (Figure 7). Sediments are deposited and eroded on the forebulge in a cyclic manner that reflects thrust loading and forebulge uplift followed by erosion. The redistribution of load evidently allows the forebulge to subside and accumulate shallow water sediments.

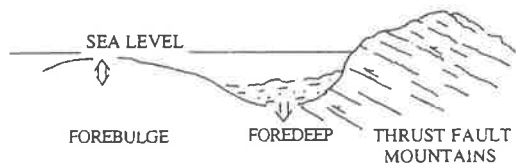


Figure 7. Model of geographic position of foreland basin and forebulge.

Cumberland Plateau Dome

Reesman and Stearns (1989) produced a series of no-load surface maps on the base of the Chattanooga Shale to examine the Nash-

ville Dome. They interpreted these maps to indicate that the dome formed during Late Tertiary to Holocene time in response to regional erosion. However, these maps did reveal an "isostatically suppressed" northeast-southwest trending elongate dome (Cumberland Plateau Dome) under the Cumberland Plateau. This dome is connected to the north-trending, dog-leg shaped Jessamine Dome in Kentucky. Mapping by Reesman and Stearns (1989) indicates a slight saddle between the Cumberland and Jessamine Domes. The northern extent of the Cumberland Plateau Dome almost reaches the Kentucky border and its southern edge extends into Alabama (Figure 8). Further, this dome is situated just west of Appalachian thrusts (including Sequatchie Valley, Figure 9) and it may have acted as a buttress against a further westward thrusting during the Alleghenian tectonic event. Reesman and Stearns (1989) suggest that this dome is a basement structure related to east continent gravity and magnetic highs, although the geographic location of the Cumberland Plateau Dome may lead one to consider this feature to be a foreland bulge, or forebulge, ala Tankard (1986), formed by crustal loading (thrust plate complex) in the area east of the Cumberland Plateau.

Mapping by Reesman and Stearns (1989) was "broad-bush" in nature and they considered the Cumberland Plateau Dome to have been activated after deposition of the Chattanooga Shale; whereupon, it influenced the Carboniferous sedimentation. Nevertheless, data presented on Figures 4 and 5 show that dome activation likely took place earlier, perhaps during Caledonian(?) or Acadian tectonic events, because the Chattanooga Shale is draped over an Ordovician karst surface.

STRUCTURAL FRAMEWORK IN EASTERN TENNESSEE

Figure 8 shows the geographic location of the Cumberland Plateau Dome in Tennessee, as well as the approximate westward limit of Appalachian thrusting. The Walden-Ridge

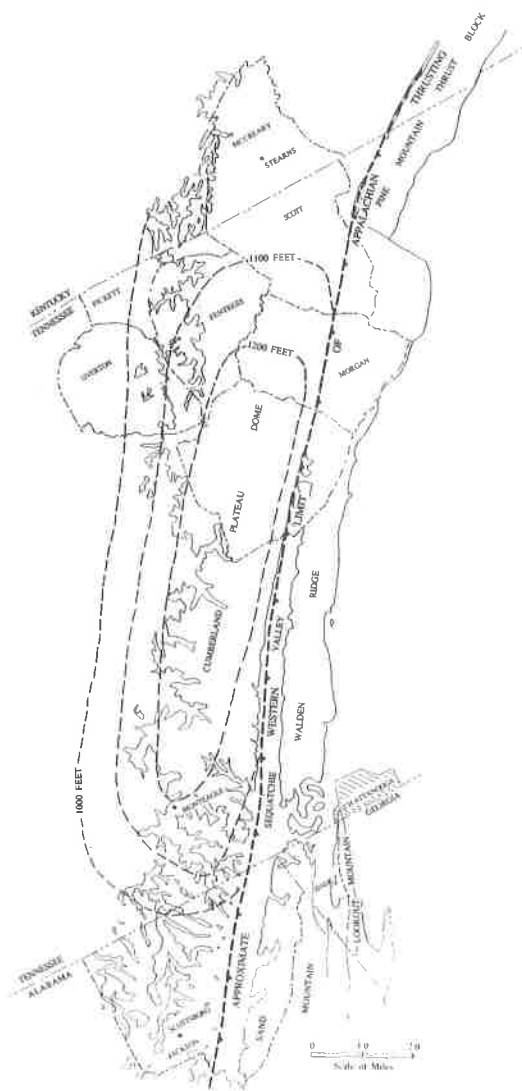


Figure 8. Tectonic elements of Cumberland Plateau, compiled from Reese and Stearns (1989).

Sand Mountain and Lookout Mountain trends are thrust blocks or plates. These thrust blocks are considered as telescoped rock units that formed in more eastern depositional environments and have been moved into their present geographic arrangement.

Mapping of Pennsylvanian rocks on the Cumberland Plateau by Wilson and others (1956) revealed a series of mini-basins on Walden Ridge (Figure 9). Research in progress suggests each basin has a distinct rate of sub-

sidence and sedimentary history. Wilson and others (1956) recognized these basins based on localized thickening of the entire Lower Pennsylvanian Gizzard Group, when actually subsequent research has shown that the thickening belongs largely to the Raccoon Mountain Formation (lowest formation in the Gizzard Group).

The origin of these mini-basins may be explained by the work of Walker and others (1992) who examined an Ordovician stratigraphic section consisting of the Upper Knox Group, the Douglas Lake Member and main body of the Lenoir Limestone, the Fetzer Member and main body of the Whitesburg Formation and the Blockhouse Shale of Dandridge, Tennessee. Shanmugam and Walker (1980) interpreted Upper Lenoir Limestone and Fetzer Member exposures to have formed during foreland basin deepening (Sevier Shale Basin) and to have possibly been associated with crustal flexure, but more likely related to basinward (foredeep) normal faulting. Thus, the sedimentational response to tectonism in this Dandridge exposure shows shallow water deposits grading to deep water deposits, which may be interpreted as a response to a basement block faulting, or rifting, along the flank of a foredeep.

In light of this interpretation of Ordovician rocks, it seems reasonable to suggest that several Pennsylvanian mini-basins, situated along the Walden Ridge-Sand Mountain trend, reflect a sedimentational response of shallow marine peritidalites of the Mississippian Pennington Formation and the overlying relatively deep water deposits (Raccoon Mountain Basin especially, Figure 9) of the Pennsylvanian Raccoon Mountain Formation, to deep-seated rifting along the flank of a foredeep that possibly existed to the northeast of the present-day Chattanooga area during the Paleozoic.

To the northeast, under the Cumberland Plateau, the Cumberland Plateau Dome was exceptionally active with respect to vertical oscillatory movement during Caledonian (?) and/or Acadian tectonic events. This is evidenced by development of a northeast-southwest trending drainage divide on the karstic surface of the Or-

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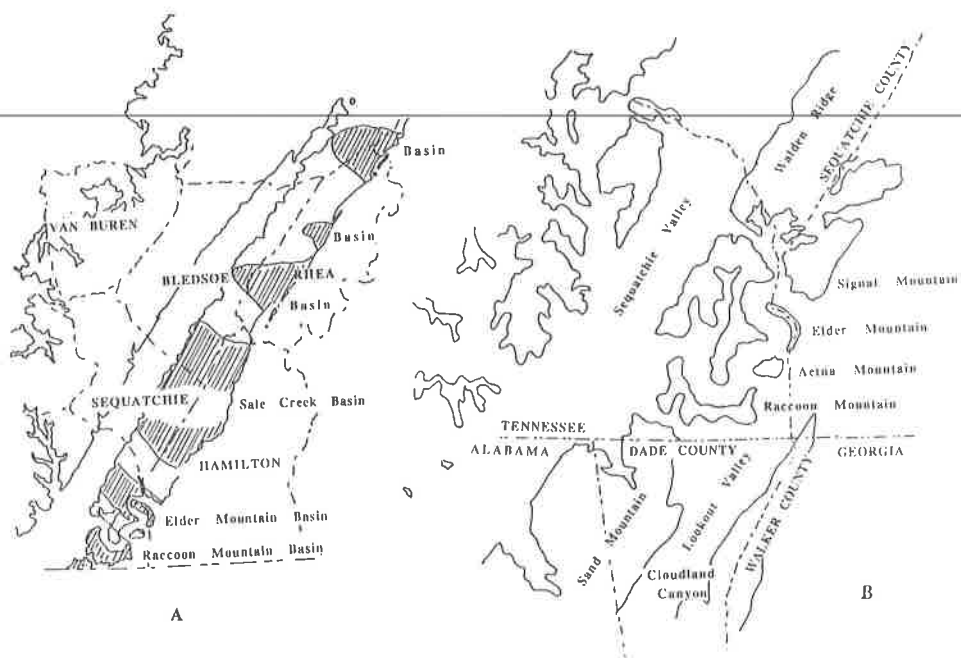


Figure 9. Pennsylvanian mini-basins in Walden Ridge.

dovician Trenton Formation which may be considered as the axis of the Cumberland Plateau Dome (Figures 5 and 8). This event resulted in the formation of a major unconformity that may be regarded as a lower stratigraphic sequence boundary.

In this same general geographic area, Bergenback and Wilson (1961) used deep core records to study the subsurface Mississippian-Pennsylvanian systemic boundary, which proved to be unconformable. It was discovered in this present study that the deepest scouring of the Pennington took place (McCreary County, Kentucky area) over what may have been the Paleozoic axis of the Cumberland Plateau Dome (Figure 8). Thus, a major unconformity, likely related to an Alleghenian tectonic event, was formed in a stratigraphic position that may be considered as an upper sequence boundary.

SUMMARY STATEMENT

An irregular eastern North American continental margin consisting of the Virginia Promontory and Tennessee Reentrant collided

with an offshore terrane during the Paleozoic. In the area of the Cumberland Plateau in Tennessee, an isostatically suppressed dome (Cumberland Plateau Dome) was tectonically active from Late Ordovician into Pennsylvanian time. The Cumberland Plateau Dome in the Tennessee Reentrant generally experienced continuous subsidence and uninterrupted sedimentation; whereas, along the southern margin of the Virginia Promontory it behaved as a forebulge with associated "flexing". The sedimentational response to this "flexing" resulted in periodic uplift and erosion, followed by subsidence and sedimentation, with the result that the stratigraphic record in this northeastern Cumberland Plateau area displays an unconformity-bounded stratigraphic sequence. The major lower unconformity is associated with a Caledonian (?) - Acadian tectonic event (Chattanooga Shale draped over an Ordovician Trenton karst) and the major upper unconformity marks the onset of the Alleghenian tectonic event (Pennsylvanian clastics infilling the scoured Mississippian Pennington Formation).

However, under the northeastern Cumberland Plateau there are a number of other strati-

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graphic levels throughout the Mississippian, such as porous zones productive of oil and gas in Fort Payne and Monteagle carbonates as well as disconformities at the base and top of the Hartselle that might be associated with lesser vertical oscillations of the Cumberland Plateau Dome. Proponents of Vail's worldwide shifts of sea level might feel that undue emphasis is placed on Cumberland Plateau Dome tectonics, but rock units of similar age in the Tennessee Reentrant show few of these erosional features. However, Monteagle, Bangor and Pennington Formations in the Tennessee Reentrant show gray shale bayfill and dolomite tidal channel infilling deposits plus possible paleosol surfaces that may be related to sea level fluctuation. Presumably, future studies in the Cumberland Plateau area will uncover myriad examples of sea level fluctuation.

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