

STORM-DOMINATED SHELF SEDIMENTATION MARGINAL TO A DELTA:
AN EXAMPLE FROM
THE DEVONIAN OF SOUTHWESTERN VIRGINIA AND EASTERN
WEST VIRGINIA

by

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(ABSTRACT)

The Chemung Formation in the south-central Appalachians constitutes part of the thick Devonian - lower Mississippian Acadian clastic wedge. Sediment in the Chemung was derived from a progressively-uplifted source area to the east and accumulated in the proximal environments of an epeiric sea. Sandstones within the dominantly muddy formation are found in a variety of sequence types characterized by hummocky cross stratification. Individual beds usually have sharp erosive bases and gradational tops. A hydrodynamic interpretation of hummocky sequences suggests that they are the result of extremely large but infrequent storm events and are surrounded by fair-weather deposits of mudrock. The Chemung shelf is envisaged as a very low-gradient (<0.5 ft./mile) clastic ramp extending hundreds of miles toward the craton interior. Transport of sand from the nearshore onto the shelf over distances up to 200 miles was facilitated by storm generated gradient currents. Coarsening/thickening- upward sequences of storm beds represent progradational shelf sand lobes. Three facies

associations represent environments of deposition and record changing styles of storm sedimentation on the shelf. The distal inner shelf environment is characterized by discrete hummocky sandstone sequences deposited by only the largest of storms. The proximal inner shelf environment is a much higher energy environment in which periodic storms and fair-weather waves shoal on the low gradient sea floor producing thicker and amalgamated storm sequences. A low-energy shoreline environment is situated landward of the proximal inner shelf and contains only minor storm and fair-weather deposits. The widespread occurrence of hummocky sequences within the Chemung illustrates the importance storm processes can have in the transportation and deposition of sediment in shallow-marine settings.

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Chapter I

INTRODUCTION

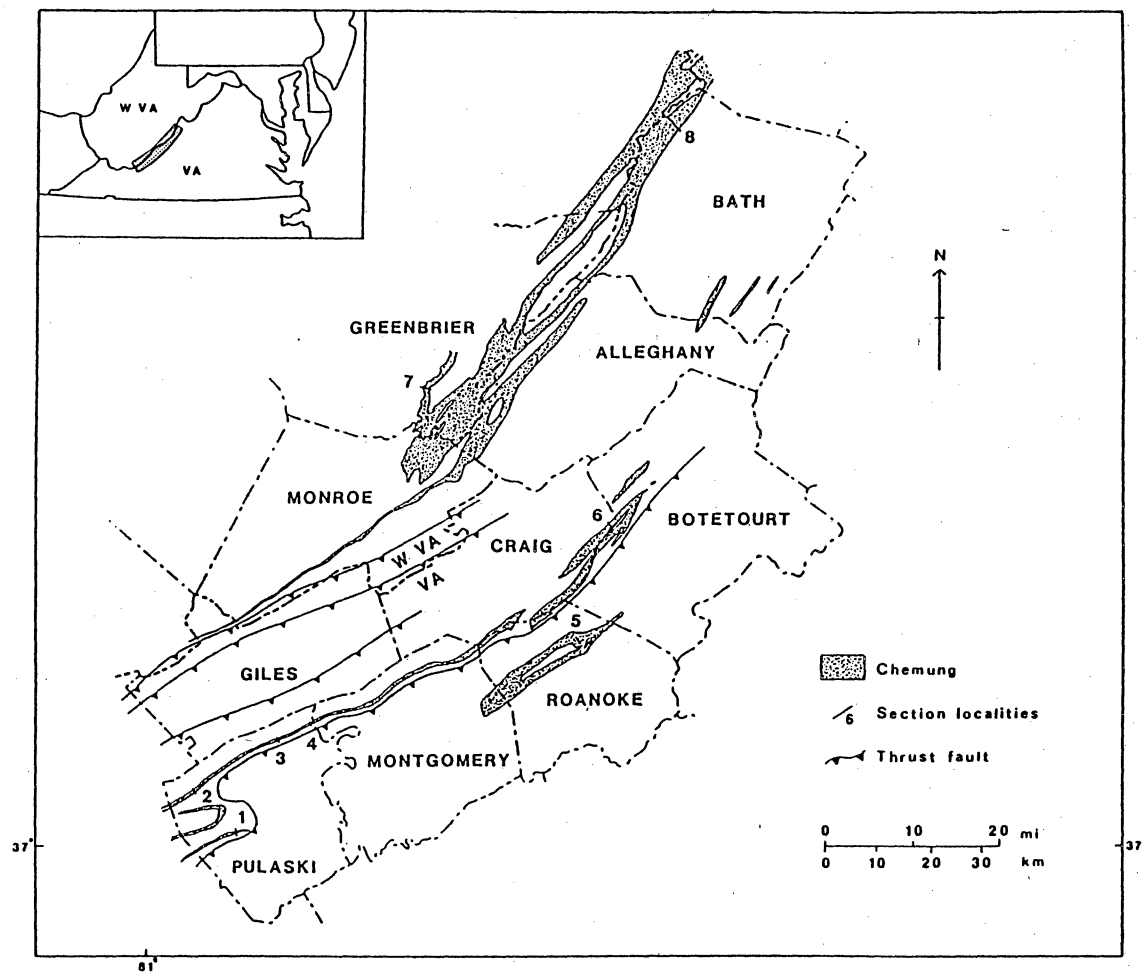
Shelf sediments are widely distributed throughout the geologic record, yet the hydrodynamic processes responsible for the diverse facies assemblages in this setting are not well understood. In recent years, storm processes have increasingly been recognized as a significant factor in shelf sedimentation. Studies of modern shelf environments affected by large storms have demonstrated the impact of such high-energy events (Hayes, 1967; Reineck and Singh, 1972; Kumar and Sanders, 1976; and Aigner and Reineck, 1982). However, observational difficulties inherent in modern shelf studies, particularly during storms, considerably limit the scope of such investigations. For this reason ancient shelf sequences have been the primary focus of research involving shelf storm deposits and their genesis (e.g. Brenner and Davies, 1973; Brenchley et al, 1979, 1982; Leckie and Walker, 1982a; and Dott and Bourgeois, 1982).

The upper Devonian Chemung Formation of Southwestern Virginia is a progradational, shallow-marine sequence that contains many of the features ascribed to storm-dominated shelves. Characteristics of the Chemung are discrete beds of sandstone and conglomerate interbedded in mudrock. The beds typically have sharp, erosional bases and gradational, hummocky tops and the majority of the sandstones exhibit hummocky cross-stratification (HCS; Harms et al, 1975). Sandstones

with HCS have been described from a wide range of environmental settings from the upper shoreface to the open shelf (Kreisa, 1981; Leckie and Walker, 1982; and Hobday and Morton, in press). Most investigators consider HCS to have formed in response to the sporadic high-energy conditions of very large storms (see review in Dott and Bourgeois, 1982). The exact processes by which HCS develops and the environments in which it can form continue to be subjects of debate.

The Chemung Formation was investigated at seven sections along roadways that transect the outcrop belts (fig. 1). One additional and spectacular exposure was afforded at a large hydroelectric project in the northernmost portion of the study area. Detailed descriptions of the lithologies, sedimentary structures, and bed morphologies were made at each section. These features have been interpreted in terms of the hydrodynamic processes responsible for their deposition. Based on the data obtained, a shelf model is presented for the Chemung. Within this shelf setting both sediment transport and depositional sequences for the coarser-grained terrigenous fraction are believed to be the result of storm activity.

Figure 1.-- Location map.



Chapter II

METHODS OF STUDY

FIELD TECHNIQUES

Seven relatively well exposed sections of the Chemung Formation (1 - 7, fig. 1) were measured and described in detail for this study. Section 8 also afforded excellent exposure, but a complete description of the Chemung in this area was impossible due to safety concerns at the construction site. While describing each section, considerable detail was paid to noting the vertical and lateral grain size changes, sedimentary structures, general fossil types, bed morphologies, and the nature of contacts between beds. When sedimentary structures were not well displayed, oriented samples were collected and later slabbed to reveal there internal features. Seven detailed stratigraphic columns totalling 2225 m of section were constructed from this data and used in interpreting the Chemung Formation (see Appendix I).

The terminology used in field work was adopted from the following sources. Mudrock terminology is that of Blatt, Middleton and Murray (1972); grain sizes are after Wentworth (1922), and bedding and thickness terms are those of Ingram (1954).

LABORATORY TECHNIQUES

As mentioned above, slabbed samples were often needed to determine sedimentary structures. In samples where slabbing did not reveal internal features, radiographs were made using standard X-ray equipment. Drawings made from these radiographs provided valuable detail of homogeneous fine-grained sandstones and siltstones. The descriptions of measured sections were greatly enhanced by this method.

Petrographic observations were conducted on 20 thin sections that represent the range of rock types found in the Chemung Formation. Constituent percentages in each thin section were determined using visual percentage estimation charts of Terry and Chilingar (1955). Sandstones are classified according to Dott (1964). Grain shape terminology follows that of Powers (1953).

Statistical analysis of the Chemung Formation was conducted using a variety of techniques. Markov chain analysis was performed on seven facies types to determine the cyclical nature of facies transitions. The procedure used was adapted from Harms (1982) and Miall (1973) with the actual fortran program modified from K. Soegaard (personal communication, 1983) (Appendix II). The distribution of total sandstone, average bed thickness, and hummocky sequence type for each measured section was demonstrated by means of histograms. These were constructed utilizing the SAS statistical package available at the Virginia Tech Computing Center.

Bivalve orientations in 12 randomly-chosen bioclastic lag samples were determined by measuring the long axis of individual shells with respect to a 180 degree semicircle. In addition the concave/ convex-up orientation was noted for each shell measurement. Rose diagrams were then constructed showing the cumulative distribution for each sample.

Chapter III

REGIONAL GEOLOGY AND PALEOGEOGRAPHIC SETTING

The Chemung Formation is exposed in the central Appalachians within the fold-and-thrust terrane of the Valley and Ridge province (fig. 1). The Valley and Ridge is bounded to the southeast by Precambrian metamorphic rocks of the Blue Ridge Province and to the west by undeformed Paleozoic rocks of the Cumberland Plateau.

Stratigraphically, the Chemung constitutes one of the uppermost units of the thick Devonian- Lower Mississippian stratigraphic interval commonly referred to as the Catskill or Acadian clastic wedge. Facies relationships and regional stratigraphy of the wedge are shown in figures 2 and 3. The Chemung is composed of shallow-marine deposits that overlie the turbidite-bearing Brallier Formation (Lundegard, 1979) which intertongues with anaerobic marine mudrock of the Millboro Shale (Potter et al, 1982). The Chemung in turn is capped by non-marine red beds of the Hampshire Formation (McDonnell, 1981) and the deltaic Price-Pocono Formations (Kreisa, 1973). The entire package forms a diachronous, westward prograding sequence which represents a transition from open-marine to continental sedimentation.

Chemung rocks are distributed over much of the central Appalachians (fig. 4). Generally the formation is thickest in the northern and eastern areas and gradually thins toward the south and west. Two depocenters are evident from the isopach map; one in the

central Valley and Ridge of Virginia and another at the West Virginia-Pennsylvania-Maryland Border (fig. 4). The distribution of Hampshire Formation red beds roughly parallels the Chemung isopach pattern in the region with progradational pulses extending no further than central West Virginia and the northern part of the study area (fig. 4). In most of the study area the Chemung is relatively thin and is overlain by the deltaic-marine Price Formation and not by Hampshire red beds.

The Acadian clastic wedge was deposited within the Appalachian sea along the eastern margin of the Laurussia plate (fig. 5). The clastic wedge formed in response to the mid- to upper Devonian Acadian Orogeny. Sediment was supplied to a gradually subsiding foreland basin to the west via the Augusta and Fulton Lobes (Willard, 1939; Dennison and deWitt, 1972) which are delineated by Chemung isopach patterns (fig. 4) and the distribution of conglomerates in the Chemung Formation (fig. 6). Conglomerates are thought to represent areas proximal to loci of sediment influx whereas bioclastics are believed to form in areas removed from the depocenters where bottom dwelling organisms can thrive (low sedimentation rates). The study area is located marginal to the Augusta lobe and contains both proximal and distal shallow marine deposits.

Figure 2.-- Stratigraphic nomenclature of Devonian-Lower Mississippian sediments in the southern central Appalachians. Stratigraphic interval studied is stippled. After Dennison (1961) and Rader (1982).

M.Y.	SYSTEM	EUROPEAN SERIES	NORTH AMERICAN SERIES	NORTH AMERICAN STAGES	WEST VIRGINIA	VIRGINIA
					W ————— E	
345	MISS	TOURNASIAN	KINDERHOOKIAN		POCONO GROUP	MACCRADY SH
						PRICE FORMATION
					HAMPSHIRE FM	
		FAMENNIAN	CHAUTAUQUAN	BRADFORD	CHEMUNG	
				CASSADAGA	FORMATION	
		FRASNIAN	SENECAN	COHOCTON		
				FINGER LAKES	BRALLIER	
		GIVETIAN		TAGHANIC	FORMATION	
		COUVINIAN	ERIAN	TIOUGHIOGA	HARREL SHALE	
370				CAZENOVIA	MAHANTANGO FM	
		EMSIAN			MARCELLUS FM	MILLBORO SHALE
				ONESQUETHAW	HUNTERSVILLE	
					CHERT	
		SIEGENIAN	ULSTERIAN		ONANDAGA LS	NEEDMORE SH
				DEERPARK	(HIATUS)	
					ORISKANY SANDSTONE	
390		GEDINNIAN		HELDERBERG	HELDERBERG GROUP	

Figure 3.-- Generalized cross-section from southwestern Virginia to southeastern Ohio showing stratigraphic relationships within the Acadian clastic wedge. Datum is the top of the Devonian system. Modified from Colton (1970), Potter et al (1982) and Rader (1982).

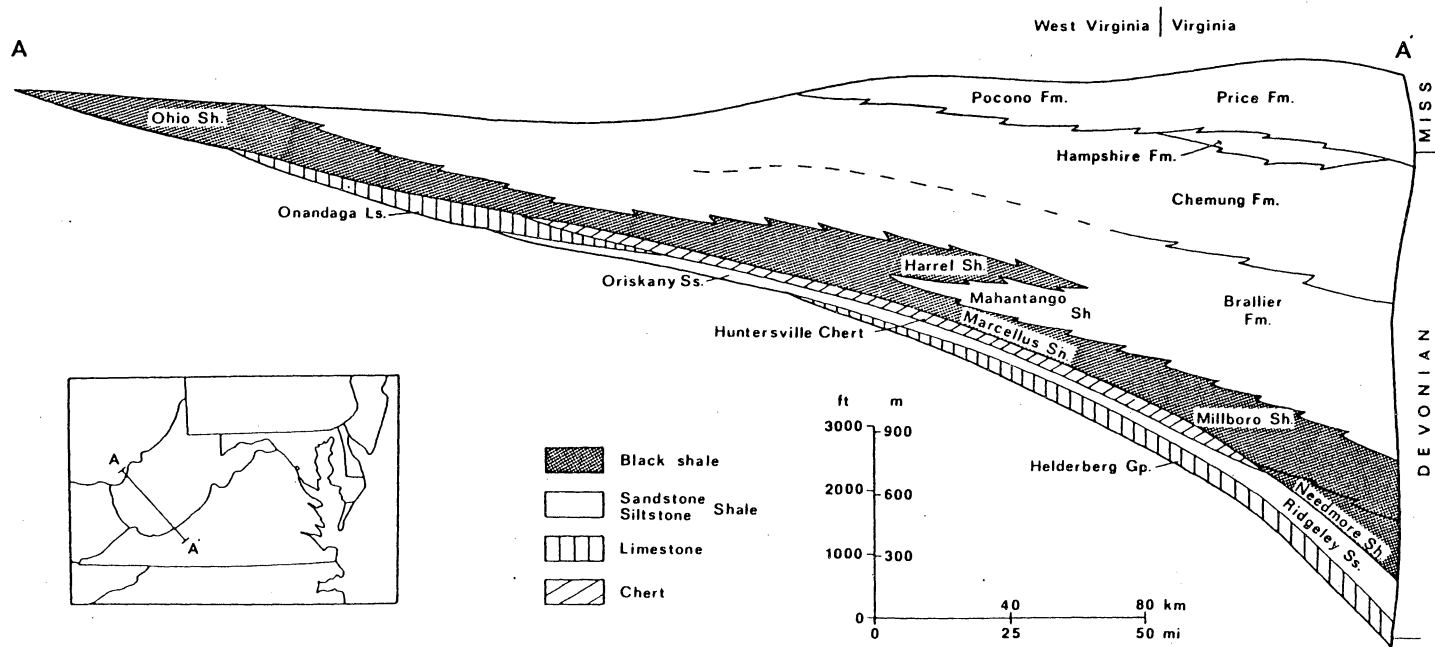


Figure 4.-- Isopach map in meters of the Chemung Formation in the south central Appalachian basin constructed on a palinspastic base. Base from J. F. Read, personal communication, 1983. Data from Woodward (1943), Dennison (1970), McClung (1983), Virginia Department of Mineral Resources Reports, and West Virginia Geological Survey County Reports. Hampshire distribution after McDonnell (1981).

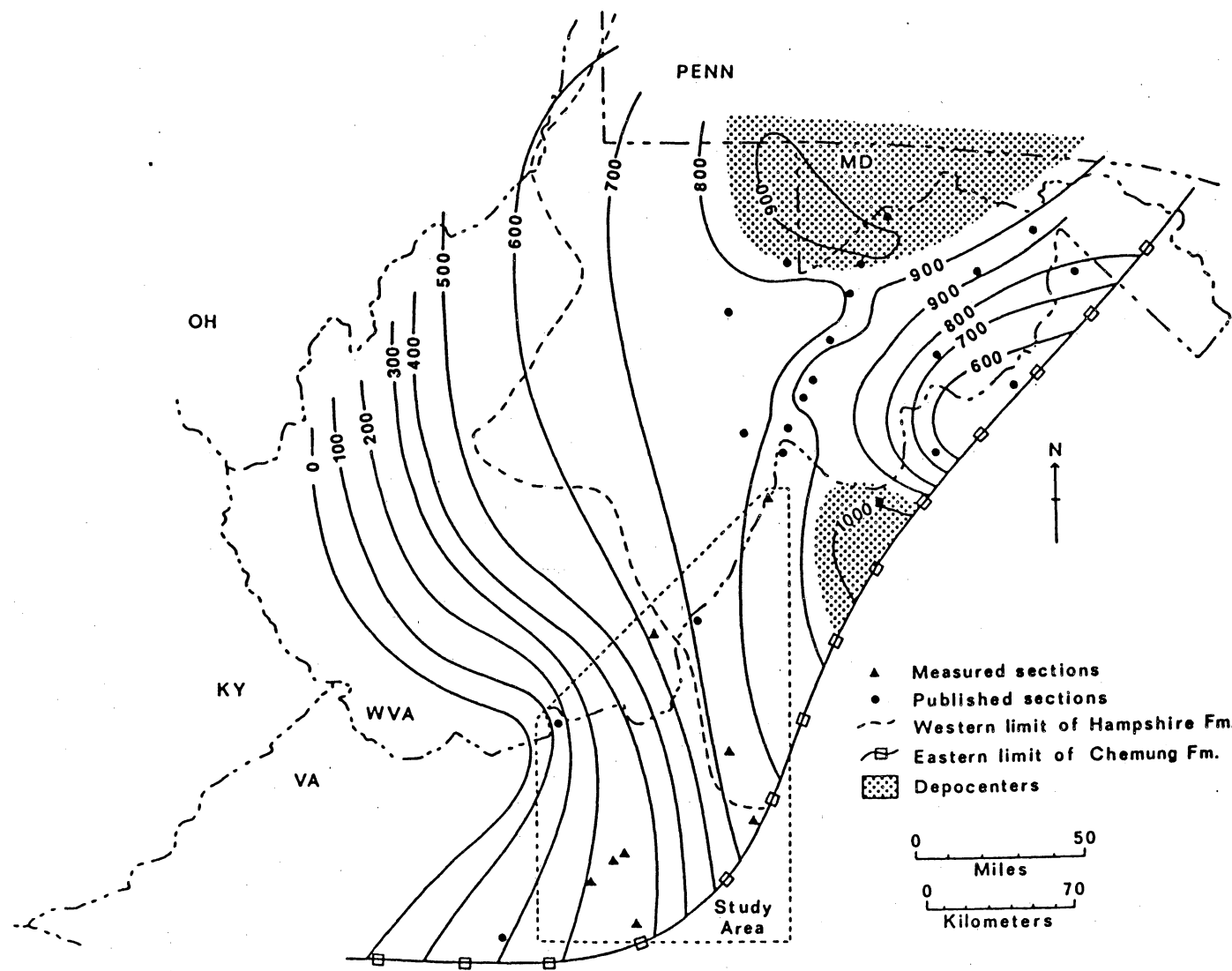


Figure 5.-- Paleogeography of the upper Devonian world. Stippled areas indicate exposed landmasses. Enclosed areas around each continent represent shallow seas. Paleogeography after Scotese et al. (1979) and Marsaglia and Klein (1983).

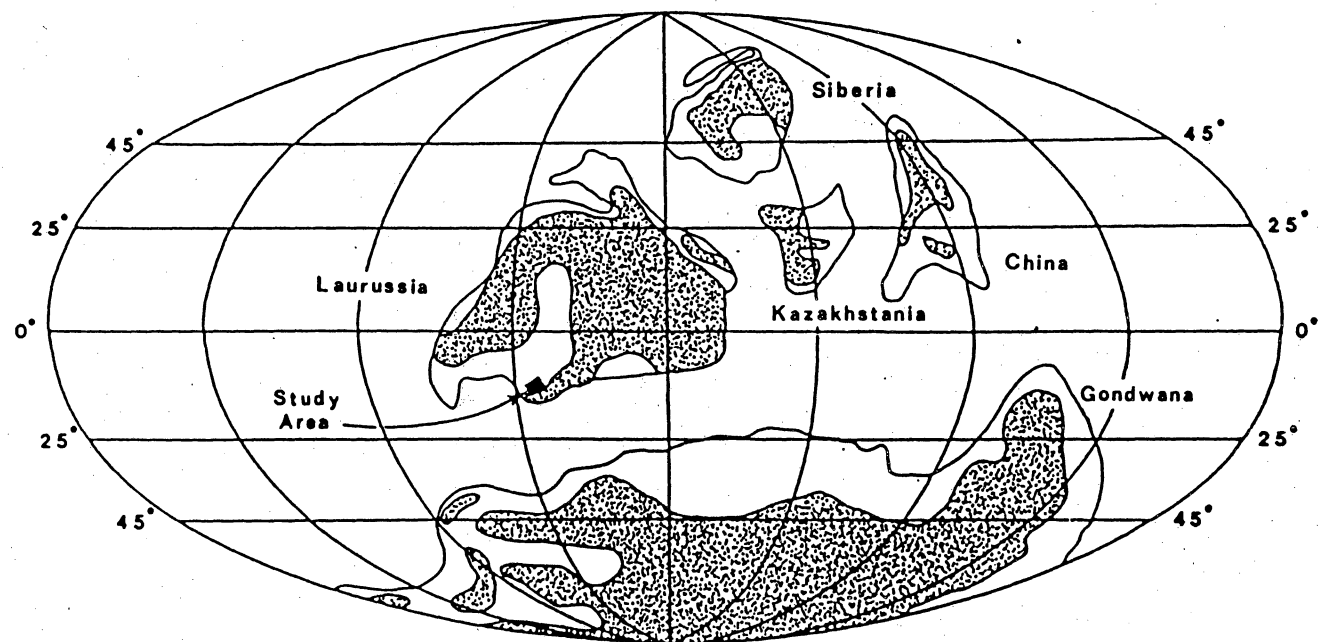
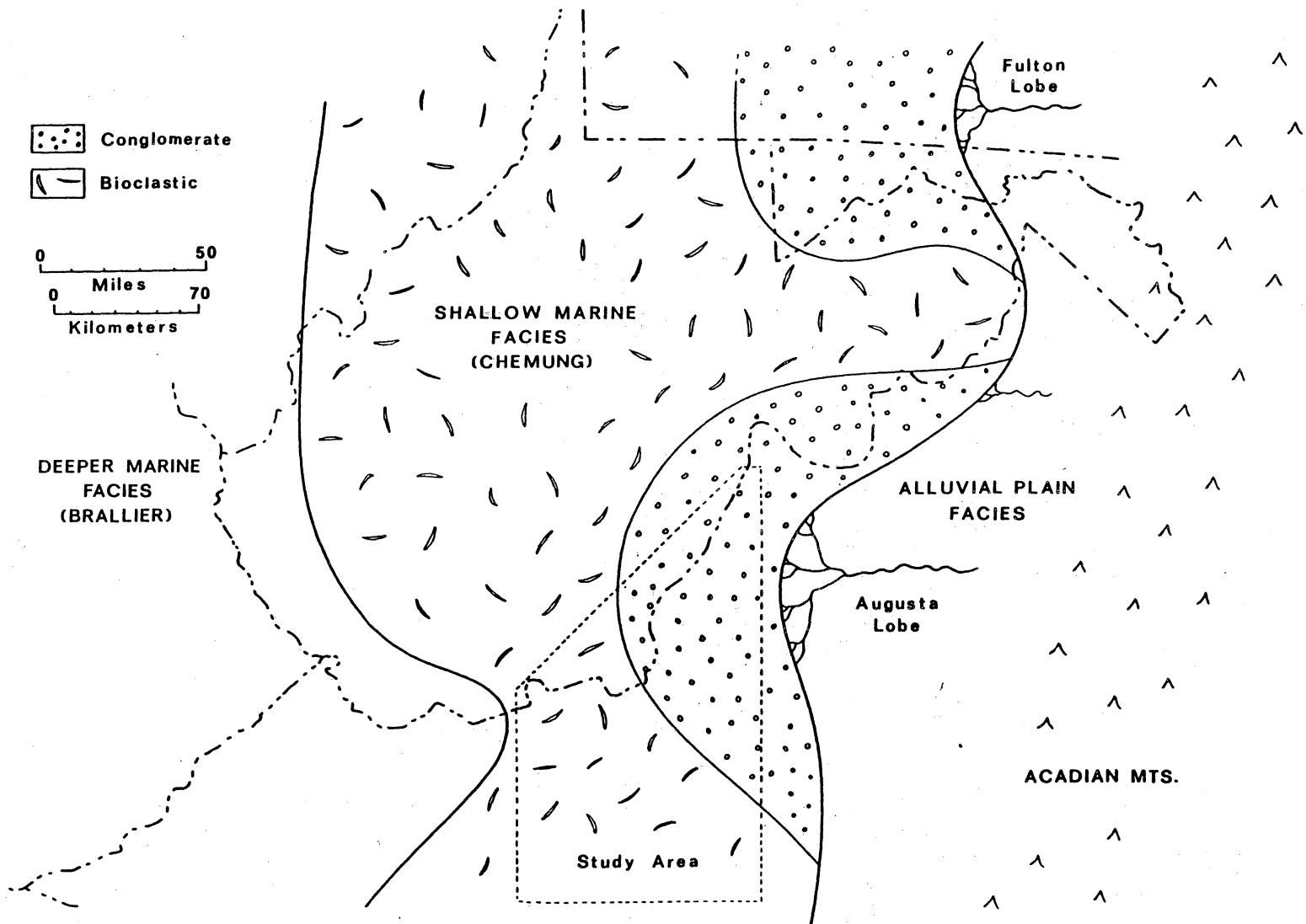


Figure 6.-- Upper Devonian paleogeography of the south central Appalachians on a palinspastic base showing entry lobes and general distribution of coarse clastics on the Chemung shelf. Paleoshoreline after Willard (1939) and Dennison and DeWitt (1972).



Chapter IV

SEDIMENTARY FACIES

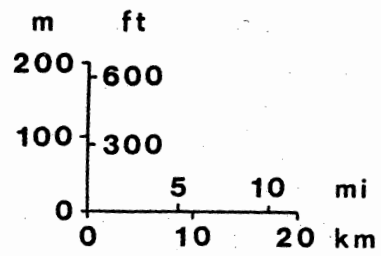
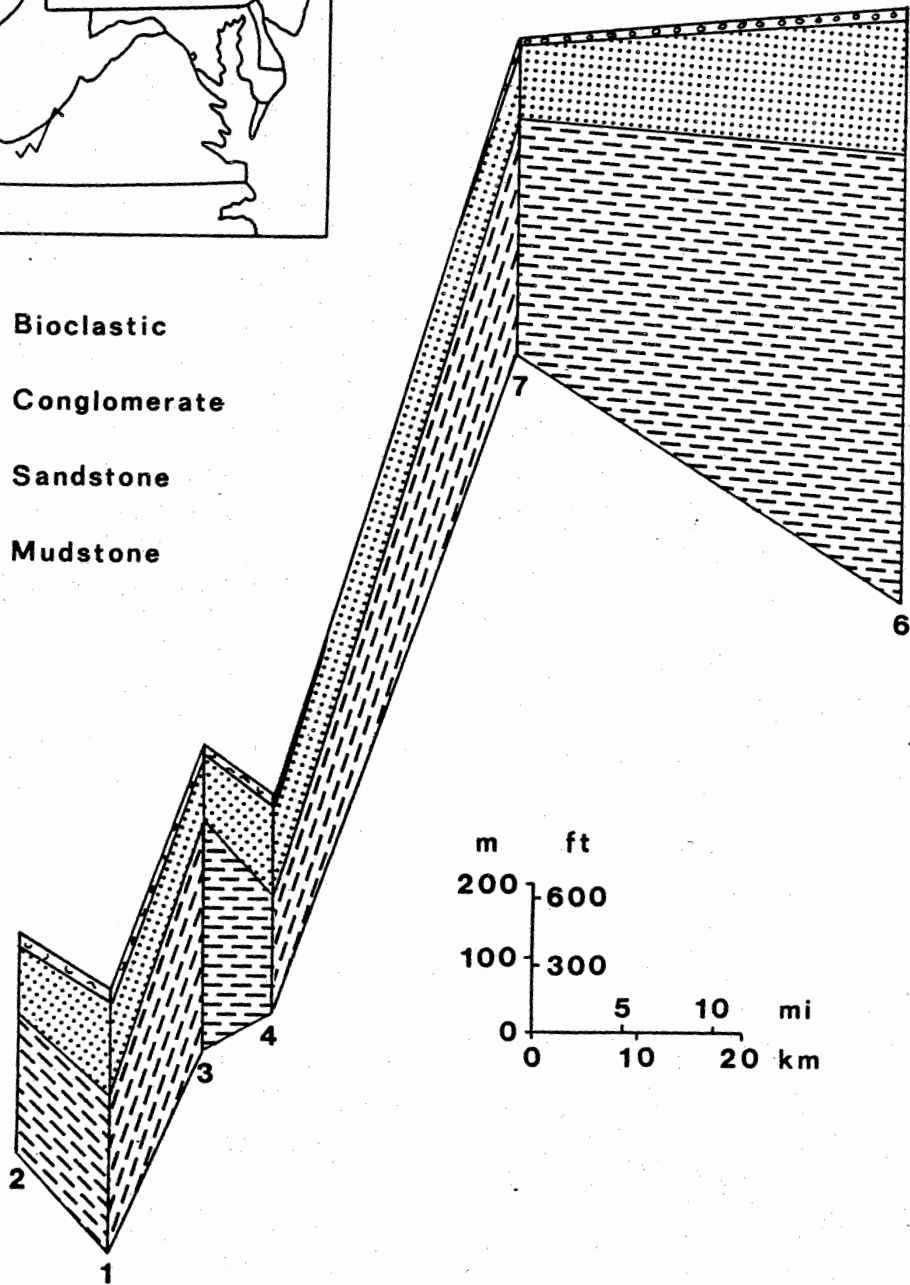
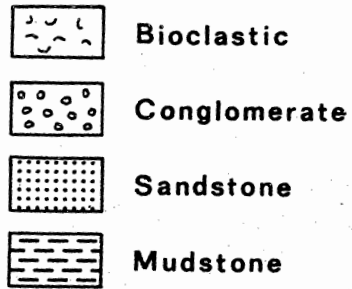
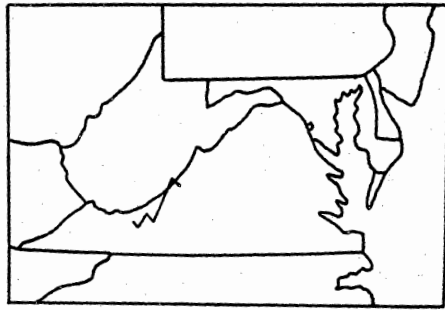
Several parameters can be used to separate rock types in a sedimentary succession. In this study four sedimentary facies have been recognized on the basis of grain size and composition and then further characterized according to their petrography, bed morphology and sedimentary structures. The recognized facies are: mudrock, sandstone, bioclastic, and conglomerate. The distribution of the four facies in the study area is shown in figure 7.

MUDROCK

Mudrock constitutes the most abundant facies found in the Chemung Formation. This group of argillaceous rocks is composed of a complex intergradation of shale, siltstone and claystone. Because of their fine grain size and frequent interdigitation it is often difficult to determine individual rock types at the outcrop. Overall, siltstone and shale occur in approximately the same amounts in the study area although shale is more abundant in the north. Claystone is found only rarely (< 1%) in beds less than 10 cm thick.

Shale occurs in lenses or beds ranging from a few centimeters to greater than 10 meters. The shales are characterized by a very-finely laminated structure which imparts an excellent fissility on weathered surfaces. Shallow scours are often present along bedding surfaces producing gentle discordances between laminae.

Figure 7.-- Fence diagram showing relative proportions of each lithofacies. Only complete chemung sections are included. Location of fence diagram shown by line in inset.



Siltstones are found in beds approximately the same thickness as shales. Horizontal lamination is the dominant structure with hummocky cross stratification and wave-ripple lamination sporadically developed. In some instances, siltstones are bioturbated with complete homogenization of internal structures.

Fossils are scarce in both shales and siltstones and when present are widely disseminated. Whole fossils are more commonly preserved in the mudrock facies than in other facies. Included are various species of brachiopoda, pelecypoda, echinodermata and bryozoa.

SANDSTONE

The Chemung sandstones are mainly very fine grained and are composed of angular quartz (57-95%), metamorphic rock fragments (2-35%), feldspars (1-5%), and accessory minerals (e.g. hematite, zircon, garnet, magnetite, hornblende and tourmaline). A matrix of illite-smectite and other argillaceous minerals is present but never exceeds 5%. Framework grains are well cemented with authigenic silica, calcite, illite-smectite, chlorite, hematite, and pyrite. All the sandstones are classified as quartz arenites or lithic arenites of metamorphic affinity (Dott, 1964) (See appendix III).

Sandstones occur in single beds or amalgamated units which intertongue with enclosing mudrock. Individual sandstone beds or lenses range in thickness from 1 to 300 cm and characteristically pinch and swell laterally. Beds usually have sharp, erosional bases with

channels up to 10 cm deep scoured into underlying strata. Bioclastic or conglomerate lags are found at the base of many beds. Sedimentary structures within the sandstones include: hummocky cross stratification, horizontal stratification, swaley cross stratification (Leckie and Walker, 1982a), wave-ripple cross-lamination, and ball and pillow structures. Hummocky cross stratification and horizontal stratification are the most common structures in the sandstones. Disseminated stringers or pods of fossil fragments and pebbles often follow laminations within sandstones. Tops of sandstone beds are usually gradational into overlying mudrock and exhibit a hummocky (undulating) topography. However, when wave ripples occur on the upper surface the contact with mudrock is very sharp. Bioturbation sometimes obscures structures in the tops of beds. The vertical arrangement of sedimentary structure types and their relationship to the bioclastic and conglomerate facies are discussed later.

BIOCLASTIC

The bioclastic facies is characterized by concentrations of whole and fragmented brachiopods, pelecypods, echinoderms, and bryozoans within a matrix of fine to coarse sand. Both fossil-and matrix-supported varieties of this facies are present. The concentrations of fossils are heavily cemented by calcite forming a coquinoid sandstone. Bioclastics preferentially form at the bases of sandstone beds in units ranging from 1 to 15 cm in thickness. Individual bioclastic beds are also present as

lenses up to 10 cm thick within mudrock intervals and as stringers within amalgamated sandstones. Bioclastics are either horizontally stratified or hummocky cross stratified.

CONGLOMERATE

Conglomerates in the Chemung consist of well-rounded, ellipsoidal quartz pebbles up to 4 cm in diameter and oblate mud clasts up to 6 cm in diameter within a matrix of angular sand. Pebbles are set in both clast-and-matrix supported fabrics. The conglomerates commonly occur as basal lags to sandstone units, but are also found as discrete 5 to 20 cm thick beds within mudrock. In addition, thickly-bedded conglomerates between 35 and 125 cm in thickness are present in the upper portion of section 6. Horizontal stratification and hummocky cross stratification are characteristic of thicker, clast-supported conglomerates whereas matrix-supported units have weakly imbricated fabrics.

Chapter V

FACIES SEQUENCES

The four facies of the Chemung Formation occur in repetitive associations or facies sequences. Two main facies sequences are developed: (i) hummocky cross-stratified sequences and (ii) channel sandstone sequences. Although not all inclusive, it is believed that these facies sequences are representative of the major depositional regimes operating on the Chemung shelf.

HUMMOCKY CROSS-STRATIFIED SANDSTONE SEQUENCES

The hummocky cross-stratified sandstone sequence is the most common depositional motif in the Chemung Formation with greater than 98 percent of the sandstones structured by one or more components of the sequence. HCS sandstone sequences will be described and interpreted in this paper in terms of an idealized sequence which contains all possible components arranged in their most commonly observed succession. The idealized sequence is considered the norm against which all variations can be compared and also acts as a basis for hydrodynamic interpretation. This approach was previously proposed by Kreisa (1981) and Dott and Bourgeois (1982) in their investigations of hummocky sequences. The idealized hummocky sequence recognized in the Chemung Formation is illustrated in figure 8.

Idealized Hummocky Sequence -- Description

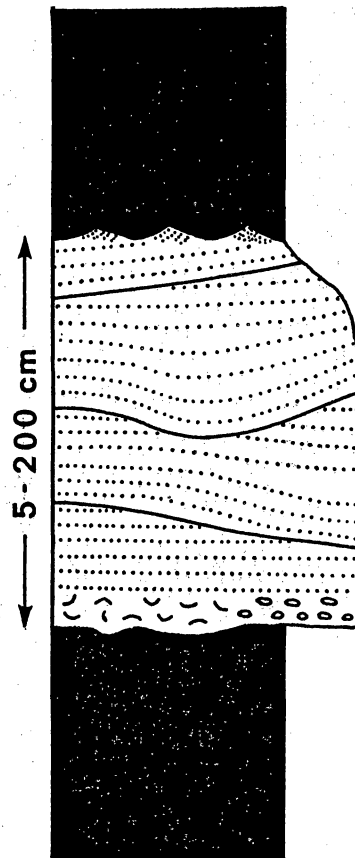
The base of hummocky sequences is usually sharp and erosional. Underlying mudrock is commonly scoured into a broad undulating topography marked with local channels from 1 to 10 cm deep, and more rarely flute casts. Load structures are also present in a small fraction of the beds exaggerating the erosional relief. Sedimentary features in underlying strata such as horizontal or cross lamination and burrows are often truncated along this surface.

Overlying the basal erosional surface is a coarse bioclastic or conglomerate lag which may contain mudrock intraclasts. Horizontal imbrication / stratification is typical of most lags, although thicker lags (15-50 cm) are often hummocky cross stratified (fig. 9). Bioclastic lags consist of whole and broken fossils in a matrix of fine to coarse sand. In figure 9 laminae of gravel, bioclasts and sand are truncated by erosional surfaces with laminae above the erosional boundary parallel to that surface. Individual laminae are usually well segregated by grain size although some do exhibit grading. Fossil bivalves preferentially lie parallel to the substrate in a concave-up: convex-up orientation ratio of 1.6:1 (fig. 10).

In the idealized sequence, lags are gradationally overlain by horizontally-stratified sandstone which occasionally exhibits parting lineation. The core of the idealized sequence is composed of sandstone structured by hummocky cross stratification. This structure, as described by Harms et al (1975), is a type of medium-to large-scale

Figure 8.-- Idealized hummocky sequence.

IDEALIZED HUMMOCKY SEQUENCE



Mudstone

Wave ripples

Hummocky cross-stratified
sandstone

Horizontally-stratified sandstone
Lag; bioclastic or conglomerate structured by
HCS or HS

Mudstone

Figure 9.-- Polished slabs of bioclastic (a) and conglomerate (b) lags exhibiting hummocky cross stratification. Individual laminae are truncated by erosional surfaces with laminae above the erosional boundary parallel to that surface. Note segregation of conglomerate and sandstone fractions into discrete thick laminae. Individual laminae may exhibit grading.

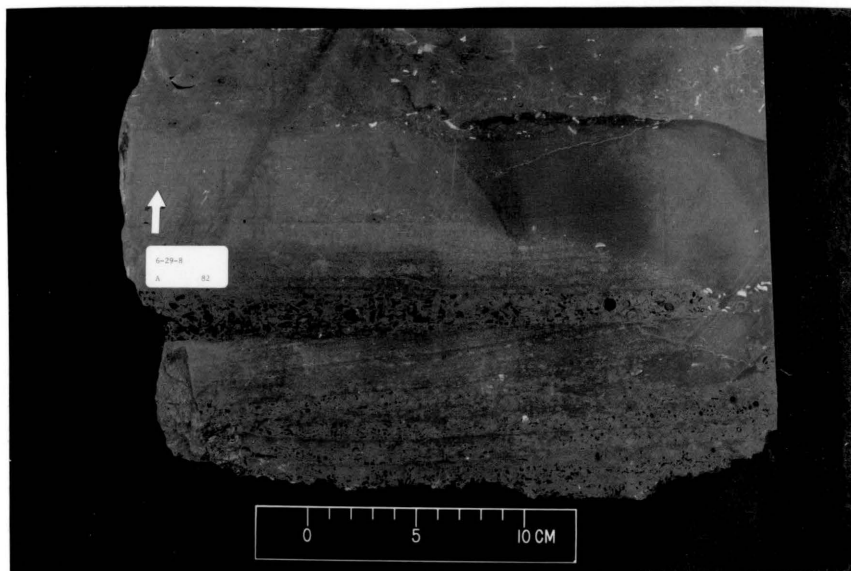
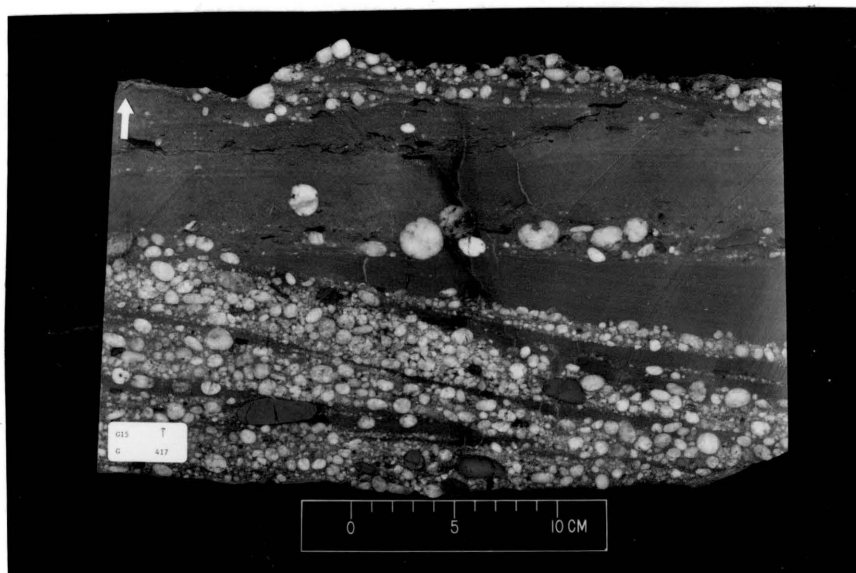
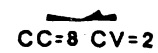
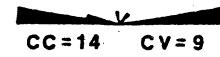
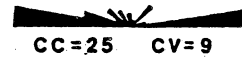
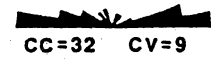
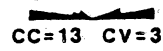
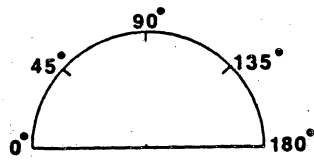
**a****b**

Figure 10.-- Bivalve orientation in bioclastic lags. Orientation of the long axis of each bivalve was measured with respect to a 180 degree semicircle while noting the concave or convex-up nature of each shell. The distribution of concave-up (cc) and convex-up (cu) shells is shown below each rose. When bivalves were parallel to the substrate both 0 and 180 degree directions were plotted.



cross stratification with the following features: "(1) lower bounding surfaces of sets are erosional and commonly slope at angles less than 10 degrees, though dips can reach 15 degrees; (2) laminae above these erosional set boundaries are parallel to that surface or nearly so; (3) laminae can systematically thicken in a set so that their traces on a vertical surface are fan-like and dip diminishes regularly; and (4) the dip directions of erosional set boundaries and of the overlying laminae are scattered."

Hummocky cross stratification in the Chemung Formation does not deviate markedly from this description. Hummocky cross stratification often begins with a thin horizontally or parallel stratified sandstone set (fig. 11). This is capped by an erosional surface which truncates individual laminae in the horizontally stratified set. Erosional set boundaries are often in excess of the 15 degree maximum set by Harms et al (1975) reaching 25 degrees in some beds. Laminae above the set boundaries are always approximately parallel to that boundary and thicken in swales and thin over hummocks. Laminae approach a near horizontal position if significant deposition occurs over the erosional surface. Subsequent scouring will truncate the sandstone set, as with the horizontally stratified set, and sandstone will again be deposited above this erosional set boundary. This stacking of hummocky cross-stratified sets can occur up to a maximum of 10 times in the thickest beds. HCS almost always persists throughout the remainder of the sequence in which case a gently-undulating or hummocky bed

morphology is formed with either a sharp or more typically gradational boundary into overlying mudrock.

On rare occasions, the hummocky cross-stratified interval is capped by symmetrical or asymmetrical wave ripples that are sharply capped by overlying mudstone (fig. 12). Internally these ripples exhibit characteristic small-scale cross lamination in which individual laminae dip randomly and are bounded by convex-downward erosional surfaces (fig. 13a and b). Simpler lamination patterns are also present with unidirectional dip of laminae (fig. 13c). The orientation of wave ripple current directions in the study area is shown in figure 14. From the rose diagrams it is evident that individual sections have well defined paleocurrent trends, however, there is little directional correlation between each section.

Storm Mechanics

Hummocky sequences are interpreted as forming from relatively rare depositional events of high intensity and short duration (Harms et al, 1975; Dott and Bourgeois, 1982). Within the shallow-marine setting that is inferred for the Chemung sediments, each sequence is thought to have been produced by the effects of a single storm and to be surrounded by fair-weather mudrock deposits. Before an explanation of the hydrodynamic processes that produce storm sequences can be presented, it is necessary to consider the various forces affecting the shelf environment during the advance and passing of a storm system.

Figure 11.-- Sketch of a hummocky cross-stratified sandstone sequence showing characteristic features of this structure. A - thickening of laminae in swales. B - thinning of laminae over hummocks.

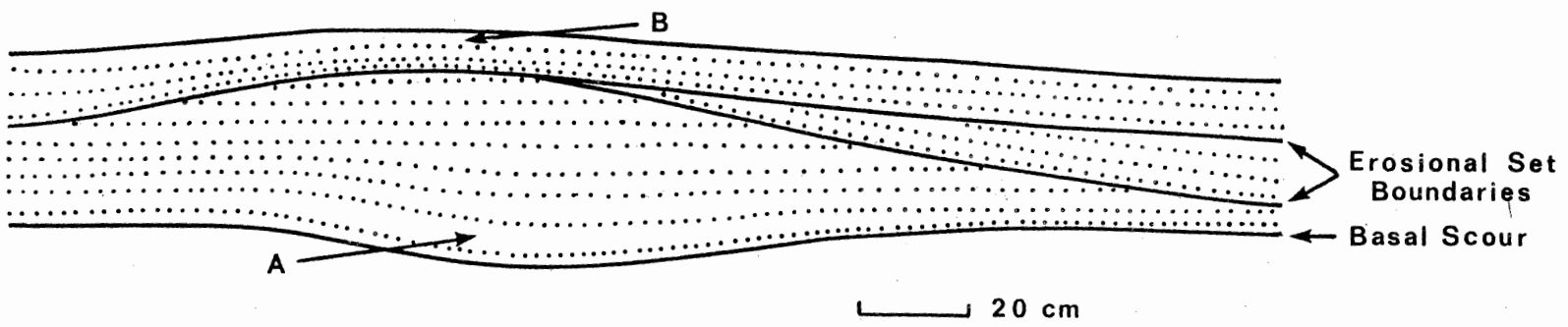


Figure 12.-- Symmetrical (a) and asymmetrical (b) wave ripples on the upper surface of hummocky cross-stratified beds.

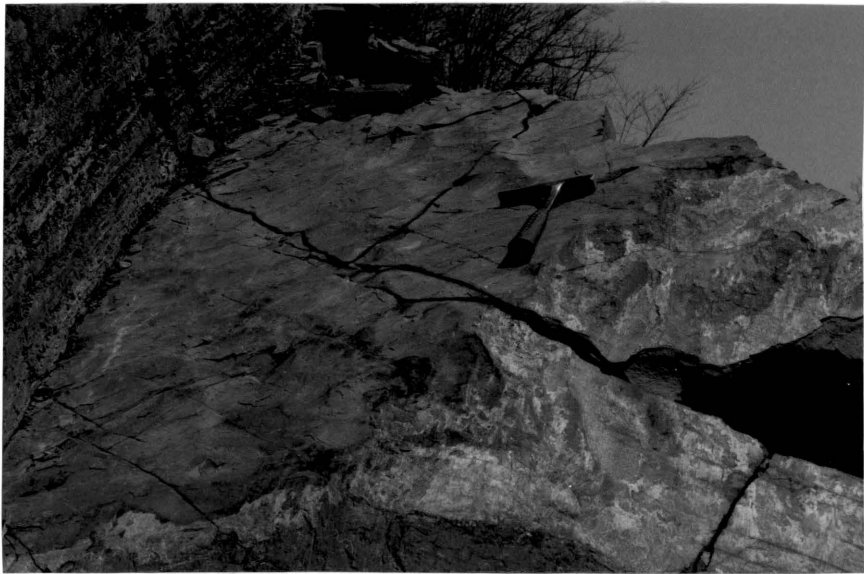
**a****b**

Figure 13.-- Sketch of small-scale cross laminations produced by wave ripples. Sand beneath ripple intervals in a and b is hummocky cross stratified.

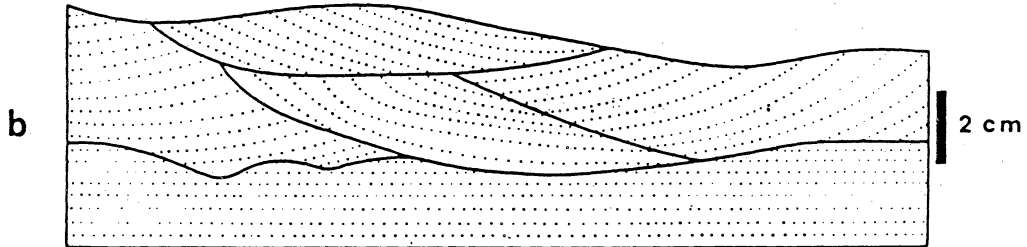
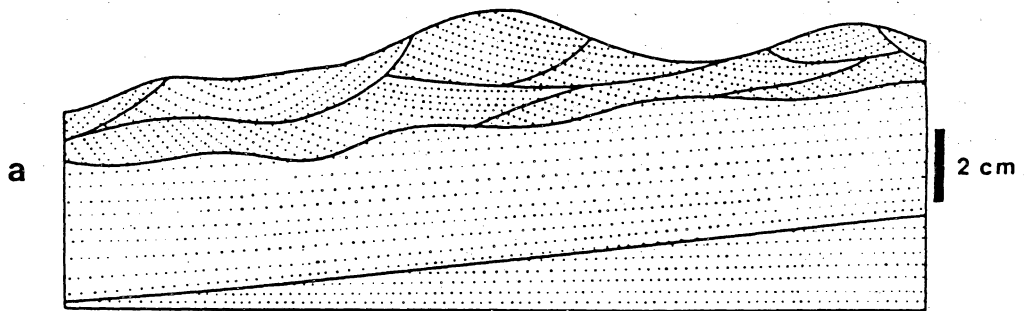
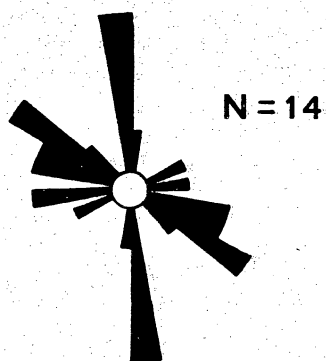
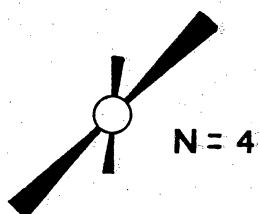
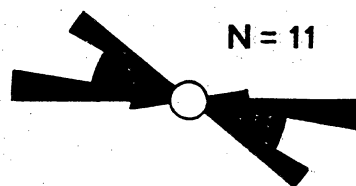


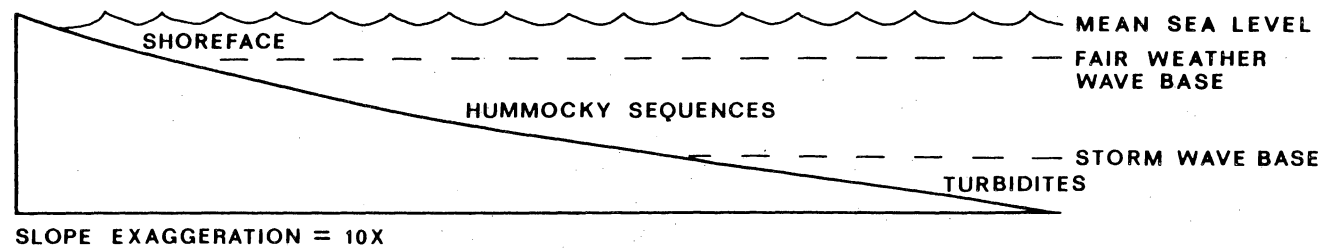
Figure 14.-- Rose diagram showing wave-ripple trends in the study area.

**Section 7****Section 5****Section 6**

As a storm system advances into a shallow-water shelf setting, the increasing magnitude of wave activity caused by high winds results first in a lowering of the maximum water depth to which wave processes affect the sea floor. This lowering of wave base from a normal datum, fair-weather wave base (FWWB), to storm wave base (SWB) greatly enhances the shelf area subject to wave activity (fig. 15) (Irwin, 1965). The effects of lowering wave base are two fold. First, the seafloor is scoured entraining previously deposited sand and mud in suspension. Secondly, bivalves and other hard shell organisms are locally transported and concentrated in parautochthonous lags on the sea bottom (Brenner and Davies; 1973, 1974).

High winds associated with storms also help to produce a phenomenon known as a storm surge or storm head. Storm surge is the increase in sea level over normal stage created by the tractive force of wind on the sea surface in conjunction with a fall in barometric pressure (Allen, 1982). Storm surges in modern hurricanes occur early in shoreward progression being ahead of the storm center and immediately after the strongest winds (Hobday and Morton, in press). The effect of storm surge is that in increasing the sea level at the shoreline, a hydraulic head is formed in which near surface "wind-drift currents" force water landward and equally strong "gradient currents" near the sea floor carry water seaward (Allen, 1980). Within the context of storm sedimentation on shelves, storm surge is significant in that it would provide a mechanism for eroding sediment in the near

Figure 15.-- Diagram illustrating probable environment of formation for hummocky cross stratification in relation to storm and fair-weather wave base. Modified from Dott and Bourgeois (1982).



shore region and transporting it to the offshore shelf. The importance of gradient currents in eroding and transporting modern shelf sediment during storms has been demonstrated by Hayes (1967) and Aigner and Reineck (1983).

Supply and deposition of sediment between fair-weather wave base and storm wave base is envisaged as being accomplished through three separate but penecontemporaneous processes: 1) transportation of sediment from the nearshore, 2) fallout of suspended matter in the water column as the storm wanes, and 3) reworking of sediment by oscillatory currents as the storm gradually wanes.

The intensity of sediment reworking between FWB and SWB is controlled by the maximum velocity wave currents can produce at the sea floor. This maximum velocity (u) is a function of wave height (H), wave period (T), water depth (h) and K , where $K=2\pi/L$ and L = wavelength (Clifton, 1976). This relationship is given in the formula:

$$u = \frac{H}{T} \sin(h) kh$$

From this formula it is evident that as a wave shoals between SWB and FWB, greater and greater reworking will occur due to shallowing water depth (h) and increased wave height (H). Storm sequence types would be expected to reflect this phenomenon.

Idealized Hummocky Sequence -- Hydrodynamic Interpretation

The idealized facies sequence (fig. 8) developed in response to hydrodynamic conditions existing at the different stages of a storm as discussed above.

Base of sequence -- Prior to the introduction of nearshore sand or coarser terrigenous sediment, the shelf bottom below fair-weather wave base is scoured by strong oscillatory currents. An undetermined thickness of the substrate is eroded creating an undulating, locally-channeled topography. Organisms inhabiting the sea floor are concentrated as parautochthonous lags above this surface.

Following the introduction of conglomerate, sandstone, and minor amounts of shell material to the offshore shelf by gradient currents, the previously deposited lags and newly introduced allochthonous sediment are reworked by oscillatory currents. Fossil bivalves with a preferred concave-upward orientation (fig. 10) indicate extremely rapid deposition of shells from a sediment laden water column. This differs from the convex-upward populations found by Brenner and Davies (1973, 1974) and Kreisa (1981) in their studies of ancient storm sequences.

Bioclastic and conglomerate lags provide valuable insight into the nature of sediment transport on shelves. Recent work by Kreisa (1981) and Aigner and Reineck (1982) has suggested that bioclastic lags are autochthonous or parautochthonous accumulations. Alternatively, studies by Brenner and Davies (1973) and Hobday and Morton (in press) have proposed extensive offshore transport of skeletal debris.

Within the Chemung the little transported (unabraded), whole-shell accumulations of fossils would suggest only local transportation of lag material. The only possible exception to this statement would be bioclastic lags in amalgamated HCS sequences. Conglomerate lags, as discussed previously, are believed to have been transported to the open shelf from nearshore beach and fluvial environments by gradient currents.

Horizontally stratified lags and sandstones -- There are two possible origins for horizontal stratification in storm sequences, both involving high shear; 1) shear related to unidirectional offshore gradient currents, and 2) shear produced by oscillatory currents on the sea floor (Clifton, 1976). The intense bed shear produced by gradient currents, as discussed previously, is known to erode sediment in the nearshore and transport it seaward. Deposition from gradient currents could possibly produce horizontally stratified sandstones and lags, but the preservation potential of such deposits between SWB and FWB is low due to reworking by later storm activity. Only sediments not reworked by oscillatory currents after being deposited by gradient currents (i.e. horizontally stratified beds) would be formed in this manner. Waves, on the other hand impart to the water an orbital motion that is essentially flat at the sea floor causing conditions of intense bed shear at the sediment/water interface (Clifton, 1976). Horizontal stratification in HCS sequences is most likely related to oscillatory wave shear as suggested by Kumar and Sanders (1976).

Hummocky Cross-Stratified Lags and Sandstones -- The hydrodynamic conditions responsible for the formation of hummocky cross-stratified lags and sandstones is not clearly understood due to the unsuccessful attempts to produce the structure in laboratories or observe it forming in nature. At the present time, theories on the formation of HCS are based on the geometry of hummocky laminations. There are two general schools of thought on this subject: A) The first proposes that hummocks grow from a horizontal substratum on the sea floor (Hunter and Clifton, 1982, P. 32), B) The second envisages that hummocks are produced by draping of sediment over a scoured hummock and swale surface (Harms et al, 1975, 1982; Dott and Bourgeois, 1982). The first proposal can be eliminated for Chemung sediments due to the absence of laminae sets that thicken to form hummocks. Laminae sets in the Chemung, for the most part, thin over hummocks and thicken in swales thereby adding support to the draping theory. This thickening/thinning pattern of stratification is thought to be produced by the tendency of oscillatory currents to selectively deposit more sand in swales (lows) than hummocks (highs). The scoured surfaces separating HCS sets are thought to occur as fluctuating oscillatory currents produce periods of net erosion alternating with periods of net deposition; scouring of strata - deposition of parallel strata over scour - scour of parallel strata (Harms et al, 1975).

The following generalizations can be made in regard to the hydrodynamic conditions which produced hummocky cross stratification in the Chemung Formation.

1) Flow is predominantly oscillatory as evidenced by the presence of 3 - dimensional hummocks and a paucity of well defined directional trends. Parting lineations are occasionally present supporting Clifton's (1976) assertion that strong unidirectional currents with highly variable current drift are associated with oscillatory flow.

2) Deposition of sand as horizontal or near horizontal laminae occurs under upper flow regime / plane bed conditions. Truncation of horizontal laminae by hummock-and-swale surfaces, as discussed above, is caused by erosive activity that separates depositional periods. Mantling of the scoured hummock-and swale surface by parallel stratified sand infers high rates of suspension fallout combined with high flow velocities at the sediment / water interface (Harms et al, 1982).

Wave Ripples - Symmetrical and asymmetrical wave ripples which cap hummocky sequences are produced during the waning stages of oscillatory flow as storm wave base retreats landward and represents reworking of previously deposited sand. The random orientation of individual laminae sets indicates a high degree of variability in ripple migration (Newton, 1968). The rarity of wave ripples in the hummocky sequences suggests a rapid rise in wave base after abatement of the storm.

Variability in Hummocky Sequences

The idealized hummocky sequence presented in this paper is a facies model which performs two important functions: 1) It serves as a framework for determining the hydrodynamics of its formation (as used above), and 2) The sequence is viewed as a conceptual standard for displaying variability. Due to the high degree of variability in hummocky sequences within the Chemung, all possible types cannot be described. To overcome this apparent randomness, a Markov chain analysis was performed on the Chemung storm beds. Later in the paper, 4 sequence types thought to best represent storm deposition on various regions of the shelf will be discussed.

Markov chain analysis, as defined by Carr (1982) is "a stochastic process in which the state of the system at time t_n is influenced by or dependent on the state of the system at time t_{n-1} , but not the previous history that led to the state at time t_{n-1} . The presence of a Markov process implies a degree of order in a system." As employed in this paper, Markov chain analysis quantifies the probability of facies transitions within the hummocky sequences and demonstrates inherent cyclicity. The procedure used here is largely after Harbaugh and Bonham-Carter (1970) and Miall (1973).

Several recent workers have noted problems concerning the procedure used in Markov chain analysis (Schwarzacher, 1975; Carr, 1982). In particular the line of structural zeroes in the various matrices has provoked considerable controversy. Despite these

problems it is felt that Markov chain analysis is none-the-less valuable for quantifying the general cyclic nature of facies changes in sedimentary sequences.

In utilizing the Markov process, it is first necessary to define the elements to be employed in the statistical analysis. Within the Chemung sequences 7 facies are recognized. These include:

- 1) Mudrock
- 2) Scoured base
- 3) Horizontally-Stratified Lag
- 4) Hummocky Cross-Stratified Lag
- 5) Horizontally-Stratified Sandstone
- 6) Hummocky Cross-Stratified Sandstone
- 7) Wave-Rippled Sandstone

The number of transitions between each individual facies is then recorded in a 2-dimensional array termed the transition count matrix (F_{ij}) (table 1). A total of 2531 transitions were recorded from the measured sections.

From the transition count matrix two probability matrices are derived. First the independent trials probability matrix (R_{ij}) displays the probability of each possible transition occurring, assuming that the sequencing is random (table 2). The formula for this matrix is:

$$R_{ij} = S_{ij} / t - S_i$$

Where S_i = Sum of the F_{ij} for the i'th row

S_j = Sum of the F_{ij} for the j 'th row

t = total number of transitions

A second matrix, the transition probability matrix (P_{ij}), represents the actual probability for each facies transition (table 3). It is given by:

$$P_{ij} = F_{ij} / S_i$$

Finally a difference matrix (D_{ij}) is constructed by subtracting independent trials probability matrix values from transition probability matrix values (table 4).

$$D_{ij} = P_{ij} - R_{ij}$$

The difference matrix determines whether or not each transition represents a Markovian dependency relationship. Difference matrix values with positive entries emphasize a Markovian property by indicating those transitions which occur with greater than random frequency (Miall, 1973).

While the results from the difference matrix do indicate a Markovian relationship, they are possibly due to random chance. For this reason, a test of significance must be employed. The chi-square test (X^2) is widely used for this purpose (Gingerich, 1969). The chi-square formula is given by:

$$X^2 = 2 \sum_{ij} F_{ij} \cdot \text{Log}_e [P_{ij} / (S_i / F_{ij})]$$

Table 1.-- Transition count matrix (R_{ij}) for all measured sections.

All transitions are from row to column. $R_{ij} = S_j / t - S_i$; F_{ij} = number of transitions from facies i to facies j ; S_j = sum of the F_{ij} for the j 'th row; total number of transitions = 2531.

TRANSITION COUNT MATRIX

		<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>S1</u>
Mudrock	1	0	430	31	6	31	127	0	625
Scoured base	2	0	0	89	81	28	468	0	666
Horiz. strat. lag	3	25	0	0	0	21	62	0	108
HCS lag	4	23	7	0	0	1	81	0	112
Horiz. strat. sandstone	5	53	8	1	0	0	32	1	95
HCS sandstone	6	563	289	3	26	1	0	21	903
Wave rippled sandstone	7	21	0	0	0	1	1	0	23
	Sj	685	734	124	113	83	771	22	

Table 2.-- Independent trials probability matrix (R_{ij}) .
 $R_{ij} = S_j / t - S_i$

INDEPENDENT TRIALS PROBABILITY MATRIX

		<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
Mudrock	1	0.00	0.39	0.07	0.06	0.04	0.40	0.01
Scoured base	2	0.37	0.00	0.07	0.06	0.04	0.41	0.01
Horiz. strat. lag	3	0.28	0.30	0.00	0.05	0.03	0.32	0.01
HCS lag	4	0.28	0.30	0.05	0.00	0.03	0.32	0.01
Horiz. strat. sandstone	5	0.28	0.30	0.05	0.05	0.00	0.32	0.01
HCS sandstone	6	0.42	0.45	0.08	0.07	0.05	0.00	0.01
Wave rippled sandstone	7	0.27	0.29	0.05	0.05	0.03	0.31	0.00

Table 3.-- Transition probability matrix (P_{ij}). $P_{ij}=F_{ij}/S_i$

TRANSITION PROBABILITY MATRIX

		<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
Mudrock	1	0.00	0.69	0.05	0.01	0.05	0.20	0.00
Scoured base	2	0.00	0.00	0.13	0.12	0.04	0.70	0.00
Horiz. strat. lag	3	0.23	0.00	0.00	0.00	0.19	0.57	0.00
HCS lag	4	0.21	0.06	0.00	0.00	0.01	0.72	0.00
Horiz. strat. sandstone	5	0.56	0.08	0.01	0.00	0.00	0.34	0.01
HCS sandstone	6	0.62	0.32	0.00	0.03	0.00	0.00	0.02
Wave rippled sandstone	7	0.91	0.00	0.00	0.00	0.04	0.04	0.00

Table 4.-- Difference matrix (D_{ij}). $D_{ij}=P_{ij}-R_{ij}$

DIFFERENCE MATRIX

		<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
Mudrock	1	0.00	0.30	-0.02	-0.05	0.01	-0.20	-0.01
Scoured base	2	-0.37	0.00	0.07	0.06	-0.00	0.29	-0.01
Horiz. strat. lag	3	-0.05	-0.30	0.00	-0.05	0.16	0.26	-0.01
HCS lag	4	-0.08	-0.24	-0.05	0.00	-0.03	0.40	-0.01
Horiz. strat. sandstone	5	0.28	-0.22	-0.04	-0.05	0.00	0.02	0.00
HCS sandstone	6	0.20	-0.13	-0.07	-0.04	-0.05	0.00	0.01
Wave rippled sandstone	7	0.64	-0.29	-0.05	-0.05	0.01	-0.26	0.00

The above formula has $(n-1)^2 - n$ degrees of freedom, with n =number of facies in the matrix. For the Chemung sequences, the following values were generated using the chi-square procedure.

$$\begin{array}{ll} X^2 & = 9005.48 \\ \text{Degrees of freedom} & = 29 \end{array}$$

Using chi-square tables from Owen (1962) and a level of significance of 99 percent, the X^2 value of 9005.48 is well above the limiting value of 49.59. This second test substantiates the cyclic affinity of Chemung sequences.

Based on the statistical analysis above it is now possible to demonstrate modal distribution cycles for the idealized hummocky sequence. This can be accomplished by utilizing the values of the transition probability matrix (P_{ij}) or the positive values of the difference matrix (D_{ij}). Difference matrix values generated with Chemung data, while providing a means for illustrating dependency relationships, are not adequate for describing the totality of facies stacking schemes in hummocky sequences. This is due to the unequal number of facies present which biases difference matrix values toward only the major facies transitions. For this reason, probability matrix values (P_{ij}) were employed to show the magnitude of transition pathways.

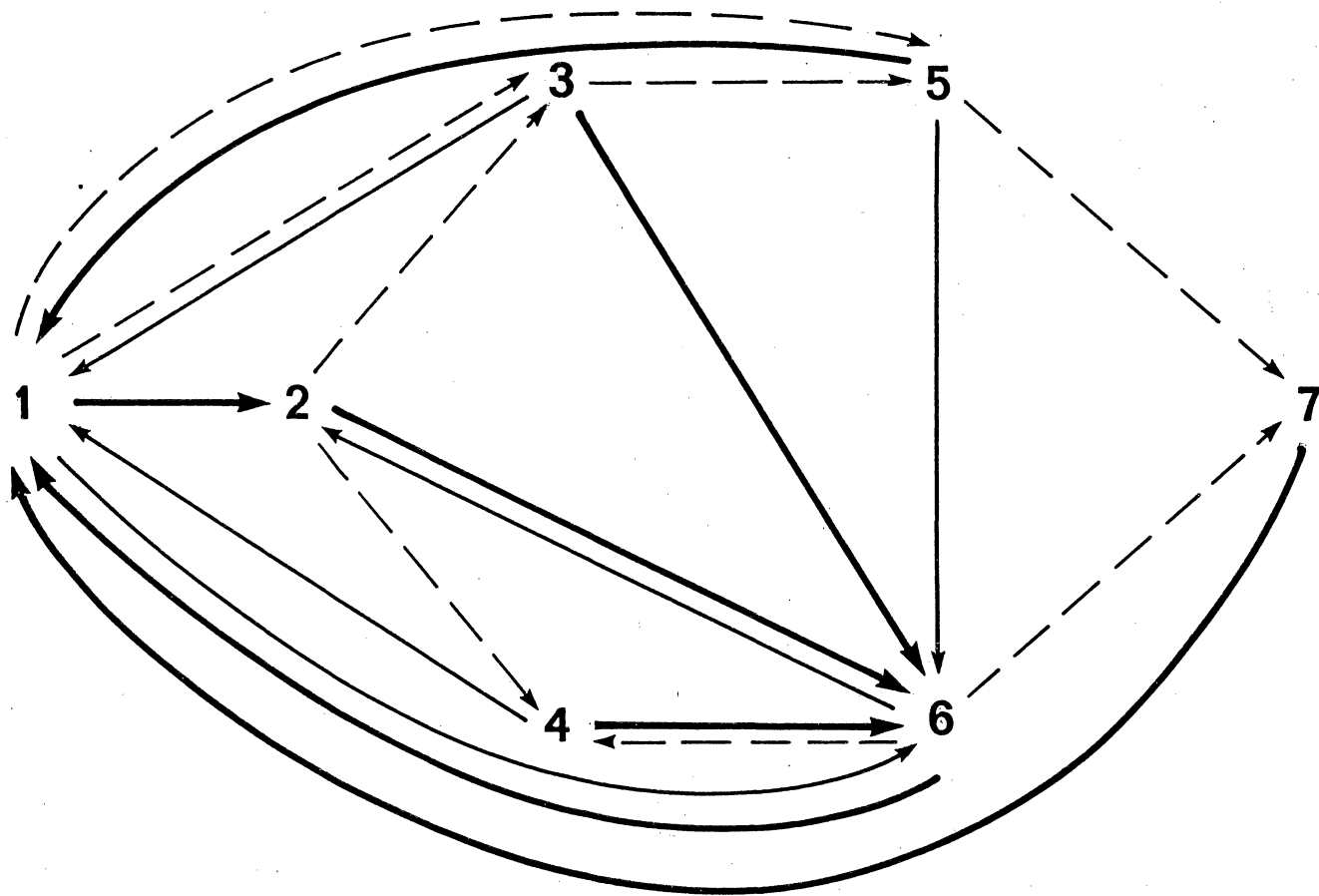
Figure 16 illustrates the preferred relationships in hummocky sequences. From this figure it is evident that certain strong facies

relationships exist. The most prominent of these are 1-2-6-1, 2-6-2 and 1-6-1 facies sequences. Less common or intermediate transition pathways include; 1-5-1, 1-2-3-5-1, 1-2-3-6-7-1, 1-2-3-5-6-7-1, 1-2-4-6-1 and 2-3-6-2 along with others.

Reverse transitions occur between several of the facies in the diagram such as 6-2, 6-1, 5-1, 7-1, 4-1, and 3-1. It is apparent from these transitions that all but one involve capping of sequences by mudrock (1). The 6-2 exception comprises scouring (2) of previously deposited HCS sandstone (6). This particular feature will be discussed in the following section.

Many possible facies transitions do not occur in hummocky sequences (fig. 16). This is thought to be due to the hydrodynamic conditions responsible for their generation. For example: horizontally-stratified sandstones (5) and lags (3) never overlie hummocky cross-stratified sandstones (6) and lags (4). Similarly wave-rippled sandstone (7) is only capped by mudstone (1) and hummocky cross-stratified sandstone (6) is followed exclusively by mudrock (1) or wave-rippled sandstone (7). In the discussion in chapter V on the hydrodynamic interpretation of hummocky sequences, a stepwise progression of hydrodynamic events associated with an advancing storm system was proposed. Under such conditions only selective stacking of facies would be expected.

Figure 16.-- Transitional facies relationships in the Chemung storm beds taken from transition probability matrix values. Heavy lines denote very common transition pathways ($.50 < f$), and light solid lines intermediate pathways ($.20 < f < .50$). Minor transition paths are shown by dashed lines ($0 < f < .20$). Transition probability matrix values with corresponding transition count matrix values less than 10 were discarded. Facies types are numbered as in matrices (1, mudstone; 2, scoured base; 3, horizontally-stratified sandstone; 4, hummocky cross-stratified lag; 5, horizontally stratified sandstone; 6, hummocky cross-stratified sandstone; 7, wave-rippled sandstone).



Hummocky Sequence -- Bedding Types

While Markov chain analysis is useful in demonstrating preferred facies transitions in hummocky sequences, it does not adequately describe the sequence - bedding types thought to best depict storm deposition on various regions of the shelf. For this reason, 4 of the representative sequence types are presented. They include: horizontally-stratified beds, thin hummocky cross-stratified lenses, thick hummocky cross-stratified beds, and amalgamated hummocky cross-stratified intervals. The distribution of these facies sequences in the stratigraphic sequence is presented later in the paper.

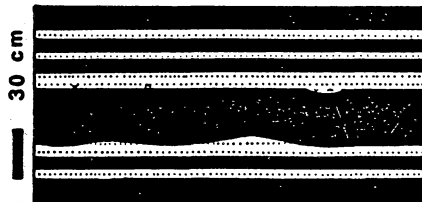
Horizontally-Stratified Beds

Sandstone beds of this type are between 3 and 30 cm thick, laterally continuous, and of uniform thickness (figs. 17 and 18a). The base of the bed is usually sharp but not erosive. Flutes and channels at the base are relatively rare. Discontinuous horizontally-stratified basal lags of bioclastic debris less than 2 cm thick are sometimes present. Horizontally-stratified sand is very continuous throughout the observable length of the bed with little variation in laminae width. Tops are usually flat and gradational into overlying mudstone. Markov transitions for this type of bed include 1-2-3-5-1 and 1-5-1.

Although these beds do not contain hummocky cross stratification, they are thought to be related to storm sedimentation and are therefore included as a storm sequence type. These beds are considered to have

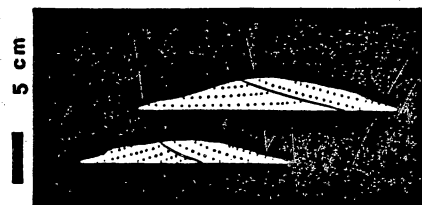
Figure 17.-- Four types of hummocky sequences in the Chemung Formation. Diagrams were constructed to illustrate lateral as well as vertical characteristics of each type. Transition pathways corresponding to Markov chain analysis (figure 16) are given for each type. Note changing vertical scale.

HUMMOCKY SEQUENCE VARIATIONS



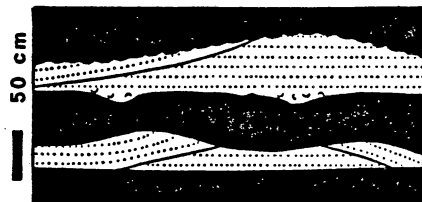
Horizontally stratified beds

1-2-3-5-1 1-5-1



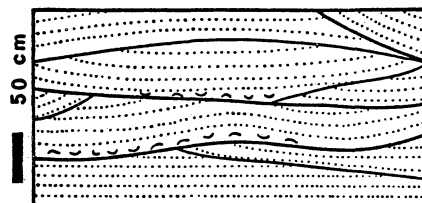
Thin HCS lenses

1-6-1



Thick HCS beds

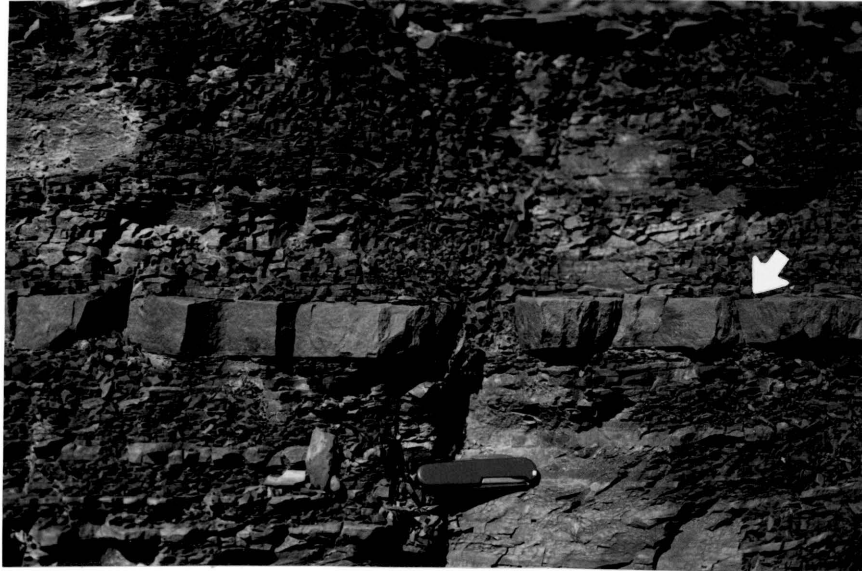
1-2-3-5-6-7-1 1-2-6-1



Amalgamated HCS

2-6-2 2-3-6-2 2-4-6-2

Figure 18.-- (a) Thin horizontally-stratified bed (arrow) of very fine-grained sandstone interbedded with shale. Note siltstone streaks within shales. (b) Thin hummocky cross-stratified beds of very fine grained sandstone in shale. Knife in upper photo is 8 cm, hammer in lower photo is 30 cm. Both photos taken from section 7.

**a****b**

formed by strong unidirectional flow associated with offshore directed gradient currents (see previous section on storm mechanics). Beds of this type are not later reworked to form hummocky cross stratification probably because they accumulated either below SWB or in protected environments landward of SWB.

Thin Hummocky Cross-Stratified Lenses

Beds of this type are usually less than 10 cm thick, laterally discontinuous in outcrop and have a relatively flat nonerosional base and gradational top (figs. 17 and 18b). Internally the beds exhibit undulating laminae closely related to hummocky cross-stratification and very rarely small scale cross lamination characteristic of wave ripples (Markov transition 1-6-1).

Dott and Bourgeois (1982) postulated that thin HCS lenses (their "micro-hummocky lenses") form under oscillatory flow conditions where sand supply is severely limited producing "wave-formed analogues of starved current-ripple structures." It can be further stated from Chemung examples of this feature that oscillatory flow was not sufficiently strong to cause significant scouring of the sea floor, but only to rework available sand into small discontinuous lenses.

Thick Hummocky Cross-Stratified Beds

Thick hummocky cross-stratified beds most closely resemble the idealized hummocky sequence (compare figures 8 and 17). The most

common Markovian transition for this bed type is 1-2-6-1 although 1-2-3-5-6-7-1 is also often developed. Beds are usually laterally continuous and range in thickness from 11 to 300 cm. Characteristic of these beds are gently undulating, highly-erosive bases with local channels up to 10 cm deep (figs. 17 and 19a). Conglomerate, or more commonly, bioclastic lags exhibiting horizontal stratification or hummocky cross-stratification overlie this basal scour. Hummocky cross-stratified sandstone constitutes the bulk of each unit, however, horizontal or near horizontal stratification is present in the lower third of some beds. Tops of sequences are often gradational when hummocky or very sharp if rippled (fig. 19a). Wave ripples are most common on the upper surface of this bed type.

The hydrodynamic processes which are believed to produce this sequence type have already been discussed in considerable detail. In general it is thought that this type of bed best records the complete spectrum of structures within a storm sequence.

Amalgamated Hummocky Cross-Stratified Sandstone

Amalgamated hummocky cross-stratified sandstone sequences range in thickness from 1 to 15m (figs. 17, and 19a). Fine-grained sandstone constitutes the great majority of the sequences, however medium- to coarse- grained sand and lags of conglomerate and bioclastic are occasionally present. The sequences consist of stacked hummocky cross-stratified sandstone beds and occasional horizontal stratification

Figure 19.-- (a) Thick hummocky cross-stratified bed of fine-grained sandstone. Base of bed is scoured into shale (1) while top is gently undulating and gradational into overlying shale (2). Knife (8 cm) for scale. (b) Portion of an amalgamated hummocky cross-stratified interval of fine-grained sandstone. Note bioclastic lags (1) separating some HCS sets. Meter stick for scale. (a) and (b) are both located in section 2.



a



b

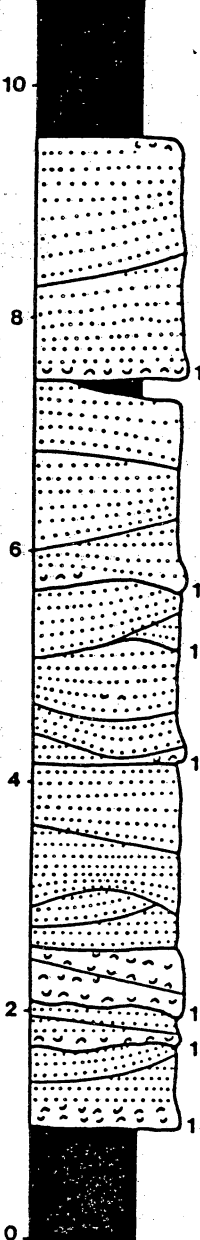
separated by erosional surfaces. Common Markov transitions are 2-6-2, 2-3-6-2 and 2-4-6-2. It is often difficult to distinguish individual beds because of the similarity between set boundaries internal to HCS beds, and the erosive coset surfaces that separate them. Basal conglomeratic or bioclastic lags are sometimes the only true indicator of separate depositional events. Figure 20 illustrates a typical amalgamated HCS unit from section 2.

This type of stratification appears to form as a result of repetitive scouring of previously-deposited sandstone beds and subsequent deposition over the eroded topography. Such conditions probably prevail either on those portions of the shelf continually influenced by storm activity or where storm events are of sufficient magnitude to continually erode all fair-weather sediments. Conglomerate lags are obviously allochthonous and introduced from proximal portions of the shelf. Bioclastic lags, in contrast to other three sequence types, are also probably transported from the nearshore as time intervals between successive storms would be too short for significant fossil communities to be established.

Thickly-Bedded Conglomeratic Sandstone Sequence

An unusual variant of amalgamated HCS sequences is present in the upper third of section 6 (fig. 1). This 8 m thick sequence of thickly-bedded, conglomeratic sandstone (fig. 21) is distinctly different

Figure 20.-- Detailed measured columnar section from section 2 illustrating a characteristic amalgamated hummocky cross-stratified sequence.

DESCRIPTION	INTERPRETATION
 Mudrock	Fair-weather suspension fallout
Fine to very fine-grained sandstone with discrete units of bioclastic lag. Sandstones are hummocky cross stratified with erosive coset (1) and set boundaries. Bioclastic lags are horizontally stratified except for large bed near base which is hummocky cross stratified.	Entire sequence is produced by storm processes. Storm activity would be of sufficient magnitude or frequency to erode all fair-weather deposits and stack HCS sequences Bioclastic lags are probably allochthonous due to insufficient time between storms for establishing fossil communities.
Mudrock	Fair-weather suspension fallout

from all other shelf deposits described in that it contains coarse-grained sandstone, has thick, horizontally-imbricated conglomerate beds, and contains one of two rare occurrences of swaley cross stratification in the Chemung Formation.

Description - The base of the sequence is very sharp and possibly erosional, although the presence of soft-sediment deformation in mudrock makes this determination tenuous. Directly overlying the sharp basal contact is a 2 m thick interval of horizontally-imbricated conglomerate. Conglomerate beds are between 30 and 75 cm thick and can be distinguished from one another by low-angle erosional discordances (<5 degrees). Internally the conglomerates comprise a clast-supported framework of pebbles and a coarse-grained sandy matrix.

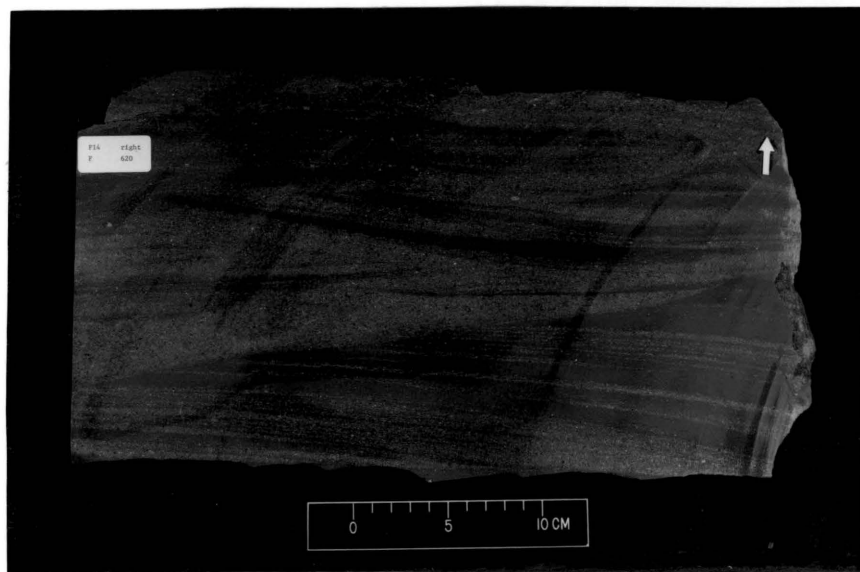
Gradational from the lower conglomerate is a 5 m thick interval of hummocky cross-stratified medium- to- coarse grained sandstone. Individual HCS beds range in thickness from 60-130 cm and are separated by erosional surfaces. This interval is roughly analagous to the amalgamated HCS sandstones described previously. The interval generally fines upward and is transitional into a swaley cross-stratified (SCS) sandstone interval (figs. 21 and 22). The SCS unit caps the entire sequence and is overlain sharply by mudrock.

Swaley cross-stratification has only recently been described from the rock record. Leckie and Walker (1982a) first defined this structure from Cretaceous shoreline deposits in western Canada. SCS is very

Figure 21.-- Detailed measured columnar section from the upper third of section 6 showing a thickly-bedded conglomeratic sandstone sequence with hydrodynamic interpretation.

	DESCRIPTION	INTERPRETATION
10	Mudrock	Fair-weather suspension fallout
	Fine- to medium-grained sandstone becoming finer at top. Swaley cross-stratified.	Produced by moderate energy storm deposits near fair-weather wave base.
8		
6	Fine- to medium-grained sandstone, generally fining upward. Disseminated granules and pebbles.	
	Hummocky cross-stratified beds with erosive coset (1) and set boundaries.	
4		
2	Conglomerate with pebbles up to 1.5 cm in matrix of very coarse sand. Horizontally-imbricated beds separated by low-angle erosive discordances.	
0	Mudrock	Fair-weather suspension fallout

Figure 22.-- Swaley cross-stratified sandstone capping sequence in figure 21.



similar to HCS except that swaley sets of laminae are more often preserved than hummocky ones. The important characteristics of swaley cross stratification summarized from Leckie and Walker (1982b) are: 1) "A series of broad, concave-upward scours (swales) 0.5 to 2 m wide and a few tens of centimeters deep. Stratification is gently curved, following the basal erosive surface of the swale, or conforming at the base and gradually flattening upward to form gently-undulating, subparallel stratification., 2) Dips of the stratification at the edges of swales rarely exceeds 10 degrees, and 3) The structure is three dimensional and looks the same regardless of the orientation of the vertical cross-section." The limited exposure of swaley cross-stratification in the Chemung appears to match this general description.

Interpretation - The thickly-bedded conglomeratic sandstone sequence is interpreted as forming on a portion of the shelf at or near fair-weather wave base. Horizontally-imbricated conglomerate and amalgamated hummocky cross-stratified sandstone are thought to represent proximal storm deposition below fair weather wave base. Both facies are thought to have formed under the same hydrodynamic conditions that produce amalgamated HCS sequences, but are composed of coarser detrital clasts.

Swaley cross stratification, which occurs in the upper meter of the sequence, has previously been noted to occur stratigraphically above HCS sandstones and below beach facies in progradational successions.

This has led Leckie and Walker (1982b) to infer that it forms above fair weather wave base from the recurrent activity of moderate energy storms. The combination of very coarse-grained clasts, amalgamated hummocky cross stratification, and swaley cross stratification suggests the sequence was deposited in shallow enough water to be at fair-weather wave base and sufficiently close to the paleoshoreline to have an abundant supply of coarse clasts.

CHANNEL SANDSTONE SEQUENCES

Description - Located in the uppermost portions of sections 4 and 7 (fig. 1) are channel shaped bodies of very fine-grained sandstone enclosed in mudrock (figs. 23, 24a). The channels have a roughly symmetrical, convex-downward base that is in sharp erosional contact with the underlying mudrock. The upper surfaces of the channel deposits are usually flat and in sharp contact with overlying mudrock. Sandstones within the channels are either massive or horizontally stratified. Towards the tops of some channel deposits ripple-shaped surfaces are developed which lack internal ripple cross lamination. They appear to be erosional in nature and of the type described as longitudinal ripple marks by Stratten (1951) (fig. 24b). These erosional ripples are capped by draping parallel laminae of fine sand.

Interpretation - This type of sequence is thought to represent infilling of previously eroded channels. The channels were probably produced by offshore directed gradient currents discussed earlier.

Figure 23.-- Sketch of channel sandstone sequence from section 7 with inset showing details of longitudinal ripple marks. Surrounding lithology (black) is mudrock. Note horizontally-stratified beds above channel.

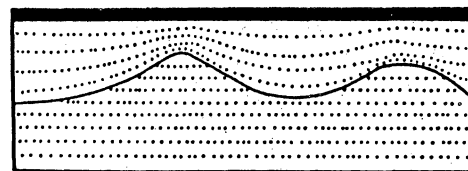
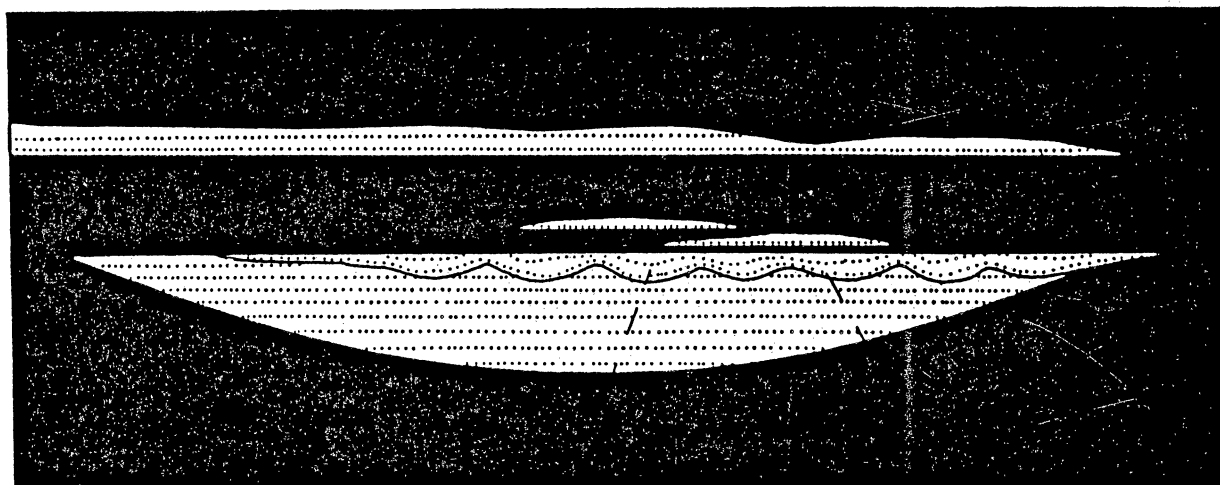


Figure 24.-- (a) Channel sandstone deposits shown in figure 16 and a close-up of longitudinal ripple marks at the top of the channel fill(b). Note knife (8 cm) for scale.



a



b

Horizontally-stratified sandstone is believed to be the result of subsequent suspension fallout into the newly-created depressions or a response to upper flow regime conditions immediately following channel scouring. Longitudinal ripple marks are produced by later erosive activity. It has been suggested that longitudinal ripple marks form from strong erosive currents running parallel to the ripple crests with simultaneous wave propagation at right angles to the current (Stratten, 1951). A situation such as this can easily be envisaged on a storm influenced shelf. Draped laminae of sand over longitudinal ripples are probably the result of suspension settling by gradient currents following erosion of the underlying sandstone.

Chapter VI

VERTICAL CHANGES THROUGH THE CHEMUNG FORMATION

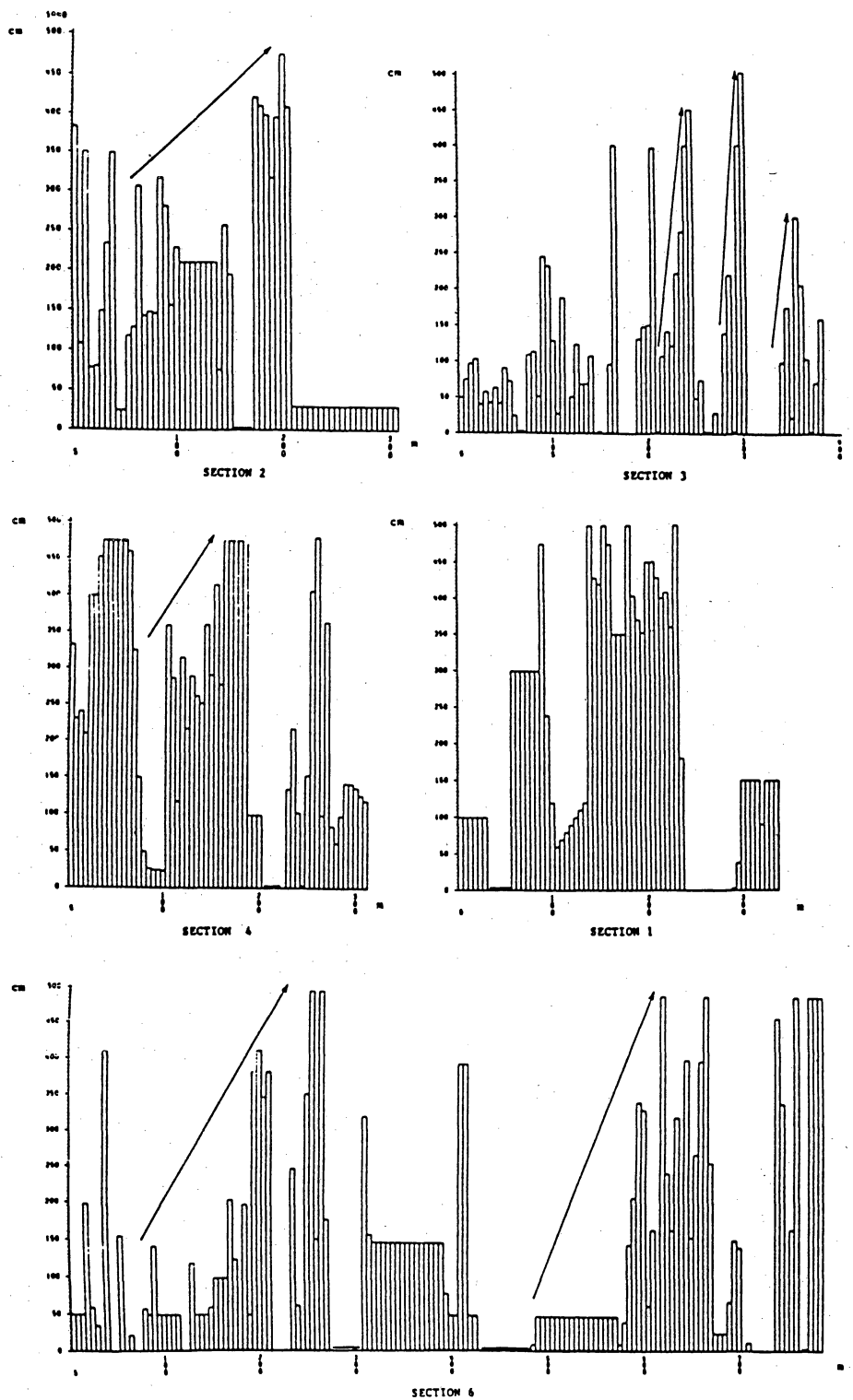
Vertical changes in the character of storm sedimentation in the Chemung can be demonstrated by utilizing selected physical parameters. For each complete section studied, histograms were constructed showing the vertical distribution of sandstone and average bed thickness. In addition, the distribution of horizontally-laminated beds, thin hummocky cross-stratified lenses, thick hummocky cross-stratified beds, and amalgamated hummocky cross-stratified intervals were plotted to assist in the recognition of facies associations.

SANDSTONE DISTRIBUTION

The vertical distribution of sandstones is illustrated in figure 25. From this histogram it is evident that sandstone is present in significant quantities throughout most of each section (bottom-top). However, within most of the sections thinner coarsening-upward sequences are present (fig. 25). The thickness of these sequences varies considerably. In section 2 the coarsening-upward sequences vary between 20 to 30 m whereas those in section 6 are up to 130 m in thickness.

The widespread distribution of sandstone throughout each section implies that gradient currents could effectively transport sand from the nearshore to all portions of the shelf which, in this study, incorporates

Figure 25.-- Distribution of total sandstone per 5 m of section.



regions of the Devonian sea between fair-weather and storm wave base. The occurrence of sandstone throughout the Chemung sections is thought to have been controlled by the shifting loci of sediment input rather than the competency of gradient currents to transport sand offshore. Previous workers on modern (Aigner and Reineck, 1982) and ancient (Johnson, 1978) storm-dominated shelves have proposed a "graded shelf" model in which sandstone content decreases seaward between FWWB and SWB. The findings in this study suggest that the "graded shelf" model may be an oversimplified guide to storm sedimentation in shallow-marine environments. The Devonian shelf studied here would be graded only if the shelf is defined as beginning at FWWB and extending below SWB into Brallier and Millboro Shale facies⁸ (fig. 3 and 6).

The coarsening upward sequences within each section are thought to represent progradation of shelf sand lobes similar to those described by Brenchley and Newall (1982). The sharp decrease in sand content at the top of each sequence (fig. 25) is considered to signal the shifting of depositional locus on the shelf as a result of avulsion of the channelways followed by gradient currents. The location of these feeder channels is controlled by such factors as location of river mouths, morphology of the coastline, and the position of tidal inlets and deltas between barrier islands (Hayes, 1967; Lewis, 1982; and Brenchley and Newall, 1982)

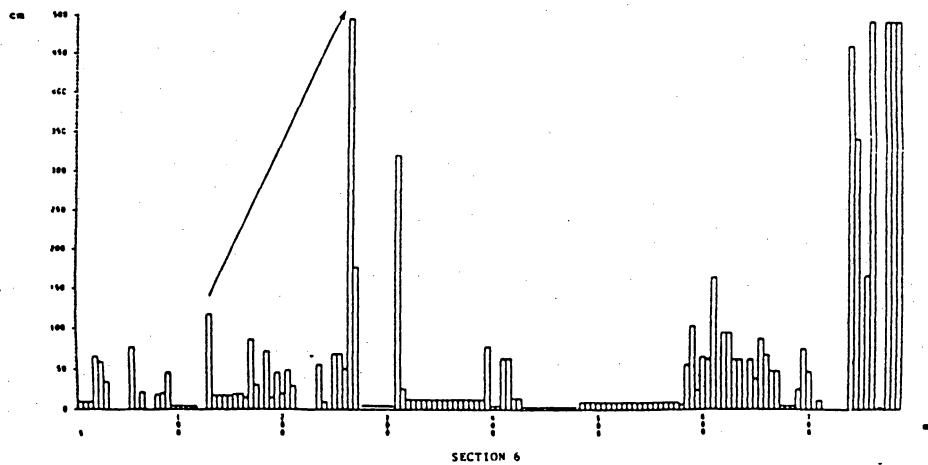
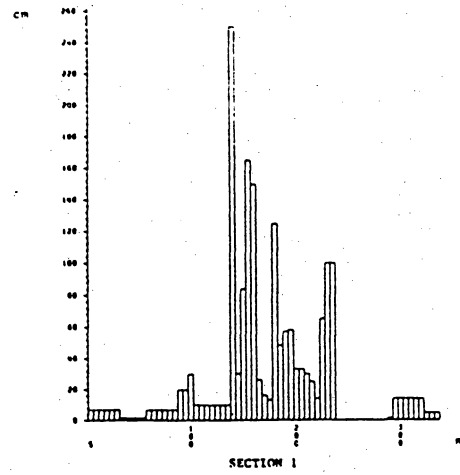
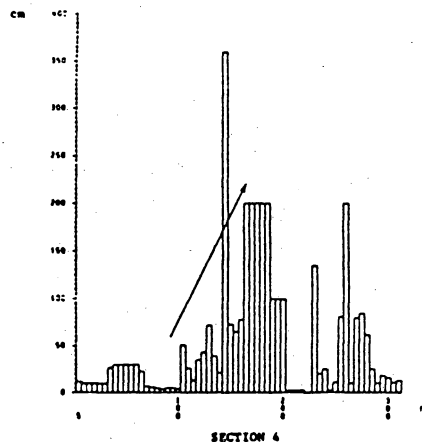
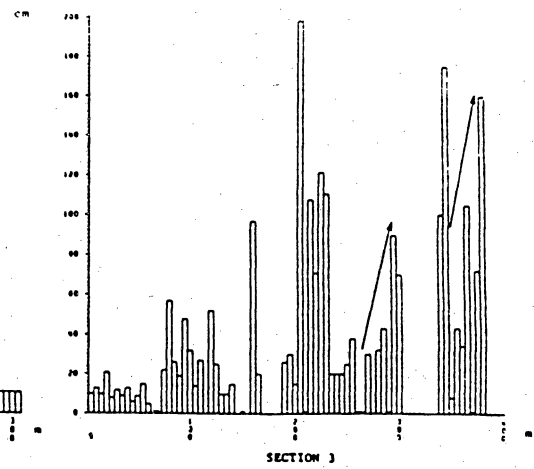
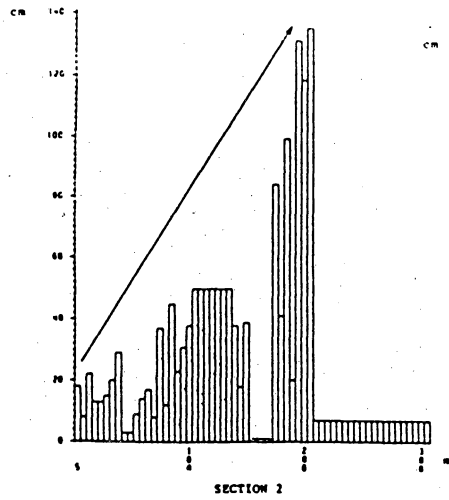
AVERAGE BED THICKNESS

The vertical distribution of average bed thicknesses in all but 1 section (section 1) shows a general thickening-upward trend (fig. 26). A comparison between sandstone and average bed thickness histograms shows that previously described coarsening-upward sequences within each section (fig. 25) have corresponding Thickening upward tendencies as well. Abundant sandstone occurrence, however, does not always correlate with thick sandstone beds.

The overall pattern of thicker beds in the upper and thinner beds in the lower parts of sections (proximal vs distal shelf) is attributed to both a decrease in oscillatory current velocities and duration of storm effects outwards on the shelf (Chapter V). Higher current velocities combined with a longer duration of storm activity are believed to repeatedly reentrain previously-deposited sediment, mix it with newly introduced sand, and produce thicker preserved storm beds on the proximal shelf. Conversely the distal shelf, with lower velocities and shorter duration of storm effects, would yield thinner beds representing sand from a single storm event. Thus individual storm beds have a much greater preservation potential on the distal than proximal shelf.

Small scale thickening/coarsening-upward sequences within each section, as mentioned previously, are thought to result from deposition on shelf sand lobes. The propensity of thicker beds at the top of these lobes can be attributed to an incremental increase in the supply of sand as a lobe system progrades.

Figure 26.-- Distribution of average bed thickness per 5 m of section.



DISTRIBUTION OF HUMMOCKY SEQUENCE TYPES

The vertical distribution of the four hummocky sequence types illustrated in figure 17 is shown in the following figures: horizontally stratified beds (fig. 27); thin hummocky cross-stratified lenses (fig. 28); thick hummocky cross-stratified beds (fig. 29); and amalgamated hummocky cross-stratified sandstone (fig. 30). The environmental significance of these distributions will be presented in the following chapter on facies associations and depositional environments.

Horizontally-stratified beds are restricted to the lowermost portion of sections 1,2,3,4 and 6 and are also present in the upper third of sections 1,4 and 6 (fig. 27). These two widely spaced occurrences of horizontally-stratified beds, although developed respectively in distal and proximal portions of the shelf, are both attributed to storm processes.

In the previous section on storm mechanics, horizontal stratification in sandstones was proposed to have formed by one of two processes; 1) deposition from unidirectional offshore-directed gradient currents or 2) deposition from storm induced oscillatory currents. Horizontally-stratified beds as discussed here are thought to have been produced by bed shear from gradient currents without subsequent reworking to form the more common HCS sequences. Distal horizontally-stratified beds (lower part of section) would not be reworked due to deposition below SWB whereas proximal beds (upper part of section) would possibly preserved being in low-energy proximal regions of the nearshore.

Thin hummocky cross-stratified lenses and thick hummocky cross-stratified beds (figs. 28 and 29) are present throughout most of each section. Thin HCS lenses show only a slight preference for the lower portions of sections 2, 3 and 6. A definite smaller-scale trend, however, is exhibited by the two HCS bed types within coarsening/thickening-upward sequences (shelf sand lobes). Thick HCS beds typically occur at the top of sequences whereas thin HCS lenses predominate at the base. This small scale distribution expectedly correlates with the average bed thickness histograms (fig. 26).

Both types of hummocky cross-stratified sequences have already been related to single storm events that induce conditions of intense oscillatory flow (see previous section on formation of HCS). The widespread distribution of these bed types in each section suggests that storm-induced oscillatory currents affected all portions of the Chemung shelf. The processes responsible for the upward-thickening of hummocky beds within smaller sequences was discussed previously in the section on average bed thickness distribution.

Amalgamated, hummocky cross-stratified sequences are found about two thirds of the way up each section (fig. 30, note exception in section 6). As discussed in Chapter V, amalgamated HCS would form under the same conditions as individual HCS sequences except that the frequency or intensity of storm activity is such that fair-weather deposits are not preserved.

Figure 27.-- Distribution of horizontally-stratified beds
per 5 m of section.

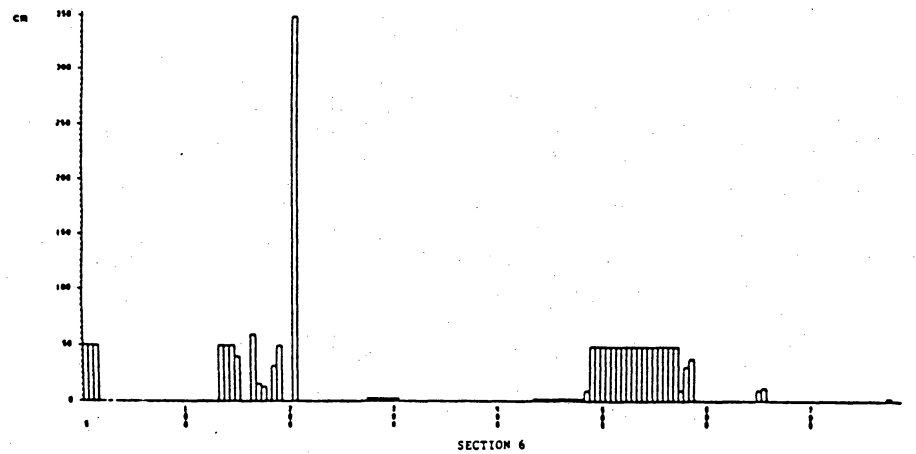
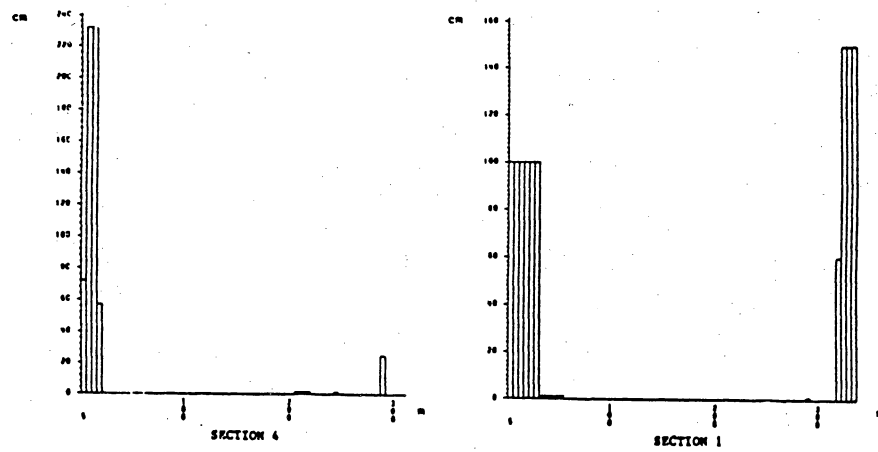
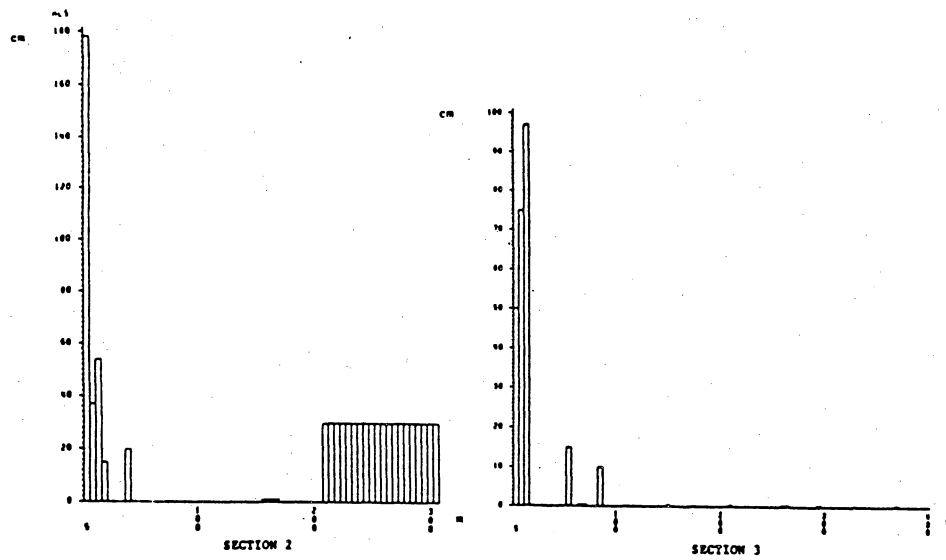


Figure 28.-- Distribution of thin hummocky cross-stratified lenses per 5 m of section.

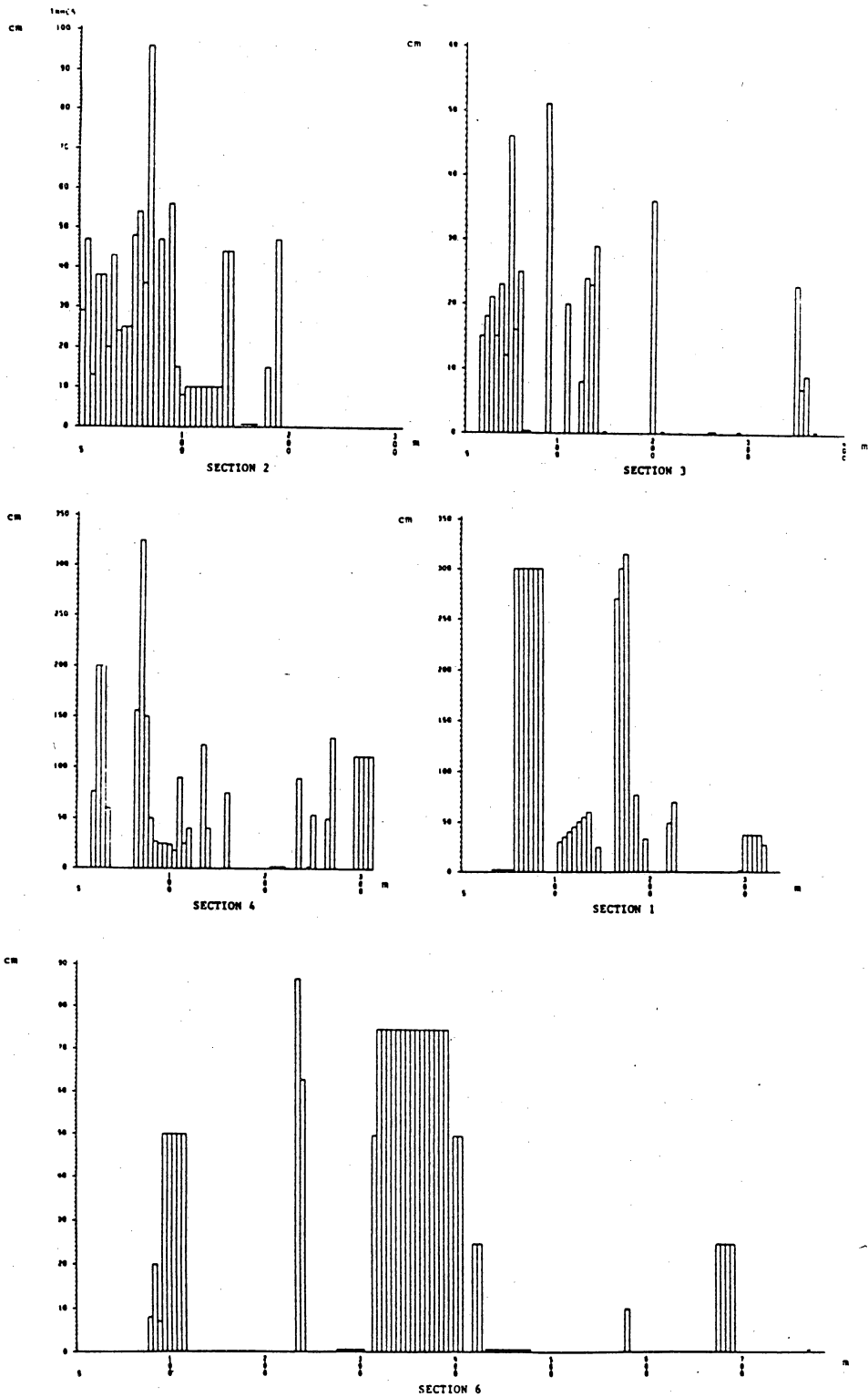


Figure 29.-- Distribution of thick hummocky cross-stratified beds per 5 m of section.

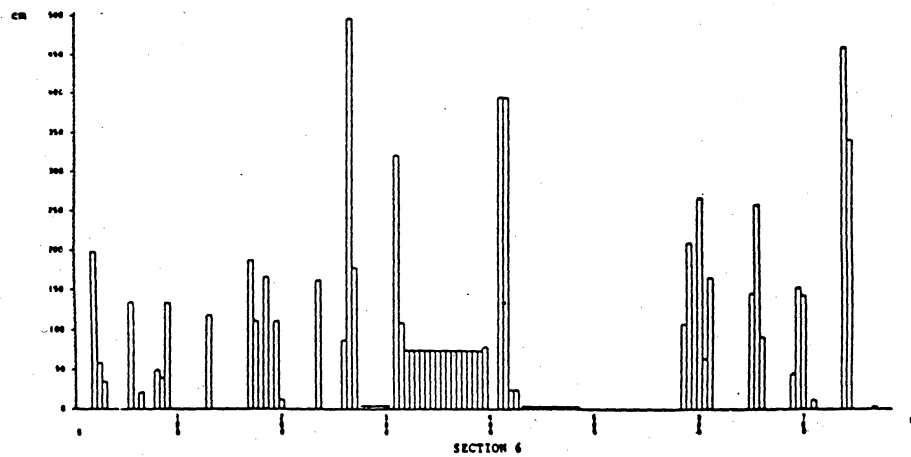
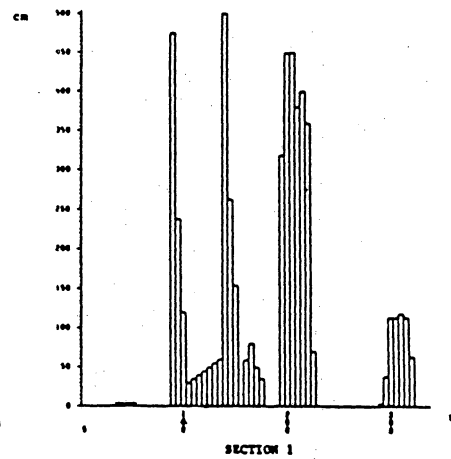
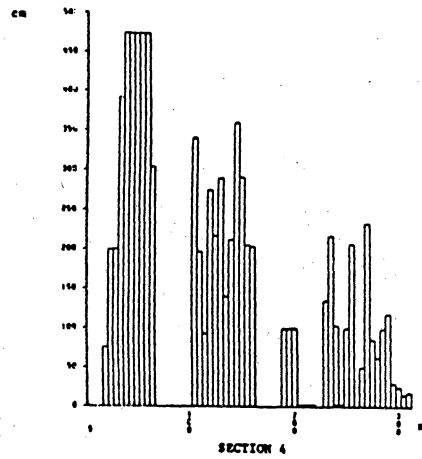
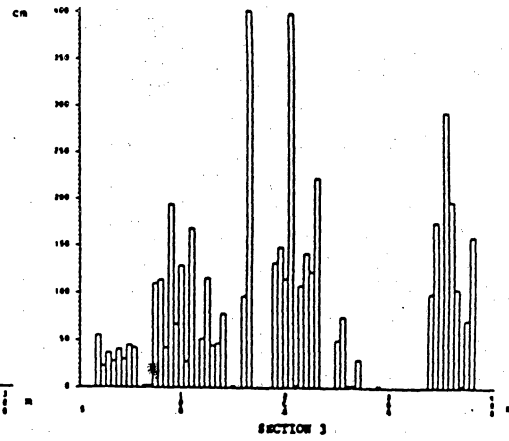
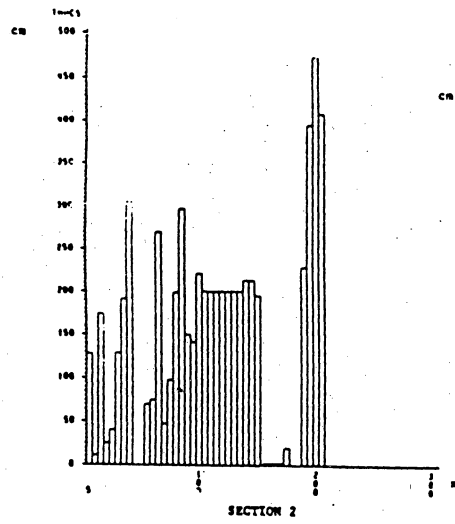
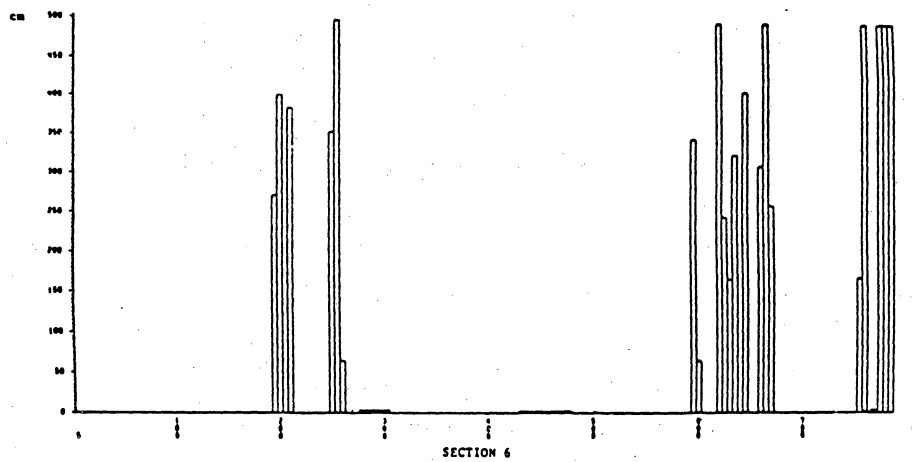
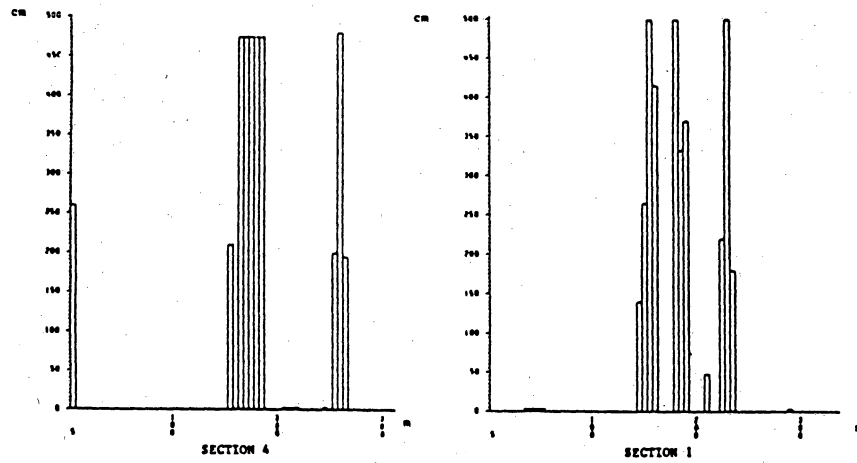
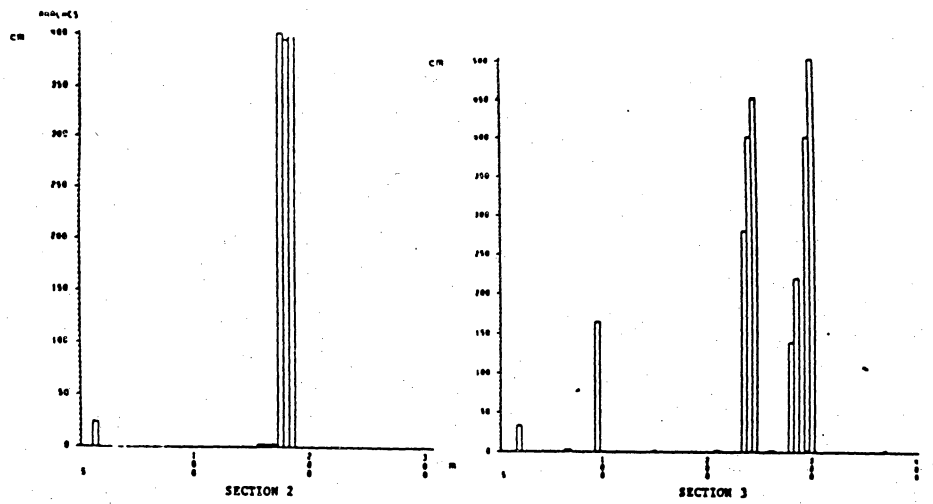


Figure 30.-- Distribution of amalgamated hummocky cross-stratified sequences per 5 m of section.



Chapter VII

FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS

The depositional environments of the Chemung shelf are reconstructed by analyzing the vertical changes throughout each section. From the chapter VI discussion, and figures 25 through 30, the following generalizations can be made about the distribution of total sandstone, average bed thickness and storm sequence types.

1) Total sandstone, Average bed thickness -- Sandstone is distributed widely in the Chemung sections but is present in thinner, more numerous beds at the base, and thicker less-numerous beds at the top. Within thinner intraformational sequences sandstone content increases upward in sympathy with an increase in bed thickness.

2) Storm sequence types -- Horizontally-stratified beds are found in the lower and uppermost portions of sections. Thin HCS beds are present throughout each section but are concentrated at the base of the intraformational coarsening/thickening-upward sequences. Thick HCS beds also occur throughout the Chemung, but are most numerous at the top of coarsening/thickening-upward sequences. Amalgamated HCS beds are present in the upper half of sections.

An analysis of the above distributions suggests the presence of three facies associations that are thought to represent distinct environments of deposition within a low-gradient, shallow epeiric sea (fig. 31). The three facies associations can best be accommodated in a

modified form of the model proposed by Irwin (1965) for epeiric sea sedimentation (fig. 32). Irwin (1965) recognized three hydraulic energy zones from the proximal (shallowest) to distal (deepest) portions of shelves (fig. 32). These are: "1. A hundreds-of-miles wide, low-energy zone occurring in the open sea beneath wave depth where marine currents are the only form of hydraulic energy acting upon the sea bottom (Zone X), 2. An intermediate, high-energy belt, tens of miles wide, beginning where waves first impinge upon the sea floor and thus expend their kinetic energy on the bottom, extending landward to the limit of tidal action (Zone Y), and 3. An extremely shallow, low-energy zone, which may be hundreds of miles wide, occurring landward of Zone Y in which there is little circulation of waters, where tides are essentially wanting and in which wave action is that produced by local storms (Zone Z)."

FACIES ASSOCIATION A

Facies association A (fig. 31) consists of thin horizontally-stratified and thin and thick hummocky cross-stratified, fine-grained sandstone sequences interbedded with mudrock. Bioclastic and conglomerate lags are rarely present. Beds range in thickness from 5-25 cm although occasionally thick HCS beds up to 150 cm are present. The bases of sandstone beds are sharp and flat at the bottom of the association and become more channelized and scoured in appearance at the top. Tops of beds are hummocky and rarely wave rippled. Flute casts were found

Figure 31.-- Schematic representation of the Chemung Formation showing the three facies associations and their interpreted environments of deposition. Thicknesses of individual coarsening and thickening-upward sequences exaggerated to show detail. Mudrock content is underestimated to emphasize sandstone distribution.

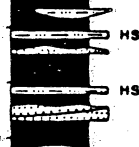
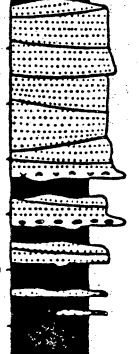
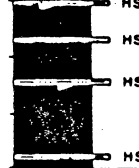
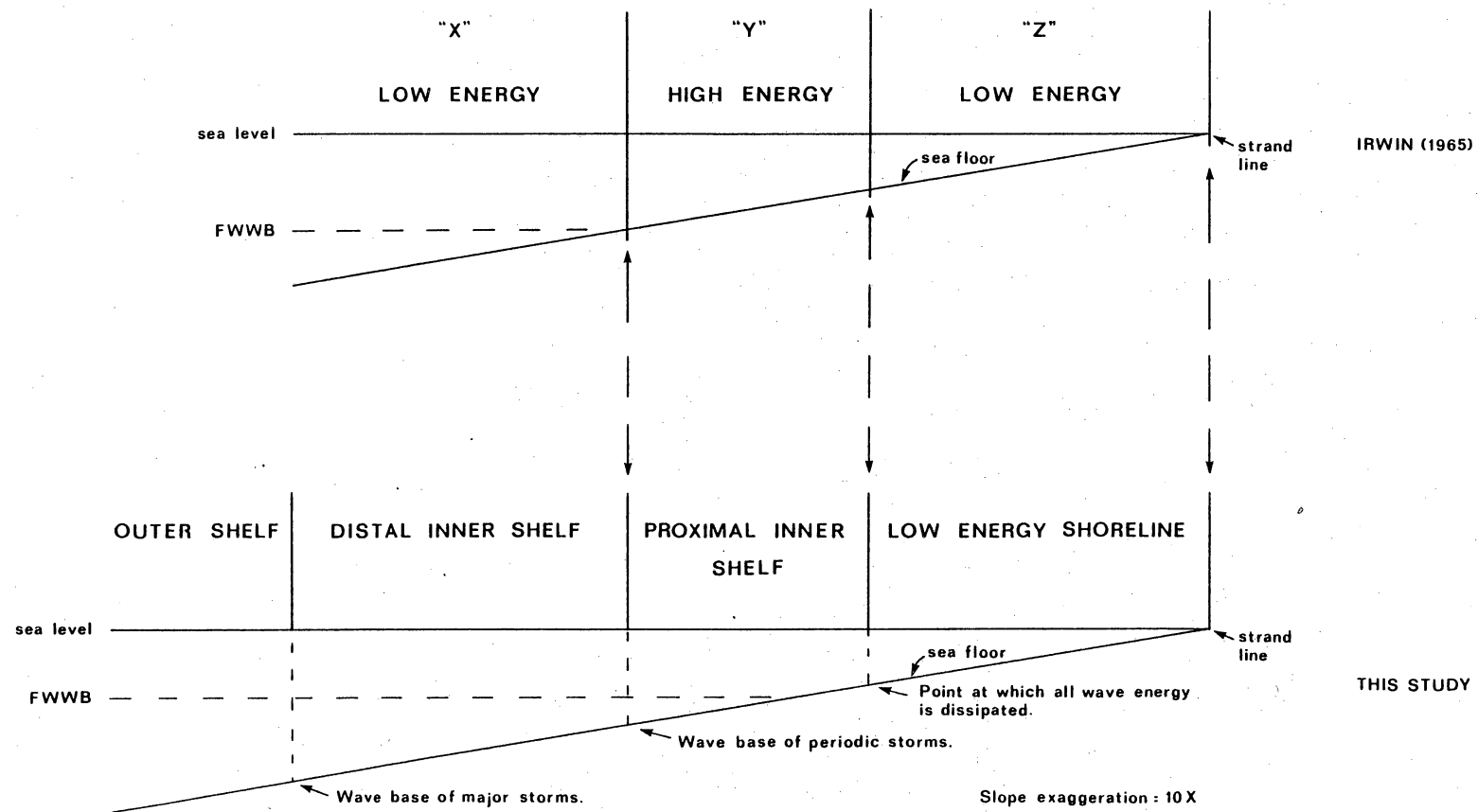
FORMATION	METERS	GENERALIZED STRATIGRAPHIC COLUMN	DESCRIPTION	PALEOENVIRONMENTAL INTERPRETATION	FACIES ASSOCIATION
CHEMUNG	400		Very fine-grained sandstone interbedded with mudrock. Facies sequences include horizontally-stratified beds (HS), thin and thick HCS and channel sandstones.	LOW ENERGY SHORELINE Deposition above fair-weather wave base in low energy protected zone.	C
	300		Very fine- to coarse-grained sandstone with bioclastic and conglomerate lags interbedded with mudrock. Individual beds are thin to thick with sharp scoured bases and hummocky, occasionally wave-rippled, tops. Amalgamated beds occur at the tops of coarsening/thickening upward sequences. Sandstones are hummocky cross stratified except for the tops of some amalgamated sequences which are swaley cross stratified.	PROXIMAL INNER SHELF Deposition above storm wave base and below fair-weather wave base under the influence of periodic storms. The very top of this association is possibly affected by fair-weather waves but little evidence for these conditions is preserved.	B
	200		Very fine-grained sandstone with occasional bioclastic or conglomerate lags interbedded with mudrock. Sandstones are in thin to medium beds. Most beds exhibit hummocky cross stratification although horizontally-stratified beds are present at the base of this association. Bases of beds are mostly sharp and nonscoured. Tops are hummocky and rarely wave rippled. Beds pinch and swell and are laterally discontinuous.	DISTAL INNER SHELF Deposition on those portions of the shelf only affected by major storms.	A
BRALLIER	?		Very fine-grained sandstone in horizontally-stratified or massive beds. Beds are laterally continuous with occasional flutes at the base.	OUTER SHELF Deposition below storm wave base.	

Figure 32.-- Section illustrating energy zones in epeiric seas after Irwin (1965) and modification of this model for the present study.



exclusively beneath horizontally-stratified beds in this association. Coarsening/thickening-upward sequences in this association are comprised of individual storm beds which thicken upwards but never become amalgamated.

A distal inner shelf environment is inferred for facies association A (figs. 31 and 32). This portion of the shelf would be characterized by reworking of storm-introduced sediment during major storms. The lower boundary would be defined by the last occurrence of HCS beds (wave base of major storms) and the upper boundary by the zone in which storm frequency is great enough that bed amalgamation is produced (wave base of periodic storms). Horizontally stratified sandstones at the base of the association are thought to represent the deposits of storm-induced gradient currents without later reworking into HCS (Chapter V). Coarsening/thickening-upward sequences in this region represent progradation of shelf sand lobes onto the distal inner shelf. Storm duration in this association is never of sufficient frequency to produce amalgamation of HCS beds. Individual storm beds, therefore, have a high preservation potential.

FACIES ASSOCIATION B

Facies association B (fig. 31) is composed of very fine- to coarse-grained sandstone with bioclastic and conglomerate lags interbedded with mudrock. All sequences in this association are hummocky cross stratified except for a rare occurrence of swaley cross-

stratification. Beds are somewhat thicker than in facies association A averaging approximately 50 cm. Individual beds have sharp scoured bases and hummocky, occasionally wave-rippled tops. Amalgamated HCS sequences are prevalent here occurring at the top of most coarsening/thickening-upward sequences. The top of this association is marked by the first occurrence of horizontally-stratified beds and the base by the first coarsening/ thickening-upward sequence capped by amalgamated beds.

A proximal inner shelf environment is envisaged for facies association B (figs. 31 and 32). This region is interpreted as that portion of the shelf where shoaling waves expend their kinetic energy on the sea floor before reaching the coastline. Storm activity in this environment is thought to have been very intense and of such frequency that bed amalgamation is produced in conjunction with rare swaley cross stratification (see Chapter V). Sandstones at the top of this zone were probably deposited above FWFB and subjected to shoaling fair weather waves, although the resulting sediments were not preserved due to subsequent storm reworking. Individual complete storm events would have little chance of preservation in this zone.

FACIES ASSOCIATION C

Facies association C (fig. 31) consists of very fine-grained sandstone interbedded with mudrock. Sandstones are mostly in thin, horizontally- stratified beds which are laterally persistent in outcrop. Thin and thick HCS sequences are also developed but constitute a relatively minor portion of the sandstone fraction. There is little evidence of scouring at the bases of beds and tops are commonly wave rippled. Plant fragments are disseminated throughout this association. Channel sandstone sequences are present at sections 4 and 7 (fig. 1).

Facies association C is thought to represent a low-energy shoreline environment. This portion of the shelf corresponds to Irwins (1965) low-energy "Z" zone or what McCave (1972) referred to as a "muddy coast". The low-energy shoreline is located landward of the proximal inner shelf (fig. 32). Association C is thought to have developed entirely above FWB. Channel sandstones in this environment are considered to be conduits along which offshore gradient currents carried sand seaward during storms. Horizontally-stratified sandstone beds are envisaged as being deposited by gradient currents. These beds are preserved as horizontal stratification because they accumulated landwards of wave energy dissipation and were thus protected from reworking by storm and fair-weather waves (compare with horizontally-stratified beds in association A). The presence of scattered HCS sequences suggests that storms were sufficiently large at times to breach the seaward shoaling zone of the proximal inner shelf.

In contrast to steep gradient shelves, a beach environment is precluded because wave and tidal action cannot extend inward to the coastline (Irwin, 1965; McClung, 1983).

Chapter VIII

PALEOENVIRONMENTAL RESUME

The upper Devonian Chemung shelf formed the eastern margin of an extensive cratonic seaway that covered much of the Laurussia plate. This region was located approximately 10 degrees south of the equator in a tropical climate and was subjected to intense storm activity. Upper Devonian paleogeography and proposed hurricane pathways for this period are illustrated in figure 33 (Marsaglia and Klein, 1983; Bambach, 1980). From figure 33 it is evident that major oceanic hurricane pathways (dark arrows) would not account for the Chemungs storm-dominated character. For this reason, a hurricane pathway originating in the Laurussia epeiric sea, deflecting southeastward and subsequently striking the eastern margin of the sea (light arrow) is proposed (R. Bambach, personal communication, 1984).

The Chemung shelf is envisaged as part of a low-gradient clastic ramp extending hundreds of miles towards the craton interior (fig. 34). Slopes characteristic of epicontinental seas rarely exceed 0.5 ft./mile (0.00009 degrees) in contrast with passive continental margin shelves where slopes reach up to 10.0 ft./mile (0.002 degrees) (Irwin, 1965). Transportation of sand from the nearshore onto the Chemung inner shelf and beyond onto the Brallier Formation distal shelf was facilitated by storm-generated gradient currents. Based on palinspastic reconstruction it is estimated that sand was transported offshore for

distances of up to 200 miles. Localization of seaward gradient-current flow from coastal sediment sources is thought to produce discrete prograding shelf sand lobes represented as coarsening/thickening-upward HCS sequences in the Chemung Formation and coarsening/thickening-upward turbidite "bundles" in the upper Brallier Formation (Lundegard, 1979).

The facies associations that record changing styles of storm sedimentation are thought to represent the varying effects of storms on the shelf (fig. 34). Deposition of sandstone in the distal inner shelf (association A) occurs as random interbedding of HS or HCS sandstones with mudrock or as coarsening/thickening-upward intervals believed to be shelf sand lobes. The proximal inner shelf environment is also characterized by sand lobes, however, the very shallow water in this setting creates a shoaling zone where periodic storms and fair-weather waves continually rework sands into shoals or bars (amalgamated HCS). The low energy shoreline (association C) forms behind the inner shelf and is protected from most storm activity. A shoreface or beach environment is not recognized.

Figure 33.-- Reconstruction of the upper Devonian world with inferred hurricane pathways. Stippled areas indicate exposed landmasses. Encircled areas around each continent represent shallow seas. Dark areas denote oceanic hurricane pathways of Marsaglia and Klein (1983). Light arrow is proposed epeiric sea hurricane pathway for this study (R. Bambach, personal communication, 1984). Paleogeography after Scotese et al (1979) and Marsaglia and Klein (1983).

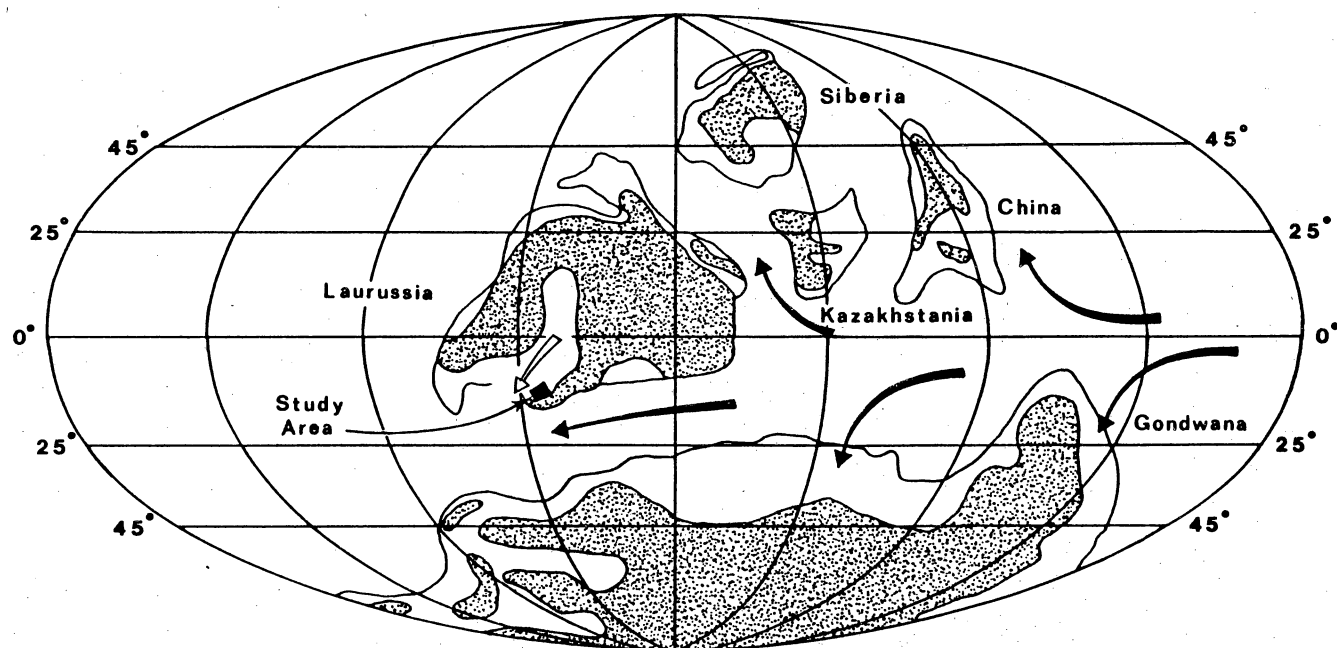
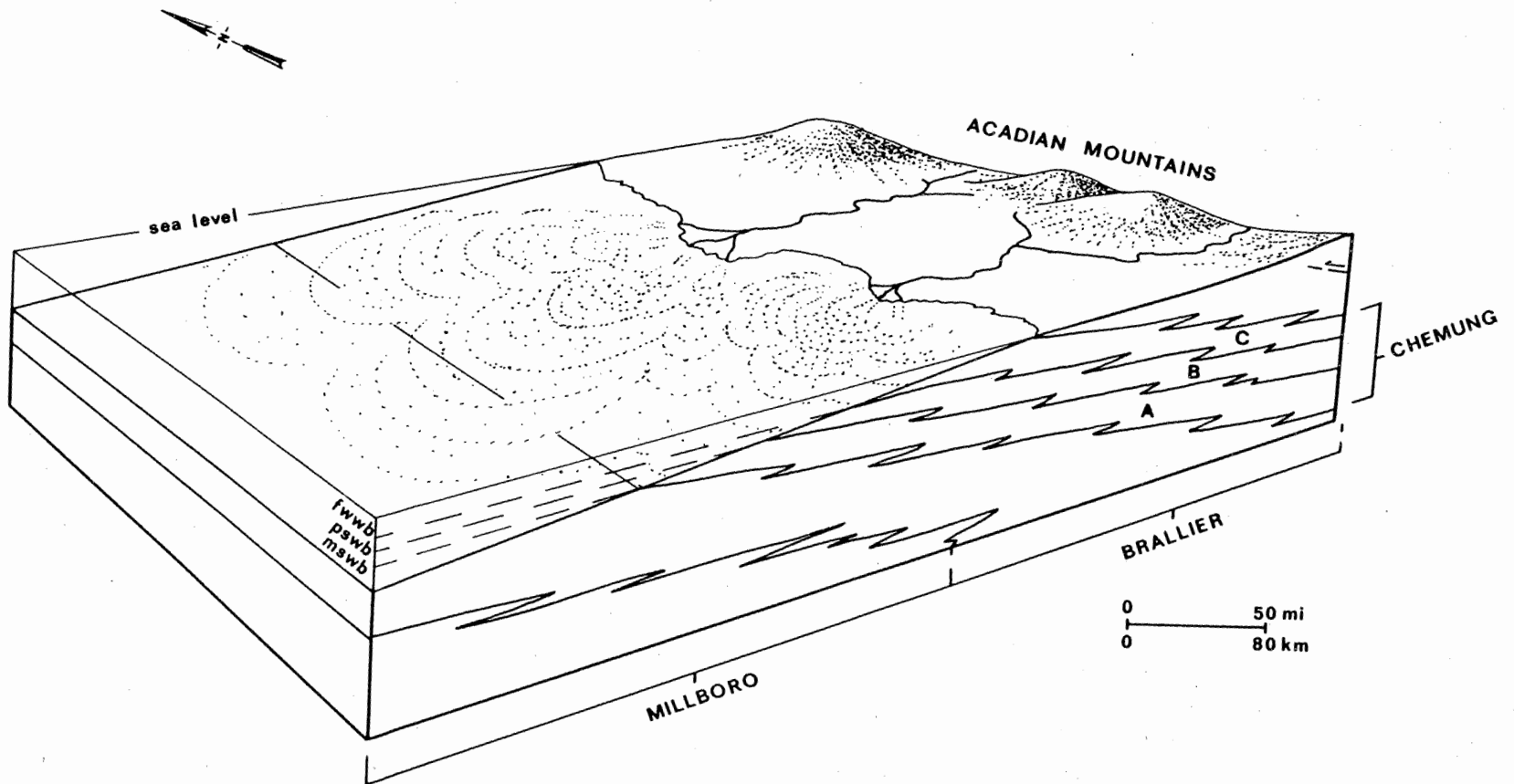


Figure 34.-- Depositional model for the Chemung shelf. Facies associations A, B and C shown on cross section.



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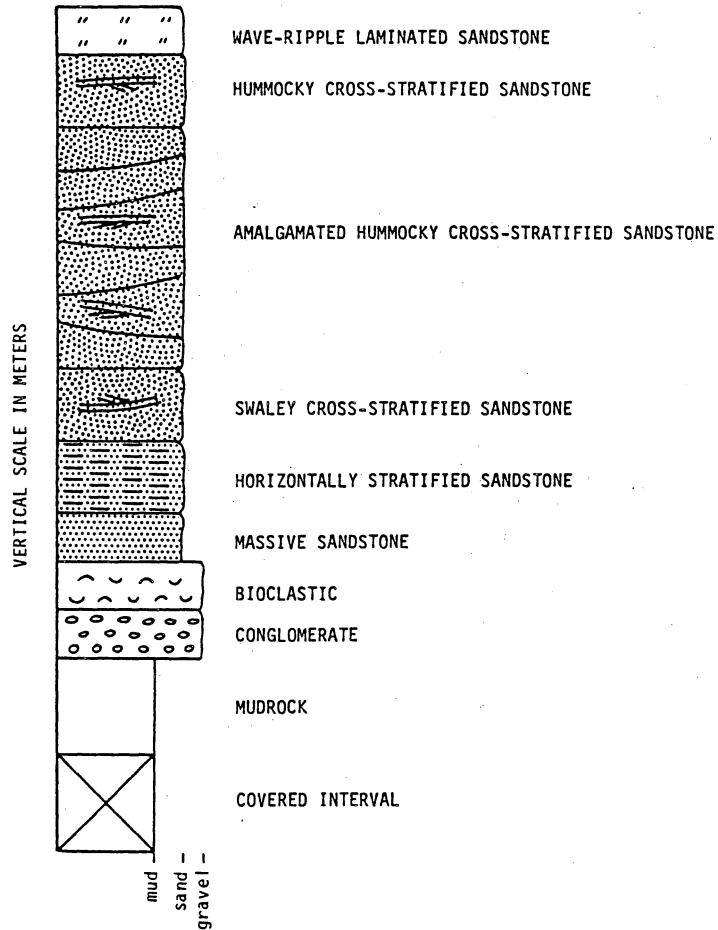
APPENDIX

Chapter IX

APPENDIX I

Measured Sections

LEGEND

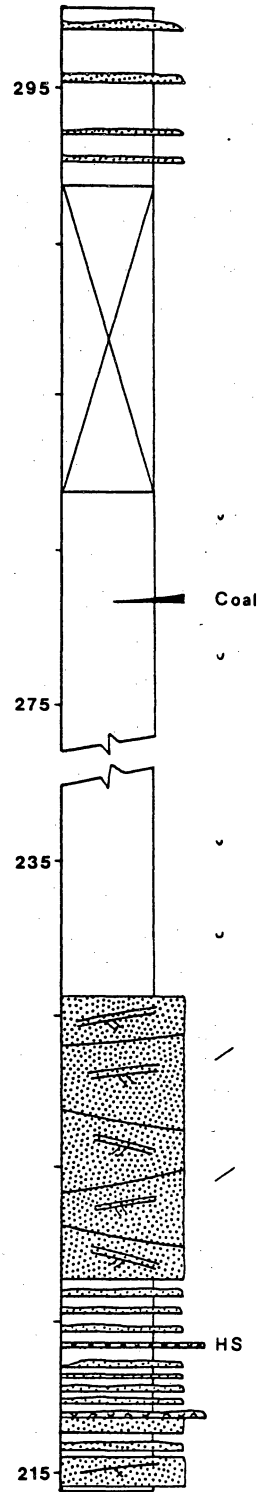
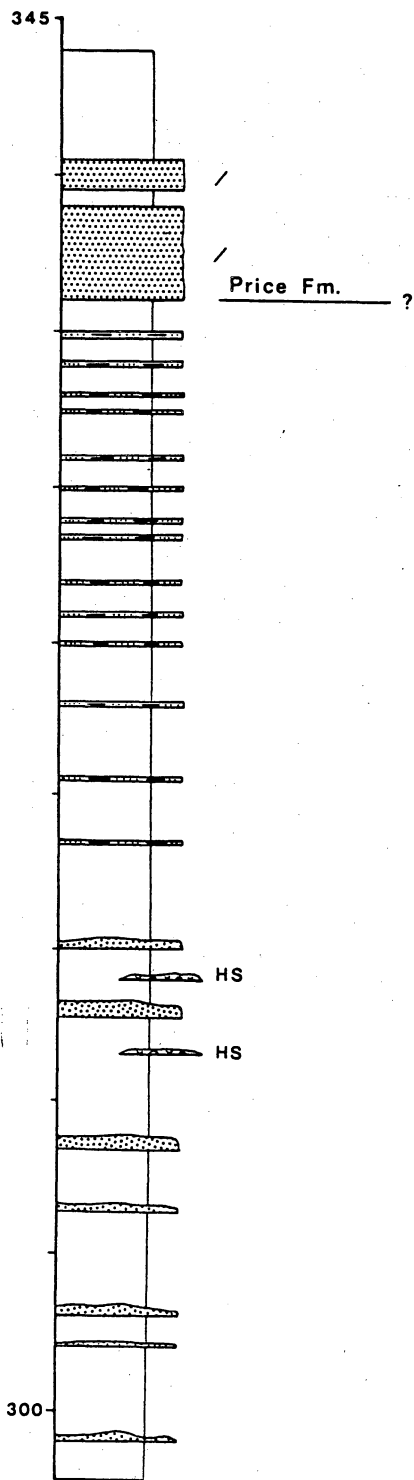


sss	BIOTURBATION
~	CHANNEL SCOUR
~	FLUTE
/	PLANT FOSSILS
c	BIOCLASTIC LENSES
◊	RIP-UP CLASTS
x	TRACE FOSSILS
~	WAVE RIPPLES
HCS	HUMMOCKY CROSS STRATIFICATION
HS	HORIZONTAL STRATIFICATION

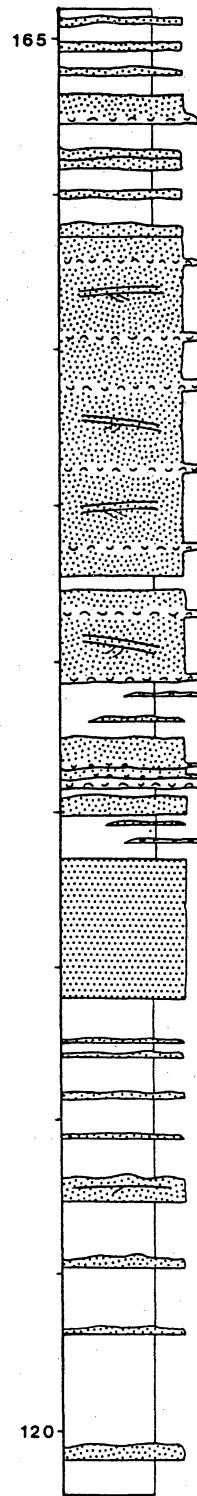
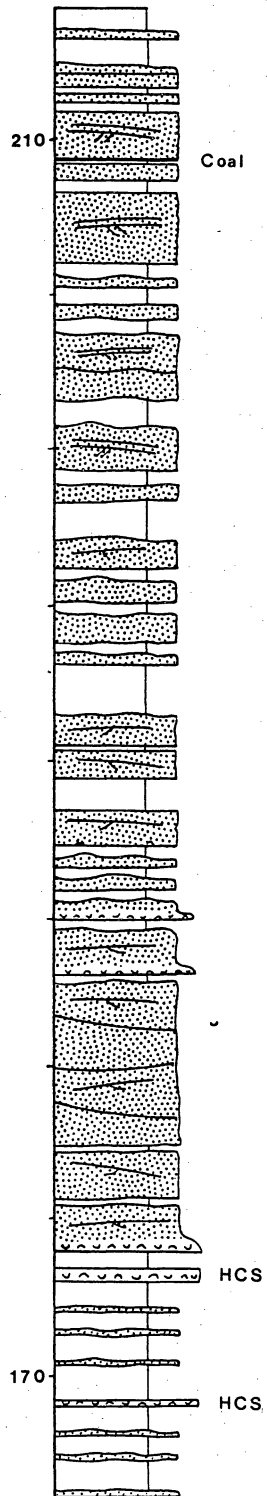
SECTION 1

Section measured along U. S. highway 11 south of Pulaski. Began measuring approximately 200 yards north of the Pulaski wayside near cinder block structure under road. From this point the exposure continues northward to 120 yards south of Hermosa Drive.

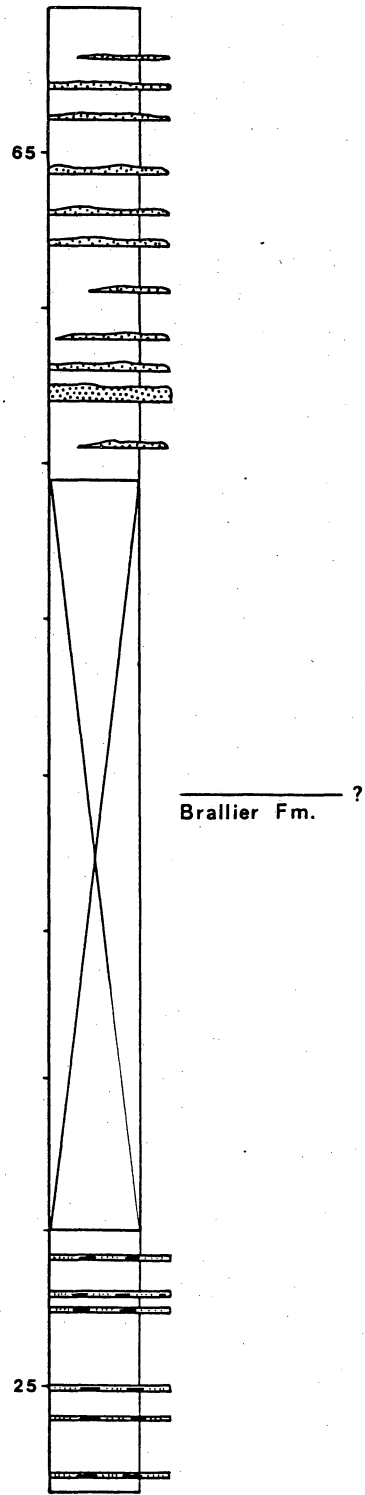
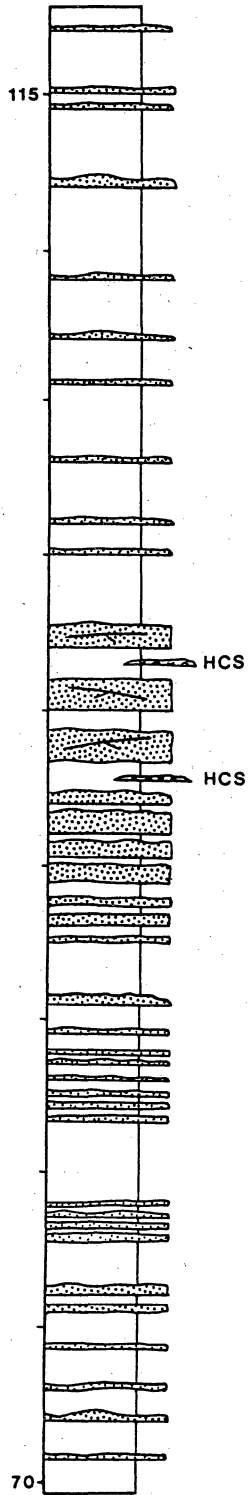
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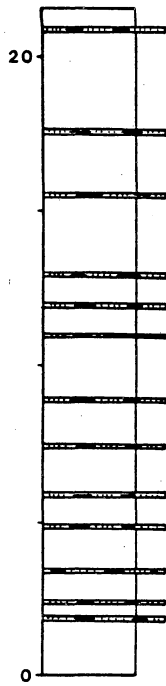
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SECTION 1



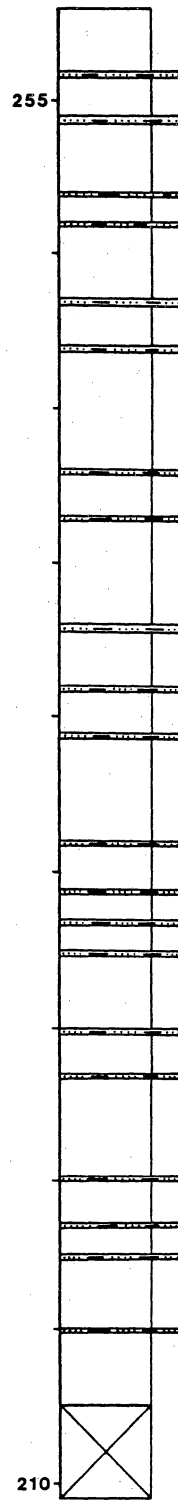
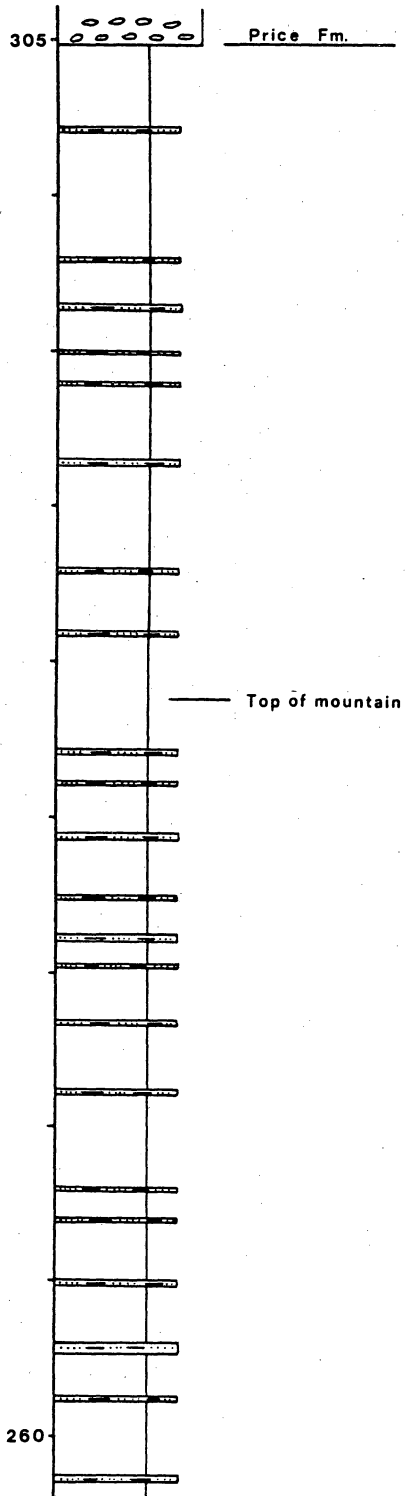
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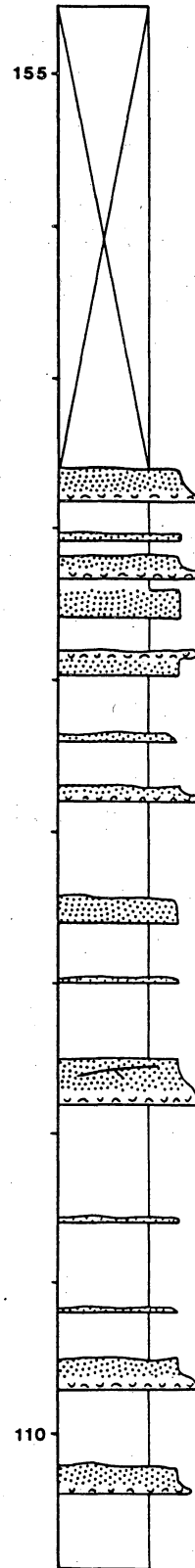
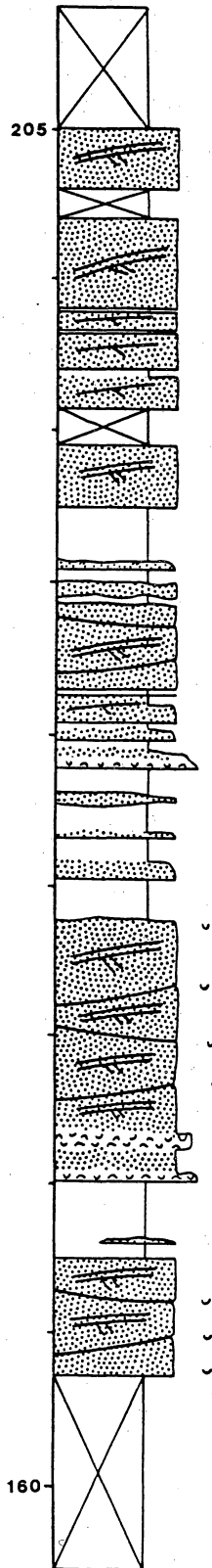
SECTION 2

Section located 5.0 miles from Pulaski on county road 738. Section begins approximately 0.5 miles west of crest of Little Walker Mountain and continues east over ridge on east side. All of section is measured along road.

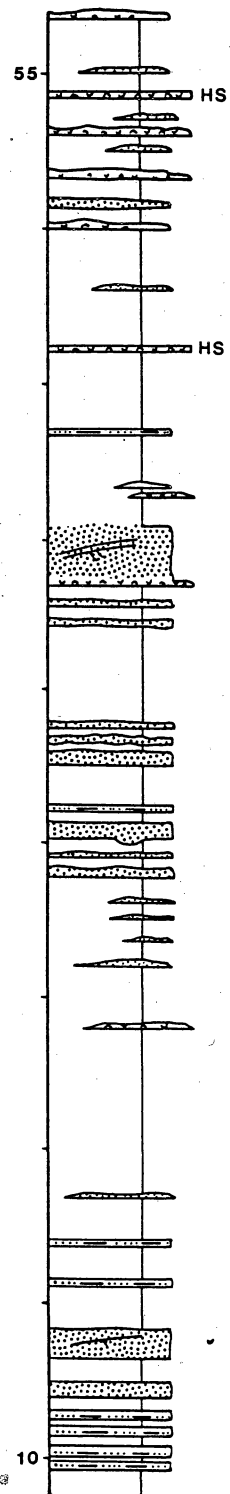
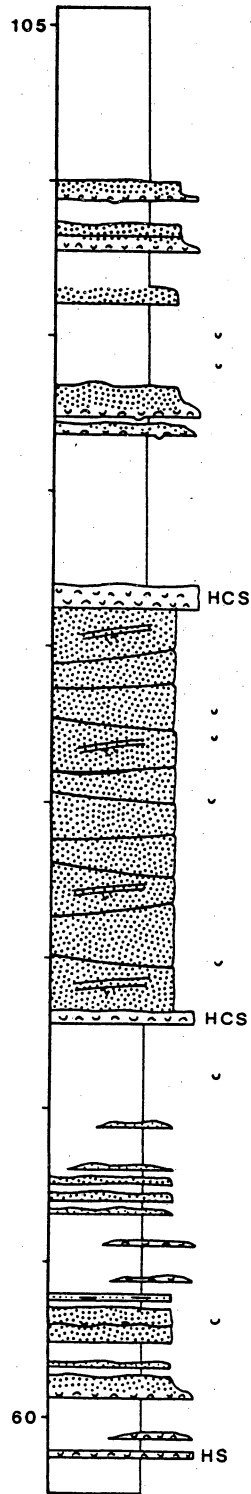
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SECTION 2



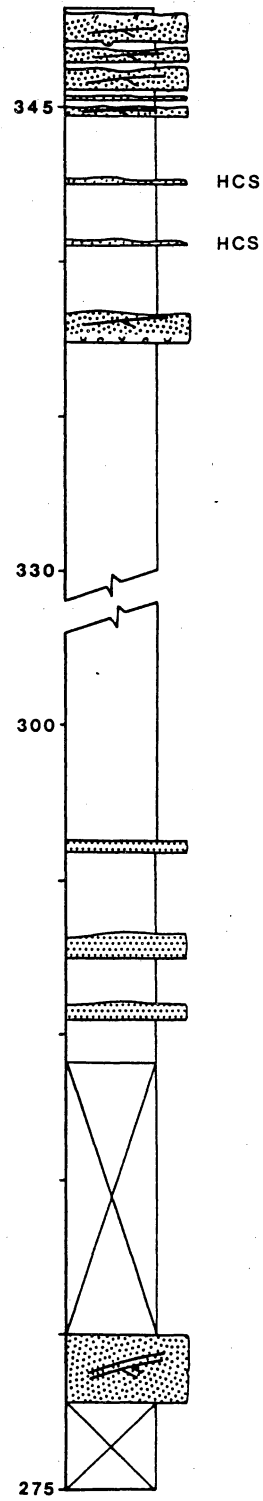
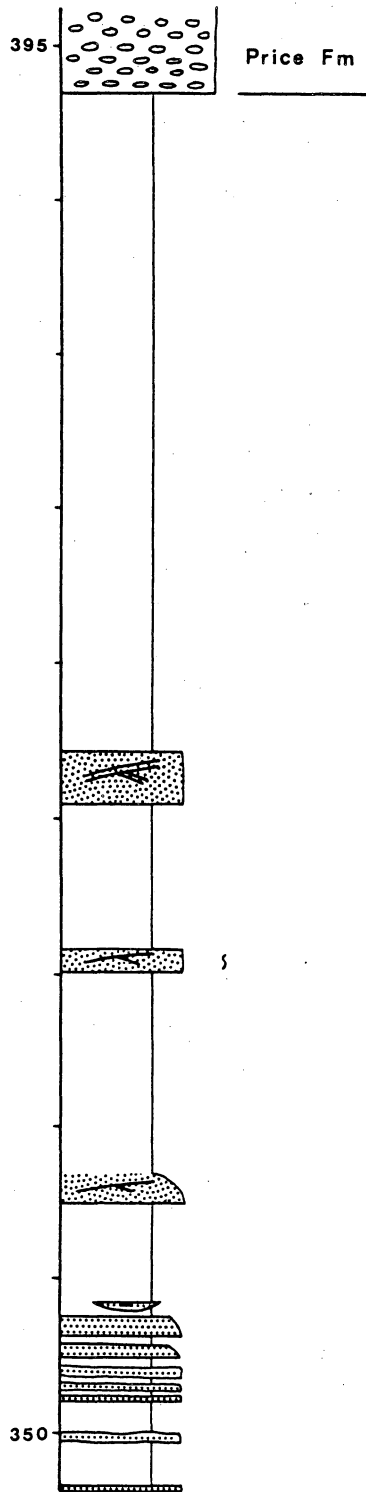
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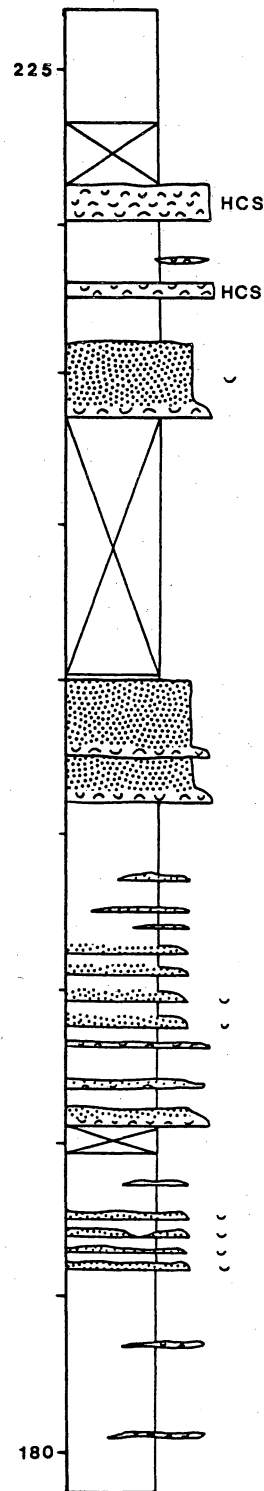
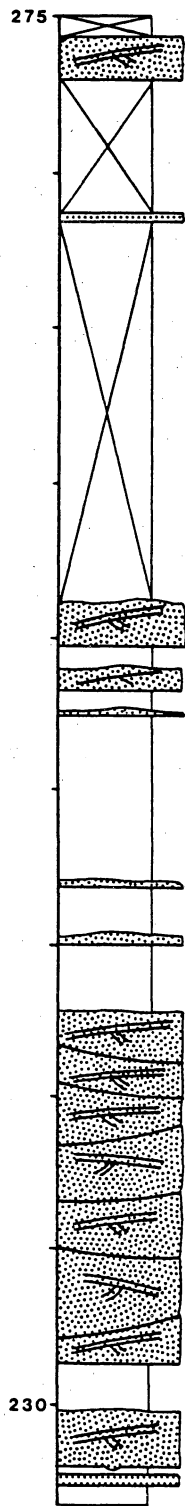
SECTION 3.

Section is located approximately 7.0 miles north of Dublin on state route 100. Exposures begin near county landfill on west side of Cloyd Mountain, then continues up and over ridge to the base of the Price Fm. (Cloyd Conglomerate).

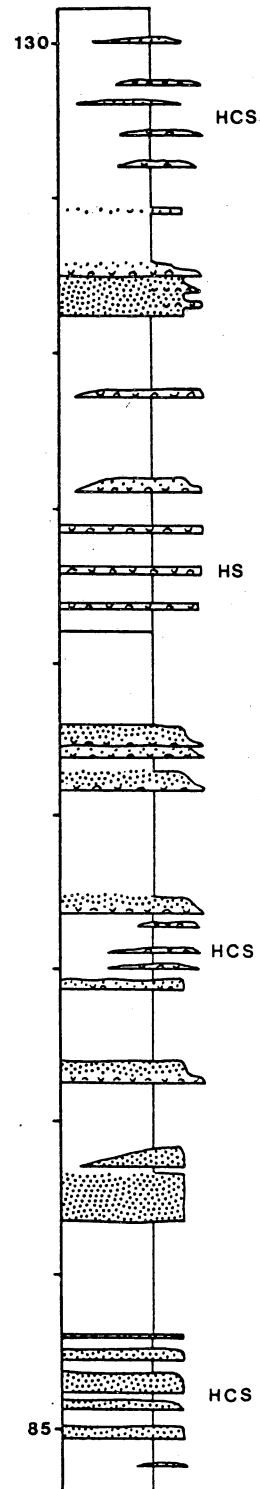
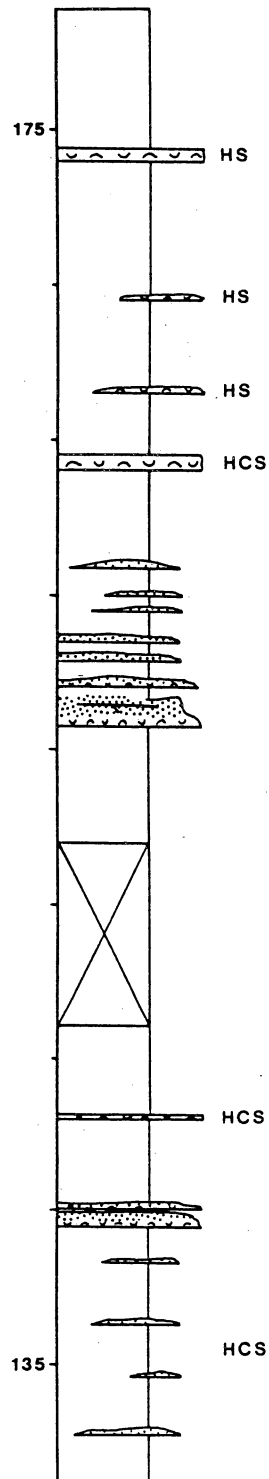
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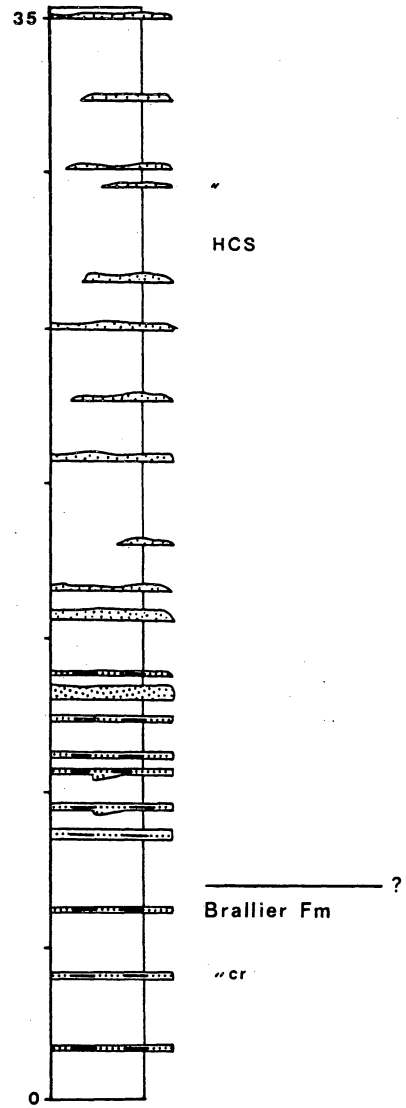
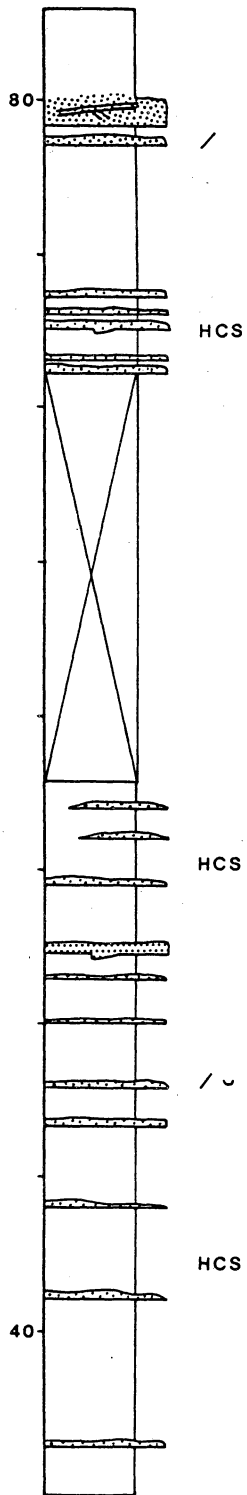
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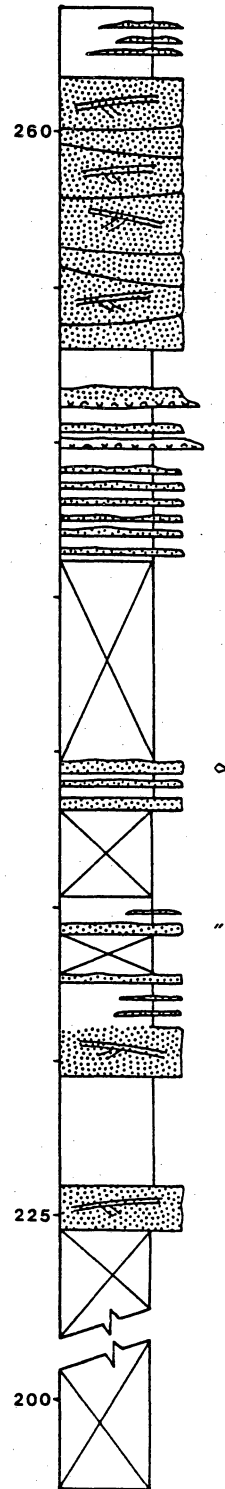
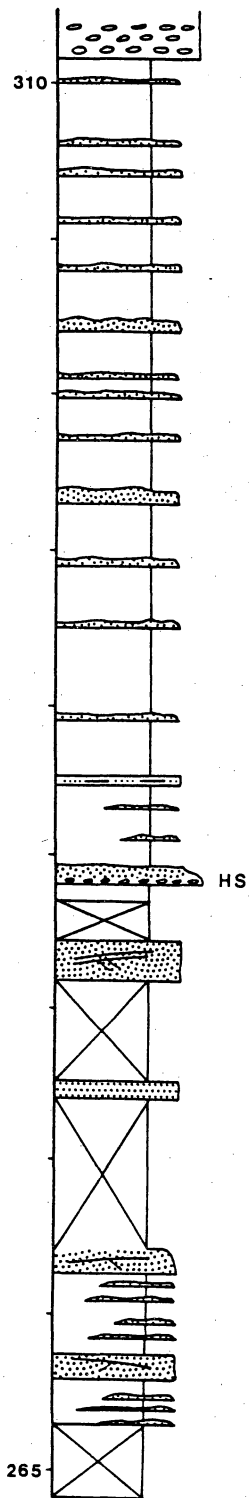
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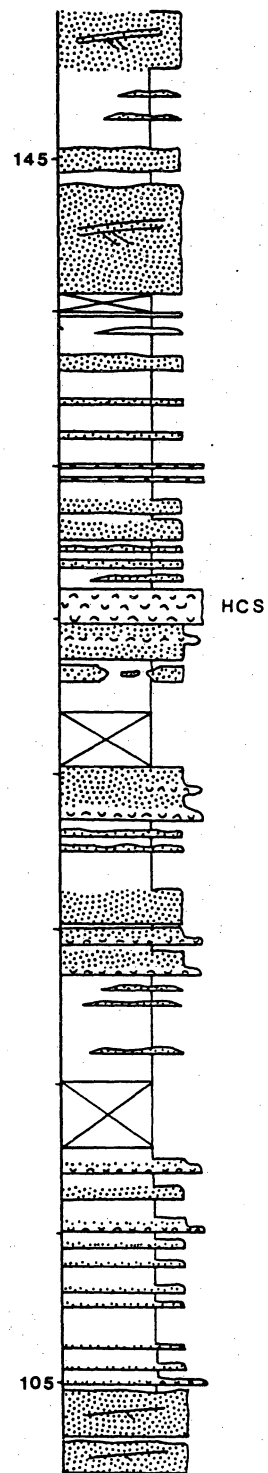
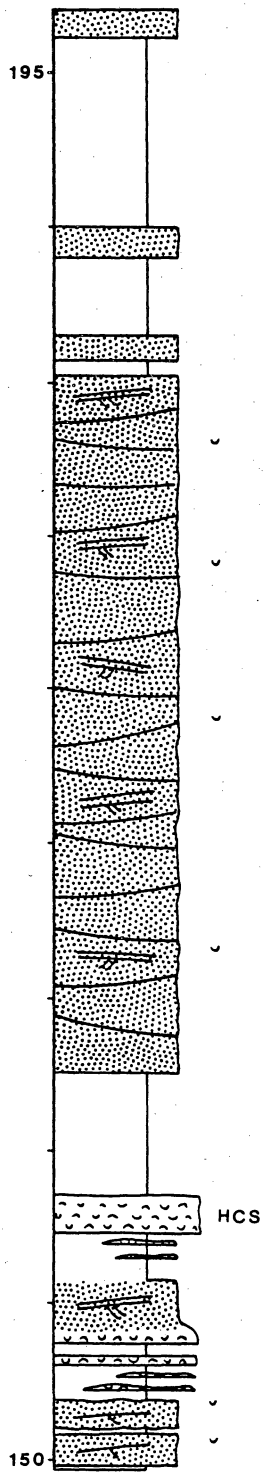
SECTION 4

Section measured along railroad cut on the south side of the New River. Section is located at Cloyd Mountain directly west of the community of Parrot, Va. Began measuring 3 telephone poles west of railroad signal 3104.

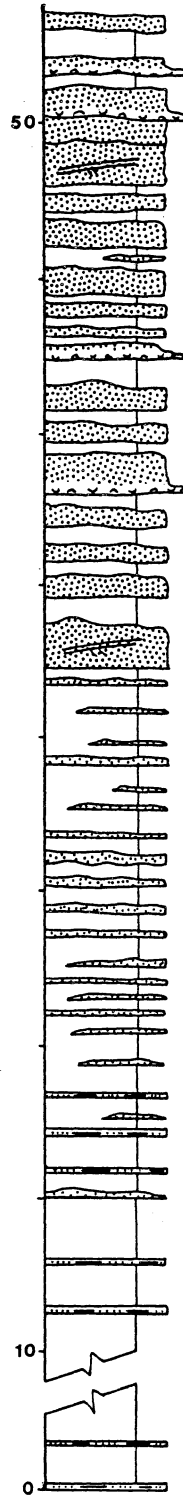
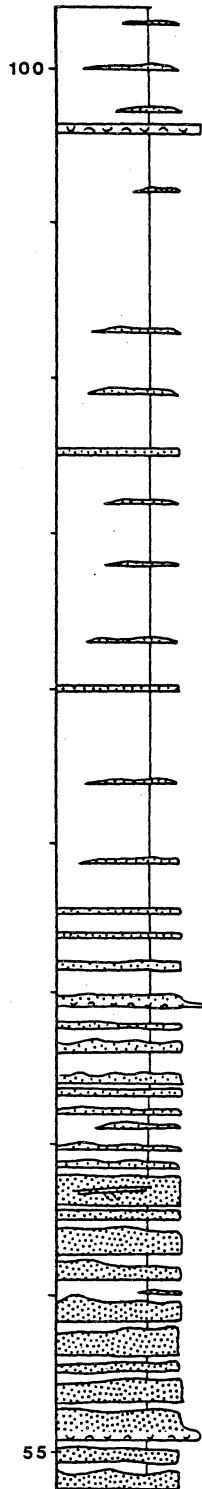
SECTION 4



SECTION 4



SECTION 4

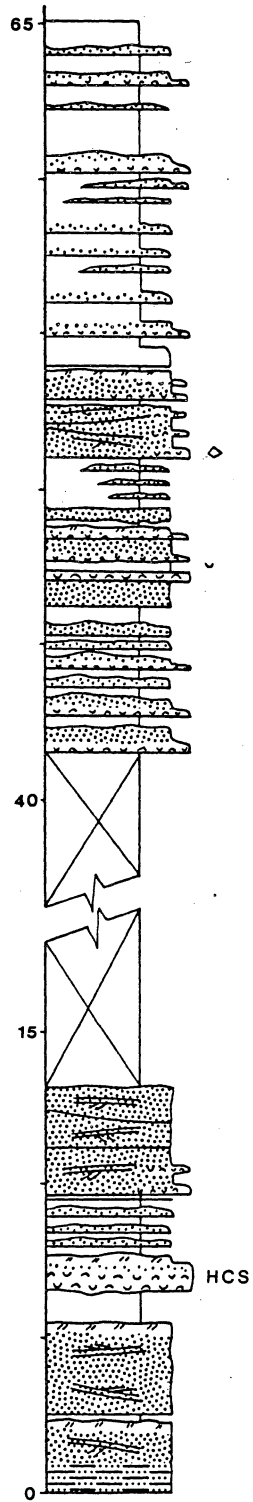


Brallier Fm. ?

SECTION 5

Section measured along state route 311. Base is marked by intersection of route 311 with county road 765. From this intersection the section continues eastward 0.2 mile.

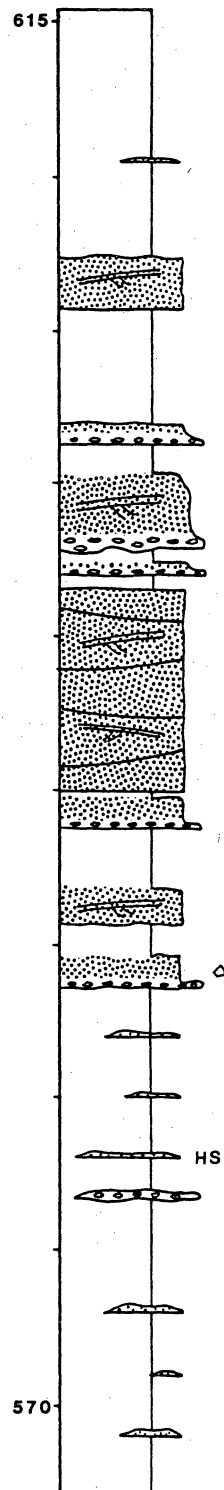
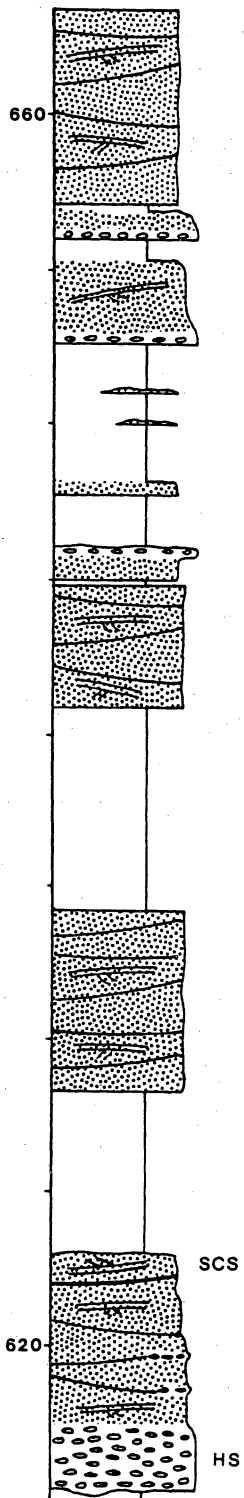
SECTION 5



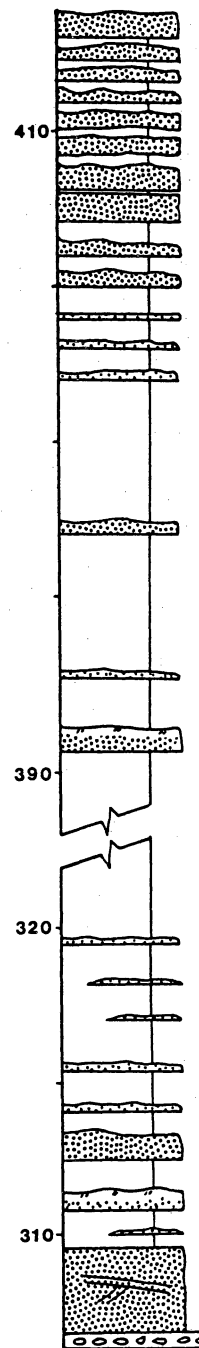
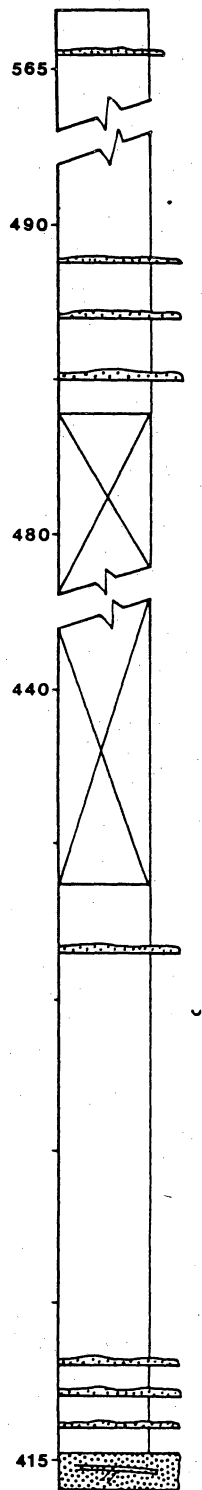
SECTION 6

Section was measured along county road 606 on the northern side of Brush Mountain. Began measuring approximately 0.35 mile north of Craig - Boutertout county line.

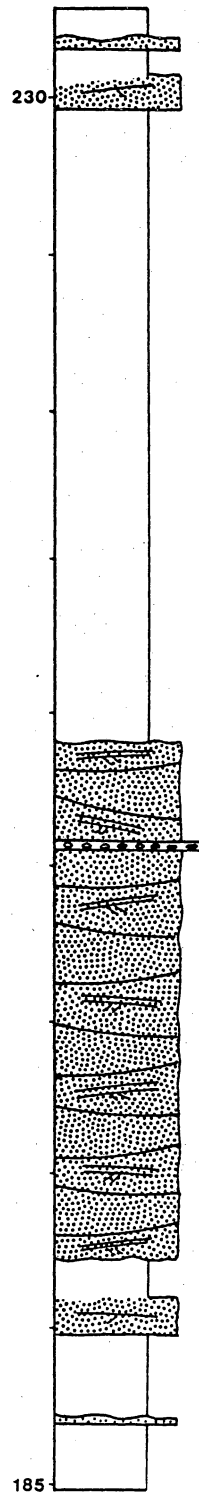
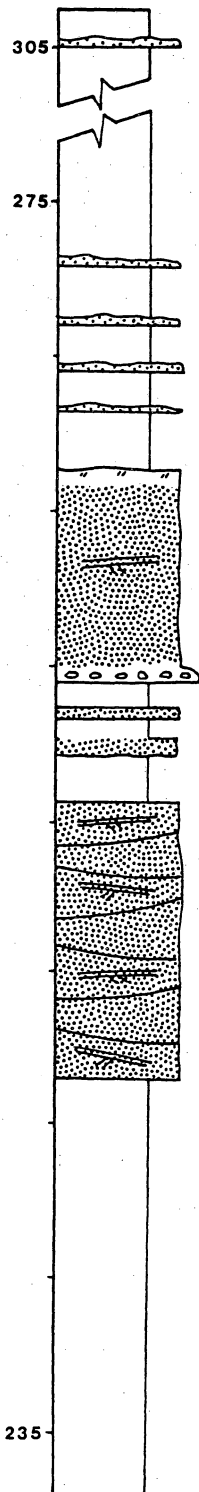
SECTION 6



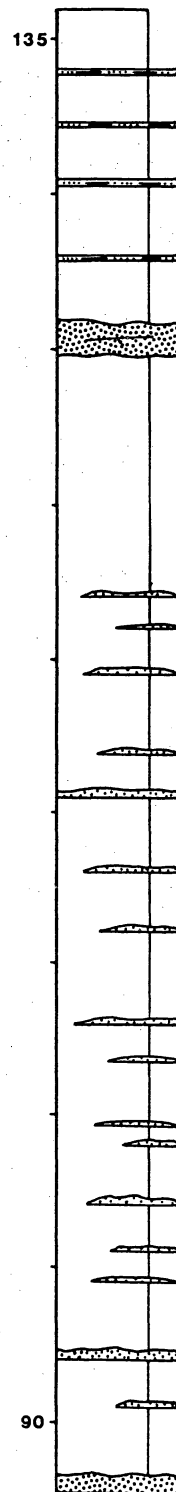
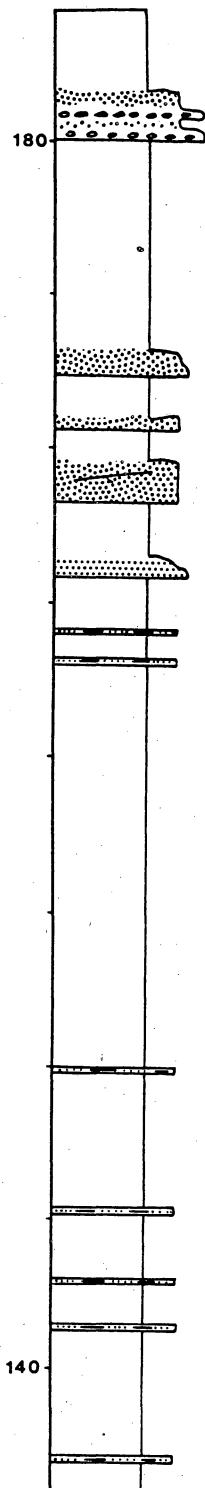
SECTION 6



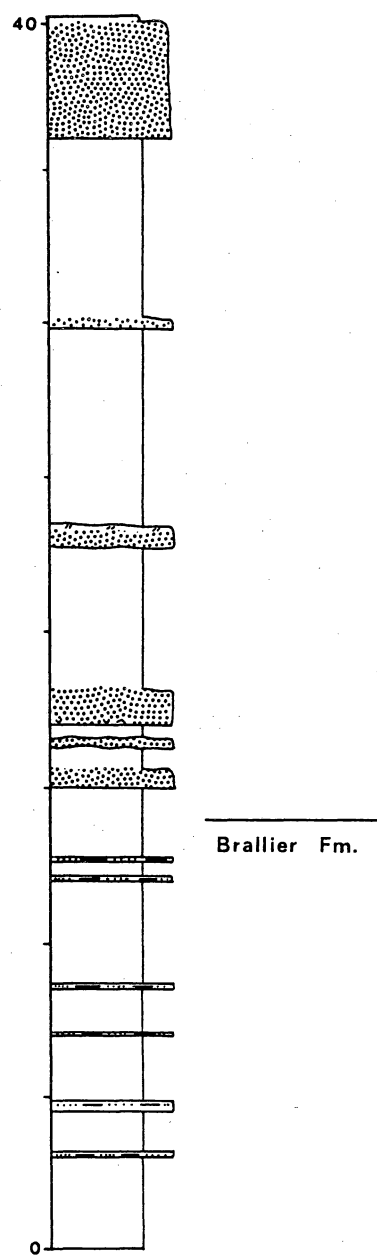
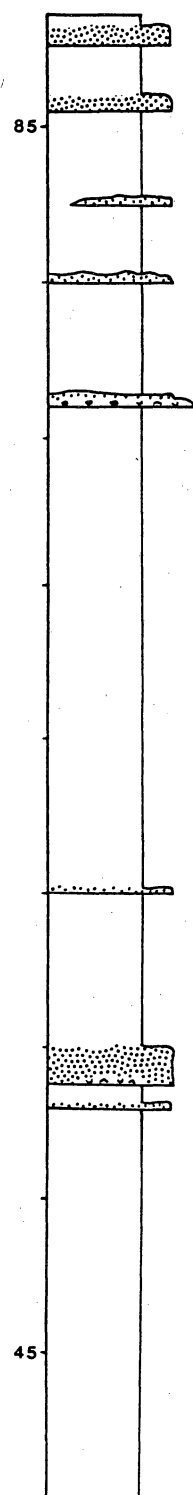
SECTION 6



SECTION 6



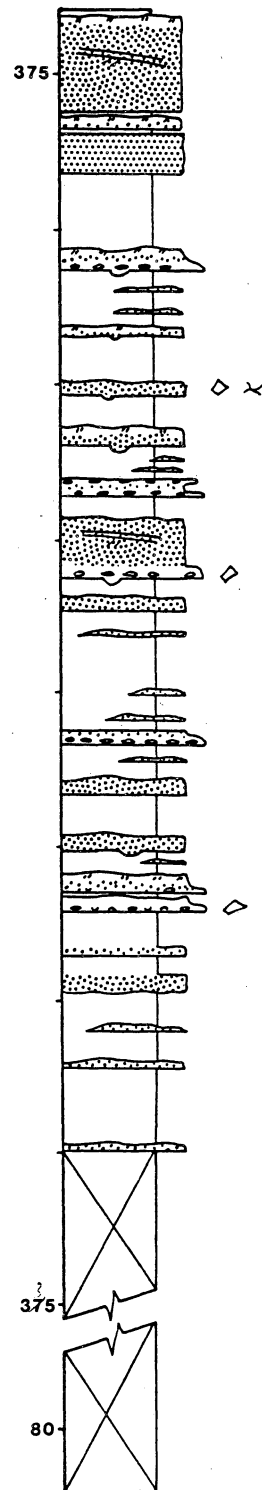
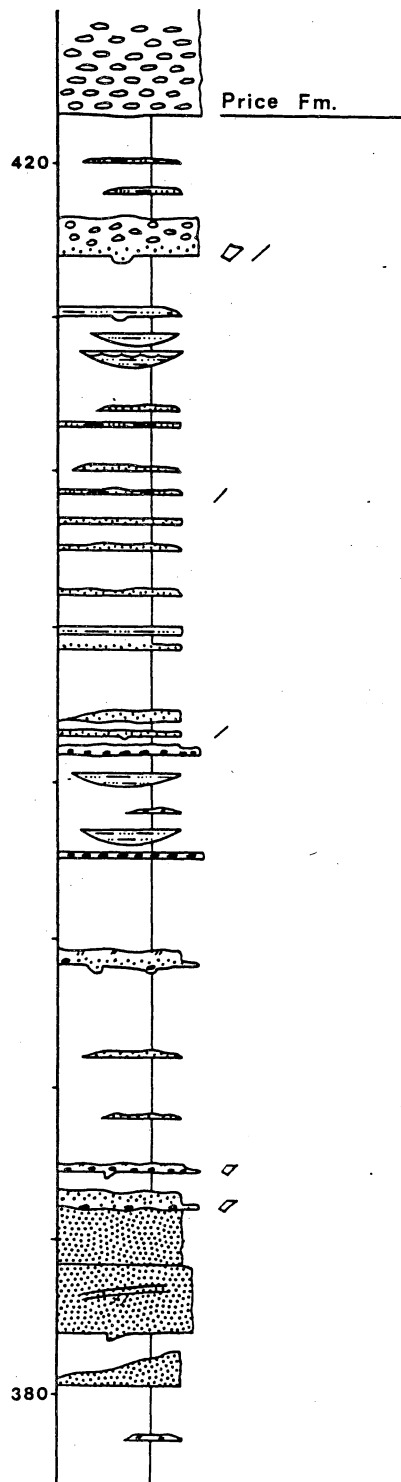
SECTION 6



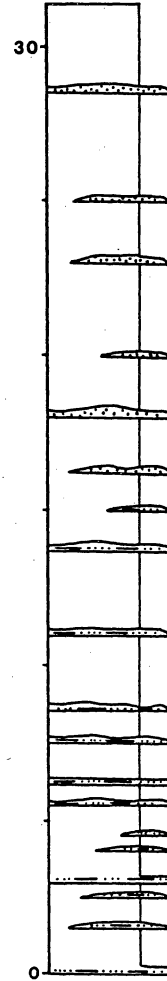
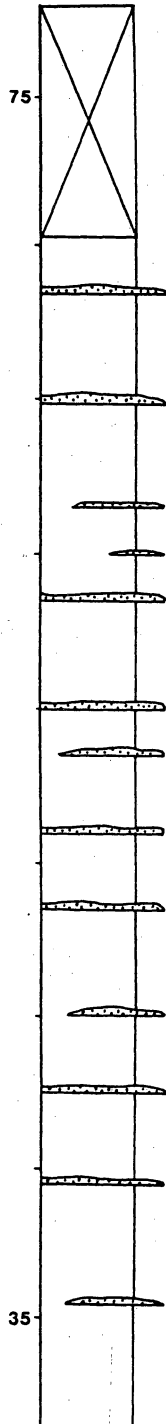
SECTION 7

Section is located along West Virginia route 60 and Interstate 64 about 2 miles northeast of Caldwell W. Va. The section begins at U.S.G.S. benchmark T197 and continues up road to exposure along I-64.

SECTION 7



SECTION 7



Chapter X
APPENDIX II

Fortran program for Markov chain analysis

After K. Soegaard (personal communication)

C

C MARKOV CHAIN ANALYSIS OF STORM SEQUENCES

C

C THE FOLLOWING COMPUTER PROGRAM IS A MARKOV CHAIN
C ANALYSIS. IT IS A STATISTICAL TECHNIQUE EMPLOYED IN
C ESTABLISHING CYCLICAL PATTERNS WITHIN A GIVEN DATA SET.

C IN THE PRESENT CASE FACIES TRANSITIONS WITHIN STORM
C SEQUENCES ARE TO BE DETERMINED. SEVEN SEDIMENTARY
C FACIES ARE INCLUDED IN THE STUDY. THESE ARE:

C

- C (1) MUDSTONE
- C (2) SCoured BASE
- C (3) HORIZONTALLY STRATIFIED LAG
- C (4) HUMMOCKY CROSS-STRATIFIED LAG
- C (5) HORIZONTALLY STRATIFIED SANDSTONE
- C (6) HUMMOCKY CROSS-STRATIFIED SANDSTONE
- C (7) WAVE RIPPLED SANDSTONE

C

C THE PROGRAM PRINTS OUT THE TRANSITION COUNT MATRIX
C FOR THE DATA SET AND CALCULATES AND PRINTS OUT THE
C TRANSITION PROBABILITY MATRIX, THE INDEPENDENT TRIALS
C PROBABILITY MATRIX AND THE DIFFERENCE MATRIX. IN
C ADDITION, A CHI-SQUARE TEST IS PERFORMED. BASED ON
C THIS STATISTIC IT IS STATED AS TO WHETHER THE DATA SET
C POSSESSES A MARKOVIAN PROPERTY OR NOT.

C

C

```

      DIMENSION ITCM(7,7), TPM(7,7), XITPM(7,7), DM(7,7),
      &RSUM(7), CSUM(7), X(7), CHSQ(7), FX(7)

```

C

C READ IN N=NUMBER OF FACIES TRANSITIONS TO BE USED

C

```

      WRITE(5,10)

```

```

10 FORMAT(6X,'ENTER NUMBER OF FACIES TRANSITIONS')

```

```

      READ(5,*) N

```

C

C READ IN K=NUMBER OF FACIES USED IN STUDY

C

```

      WRITE(5,11)

```

```

11 FORMAT(6X,'ENTER NUMBER OF FACIES USED')

```

```

      READ(5,*) K

```

```

      DO 12 I=1,K

```

```

          X(I)=I

```

```

12 CONTINUE

```

C

C READ IN DATA RELATING TO FACIES TRANSITIONS

C

```

      WRITE(5,13)

```

```

13 FORMAT(6X,'ENTER FACIES TRANSITIONS RECORDED')

```

```

      READ(5,*) ((ITCM(I,J), I=1,K), J=1,K)

```

C

C CREATE (PRINT) THE TRANSITION COUNT MATRIX (ITCM)

C

WRITE(6,121)

121 FORMAT(//,18X,'TRANSITION COUNT MATRIX',/)

WRITE(6,120) (I, I=1,K)

WRITE (6,100) (J, (ITCM(I,J), I=1,K), J=1,K)

100 FORMAT(1X,I1,7I7)

C

C CREATE AN ARRAY GIVING THE ROW SUMS IN THE TMC

C

DO 200 J=1,K

SUM=0.0

DO 201 I=1,K

SUM=SUM+ITCM(I,J)

201 CONTINUE

RSUM(J)=SUM

200 CONTINUE

WRITE(6,101)

101 FORMAT(/,6X,'ROW SUM',//)

WRITE(6,102) (RSUM(J), J=1,K)

102 FORMAT(6X,F6.0)

C

C CREATE AN ARRAY GIVING THE COLUMN SUMS IN THE TMC

C

```

      DO 202 I=1,K
        SUM=0.0
        DO 203 J=1,K
          SUM=SUM+ITCM(I,J)
203    CONTINUE
        CSUM(I)=SUM
202 CONTINUE
      WRITE(6,103)
103  FORMAT(/,6X,'COLUMN SUM',/)
      WRITE(6,104) (CSUM(I), I=1,K)
104  FORMAT(6X,F6.0)

```

C

C CREATE A TRANSITION PROBABILITY MATRIX (TPM) BY
 C DIVIDING EACH ELEMENT ITCM(I,J) IN THE TRANSITION
 C COUNT MATRIX BY ITS APPROPRIATE ROW SUM (RSUM(J)).

C

```

      DO 204 I=1,K
        DO 205 J=1,K
          IF (I .EQ. J) GO TO 400
          TPM(I,J)=ITCM(I,J)/RSUM(J)
          GO TO 205
400    TPM(I,J)=0.0
205    CONTINUE
204 CONTINUE
      WRITE(6,105)

```

```
105 FORMAT(//,15X,'TRANSITION PROBABILITY MATRIX',/)
```

```
WRITE(6,120) (I, I=1,K)
```

```
WRITE(6,106) (J, (TPM(I,J), I=1,K), J=1,K)
```

```
106 FORMAT(1X,11,7F7.2)
```

```
C
```

```
C CREATE AN INDEPENDENT TRIALS PROBABILITY MATRIX
```

```
C (XITPM) DIVIDING THE SUM OF THE ELEMENTS WITHIN A
```

```
C COLUMN (CSUM (I)) BY THE DIFFERENCE BETWEEN THE
```

```
C TOTAL NUMBER OF FACIES TRANSITIONS RECORDED (N)
```

```
C AND THE SUM OF THE ELEMENTS WITHIN THE CORRESPONDING
```

```
C ROW (RSUM(J)).
```

```
C
```

```
DO 206 J=1,K
```

```
FX(J)=FLOAT(N)-RSUM(J)
```

```
206 CONTINUE
```

```
DO 207 I=1,K
```

```
DO 208 J=1,K
```

```
IF (I .EQ. J) GO TO 401
```

```
XITPM(I,J)=CSUM(I)/FX(J)
```

```
GO TO 208
```

```
401 XITPM(I,J)=0.0
```

```
208 CONTINUE
```

```
207 CONTINUE
```

```
WRITE(6,107)
```

```
107 FORMAT(//,10X,'INDEPENDENT TRIALS PROBABILITY
```

MATRIX',/)

WRITE(6,120) (I, I=1,K)

WRITE(6,108) (J, (XITPM(I,J), I=1,K), J=1,K)

108 FORMAT(1X,I1,7F7.2)

C

C CREATE A DIFFERENCE MATRIX (DM) BY SUBTRACTING
C ELEMENTS FROM THE INDEPENDENT TRIALS PROBABILITY
C MATRIX (XITPM) FROM THE CORRESPONDING ELEMENTS
C IN THE TRANSITION PROBABILITY MATRIX.

C

DO 209 I=1,K

DO 210 J=1,K

IF (I .EQ. J) GO TO 402

DM(I,J)=TPM(I,J)-XITPM(I,J)

GO TO 210

402 DM(I,J)=0.0

210 CONTINUE

209 CONTINUE

WRITE(6,109)

109 FORMAT(//,20X,'DIFFERENCE MATRIX',/)

WRITE(6,120) (I, I=1,K)

120 FORMAT(/,7I7,//)

WRITE(6,110) (J, (DM(I,J), I=1,K), J=1,K)

110 FORMAT(1X,I1,7F7.2)

C

C TEST FOR MARKOVIAN PROPERTY BY DEPLOYING THE
 C CHI-SQUARE TEST. CALCULATE THE DEGREES OF
 C FREEDOM (M).

C

M=(K-1)**2-K

WRITE(6,111) M

111 FORMAT(//,2X,'DEGREES OF FREEDOM='I3).

CHISQ=0.0

CHIS=0.0

DO 211 I=1,K

DO 212 J=1,K

IF (I .EQ. J) GO TO 212

IF (ITCM(I,J) .EQ. 0) GO TO 212

CHSQ(J)=ITCM(I,J)*ALOG(TPM(I,J)/

(CSUM(I)/ITCM(I<J)))

CHISQ=CHISQ+CHSQ(J)

GO TO 212

212 CONTINUE

211 CONTINUE

CHIS=2.*CHISQ

WRITE(6,112) CHIS

112 FORMAT(//,2X,'CHI-SQUARE= ',F15.2)

C

C TEST FOR MARKOVIAN PROPERTY AT 98 PERCENT CONFIDENCE
 C LEVEL.

C

IF (CHIS .LT. 46.69) GO TO 403

WRITE(6,113)

113 FORMAT(//,2X,'THE SEQUENCE DOES NOT EXHIBIT A
MARKOVIAN PROPERTY')

GO TO 213

403 CONTINUE

WRITE(6,114)

114 FORMAT(//,2X,'THE SEQUENCE EXHIBITS A MARKOVIAN
PROPERTY')

213 CONTINUE

STOP

END

Chapter XI
APPENDIX III

Summary Table of Petrographic Data

	SAMPLE	GRAIN SIZE & SHAPE	FRAMEWORK	GRAINS (%)	MATRIX (%)	CEMENTS (%)	ROCK TYPE
Sandstones (Quartzose)	1	very fine, angular	Quartz-90 Fossils-5 heavy minerals-4 feldspars-1			Calcite-8 Smectite & Illite-2	Quartz Arenite
	2	very fine, angular	Quartz-95 Metamorphic frag.-4 feldspar-1		Smectite & Illite-1	Silica-3 Chlorite-Tr Calcite-Tr	Quartz Arenite
	3	very fine to fine angular	Quartz-92 fossils-3 feldspar-3 metamorphic frag.-2		Smectite & Illite-1	Silica-5 Calcite-10 Hematite-1	Quartz Arenite
	4	very fine to coarse, angular	Quartz-90 metamorphic frag.-5 fossils-2 feldspar-1		Clays-Tr	Calcite-5 Silica-2 Smectite-2	Quartz Arenite
	5	very fine subangular	Quartz-94 metamorphic frag.-5 Mica-1		Smectite & Illite-5	Silica-5 Clay-Tr Pyrite-Tr Chlorite-Tr	Quartz Arenite
	6	very fine angular	Quartz-90 metamorphic frag.-5 feldspar-2 Mica-2 heavy minerals-1		Clays-5	Smectite and Illite-8 Hematite-3	Quartz Arenite
	7	very fine to fine subangular	Quartz-90 feldspar-5 metamorphic frag.-3 heavy minerals-2		Clays-2	Silica-5 Smectite & Illite-3	Quartz Arenite
	8	medium to coarse rounded	Quartz-95 Metamorphic frag.-4 Intraclast-1			Silica-10	Quartz Arenite
Sandstones (Lithic)	9	very fine angular	Quartz-78 Metamorphic frag.-18 Mica-3 heavy minerals-1		1	Smectite & Illite-5 Silica-2 Calcite-2 Chlorite-2	Lithic Arenite
	10	very fine to medium angular	Quartz-75 metamorphic frag.-20 heavy minerals-2 feldspar-2 Mica-1		Tr	Smectite & Illite-5 Chlorite-5 Silica-1	Lithic Arenite
	11	very fine to fine angular	Quartz-57 metamorphic frag.-35 heavy minerals-5 feldspar-2 Mica-1		Tr	Silica-5 Smectite-4 Chlorite-1	Lithic Arenite
	12	very fine to coarse subangular	Quartz-85 Metamorphic frag.-10 feldspar-3 Intraclast-1 Heavy minerals-1		Clays-5	Hematite-8 Calcite-1 Silica-2 Pyrite-1	Lithic Arenite
	13	very fine to fine subangular	Quartz-80 Metamorphic frag.-18 heavy minerals-1 Mica-1		Tr	Smectite & Sericite-10 Fe Calcite-1 Hematite-1	Lithic Arenite
Bioclastic	14	very fine very angular	Quartz-70 fossils-25 feldspars-1 Intraclasts-1 Mica-2		Tr	Silica-5 Smectite-4 Chlorite-1	Fossiliferous Quartz Arenite
	15	very fine very angular	Quartz-81 fossils-15 feldspar-2 heavy minerals-1 Mica-1		Clays-5	Hematite-8 Calcite-1 Silica-2 Pyrite-1	Fossiliferous Quartz Arenite
	16	very fine angular	Quartz-65 fossils-30 heavy minerals-3 feldspar-2		Tr	Smectite & Sericite-10 Fe Calcite-1 Hematite-3	Fossiliferous Quartz Arenite
Conglomerate	17	gravel and v.f - c. sand pebbles-round; sand-angular	Quartz-90 metamorphic frag.-5 Intraclast-3 heavy minerals-2		Tr	Chlorite-5 Smectite & Illite-3 Pyrite-1 Hematite-1	Clast supported Quartzose Cgl.
	18	gravel and v.f - c. sand pebbles-round; sand-angular	Quartz-70 Intraclasts-20 Meta. frag.-5 heavy minerals-2 feldspar-1 Mica-2			Chlorite-5 Calcite-5 Silica-2 Smectite-1	Matrix supported Quartzose Cgl.
	19	gravel and f. - c. sand pebbles-rounded;sand-angular	Quartz-85 Intraclast-10 Meta. frag.-5 feldspar-1 heavy minerals-1 Mica-1			Calcite-8 Chlorite-2	Clast supported Quartzose Cgl.
	20	gravel and f. - c. sand pebbles-rounded;sand-angular	Quartz-88 Metamorphic-10+ feldspar-<1 heavy minerals-<1			Hematite-7 Smectite-1	Clast supported Quartzose Cgl.

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