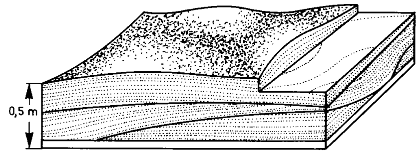
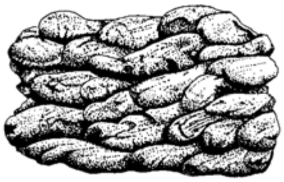
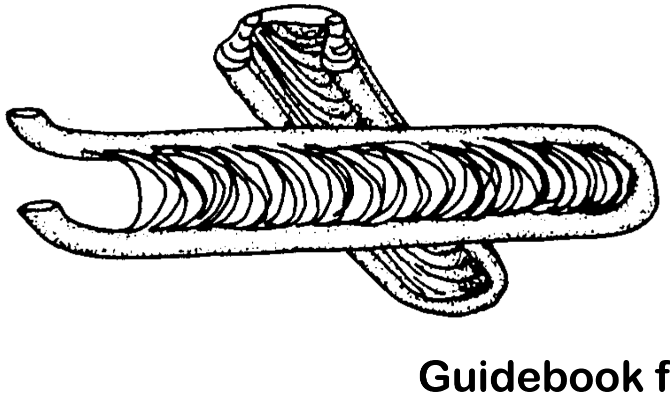




GEOLOGY OF THE LOWERMOST VENANGO GROUP (UPPER DEVONIAN)

SOUTHEASTERN FAYETTE COUNTY, PENNSYLVANIA



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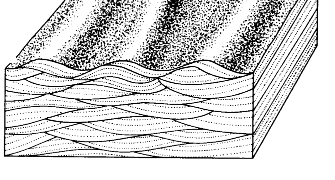
Spring Field Trip



June,16, 1984

Guidebook for the

PITTSBURGH GEOLOGICAL SOCIETY
SPRING FIELD TRIP

June 16, 1984

Geology of the Upper Devonian Venango Group Reservoir Rocks
in Fayette County, Pennsylvania

Trip leaders: John A. Harper and Christopher D. Laughrey, Pennsylvania Geological Survey

For additional copies of this field trip guidebook, contact:

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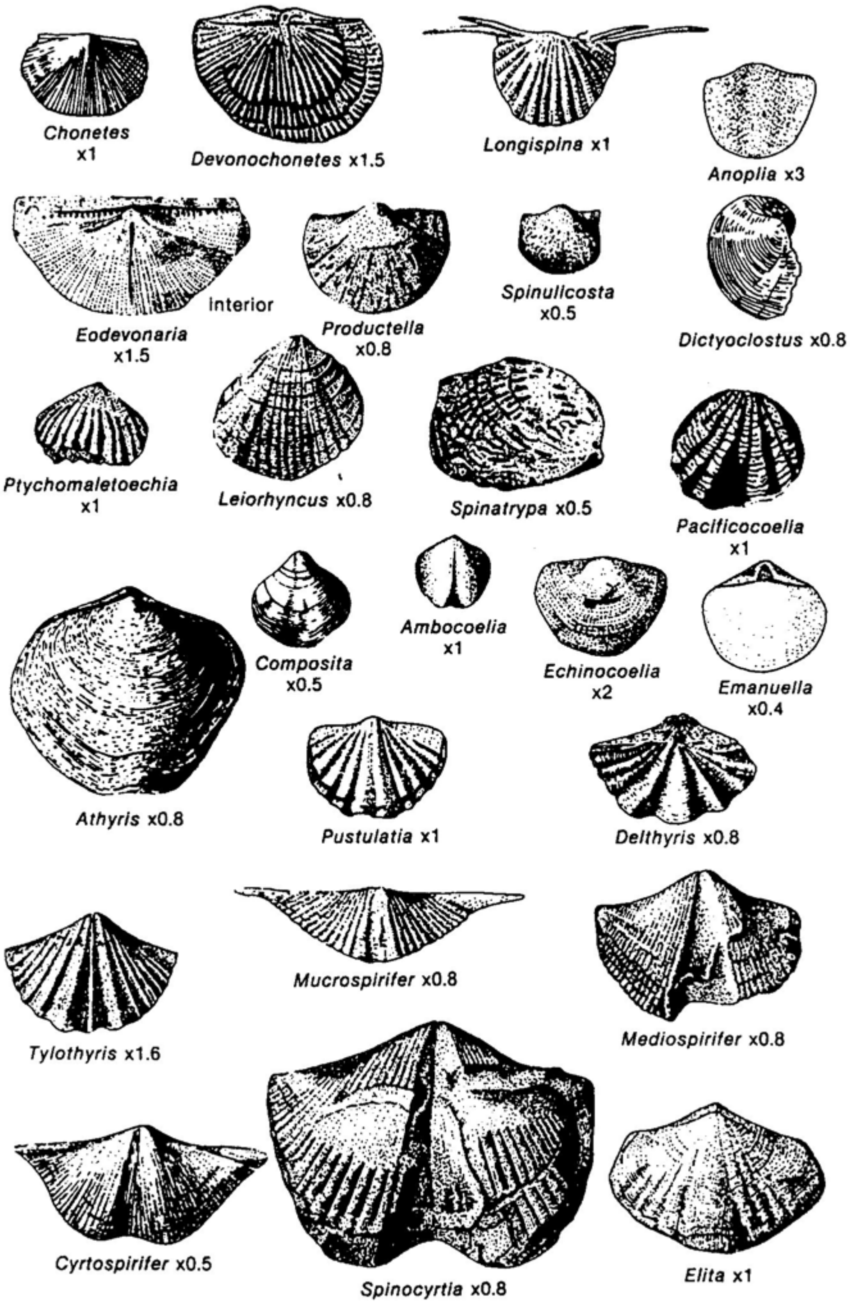
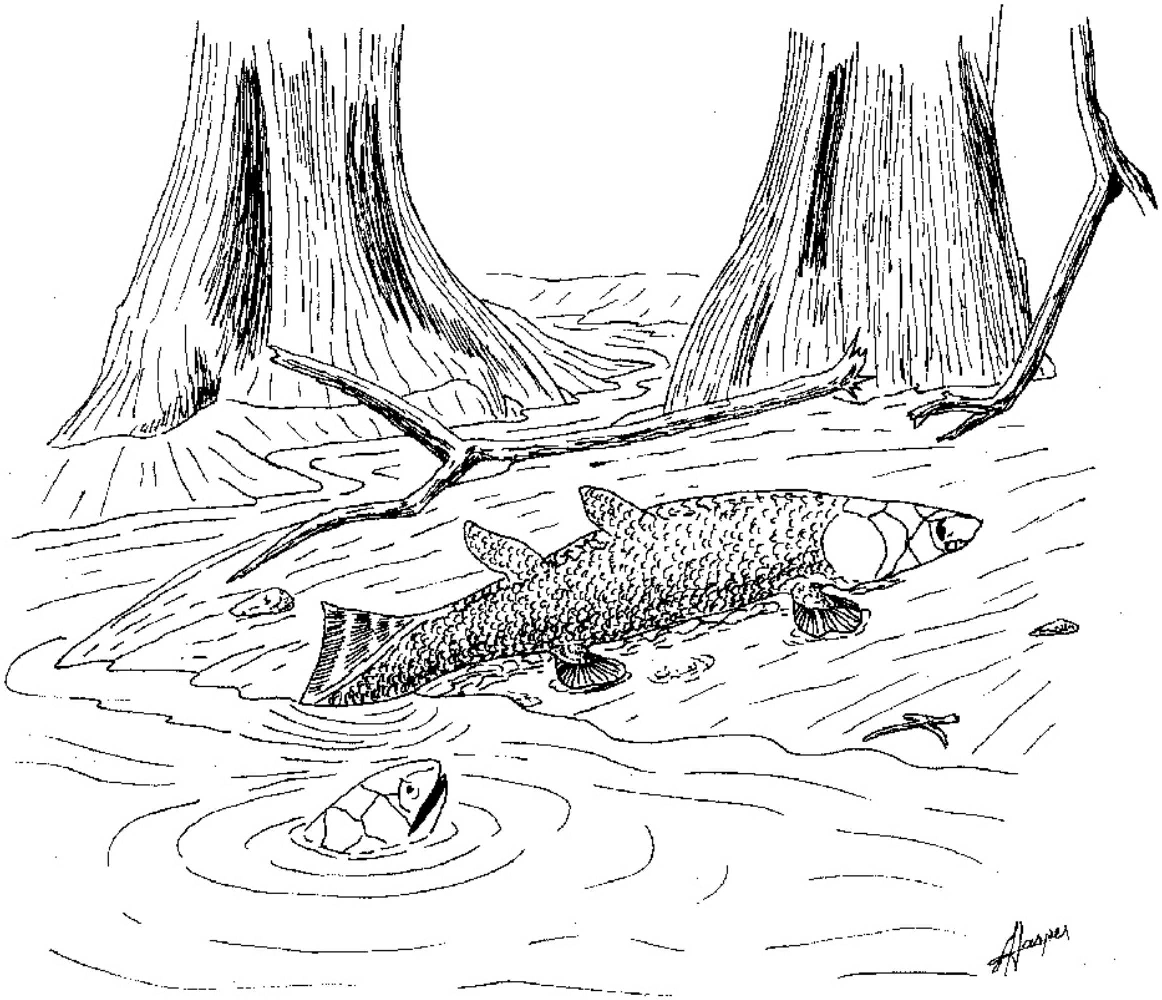


Some common Devonian brachiopods

GREAT MOMENTS IN GEOLOGIC HISTORY
Part 10 – The Devonian



George! What the hell do you think you're doing? You get back in here right this very minute. You're going to catch your death. What'll the neighbors think?

Geology of the Upper Devonian Venango Group Reservoir Rocks
in Fayette County, Pennsylvania

John A. Harper and Christopher D. Laughrey
Pennsylvania Geological Survey

INTRODUCTION

The oldest rocks exposed in southwestern Pennsylvania crop out in the stream gorges that traverse the major anticlines, Laurel Hill and Chestnut Ridge. These rocks are of Late Devonian and Early Mississippian age and correlate in part to the thick sequences of red beds of the Catskill Formation in central and eastern Pennsylvania.

Although oil and natural gas have been produced from Upper Devonian reservoir sandstones in Pennsylvania for almost 140 years, relatively little is known about the lithologic nature of the rocks outside of what has been gleaned from a few cores and numerous well cuttings. Except for the petroliferous Venango First, Venango Second, and Venango third sands, which crop out in northwestern Pennsylvania, outcrops of reservoir rocks are rare to non-existent. Perhaps the best and most complete such outcrop (outside of the aforementioned Venango sands) is the exposure of Lock Haven Formation at the Allegheny Front, only three to five miles east of the prolific Council Run field in Centre and Clinton counties. It is unfortunate that there are no outcrops of the Bradford Group sandstones, the most gas-productive formation in Pennsylvania.

On this trip we will be examining an outcrop of the oldest rocks exposed in southwestern Pennsylvania. These rocks crop out along the CSX railroad line at Victoria in the Youghiogheny River gorge through Laurel Hill anticline in Fayette County (Figure 1). They are equivalent to the lower productive sandstones of the Venango Group in Greene, Washington, and Allegheny Counties (the Bayard and Elizabeth sands of drillers).

The information contained in this guidebook is based primarily on work done during the course of a project detailing the geology of the oil and gas fields of southwestern Pennsylvania (Harper and Laughrey, 1987). We visited the Victoria outcrop several times to see if there was any lithologic correlation of the exposed rocks to the subsurface reservoir rocks west of Fayette County. To our surprise there appears to be no petrographic or petrologic differences between exposed rocks at this outcrop and samples of the Gordon and Fifth oil sands in the McDonald-McCurdy and Washington-Taylorstown fields (Washington and Allegheny counties), two of the most important and productive areas south of Venango County.

PREVIOUS GEOLOGIC INVESTIGATIONS

Stevenson (1877) first recognized the existence of the Catskill red beds in Fayette County. He noticed that the break between the Devonian and overlying “Pocono sandstone” was distinct, that the sandstones of the “Pocono” graded downward through sandy shales into the well-defined reddish shales and sandstones of the Catskill. In a later report (Stevenson, 1878)

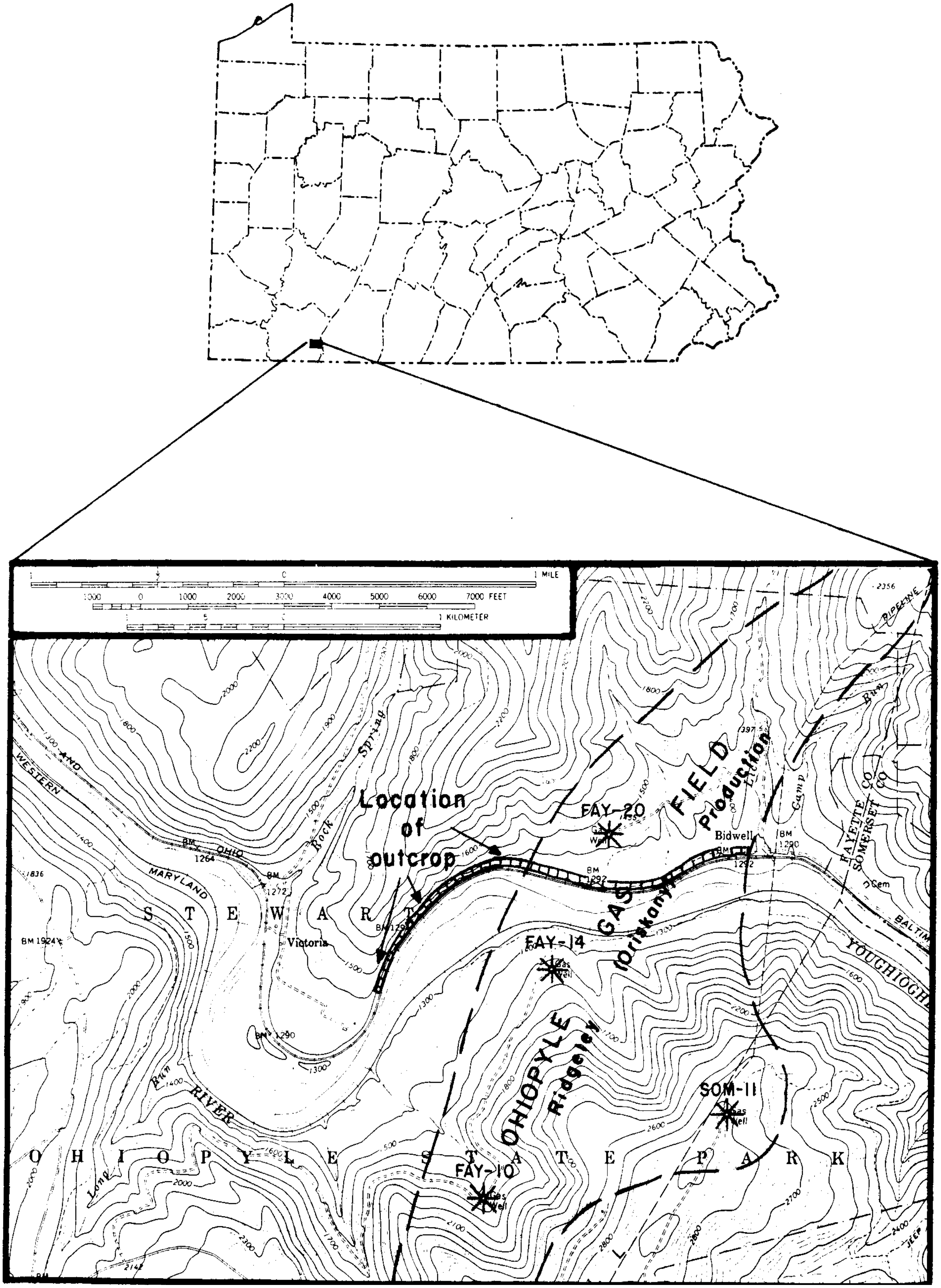


Figure 1. Location of the lower Venango Group outcrop along the CSX railroad track in the Youghiogheny gorge through Laurel Hill anticline. Also shone is the Ohiopyle gas field with wells producing from the Ridgeley Sandstone. Ohiopyle is down river (to the left).

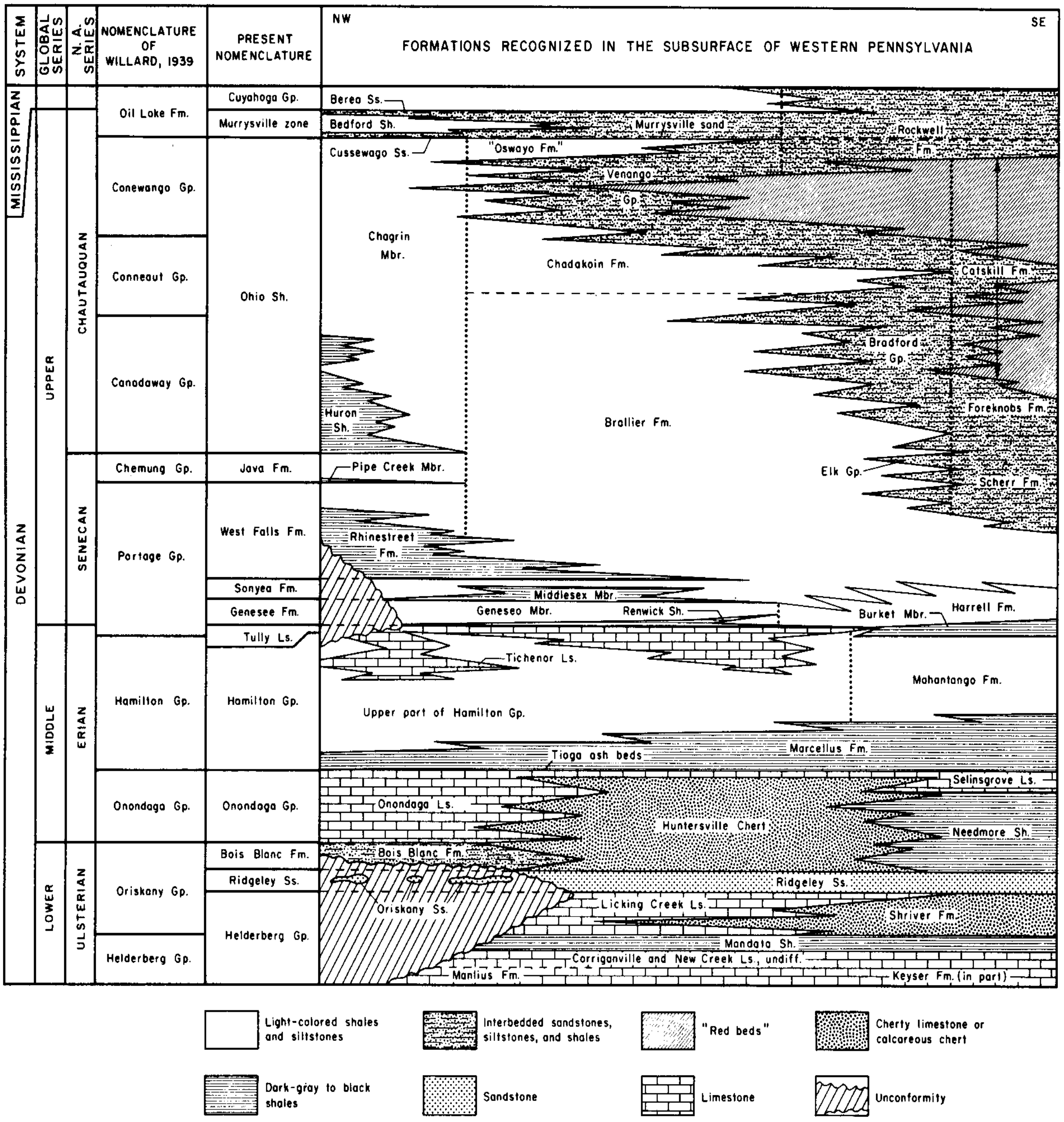


Figure 2. Schematic diagram of Devonian stratigraphic units in the subsurface of western Pennsylvania (modified from Harper and Laughrey, 1987).

he suggested that the Catskill and part of the underlying "Chemung" were probably missing in southwestern Pennsylvania, based on fossils collected during the work for the earlier report. Thus, he considered the Devonian rocks exposed in the Youghiogheny gorge at Victoria to be "Chemung" in age. The term "Chemung", although still used by some Appalachian geologists, is an obsolete name originally used for rocks equivalent to the Java and Dunkirk formations in New York (Figure 2). Over the years it became either lengthened or shortened, depending on the geologist. In the first half of this century, when biostratigraphy formed much of the basis for formation designations, “Chemung” became synonymous with everything between the Catskill red beds and the black shale (whichever particular black shale formation it might happen to be), simply because the rocks contain much the same marine fauna throughout.

Butts (1908) studied the faunas of the Upper Devonian rocks in the several inliers in southwestern Pennsylvania and determined that all exposed rocks were equivalent to the “Conewango Series” of the northwestern counties. Willard (1933; see also Willard and Caster, 1935) reopened the Devonian question after a hiatus of 15 years by reasserting Stevenson’s conclusions that the Devonian rocks of the Chestnut Ridge and Laurel Hill inliers were of “lower Chemung” age. In his classic compendium of the Upper Devonian Willard (in Willard and others,1939, p. 268) stated, “At Ohiopyle in northeastern [sic] Fayette County, marine Devonian and Catskill continental beds are exposed along the Youghiogheny River, but the few poorly preserved fossils collected were inadequate as evidence of the precise age of these beds, although they are perhaps not younger than latest Chemung.”

The only comprehensive work done on the geology of the Youghiogheny River gorge between Confluence and Ohiopyle was the doctoral work of Wilson M. Laird. The most comprehensive literature on Mississippian and Devonian rocks of this area is Laird’s dissertation (Laird, 1942), but his work was condensed and published by the Pennsylvania Geological Survey prior to completion of the doctorate (Laird, 1941), and this is the most readily available information. Later in the decade, Bayles (1949) performed a subsurface investigation of Upper Devonian rocks throughout southwestern Pennsylvania, including in the vicinity of the Youghiogheny gorge. Although he could not confirm nor deny the age of the rocks in the gorge, he showed through physical stratigraphic correlation that the section exposed east of Victoria was equivalent with the “Conewango” of northwestern Pennsylvania.

Since that time, little direct work has been done on the Lower Mississippian and Upper Devonian rocks in Fayette County. Of the two state geological maps compiled since 1950, Gray and others (1960) labeled all Devonian rocks in the gorge “Catskill”, whereas Berg and others (1980; also Berg and Dodge, 1981) separated them into Catskill and Foreknobs formations. Harper and Laughrey (1987; also Laughrey and Harper, 1989) studied the Devonian portion of the outcrop in detail, labeling the older, non-red rocks Venango Group. The work done during this study forms the basis of this field trip. Subsequent work by McElroy (1988) and LaSota (1988: also LaSota and Kennedy, 1992) added nothing new to the arguments.

At least the most recent geologic map of the area (McElroy, 1988) recognizes that there are pre-red Upper Devonian rocks exposed in the gorge, but the name “Foreknobs” is incorrect in terms of both stratigraphy and geography. As shown in Figure 2, true Foreknobs formation is equivalent to rocks considerably older than those that crop out in southwestern Pennsylvania. The name Foreknobs should be restricted to those counties east of the Laurel Hill anticline and south of Altoona.

THE DEVONIAN SYSTEM

General

The Devonian System in the central Appalachians, particularly the Middle and Upper Devonian, constitute one of the most complex sequences of rock in North America. The laterally interfingering and upwardly coarsening rocks are classic examples of the facies concept. Yet, despite more than 160 years of intense scrutiny, especially in outcrop, many of the stratigraphic relationships of this system are only now being satisfactorily defined. In Pennsylvania the Devonian is a westward-thinning wedge of sediments, measured and estimated at thicknesses of 2,400 ft (730 m) in Erie county and over 13,000 ft (3,960 m) in the eastern part of the state. In the laurel Highlands of Fayette and Somerset counties it is 7,000 to 8,000 ft (2,134-2,438 m) thick. The Devonian sequence is dominated by mudrocks, but small amounts of chert and limestone, in the lower half of the Devonian, and larger quantities of sandstones and conglomerates, important in the upper half, contribute to the total volume of sediments. The upper and lower boundaries of the system are basically conformable everywhere except in eastern Pennsylvania, near the major sediment source areas, and in northwestern Pennsylvania along the margins of the craton.

The Devonian System is the single most important sequence of oil- and gas-related rocks in Pennsylvania. The Lower Devonian Ridgeley Sandstone (Oriskany of drillers) and the Upper Devonian sandstones of the Venango and Bradford groups produce 75 percent of the Commonwealth’s natural gas, and the Upper Devonian alone produces almost 97 percent of the crude oil. These figures have changed somewhat over the last 25 years and are likely to change a little more over the next 25, but the change is not expected to be great. In addition to reservoir rocks, the Devonian, particularly the Upper Devonian, includes hundreds of meters of dark shales that constitute the most important hydrocarbon source rocks in the Appalachian basin (Laughrey and Baldassare, 1998)

Southwestern Pennsylvania

In southwestern Pennsylvania the Devonian consists of two lithologic and environmental “megafacies” comprising Lower Devonian marine carbonates, cherts and shales, and Upper Devonian marine to nonmarine, coarse- to fine-grained terrigenous rocks deposited by the prograding Catskill deltaic system. These two “megafacies” converge and interfinger in the Middle Devonian. Because many of these rocks represent facies that do not crop out anywhere in the Appalachian basin, they have not been sufficiently described or defined, and have not been formally named in the subsurface of western Pennsylvania.

The Devonian System is divided into four series (Figure 2) based on major changes in lithology. These series include, from bottom to top: the Ulsterian or Lower Devonian, dominated by shallow shelf carbonates and tabular sandstones; the Erian or Middle Devonian, consisting of dark marine shales and thin siltstones sandwiched between two carbonate or carbonate-chert facies; and the combined Senecan and Chautauquan or Upper Devonian, a (generally) upwardly and eastwardly coarsening sequence of intergrading dark shale, siltstone, and sandstone facies developed as a series of prograding deltaic and marine deposits. The boundary between the Senecan and Chautauquan series is evident only in the subsurface of the northwestern counties. For the sake of simplicity, therefore, we use the global series term “Upper Devonian” in place of the two North American series names. This series is the one we are primarily concerned with here.

Depositional Basin And Provenance

The Appalachian basin during the Devonian was part of an extensive inland sea (Figure 3) receiving intermittent influx of terrigenous sediments from a source area (Appalachia) that first developed during the Ordovician Taconic orogeny. Appalachia consisted originally of uplifted and metamorphosed Precambrian(?) through Early Ordovician sediments, volcanics, and intrusives, but subsequent tectonic activity added Middle Ordovician through Silurian-aged sediments to the eroding uplands. Continued sediment influx throughout the intermittent periods created an asymmetrical, wedge-shaped deposit due to differences in the subsidence and sedimentation rates at the opposite sides of the basin. Large volumes of coarse-grained sediment poured into the eastern trough area, whereas in the west, adjacent to the stable craton, the Devonian sediments were mostly fine-grained particles falling out of suspension. As erosion of the rejuvenated Appalachia continued, the Catskill delta complex prograded westward, filling the basin. Progradation continued through the Late Devonian, moving the coarser sediments increasingly westward, and leaving a broad alluvial plain to the east (Sevon, 1985). When erosion of Appalachia ceased in the latest Devonian, erosion of the alluvial plain, especially near the eastern mountains, provided a new sediment source in the west. From the end of the Devonian through to the Alleghanian orogeny in the Late Paleozoic, the sediment brought into the basin from the southeast probably resulted from stream cannibalization of the proximal portions of the alluvial plain (Inners, 1987). Sediments consisted of fine- to coarse-grained clastics composed mostly of quartz, rock fragments, and mica deposited in settings ranging from estuaries to the upper delta plain. Only a few relatively minor transgressions occurred during this time, bringing dark-colored muds or light-colored carbonates into the western portion of the basin.

Available paleomagnetic data indicate the Appalachian basin lay in the low latitudes of the southern hemisphere during the Devonian (Kent, 1985), as shown in Figure 3. Woodrow and others (1973; also Woodrow, 1985) determined that the configuration of Devonian land masses in relation to the earth's climate system probably resulted in a tropical-dry or savannah-like climate, hot and with seasonally restricted rainfall. The Late Devonian stratigraphic record, as much as 80 percent of the total thickness of Devonian sediments (Colton, 1970), might be the result of long-term cyclic storm patterns affecting deposition on Catskill coastal plains and continental shelves.

UPPER DEVONIAN SERIES

The Upper Devonian rocks in southwestern Pennsylvania were deposited as marine and nonmarine sediments of the Catskill deltaic system, a series of "multiple contiguous deltas operating in the same sedimentary basin at approximately the same time" (Sevon and Woodrow, 1981, p. 11). The Catskill deltaic system is the type example of a *tectonic delta complex*, a delta system dominated by orogenic sediments built by erosion of an active tectonic complex in an adjacent marine basin (Friedman and Johnson, 1966).

As the Catskill deltaic system prograded westward across the basin in the Late Devonian, the shape of the shoreline, controlled by rate of sediment supply, position of different sediment-input systems, tectonic perturbations, and oceanic processes, must have been very irregular (Willard, 1934; also, Figure 4). The gradual increase in distance from source area to shore during progradation was accompanied by a decrease in transport gradient, creating a decrease in grain size and a concomitant increase in depositional complexity across the basin. Sediments ranged from muds, sands, and gravels deposited in alluvial fans, braided rivers, and other typical continental environments, to clays and muds settling out of suspension onto the anoxic basin floor.

The Upper Devonian of western Pennsylvania consists of five broadly defined lithosomes ("megafacies") (Figure 5) that remain relatively lithologically consistent throughout the geologic and geographic section despite the differences in specific provenance, transport

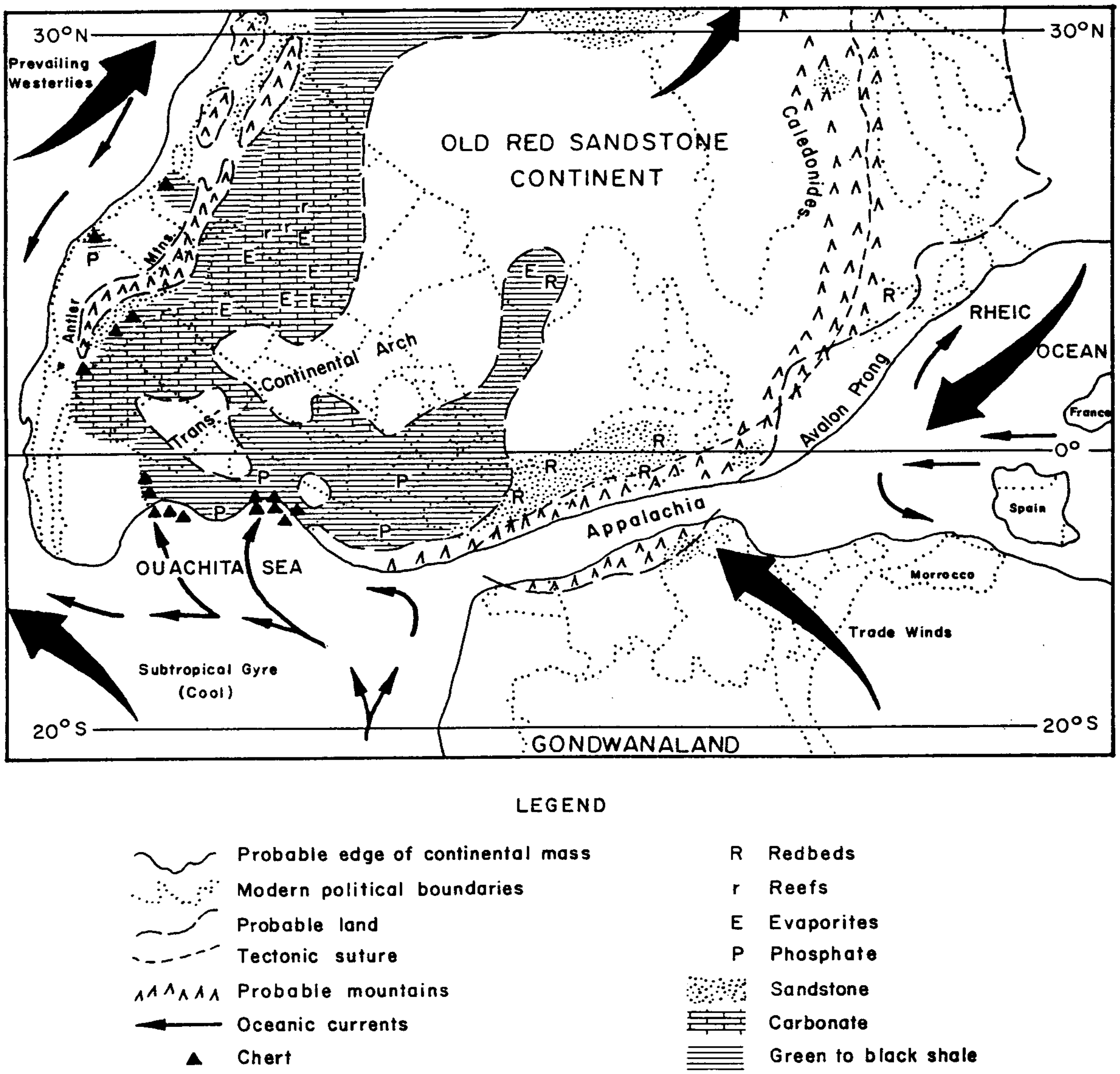


Figure 3. Paleogeography and generalized lithofacies map of North America during the Late Devonian when Pennsylvania and most of the Appalachian basin was in the southern hemisphere (from Sevon and Woodrow, 1981).

system, and depositional setting (Harper and Laughrey, 1987). These lithosomes include, from offshore to onshore (generally speaking, from west to east or from bottom to top): 1) dark-gray to black marine shales deposited under anoxic or dysoxic conditions on the sea floor; 2) slope-spread turbidite sequences; 3) shallow-water, open shelf, sandy siltstones and mudstones; 4) delta and delta-influenced marine conglomerates, sandstones, siltstones, and mudstones; and 5) fluvial-deltaic red and green claystones, mudstones, and sandstones typically called Catskill wherever they are encountered. At almost any given time interval in the Late Devonian of the central Appalachians these five lithosomes can be traced as lateral equivalents. Only lithosomes 4 and 5 are present in the Youghiogheny gorge at Victoria. Lithosome 4 includes the Venango and Bradford groups, and the Foreknobs Formation which is a facies equivalent to

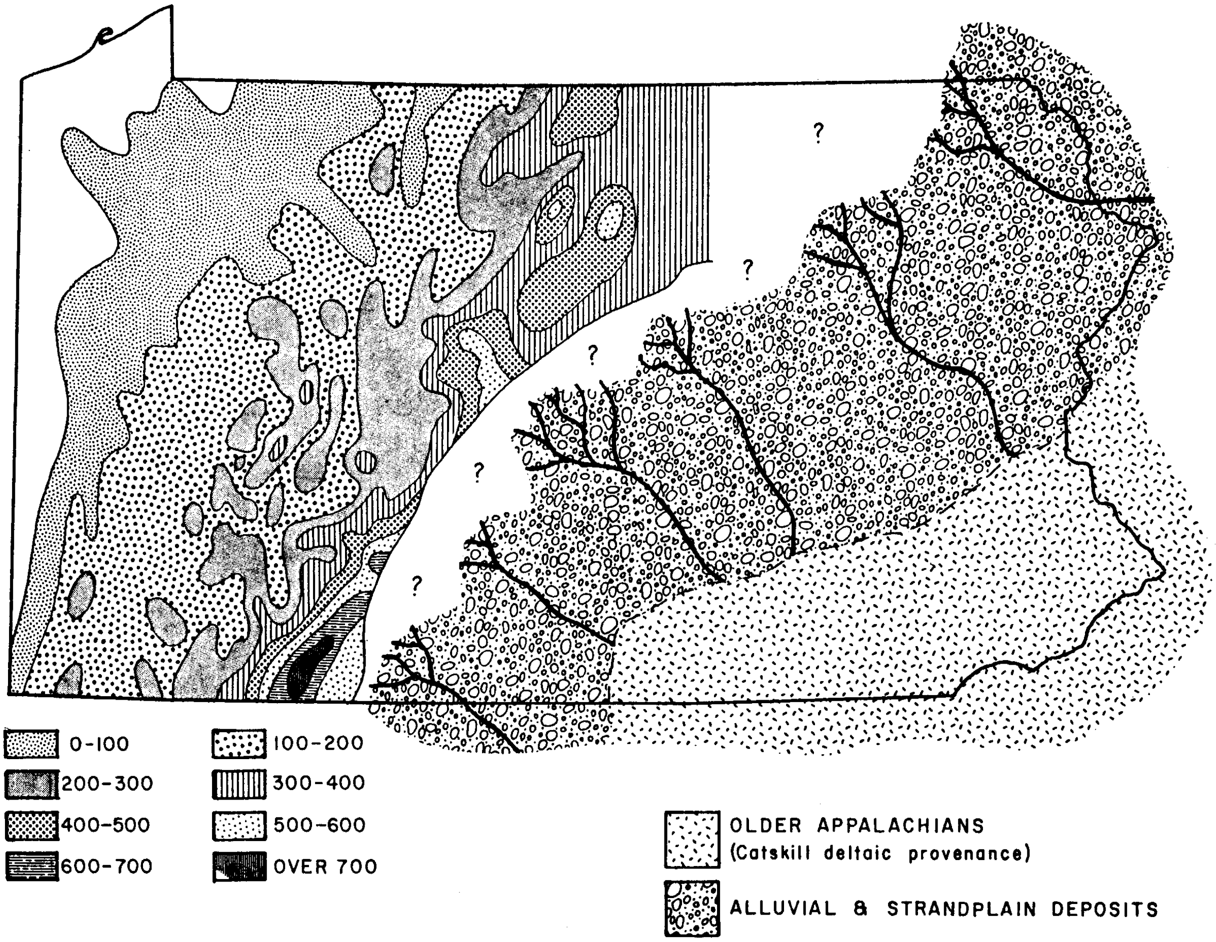


Figure 4. Thickness and distribution of Upper Devonian sandstones, based on gamma ray 50% "clean sand." And generalized depositional framework of the Catskill deltaic system in Pennsylvania (from Laughrey and Harper, 1986). Compare the sediment input subsystems (river and distributary systems), determined by distribution of subsurface rocks in western Pennsylvania sandstones, with those of Willard (1934) and Sevon and Woodrow (1981), which were based on outcrop studies in central and eastern Pennsylvania.

them. The Venango is the dominant oil and gas producing formation west of the Allegheny and Monongahela Rivers whereas the Bradford is dominant east of the rivers.

Stratigraphy

EXPLANATION OF NOMENCLATURE

Some of the Devonian and Mississippian nomenclature presently used in western Pennsylvania is based on the outmoded stratigraphic philosophy used in the late 1800s and early 1900s in which formations were based largely on biostratigraphic data, rather than strictly on lithostratigraphy (e.g., the "Chemung" Formation). Laird (1941 and 1942) created his own classification scheme based on that recommended by Ashley and others (1933). His hierarchy included system, series, stage, member, and bed or lentil. Laird substituted the term "member" for formation in this classification.

To make matters worse, many geologists, engineers, and drillers who have been active in

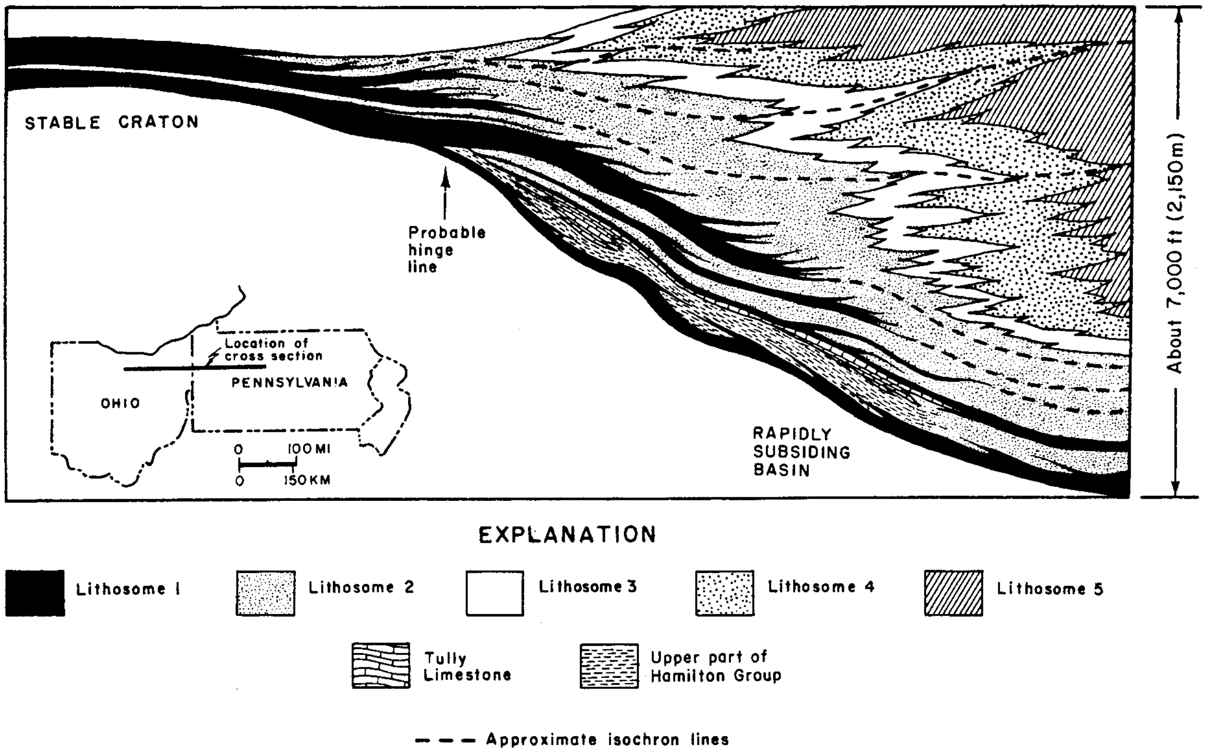


Figure 5. Schematic diagram of the Upper Devonian lithosomes across the Appalachian basin (from Harper, 1989a).

western Pennsylvania and adjacent states disregard the structured formality of stratigraphy in favor of a "whatever works" approach. Names such as Burgoon Sandstone, Pocono Formation, and Big Injun sand have been used interchangeably at professional meetings, and in published and unpublished reports. There exists a plethora of informal drillers' names that have been applied to subsurface formations in western Pennsylvania for more than 100 years (see, for example, Figure 6 which was a standard illustration in Pennsylvania Geological Survey oil and gas development reports for many years). Unfortunately, many of these names are carried beyond the areas in which they were first used, giving rise to numerous problems of regional correlation.

Early research into the Devonian section of the Appalachian basin quickly established a stratigraphic nomenclature that is still considered valid in some areas today (e.g. New York - see Rickard, 1975, pl. 3). Through the years, however, the nomenclature underwent considerable change depending on the seeming vagaries of acceptable stratigraphic philosophies or codes of stratigraphic nomenclature. Berg and Edmunds (1979) provide a good example of the changing concepts of stratigraphy and facies as related to the Mississippian-Devonian boundary in northern Pennsylvania and southern New York during the last 150 years. Examples of this sort can be found for the Upper Devonian throughout western Pennsylvania.

The unacceptability of much of the historical Upper Devonian stratigraphic nomenclature in the subsurface of Pennsylvania became especially apparent during recent studies of the regional Upper Devonian framework (Kelley and Wagner, 1970; Piotrowski and Harper, 1979). The authors of these studies preferred to use informal zonation for much of the Upper Devonian

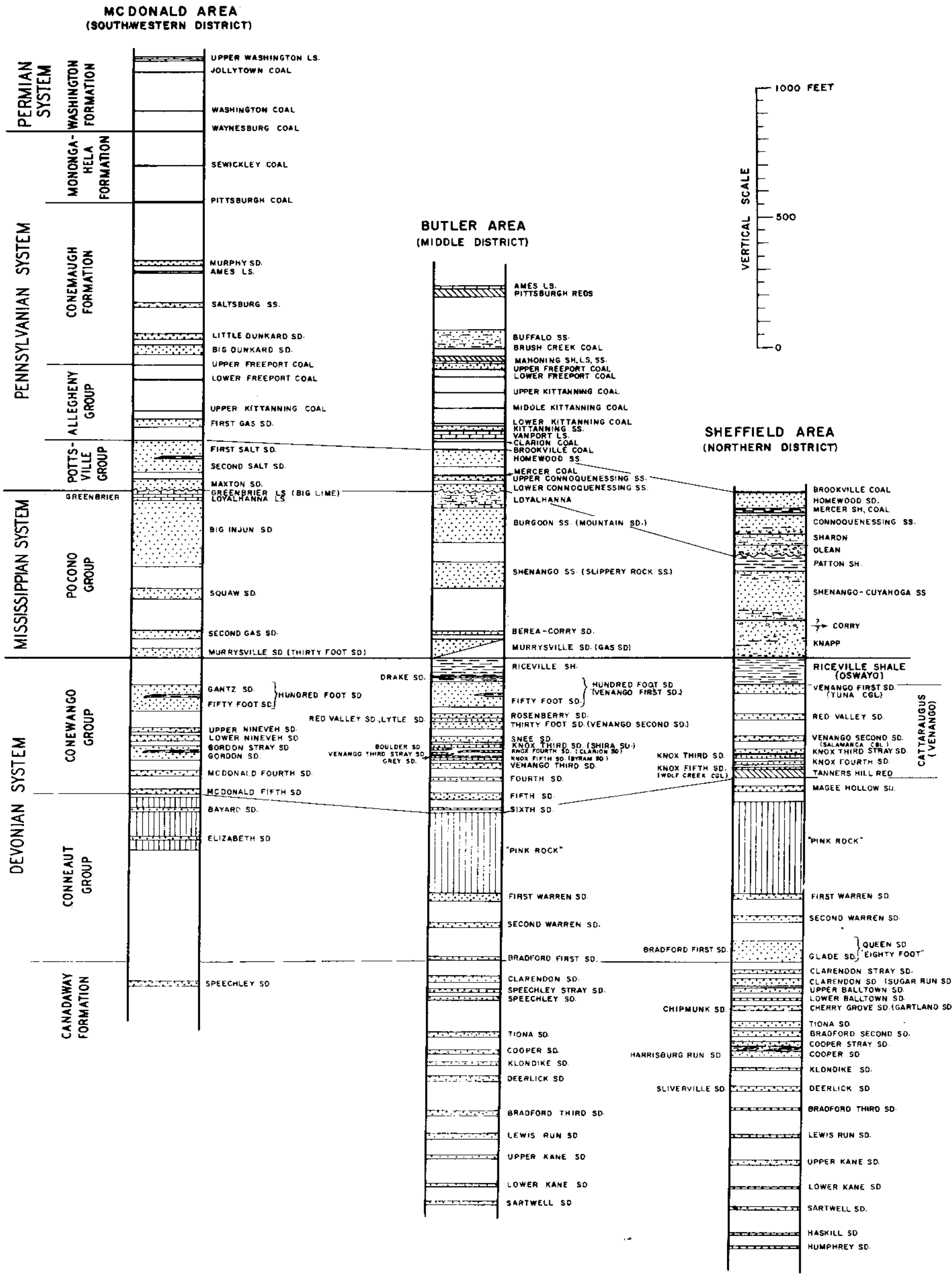


Figure 6. Columnar sections showing the stratigraphic positions of the oil and gas sands of western Pennsylvania (from Lytle and others, 1962).

section (Table 1), rather than become involved in the complexities of establishing an adequate formal nomenclature. However, during the course of studies of this regional framework, it became apparent that there was a natural division of Upper Devonian rocks in western Pennsylvania into at least three groupings of sandstone-dominant lithosomes interspersed with lithosomes dominated by shales and siltstones. Harper (1979) and Harper and Laughrey (1980) applied the names Venango, Bradford, and Elk groups, originated by Carll (1880, 1890) and Ashburner (1880), to the sandstone-dominant lithosomes that occur throughout the subsurface of western Pennsylvania. Over the years much has been discovered concerning the lithologic nature, geographic extent, and stratigraphic relationships of the rocks in these three groups. It is unfortunate, however, that much of this information has never been compiled into a comprehensive report detailing the Upper Devonian stratigraphy and petrology of western Pennsylvania. The need for such a report is apparent.

VENANGO GROUP

In the type area of Venango County, the Venango Formation is defined as all the strata between the top of the Woodcock Sandstone and the base of the Panama Conglomerate (Venango First and Third sands of drillers). Toward the south and east, the formation expands downward at the expense of the underlying Chadakoin Formation, acquiring sandstones with drillers' names such as Magee Hollow, Deemer, White Gravel and, in southwestern Pennsylvania, fourth, Fifth, Bayard, and Elizabeth sands (Table 1). The most general definition of the Venango Formation, therefore, is all the strata between the base of the Oswayo Formation (or Riceville Formation) and the top of the Chadakoin Formation (the "pink rock" of drillers).

The Venango interval in southwestern Pennsylvania comprises interbedded conglomerates, sandstones, siltstones, and shales in varying quantities. There is a noticeable lithologic change in the Venango across a zone about 5 to 10 miles wide that contains the paths of the Monongahela and Allegheny Rivers. Harper (1987) suggested that this zone, and the rivers, might be related to the basement extensional faulting of the Rome trough, a Late Precambrian through Early Ordovician failed rift that has influenced geologic processes in western Pennsylvania since it first formed. West of the Monongahela and Allegheny rivers the Venango consists of from 4 to 7 distinct sandstone subgroupings or zones generally correlatable over long distances. Minor variations within each zone account for many of the drillers' sand names employed over the years, including, from top to bottom, the Hundred-Foot, Nineveh, Gordon, Fourth, Fifth, Bayard, and Elizabeth (Figure 6 and Table 1). East of the Monongahela and Allegheny rivers the interval becomes increasingly shaly and red by increased development of the Catskill lithosome (Lithosome 5 in Figure 4). Here, the interval can be divided into three informal formations, or zones, best described as the Upper Sandy, Middle Shale, and Lower Sandy. Laird (1941, 1942) proposed the names Jumonville, Youghiogheny, and Maple Summit formations, respectively, for these divisions, but they were never formally designated and mapped. Because of these recognizable formation-rank zones, we prefer to think of the Venango as a group rather than a formation, especially east of the rivers.

The Upper Sandy zone comprises rocks equivalent to the Hundred-Foot and Nineveh sand zones west of the rivers, whereas the Lower Sandy zone contains the Fifth, Bayard, and Elizabeth intervals. The rocks we will be examining on this trip belong to the Lower Sandy zone or "Maple Summit formation" of Laird (1942). The predominantly shallow- or marginal-marine sandstones of the Gordon and Fourth intervals (and, sometimes, portions of the Nineveh and Fifth intervals) disappear eastward, replace primarily by marginal marine to nonmarine

Table 1. Correlation of lithostratigraphic nomenclature and commonly used drillers' sand names within the general area of the natural gas producing belt of Pennsylvania (modified from Harper and Laughrey, 1989).

SYSTEM	Piotrowski & Harper, 1979		Harper & Laughrey, 1987	Harper & Laughrey, 1989	Drillers' nomenclature in southwestern Pennsylvania
PENNSYLVANIAN (in part)			Pottsville	Pottsville	Salt
MISSISSIPPIAN	Pocono		Mauch Chunk Loyalhanna Burgoon Shenango Cuyahoga	Mauch Chunk Loyalhanna Burgoon Rockwell Riddlesburg	Maxton Big lime Big Injun Squaw, Papoose Weir, Bitter rock
			Berea Bedford Cussewago	Murrysville	Berea, Murrysville, Butler
DEVONIAN (in part)	Riceville		Oswayo	Oswayo	Gantz
	D	D3	Venango	Upper Sandy zone	Fifty-Foot, Hundred-Foot Thirty-Foot, Upper Nineveh Snee, Lower Nineveh
		D2		Middle Red Shale zone	Gordon Stray, Boulder, Gordon, Third, Fourth
		D1		Lower Sandy zone	Fifth, Fifth Stray Bayard, Bayard Stray Elizabeth, Sweet Richard
	C		Chadakoin	Chadakoin	Pink rock
	B	B4	Bradford	Bradford	First Warren Second Warren Third Warren
		B3			Speechley Stray Speechley
		B2			Tiona First Balltown Second Balltown Third Balltown
		B1			First Bradford Second Bradford Third Bradford Kane
	B0		Elk	Elk	Riley, Elk Benson Alexander
	A		Brallier Rhinestreet Sonyea Genesee	Brallier Harrell	Devonian shales

siltstones and shales of the Middle Shale zone. Only occasionally does a “clean” sandstone appear within this section.

EUSTATIC SEA LEVEL VARIATIONS

There has been considerable interest in the subject of cyclic sedimentation in the Paleozoic rocks of eastern North America for over two decades. Discussions of eustatic sea level changes, punctuated aggradational cycles (PACs), and hierarchical transgressive-regressive (T -R) units have often dominated professional meetings and publications, arousing comments from all sides as to the validity and applicability of the subjects. Some debate has centered around the causes of cyclic sedimentation with topics focusing on regional tectonics, global sea level changes, Milankovitch (astronomical) cycles, etc. Other discussion has dealt with whether cyclic sedimentation results from changes in sea level (allocyclicity) or from changes in coastal processes such as delta building ad degradation (autocyclicity).

Harper and Laughrey (1987) recognized at least five orders of transgression and regression (or progradation) during the Late Devonian. Besides the general first-order transgressive-regressive event of the Paleozoic and the overall progradation throughout the Late Devonian and Early Mississippian (second order), documented on a worldwide scale by Vail and others (1977), the Catskill deltaic system seems to have undergone several major (third order), and numerous relatively minor (fourth and fifth order), events in the Late Devonian. Dickey and others (1943) showed very clear evidence of the smaller-scale, fifth-order events in the Venango Formation oil-producing sandstones of Venango County. They documented transgressive-regressive cycles of deposition from the Venango Third sand to the Venango First sand (Figure 7). Although such “cycles” could also be caused by autocyclic events such as delta switching, the Venango sands, or the informal zones that include them, are geographically far-ranging, and are unlikely to be caused by simple depositional changes (Harper and Laughrey, 1987).

The sandstone lenses of the Venango Group apparently formed as repetitive series of fluvial-deltaic to open marine bars, dunes, channels, and beaches that shifted back and forth with successive rises in sea level, interspersed with increases of terrigenous influx from the east. In contrast to these small-scale event, the third-order cycles show up (in Figure 2) as the major sandstone groupings (Venango, Bradford, Elk). These are large-scale wedges of coarser clastics and intercalated marine shale formations.

Slow, steady, westward progradation of the Catskill deltaic system through the Late Devonian, punctuated at irregular intervals by third-order pulses of regression and/or progradation, resulted in vertical and lateral facies changes of marine black shales (Lithosome 1 in Figure 4) at the bottom and west (Marcellus, Geneseo, Middlesex, Rhinestreet, and Huron) to coarser clastics at the top and in the east (Figure 2). Two periods of more rapid influx of terrigenous sediments in the lower Middle Chautauquan Series, punctuated by a medium-scale transgression, resulted in the overall large-scale event of the Bradford Group. There followed another marine transgression, somewhat larger than the previous one, that resulted in deposition of the Chadakoin formation. Either a major drop in sea level or a large-scale erosional event in the eastern mountains resulting from tectonic uplift caused a second rapid, massive influx of terrigenous sediment in the upper part of the Upper Devonian. Deposition of the Venango Group resulted from this event that represents the most westward extent of the Catskill coarser clastics in the Devonian. Toward the end of the Devonian another transgression occurred as the Oswayo Formation marine shales and thin siltstones and sandstones were deposited over the

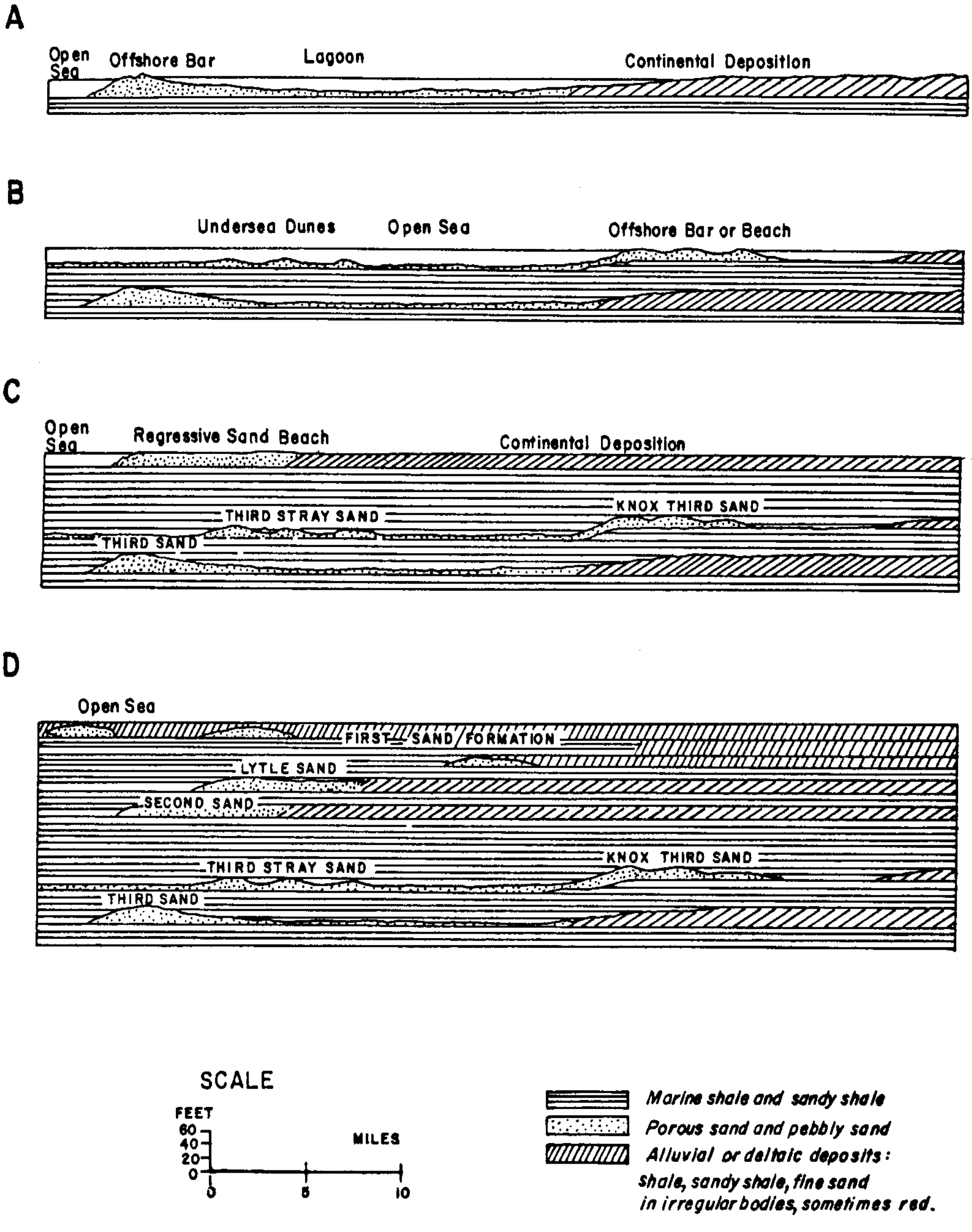


Figure 7. Probable origins of the Venango oil-producing sandstones of Venango County as beach and bar deposition during fifth-order eustatic sea level changes (modified from Dickey and others, 1943).

Venango Group. Boswell (1988) concluded that these Late Devonian transgressive-regressive cycles occurred as a result of both regional tectonic events (the Acadian orogeny) and eustatic sea-level variations. Tectonism dominated during the Senecan State whereas ecstasy dominated during the Chautauquan Stage.

PETROGRAPHY AND DEPOSITIONAL ENVIRONMENTS

Provenance

Detrital grains in the Venango Group sandstones can be divided into two principal groups on the basis of origin: 1) first cycle grains that were formed during the time and in the place of deposition; and 2) recycled grains that came from earlier sedimentary, metamorphic, and metavolcanic sources and were subjected to a substantially long period of physical and/or chemical weathering, as well as varying amounts of metamorphism.

The first group consists of grains formed in the marine or transitional marine environment (allochems and intraclasts) and detritus of plant origin. The source of the allochems, intraclasts, and plant debris was in the basin of deposition. All of these components are present in subordinate amounts in the Venango Group sandstones.

In the second group, detritus (quartz, sedimentary and metamorphic rock fragments, heavy minerals) formed by the weathering of sedimentary, metasedimentary, and some metavolcanic rocks. Grains of the second group constitute the principal framework of the Venango Group sandstone. Presumably, the detrital grains of the second group were formed as a result of the erosion of sedimentary, metasedimentary, and metavolcanic rocks exposed east and south of the depositional area. The transporting medium was water. Sevon (1979) and Sevon and Woodrow (1981) identified the position of 8 sediment-input system axes for the Pennsylvania portion of the Appalachian basin. According to their figures, the Fulton Lobe of Willard (1934) was the most important center of sediment input into the Upper Devonian depositional basin in southwestern Pennsylvania.

The source of the volcanic rock fragments is different from any of the other framework grains. A likely source is the northern terminus of the Blue Ridge to the southeast of the study area. Precambrian volcanic rocks of the Catoctin Formation include metarhyolites that contain phenocrysts of both feldspar and quartz (Fauth, 1968). These lithologies are strikingly similar to the volcanic rock fragments found in Venango Group sandstones. There are also metavolcanics in the Wissahickon Formation of the York area and to the south of York that might have contributed detritus to the sands.

Depositional Setting and History

Examination of the Devonian exposures in southwestern Pennsylvania helps in interpreting the depositional environments of the Venango Group in the subsurface to the west. This was accomplished by relating observed compositions, textures, sedimentary structures, and sandstone-body geometry to depositional processes. Distinct facies were described from outcrop data and statistical analyses were utilized to relate composition and texture to specific sandstone facies according to the methods of Davies and Ethridge (1975). We found that petrographic characteristics within distinct sandstone facies are environmentally segregated. *Thus, even small samples, such as those from well cuttings and sidewall cores, can be used to recognize genetically discrete sand bodies in the subsurface.*

Sandstone Facies

Venango Group sandstones can be divided into six sandstone facies that are characterized by unique combinations of mineralogy, textural character, sedimentary structures, fossils, and gross geometry.

Facies 1 - This sandstone facies comprises greenish-gray (5 GY 6/1) to yellowish-gray (5 Y 7/2), moderately well-sorted, fine-grained sublitharenites occurring in fining-upward sequences 10 to 15 ft (3-5 m) thick. Fining-upward sequences may occur singly or as multiply stacked sets. Trough and planar cross bed sets are the dominant sedimentary structures characterizing this sandstone type. The bases of the fining-upward sequences are typically marked by a scour surface that is overlain by a lag deposit of clay pebbles and plant debris. The lower 3 to 5 ft (0.9-1.5 m) of the sequence is planer bedded. Above this are well-developed trough cross beds 3 to 5 ft (0.9-1.5 m) thick. The trough sets are, in turn, overlain by planar-bedded sandstones that grade upward into ripple-bedded sandstones and mudstones. Paleocurrent indicators in this sandstone facies (cross beds, ripple marks, and current lineations) have a predominantly westerly to southwesterly distribution.

The average ratio of monocrystalline quartz to total quartz (monocrystalline quartz + polycrystalline quartz + chert) is 0.074 (C/Q ratio). This is the smallest value for the C/Q ratio calculated for the Venango Group sandstones, and it reflects the abundance of chert within the fine-grained sand-size fraction. Facies 1 sandstones contain more detrital feldspar than any of the other types and the ratio of plagioclase to total feldspar is relatively high (Table 2).

Facies 2 - Facies 2 sandstones are characterized by yellowish-gray (5 Y 7/2), very poorly to moderately sorted, medium- to coarse-grained, conglomeratic, feldspathic, and lithic graywackes. The rocks occur as matrix- to clast-supported, well-imbricated conglomerates interbedded with horizontally stratified conglomeratic sandstones and lenses of fine-grained sandstones. The sandstones have an average bed thickness of 2 to 3 ft (0.6-0.9 m). No consistent vertical sequence of grain size or internal structures is present. Facies 2 sandstones locally overlie and interfinger with Facies 1 sandstones. The contact with the underlying, rippled top of Facies 1 is typically conformable, although local scour surfaces were observed. Facies 2 sandstones are capped by a thing transition zone consisting of finely laminated to massive, very fine-grained sandstone and siltstone.

The average C/Q ratio of Facies 2 sandstones is 0.45 and the P/F ratio averages 0.94 (Table 2). The average amount of matrix in these sandstones is 20 percent, and the dominant matrix type (67 percent) is epimatrix, derived from the extensive sericitization of feldspar grains. About 1/3 of the matrix is pseudomatrix derived from the crushing of soft intraclasts and lithic grains.

In outcrop, Facies 2 sandstones occur as relatively small, lenticular bodies associated with Facies 1 sandstones. In the subsurface, the sandstones are readily identified by the imbrication of granules and pebbles, and the high amount of matrix, both characteristics of which are apparent in hand samples (cores and rock clean-out from the formation after shooting). Thin-section analysis of core and cutting samples of Facies 2 sandstone reveal the abundant matrix (with epimatrix dominant) and characteristic C/Q and P/F ratios.

Facies 3 - Facies 3 sandstones are light olive gray (5 Y 6/1) , moderately to moderately-well sorted, fine-grained quartz arenites and quartz wackes. Matrix averages 14.3 percent of the

Table 2. Composition and texture of Venango Group deltaic sandstone in southwestern Pennsylvania*.

Facies	Interpreted Depositional Environments	Quartz	C/Q	Feldspar	P/F	Rock Fragments	Mica	Matrix	Other	Mean Grain Size of Quartz (in phi)	Standard Deviation of Quartz Grain Size
6	Shelf	88.5	0.652	2.5	0.66	0	Tr	0	Tr	0.059	1.16
5	Foreshore	94.25	0.935	2.15	0.64	0.6	Tr	0	3	1.7	0.0489
4	Bar crest	82	0.393	5	0.8	2	2	9	Tr	1.72	0.68
3	Backshore	80.2	0.452	2.2	1	1.1	2.2	14.3	Tr	2.2	0.54
2	Fluvial: Conglomeratic bedload channel fill	66	0.45	4	0.94	5	4.5	20	0.5	1.82	0.851
1	Fluvial: Sandy bedload channel fill	77.8	0.074	6.02	0.837	8.76	1.05	3.41	2.96	2.6	0.67

**Data derived from petrographic analyses of 42 thin sections from 6 interpreted depositional environments within the Venango Group deltaic sequence. Compositional values are expressed as percentages. Analyses by C. D. Laughrey, Pennsylvania Geological Survey and R. M. Harper (deceased).

bulk mineralogy. The sandstones coarsen-upward slightly. They display cross bedding and current ripples, and typically contain abundant clay pebbles and plant debris. The bases of sandstone beds appear relatively flat and conformable with underlying Facies 1, 2, or 4 lithologies. C/Q and P/F ratios are 0.45 and 1.0, respectively (Table 2), and are probably not as diagnostic of sandstone type as in other facies. Most of the matrix is pseudomatrix ands this factor, combined with mean quartz size (2.2 phi) and standard deviation (0.54) of quartz grain size, may be useful in correctly identifying this sandstone type. It most commonly occurs interbedded with Facies 4 lithologies. Facies 3 sandstone beds have a tabular to sheet geometry with an average thickness of 6 to 8 ft (1.8-2.4 m). On isopach maps they appear as isolated pods and sheets near the northwest terminations of interpreted channel trends.

Facies 4 - Facies 4 sandstones consist of thin beds of light brown (5 YR 4/4) to moderate yellowish-brown (10 YR 5/4), medium-grained, moderately-well sorted subarkose. They contain occasional quartz pebbles and granules, and contain locally high concentrations of mica. The sandstones exhibit horizontally burrowed bases, parallel laminations, wavy bedding, and symmetrical ripple marks. Bioturbation is common and a marine fauna is indicated by the presence of a few scattered bivalve fossil molds (mainly *Eoschizodus* and ?*Glossites*). Sandstone thickness varies from 2 to 3 in (5-7.6 cm) to about 1 ft (30.5 cm). The sandstones are interbedded with shale. Occasional isolated ripples of sandstones (lenticular bedding) are found within the shale. The entire section of sandstone and shale averages 15 ft (5 m) in thickness and displays a very uniform, lateral distribution. The Facies 4 lithology overlies Facies 1 and 2 and overlies or interfingers with Facies 3. This type of sandstone is common at the outcrop localities but has not been confidently identified in the subsurface.

Facies 5 - Facies 5 sandstones are characterized by moderate yellowish-brown (10 YR 5/4) to yellowish-gray (5 Y 7/2), well sorted, medium-grained quartz arenites. The sandstones frequently contain concentrated lenses of granule- and pebble-size quartz conglomerate. The sandstones are 10 to 20 ft (3-6 m) thick, and have flat bases and convex-upward tops. The sandstones abruptly overlie Facies 4 lithologies and are transitional upward with Facies 6 sandstones and associated shales. Facies 5 sandstones coarsen upwards. The dominant sedimentary structures are subhorizontal to horizontal parallel laminations; evenly laminated sandstone with low-angle discordances also occur. Associated with these structures are symmetrical wave ripples and strongly undulatory current ripples. The sandstones contain small amounts of plant debris and a few scattered fossil bivalve molds. The upper surface of the sandstone has occasional horizontal trace fossils.

Facies 5 sandstones have an average C/Q ratio of 0.035, the highest of any of the Venango Group sandstones, and an average P/F ratio of 0.64,which is one of the lowest of all the sandstones (Table 2). This ratio reflects the presence of a larger amount of more stable potassium feldspars in Facies 5 sandstones than in the other types discussed thus far. Facies 5 sandstones also have the smallest amount of lithic grains and the largest concentration of heavy minerals of the various Venango Group sandstone types.

Facies 6 - Facies 6 sandstones consist of light-brown (5 Y 6/4), yellowish-gray (5 Y 7/2), and very light-gray (N 8), moderately to moderately well sorted, medium- to very coarse-grained sublitharenites. Distinct coarsening-upward and graded fining-upward sequences occur. Coarsening-upward sequences consist of medium-grained sandstones that occur as 2 to 4 ft (0.6 -1.2 m) thick, tabular to lenticular sandstone bodies encased in medium-gray shales and siltstones. The units have flat bases that are occasionally interrupted by large to small gutters. The upper surfaces are undulatory and the whole sandstone body appears to swell and pinch.

Symmetrical ripples are sometimes superimposed on otherwise smooth upper surfaces. Internal bedding is dominated by subhorizontal laminations that appear convex upward. Large vertical burrows are common at the tops of the sandstones.

The graded fining-upward sequences occur within multiply stacked, 6 to 18 in (15-46 cm) thick, tabular beds that display a basal scour surface and an upper surface having strongly undulatory ripple marks. The scour surface is overlain by a massive, quartz-granule and quartz-pebble conglomeratic lag containing quartz granules. Current ripples overlie the parallel laminae. Both the ripples and the subjacent parallel laminae are truncated by localized scour surfaces that obviously formed during rapid excavation of the current-ripple troughs. Other features of the beds include: 1) oriented tool marks on the bases of the beds; 2) broken, clay-filled fossil mollusk fragments in the conglomeratic lag; and 3) vertically burrowed upper surfaces. There is no imbrication within the basal conglomeratic sandstone. The total thickness of the multiply stacked, graded beds ranges in thickness from 2 to 10 ft (0.6-3 m).

The average C/Q ratio of Facies 6 sandstones is 0.652 and the average P/F ratio is 0.666 (Table 2). The average quantity of lithic grains is 9 percent and chert is the dominant rock fragment. Facies 6 sandstones overlie and interfinger with Facies 5 sandstones.

Depositional Environments

From the preceding data, we interpret the Venango Group sandstones as an overall progradational sequence deposited in a variety of paralic and foreshore-shoreface environments along the margin of a Late Devonian epeiric sea. The vertical sequence of Venango sandstone facies resembles the generalized sediment column for the shallow subsurface of the Maryland inner continental shelf (Field, 1980). This comparison, if valid, is important because it suggest that transgressive models of Upper Devonian deposition are potentially as useful as the more commonly cited regressive models. The Venango Group sequences might have originated, in part, as seaward-accreting, transgressive coastal sequences. Specific environments and their associated lithologies are discussed below.

Fluvial-Deltaic - Fluvial-deltaic environments and their representative sandstone types are represented by: 1) sandy bedload, channel-fill deposits (Facies 1); 2) conglomeratic bedload, channel-fill deposits (Facies 2); and 3) distributary mouth-bar deposits (Facies 3).

We interpret the cross bedded, fining-upward sandstones of Facies 1 as distributary-channel deposits. Allen (1965) and Collision (1978) described similar sequences having scoured bases, basal lags of intraclasts and plant debris, and fining-upward sequences as classic features of channel deposits. Channel floor, point bar, and point bar-top deposits are well represented by the basal lag and lower planar beds, the trough cross beds, upper planar beds, and ripple-laminated beds, respectively. Migrating sandwaves and dunes produced the trough cross bedding during lower flow-regime conditions (Harms and others, 1982). Planar bedding developed under the upper flow-regime conditions of high current velocity or shallow depth (Harms and others, 1982). Ripple-laminated sandstone and mudstone represent waning current flow possibly related to abandonment of the channel by avulsion (Collision, 1978).

Imbricated conglomerates interbedded with horizontally stratified conglomeratic sandstones and lenses of fine-grained sandstone (Facies 2) were probably deposited during floods as various types of channel bars (longitudinal, transverse, and marginal) interspersed with small braid channel lenses and flood channels. The association of Facies 2 sandstones with the channel deposits of Facies 1 is analogous to the association of conglomeratic and sandy bedload channel fills described by Galloway (1981) in the Cenozoic Gulf Coast fluvial systems. We interpret the relatively thin Facies 3, pod- and sheet-shaped sandstones as destructional delta-mouth bars that formed as marine processes reworked the prograding deposits at the distributary-river mouths.

Tidal Flat - Tidal-flat environments are represented by Facies 4 sandstones and their associated lithologies. Diagnostic criteria include symmetrical ripples, wavy bedding, and bioturbation (Klein, 1977). The interpreted tidal-flat environment developed on the lower and marginal delta plain. The restricted fossil assemblage and locally abundant plant debris found in this lithology suggest restricted marine conditions and the sporadic input of terrestrial materials. The latter include local mica and pebble concentrations as well as plant material. These materials were likely introduced into the tidal flats when distributary channels flooded and overbank flow inundated the lower and marginal delta plain. Shales associated with the Facies 4 sandstones might have been deposited as adjacent interdistributary bay-fill muds.

Foreshore-Shoreface - the sandstones of Facies 5 and 6 are interpreted as foreshore and shoreface deposits that were part of a delta front sheet sandstone laterally adjacent to the distributary-channel complexes.

Subhorizontal to horizontal laminae and even laminations having low discordances are common in foreshore deposits (Reineck and Singh, 1980, p. 363-368). The nearly horizontal laminae are deposited during fair-weather conditions by wave swash and backswash, and generally slope gently in a seaward direction. The laminae with low-angle discordances develop on the landward side of asymmetrical longshore bars and dip in that direction. Intercalated layers and lenses of coarser sand and conglomerate are deposited under higher energy wave conditions and commonly occur as washover deposits (Orford and Carter, 1982). Wave and current ripples are commonly superimposed on the larger bar bedforms by oscillatory wave action and longshore current motion. All of these features characterize the Facies 5 sandstones.

The coarsening-upward tabular and lenticular Facies 6 sandstones are thought to have formed as sandy offshore bars on a largely muddy shoreface. The sandstones developed as very large, migrating sand waves that moved across the muddier offshore deposits in response to prevailing current regimes and periodic storms. In contrast, the graded, fining-upward Facies 6 sandstones display well-developed normally graded (Bouma) sequences (see Appendix). Division A is massive to graded and was deposited from suspension as grains rapidly settled in large amounts and expelled water upward, fluidizing the bed. Fluidization would have destroyed any sedimentary structures. Division B is parallel laminated and reflects traction in the upper flow regime. Division C is ripple laminated and represents traction in the lower flow regime. Divisions B and C are truncated in the ripple troughs, indicating further concentrated scour after deposition of the bed. These Facies 6 sandstones, as described, are turbidites (Bouma, 1978). Each bed, or graded sequence is the deposit of a turbidity current, which is defined as a gravity-induced, subaqueous flow of dense suspended sediment beneath a surrounding fluid that is relatively less dense (water). Turbidites are most commonly associated with sedimentation in deep ocean basins but can be found in many environments where density currents occur, including lakes and reservoirs, delta fronts, and continental shelves (Walker, 1984). The turbidites in the Venango Group are associated with delta front deposits and are interpreted as having originated as shallow-water, graded-sand layers that formed from turbidity currents induced by storm surges. Such turbidites have been described in modern environments off the Yukon Delta in Norton Sound, Alaska (Nelson, 1982) and off the Texas Gulf Coast (Hayes, 1967).

Summary

All of the sandstone types that occur in the Venango Group deltaic sequence may also be present within any one or more of the informal stratigraphic zones. Each zone represents a specific time and place of delta progradation and or destruction during transgression. Various genetic sandstone bodies were deposited and subsequently reworked and partially destroyed during eustatic sea level changes during Late Devonian time. As a result, the various lithologies encountered in drilling can vary rapidly over a few tens to hundreds of ft laterally. Reservoir intervals have variable thicknesses and variable lateral extents, and porous, productive zones are erratic in occurrence. Careful attention to composition, texture, and geometry can lead to the correct recognition of vertically arranged sandstone types, the probable interpretation of depositional type, and the optimum prediction of reservoir quality and extent.

STRUCTURE AND TECTONICS

General

Pennsylvania is situated in the approximate center of the Appalachian orogenic belt, exhibiting structural styles characteristic of most of the Appalachian structural regimes. Fayette County falls within the Allegheny Plateau regime, a broad area of nearly flat-lying surface rocks. Except for numerous small-scale folds and the overall regional dip, the surface rocks of southwestern Pennsylvania present little evidence of major orogenic influence other than joint patterns. At depth, however, the intensity of folding and faulting increases markedly.

The structural grain of southwestern Pennsylvania trends approximately N35°E. Surface folds are the most obvious features, but their low intensity has only a minor effect on the physical aspects of the terrain. Large scale surface faults are almost non-existent; Minor faults having less than 10 ft (3 m) of offset can be seen in some outcrops, especially in the more brittle sandstones and carbonates, but no major faults have been described from the area. Coal cleat, joints, and lineations apparent from mapping and remote sensing constitute other surface structural features that provide evidence of the structural history of southwestern Pennsylvania. Within the subsurface, folding and faulting seem to maintain approximately the same intensity as surface folds to a depth of about 6,600 ft (2,012 m) to the shale formations well above the Middle Devonian Tully Limestone. From the Tully to, at least, the Lower Devonian Helderberg Group, intense folding and faulting seem to be more the rule than the exception.

Tectonics And Sedimentation

Despite the amount of work done over the last 50 years suggesting a relationship between penecontemporaneous tectonic activity and sedimentation in the Appalachians, many people are convinced that the structural patterns seen in the Allegheny Plateau of Pennsylvania resulted solely from the tectonic stresses of the Alleghanian orogeny at the end of the Paleozoic. In reality, many of the anticlinal trends in the area, such as Laurel Hill, were already “growing” by the end of the Early Devonian and were well established by the time of the Acadian orogeny in the Middle and Late Devonian (Harper and Piotrowski, 1979; Harper, 1987 and 1989). Evidence for this contention exists in many forms, particularly through stratigraphic studies. For example, Figure 8 illustrates the net ft of shale in the Middle Devonian Marcellus

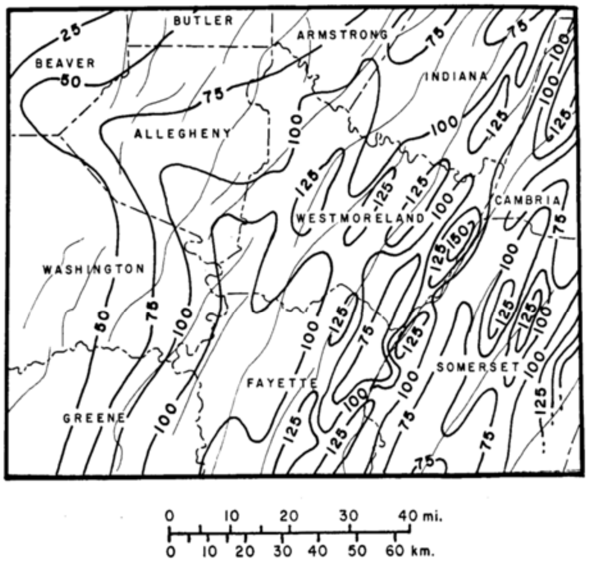


Figure 8. Lithofacies map of the Middle Devonian Marcellus "radioactive" shale, with overprint of present structural axes (modified from Piotrowski and Harper, 1979).

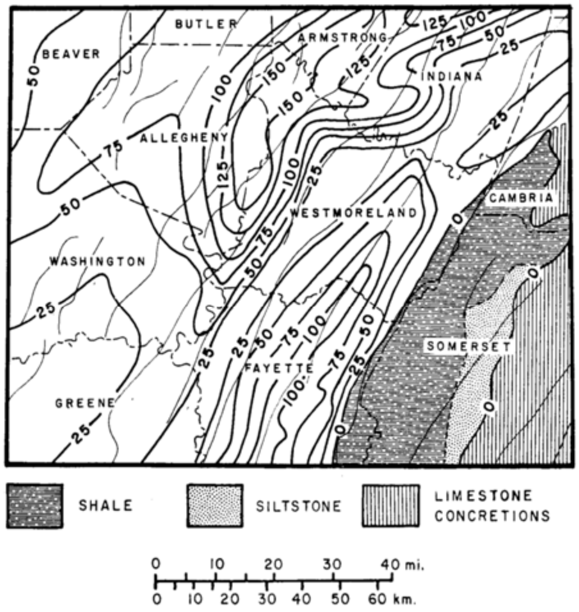


Figure 9. Isopach map of the Middle Devonian Tully Limestone, with overprint of present structural axes (fine lines). Contour interval = 25 feet (modified from Harper and Piotrowski, 1979).

Formation having a gamma ray signature greater than 200 API units on geophysical logs. This map of "radioactive" Marcellus shales shows a consistent pattern of thickening and thinning coincident with many of the present structural trends. These patterns are, however, independent of post-depositional faulting and tectonically-controlled shale flowage (as determined by log correlation). This suggests that the thicker accumulations of "radioactive" shale are at least partly depositional in origin, rather than completely structural. Because of the coincidence of structure and depositional pattern in this and other cases, it is probable that the two are related. Therefore, the structures must have existed at the time deposition took place.

Similar relationships like this have been cited for formations and facies deposited by the Catskill delta complex from Early Devonian through Late Pennsylvanian (see Harper, 1989). Examples can be found for the Lower Devonian Ridgeley Sandstone in New York (Bradley and Pepper, 1938), Middle Devonian Tully Limestone (Harper and Piotrowski, 1979) (Figure 9), Upper Devonian Bradford Group sandstones (Harper, in press), Early to Middle Pennsylvanian Pottsville and Allegheny Group rocks (Williams and Bragonier, 1974), and the Late Pennsylvanian Pittsburgh coal bed (McCulloch and others, 1975) just to name a few. These and other examples help establish the probability that pre-Alleghanian tectonics, although not so important as the Alleghanian orogeny itself in building the present Appalachian mountains, were important enough to have affected depositional processes in the Plateau.

CAUSES OF TECTONIC DISTURBANCES

The probable cause of pre-Alleghanian (and even pre-Acadian) tectonic movement appears to have been a combination of salt movement in the Upper Silurian Salina Group (Frey, 1973; Shumaker, 1974) and reactivated basement movement. In many cases the two were

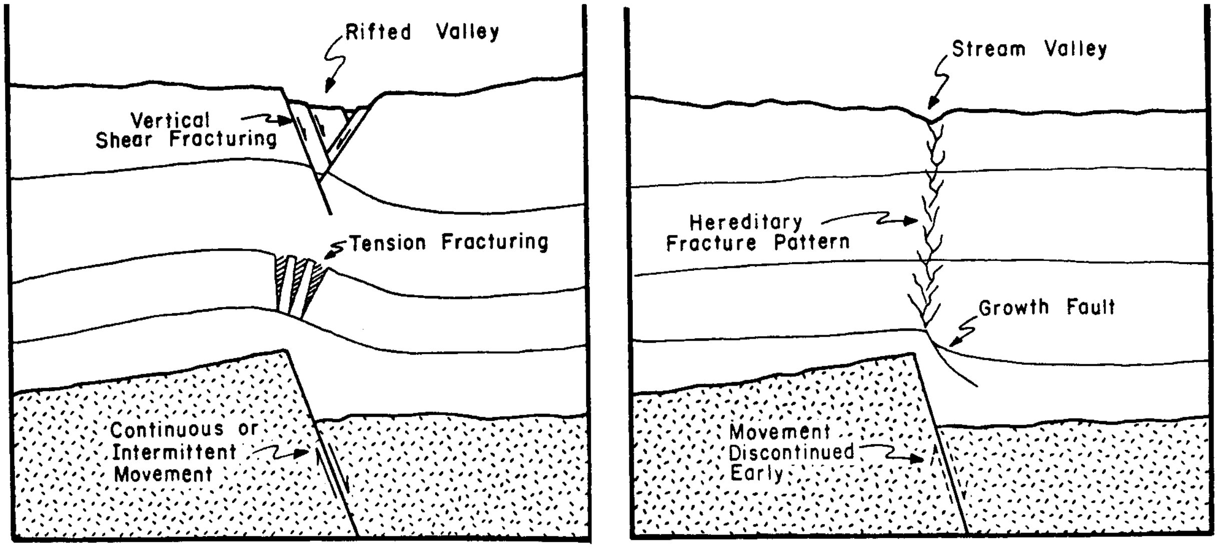


Figure 10. Schematic diagrams showing the effects of deep-seated tectonic activity on subsurface structure and stratigraphy, and on surface physiography. A. Continuous or intermittent basement movement, resulting in folded strata and fracturing of surface and subsurface rocks. B. Discontinuous basement movement, resulting in an inherited fracture patter up-section.

probably related (Shumaker, 1974; Root, 1978a and 1978b; Harper, 1987 and 1989). Seismic surveys and structural cross sections in southwestern Pennsylvania indicate complex faulting in the Lower and Middle Devonian Helderberg-through-Selinsgrove sequence overlying the Salina, but relatively little distortion below the Salina (Harper and Laughrey, 1987). Early movement (salt flowage) along planes of weakness parallel to the present regional strike may have created positive features of salt build-up in linear zones. The planes of weakness in the Salina may in turn have been related to deep-seated vertical or near-vertical faulting, or flexural movement. Basement faults or warps of the Rome trough were either reactivated at periodic intervals or, early on, created a pattern of fractures inherited by the overlying rocks (Figure 10). Some features that affected deposition might have been due to reactivated basement movement or hereditary fracture systems independent of salt effects. The resultant structures were probably of very low relief, but must have been coarse enough to have disturbed marine current systems and depositional patterns.

RESULTANT SEDIMENTATION PATTERNS

The Catskill Formation is found primarily east of the Laurel Hill anticline in southwestern Pennsylvania. West of the anticline, the Catskill red beds are, where they occur, simply members of other formations. (A few geologists from eastern Pennsylvania, where the Catskill occupies almost the entire Upper and Middle Devonian section, insist on giving the name “Catskill” priority over other formation names even where there are only a few ft of red beds submerged within hundreds of ft of other lithologies. This makes for extremely awkward stratigraphy, requiring perfectly good formation names to be abandoned and others to be further subdivided and renamed in order to wedge the Catskill into a section where it doesn’t really belong.) There are only a few pulses of Catskill lithosome found west of the eastern flank of the anticline (Figure 11), and only the final great Devonian progradation of the Venango Group carried the red beds beyond the crest of Laurel Hill. Other, earlier, evidence for structural

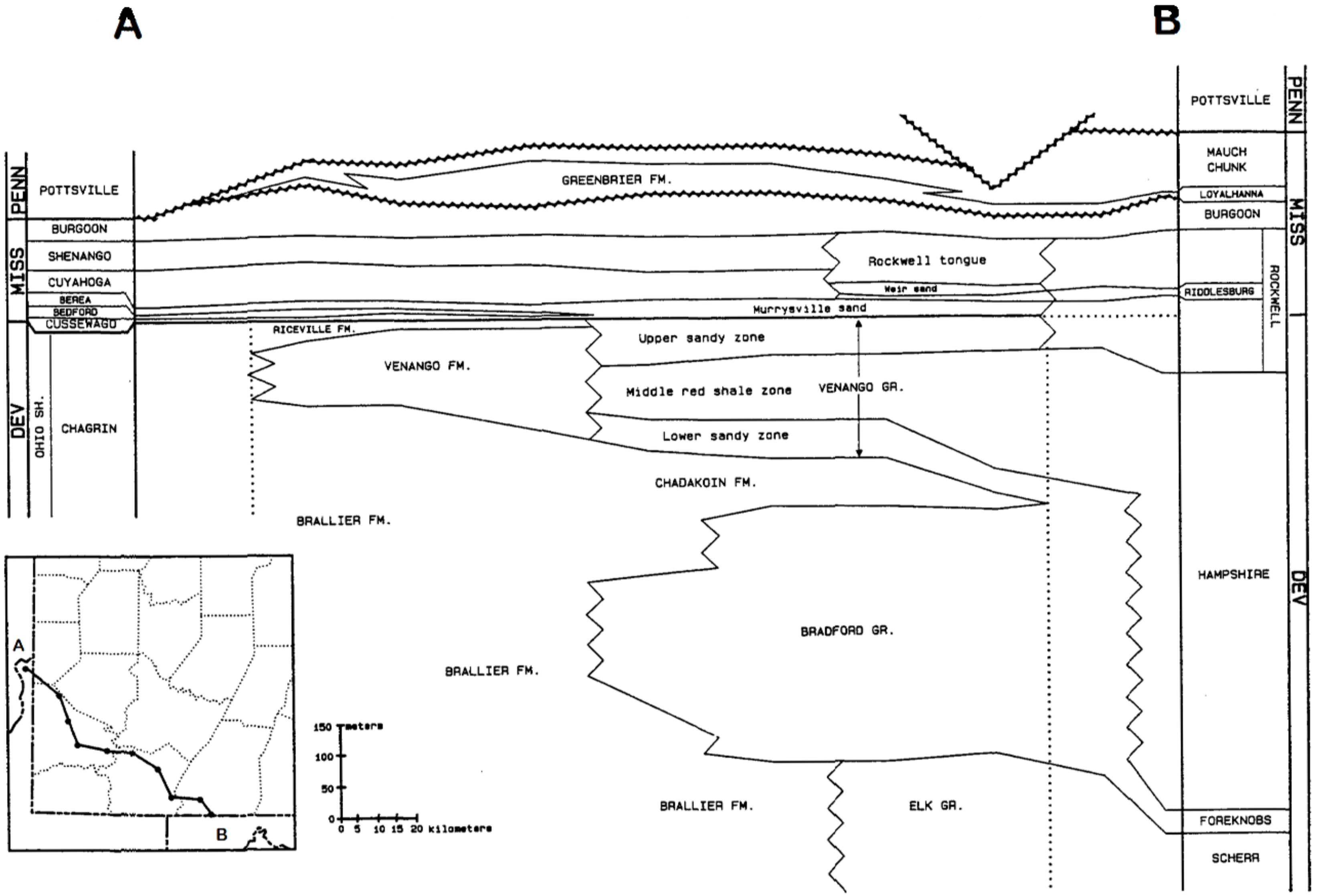


Figure 11. Correlation of Mississippian through Upper Devonian formations and groups in southwestern Pennsylvania, based on gamma ray logs and sample descriptions. Terminations of most facies –formations (Elk Group, Middle Shale zone of the Venango Group, Catskill Formation, etc.) are coincident with structural axes and/or zones of deep-seated fracturing (i.e. between wells #1 and #2). From Harper and Laughrey, 1989.

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control of deposition by the anticline also exists. For example, at the time of Tully Limestone deposition in the basin, Laurel Hill anticline must have acted as a sediment trap; there is little or no limestone to the east of the structures. The Tully is actually replaced by shale between Laurel Hill and Negro Mountain anticlines, and by shale and siltstone east of Negro Mountain and the Boswell dome (Figure 9). Harper and Piotrowski (1979) speculated that these structures created a sediment filter, trapping coarser clastics to the east and allowing for development of Tully carbonate deposition, undisturbed by clastic influx, to the west (but - see Dennison, 1982 for an alternative explanation of this sedimentological phenomenon).

The Elk Group, the oldest of the three Upper Devonian sandstone packages, is well developed in the eastern part of the Plateau, but phases out almost completely at the Chestnut Ridge anticline (Figure 11). West of this structure, the equivalent section contains mostly finer-grained turbidite sequences characteristic of the Brallier lithosome. However, in Indiana County Elk Group rocks commonly occur as far west as the Grapeville-Kinter Hill anticline. Deposition of the Tully Limestone also must have been influenced by the Chestnut Ridge "growing" anticline. The limestone is greater than 100 ft (30 m) thick along the structural crest, even accounting for thickening by faulting (Figure 9). The Chestnut Ridge might actually have served as a platform or carbonate bank adjacent to the (relatively) deeper, colder water trough of the adjacent Ligonier syncline.

The Bradford Group is most well developed in the central Plateau area where it represents the most prolific set of natural gas reservoirs in the state. In the northern counties (Warren, Forest, Elk, McKean, and Potter) it has the most productive crude oil reservoirs. The group is not quite so productive in Fayette County as it is farther north, but it is nonetheless a well developed lithologic unit. However, with the exception of a few "stringers" of sandstone that can be found intermixed with Brallier lithosome rocks as far west as Washington and Greene counties, the Bradford Group ends at the Monongahela River (Harper and Laughrey, 1987) (Figure 11). Although it is not, in and of itself, a pre- or post-Alleghanian structure, the Monongahela River (and the Allegheny River to the north) occupies a 5- to 10-mi (8-16 km) wide zone in which many stratigraphic and structural changes occur throughout the Phanerozoic. This suggests control of the zone by deep-seated structures such as basement faults, perhaps one or more of the Rome trough normal faults or small high-angle reverse faults within the trough complex. Other examples of stratigraphic changes across this "Monongahela River zone" include (Figure 11) a change from the sandstone-dominated Venango Formation on the west to shale-dominated Venango Group on the east, and changes in the rocks in the uppermost Devonian from a single, thick sandstone unit in the east (the Murrysville sandstone) to a bifurcated unit in the west (a lower Cussewago Sandstone, middle Bedford Shale, and upper Berea Sandstone). Some deep formations might show significant changes as well. For example, the Middle Devonian Huntersville Chert changes from a cherty limestone in the west to a calcareous siltstone east of the Monongahela River (Jones and Cate, 1957). Not all formations exhibit significant changes across this zone; there appears to be little stratigraphic change in the Lower Devonian Ridgeley Sandstone. There is, however, a difference in degree of deformation in the Ridgeley across the river that might be an effect of Salina salt deposition. This suggests that tectonic-control of the Monongahela River zone was intermittent, rather than continuous, during the Middle and Late Paleozoic.

That pre-Alleghanian tectonic movement affected sedimentation in the Late Devonian and Early Mississippian seems undeniable. The extent of this influence, both geographic and stratigraphic, is not yet certain. Geographically, for example, it appears that the structural/ stratigraphic regime south of the Conemaugh River (the boundary between Indiana and

Westmoreland counties) is significantly different from that north of the river (Harper, 1987). Inasmuch as the Conemaugh River flows along the trend of a distinct lineament, the Blairsville-Broadtop lineament of Parrish and Lavin (1982; also Lavin and others, 1982), it could very easily mark the boundary between separate crustal blocks or decollement zones, or it could be a tear-fault zone between adjacent areas of tectonic disturbance in the Salina salt. The effects of tectonic control on sedimentation is not evident throughout the stratigraphic section, nor even through the Late Devonian. More than likely, any tectonics influencing depositional patterns during this span of time did so intermittently.

FIELD GUIDE TO THE VICTORIA OUTCROP

In southeastern Fayette County the Youghiogheny River crosses Laurel Hill in a deep gorge. Rocks of late Devonian age crop out in the deepest part of the gorge between Victoria and Bidwell (Figure 1). The Lower Sandy zone of the Venango Group (Elizabeth and Bayard sands of drillers) crops out along the CSX railroad tracks on the west flank of the Laurel Hill anticline on the north side of the gorge. The outcrop is partially brush covered and greatly mantled with talus and slump, but many sedimentary, biogenic, and structural features are exposed and evident in the rocks despite the partial cover. Many of the sedimentary structures and trace fossil types you can see are illustrated in the Appendix. Geophysical logs from a gas well located about 5,000 ft (1,524 m) northeast of the outcrop (Figure 1) facilitate the determination of the gamma ray signature of the different sedimentary units exposed along the tracks (Figure 12).

This exposure demonstrates the relationship of typical Venango Group sedimentary facies to various processes that acted on the original sediments during a fifth-order regressive-transgressive cycle of Late Devonian sea level fluctuations (such as those shown by Dickey and others, 1943, and, later, by Kelley, 1967). A progradational-retrogradational sequence is represented here at Victoria within approximately 100 vertical ft (30 m) of sandstone and mudrock. The imprints of fluvial, paralic, and marine processes are evident in this mere bit of section! We feel that the facies sequence exposed at Victoria deigns even the most adroit of subsurface interpreters among us who depend on geophysical log data for mapping depositional trends. Let us know what you think after studying the outcrop and comparing it with the log of the adjacent subsurface section.

We have divided this Victoria section into three principal depositional units. These are: !) a progradational fluvial-deltaic unit; B) a retrogradational barrier-bar unit; and C) a transgressive basin-margin unit (Figure 12). The interpretation of these three units is based on the recognition of six sedimentary facies (also shown in Figure 12). Each of these units and their particular facies are described and discussed under the Petrography and Petrology section beginning on page 15.

Fluvial-Deltaic

FACIES 1

Lithology and Texture - Medium- to fine-grained, siliceous subarkose and sublitharenite. Fines upward into bedded siltstone and mudrock.

Sedimentary Structures - Planar beds, trough cross beds, climbing ripples.

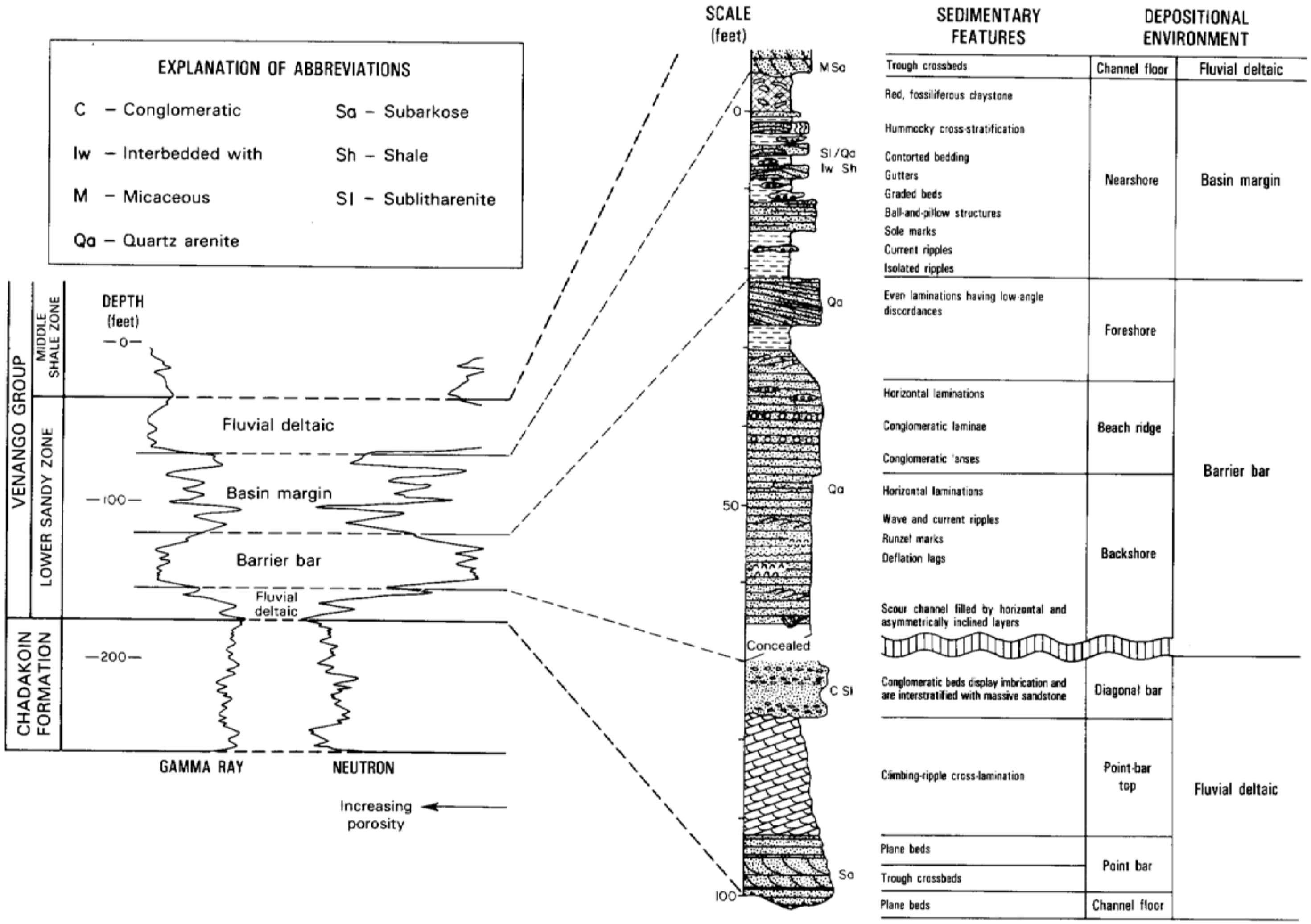

Figure 12. Correlation of the outcrop east of Victoria with the gamma ray-neutron signatures in a nearby well (well 051-20020 in Figure 1), and diagnosis of the sedimentary structures and depositional environments of the exposed rocks.

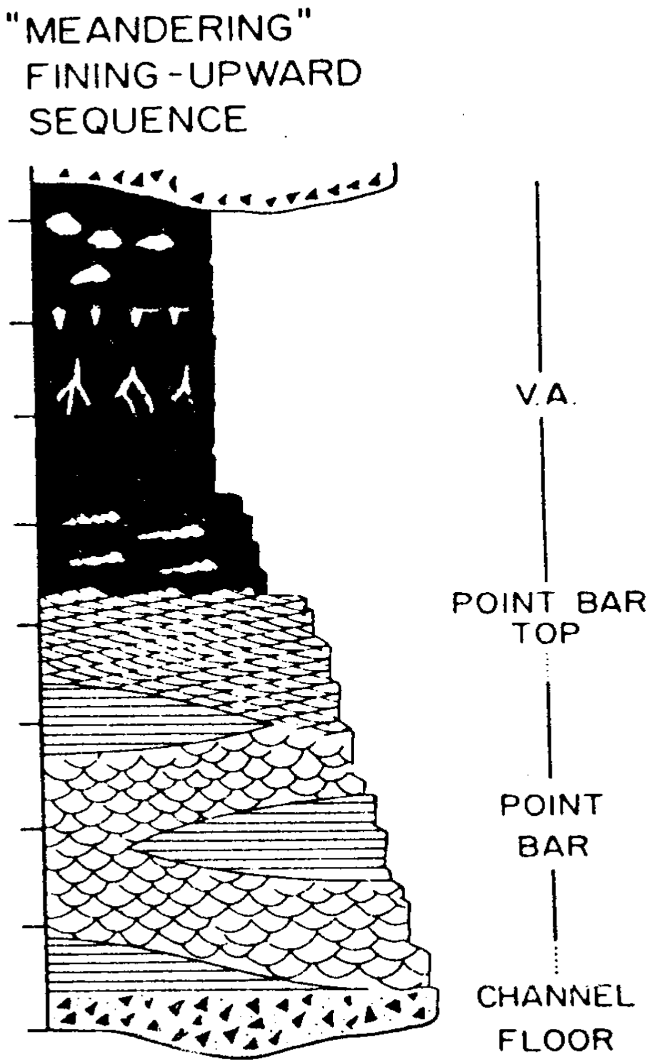

Figure 13. Model for lateral and vertical accretion deposits of meandering rivers (modified from Allen, 1970).

Fossils and Trace Fossils - None.

Depositional Environment - Fluvial distributary channel. This sequence matches the classic point bar model of Allen (1970) (Figure 13). Lowermost plane beds represent sandy bedload channel flow deposits. The trough cross beds and upper planar beds represent point bar deposits. The climbing ripples represent the point bar top.

Things To Look At: Planar beds, trough cross beds, climbing ripples.

Questions/Problems:

1. What flow regimes are represented by the different sedimentary structures?
2. Tidal inlet fills often exhibit the same sequences of sedimentary structures as do fluvial channel fills. As you soon will see, much of the associated sediments here are clearly paralic to marine. What criteria led us to assign this facies a fluvial origin? (Consider Facies 2 and the composition of this facies.)

FACIES 2

Lithology and Texture - Medium- to coarse-grained, conglomeratic, feldspathic sublitharenite.

Sedimentary Structures - Conglomeratic beds display imbrication and are interstratified with massive sandstones.

Fossils and Trace Fossils - None.

Depositional Environment - Fluvial distributary channel (probably longitudinal, transverse, or marginal channel bars interspersed with small braided channel lenses).

Things To Look At: Poor to fail pebble imbrication, size and angularity of the feldspar grains, position of the coarser fluvial sediments of Facies 2 with respect to Facies 1 fluvial sediments. Compare this sequence (Facies 1 and 2) with that of the George West fluvial axis of the Texas Cenozoic Gulf Coast fluvial system (Figure 14).

Questions/Problems:

Note the vertical lineations (foliations?) in the sandstone that is sandwiched between the

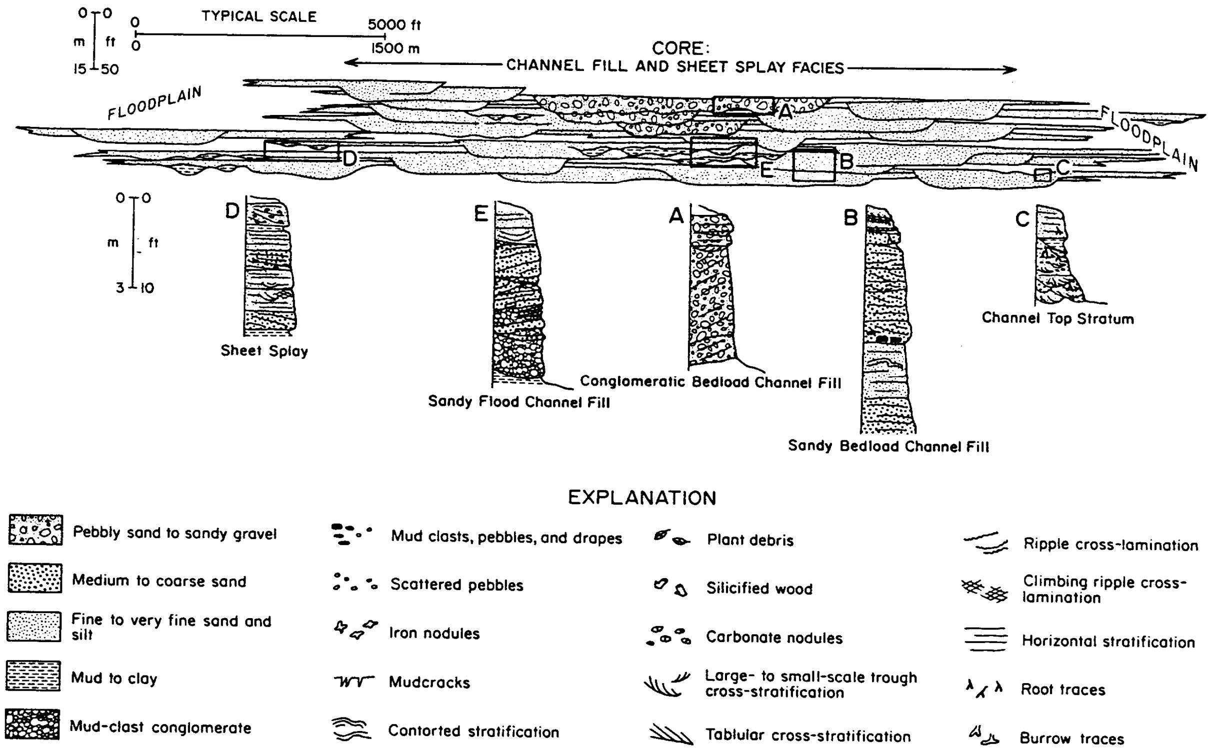

Figure 14. Schematic facies architecture of a composite sand belt typical of the George West fluvial axis. The sand body consists of amalgamated sandy and conglomeratic channel fill and sheet splay units interfingering laterally with floodplain deposits. Measured sections illustrate common internal features of component sand facies (from Galloway, 1981).

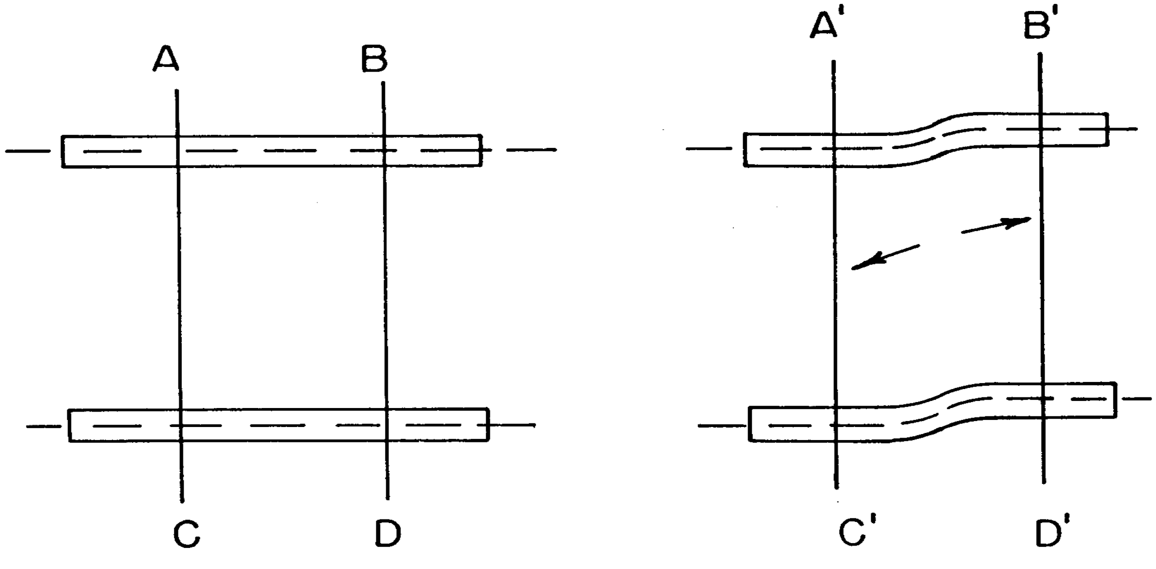

Figure 15. Graphic demonstration of the vertical lineations seen in Facies 2 (see text for explana-

conglomertic sandstones. In more weathered parts of the sand, these features appear step-like and resemble columnar jointing typical of basalts. In some places these joints become open fractures with curved surfaces. We suspect that these features are a kind of axial plane foliation, i.e. cleavage developed parallel to the axial plane of the anticline (fracture cleavage then would be the proper name for the closely-spaced open fractures). Such cleavage could be the result of shear; in this case, the cleavage is a shear surface parallel to a principal plane of the mean strain ellipsoid. This situation occurs when the bed surfaces, which were initially perpendicular to the cleavage, is also perpendicular after deformation (folding). Petrographic examination of the sandstone reveals that it is micaceous. The micas show deformation as sketched in Figure 15. The micas might have behaved as strong fibers. When lateral stress was applied, asymmetrical kinks or crenulations developed in the micas. The length of the micas, however, remained constant (AB = A’B’ and CD = C’D’) and continuity was preserved along the boundaries AD and BC. Therefore, the area of rectangle ABCD decreased with increasing strain (AB X CD > A’B’ X C’D’). Development of the folds established the pressure gradient shown by the arrows. Material in solution migrated away from the area ABCD resulting in the observed cleavage.

Barrier Bar

FACIES 3

Lithology and Texture - Fine-grained quartz arenite and sublitharenite. Micaceous.
Sedimentary Structures - Horizontal laminations, wave and current ripples, runzel marks, deflation lags, scour channels filled by horizontally layered and asymmetrically-inclined layers.

Fossils and Trace Fossils - Macerated and carbonized plant debris, burrows, brachiopods and bivalves, horizontal tracks and trails.

Depositional Environment - Barrier bar, backshore.

FACIES 4

Lithology and Texture - Fine- to medium-grained, occasionally pebbly quartz arenite, coarsening-upward sequences.

Sedimentary Structures - Horizontal laminations, conglomeratic laminae and lenses.

Fossils and Trace Fossils - Some scattered brachiopod fragments.

Depositional Environment - Barrier bar, beach ridge.

FACIES 5

Lithology and Texture - Fine- to medium-grained quartz arenites that coarsen upwards.

Sedimentary Structures - Even laminations with low-angle discordances.

Fossils and Trace Fossils - Broken shell fragments.

Depositional Environment - Barrier bar, foreshore.

Basin Margin (Transgressive Marine)

FACIES 6

Lithology and Texture - Fine-grained sublitharenites and quartz arenites interbedded with mudrock.

Sedimentary Structures - Hummocky cross stratification, contorted bedding, slump structures, ball-and-pillow structures, sole marks, graded beds, current ripples, isolated ripples.

Fossils and Trace Fossils - Brachiopods and bivalves, vertical burrows, horizontal track and trails.

Depositional Environment - Muddy nearshore with isolated lenticular sand bodies. Sands were introduced to the muddy lower shoreface by storm-generated turbidity currents (observe the Bouma sequences) that transported sands from the foreshore and upper shoreface. Sands were reworked by storm-related currents and waves (hummocky cross stratification) but were enclosed in mud during more normal, fair weather conditions.

Things To Look At: Hummocky cross stratification, Bouma sequences, fossils.
Questions/Problems:

We propose that all of the sand in this facies was introduced onto the muddy shelf by turbidity currents.

1. Why?
2. The turbidites and the hummocky sequences are well-preserved in the rock record. How did these physical structures escape extensive reworking by organisms?

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My new milkman is an unemployed geologist, so now I get my milk delivered in quartz!

Appendix 1

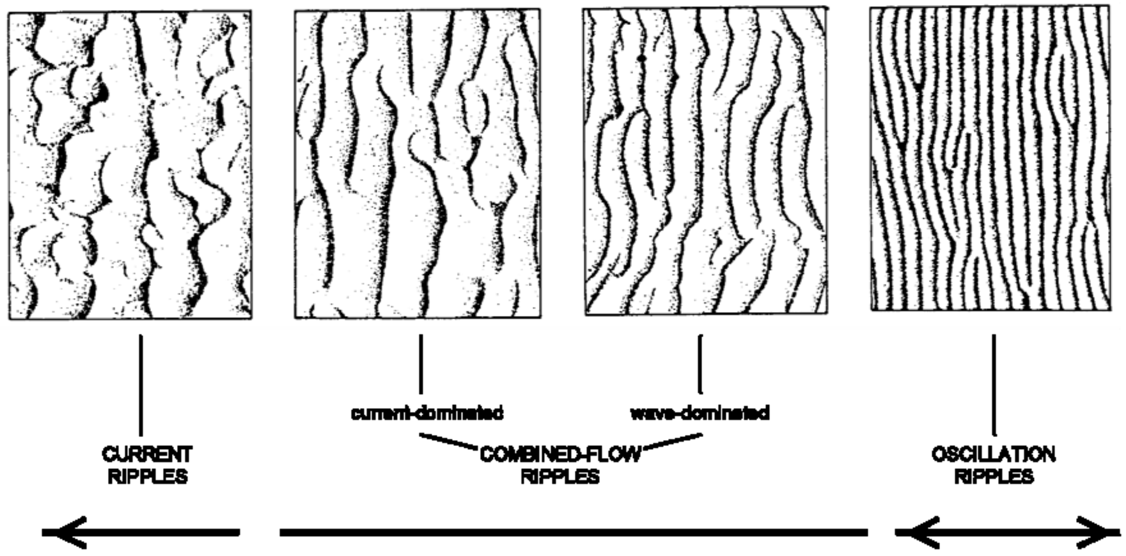
Stratigraphic Section Measured by Laird (1941)

Lower Venango Group Stratigraphic Section Exposed in the Youghiogheny Gorge Through Laurel Hill (modified slightly from Laird, 1941).

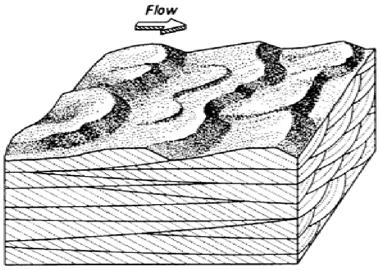
Unit Number	Lithologic Description	Feet
22	Thin-bedded green shale	11.0
21	Massive, green-gray, micaceous sandstone weathering to a rusty color. Contains layers of clay-gall conglomerate with some gray, sandy shale interbedded. Few fossils. Makes almost vertical cliff.	22.0
20	Mainly gray, thin-bedded shale with some few interbedded sandstone layers. Few round quartz pebbles present, and layers of limonitic concretions. Worm burrows and spheroidal weathering noticeable	41.0
19	Massive, green-gray, micaceous sandstone containing some clay galls	4.0
18	Gray-green, thin-bedded shale weathering rusty	6.0
17	Gray-green, micaceous sandstone tending to show cross bedding. Ironstone concretions. The fossils in this member are preserved as internal and external molds covered with dark limonitic stain. *Schizodus* very abundant	6.0
16	Green sandstone growing shaly and more thin-bedded toward the top	19.0
15	Gray-green, fairly coarse-grained, massive sandstone containing clay galls. Sandstone tends to fracture concoidally. Suggestions of vertical worm tubes. Weathers rusty brown	21.5
14	Concealed	4.0
13	Massive, gray, quartz-pebble conglomerate tending to be more thin-bedded toward the top. Quartz pebbles are about of pea size and tend to be oriented along the bedding planes	6.0
12	Massive, thin-bedded gray, sandy, micaceous shale. Makes a cliff. Tends to weather brown. The shale has a slightly laminated appearance with ripple cross-bedding indistinctly developed. Sandstone layer 2 feet thick near the base	15.0
11	Coarse, gray sandstone containing an occasional quartz pebble the size of a pea. Some clay galls also present. Cross-bedding and many disconformities present in the member. Sandstone tends to grade upward into the overlying shale	8.0
10	Concealed with shale and sandstone blocks	61.0
9	Gray-green to brown, micaceous sandstone weathering rusty	6.0
8	Concealed	27.0
7	Reddish-gray sandstone with layers of reddish shale. Weathers rusty on joint planes. Exposed	6.0
6	Concealed and green-brown shale	3.0
5	Reddish, rusty-colored shale with carbonaceous films on some weathered surfaces. Some red shale mud chips or clay galls present	2.0
4	Massive, mottled, gray sandstone; more massive toward the bottom, less so at the top. Contains macerated plant fragments	22.0
3	Concealed	85.0
2	Coarse, gray-white sandstone interbedded with quartz-pebble and clay-gall conglomerate. *Camarotoechia*, *Leptodesma*, and *Ptychopteria* (?) found	8.0
1	Gray, thin-bedded shale weathering rusty	4.0
	Total for "Sandstone A"	386.5

Appendix 2

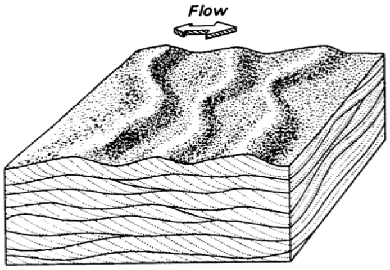
Illustrations of Common Sedimentary Structures, Trace Fossils, and Body Fossils



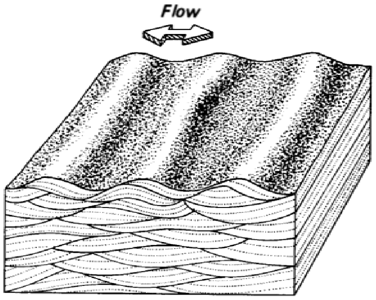
Relationship of ripple marks to current flow



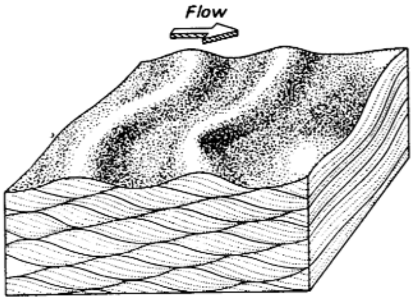
Current ripples



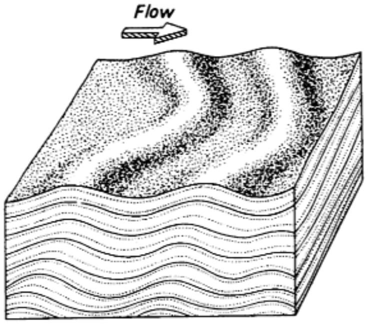
Combined flow ripples



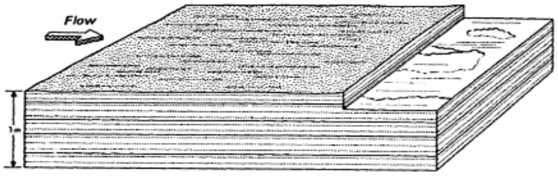
Asymmetrical wave ripples



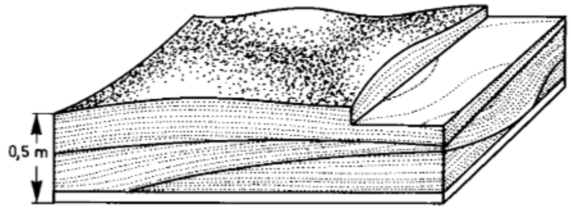
Climbing ripples



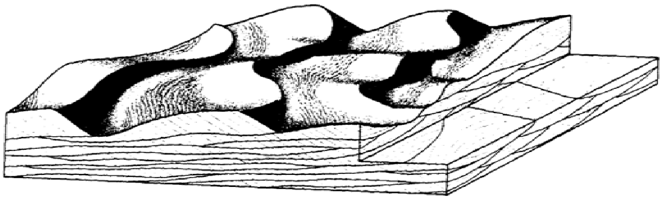
Symmetrical wave ripples

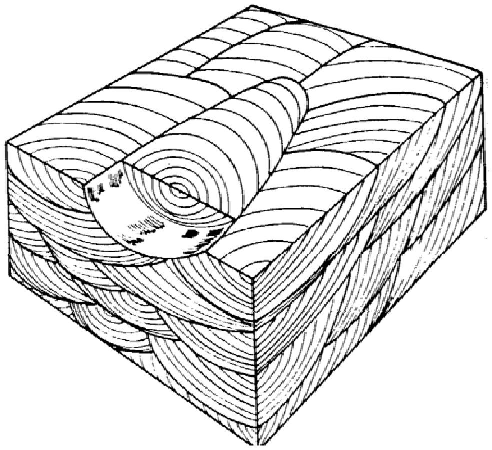


Planar bedding (laminations)

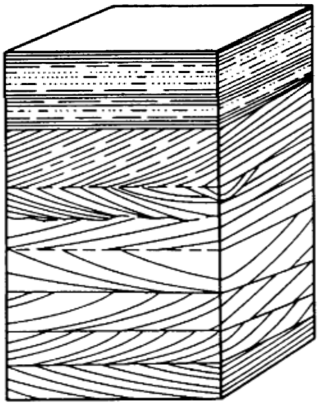


Hummocky cross stratification

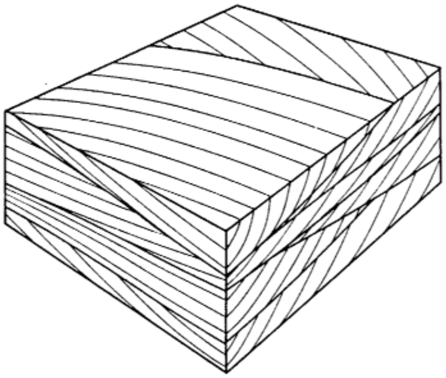




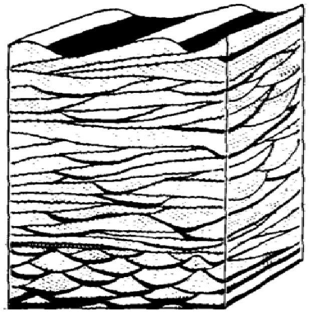
Large-scale trough cross stratification



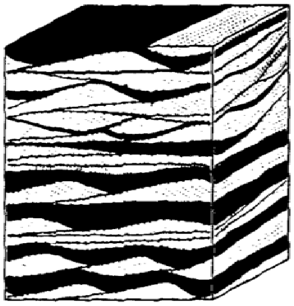
Herringbone cross bedding



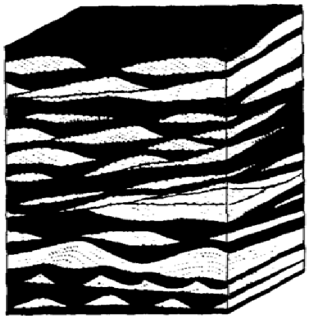
Planar cross bedding



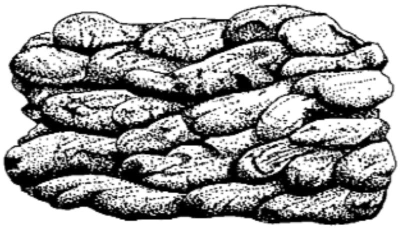
Flaser bedding



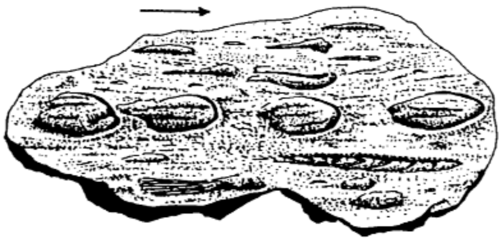
Wavy bedding



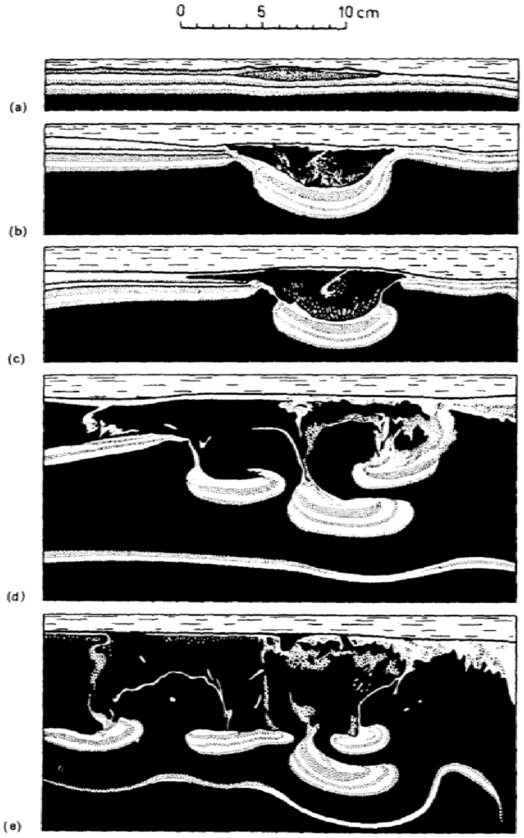
Lenticular bedding



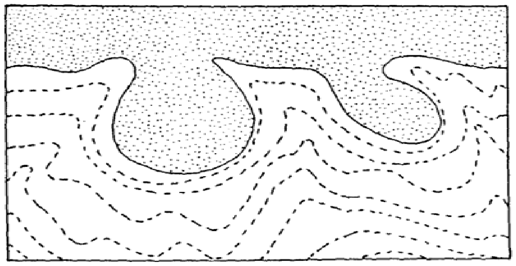
Sole marks



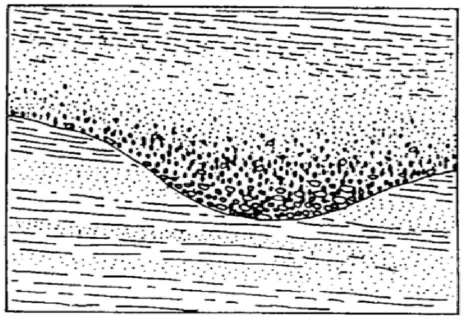
Tool marks



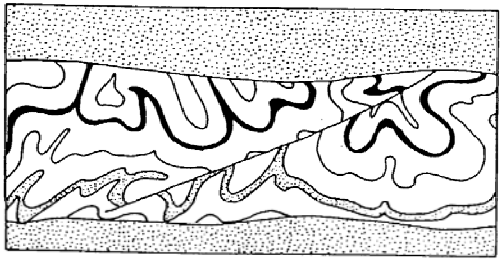
Formation of ball and pillow structures



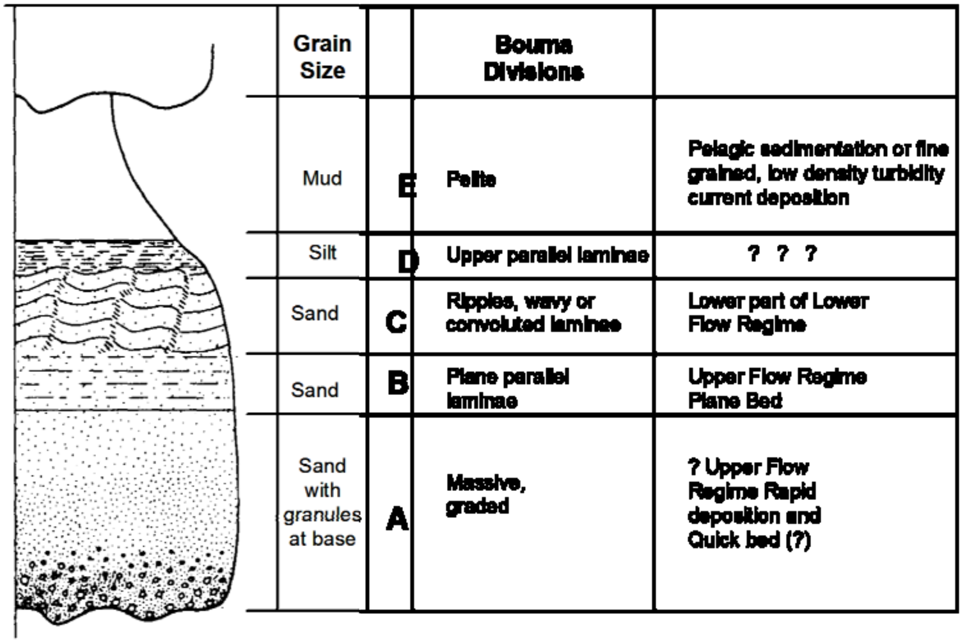
Load casts



Scour and fill

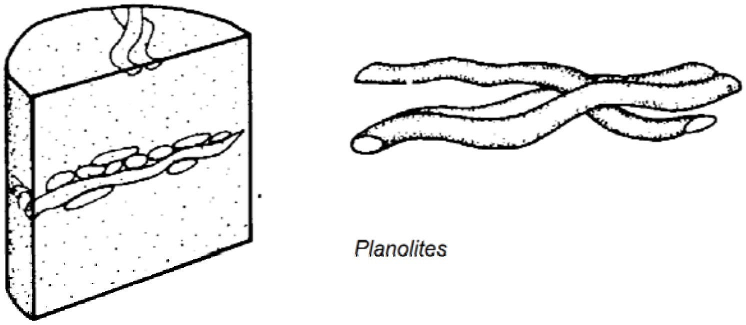


Slumps and disturbed bedding



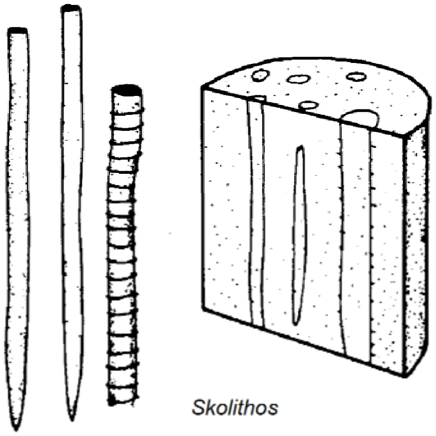
Grain Size		Bouma Divisions	
Mud	E	Pelite	Pelagic sedimentation or fine grained, low density turbidity current deposition
Silt	D	Upper parallel laminae	? ? ?
Sand	C	Ripples, wavy or convoluted laminae	Lower part of Lower Flow Regime
Sand	B	Plane parallel laminae	Upper Flow Regime Plane Bed
Sand with granules at base	A	Massive, graded	? Upper Flow Regime Rapid deposition and Quick bed (?)

Bouma sequence

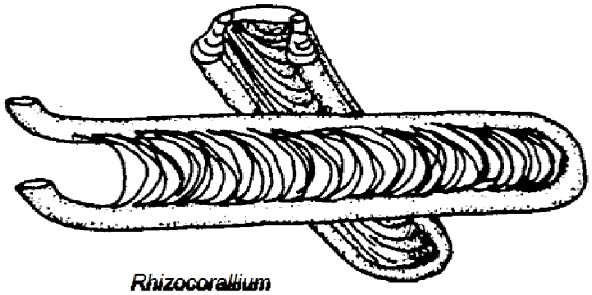


Planolites

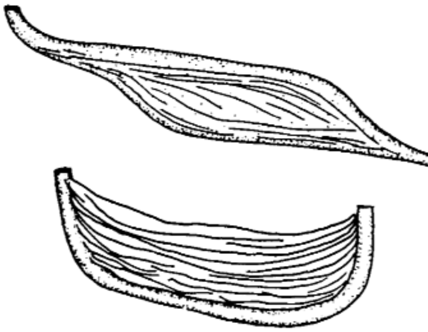
Zoophycos



Skolithos

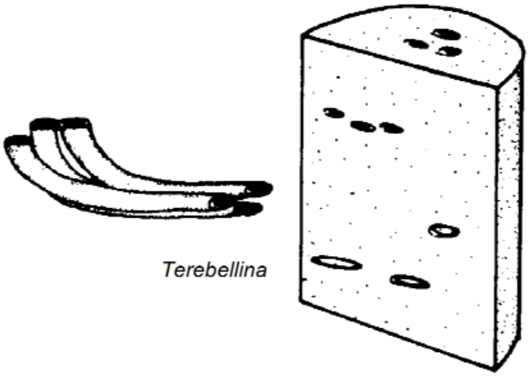


Rhizocorallium

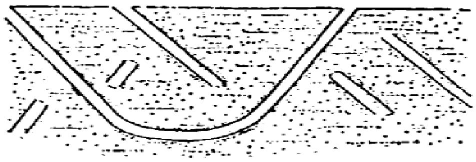


Teichichnus

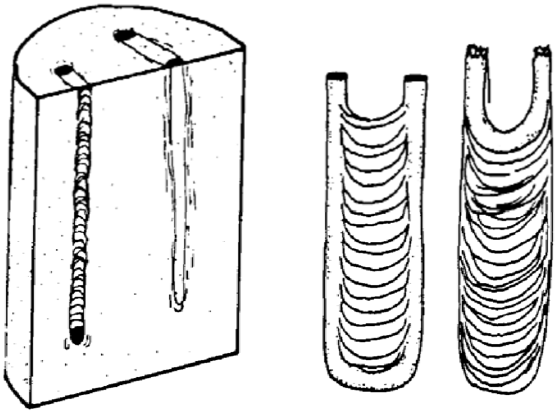
Conostichus



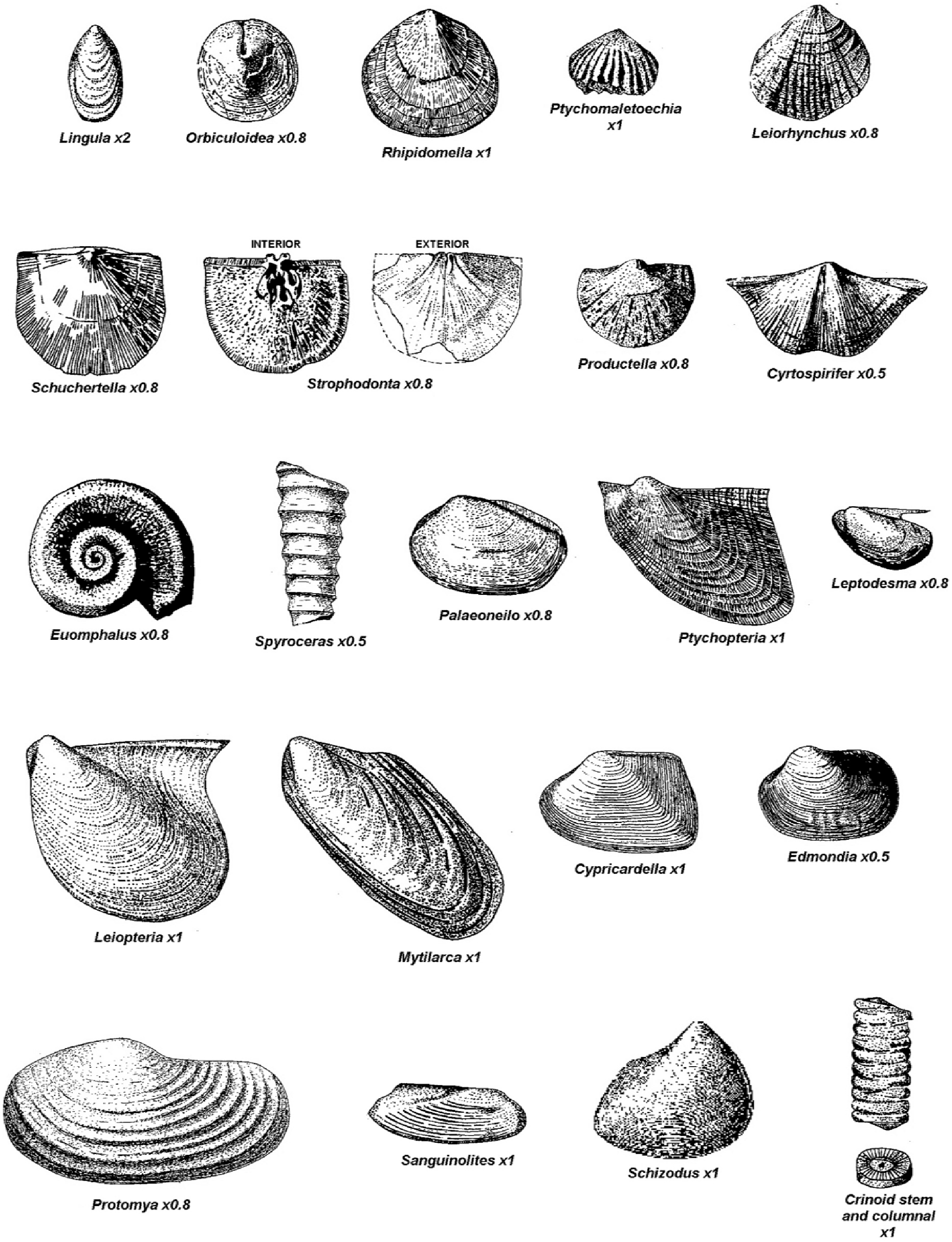
Terebellina



Arenicolites



Diplocraterion



Lingula x2

Orbiculoidea x0.8

Rhipidomella x1

Ptychomaletoechia x1

Leiorhynchus x0.8

Schuchertella x0.8

Strophodonta x0.8

Productella x0.8

Cyrtospirifer x0.5

Euomphalus x0.8

Spyroceras x0.5

Palaeoneilo x0.8

Ptychopteria x1

Leptodesma x0.8

Leiopteria x1

Mytilarca x1

Cypricardella x1

Edmondia x0.5

Protomya x0.8

Sanguinolites x1

Schizodus x1

Crinoid stem and columnal x1

Some Common Upper Devonian Fossils