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DEPARTMENT OF GEOLOGY
OLD TECH BUILDING

January 25, 1980

Mr. Arlen Hunt
Morgantown Energy Technical Center
Collins Ferry Road
P. O. Box 880
Morgantown, West Virginia 26505

Dear Mr. Hunt:

It is a pleasure to send you the final report of SPECIAL GEOLOGICAL, GEOCHEMICAL AND PETROLOGICAL STUDIES OF THE DEVONIAN SHALES IN THE APPALACHIAN BASIN by Professors J. Barry Maynard, Wayne A. Pryor and myself, Paul Edwin Potter, for contract DE-AC21-76-MO5201 (originally EY-76-C-05-5201).

To facilitate its use and evaluation, this report is organized according to the major responsibilities of our revised contract. We believe this report accurately reflects our accomplishments. The report also contains a discussion of some of the problems we encountered including some initial objectives which were not accomplished.

The contract was initially funded for three years, July 1, 1976, to October 30, 1979, for $465,533 and had a no-cost extension until December 31, 1979, to prepare the final report. Professor Potter was supported 15 percent of his time during the school year and Professors Maynard and Pryor 10 percent each. In the three summers of the contract the three of us worked full time for a total of 11 months. The contract also supported four full-time graduate students, four graduate students received summer support and field money, and we had two part-time secretaries and a full-time technician for one year.

On behalf of the Department of Geology and the University of Cincinnati all three of us from the H. N. Fisk Laboratory of Sedimentology thank you and the U. S. Department of Energy for the opportunity to participate in the Eastern Gas Shales Project. We also wish to thank you and your associates at Morgantown for your sustained administrative support.

Sincerely yours,

Paul Edwin Potter

Paul Edwin Potter
Principal Investigator

SPECIAL GEOLOGICAL, GEOCHEMICAL, AND PETROLOGICAL STUDIES

OF THE DEVONIAN SHALES IN THE APPALACHIAN BASIN

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PRINCIPAL RESULTS

Below are listed the principal results of our efforts including those of the eight students who were supported either totally or in part by the contract. To a lesser degree, the results also include contributions from our interaction with other contractors and from our fortunate association with Dr. Roy C. Kepferle of the U.S. Geological Survey, who has been housed in our department since the inception of the project.

The *Chagrin Shale* in parts of western Pennsylvania, Ohio and the *Brallier formation* in parts of West Virginia, Maryland, Pennsylvania and Tennessee are broadly correlative and both consist of a wedge of gray and greenish-gray shale, interbedded siltstones, and some sandstones and represent deposition on a submarine slope by distal turbidites derived from the east. Siltstone-sandstone bundles as well as siltstone beds and laminae within the shales of these two units have gas potential and, along Lake Erie at least, have more gas shows than the underlying black shales. These siltstones and sandstones were deposited on the distal parts of submarine fans, models of which are fairly well established and can be used as guides for improved exploration. The outer limits or toes of these fans may be the best areas for gas development, because it is here that siltstones and greenish-gray silty shales are interbedded with the black bituminous shales—the principal source rock of the gas in the Upper Devonian of the Appalachian Basin.

The *Upper Devonian of the Appalachian basin* has a very uniform paleocurrent system, one that indicates a source to the east. Studies of paleocurrent structures in oriented cores fully corroborate abundant outcrop data: wood fragments are exceptionally good indicators of paleocurrents in cores, are nearly always well oriented and easy to measure and sole marks on very thin siltstones (millimeters thick) are also commonly present and very well oriented. Such thin siltstone laminae were deposited as far distal turbidites and could be important for gas from the shale.

Lithologic continuity of black shales, with almost no exceptions, is greater north-south than east-west in the central and western part of the basin, a generalization that also probably applies to beds of a few meters or less in thickness.

Black shales in the basin have, almost without exception, sharp bases and grade both upward and eastward into gray and greenish-gray shales—<u>why</u> their basal contacts are sharp we do not as yet understand.

Most of the *marine shales* of the basin belong to two major types—gray and greenish-gray on the one hand, and bituminous black shale on the other; the former, however, can be divided into as many as five different petrographic subtypes.

Burrowed zones, even though they may be very thin (perhaps only a few centimeters) can be very widespread and probably are poor conduits of gas because they lack primary lamination. Burrowed beds developed in oxygenated water and hence, when regionally mapped and integrated with facies and thickness, may be valuable paleogeographic indicators.

The *Foerstia zone,* a zone defined by a fossil algae, appears to be a very useful basinwide time marker, one that is identifiable in both outcrops and cores, and possibly even cuttings; this zone extends from Lake Erie, Pennsylvania and New York on the north side of the basin into Tennessee; its greater thickness to the east reflects a higher rate of sedimentation, closer to the eastern shelf break of the basin.

Trace fossils indicate progressively deeper water in the western part of the basin and thus imply a classic shelf-to-basin transition as Upper Devonian time progressed. Trace fossils are absent in the black bituminous shales, because water was too anoxic for bottom dwellers.

Black shales in the Upper Devonian were deposited for the most part in water about 200 or more meters deep whereas the greenish-gray and gray shales were, as a rule, deposited in shallower water. Exceptions to this generalization occur where gray and black shales are closely interbedded; here the thinly interbedded gray shales may represent rapid, far distal deposition by turbidity currents that carried denser, oxygenated water into anoxic water (we fully recognize, of course, that the anoxic conditions required to produce black shales may develop in shallow as well as deep water in other basins).

Gas production in the Devonian shale chiefly depends on the amount of carbon and its maturity, abundance and thickness of siltstone laminae, amount of bioturbation (which destroys lamination), and micro- or macrofractures, all of which need to be considered for effective gas exploration and recovery. The right combinations of most of these factors are more likely to occur in thick rather than thin sections.

Pay zones within the shale sequence may be very thin and widespread or may have a more restricted distribution related to the distal parts of submarine fans. In the Pine Mountain Overthrust Block and perhaps elsewhere in the Appalachian thrust belt and/or foreland, the possibility of thin glide zones, zones that may have complex folding and shearing, should be considered and explored for gas—

because of their excellent potential fracture permeability. Such glide zones may be very much more widespread than is yet fully appreciated, because they may develop preferentially only in selected, thin stratigraphic horizons such as the Marcellus Shale.

The *source of the organic carbon* in the bituminous shales was twofold judging by its isotopic composition—a terrestrial source to the east and a pelagic source within the basin; as individual black shales are traced westward, the pelagic source becomes predominant. Because marine carbon is better as a source of oil than terrestrial carbon, highest values of oil recovery will occur in those shales with the most marine carbon along the western outcrop of the basin. Variation of carbon isotopes within the basin dovetails nicely with evidence from paleocurrent mapping and both indicate an eastern source.

Gas-bearing stratigraphic units within the basin, structural factors such as fracturing aside, should have an optimum zone for gas, a zone lying between paleo-temperatures too low in the west and too little carbon in the east.

Thermal maturity is about the same for every stratigraphic unit in a well, but increases regionally toward the southeast. Illite crystallinity appears to be every where about the same across the basin and we consider it to reflect a detrital provenance that was never exceeded by temperatures of later burial.

Sedimentation rate and oxygen content of bottom water seem to be important controls on the geochemistry of shales, probably because together they determine the amount of organic material. Sulfur isotopes are useful, at least on a relative scale, to estimate the sedimentation rate of ancient shales.

Thin-section petrology and X-ray radiography appear to be the best for the petrographic study of Devonian shales—and possibly even for shales in general. The abundance, thickness and cementation of siltstone laminae within a shale as well as its fine-scale interlamination with organic matter appear to be most significant, from a depositional viewpoint, for gas potential. Thin section study determines these variables very well, especially when supplemented by radiography, which can give a very good overview of a large specimen of shale. Radiography is also attractive because it is rapid. The recognition and possible later filling of microfractures developed within the shale and careful description of siltstone and other types of laminae deserve full attention in future petrographic studies.

Siltstone laminae within the Devonian shales—their thickness, abundance, and cementation—appear to be a major factor for gas production, in so far as original sedimentation controls it, and it is even possible that the abundance of later microfractures within the Devonian shale may be relatable to wuch laminae; that is, when fracture intensity was low, original lithology may have had a major control on its development.

The *Pine Mountain Overthrust Block* is divided into six structural segments, which together contain a total volume of about 254 cubic miles. The gas potential of these six structural segments varies considerably and depends chiefly on thickness of the shale, its deformation and to lesser degree on thermal maturity.

Isopach studies indicate little or no displacement of the overthrust block at its northeasternmost end along the Russell Fork Fault and only about nine miles along its southwesternmost end along the Jacksboro Fault. The Devonian shale sequence is a very good one to use to assess differential movement of the overthrust block, because its thickness increases thirtyfold from southwest to northeast.

Fault traces of both the Russell Fork Fault (two slightly curved segments) on the northeast and the Jacksboro Fault (one straightline segment) on the southwest are related to the differential movement of the overthrust block, whose immediate cause appears to be the depth of the fault plane—about minus 1500 feet on the southwest and about minus 5800 feet at the northeast end of the block.

Failure within the shale of the overthrust block appears to be localized along very thin zones, some of which contain isoclinal fold trains as well as bedding plane thrusts. Such zones may be the most favorable for gas production within the syncline and, in fact, the "blow out" zone in the eastern part of the overthrust block appears to be such a zone.

SELF-EVALUATION

We were most successful in using the standard methods of subsurface and field geology to determine the internal stratigraphy of the Devonian shales, their facies geometry and environments, and in mapping paleocurrents to determine the source of the Upper Devonian of the Appalachian Basin. The use of C^{13}/C^{12} isotopes also belongs with these accomplishments because, although it is not a standard sedimentological provenance technique, it yielded results that dovetailed nicely with paleocurrents independently determined and measured. Still another standard technique that we used to advantage was the thin section study of the Devonian Shale--although not until the very end of the project did we begin to perceive the essential variables, primarily thanks to the efforts of Mr. Broadhead, an M.S. student, who worked along Lake Erie. We also pioneered, east of the Mississippi River, the use of the gamma ray scan for both field and core descriptions of shales. Our determinations of CHN also served us well as a routine assessor of the source rock characteristics of the Ohio Shale along Lake Erie.

As a rule, we had less success with the study of shale fabric by X-ray or by the SEM, or the chemical studies of the phenolic aldehydes, or of BET sorptometry. The SEM and its elemental analyzer was, of all of these, the greatest disappointment and we doubt that more work with it will be rewarding as far as shale petrology is concerned. However, in defense of X-ray fabric studies, some more effort should be expended on it, because it appears to have some promise as an indicator of tectonic deformation and, in fact, we wonder if X-ray methods do not measure tectonic fabrics better than depositional fabrics? The study of phenolic aldehydes was not successful chiefly because there are too few in the Upper Devonian of the Appalachian Basin to effectively analyze. We did not pursue BET sorptometry because the Illinois Geological Survey did so well with it.

Because our initial contract expired before much of the other subsurface data needed for a basin analysis was gathered, we did not attempt one, although we have provided two regional cross sections and a series of perspective block diagrams as well as the regional paleocurrent map that can be used with profit by whoever does so. Nor did we attempt to integrate all the numerous petrologic data with relevant physical measurements generated by the other contractors and the many fracture studies--a truly gigantic task. On the other hand, we have completed the three areal studies--the area of the Pine Mountain Overthrust Block, the Brallier Formation along the southeast side of the basin, and a study of Ohio and Chagrin Shales along Lake Erie. In addition, we integrated much of the available data on thermal maturity to obtain an insight into how gas generation within the basin depends on the quantity of carbon versus its thermal maturity and <u>where</u> in the basin this pair is most favorable.

As yet unresolved, at least in our eyes, consists of six structural seg-depositional controls—lamination, petrographic type and bioturbation versus later micro- and macrofractures—on gas production. We are not sure how to evaluate their relative importance or even how to start on this problem, which certainly is the major one for improved gas production from the Devonian shale sequence of the Appalachian Basin.

We found it was to our great advantage not to be confined to a single geographic area, such as a state, and we much enjoyed and profitted by cooperating with the other contractors, who worked with stratigraphy. On the other hand, because we three are not members of a research or service organization—only three professors voluntarily working together—we totally depended on mutual goodwill to carry out our contract responsibilities. Recognizing the human fallibility of this, it would be far better, it seems to us, to give future contracts to individual professors rather than groups of professors. By so doing, each would be his own principal investigator and hence should be much more responsible. It is also clear to us that professors and their students are more suitable for research grants than contract research such as this.

We also found that our technicians served the project better, as a rule, than did most of our graduate students, although some of the latter made very significant contributions. Full and part-time technicians have a very strong multiplier effect on the productivity of professors. The problem with graduate students is the early identification of those who will or will not contribute effectively, and thus to minimize support of someone who is not really interested in the contract and its diverse responsibilities, many of which are quite different from the usual academic ones faced by graduate students. On the other hand, field support for a graduate student—rather than full-time support during the academic year—appears to be, as a rule, a much better investment. While the proportions of full to part-time graduate support versus technicians will vary with the type of contract and the academic group carrying it out, some type of balance between these different kinds of technical labor is needed, because clearly they each reinforce one another. We have also noticed, as a rule, that it takes at least one year for a graduate student to make any significant contribution to a contract or grant.

Finally, our effort greatly benefitted from the presence of Dr. Roy C. Kepferle of the U.S. Geological Survey, who had an office in one of our two geology buildings. He always helped our students and us and he was always full time on the project. He also generated many ideas and did a vast amount of work. In addition, trips with Dr. Kepferle in his Survey-financed car greatly amplified our travel budget. We also suspect that Dr. Kepferle's residence with us provided both him and the U.S. Geological Survey with benefits. Hence we heartily endorse the concept of "detached service" at universities by selected personnel of the U.S. Geological Survey and, should the occasion arise, would certainly welcome another opportunity to be a host for someone from the U.S. Geological Survey, or from another government agency such as METC, who may temporarily share a common research interest with us.

PALEOCURRENT STUDIES (3.2.1.1)

Paleocurrent studies were made on outcrops along both the north and southeast sides of the basin and on seven oriented cores (Fig. 1). The full, detailed results of this effort are reported in "Devonian Paleocurrents of the Appalachian Basin" (Potter et al., 1979) and since its publication, we have also measured orientation of wood fragments and other directional structures in the New York No. 1 core, which also shows the gas-bearing black and greenish-gray shales of the basin to have had westwardly flowing currents.

Paleocurrent study indicates that the depositional strike of the basin in Upper Devonian time was north-south with but little variation and that sediment was uniformly derived from the east. Study of paleocurrent structures within the cores shows very good agreement with those in nearby outcrops and thus confirms the reliability of the method of core orientation.

Reference Cited

Potter, Paul Edwin, Pryor, Wayne A., Lundegard, Paul, Samuels, Neil, and Maynard, J. B., 1979, Devonian Paleocurrents of the Appalachian Basin: U. S. Dept. of Energy, Morgantown Energy Technical Center, METC/CR-79-22, 60 p.

SPECIFIC AREA STUDIES (3.2.1.2)

We undertook studies of the shale sequence in three specific areas: along the southeast side of the basin from southern Pennsylvania into Tennessee where two students, Messrs. Lundegard and Samuels working under

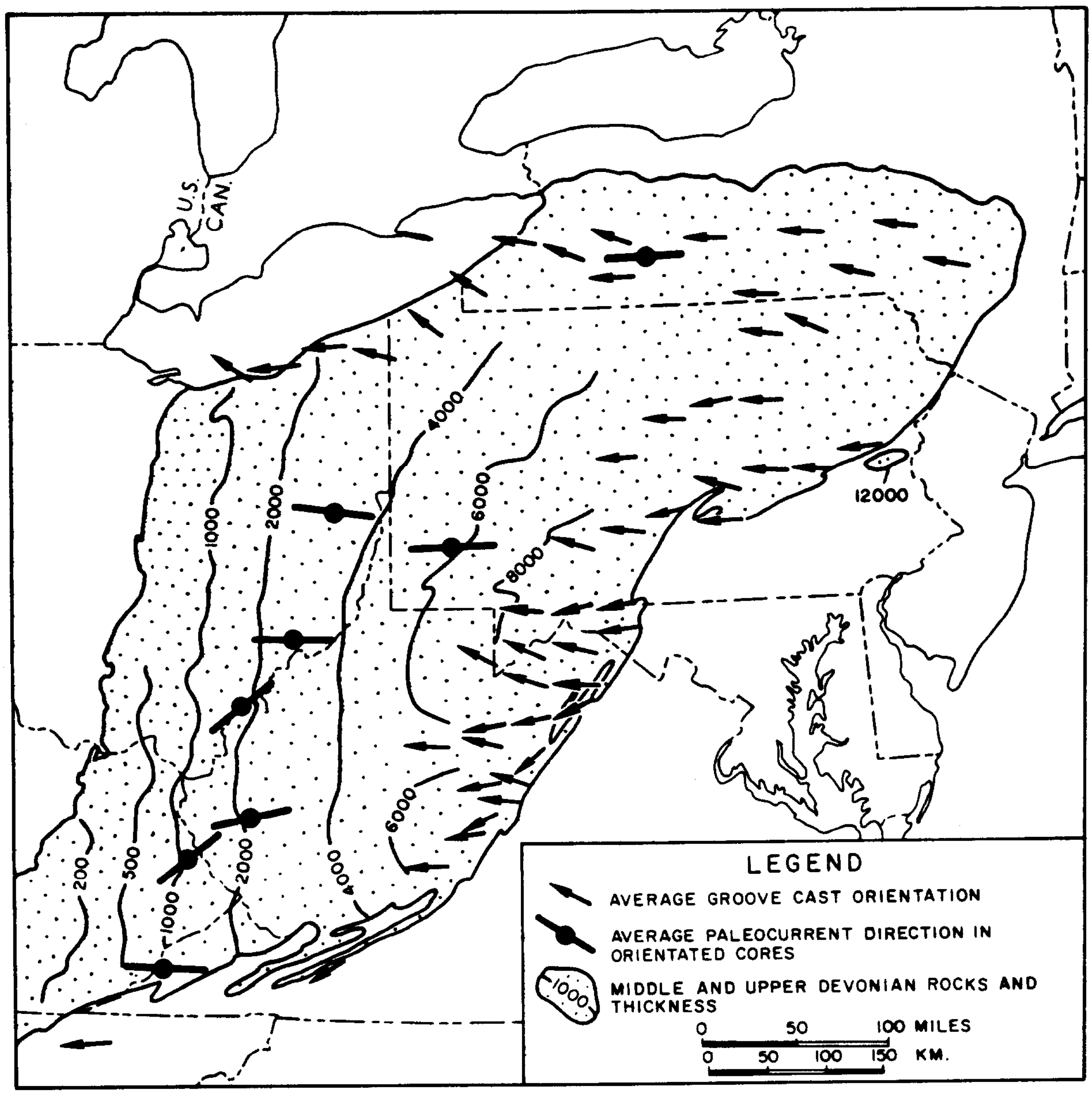

FIGURE 1. Generalized paleocurrent map of Devonian sediments in Appalachian Basin. Note uniformity of flow.

Professor Pryor, measured over 20,000 feet of section in the Brallier Formation and inferred its depositional environment; along Lake Erie, where the Ohio Shale was studied in both outcrop and subsurface in seven counties; and in and near the Pine Mountain Overthrust Block in adjacent parts of Virginia, West Virginia and Kentucky. We successfully completed all three of these studies.

Pine Mountain Overthrust (3.2.1.2.a)

This work developed very differently than we proposed, and although very late, has been most successful, primarily because of our cooperation both with the U.S. Geological Survey and the Kentucky Geological Survey. We have submitted a manuscript to the U.S. Geological Survey which is being published as a bulletin, "Stratigraphy of the Chattanooga Shale (Upper Devonian and Lower Mississippian), Wise County, Virginia", hopefully in 1980, and we have completed a combined thickness and structure map of the Devonian shale sequence in and near the overthrust in cooperation with Messrs. E. N. Wilson and J. Zafar of the Kentucky Geological Survey. We also have summarized the petrology of the available cores in and near the overthrust (please see the work of Mr. T. Stenbeck, discussed under Composition Fabric, Texture, Bedding and Paleontology).

The combined isopach and structure map at a scale 1:250,000 covers all of the overthrust block in adjacent parts of Tennessee, Virginia and Kentucky, and is based on over 700 data points, most of which lie adjacent to the overthrust sheet, and also contains a brief explanatory text. The title is "Structure and Thickness of the Devonian-Mississippian Shale Sequence in and Near the Middlesboro Syncline in Parts of Kentucky, Tennessee, and Virginia." The map area is 90 x 100 cm and both maps, text, four supplemental figures and three tables and a cross section have been submitted to the Kentucky Geological Survey for review. They will publish it in cooperation with the Tennessee and Virginia Geological Surveys. We plan to discuss the geological interpretation with Messrs. John Roen, Lynn Harris and R. Milichi in early 1980. We do not know when the final map will be published, but perhaps in late 1980 or early 1981.

The base map showing counties, the Carter coordinate system, and faults plus the outcrop of the Devonian shale, also will be available from the Kentucky Geological Survey and is in itself a most valuable contribution to development of gas resources in and near the overthrust block.

Subsurface mapping developed the following conclusions:

1) The overthrust sheet has six structural subdivisions named (from southwest to northeast) La Follette, Varilla Pinch, Harlan-Wise, Buck Knob, Powell Mountain, and Nora, each of which has a very different gas potential.

2) The total volume of the shale sequence within the overthrust sheet is 254 cubic miles.

3) The blowout zone of Young (1957) was identified stratigraphically and largely lies in the Olentangy and Marcellus Shales. This zone also appears to have failed in Gulf, No. 1 Price well in Russell County, Virginia, and thus may be a fairly widespread zone of failure in the central part of the folded Appalachians and its adjacent foreland.

4) Overthrusting was accompanied by rotation so that the southwestern part of the sheet advanced about nine miles and the northeast part perhaps only a mile (the greater thickness and depth to the shale at the northeast end of the block may be the immediate explanation of this).

Brallier Formation (3.2.1.2.b)

The least known outcrop of the Upper Devonian on the east side of the Appalachian Basin is from southern Pennsylvania into eastern Tennessee, a distance of over 450 miles. To document this part of the basin better, Messrs. Paul Lundegard and Neil Samuels, working under the direction of W. A. Pryor, measured about 20,000 feet of section and over 700 paleocurrent structures. Their study is in press with METC with the title, "Sedimentology, Petrology and Gas Potential of the Brallier Formation--Upper Devonian Turbidite Facies of the Central and Southern Appalachians," and is abstracted below.

> The Upper Devonian Brallier Formation of the central and southern Appalachian Basin is a regressive sequence of siltstone turbidites interbedded with mudstones, claystones, and shales (Fig. 2). It reaches 1000 meters in thickness and overlies basinal mudrocks and underlies deltaic sandstones and mudrocks. Facies and paleocurrent analyses indicate differences between the depositional system of the Brallier Formation and those of modern submarine fans and ancient Alpine flysch-type sequences. The Brallier system is of finer grain size and had a lower flow intensity. In addition, the stratigraphic transition from turbidites to deltaic sediments is gradual and differs in its facies succession from the deposits of the proximal parts of modern submarine fans. Such features as massive and pebbly sandstones, conglomerates, debris flows, and massive slump structures are absent from this transition.
>
> Paleocurrents are uniformly to the west at right angles to basin isopach. This suggests that turbidity currents had multiple point sources (Fig. 2) around which black shales occur. The depositional system of the Brallier Formation is interpreted as a series of small ephemeral turbidite lobes of low flow intensity which coalesced in time to produce a laterally extensive wedge. The lobes were fed by deltas rather than submarine canyons or upper fan channel systems.
>
> This study shows that the present-day turbidite facies model, based mainly on modern submarine fans and ancient Alpine flysch-type sequences, does not adequately describe prodeltaic turbidite systems such as the Brallier Formation.
>
> The petrography and paleocurrents of the Brallier Formation indicate an eastern source of sedimentary and low-grade megasedimentary rocks with moderate relief and rainfall.

Are there gas reservoirs in the Brallier Formation? Which facies has the most potential? Where will these rocks be found in the subsurface? Outcrop study suggests that the siltstone bundles show promise of being natural gas producers in the subsurface, especially if they are fractured and not totally cemented.

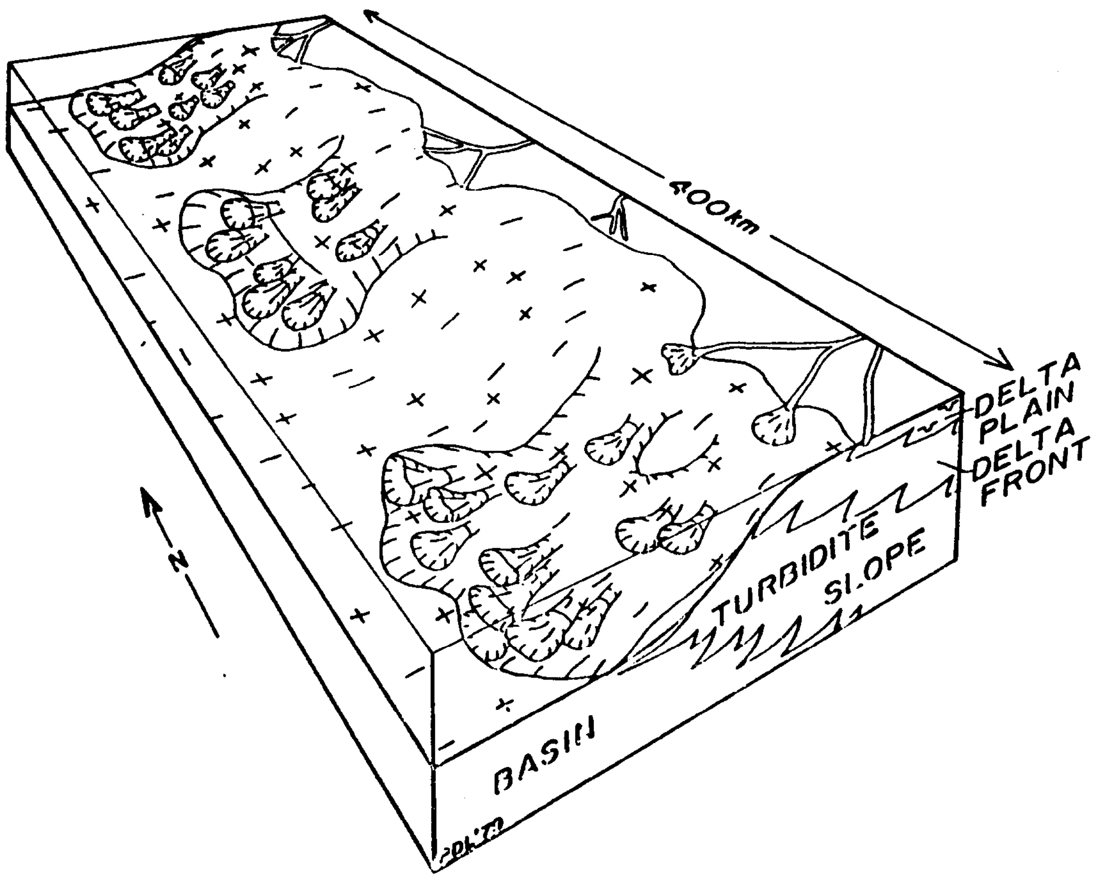

FIGURE 2. Interpretative reconstruction of the Late Devonian paleoslope. Small ephemeral submarine fans coalesced in time along the slope and base-of-slope. Black shales were deposited marginal to such fans.

The siltstones of the siltstone bundle facies contain appreciable fine interstitial clay matrix and carbonate and silica cement, and therefore are of rather low primary reservoir quality. Local fracture porosity and permeability could greatly improve their potential. Similar "tight" siltstones in the Benson field of northcentral West Virginia show moderate gas production (Cheema, 1977, p. 31-44). In the Benson field, only 20 miles west of Brallier Formation outcrops, gas is exploited from linear bundles of Upper Devonian middle to lower-slope turbidites (Cheema, 1977). These bundles are similar to our siltstone bundles and are composed of siltstones with permeabilities less than 2.0 Md (Cheema, 1977, p. 40-42), suggesting significant fracture porosity and permeability. Judging from the Benson field, the turbidite bundles of the Brallier Formation are easily the most attractive potential gas reservoirs. The ubiquitous occurrence of these siltstone bundles along the outcrop in West Virginia and west-central Virginia suggests that similar reservoir units should be present in the subsurface immediately to the west in southern West Virginia. Cheema (1977, p. 29-31) showed that these linear siltstone bundles have high continuity into the basin. Although outcrop samples of the Brallier Formation mudrocks have low organic carbon contents (Table 1), more organic-rich source beds are present farther basinward to the west.

Judging from the organic contents of mudrock in our Brallier outcrops, these rocks do not have much promise as source beds. However, farther to the west in the deeper and more poorly oxygenated parts of the basin organic-rich shales equivalent to the Brallier are common and Harris et al. (1978) discuss their significance and their Figure 1 shows a generalized basinwide map of black shales that has very distinct lobes.

Our study of the Brallier yielded thirteen conclusions:

1) The present-day turbidite facies model, based mainly on modern submarine fans and ancient flysch sequences, does not adequately describe the depositional system of the Brallier Formation.

2) The Brallier Formation turbidites are finer grained and thinner bedded than the deposits of most modern submarine fans and ancient flysch systems.

3) The entire stratigraphic sequence from basinal to topset deltaic deposits contains only the classic turbidite member of the resedimented coarse clastic family.

4) The stratigraphic transition from turbidites to the overlying deltaic traction deposits is gradual and

TABLE 1. Organic Carbon, Nitrogen, and Hydrogen Analyses

Part A: Data

STRAT. UNIT	SAMPLE NUMBER	PERCENT Carbon	WHOLE Nitrogen	ROCK Hydrogen
BRALLIER FORMATION	BS1-54.8	0.27	0.06	0.46
	BS1-59.6	0.18	0.07	0.50
	BS1-70.3	0.19	0.04	0.37
	BS1-85	0.09	0.00	0.45
	BS2-100	1.13	0.11	0.45
	BS4-32	1.10	0.03	0.48
	GC1-1	0.15	0.08	0.40
	HG1-4	2.59	0.47	0.55
	HI1-1	0.37	0.10	0.51
	MC1-1	0.20	0.14	0.55
	MC1-13	0.12	0.09	0.44
	MH2-5	0.05	0.17	0.41
	McD-182	0.24	0.06	0.47
	R16-BLK	1.05	0.11	0.57
	ST1-36	0.10	0.12	0.50
	ST1-37	0.23	0.05	0.46
	ST1-38	0.00	0.07	0.29
	ST1-42	0.14	0.06	0.61
	ST1-43	0.05	0.13	0.56
	ST1-45	0.05	0.11	0.52
	ST1-46	0.05	0.06	0.56
	ST1-53	0.85	0.10	0.59
	ST1-54	0.86	0.11	0.45
	ST1-60	0.14	0.03	0.36
	ST1-67	0.11	0.04	0.43
	ST1-73	0.08	0.04	0.44
	ST1-75	0.31	0.10	0.58
	ST1-77	0.49	0.17	0.47
	ST1-78	0.32	0.04	0.47
	ST2-149	0.19	0.17	0.50
	ST3-817	0.20	0.06	0.50
	ST3-888	0.21	0.03	0.48
	ST3-893	0.68	0.15	0.31
MILLBORO SHALE	BS1-4.5	2.13	0.09	0.42
	BS1-34.6	0.18	0.07	0.41
	BS1-43.7	0.37	0.11	0.51
	BS1-48.7	0.24	0.07	0.41
	BR1-2	1.58	0.14	0.52
	BR1-3	0.91	0.16	0.49
	ST1-31	0.20	0.09	0.53
	ST1-32	0.19	0.09	0.41
*	PH1-1	0.54	0.07	0.32
	TO-6	0.09	0.04	0.47
**	R16-BSG	1.10	0.13	0.48

TABLE 1 (continued)

Part B: Locations of Samples

SAMPLE	LOCATION
BS1-54.8	Bastian Section; 0.3 ft above base of unit 2.
BS1-59.6	Bastian Section; 5.1 ft above base of unit 2.
BS1-70.3	Bastian Section; 7.4 ft above base of unit 2.
BS1-85	Bastian Section; 5.0 ft above base of unit 3.
BS2-100	Bastian Section; 100 ft above base of unit 5.
BS4-32	Bastian Section; 6.5 ft below top of unit 18.
GC1-1	Nottingham Section; 110 ft above base of unit 1.
HG1-4	Hayters Gap Section; 2.5 ft above base of unit 20.
HI1-1	Hilton Section; 11.4 ft above base of unit 1.
MC1-1	Gauley Ridge Section; 23 ft above base of unit 5.
MC1-13	Gauley Ridge Section; 23 ft above base of unit 5.
MH2-5	Minnehaha Springs Section; 10 ft below top of unit 7.
McD-182	McDowell Section; middle of unit 30.
R16-BLK	Virginia Route 16 Section; unit 32.
ST1-36	Cloyds Mountain Section; top of unit 3.
ST1-37	Cloyds Mountain Section; 1.6 ft below top of unit 4.
ST1-38	Cloyds Mountain Section; base of unit 5.
ST1-42	Cloyds Mountain Section; 2.8 ft above base of unit 6.
ST1-43	Cloyds Mountain Section; 8.1 ft above base of unit 6.
ST1-45	Cloyds Mountain Section; 9.2 ft above base of unit 6.
ST1-46	Cloyds Mountain Section; 10.3 ft above base of unit 6.
ST1-53	Cloyds Mountain Section; 8.5 ft above base of unit 7.
ST1-54	Cloyds Mountain Section; top of unit 7.
ST1-60	Cloyds Mountain Section; 8.5 ft above base of unit 12.
ST1-67	Cloyds Mountain Section; 79.9 ft above base of unit 16.
ST1-73	Cloyds Mountain Section; 12.1 ft below top of unit 16.
ST1-75	Cloyds Mountain Section; 12.9 ft above base of unit 18.
ST1-77	Cloyds Mountain Section; 13.2 ft above base of unit 24.
ST1-78	Cloyds Mountain Section; 11.5 ft above base of unit 27.
ST2-149	Cloyds Mountain Section; 20 ft above base of unit 38.
ST3-817	Cloyds Mountain Section; 8 ft above base of unit 53.
ST3-888	Cloyds Mountain Section; 1 ft below top of unit 60.
ST3-893	Cloyds Mountain Section; 4 ft above base of unit 61.
BS1-4.5	Bastian Section; 4.5 ft above base of unit 1.
BS1-34.6	Bastian Section; 34.6 ft above base of unit 1.
BS1-43.7	Bastian Section; 43.7 ft above base of unit 1.
BS1-48.7	Bastian Section; 48.7 ft above base of unit 1.
BR1-2	Broadford Section; 15 ft above base of unit 3.
BR1-3	Broadford Section; 38 ft above base of unit 3.
ST1-31	Cloyds Mountain Section; 7.5 ft above base of unit 1.
ST1-32	Cloyds Mountain Section; 17.5 ft above base of unit 1.
PH1-1	Little War Gap Section; 26 ft above base of unit 7.
TO-6	U.S. Highway 25-E Section; 4 ft above base of unit 10.
R16-BSG	Virginia Route 16 Section; 175 ft above top of unit 60.

lacks the facies characteristic of the proximal parts of modern submarine fans.

5) Turbidite paleocurrents indicate a homogeneous transverse dispersal pattern, atypical of flysch sequences, which suggests that turbidity currents had multiple sources.

6) The Brallier turbidites were deposited on a relatively smooth surface lacking major channels.

7) Turbidites were deposited on a series of small ephemeral turbidite lobes of low flow intensity which coalesced in time to form a laterally extensive wedge.

8) The turbidite lobes were fed by deltas rather than submarine canyons or upper fan channels.

9) Bioturbated olive gray mudstone accumulated by hemipelagic sedimentation on the slope, lateral to areas of active turbidite deposition.

10) Bioturbated claystone and shale with turbidite silt laminae were deposited at the margins of turbidite lobes and on the lower reaches of the slope.

11) Black shales were deposited by hemipelagic sedimentation of mud and organic matter basinward of the turbidite lobes.

12) The ultimate source for the Brallier Formation was an eastern complex of sedimentary and low-grade metasedimentary rocks.

13) The siltstone bundle facies may make good gas reservoirs in the subsurface of southern West Virginia, especially if fracture porosity is well developed.

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Geology of Ohio Shale Along Lake Erie (3.2.1.2.c)

The gas-bearing Ohio and Chagrin Shales, which have produced marginally commercial amounts of gas for over 100 years in the heavily populated and industrialized area of northern Ohio along Lake Erie (Fig. 3), were characterized in terms of their stratigraphy, petrology, geochemistry, and sedimentology.

The study area is located in the northwest part of the Appalachian Basin and is separated from the Michigan Basin to the northwest by the Findlay Arch. Low regional dips of the Upper Devonian shale sequence are eastward off the Findlay Arch in the western part of the study area, and to the southwest off the Canadian Shield in the eastern part of the study area. Depth to Precambrian basement varies from about 4950 feet (1500 m) in Erie County to about 6300 feet (1900 m) in Ashtabula County.

The rationale for this study of the Ohio and Chagrin Shales has been very well stated by Harris and Hewitt (1977, p. 761) in their work on sandstone reservoirs.

> Rather than being homogeneous tanks or uniformly layered entities, most reservoirs exhibit complex variations of reservoir continuity and thickness patterns and of pore space attributes (porosity, permeability, and capillary-pressure properties). The reservoir interval is commonly subdivided vertically and aerially into "pay zones" that are separated by impermeable rock units; the pay zones themselves often contain shale or tight carbonate streaks. Thickness distributions of pay zones may be sheet-like or linear and, within the rock framework, pore-space attributes may vary in a predictable or random manner. It is this complexity of rock framework and pore space variation that challenges petroleum scientists to apply their technology and experience in reservoir description, with the aim of improving recovery.

Although most shales differ greatly from sandstones in lateral continuity, porosity, and many other characteristics, the basic questions regarding

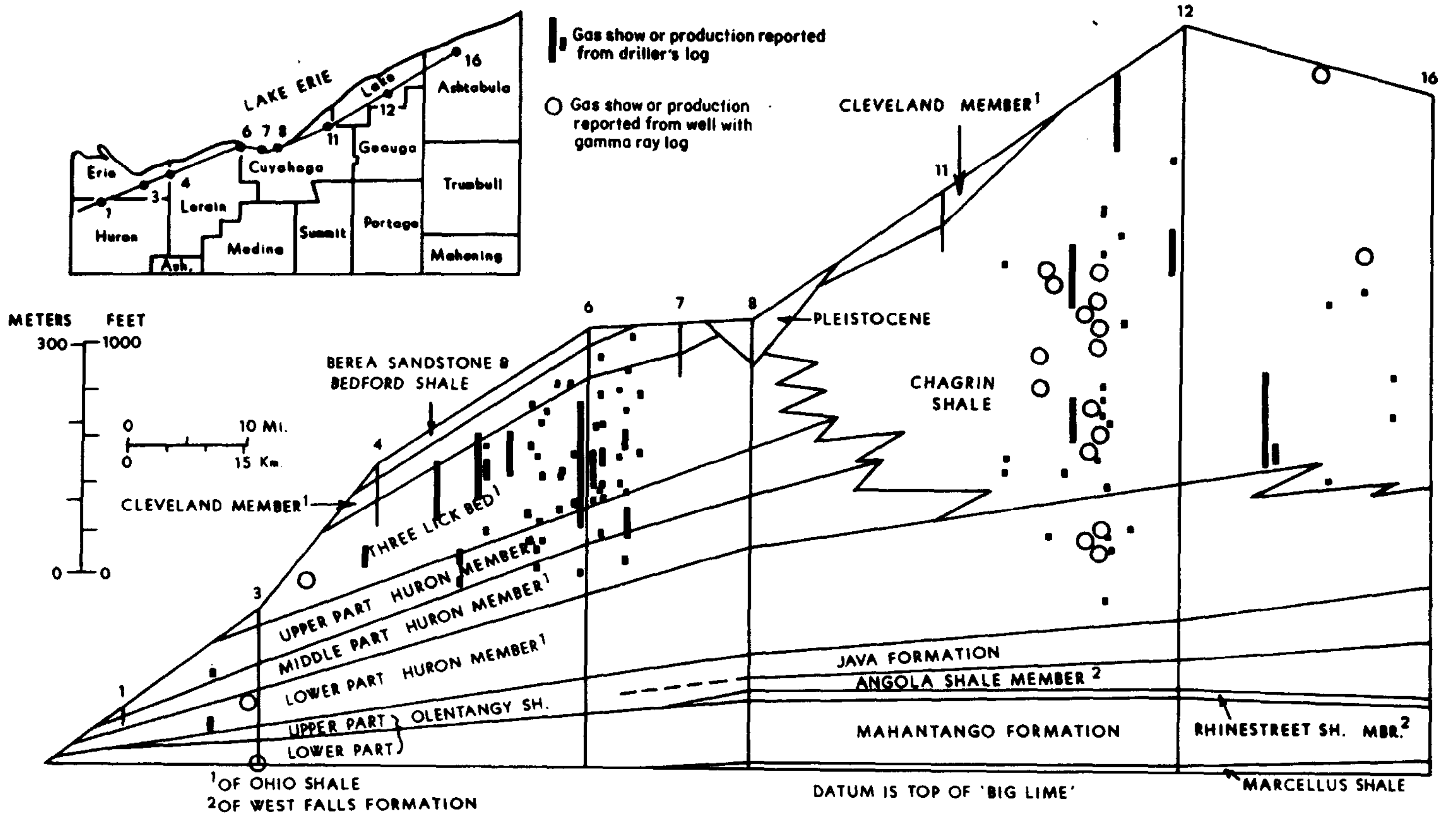

FIGURE 3. Stratigraphy and facies of Ohio and Chagrin Shales along Lake Erie and gas shows projected into line of section.

shale reservoirs are similar--is gas production and/or potential in shales random or ordered, is it mappable, and is it controlled by primary or secondary factors? This study elaborates the efforts of Janssens and de Witt (1976), who made a reconnaissance study of gas occurrences in the Devonian shale sequence of Ohio. Although they did not concentrate on the region along Lake Erie, they concluded that siltstones in the Chagrin Shale have produced much of the gas already recovered. They calculated that 67.17 x 10^{12} ft^3 of gas could be obtained from all the Upper Devonian shales in Ohio by using fracture treatments on drill holes.

Stratigraphy: The most recent stratigraphic studies on the Ohio and Chagrin Shales were made over 65 years ago (Newberry, 1870; Ulrich, 1912; Kindle, 1912; Cushing, 1912; Prosser, 1912). Pepper et al. (1954) studied these shales as part of their work on the Bedford Shale and Berea Sandstone. Hoover (1960) comprehensively summarized previous research on Upper Devonian and Lower Mississippian shales throughout Ohio. Janssens and de Witt (1976) studied the stratigraphy of the Ohio Shale in the subsurface of Ohio. Wallace et al. (1977) constructed a regional cross section which cuts across the eastern part of the study area. Schwietering (1979) made a thorough surface and subsurface stratigraphic investigation of Upper Devonian shales throughout the Appalachian Basin, but he did not concentrate on the Lake Erie region.

Study along the lake has been popular because of the good exposures on shoreline cliffs and along the spectacular bluffs of the rivers, which drain into Lake Erie. These outcrops parallel the lake shore in a belt 2 miles to 30 miles wide. Stratigraphic units change across the area and reflect a facies transition from black shales in the west to greenish-gray shales and siltstones in the east.

Eleven outcrops and nine cores from six counties along Lake Erie were studied to define lithostratigraphy and megascopic sedimentology. Cores and outcrops were correlated with subsurface gamma-ray logs to relate better subsurface gamma-ray signatures to their lithofacies. Nine radioactivity profiles were made of outcrops and cores with a gamma-ray scintillometer to facilitate correlation. Subsurface gamma-ray logs were examined to delineate stratigraphy.

Gas Potential: Ninety-three well records with reported shows of gas and/or gas production were examined to delineate gassy zones and determine what geologic factors control gas occurrence in the Ohio and Chagrin Shales along Lake Erie. All of these drill holes penetrate the entire Ohio and Chagrin Shales and all but two reach the "Big Lime". Nine drill holes with reported shows of gas have gamma-ray borehole logs which help delineate the stratigraphy. The depth of most gas shows in a drill hole comes from information supplied by the driller at the wellsite. Gas shows were identified by a temperature log.

Gas shows were projected into the regional cross section (Fig. 3). There are concentrations of gas shows in the Three Lick Bed in the eastern part of the area and in the lower two thirds of the Chagrin Shale. Gas shows are best related to shale types (please see Composition, Fabric, Textures, Bedding and Paleontology) rather than to source-rock evaluation, burial depth and thermal maturity of organic matter. Cementation patterns of interbedded siltstones did not seem to be an important factor.

TABLE 2. Drill Holes With Gamma-Ray Logs and Gas Shows

A. Erie County Nuclear Power Plant
Drill hole B -19
Berlin Township, Erie County, Ohio
See Appendix A for gamma-ray log and core log

B. Hefner Producing Company
Esther A. Hurst, Eleanor Ann & W. W. Marshall No. 1
Townsend Township, Huron County, Ohio

C. Patrick Petroleum
F. J. Finch No. 1
Clarksfield Township, Huron County, Ohio

D. Diamond Shamrock Corporation
Drill hole No. 262
Mentor Township, Lake County, Ohio
See Fig. 15 gamma-ray and temperature logs

E. Diamond Alkali Company
Drill hole No. 141
Painesville Township, Lake County, Ohio

F. Diamond Alkali Company
Drill hole No. 204
Painesville Township, Lake County, Ohio

G. Diamond Alkali Company
Drill hole No. 32
Painesville Township, Lake County, Ohio

H. N. T. Smith & Keith Mouser
John Roach No. 1
Hartsgroove Township, Ashtabula County, Ohio

I. Buckeye Resources Inc.
M. Woodworth No. 1
Geneva Township, Ashtabula County, Ohio

Gas shows are concentrated in stratigraphic units which contain more than 20 percent mudshale, siltshale, and siltstone. The thick quartz laminae in these lithologies probably act as permeable conduits and reservoirs for gas. In order for a shale to be a gas reservoir along Lake Erie, it must have abundant quartz laminae with a minimum thickness of 0.2 mm. Most of the stratigraphic units in which gas shows are most common contain abundant laminated shale and abundant quartz laminations.

On the other hand, units which contain only claystone, bituminous shale, and/or clayshale do not have abundant gas shows. Quartz laminae in clayshales have about the same average thickness as quartz laminae in bituminous shales, about 0.1 mm, and the lognormal distributions of lamination thickness are about the same in these two petrofacies; moreover, only about 10 percent of the laminae in both of these shale types exceed 0.2 mm in thickness. In mudshales, however, average quartz lamination thickness is about 0.3 mm and about 60 percent of all quartz laminae are thicker than 0.2 mm. There are also more quartz laminae in mudshales than in clayshales and bituminous shales. Beds of siltstone and siltshale are composed almost entirely of quartz laminae, which have been bioturbated in the siltstones.

Grain-to-grain contacts in the quartz laminae of mudshales, clayshales, bituminous shales, and siltshales are mostly long and point, and thus favor the flow of gas.

Gas shows are not primarily dependent on source rock evaluation, because they are concentrated in the two stratigraphic units which have the lowest source rock evaluations—the Three Lick Bed of the Ohio Shale and the Chagrin Shale.

Thermal maturity of organic matter does not control gas distribution, because the concentrations of gas shows are unrelated to present burial depth even though, as a generalization, thermal maturity of organic matter does control the total amount of gas present in the shale (Rissot et al., 1974; Hood et al., 1975, p. 986, 991-994). Nor do cementation patterns of quartz laminae control the distribution of gas shows. More quartz laminae, siltstones, and siltshales in the Three Lick Bed and Chagrin Shale are cemented and replaced by carbonate than in any of the other stratigraphic units; yet this regional cementation pattern does not control the localization of gas shows. Perhaps this is because many quartz laminae remain uncemented.

In summary, stratigraphic units which contain abundant mudshales, siltshales, and siltstones make the best gas reservoirs in the Ohio and Chagrin Shales along Lake Erie. These three petrofacies contain abundant, thick (greater than 0.2 mm) quartz laminae and/or quartzose siltstone and siltshale beds, which act as permeable reservoirs and conduits for gas.

Sedimentology: Sedimentology helps to reconstruct the depositional environments of the Ohio and Chagrin Shales along Lake Erie and thus aids our understanding of the distribution and extent of potential source rocks and reservoir strata.

The siltstones, siltshales, and mudshales of the Ohio and Chagrin Shales were deposited by turbidity currents on a turbidite slope west of the Catskill delta complex (Walker, 1978, p. 933-936). Their turbidite origin is indicated by their sedimentary structures (partial Bouma sequences, abundant grooves and common flutes on soles plus coarse-tail and distribution grading of individual quartz laminae), wide lateral continuity, and uniform orientation of directional structures. Thus they sharply contrast with the interbedded finer-grained claystones, clayshales, and bituminous shales. The Bouma sequences (Bouma, 1962, p. 48-51 and p. 100) are base-truncated Tbcde, Tcde, and Tde partial sequences indicating that these turbidites were deposited by fairly low-velocity turbidity currents. The wide continuity of individual siltstone beds, the low silt-to-shale ratio, the thinness of the siltstone beds (mean thickness of 0.06 ft. or 1.8 cm), and the paucity of siltstone beds with a basal Ta unit all indicate that these are distal turbidites (Walker, 1967, p. 31-33). Directional structures indicate paleocurrent flow to the west, and therefore a westward-deepening basin and an eastern sediment source for the turbidites, the Catskill delta (Lewis, 1976, which prograded westward during the Lake Devonian.

Interbedded muds also had an eastern source area. This is indicated by the eastward thickening of the section. The lack of grading in the quartz laminae of the clayshales and bituminous shales and their fine grain suggests that the muds were deposited higher as hemipelagic sediment or by low-velocity, low-density turbidity currents. Distinction between these two depositional processes is difficult, because they probably leave deposits of similar appearance.

Overall, black shale was deposited in deeper water than the greenish-gray and gray shale. Evidence for this is twofold. First, black shale is present mainly west of the turbidite-siltstone wedge, down paleoslope. Such an interpretation must be used with caution, however, because turbidites may flow parallel to a basin axis as well as perpendicular to it and down paleoslope (Potter and Pettijohn, 1977, p. 178 and 179). Secondly, if we accept the hypothesis of Schopf and Schwietering (1970, p. 6 and 7) related the extinction of Foerstia to a general and widespread marine transgression, then the event which caused deposition of the dark-gray to black shales of the upper part of the Huron Member coincided with this transgression. Application of Walther's Law of Succession of Facies (Blatt et al., 1972, p. 187) to the time-equivalent rocks containing Foerstia leads to the conclusion that the dark-shale deposits such as the upper part of the Huron Member were deposited in deeper waters than units such as the middle part of the Huron Member, which consists of interbedded black and gray shales. Hallam and Bradshaw (1979) concluded, for different reasons than stated here, that thin, widespread bituminous shales of the European Jurassic were deposited in deeper water than contemporaneous non-bituminous shales. Because the deposition of black organic-rich shale requires accumulation in anoxic water, a widespread stratification of oxygen levels in the Late Devonian epeiric sea is implied, with anoxic water beneath oxygenated water. Where greenish-gray shale is finely interbedded with black shale, the former probably represents rapid deposition by very distal turbidity currents, deposition too rapid to have been influenced by the poorly oxygenated bottom waters that produced the black shales.

Figure 4 is an interpretive sedimentologic cross section of the study area at the end of *Foerstia* time. Lundegard *et al*. (in press, Table 4) proposed a general depositional model for turbidites in the Upper Devonian Brallier Formation of the Appalachian Basin (Fig. 2), which emphasizes a delta-front facies that is not present in the Ohio and Chagrin Shales along Lake Erie. The turbidite slope, interlobe slope, and lobe margin facies are represented, however, by the Chagrin Shale and the eastern part of the Three Lick Bed. The upper, middle, and lower parts of the Huron Member, the western half of the Three Lick Bed, and the western half of the Cleveland Member of the Ohio Shale constitute the basinal facies, with the middle part of the Huron Member and the Three Lick Bed representing deposition in shallower water than the upper and lower parts of the Huron Member and the western part of the Cleveland Member. The thin bedding, wide lateral continuity and partial Bouma sequences of the turbidites in the Three Lick Bed and the Chagrin Shale suggest that these units are best assigned to the turbidite slope facies. Interlobe slope and lobe margin

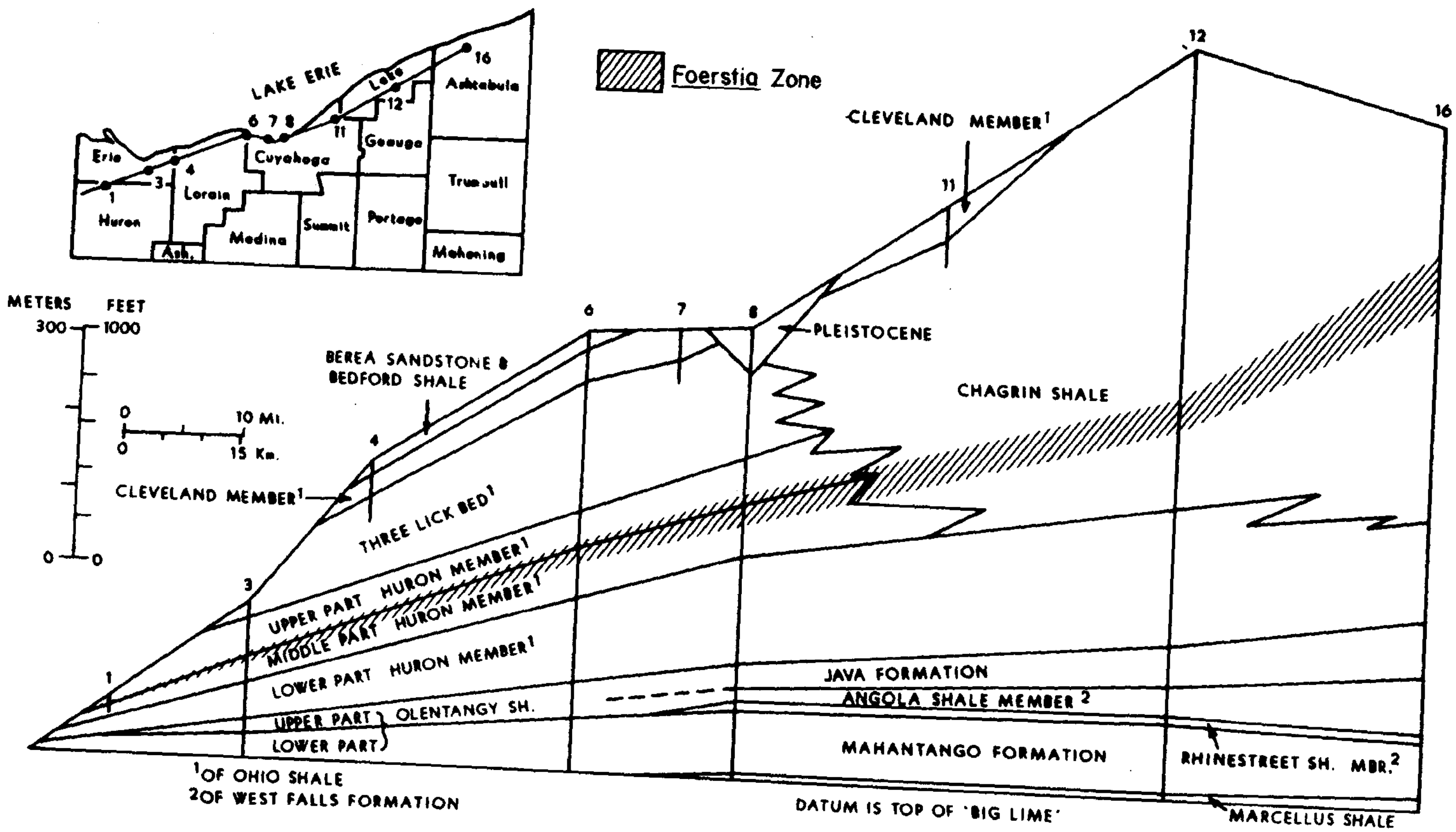

FIGURE 4. Foerstia zone, a very good time marker, thickens eastward and extends through both the Huron and Chagrin Shales.

facies are minor and present only locally in the Chagrin Shale and in the Three Lick Bed, suggesting that lobes were few and poorly developed on the turbidite slope along Lake Erie. The thick-bedded siltstones and fine-grained sandstones of the eastern half of the Cleveland Member belong to turbidite channel deposits--the shale rip-up clasts in the sandstones and the contorted bedding in the siltstones suggest that these sandstones were transported by higher velocity turbidity currents and deposited quickly.

Units such as the lower part of the Huron Member, which is composed almost entirely of black shale, were deposited on a basin plain. Therefore, the base of the lower part of the Huron Member was an approximately horizontal datum during the Late Devonian. Neglecting the effects of differential compaction, a minimum water depth of 700 feet (230 m) for the Late Devonian sea at the end of Foerstia time can be calculated using the method of Klein (1974). Water depth was greater than this because this estimate is based only on the thickness difference between the turbidite slope and basin plain environments, and does not include the depth from sea level down to the turbidite slope nor does it consider compaction. Our estimate of about 700 feet is similar to the maximum depth of 675 feet (223 m) given by Rich (1951, p. 2020) for the Ohio Shale. A westward depositional slope of 7.4 feet/mile (1.4 m/km; 0°05') for the turbidite slope and basin plain is indicated. This is somewhat lower than the average gradient of 0°07' of modern continental shelves (Shepard, 1973, p. 277) and higher than the 0°03' given by Byers and Larson (1979, p. 359) for the depositional slope of the Cretaceous Mowry sea in Wyoming.

The Ohio and Chagrin Shales along Lake Erie record a generally regressive sequence, which was interrupted by three short transgressive phases of black shale deposition—the lower and upper parts of the Huron Member and the Cleveland Member. The westward-thinning siltstone wedge suggests a westward progradation of the turbidite slope, which advanced westward with progradation of the Catskill delta. This supports the interpretation of Piotrowski and Harper (1978, p. 35), who found evidence in the subsurface for three progradational phases of the Late Devonian clastic wedge in northwestern Pennsylvania. Each progradational (regressive) phase, extended farther northwest than the preceding one and each is underlain by a transgressive phase. Earlier, Kohout and Malcuit (1969, p. 204) concluded that the Ohio and Chagrin Shales and the Bedford Shale formed during a general regression of a Late Devonian-Early Mississippian epeiric sea. Schwietering (1979, p. 43-46) concluded that the Upper Devonian shales of the Appalachian Basin were deposited by a transgressive epeiric sea, however.

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BASIN ANALYSIS (3.2.1.3)

Below we have summarized present available knowledge (30 September, 1979) pertaining to the distribution and origin of the Upper Devonian sediments of the Appalachian Basin, especially its shales. Table 3 contains general information about the basin as a whole and below is a brief summary of the basin's shaly facies, the prime object of the Eastern Gas Shales Project. Cross sections and block diagrams support this summary and all are based on the network of cross sections made by the different contractors (Fig. 5). The cross sections published by Piotrowski and Krajewski (1979) are especially informative. Because basin-wide maps were unavailable in June 1979, our summary is less complete than we expected. The summer and fall of 1980 might be a good time to undertake such an effort, judging by the publication rate of the different contractors.

Historically, cross sections of the basin, or large parts of it, date from the 1930's and show progressively more detail with time as more and more subsurface stratigraphic information was used (Fig. 6); of all of these cross sections that of John L. Rich is perhaps closest to our present-day perception, primarily because he showed basin configuration and facies as he inferred them at the end of Devonian time.

Shale and siltstone are the dominant lithologies of the Upper Devonian in the Appalachian Basin and constitute nearly all of it in its western half. The shales of the basin are of two general types: green-gray and gray shales, which are commonly interbedded with siltstones and minor sandstones and much less abundant black bituminous shales (Table 4). These bituminous shales commonly contain only a few, thin silt laminae that rarely exceed one or two millimeters in thickness. The gray shale

TABLE 3. Basin Analysis (from Potter, et al., 1979, Table 1), Devonian and Mississippian Shales.

Time Span - *Fifty million years.*

Geometry and Size - *Large incompletely preserved wedge covering about 110,000 square miles (280,000 km^2) north of Tennessee with greatest thickness of 12,000 ft (3658 m) along the southeastern side of the basin in Pennsylvania.*

Lithic Fill - *Lithology is varied and includes red pebbly sandstones and red shales, fluvial, deltaic, beach and shelf sandstones plus slope and basin siltstones mostly of turbidite origin, widespread greenish-gray and black marine shales and some shallow-water carbonates. Greenish-gray shale is more abundant than black shale and may have a greater gas potential than black shale.*

Basin has systematic arrangement of facies. Progression is from east to west of non-marine clastics through beach, shelf, and slope to deep basin with prominent clinoform deposition and westward overlap. Depositional strike is possibly near present western limit and thus even thin shale units have much better north-south than east-west lithologic continuity. Black shales are thin and widespread and fan eastward where they pass into greenish-gray shales that form wedge-shaped masses which mostly accumulated on a westward dipping slope or at its base.

Composition - *Sublithic to subfeldspathic arenites and wackes plus illitic and chloritic, organic rich shales and greenish-gray mudstones, whose various subtypes have yet to be fully defined and mapped over entire basin. Siltstone laminae within both types, as well as possible microfacies, appear to be significant for gas.*

Paleocurrent System - *Interbedded siltstones and sandstones, and apparently almost all of the shale in the basin, deposited by currents from the east, generally perpendicular to isopach lines even though black shales, which dominate only in the western part of basin, imply deposition in a restricted basin.*

Paleogeography and Tectonic Setting - *Large, delta complex, now beheaded by continental separation, overlaps craton margin and has a linear, deep marine basin striking north-south. Deepest water may have ranged from 500 to 2500 ft but was negligible to the east and possibly only several hundred feet to the west. Delta-shelf-slope system prograded westward as a uniform clastic ramp and was supplied by a large river which drained a stable, continental land mass, lacking volcanic rocks.*

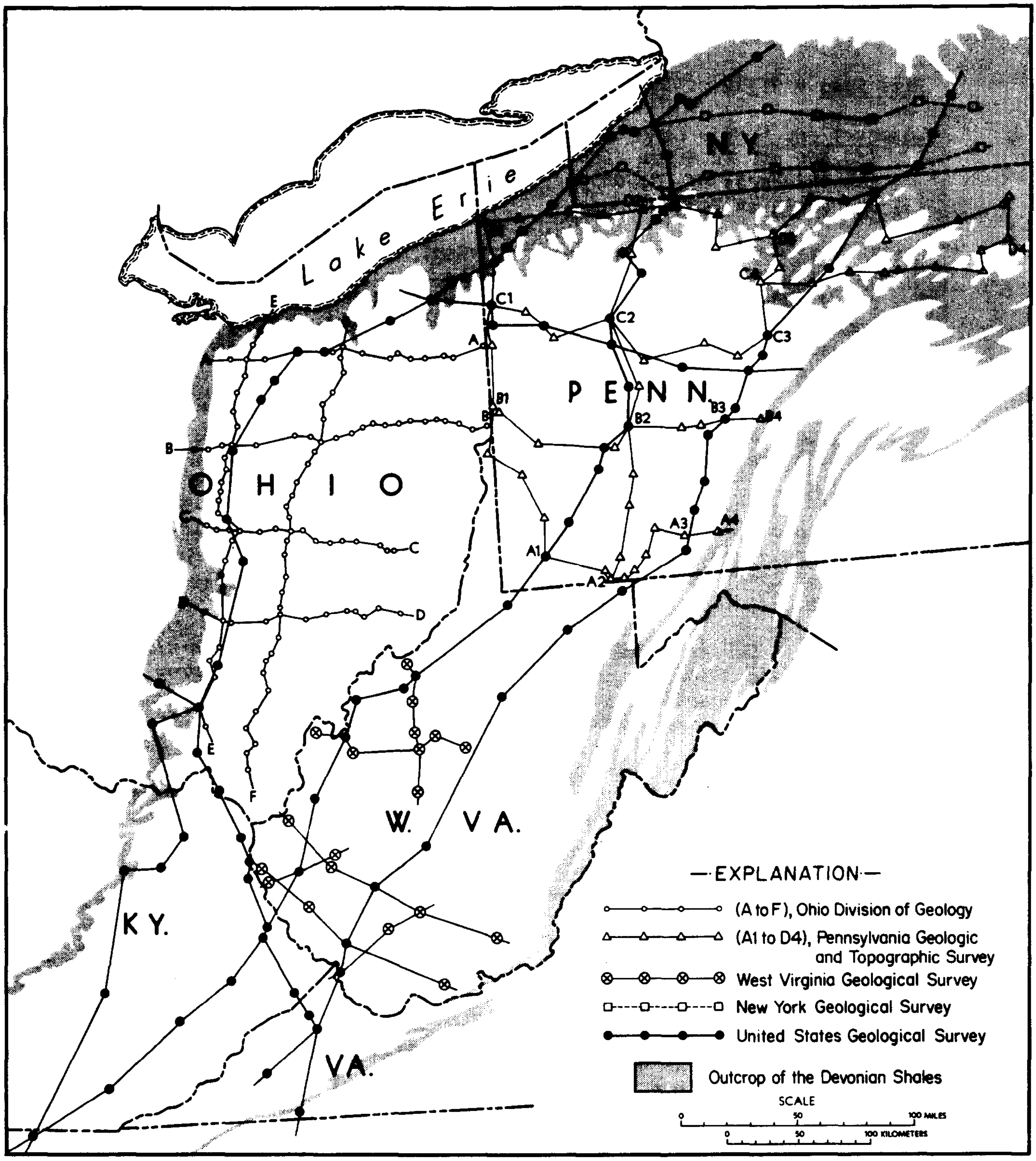
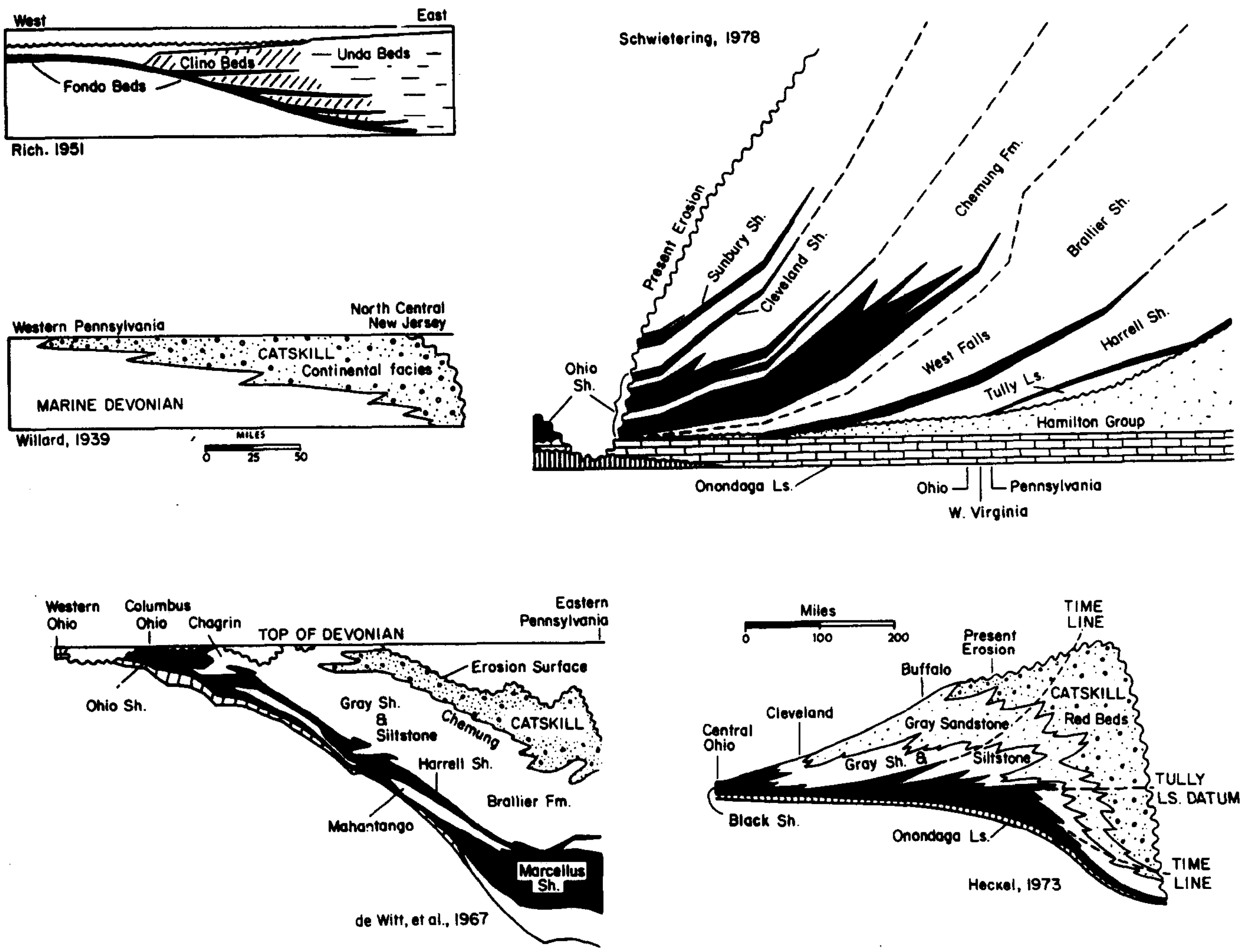


FIGURE 5. Published Cross Sections of the Devonian Shales, Appalachian Basin

EAST-WEST BASINWIDE SECTIONS



NORTHEAST - SOUTHWEST BASINWIDE SECTION
OBLIQUE TO DEPOSITIONAL STRIKE

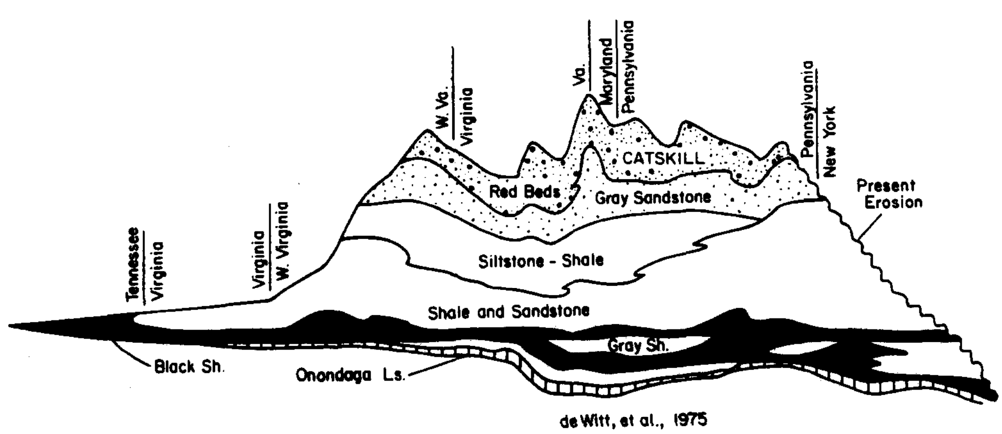


FIGURE 6. Changing perceptions of the Devonian stratigraphy of the Appalachian Basin.

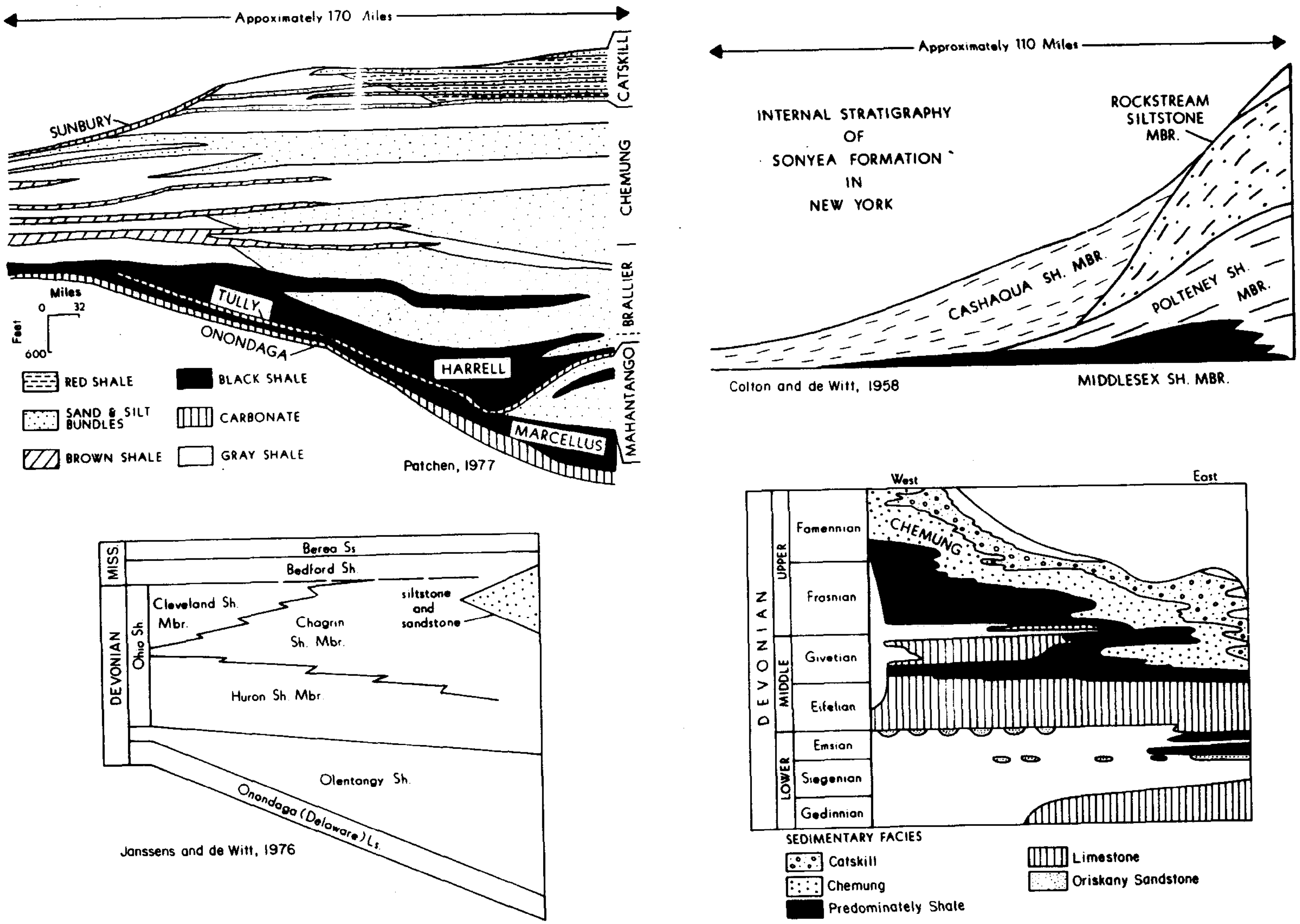


FIGURE 6. (continued)

TABLE 4. Petrographic Composition of Representative Gray and Black Shales Along Lake Erie

	Modal Gray Shale (350.0 ft., Perry Nuclear Power Plant Core TX-7)	Modal Black Shale (422.0 ft., Whiskey Island Core, International Salt Company
QUARTZ + FELDSPAR	17	14
CLAY	67	53
MICA	3	2
ORGANICS	6	23
TASMANITES	0	1
PYRITE	4	6
CARBONATE	3	1
OTHER	T	0
	100%	100%

facies, of which the Chagrin Shale in northern Ohio and the Brallier Formation along the southeast side of the basin are good examples, is thickest in the central part of the basin, where it attains about 4000 feet; westward it thins rapidly and interfingers with the bituminous, black shale (Plates 1, 2 and 3). Thus the gray shale facies forms a westward thinning wedge that is largely absent in the western outcrop of the Appalachian Basin, east of the Cincinnati and Findlay Arches. The cross section of Harris et al. (1978, Fig. 1) nicely shows this wedge of gray and greenish-gray shale with its interbedded siltstones. The greenish-gray and gray shale facies were deposited on a westward dipping submarine slope by turbidity currents and all of this facies was derived from the marine shelf and alluvial plain of the Catskill delta. An idealized genetic section plus the model of Wolff (1969), and a simplified cross section using the top of the Devonian as level line all rather harmonize nicely (Fig. 7).

Black shales are widespread. Most can be traced throughout large areas of the western and central parts of the basin and are rarely more

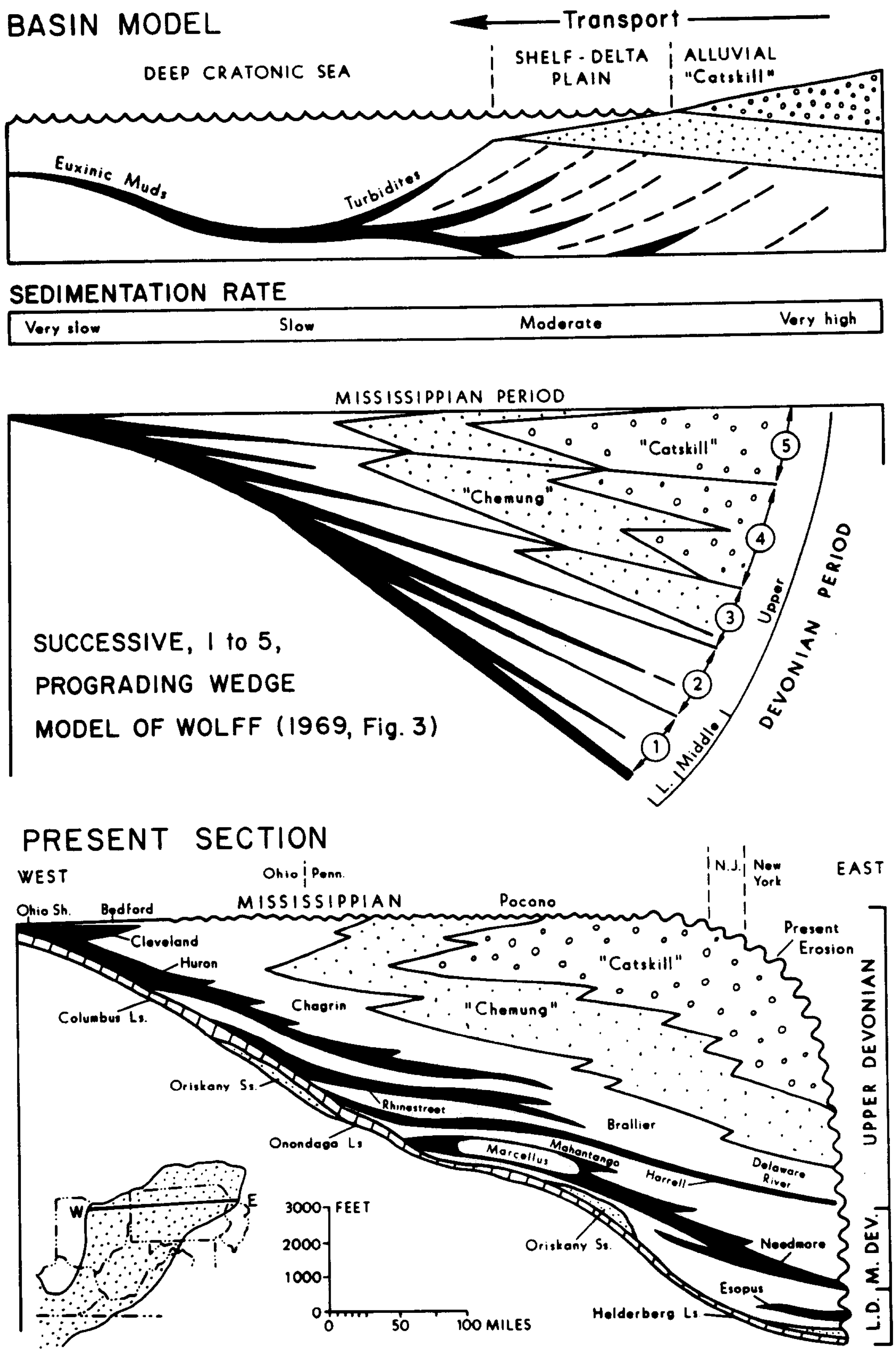


FIGURE 7. Idealized facies model, model of Wolff and generalized east-west cross section.

than 200 feet thick. They are the dominant lithology only along the western outcrop of the Appalachian Basin between Cleveland, Ohio, and central Tennessee. The black shales almost always have a sharply defined basal contact and grade both upward and eastward into the gray shale facies--why, we don't fully know. Black shales appear to differ from greenish-gray shales in their greater content of organic material (Table 4). The high organic content of the black shales is the result of anoxic bottom conditions, which precluded the existence of bottom dwelling organisms; bottom dwellers were, on the other hand, fairly abundant in the greenish-gray shale facies. The organic material of the black shales has had two sources: a terrestrial source to the east and a marine pelagic source within the basin. The former prevails in the black shales in the eastern part of the basin, whereas the latter is predominant in the black shales of the western part of the basin (please see the Summary in Chemical Characterization, 3.2.2). The black shales represent slow deposition by pelagic muds with some contributions by distal turbidites from the east. Trace fossils indicate a gradual deepening of the basin with passage of time (please see Composition, Fabric, Texture, Bedding and Paleontology, 3.2.2.2 for details).

In the absence of gas-show maps for individual stratigraphic units or plots of gas shows projected into regional cross sections, we cannot suggest which shale units are the best reservoirs. It may well be that such generalizations are as yet best restricted to smaller areas such as states rather than the entire basin. A short conference on this question by all the contractors and industry representatives would be very worthwhile, in late spring 1980.

We also include some suggestions for a basin analysis. This report should not exceed 150 typed manuscript pages but should have ample figures, tables, and appendices and have several oversize maps in an accompanying pocket. There could be at least two such reports—one on basin analysis and the relevant geochemistry, and another on well stimulation. Below is one possible format for the basin analysis.

Abstract

Short and key worded.

Objective

What controls gas production, what is its potential and how can it best be obtained?

Conclusions

These should be subdivided into stratigraphy, paleocurrents, lithofacies, thermal history, etc. and together this section, along with reservoir potential, will represent the very heart of the study.

Introdution

History of the project and brief review of other studies of gas recovery from shaly basins.

Basin Analysis

Stratigraphy (correlation network, summary of all cores in the basin etc., paleocurrents, facies geometry, shale and other rock types (lithology and petrology and the possibility of recognizing the diverse types on wire line logs), geochemistry (CHN analysis, C^{13}/C^{12} ratio and types of organic material), structure and tectonics. Brief summary of outstanding local studies that have been made in Pennsylvania (by Piotrowski and his coworkers), Ohio, Kentucky, New York and West Virginia (by Patchen and Schwietering). Include here a list of all the relevant maps and cross sections by states and reproduce a few, simplified at page size, and have one basinwide structure and isopach map, perhaps created from the cross section network supplemented by 100 or less extra wells.

Resource Potential

Probably it is best to appraise resources by state or by natural subregions of the basin, even though basinwide totals will be finally needed. Relation of gas to stratigraphy, and thermal history? Are fractures important? What lithologies are locally the most gas bearing? Total reserves? Do we know any more about gas recovery from the shale now than in 1976, when the project started? This section will be by far the most difficult—and also the most important part of the report and we at Cincinnati are not certain as to how to prepare this part of the report or of the answers to many of the above questions.

Unresolved Questions

What Should be Done Next?

A conference on this question, wherein selected contractors are invited to Morgantown sometime in spring before the characterization phase of the EGSP ends, seems most appropriate.

Appendices

These should be numerous and each more or less self-contained with a brief explanation of why the material in it is relevant and was included.

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CHEMICAL CHARACTERIZATION (3.2.2)

Main Conclusions

The source of the organic matter, terrestrial or marine, in the Devonian-Mississippian shales was studied using carbon isotopes. The results show a terrestrial component with $\delta C^{13} = -26$ combined with a marine component of $\delta C = -31$. The proportion of the marine component, as judged by present information, increases steadily westward within stratigraphic horizons. Paleocurrent studies show that this is the major direction of transport in the basin and thus support our interpretation of a binary mixture of terrestrial and marine carbon. The carbon isotopes suggest that, for the Appalachian Basin, the only source of terrestrial carbon was to the east. That is, the Cincinnati Arch was not emergent, or at least did not have any significant development of land plants.

The range of variation of carbon isotopes within a given stratigraphic horizon is, however, probably not great enough to influence the areal distribution of gas production. Instead, the amount of carbon in the shale and its thermal maturity are more important provided there is a reservoir for it such as intercalated siltstone beds and siltstone laminae and/or a system of microfractures.

The relationship of the amount, source and maturity of the organic matter to gas potential is shown in Figure 8. The amount of carbon within a given stratigraphic horizon decreases steadily eastward, and the thermal maturity of the entire section increases steadily in the same direction.

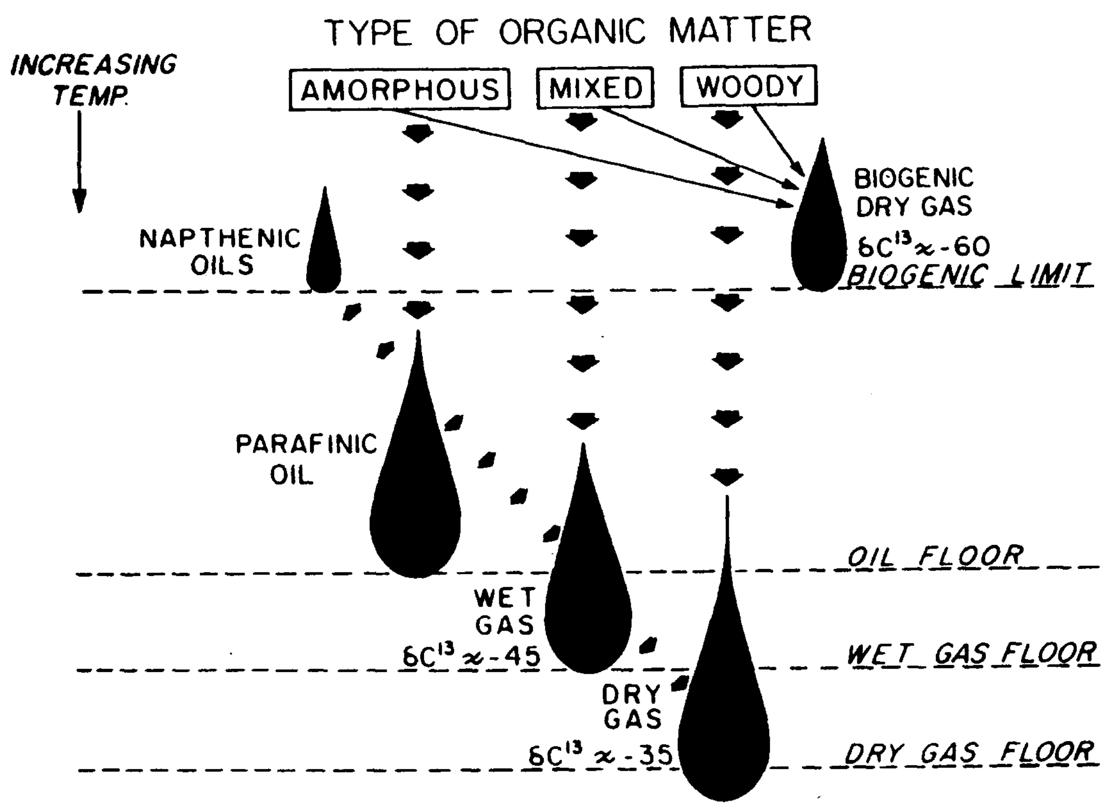

FIGURE 8. Relationship of type of organic matter and the temperature to the generation of oil and gas. It is suggested that more gas is produced from the amorphous organic matter, with oil being produced at an intermediate stage, than is produced in the direct reaction from woody organic matter (redrawn from Dow, 1978, Fig. 2).

Consequently, there is a balance between these opposing trends that ideally leads to an optimum zone for gas potential. *That is, there will be a north-south trending band of favorable shale lying between immature carbon in the west and too little carbon in the east.* Because the distribution of the carbon is different in each stratigraphic horizon, each band will have a somewhat different position within the basin.

Mrs. Kao, our part-time chemical technician and a professional chemist, was a great help to our geochemical effort.

Carbon 13 to Carbon 12 Ratio, C^{13}/C^{12}, and Isotopes of Sulfur (3.2.2.a)

The organic matter preserved in shales is derived from either marine sources, usually plankton, or non-marine sources, mostly woody material. In some lakes, planktonic algae may supply most of the organic matter, resulting in a marine aspect to the organic carbon in the sediment. The Green River Formation is a well-known example. A non-marine source in no way implies a non-marine environment of deposition, because just as with mineral particles, organic matter in a shale can be carried from land areas into marine basins by rivers and winds.

The "marine" or algal organic matter yields more hydrocarbons. It produces both oil and gas, whereas the woody organic matter gives only gas (Fig. 8). Accordingly, the woody organic matter would seem to be more desirable for gas, the algal for oil. However, recent laboratory work (Harwood, 1978, Fig. 18) suggests that the algal type of organic matter actually generates more gas than the woody material.

How can these two types of organic matter be distinguished? A variety of methods are now in use. In the most popular, the proportions of woody and amorphous (mostly algal) particles are estimated petrographically, using samples from which all the mineral matter has been dissolved. We tried two chemical methods: carbon isotopes and lignin derivatives. Here we discuss the results of our carbon isotopes studies and the lignin derivatives are discussed under phenolic aldehydes in section 3.2.2.d.

In modern sediments, terrestrial organic matter differs appreciably from marine in its carbon isotope composition (Fig. 9). Further, this difference can be used to infer the porportion of each type at a given site. That is, maps can be made that show the direction of increasing terrestrial influence, which normally should be the direction of the shoreline. In a vertical section, fluctuations in the carbon isotopes can be used to reconstruct changes in the proportions of these two types with time (Fig. 10) and hence give some idea of relative proximity to shoreline.

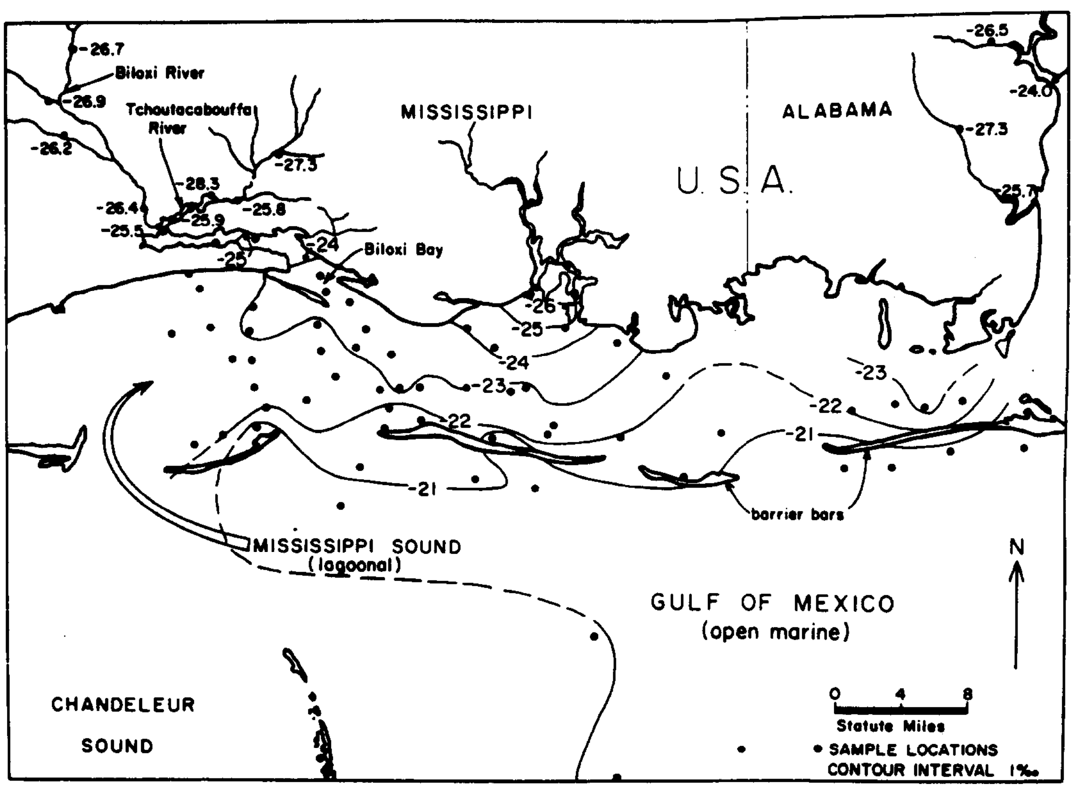

FIGURE 9. Offshore decrease in δC^{13} in the Eastern Gulf of Mexico reflecting decreasing terrestrial organic matter (Sackett and Thompson, 1963, Fig. 1).

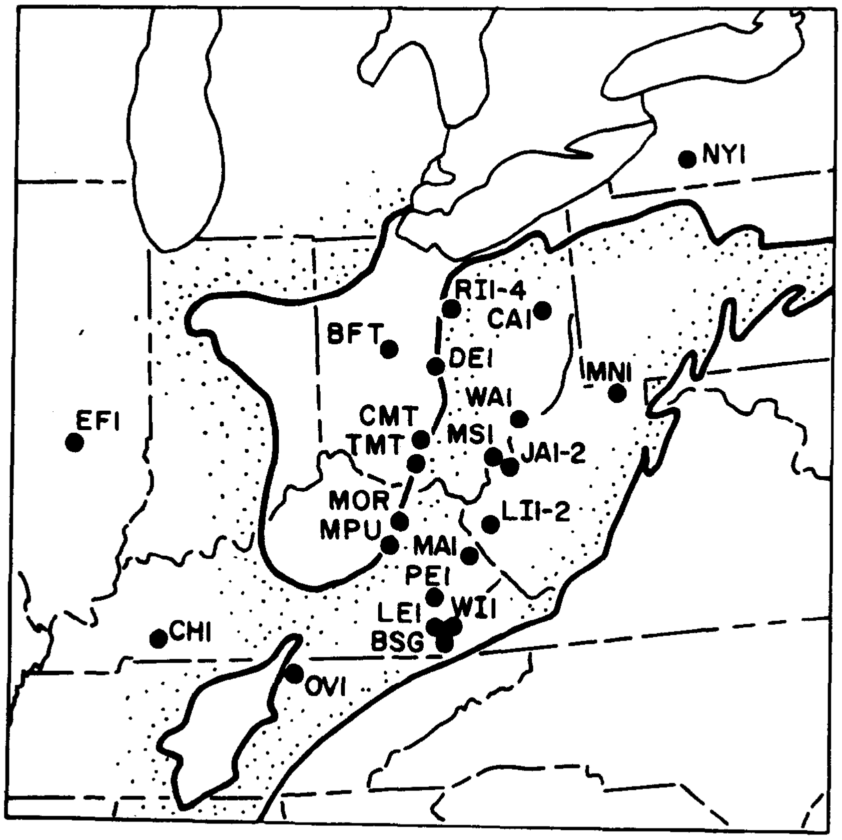

FIGURE 10. Locations of wells and outcrops studied by the Cincinnati group for carbon isotopes.

The number in both of these figures is expressed as δC^{13} where

$$\delta C^{13} = 1000[(C^{13}/C^{12}_{sam} \div C^{13}/C^{12}_{std})] - 1$$

Similar horizontal and vertical patterns can be seen in the Devonian-Mississippian shales (Figs. 10, 11 and 12). The map pattern closely follows that of the westward oriented paleocurrents in the basin (please see Fig. 1), that is the isotope values become steadily more negative away from the source area. Note, however, that this trend is the reverse of

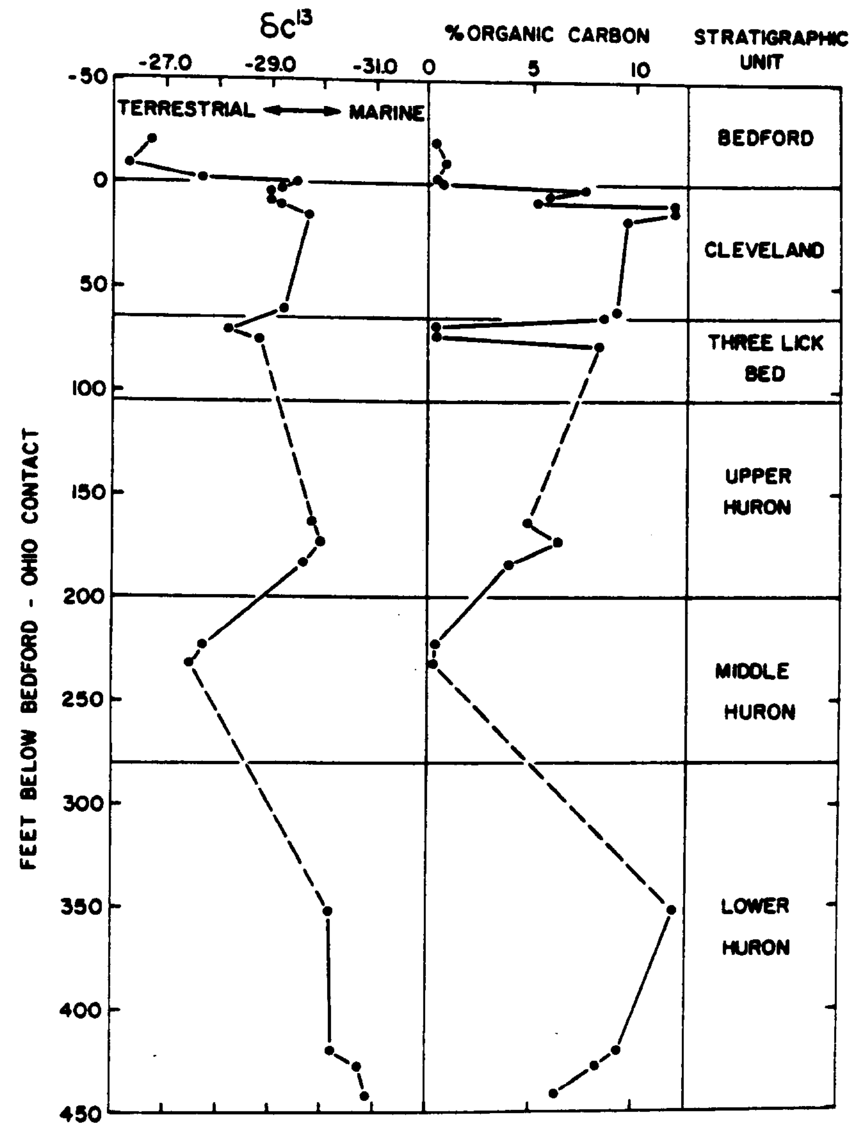

FIGURE 11. Vertical variations in δC^{13} of the Devonian-Mississippian shales in Richland County, Ohio. Lines are dashed between samples that are too widely spaced to reflect the stratigraphy.

that in modern sediments where the off-shore samples are less negative (Fig. 9). Completely non-marine carbon, as found in wood pieces and non-marine shales in the Devonian Catskill fluvial sediments to the east, has a δC^{13} of about -26 per mil (Table 5). A diagenetic process, whereby the light isotope, C^{12}, is preferentially enriched in marine carbon is discussed in a paper submitted to Geology. Accordingly, we believe that there are only two important sources of carbon in the basin: a non-marine

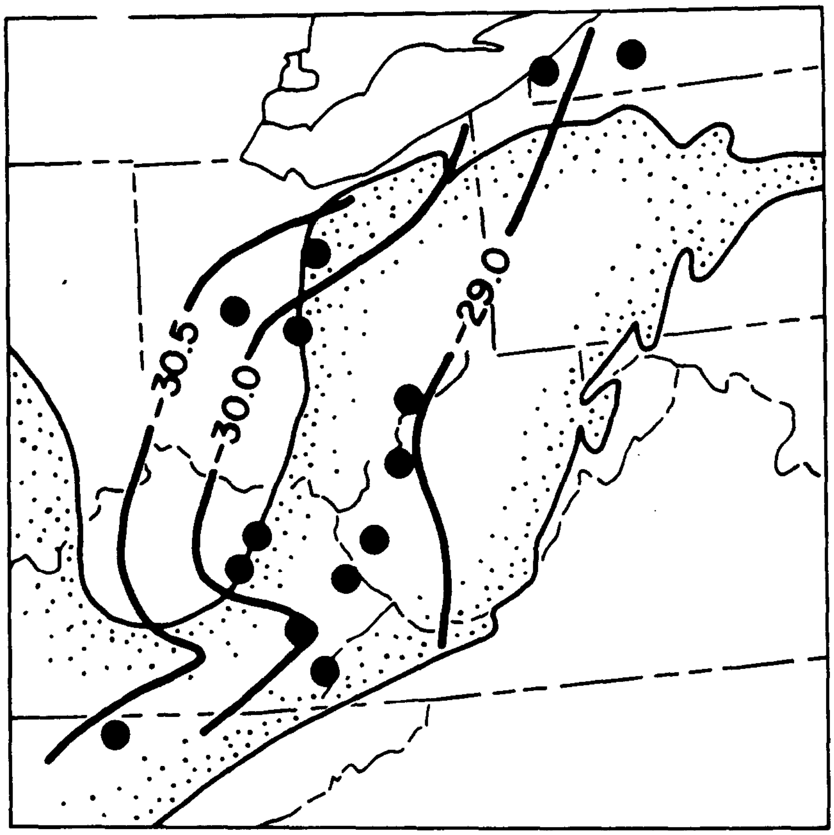

FIGURE 12. Areal distribution of carbon isotopes in the Lower Huron Member of the Ohio Shale. The carbon becomes steadily more marine in character westward.

TABLE 5. Average and standard deviation of carbon isotopes in Devonian and Mississippian shales of Appalachian Basin by stratigraphic unit.

Stratigraphic Unit	Average δC^{13}	Number of Samples
1. Appalachian Basin		
a. Marine Samples		
Sunbury	-30.1 ± 0.2	8
Bedford	-27.7 ± 1.0	9
Ohio Shale		
Cleveland Member	-28.9 ± 0.6	36
Chagrin Member	-27.4 ± 0.9	16
Huron Member		
Upper	-29.2 ± 0.5	17
Middle	-29.0 ± 0.7	26
Lower (Dunkirk)	-29.8 ± 0.6	39
Java Group		
Hanover	-28.4 ± 1.2	3
Pipe Creek	-29.7 ± 0.9	3
West Falls Group		
Angola	-27.6 ± 0.4	2
Rhinestreet	-29.7 ± 0.7	19
b. Non-marine Samples	-25.7 ± 0.8	3
Catskill Shale, Gilboa, NY		
Wood Fragment, Olentangy Sh, OH		
Wood Fragment, Huron Sh, KY		
2. Illinois Basin		
New Albany Shale		
Grassy Creek Member	-29.6 ± 0.5	12
Swetland Creek Member	-29.8 ± 0.6	7
Blocher Member	-30.2 ± 0.2	3

source ($\delta C^{13} \simeq -26$) and a marine source ($\delta C^{13} \simeq -32$), and that the carbon isotopes of the organic matter reflect the proportions of these two end members. The isotope values can then be used to reconstruct the proximity to the shoreline and the direction of transport, when samples from a single stratigraphic horizon are compared. Such analysis suggests that non-marine carbon was derived only from the east; that is, that the Cincinnati Arch was not emergent as postulated in some models for the basin's history (cf. Schwietering, 1979).

There are also pronounced vertical variations at a single location, which tend to follow the stratigraphy. With some exceptions, such as the Bedford Shale, the greenish-gray shales tend to show more terrestrial δC^{13} values, the black shales more marine (Table 5). Why the contrast between greenish-gray and black shales? Some of the greenish-gray shales, such as the Bedford, were probably deposited closer to the shoreline and received more terrestrial carbon. However, closely interbedded greenish-gray and black shales in some units such as the Three Lick Bed also have this contrast in δC^{13} values. Surely the greenish-gray interbeds were not deposited closer to the shoreline, but may well represent deposition by far distal turbidites which carried sediment-laden and oxygenated water into anoxic bottom waters.

The important difference in the deposition of the greenish-gray and black shales seems to have been the amount of oxygen. Based on the presence of bioturbation in many of the gray shales and its absence in the black, except where immediately overlain by a gray shale, most of the gray shales must have been deposited from water containing free oxygen, thus allowing a burrowing fauna to develop, whereas the black shales were deposited in anoxic water. This difference in oxygenation might affect the type of organic matter that is eventually preserved in the sediment. Woody organic matter is probably more resistant to decomposition than algal. Thus it is preferentially concentrated under the conditions of higher biological activity prevailing during the deposition of the gray shales. The marine, or algal, organic matter only survives in large amounts in the black, anoxic muds. Therefore, the more non-marine δC^{13} values in some of the greenish-gray and gray shales may be caused by diagenetic enrichment rather than by provenance. In conjunction with our study of the isotopes of carbon we also examined isotopes of sulfur in pyrite. This helped us estimate sedimentation rates in the basin (Fig. 13), which are related to the carbon content of the shale (please see Publications, Maynard).

Vanadium-Nickel Ratio (3.2.2.b)

The Devonian black shales are rich in heavy metals, uranium being of particular economic interest. It has been suggested that these can be used to infer the source of the organic matter or the environment of deposition (Keith and Degens, 1951). Vanadium and nickel are two elements that are commonly cited as being valuable for environmental analysis. One of our students, Michael Lewan, has studied the vanadium and nickel in extractable organic matter from a number of shales, including the Ohio and the New Albany. His results suggest that, for the most part, the amount of carbon controls the amount of the metals present. Leventhal (1978) reports similar results. The relative amounts of vanadium and nickel, however, are controlled by the sedimentation rate, as measured by sulfur isotopes (Fig. 14).

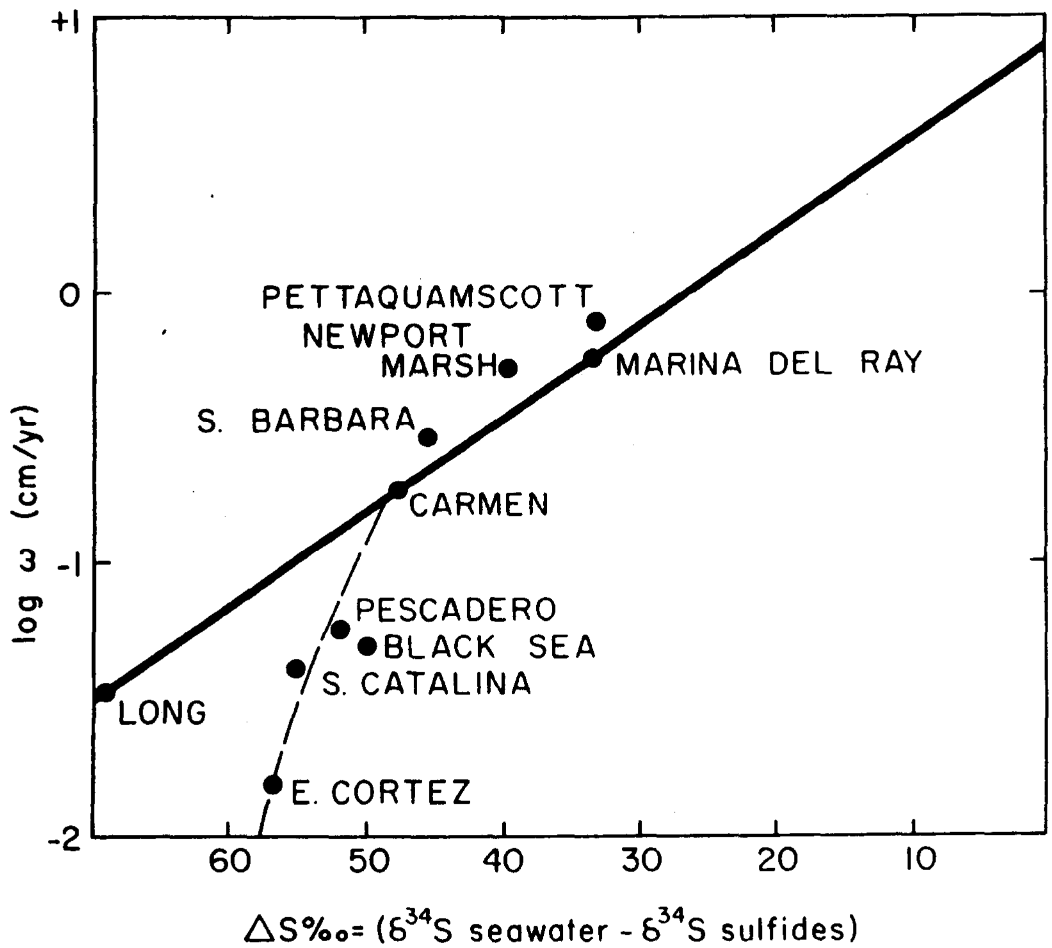

FIGURE 13. Relationship of sulfur isotopes to rate of sedimentation, ω, in recent sediments. Curves of this type may provide a supplementary means of estimating relative rates of sedimentation of the Devonian Shales of the Appalachian Basin and possibly for other shales as well.

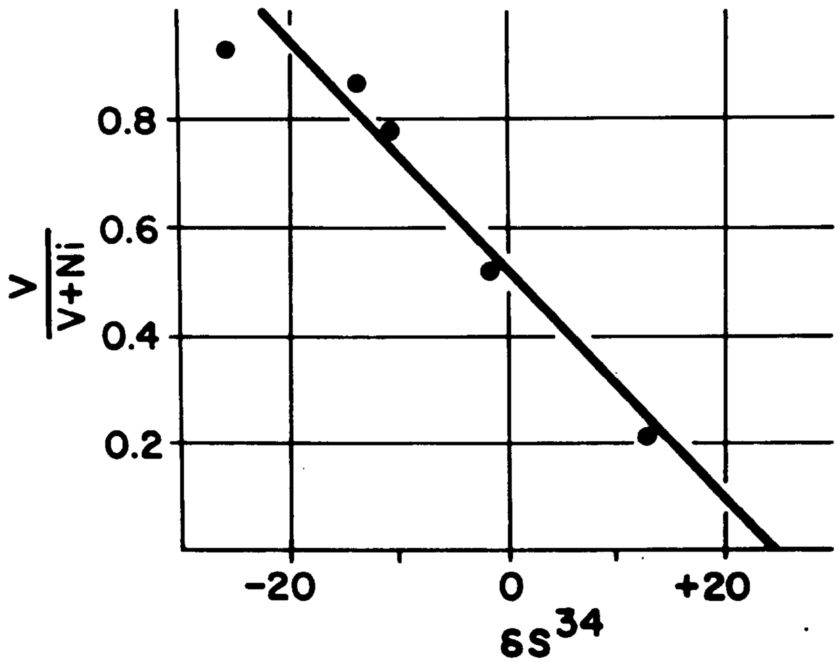

FIGURE 14. Relationship between V and Ni and sulfur isotopes, which suggests control of the V/Ni ratio by the rate of sedimentation.

Sedimentation rate appears to be one of the most important influences on shale geochemistry (Curtis, 1978). As noted earlier, we proposed that the rate of sedimentation of ancient shales can be estimated, at least on a relative scale, from the sulfur isotopic composition of pyrite (see Publications, Maynard). In both recent sediments and in the Devonian shales we studied, δS^{34} becomes increasingly more negative at lower sedimentation rates.

Application of this scale to the V and Ni data of Figure 14 shows that at low sedimentation rates the organic matter incorporates a large amount of vanadium relative to nickel. One explanation for this is that in slowly deposited sediments the organic matter spends more time in contact with seawater and so can absorb more vanadium. Conditions in most basins do not favor much uptake of nickel from seawater, thereby producing the high V/Ni ratios of the slowly deposited sediments. Thus distal slowly deposited shales are enriched in vanadium. Uranium probably follows the same pattern. Could it be that much of the scatter in plots of uranium vs. carbon can be explained by variations in sedimentation rate? We are inclined to think this is the explanation. One way to test this hypothesis would be to make detailed comparisons of sulfur isotopes and uranium concentrations.

Carbon, Hydrogen, and Nitrogen Analysis (3.2.2.c)

Cincinnati and other contractors have made a large number of analyses of the C, H, and N content of the Devonian shales. For the most part, these analyses were made using a combined CHN analyzer such as the Perkin-Elmer 240, although it is also possible to determine the amount of carbon petrographically (Fig. 15). These carbon analyses have a very skewed distribution (Fig. 16), a pattern that appears to be typical of shales (Gehman, 1962, Fig. 2). However, because all of the samples with carbon higher than 3 percent are black, there is actually a bimodal distribution, with respect to color, into two populations of gray and black. The basic stratigraphic subdivisions reflect this distribution (Table 6). Carbon content can also vary within as well as between stratigraphic units. For instance, within the Lower Huron (or Dunkirk) average carbon decreases dramatically from west to east (Fig. 17). Two factors are responsible: first, there is an increase going eastward in the number of gray and greenish-gray shale interbeds and secondly, the carbon content of the black shale interbeds also decreases. In this way, the black shale units pass eastward into gray shales and are no longer identifiable.

The amount of carbon should be related to a shale's hydrocarbon potential. Confirmation comes from a comparison of the oil yield by

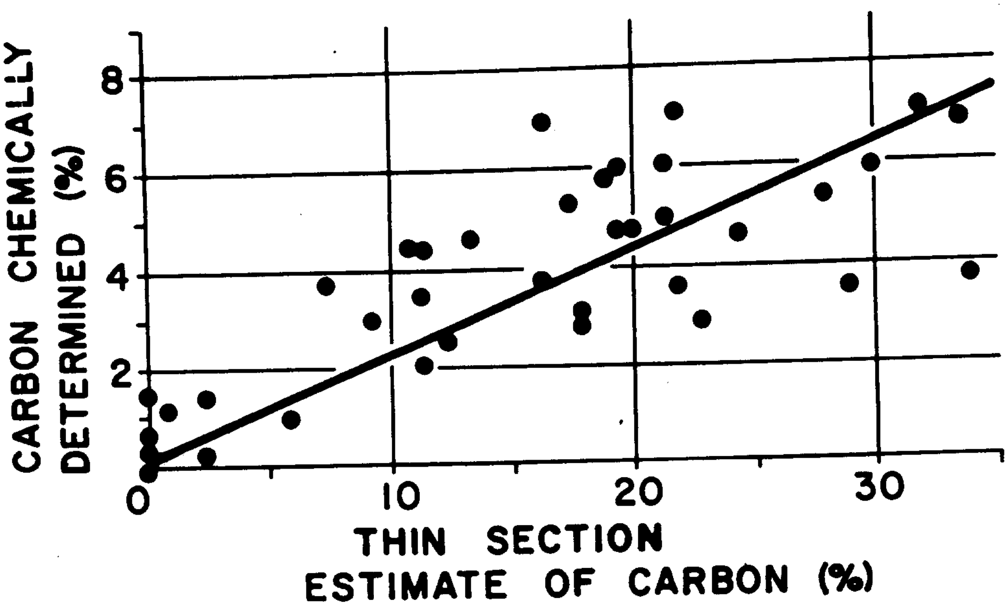

FIGURE 15. Comparison of organic matter determined by petrography (a volume measurement) to chemical determination (weight precent).

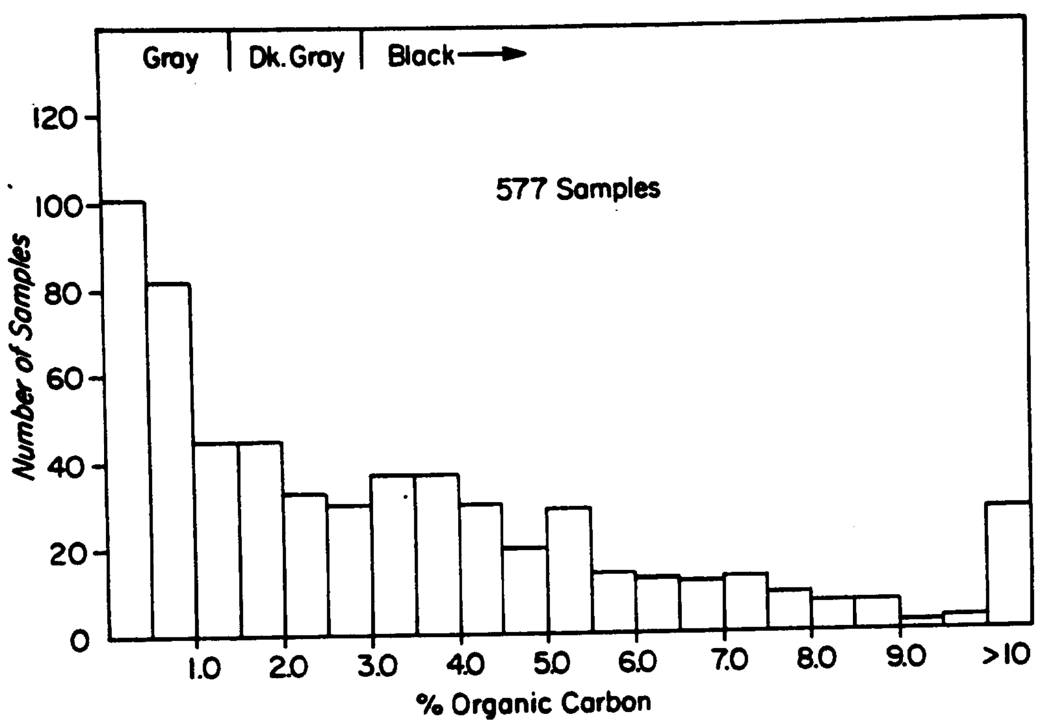

FIGURE 16. Distribution of carbon analyses. Note that most of the shales are either gray or black although the carbon content varies continuously.

TABLE 6. Average organic carbon content (weight percent) in stratigarphic units of the Devonian-Mississippian shale in the Appalachian Basin. (See Fig. 17 for locations.)

Unit/ Well	WV. MS1	WV. MN1	WV. JA1-2	WV. LI1-2	VA. WI1	VA. BSG	NY. CT1	NY. DNK	OH. CA1	OH. WA1	OH. RI1-4	OH. DE1	OH. AS1	OH. BFT	KY. PE1	KY. MA1	KY. LE1	KY. MPW	KY. MOR
Bedford Shale						0.82					0.48								0.33
Ohio Shale																			
Cleveland Member					5.11	4.50					7.41				6.14	5.50	4.43	15.0	9.23
Chagrin Shale*				0.37	1.08	1.69									0.66	1.21*	0.24	0.36	0.47
U. Huron Member				1.07	--	5.04					5.10				4.22	3.56	2.86	--	3.77
M. Huron Member	0.68		1.49	0.91	1.66	1.39			0.30		0.33				3.19	2.18	--	10.1	--
L. Huron Member	1.72		2.83	3.69	3.23		1.10	1.74		2.57	6.28	8.68	2.95	10.9	5.37	3.96	4.67	17.3	9.55
Hanover Shale	0.21		0.23	--			0.78						--		0.73	0.80			
Pipe Creek Shale	2.51		1.85	--			4.01						9.88			3.57			
Angola Shale	1.02			--			0.17						--						
Rhinestreet	3.27			4.62			1.67		5.43				6.73						
U. Mahantango									0.65				--						
L. Mahantango		1.91											--						
Marcellus Shale		5.34											4.30						

*Excludes black shales of the Three Lick Bed. A dash indicates that the unit is present, but was not sampled.

Sources: Cincinnati Quarterly Reports; Mount Laboratory Quarterly Reports (METC Open file #051); Lamey and Wilders, 1977; Lamey, et al., 1978.

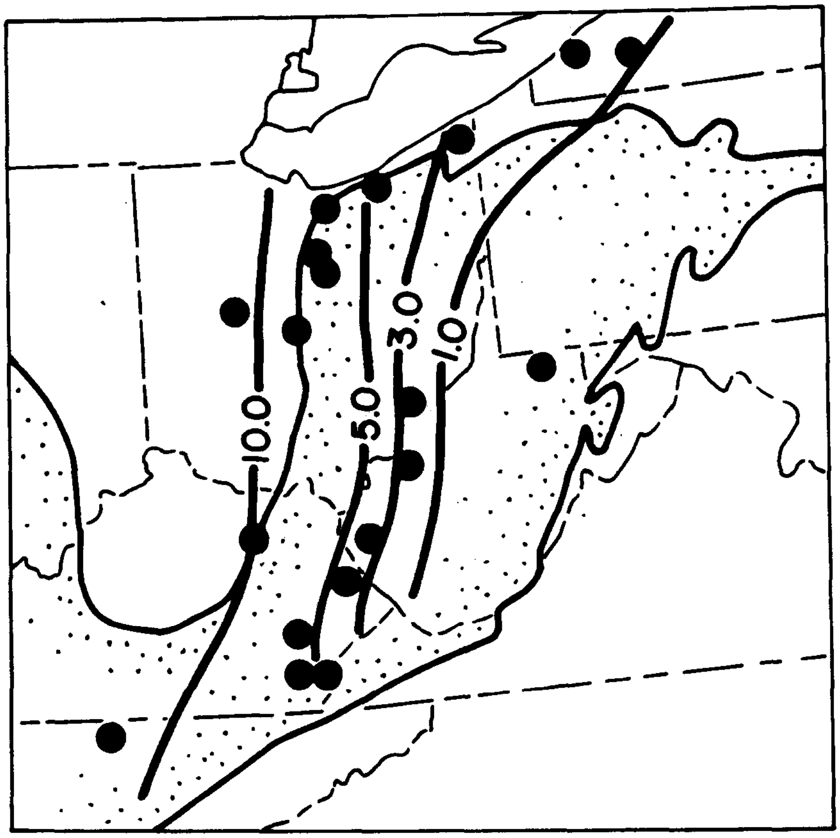

FIGURE 17. Distribution of organic carbon (weight percent) in the Lower Huron Member of the Ohio Shale or Dunkirk Shale in New York.

Fischer Assay with the amount of carbon (Fig. 18). Gas yield by material balance assay is similar but was noted to vary with geographic position. This variation is probably due to differences in thermal maturity of the organic matter.

Along with carbon, measurements were also made of hydrogen and nitrogen. Their distribution seems to be controlled by thermal history. We determined H and N on the whole sample, after removing carbonates, instead of on kerogen isolates. Thus the raw data reflect total H and N—that in the organic matter plus that contained in minerals. To correct for this mineral contribution, a plot is made for each well of H and N versus C (Fig. 19). The intercept at zero carbon gives the amount of mineral H or N, and the slope gives the H/C or the N/C ratio. The relationship of these two quantities to thermal maturity can be seen by comparing the H/C or N/C ratios for a given well with vitrinite (small coaly particles) reflectance data (Fig. 20).

The reflectance of vitrinite is probably the best estimator of thermal maturity in the shales. In the Devonian shales of the Appalachian Basin, reflectance reveals steadily increasing maturity to the east and southeast (Fig. 21). Most of the other organic chemical measurements on the shale samples follow thermal maturity closely (Table 7). We have already pointed this out for H/C ratios; N/C is much the same, despite the fact that the source of the organic matter in a given well fluctuates sharply with stratigraphic position. In recent sediments, the N/C ratio has been used to describe the nature of the organic matter (Stuerman, et al. 1978, p. 993), but temperature seems to be the only important control in the Devonian shales.

Another common measure of thermal maturity is the crystallinity of illite, which has been shown to improve significantly during advanced diagenesis in some basins (e.g., Foscolos, et al., 1976). For the Devonian shales in the Appalachian Basin, however, the illite crystallinity is uniformly good throughout (Table 8), and shows no tendency to improve with increasing reflectance values, except at the eastern limit of subsurface samples in Monongalia County, West Virginia. We conclude that the illite in the Devonian shales inherited a good crystallinity from their source area. Only to the east of central West Virginia were burial depths great enough to enhance crystallinity.

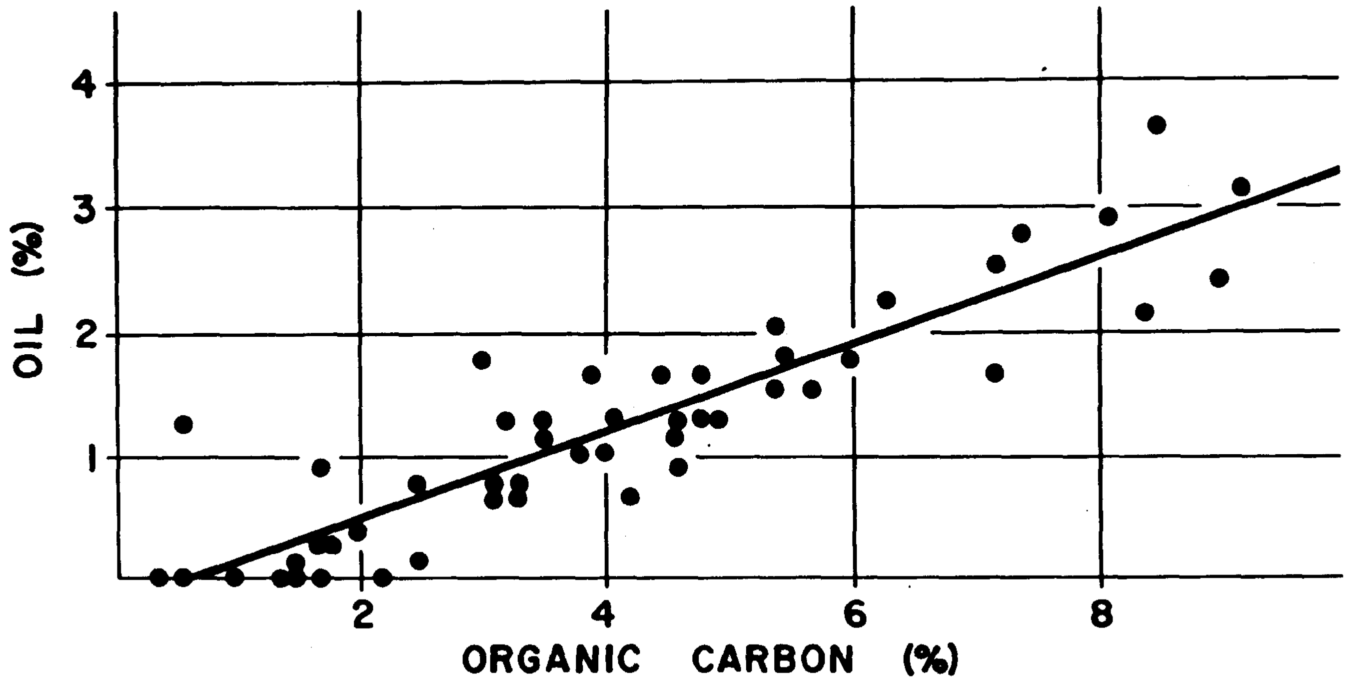

FIGURE 18. Oil yield by Fischer Assay versus carbon in the Perry County, Kentucky core. Data from Lamey and Childers, 1977.

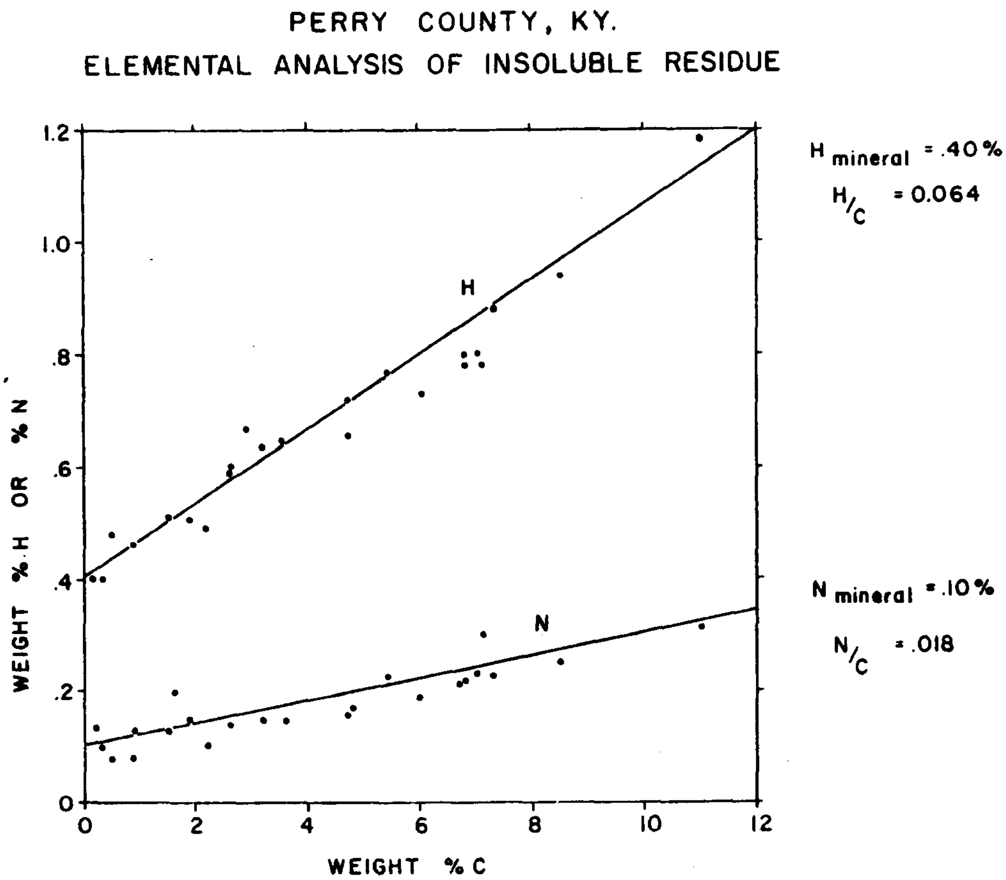

FIGURE 19. H and N versus organic carbon. The slope of the line gives the H/C or N/C ratio of the organic matter in the well.

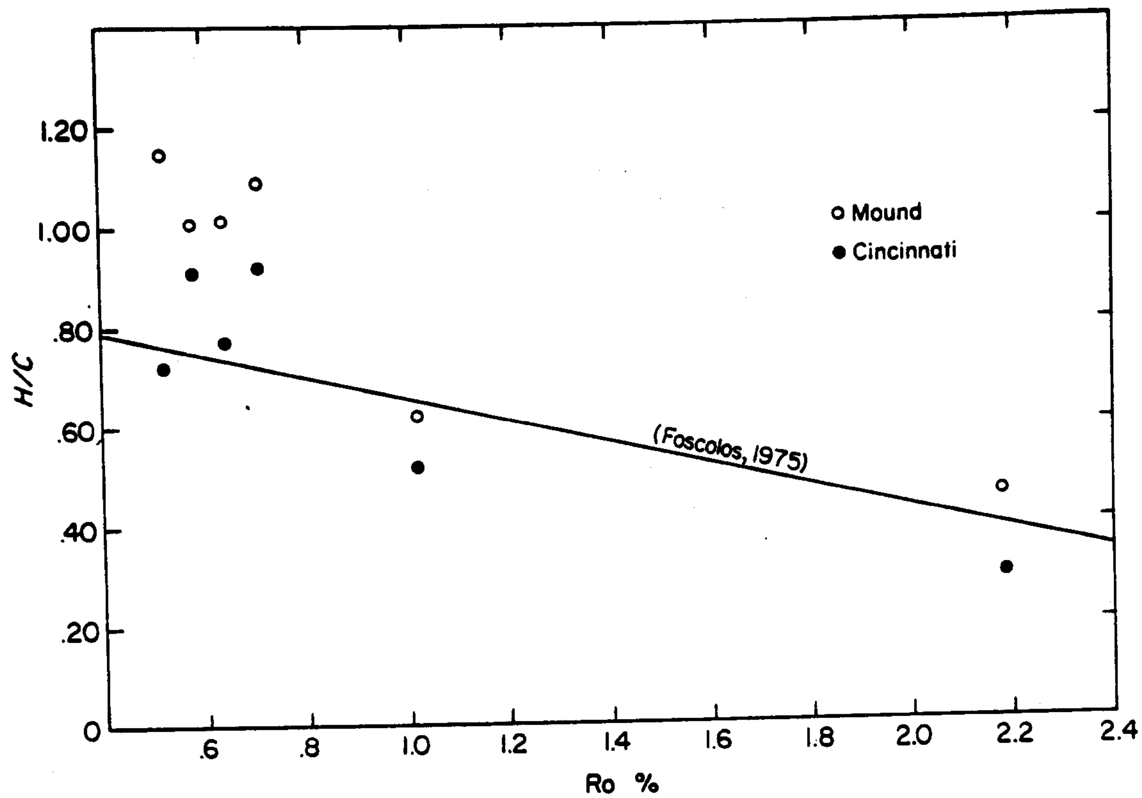

FIGURE 20. Comparison of atomic H/C ratio and vitrinite reflectance

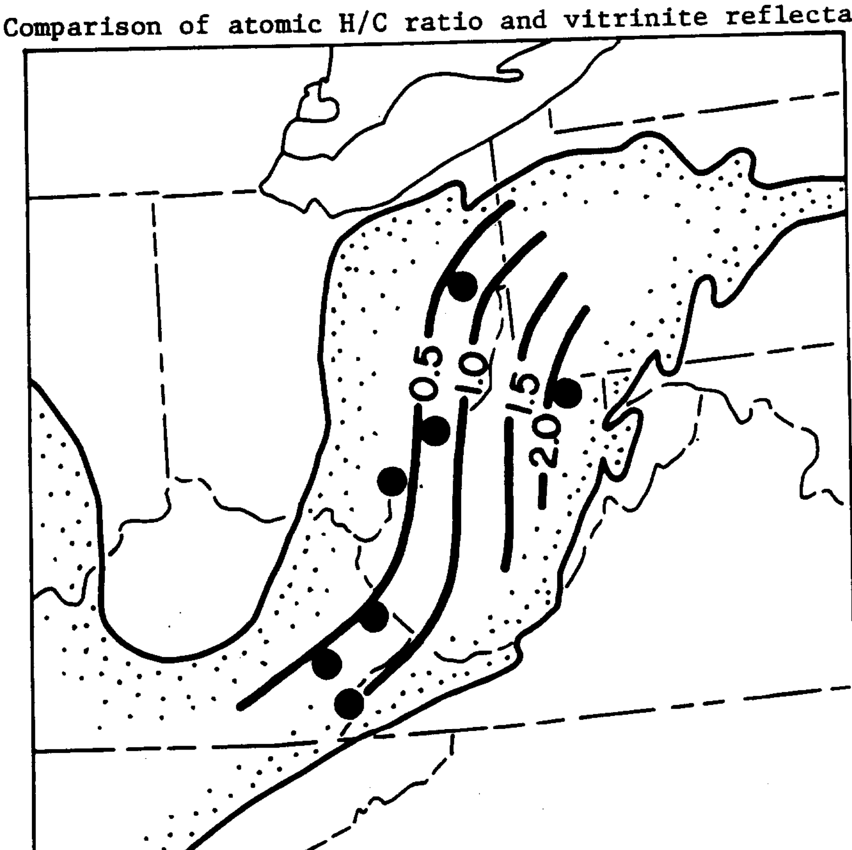

FIGURE 21. Thermal maturity of organic matter in the Appalachian Basin as indicated by vitrinite reflectance. Values are $\%R_o$.

TABLE 7. Various indicators of thermal maturity of organic matter in the Devonian-Mississippian shales of the Appalachian and Illinois Basin. (See Fig. 10 for well locations.)

		Reflectance % Ro	H/C Mound	H/C Cinti.	N/C Cinti.	Aliphatic/Aromatic Hydrocarbons	Extraction Ratio
1. Appalachian Basin							
WV.MN1	WV6	2.19	0.46	0.38	0	3.35	0.17
VA.WI1	VA1	1.02	0.62	0.52	.012	1.27	1.4
OH.CA1	OH1	0.71	1.09	0.92	.019	1.00	9.6
KY.PE1	KY1	0.68	--	0.77	.015	--	8.4
WV.MS1	WV5	0.64	1.18	--	--	0.91	12
OH.WA1	R109	0.58	1.10	0.91	.019	1.09	9.3
KY.MA1	KY2	0.52	1.15	0.72	.012	0.96	9.4
WV.JA1-2	--	--	--	0.95	.014	--	9.9
WV.L11-2	--	--	--	0.97	.016	--	--
OH.R11-4	--	--	--	0.86	.022	--	--
KY.LE1	--	--	--	0.89	.020	--	--
NY.CT1	--	--	--	0.86	.020	--	--
OH.DE1	--	--	--	1.03	.020	--	--
2. Illinois Basin							
IL.TA1	I3	0.46	1.17	--	--	0.55	4.7
IN.SU1	P1	0.46	1.25	--	--	1.24	8.9
IL.EF1	I1	0.45	1.26	1.30	.017	0.94	4.8
KY.CH1	O1	0.45	1.17	0.91	.024	0.57	4.6
IL.HE1	I2	0.40	1.47	--	--	0.54	7.9
TN.OV1	--	--	--	0.88	.015	--	--

Sources: Cincinnati Quarterly Reports; Mound Laboratories Quarterly Reports (open file #051); Lamey and Childers, 1977; Lamey, *et al*. 1978.

TABLE 8. Average crystallinity of illite (m.m.) of each formation by well. (See Fig. 10 for locations.)

Stratigraphic Unit	VA.WI-1	KY.LE-1	KY.MA-1	KY.PE-1	OH.RI(1-4)	TN.OV-1	WV.MN-1
Sunbury		9.4					
Bedford		8.1			7.4		
Cleveland	7.35			7.7	7.25	6.65	
Three Lick Bed	6.45	5.85	5.75	6.05			
Upper Huron			6.2	6.85	6.7		
Middle Huron	5.90	6.2	6.55	5.65	6.2		
Lower Huron	6.25	5.8	7.0	5.9	6.15		
Olentangy			7.13	5.45			
Marcellus							
Mahantango							4.2

What effect does thermal maturity have on gas production? We have already argued that the source of the organic matter is relatively constant _within_ a given stratigraphic unit. Therefore the principal controls on gas generation, considering both original sedimentation and diagenesis, are the amount of carbon and its maturity. Figure 22 illustrates the effect of the amount of organic carbon on gas yield and the effect of increasing maturity is shown, schematically, in Figure 23. Note that gas yield increases with increasing maturity, up to a limit beyond which no hydrocarbons are found. Thus the balance between the amount of organic matter and its maturity will determine the potential for gas production. In the Appalachian Basin these two have nearly opposite trends: carbon decreases eastward while maturity increases. Consequently, for each individual stratigraphic horizon, there should exist an optimum zone for gas, structural factors such as fracturing aside, lying between temperatures too low in the west and too little carbon in the east (Fig. 23). The thermal maturity is about the same for every stratigraphic unit in a given well. The carbon distribution, however, is not. Because the delta that filled the basin prograded from east to west, the position of the distal, carbon-rich black shales shifted westward with time. As a result, this zone of optimum gas yield should lie farther and farther east with each older and deeper tongue of black shale. In practical terms, older units like the Rhinstreet and the Marcellus may be good producers of gas east of present gas production. Earlier Harris _et al_. (1978, p. 165) suggested this possibility using the gamma-ray stratigraphy of the shale sequence.

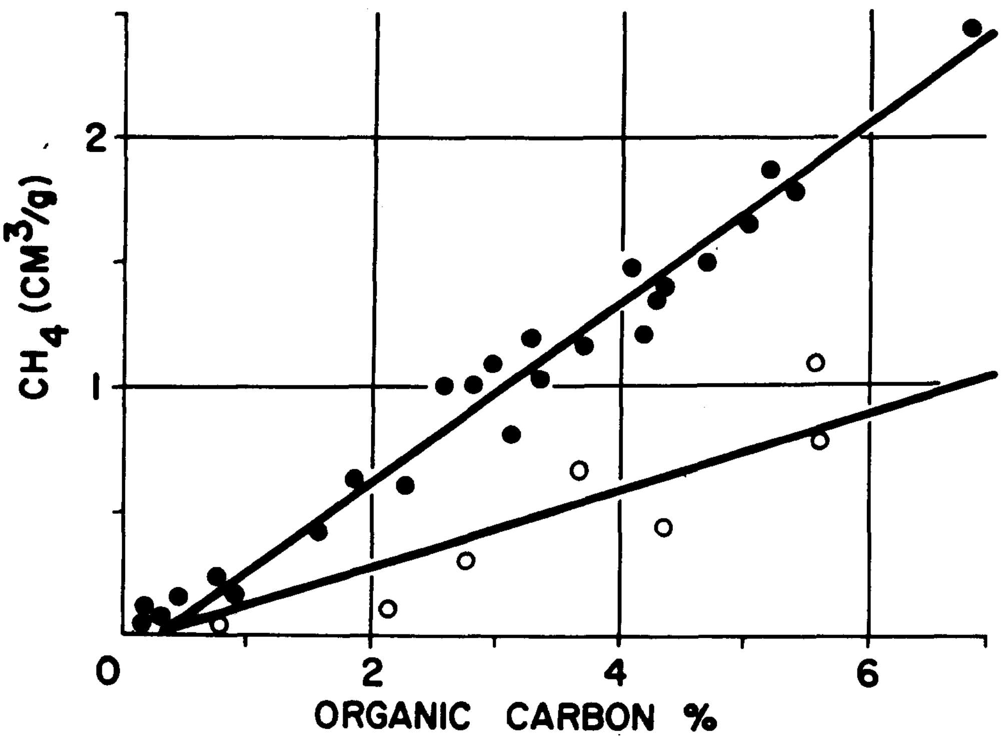

FIGURE 22. Gas yield versus organic carbon. Solid circles Martin County, Kentucky; open circles Wise County, Virginia. Data from Mound Laboratory quarterly reports.

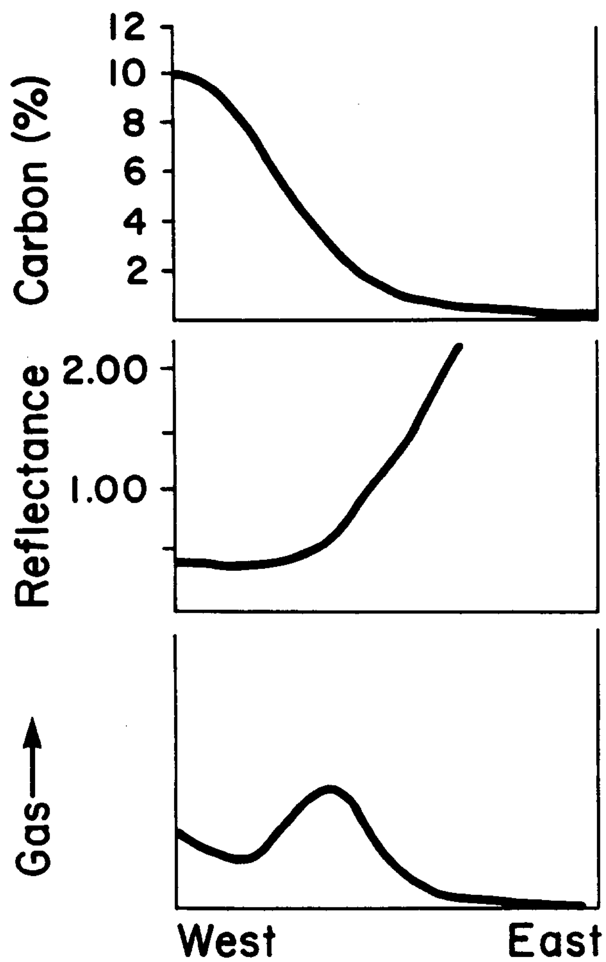

FIGURE 23. Possible relationship of gas yield to the balance between the amount of carbon and its thermal maturity. Top two graphs are for the Lower Huron on east-west line at the latitude of the southern border of Pennsylania. The bottom curve is speculative.

Phenolic Aldehydes (3.2.2.d)

Terrestrial plants, in contrast to marine, contain large amounts of lignin. This substance breaks down in sediments to yield various phenolic compounds. These can then be analyzed in the sediment and used as a measure of the relative contribution of these two sources of organic matter (Gardner and Menzel, 1974). Unfortunately, these compounds occur in amounts too small to analyze quantitatively in these rocks, so this measurement was abandoned.

Aliphatic and Aromatic Hydrocarbons (3.2.2.e)

Another measurement that has been proposed as a provenance indicator is the ratio of aliphatic to aromatic hydrocarbons (Baker, 1972, Fig. 4). These are determined by column chromatography of benzene-methanol extracts from the shale. Baker has suggested that high aliphatic to aromatic ratios indicate marine organic matter. This ratio is very constant for all of the wells in the Appalachian Basin, except Monongalia County, West Virginia (WV.MN1), which has the highest thermal maturity (Table 7). This ratio does not vary with stratigraphic position in a given well. As is true for the CHN analyses, such a pattern suggests strongly that there is little control by the type of organic matter. The Illinois Basin data are, by contrast, quite variable, although there does not seem to be any relationship to position in the basin or to thermal history.

Another interesting quantity that can be determined at the same time as the aliphatic and aromatic hydrocarbons is the extraction ratio. This quantity is the weight of material extracted divided by the weight of organic carbon (mg) x 100. Again, this quantity shows some correlation with thermal maturity (Fig. 24), but very little with stratigraphic position. Some gray and greenish-gray shale samples, however, particularly those near beds of black shale, show anomalously high ratios. That is, they have too much extractable material for the amount of carbon present. This deviation may reflect the increasing error in the measurements at very low carbon contents, but it may also indicate migration of hydrocarbons from the black to the gray shales. Many samples with low carbon also show anomalously high H/C ratios, a relation again consistent with the introduction of hydrocarbons. For this reason, only values from those samples with C exceeding 1 percent were used in Table 7. This pattern suggests that, at least in some places in the basin, the black shales may act as source beds while the adjacent gray shales act as reservoir rocks—a conclusion obtained independently by Mr. Broadhead in his Study of the Ohio Shale along Lake Erie.

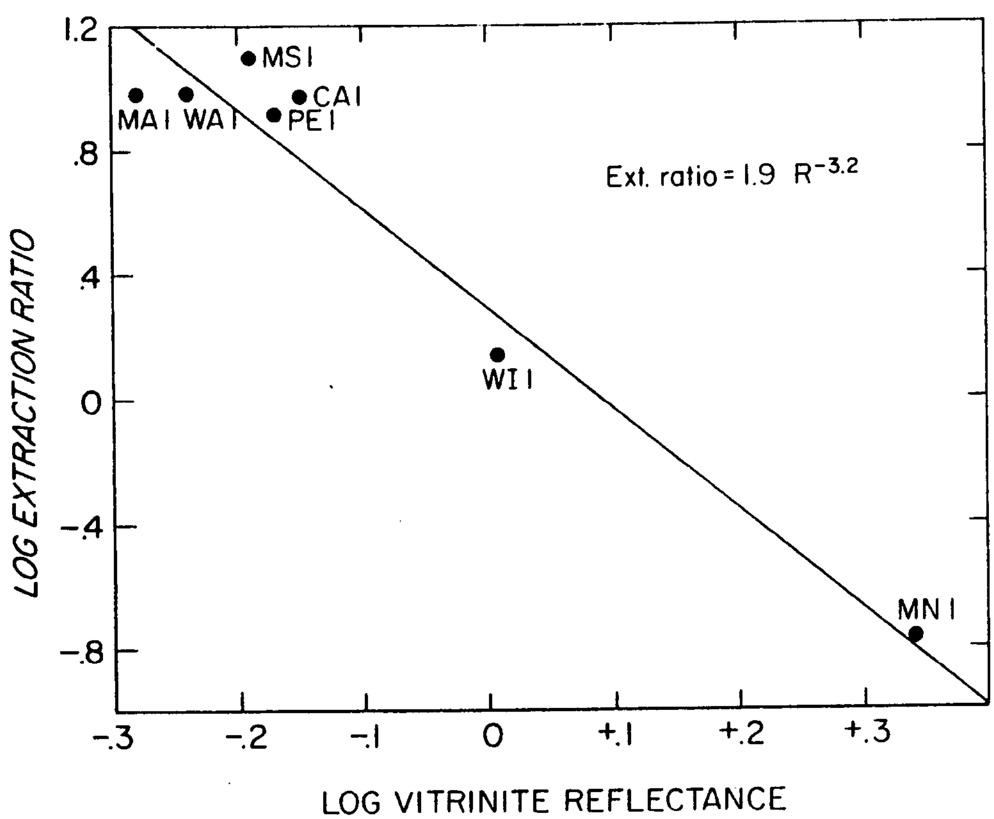

FIGURE 24. Amount of extractable carbon in the Devonian Shales (normalized by percent carbon) compared to thermal maturity.

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COMPOSITION, FABRIC, TEXTURE, BEDDING AND PALEONTOLOGY (3.2.2.2)

This work was largely done by four students: Thomas Stenbeck, who worked on core and outcrop materials in and near the Pine Mountain Overthrust; Ronald Broadhead, who studied the petrology of the Devonian Shale along Lake Erie and related both petrology and stratigraphy to gas shows; and Paul Lundegard and Neil Samuels, who developed a field classification of the shales associated with the Brallier Formation along the southeast side of the basin. In addition, Mr. Greg Hinterlong, a technician hired in the last year of the project, did all the x-ray fabric work. The work of each degree candidate is available in his thesis (Lundegard, Samuels and Broadhead have defended), and in some derivative publications which are in press "Field Classification of Fine-Grained Sedimentary Rocks" by Lundegard and Samuels and will be published by the Journal of Sedimentary Petrology, or in review with the U.S. Geological Survey, "Geology and Gas Potential of the Devonian Shale Along Lake Erie" by Broadhead, Kepferle and Potter. Below is a summary and evaluation of this work.

Almost all the petrology was done with thin sections using either a Zeiss Student microscope or a Zeiss Ultraphoto at 300 to 400 magnification. Minor effective use made of the SEM, a model ISI Miniscan II, although considerable effort was expended on it. Thus our experience suggests that thin section study is superior to SEM study for shale petrography, at least for the Devonian shales of the Appalachian Basin. The x-ray was used to help identify components and shale fabric, but not for radiographs. The latter technique appears to be very useful, however, because of its ability to effectively define lamination and/or bioturbation and has been used to great advantage by the Illinois Geological Survey.

The most relevant is the work of Broadhead, because he related shale types based on thin section petrology to gas shows. This was clearly not possible in the outcrop study of Lundegard and Samuels and was not done by Stenbeck. Additional information generated by these petrographic studies include average composition of stratigraphic units, origin and significance of silt laminae within the shale and how to classify shales petrographically. Judged in their entirety, all of the above studies should be considered exploratory, because none of them attempt to marshall or characterize the shale petrology of the entire basin—a gigantic task, which we as yet are not totally certain how to do. Hence the petrographic results below are probably most useful as a guide to what direction possible future petrologic studies of the Devonian Shales of the Appalachian Basin should take and to decide what role, if any, shale petrology plays in assessing the gas potential of the basin.

Devonian Shale Along Lake Erie

In the study of the Devonian Shale along Lake Erie, textural analysis concentrated on lamination and coarsest grain size both of which were studied in 136 thin sections obtained from both outcrops and cores. Lamination was studied, because it is the most striking sedimentary structure of shales and its presence or absence was thought to be very relevant to gas potential. The study of lamination aids reservoir analysis, because it helps to define the distribution and continuity of lithologic facies and also aids in the interpretation of depositional environemnts (Hallam, 1967; Reineck, 1974). Three basic types of lamination were found in the Ohio and Chagrin Shales along Lake Erie (Table 9): clay laminae, organic laminae, and quartz laminae. Laminae were described in terms of their thickness, nature of the contacts with the surrounding rock, lateral continuity, and for the quartz laminae, type of grading: quartz laminae are ungraded, coarse-tail graded and distribution graded (Middleton, 1967, p. 487).

TABLE 9. Lamination types in the Ohio and Chagrin Shales along Lake Erie.

Clay Laminae: More than 95 percent clay minerals, oriented parallel to lamination, produced aggregate polarization; sharp contacts with surrounding shale.

Organic Laminae: Quartz + clay + organics—more organics than surrounding shale; most contacts with surrounding shale sharp, some gradational.

Quartz Laminae: These are of three distinct types and each can be continuous as well as discontinuous. Many are cemented by carbonate, which can replace much of the framework.

Ungraded: More than 75 percent quartz; no grain size variation in vertical direction; most grain-to-grain contacts long and point; carbonate cements some laminae, locally replaces quartz extensively.

Coarse-tail graded: More than 75 percent quartz; quartz content decreases vertically with an increase in clay + mica, grading mostly normal, some reverse; most grain-to-grain contacts long and point; carbonate cements some laminae, locally replaces quartz extensively.

Distribution graded: More than 90 percent quartz; quartz size decreases upward within lamination; most grain-to-grain contacts long and point; carbonate cements some laminae, locally replaces quartz extensively.

Coarsest grain size is defined as the average of the long diameters of the five largest quartz grains in a thin section. Coarsest grain size was studied, because it is easy to measure and may reflect the depositional environment and/or provenance of the sediment (Pettijohn et al., 1972, p. 68). We found it to have little bearing gas potential, however.

Shale types types were defined using the percent of clay plus mica as well as the amounts of organic, carbonate and pyritic material (Fig. 23). Six major shale types were found in the Ohio and Chagrin Shales along Lake Erie (Table 10: claystone, clayshale, mudshale, bituminous shale, siltstone, and siltshale). Minor lithologies are marlstone, sandstone, carbonate rock and pyritic shale. Detailed descriptions of each of these are given in Appendix B of Broadhead's thesis along with shorter descriptions of the minor petrofacies.

The volume percentage of shale types in each stratigraphic unit in the Ohio and Chagrin Shales along Lake Erie was estimated as was the average petrographic composition of each unit (Table 11).

The lower part of the Huron Member of the Ohio Shale contains the greatest amount of bituminous shale of any stratigraphic unit of the Ohio and Chagrin Shales along Lake Erie.

The Three Lick Bed, although locally composed of as much as 67 percent dark-gray shale, does not contain any bituminous shale. The dark-gray shales are organic-rich claystones and clayshales, as in the upper part of the Huron Member. Siltstone, siltshale, and mudshale are the only lithologies present in the Three Lick Bed in Cuyahoga County, but to the west in Lorain and Erie Counties, claystone and clayshale are dominant and siltstone, siltshale, and mudshale are minor constituents.

TABLE 10. Petrology of Shale Types in Ohio and Chagrin Shales Along Lake Erie.

SHALE TYPE	AVERAGE MODAL COMPOSITION								QUARTZ LAMINAE (mm)	MAXIMUM GRAIN SIZE (mm) (Mean and Range)
	QUARTZ AND FELDSPAR	CLAY	MICA	ORGANICS	SPORES	PYRITE	CARBONATE	OTHER		
Claystone	10.8	79.2	2.5	3.3	T	2.2	2.1	T		0.049(0.017-0.078)
Clayshale	13.8	71.3	2.5	5.0	T	4.8	2.5	T	0.11(0.06)	0.064(0.034-0.095)
Mudshale	31.2	50.2	3.5	7.2	1.0	5.0	1.5	T	0.32(0.30	0.077(0.049-0.108)
Bituminous Shale	13.0	50.3	2.5	24.3	1.4	5.8	2.2	T	0.096(0.07)	0.071(0.046-0.089)
Siltstone and Siltshale	68.5	6.1	3.9	T	0	T	19.1	1.0		0.12(0.075-0.17)

TABLE 11. Shale types and average petrographic composition.

Part A. Volume Percentage of Shale Types in Ohio and Chagrin Shales Along Lake Erie

Stratigraphic Unit	Samples	Claystone	Clayshale	Mudshale	Bituminous Shale	Siltstone and Siltshale	Marlstone	Sandstone
Ohio Shale								
Cleveland Member	6	14	0	0	47	19	0	19
Three Lick Bed	21	38	35	11	0	12	5	0
Upper part of Huron Member	11	44	26	0	30	0	0	0
Middle part of Huron Member	10	18	11	0	51	0	20	0
Lower part of Huron Member	22	11	9	0	74	0	7	0
Chagrin Shale	22	23	55	18	0	5	0	0

Part B. Average Composition

Stratigraphic Unit	Quartz Plus Feldspar	Clay	Mica	Organics	Tasmanites	Pyrite	Carbonate	Other[2]
Ohio Shale								
Cleveland Member, 6[1]	21.3	54.6	3.1	15.0	T	5.8	T	T
Three Lick Bed, 16[1]	19.4	55.9	2.5	5.4	T	3.8	12.4	T
Upper part of Huron Member, 6[1]	14.0	61.0	1.2	13.8	1.2	4.7	3.2	T
Middle part of Huron Member, 5[1]	9.8	51.0	1.6	21.8	1.2	5.8	8.6	0
Lower part of Huron Member, 19[1]	13.3	52.2	3.1	20.8	1.3	7.0	2.5	T
Chagrin Shale, 21[1]	17.7	69.7	2.9	2.8	T	4.4	2.2	T

[1]Sample size.

[2]Rock fragments, chert, heavy minerals and bone fragments.

Many of the siltstones, siltshales, and mudshales in the Three Lick Bed have been cemented and partially replaced by calcite and/or siderite.

Together, the middle and upper parts of the Huron Member and the Three Lick Bed of the Ohio Shale exhibit a steady upward increase in the clay-plus-mica and quartz-plus-feldspar fractions and an accompanying upward decrease of the organic fraction of the shales. There is also a somewhat irregular upward decrease of coarsest grain size in these stratigraphic units. Coarsest grain size varies between 0.05 mm and 0.09 mm at the base of the middle part of the Huron Member and decreases to between 0.03 mm and 0.07 mm at the top of the Three Lick Bed.

The Cleveland Member of the Ohio Shale everywhere contains black bituminous shales and dark-gray to medium-gray clayshales. In addition, siltstones, siltshales, and black very fine-grained sandstones are present east of the city of Cleveland, and there only in the lower two thirds of the Cleveland Member.

The Chagrin Shale is composed mostly of clayshale and contains minor claystone and mudshale, and only a few percent siltstone and siltshale. Moreover, carbonate rock is rare. The Chagrin Shale has a general but irregular upward increase in the quartz-plus-feldspar fraction and corresponding upward increase in the clay-plus-mica fraction. Coarsest grain size has no overall vertical trend and varies irregularly between 0.04 mm and 0.09 mm.

The data indicate that two geochemical facies exist in the Ohio and Chagrin Shales along Lake Erie: a carbon-rich facies and a hydrogen-rich facies. The carbon-rich facies is represented by the dark-gray to black shales of the Cleveland Member and upper and lower parts of the Huron Member of the Ohio Shale. The hydrogen-rich facies is represented by the gray shales of the Chagrin Shale. The interbedded dark-gray and medium-gray shales of the Three Lick Bed and middle part of the Huron Member represent a transition between these two facies.

Percentage of organic carbon was used to evaluate the source rock potential of each stratigraphic unit according to values given by Thomas (1979, p. 1096). The average bituminous shale from each stratigraphic unit was also evaluated, and all are excellent potential source rocks.

The foregoing petrologic information was combined with carbon and whole rock hydrogen and nitrogen analyses of organics to make an integrated evaluation of gas potential in the shales along Lake Erie (Table 12). Central to this evaluation was the identification of 93 wells with gas shows and/or production. The gas shows of these wells were projected into an east-west cross section, which indicates the Three Lick Bed and the Chagrin Shale to have the most gas shows, especially where they contain more than 20 percent mudshale, siltshale, and siltstone—shale types which have the most silt laminations (Table 11). Thick quartz laminae probably act as permeable conduits and reservoirs for gas—despite the fact that some have carbonate cement. Could it be that microfractures in these laminae are more important than intragranular porosity and permeability? In order for a shale to be prospective for gas along Lake Erie, it must have abundant quartz laminae with a minimum thickness of 0.2 mm. Quartz laminae in clayshales have about the same average thickness as quartz laminae in bituminous shales, about 0.1 mm, and the lognormal distributions of lamination thickness are about the same in these two shale types, with only about 10 percent of the laminae exceeding a thickness of 0.2 mm. In mudshales, however, average quartz lamination thickness is about 0.3 mm and about

TABLE 12. Source Rock and Reservoir Characteristics of Ohio and Chagrin Shales.

Stratigraphic Unit	Geochemical Source-Rock Evaluation	Gas Shows	Dominant Shale Type	RESERVOIR CHARACTERISTICS Laminated Shale (%)	Mudshale, Siltshale and Siltstone (%)	Cemented Quartz Laminae and Siltstone
Ohio Shale Cleveland Member	Excellent	Sparse	Bituminous Shale	84	19	some
Three Lick Bed	Good	Abundant	Claystone & Clayshale	58	23	many
Upper part of Huron Member	Excellent	Sparse	Claystone	56	0	some
Middle part of Huron Member	Excellent	Sparse	Bituminous Shale	62	0	some
Lower part of Huron Member	Excellent	Sparse	Bituminous Shale	82	0	some
Chagrin Shale	Poor	Abundant	Clayshale	77	23	some

60 percent of all quartz laminae are thicker than 0.2 mm. There are also more quartz laminae in mudshales than in clayshales and bituminous shales. Beds of siltstone and siltshale are composed almost entirely of quartz laminae, which have been bioturbated in the siltstones. Clayshales, bituminous shales and siltshales are mostly long and point and thus are permeable to gas.

In summary, stratigraphic units which contain abundant mudshales, siltshales, and siltstones make the best gas reservoirs in the Ohio and Chagrin Shales along Lake Erie. All of these shale types contain abundant, thick (thicker than 0.2 mm) quartz laminae and/or quartzose siltstone and siltshale beds, which appear to act as permeable reservoirs and conduits for gas—even though some are cemented by carbonate.

Devonian and Mississippian Shale in and Near the Pine Mountain Overthrust

In and near the Pine Mountain Overthrust, shale petrology, based on 142 samples from four cores and one outcrop, was used to define the composition of major stratigraphic units (Table 13), and to estimate the abundance of shale types in the different formations of the area (Table 14), using the classification shown in Figure 25. An additional byproduct was a classification of shale types based on lamination (Fig. 26). The types of lamination vary markedly in the different stratigraphic units (Table 15).

TABLE 13. Average composition of Devonian and Mississippian in and near the Pine Mountain Overthrust (percent from thin section).

Stratigraphic Units	Mica	Clay	Silt	Total Organics	Pyrite	Carbonates	Rock Fragments	Feldspar	Peloids	Heavy Minerals	Number of Samples
Sunbury Shale	1.5	43.0	19.5	17.5	12.5	3.5	trace	--	--	--	7
Bedford Formation	0.5	24.0	42.0	10.5	6.0	18.0	trace	trace	--	trace	4
Cleveland Shale	1.4	27.5	30.5	19.4	15.4	2.4	trace	trace	--	trace	24
Three Lick Bed	3.1	44.4	31.0	6.5	5.8	9.0	trace	trace	trace	trace	29
Upper Huron Member	1.5	32.0	26.0	19.3	14.3	4.8	trace	trace	trace	trace	16
Middle Huron Member	1.7	49.8	20.5	13.0	12.0	2.4	trace	trace	trace	trace	26
Lower Huron Member	0.9	38.0	15.0	21.6	15.6	8.0	trace	trace	trace	trace	34
Olentangy Shale	2.4	57.0	15.0	2.0	2.6	19.8	trace	trace	trace	trace	7

TABLE 14. Shale Types in and Near Pine Mountain Overthrust

Part A: Shale Types by Stratigraphic Unit

Unit	Clayshale	Claystone	Mudshale	Mudstone	Siltshale	Siltstone	Argillaceous Limestone	Total Samples
Sunbury Shale	14 (1)*	--	57 (4)	--	29 (2)	--	--	7
Bedford Shale	--	--	25 (1)	--	50 (2)	--	25 (1)	4
Ohio Shale								
Cleveland Member	--	--	13 (3)	8 (2)	75 (18)	4 (1)	--	24
Three Lick Bed	7 (2)	11 (3)	37 (10)	15 (4)	30 (8)	--	--	27
Upper Huron Member	6 (1)	--	44 (8)	--	50 (9)	--	--	18
Middle Huron Member	8 (2)	12 (3)	69 (18)	4 (1)	8 (2)	--	--	26
Lower Huron Member	3 (1)	9 (3)	41 (14)	--	32 (11)	9 (3)	6 (2)	34
Olentangy Shale	14 (1)	--	29 (2)	43 (3)	--	--	14 (1)	7
	5 (8)	6 (9)	41 (60)	7 (10)	35 (52)	3 (4)	3 (4)	147

Part B: Percentages of Shale Types Within and Outside the Overthrust

Unit	Clayshale	Claystone	Mudshale	Mudstone	Siltshale	Siltstone	Argillaceous Limestone
Ohio Shale							
Cleveland Member	--/--	--/--	17/10**	--/20	83/60	--/10	--/--
Three Lick Bed	--/13	17/7	25/47	8/20	50/13	--/--	--/--
Upper Huron Member	--/7	--/--	--/53	--/--	100/40	--/--	--/--
Middle Huron Member	11/--	16/--	63/86	--/14	10/--	--/--	--/--
Lower Huron Member	8/--	8/10	46/38	--/--	15/42	23/--	--/10

*Number of observations

**Percent within/Percent without

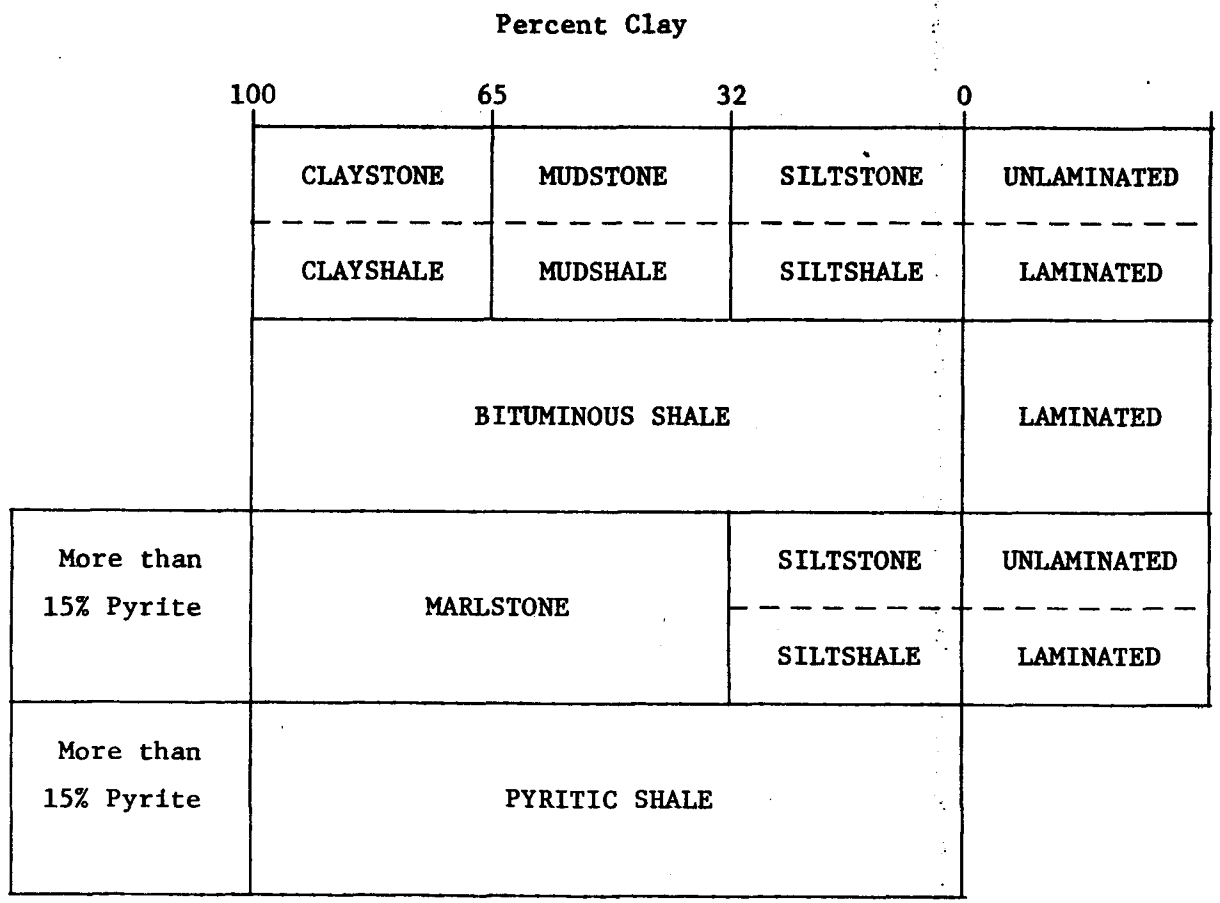

FIGURE 25. Classification of shale types.

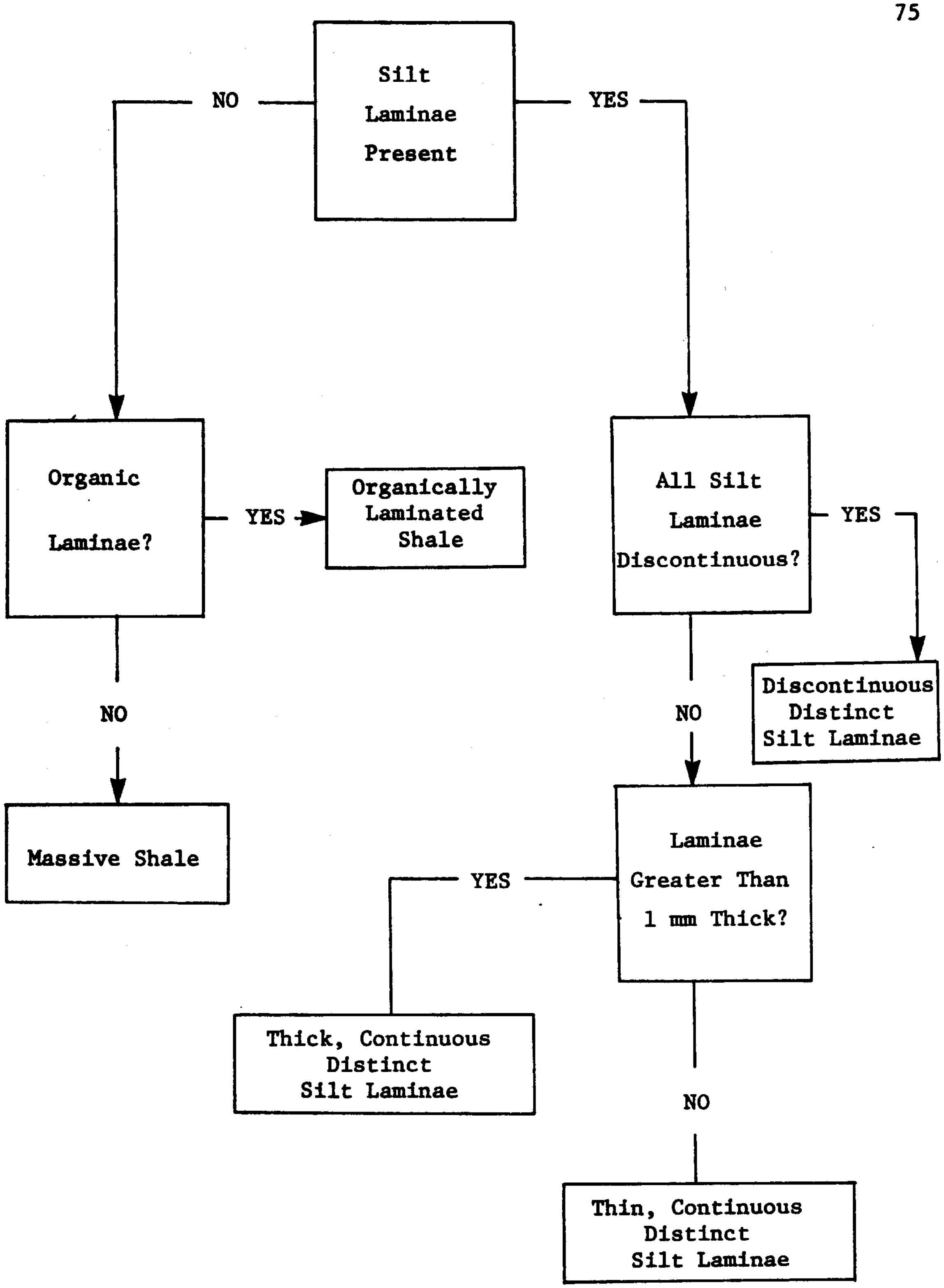

FIGURE 26. Flow Chart for Classification of Shales Used by Stenbeck.

TABLE 15. Lamination types of Devonian and Mississippian shales in and near the Pine Mountain Overthrust.

Part A. Definition of Lamination Types

Massive

Totally random arrangement of elongate particles with no continuous silt laminae.

Organic

Organic matter in varying amounts throughout the thin section creates continuous light and dark laminae.

Discontinuous Distinct Silt

Silt laminae are present in the thin section but are disrupted and not continuous within it.

Thin, Continuous and Distinct Silt

Silt laminae each less than/or equal to 1 mm in thickness and continuous throughout the thin section.

Thick, Continuous and Distinct Silt

Silt laminae each greater than 1 mm in thickness and continuous throughout the thin section.

Part B. Lamination Types by Formation (percent)

	Massive	Organic	Silt	Number of Samples
Sunbury Shale	0	100	0	7
Bedford Shale	13	25	62	8
Cleveland Shale	8	28	64	25
Ohio Shale				
Three Lick Bed	34	13	53	30
Upper Huron Member	0	44	56	16
Middle Huron Member	15	50	35	26
Lower Huron Member	22	42	36	36
Olentangy Shale	50	25	25	8

In and near the Pine Mountain Overthrust, as is true elsewhere in the basin, five constitutents dominate the black shale composition: mica plus clay, silt, organic matter, pyrite and carbonate. Variations in mica, clay and silt reflect changing input from the source area and suggest declining supply from the Olentangy to the middle of the Lower Huron followed by increasing input to the lower part of the Middle Huron and finally declining input upward into the Bedford. The Sunbury shows an increasing supply of clay and mica.

X-Ray Fabric

Fabric defined by the x-ray technique of Odum (1967) was studied on 22 shale samples from this area (Table 16). Most of this work was done by Greg Hinterlong. From each sample two chips were taken—one to be cut parallel to bedding and one cut perpendicular to it—and then encased in a resin and cut. The ratio of the 4.46 Å (110) illite peak was used to assess fabric parallel and perpendicular to bedding with the formula

$$P/PV = \text{Fabric Index}$$

where P is reflection intensity parallel to bedding and V is reflection intensity perpendicular to bedding. Four runs were made on different parts of each chip. Using this procedure clay fabric was found to range from 0.10 to 0.57 (Table 16).

The 22 samples studied appear insufficient to draw many significant major conclusions. However, Mr. Stenbeck's data suggest that where the shale is proximal to faulting or involved with faulting, the fabric index will increase (shale particle orientation decreases). The two wells not directly affected by thrusting in Perry and Martin Counties, Kentucky, have average fabric indices of 0.19 and 0.24, whereas the well in Letcher County, which intersects the overthrust, has a value of 0.45 (Table 8) and poor clay orientation. The Wise County well in the overthrust block has an average value of 0.22, good orientation, and appears to have been unaffected by the overall northwestward transport of the block. In other words, although it is in the overthrust block, x-ray fabric suggests that there was little differential movement with in it. Thus our study offers limited evidence that deformation reduces the orientation of clay minerals in shales. Odom's observation (1967, p. 618) that orientation is proportional to organic content was not confirmed for the Devonian shales we studied.

Mr. Stenbeck also made many photographs of shale fabric with our ISI Miniscan II and obtained better pictures than anyone else. Unfortunately, no significant conclusions were forthcoming. Earlier, Professor Pryor and Mr. Stenbeck also used the SEM to examine clay minerals and other particles for orientation in the plane of the bedding—unfortunately, also without success. Thus our experience suggests that the SEM is not as effective for shale petrology as either thin section or x-ray radiography.

Shale Petrology of the Brallier Formation

The efforts of Messrs. Lundegard and Samuels relating to shale petrology lead to a separate classification of shales—one specifically designed for field use (Fig. 27). We were most pleased that they developed this classification and think it will be a significant contribution to the improved field study of shales.

TABLE 16

X-Ray Fabric of Devonian Shales in and Near the Pine Mountain Overthrust

Well Depth		Fabric Index	Percent Organic Carbon
PERRY COUNTY, KY[1]			
2407		0.140 (Good)[5]	5.43
2441		0.203 (Fair)	4.75
2449		0.192 (Good)	0.22
2452		0.230 (Fair)	3.18
2479		0.217 (Fair)	3.71
2691.8		0.166 (Good)	0.85
	Average	0.19 (Good)	
WISE COUNTY, VA[2]			
4887		0.172 (Good)	5.78
4961		0.101 (Good)	0.70
5210		0.246 (Fair)	0.61
5360		0.325 (Poor)	6.40
	Average	0.22 (Fair)	
LETCHER COUNTY, KY[3]			
185		0.314 (Poor)	3.01
244		0.487 (Very Poor)	4.74
277		0.375 (Poor)	3.74
300		0.261 (Fair)	2.84
341		0.552 (Bad)	2.41
	Average	0.45 (Very Poor)	
MARTIN COUNTY, KY[4]			
2430.3		0.254 (Fair)	7.45
2432.9		0.221 (Fair)	1.06
2560.5		0.204 (Fair)	0.18
2581.0		0.262 (Fair)	--
2636		0.388 (Poor)	0.54
3252.4		0.195 (Good)	0.08
	Average	0.24 (Fair)	

[1]Ky-W. Vir., EGSP-KY. No. 1, 19-K-76.
[2]Columbia Gas Transmission Corp., Penn-Virginia Corp. No. 20338, 37°00'37" N, 82°41'14" W.
[3]Stokley and Associates, Ky. Hwy. Dept., Pine Mountain Tunnel CH-5, 14-G-80.
[4]Columbia Gas, EGSP-KY, No. 2, 16-P-85.
[5]Degree of orientation as defined by Odum (1967).

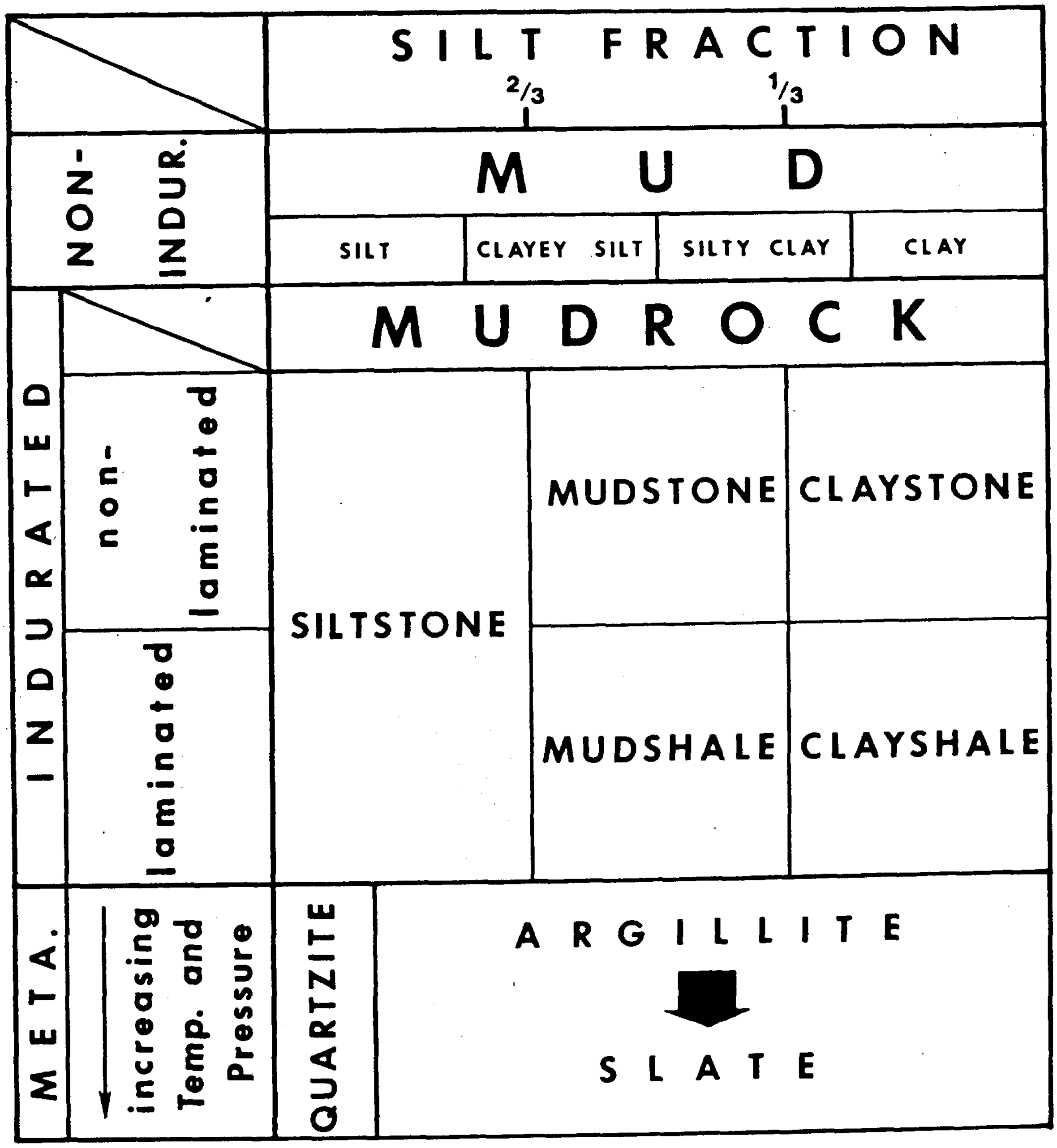

FIGURE 27. Field classification of mud and mudrock and their low-grade metamorphic equivalents. Classification is based on texture (grain size) and structure (lamination). In practice, no sharp boundaries exist between non-indurated, indurated, and low-grade metamorphic members.

Paleontology

Trace fossils are tracks, trails or burrows which reflect the life activities of organisms. Trace fossils, both kinds and abundance, can be used to infer environmental conditions, especially on shelf-to-slope-to-basin transitions, because they reflect such diverse factors as firmness of the bottom, rate of deposition, availability of nutrients, and bottom oxygenation. They are also attractive, because they can be studied fairly easily by sedimentologists and add another important biological dimension to comprehensive sedimentological investigations.

Our results largely stem from the Master of Science thesis of Douglas W. Jordan, "Trace Fossils and Stratigraphy of the Devonian Black Shale in East-Central Kentucky" and to a lesser degree from the study of the Ohio Shale along Lake Erie by Mr. Ronald A. Broadhead. Although the results below represent only a very small part of our total sedimentological effort, a number of important conclusions follow from the study of trace fossils.

1) Trace fossils in the Devonian shales of east-central Kentucky occur in the Boyle Dolomite, the Huron Member of the Ohio Shale, and Three Lick Bed, but not in the Cleveland Member of the Ohio Shale (Table 17). However, careful field observations show that they are limited to the gray and greenish-gray shale interbeds and dolomites within the above units.

2) Overall, both the greenish-gray shales and dolomites show an upward sequential change in the abundance and kinds of their trace fossils, a change from an initial shallow basin to a later, deeper one. The trace fossil vertical zonation is good enough to identify the stratigraphic position of isolated outcrops of the interbedded greenish-gray shales, should this be necessary.

3) Burrowed zones in the gray and greenish-gray shales can be traced as far as 90 miles along the east side of the Cincinnati Arch and thus show how widespread they can be.

TABLE 17. Trace fossils and their interpretation in outcrop of Devonian Shale along east side of Cincinnati Arch in Kentucky.

STANDARD STRATIGRAPHIC SECTION	THIS STUDY	TRACE FOSSILS	ENVIRONMENTAL INTERPRETATION (AND ICHNOFACIES)	WATER DEPTH	REMARKS
Cleveland Member	Cleveland Member	None	Lower subtidal on shelf?	Water depth increases upward from 50 to 400 feet	Little oxygen
Three Lick Bed	Three Lick Bed	Planolites-like*, Chondrites C&D, Zoophycos, pyritic burrows	Lower subtidal on shelf (lower Cruziana to upper Zoophycos)		Variable oxygenated zones (0.1-1.0 ml/l diss. O_2) intermixed with poorly oxygenated zones
Huron Member: Upper Part	Huron Member: Upper Part	None	Middle to lower subtidal on shelf?		Little oxygen
Huron Member: Middle Part	Huron Member: Upper Part	Planolites*, Chondrites B*, Rhizocorallium, Zoophycos, and Teichichnus in interbedd. gry and blk sh.	Middle to lower subtidal on shelf (middle to lower Cruziana)		Variable oxygenated zones (0.1-1.0 ml/l diss. O_2) intermixed with poorly oxygenated zones
Huron Member: Lower Part	Huron Member: Lower Part	Planolites*, Chondrites A*, Zoophycos*, Teichichnus, Trichichnus, Cruziana, Phycodes, and Laevicyclus in interbedded dol. and sh.	Upper to middle subtidal on platform and shelf (upper Cruziana)		
Boyle Dolomite	Boyle Dolomite	Planolites*, Cruziana, and Rusophycus	Upper to middle subtidal on platform (upper Cruziana)		Full marine with oxygen exceeding 1.0 ml/l diss. O_2

* Abundant

4) Strongly burrowed zones are probably poor for gas delivery from the shale, because they lack lamination; they may also fracture less readily than laminated shales, although we know of no data testing this inference.

Along the northwest side of the basin along Lake Erie, Mr. Broadhead found an essentially similar stratigraphic occurrence of trace fossils (Table 18). Griffith (1977) also found a stratigraphic zonation of trace fossils in the nearby Illinois Basin.

Table 18. Stratigraphic Distribution of Trace Fossils in Ohio Shale Along Lake Erie.

<u>Arenicolites</u> (Hantzschel, 1975, p. 88-89):
Chagrin Shale, Three Lick Bed of Ohio Shale

<u>Chondrites</u> (Hantzschel, 1975, p. 49-52):
Three Lick Bed and Lower part of Huron Member of Ohio Shale

<u>Cruziana</u> (Hantzschel, 1975, p. 55):
Three Lick Bed of Ohio Shale

<u>Palaeophycus</u> (Hantzschel, 1975, p. 88-89):
Chagrin Shale, Three Lick Bed of Ohio Shale

<u>Paleodictyon</u> (Crimes, 1977, p. 85):
Three Lick Bed of Ohio Shale

<u>Skolithos</u> (Hantzschel, 1975, p. 106):
Chagrin Shale

Unidentified crawling and resting traces:
Three Lick Bed of Ohio Shale

Unidentified subvertical to vertical tubular burrows filled with shale and silt:
Cleveland Member of Ohio Shale

Unidentified horizontal to subvertical shale-filled burrows with spreite:
Lower, middle, and upper parts of Huron Member of Ohio Shale

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Last Pending Thesis

"Petrology of Devonian-Mississippian Shale Sequence in and Near the Middlesboro Syncline" (M.S.) by Thomas Stenbeck.