METC/CR-79/22

DEVONIAN PALEOCURRENTS OF THE APPALACHIAN BASIN

By

Paul Edwin Potter, Wayne A. Pryor, Paul Lundegard,
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Prepared for
UNITED STATES DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
Morgantown, West Virginia

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy $5.25
Microfiche $3.00

Printed in the United States of America
USDOE Technical Information Center, Oak Ridge, Tennessee

METC/CR-79/22
Distribution Category UC-92a

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by

H. N. Fisk Laboratory of Sedimentology
University of Cincinnati
Cincinnati, Ohio 45221

Under

Contract DE-AC21-76MC05201

CONTENTS

FIGURES

contents...continued

contents...continued

contents...continued

Figures		Page

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by

Paul Edwin Potter[1]/, Wayne A. Pryor[1]/, Paul Lundegard[2]/,
Neil Samuels[2]/, and J. Barry Maynard[1]/

ABSTRACT

The paleocurrent system of the Devonian clastics of the central and northern Appalachian basin is uniformly oriented to the west judging by the orientation of sole marks on interbedded siltstones and sandstones and by the available directional data from interbedded black and gray shales. Paleocurrent indicators are at right angles to isopach of total Devonian thickness, which decreases westward from 12,000 ft. in eastern Pennsylvania to a few hundred feet in west-central Ohio. This clastic wedge is largely of Upper Devonian age and includes alluvial and delta plain environments (in the east) as well as shelf (east-central), turbidite slope, and basin plain environments (west-central and west), the latter representing most of the black shales. Lithologies within the wedge are more continuous north-south parallel to depositional strike than east-west. The gradient of carbon isotopes, which shows more marine than terrestrial carbon in the western part of the basin, closely parallels the average paleocurrent direction of the basin.

The methodology of paleocurrent studies in shaly basins based on both outcrops and oriented cores, is set forth as is the relationship between paleocurrents and gas potential.

Key ideas: *Paleocurrent systems in shaly basins and gas potential, methodology, unresolved problems, annotated bibliographies and Devonian of Appalachian basin.*

INTRODUCTION

Gas production in shaly basins such as the Devonian of the Appalachian basin depends on a combination of both primary sedimentation and burial history, the latter including fracturing, faulting and folding as well as thermal history.

Total thickness of shale, shale types and their spatial distribution, organic content (both total amount and proportion of marine to terrestrial carbon), lamination and silt content of the shale plus the relation of shaly to non-shaly facies are but a short list of the primary depositional

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[1] Faculty, [2] Graduate Students, University of Cincinnati

features of shaly basins most of which have a direct relation to the gas potential.

Knowledge of the paleocurrent systems in shaly basins is the principal integrating factor in basin analysis for most of the above-listed primary depositional features, largely because it "puts all the parts together". Consider, for example, some of the following questions. Did the basin have one major source of mud, silt, and terrigenous carbon or several? Where were these sources with respect to present basin margins? Did sediment dispersal within the basin remain the same or change as it filled? Did interbedded silts follow a different transport path than their surrounding muds? Were different kinds of muds derived from different sources? How is one shaly facies related to another or perhaps to a non-shaly one? What are the general directions of maximum and minimum lithologic continuity in the basin? What is the depositional strike and dip of basin fill?

Knowledge of paleocurrents in shaly basins can thus help explain

(1) paleocirculation and its relation to original and present basin shape,

(2) textural gradients in both the basin as a whole and in its shaly lithologies, and

(3) the areal distribution of terrestrial and marine carbon.

Mapping the paleocurrent system of a shaly basin along its outcrop is the quick, easy and inexpensive way to answer most of the above questions. And even more detail can be derived from the study of paleocurrent structures obtained from oriented cores within a basin.

Below, after a brief outline of the basin and its fill, we report on the results of paleocurrent mapping in the Devonian of the Appalachain basin and provide a simple how-to-do-it manual for the future study of other shaly basins. For those unfamiliar with paleocurrent structures, especially as they appear in cores, many drawings and photographs are provided. Also included is a discussion of some unresolved problems. Annotated references direct the reader to much of the relevant literature.

REGIONAL SETTING

The Devonian of the middle and northern portions of the Appalachain basin covers about 110,000 square miles (280,000 km^2) in Pennsylvania, New York, Ohio, Kentucky, West Virginia, Virginia, and Maryland and southern Ontario, and ranges from as little as 25 ft (7.6 m) thick in south-central Kentucky to more than 12,000 ft (3,657 m) in eastern Pennsylvania (Fig. 1), is chiefly shale and siltstone but also contains some sandstones and minor carbonates. The Devonian system consists of

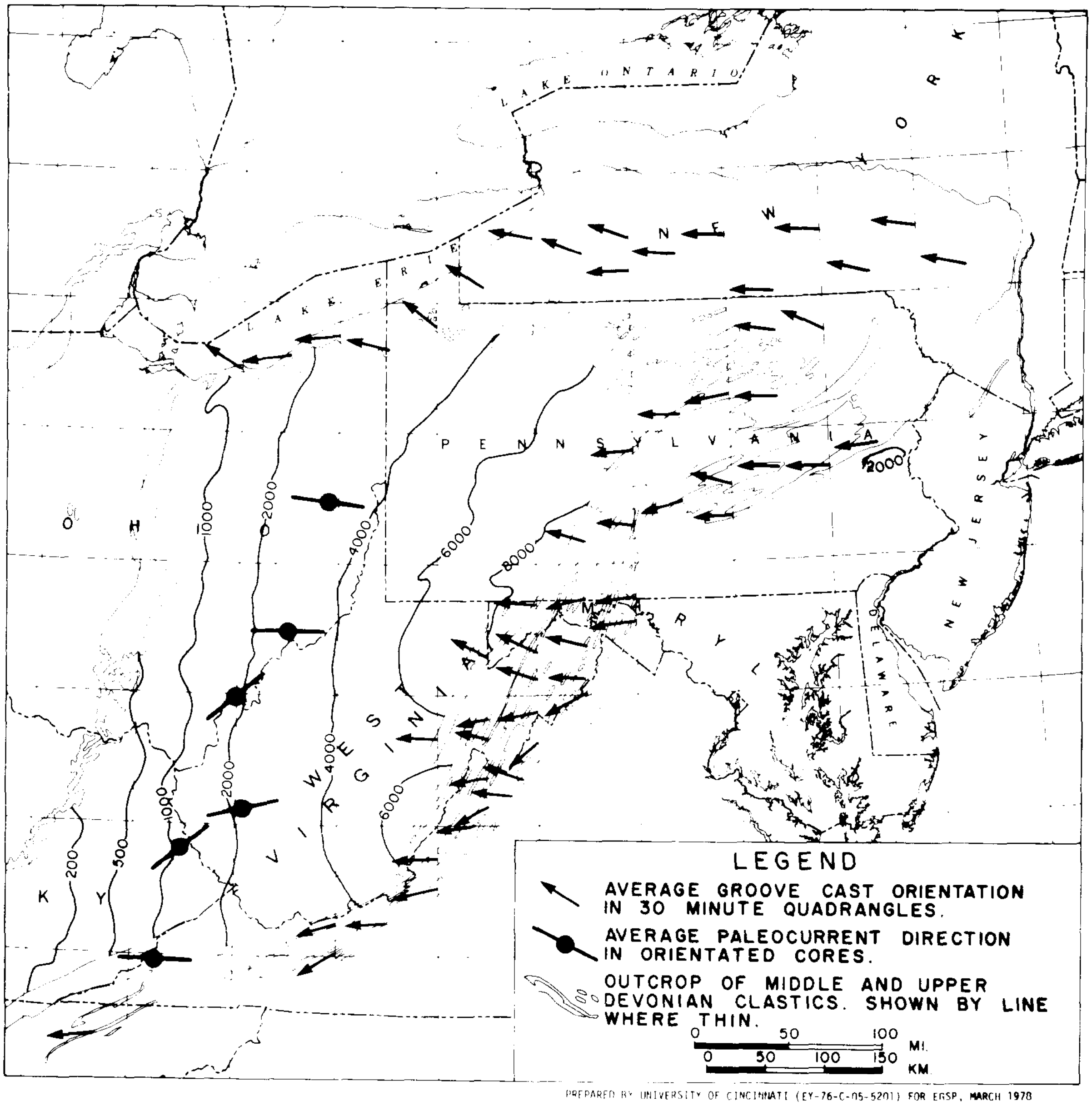

FIGURE 1 Basinwide paleocurrent and thickness map of Devonian strata (contours taken from de Witt and others, 1975, Sheet 1 of 4).

lithologies as diverse as black marine shales and continental redbeds, has many complex facies and facies changes that have long puzzled stratigraphers, contains fluvial, deltaic, shoreline, shelf, slope and basinal deposits and is a very significant producer of oil and gas. In sum, the Devonian of the Appalachian basin is a complex giant, which all too often has been studied only locally rather than regionally.

Task Force for Hot Gas Cleanup (1978) "Chemistry of hot gas cleanup in coal gasification and combustion," Publication METC/SP-78/2, Morgantown Energy Research Center, U.S. Department of Energy, Morgantown, West Virginia.

G.D. Case, W.L. Farrior, D.A. Green, and G.W. Stewart (1978) "Aerobic hydrolysis products and kinetics of iron sulfide," Paper ENVR-172, Presented at 176th Nat. Meet. Amer. Chem. Soc., Miami Beach, Florida, September 10-15.

G.D. Case, J.S. Dixon, and J.C. Schooley (1979) "Interaction of blood metalloproteins with nitrogen oxides and oxidant air pollutants," Environ. Res. 14, in press.

G.D. Case and P.J. Bekowies (1979) "Kinetics and mechanisms of NO_x and O_x pollutant metabolism in whole blood," Biophys. J. 25, 60a.

G.D. Case, W.L. Farrior, D.A. Green, and G.W. Stewart (1979) "Kinetics and reaction products of aerobic pyrrhotite (FeS) hydrolysis at ambient temperatures," Publication METC/RI-79/3, Morgantown Energy Technology Center, U.S. Department of Energy, Morgantown, West Virginia.

G.D. Case, D.A. Green, and G.W. Stewart (1979) "Aqueous scrubber reactions of pyrrhotite (FeS) with sulfur dioxide," submitted for publication to Environ. Sci. Tech.

G.D. Case, W.L. Farrior, D.A. Green, and G.W. Stewart (1979) "Kinetics and products of aqueous iron sulfide reactions," submitted for publication to J. Phys. Chem.

G.D. Case and P.J. Bekowies (1979)"Aqueous scrubber reactions of limestone with sulfur dioxide," manuscript in preparation.

G.D. Case and P.J. Bekowies (1979)"Aqueous scrubber reactions of lime with sulfur dioxide," manuscript in preparation.

P.J. Bekowies and G.D. Case (1979)"Chemical kinetics matrix modeling of sulfur dioxide solution reactions in a flue gas desulfurization scrubber," manuscript in preparation.

G.D. Case and P.J. Bekowies (1979) "Sodium and temperature measurements for low-BTU gas combustion on the METC 42-inch stirred-bed coal gasifier," manuscript in preparation.

The literature of this basin is vast and scattered and we have annotated only a small part of it (please see Annotated References). Certainly, the best single reference is by Oliver and others (1967), which provides many cross sections, thickness maps and several facies maps of the Devonian in the entire Appalachian basin and is the only general overview that contains many details. Drawing largely from Oliver and others, the salient features of the basin are summarized in Table 1.

TABLE 1

BASIN SUMMARY OF DEVONIAN OF APPALACHIAN BASIN

Time Span

Fifty million years (Friend and House, 1964).

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: *Exceedingly 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 gray and black marine shales and some shallow water carbonates.*

Arrangement: *General progression 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 very uniformly oriented north-south throughout the basin except possibly near present western limit and thus even thin shale units have much better north-south than east-west lithologic continuity.*

Composition

Sublithic to subfeldspathic arenites and wackes plus illitic and chloritic, organic rich shales and gray mudstones, whose various subtypes have yet to be fully defined and mapped over the entire basin.

Paleocurrent System

Interbedded siltstones and sandstones, and apparently most of the shale in the basin, had paleocurrents very uniformly oriented to the west and generally perpendicular to isopach lines even though black shales, which dominate in the western part of basin, imply deposition in a restricted basin.

Paleogeography and Tectonic Setting

Large, delta complex in Upper Devonian, now beheaded by continental separating, overlaps craton margin and had a linear, deep marine basin that strikes north-south. Water depth in deepest parts of this basin may have ranged from 500 to 2500 ft but was negligible to the east and may have been only several hundred feet to the west. The delta-shelf-slope system prograded westward through time as a uniform clastic ramp and was supplied by a large river system which drained a stable, continental land mass, in which volcanic rocks were largely absent.

The Devonian of the Appalachian basin (Fig. 1) is a vast wedge of clastics that extends from the Appalachian geosyncline onto the craton, where rocks of the Middle and Upper Devonian age are represented by thin and widespread limestones and black shales whose lateral equivalents to the east are mostly shales and siltstones more than 12,000 ft (3,657 m) thick (Fig. 2).

The Devonian of the Appalachians is a craton-margin, beheaded delta, one whose hinterland can be inferred only by the reconstruction of North America and Europe. Several have attempted this, including Allen and Friend (1968), Woodrow and others (1973), and Dineley (1975); the latter suggested that the Upper Devonian detritus of the Appalachians was supplied by an ancient river that drained part of the "North Atlantis", Old Red Sandstone Continent. A semi-popular article, Old Red Land of the Atlantic by Friend (1969), also has an intercontinental overview of the Devonian and several excellent maps which show the distribution of Devonian facies and tectonic elements around the North Atlantic. The persistence of paleocurrent direction within the Upper Devonian clastic wedge and the high degree of facies organization shown in the east-west cross section of Figure 2, all point to deposition in a stable basin by one major river system, but one possibly with numerous distributaries, at least in the area of the present Appalachian basin. This river system may have been localized by deep-seated faulting oriented at a high angle to the Upper Devonian shoreline.

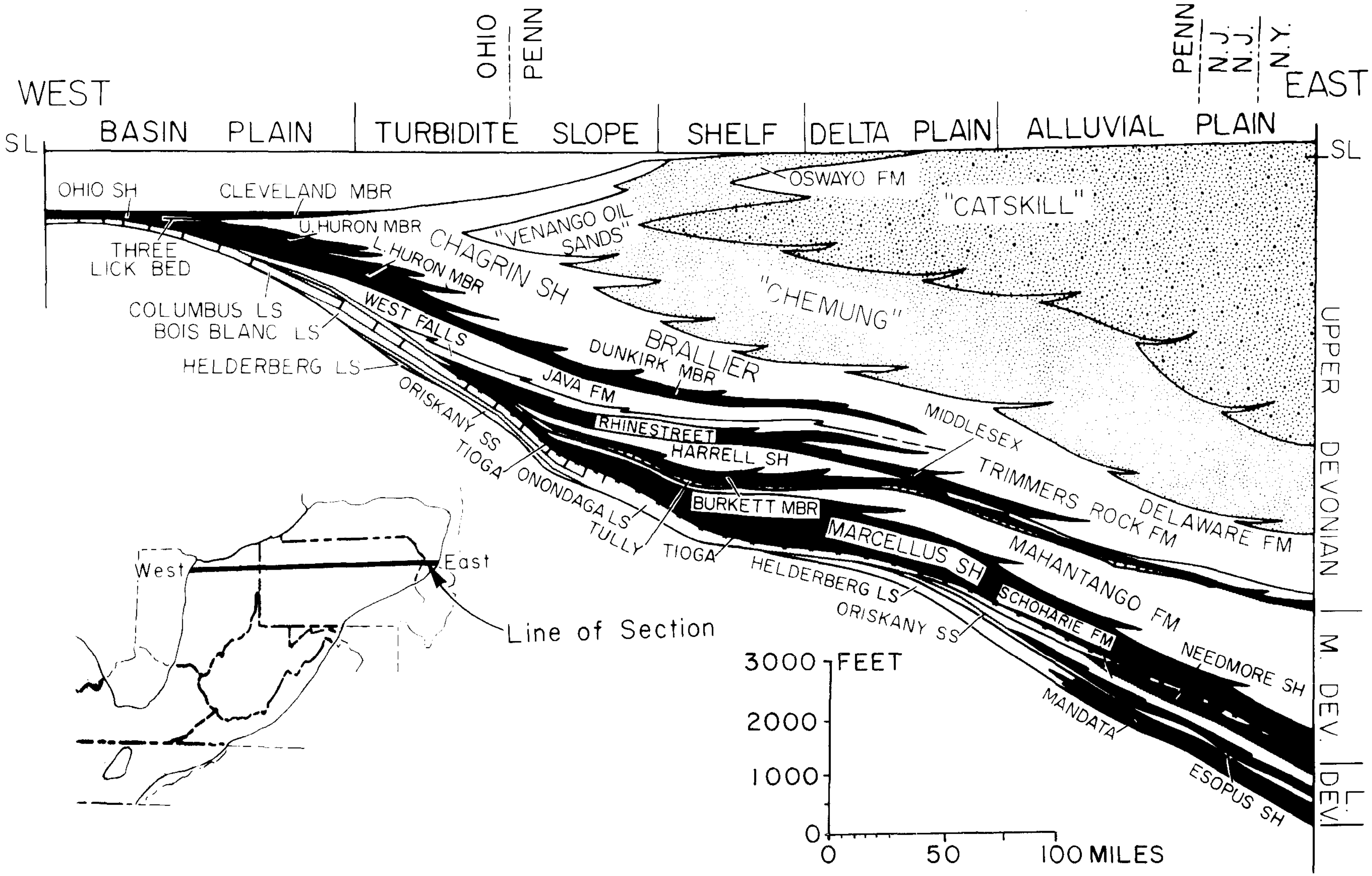

FIGURE 2 East-west diagrammatic cross section of Upper Devonian clastic wedge at end of deposition of the Cleveland Member of the Ohio Shale. Water depths not to scale and may have been much shallower in west central Ohio. Cross section parallels downdip transport direction (cf. Fig. 1). Compiled from diverse published sections and modeled after Rich (1951, Fig. 1).

In plate tectonic terms, the Upper Devonian of the Appalachian clastic wedge probably best corresponds to a retroarc basin (Dickinson, 1974, Fig. 10). A very comparable basin occurs in the Franklin geosyncline of the Arctic Islands of Canada where the Middle-Upper Devonian forms a clastic wedge over 15,000 ft (4,572 m) thick, which thins toward the craton and contains six major facies (submarine fan, marine slope, deltaic-marine shelf, open-marine shelf, and both braided and meandering environments), but does lack an extensive black shale facies (Embry and Klovan, 1976).

BASINWIDE PALEOCURRENT PATTERN

Paleocurrents in the Devonian of the northern and central Appalachian basin, are uniformly oriented to the west (Fig. 1 and Table 2), show little change vertically almost everywhere in the basin (Fig. 3), and are the same in all the facies that contain paleocurrent indicators. Thus from a paleocurrent standpoint the Upper Devonian fill of the Appalachian basin is remarkably persistent.

TABLE 2

PALEOCURRENT STUDIES OF DEVONIAN SYSTEM IN APPALACHIAN BASIN

Allen and Friend, 1968

Description of the fluvial-deltaic portion of the Devonian fill of the Appalachian Basin and comparison with the old Red Sandstone. Block diagram of Figure 10 exceptional (cf., Harms and Walker, 1971). Some paleocurrent data.

Burtner, 1963

Paleocurrents in three stratigraphic intervals all indicate east to west transport. Principal directional structures are crossbedding followed by parting lineation, ripple marks, and flute and groove casts.

Colton, 1967a

Integrated paleocurrent study of turbidites: flute casts, ripples, plant fragments, and a problematical trace fossil, Fucoides graphica, the latter possibly related to transport of waterlogged fecal pellets of fish. Short and well done.

Colton, 1967b

Orientation of 647 elongate concretions agrees well with that of sole marks in distal siltstones of turbidite origin.

Frakes, 1967

Four thousand feet of shale, sandstone and conglomerate of Middle and Late Devonian age, called the Trimmers Rock, was divided into informal units and isopached; paleocurrents (flutes, grooves, and ripples) plus slump structures studied in detail. Paleocurrents initially came from southeast and are believed to turn to southwest at base of depositional slope. Major paleocurrent study closely integrated with lithology.

Jones and Dennison, 1970

Because fossils in shales are commonly small, a single bedding plane may contain hundreds and consequently they are potentially good current indicators in shales. The examples studied generally have preferred orientation: paleocurrents, based chiefly on orientation of Lingula and Tasmanites, show west to northwest orientation in eastern Tennessee and far western Virginia. Only published study of fossil orientation of Devonian shale sequence.

Leeper, 1963

Paleocurrent directions average 277° and 311° for the Jennings (Chemung) and Catskill in Somerset County, Pennsylvania. Detailed local study.

McCave, 1968

Paleocurrents were studied above and below a time plane, which outcrops along the eastern end of the Devonian in New York state. Marine, tidal and fluvial paleocurrents recognized with dominant flow to west.

McIver, 1970

Upper Devonian turbidites are reviewed and their directional features summarized (p. 74-79), based on the most thorough (over 2,400 observations) and widespread systematic study in the basin. Short but essential article.

Nagle, 1967

Fossil orientation in Catskill of eastern Pennsylvania shows paleocurrents to have been generally from the southeast.

Sutton, 1959

Early study in the Finger Lakes region of New York demonstrated strong westward orientation of flutes and grooves in slope deposits. Additionally, it is noted that different beds have distinctive sole mark characteristics that are helpful for correlation.

Sutton, Bowen and McAlester, 1970

Very comprehensive study of paleocurrents, sedimentary structures and fossil abundances of the shelf-to-basin transition of the Upper Devonian. Flow uniformly to west. Informative illustrations.

What conclusions are to be drawn from this homogeneity?

The foremost concerns depositional strike, a line parallel to shoreline, along which similar facies normally prevail. Depositional strike of the Devonian was almost exactly north-south for all but possibly a part of the western outcrop. Thus, thick as well as thin shaly units in the basin can be expected to have a north-south dimension many times longer than their east-west dimension.

As a consequence, lithologic continuity within the basin is much greater north-south than east-west, an inference fully supported by regional stratigraphic cross sections. Deviations from the foregoing generalizations most likely occur where local lobes of turbidite siltstones extend farther westward into the central parts of the basin.

Third in importance is the overwhelming predominance of an eastern source, an old land mass, from which a large river and its distributaries supplied mud, silt and sand, and woody material to a marine basin, where it was carried far onto the North American craton.

Fourth, turbidity currents carried most of the mud and silt across the basin from central Pennsylvania and New York as far west as Ohio and Kentucky.

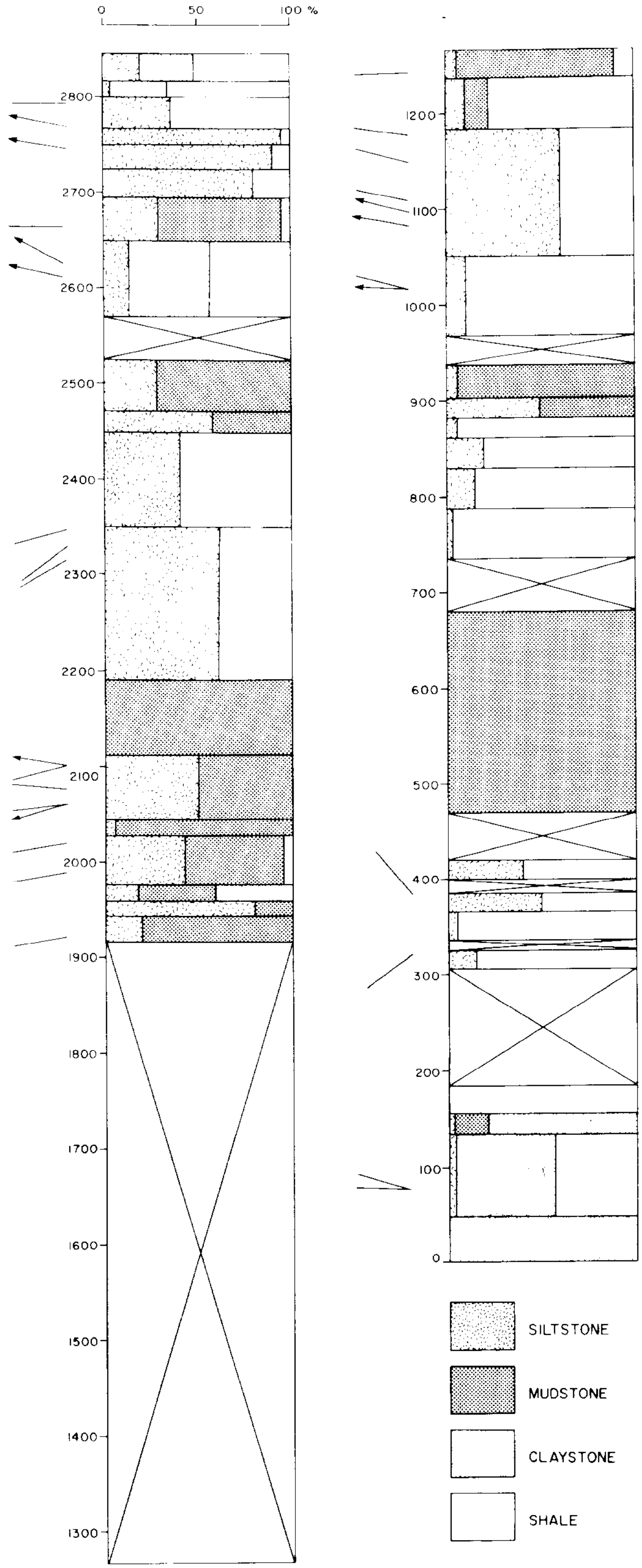

FIGURE 3 Vertical profile of orientation of flute casts and prod marks (arrows) and groove and bounce casts (line segments) plotted against lithology in the Brallier Formation shows very little variation. State Route 100, near French's Chapel, Pulaski County, Virginia (Staffordsville Quadrangle).

PALEOCURRENT STUDIES OF SHALY BASINS

Two approaches are available to determine the paleocurrent system of a shaly basin: study the paleocurrent structures of interbedded siltstones, sandstones, and skeletal carbonates, or study the directional or scalar properties of the shale itself. Siltstone, sandstone, and/or carbonate are nearly always present in most shaly basins, so the first approach is the best path to follow and was, indeed, the one we chose.

But suppose only shales are present? If so, the tools available include:

(1) measurement of fossil orientation,

(2) measurement of the orientation of virtually ever-present silt grains in the shale,

(3) mapping scalar properties to define dispersal patterns which can be related to basin shape, and

(4) measurement of the orientation of concretions.

In pure shales, fossil orientation has been the most widely used paleocurrent indicator; studies of graptolites in Lower Paleozoic shales are especially notable. Because they were light and elongate, graptolite rhabdosomes responded to the most gentle of currents, and thus provide sensitive indicators of paleocurrent systems (Fig. 4). Most studies (cf. Moors, 1969) show remarkably little variance in their orientation; Ruedemann's (1897) study in the Utica Shale is a good example (Fig. 5). To judge the importance of paleocurrent systems in muds and shales, simply ask yourself, after examining Ruedemann's map, how complete any interpretation of the Utica Shale would be if it did not consider the uniform orientation of the graptolite rhabdosomes that Ruedemann measured? Fine charcoal and woody debris also promise much potential benefit, judging by our studies of the Devonian shales. Few studies appear to have been made in other shales, even though charcoal orientation is commonly reported in the siltstones and sandstones of turbidite sandstones, where it is generally well oriented and correlates well with the primary directional structures such as sole marks and parting lineation. The process and transport paths of woody land plant debris, as it is dispersed into marine basins are poorly known, although our experience suggests that bimodal orientation may be the rule for elongate woody fragments.

Oriented brachiopod valves (especially Lingula), high spired gastropods, ostracodes, and foraminifers all occur in mudstones and shales and can have remarkably little variance in orientation in single outcrops. To this list should be added cephalopods and other conical forms such as Tentaculites. An example is the good orientation of ostracodes in the mudrocks and shales of the Pennsylvanian Monongahela and Dunkard strata

FIGURE 4 Graptolite orientation in Ordovician shale from Cincinnati arch, southwestern Ohio.

of West Virginia reported by Jones and Clendenning (1968). Jones and Dennison (1970) have made one of the most comprehensive studies of fossil orientation in the Paleozoic shales of the Appalachian basin. They measured more than 13,000 fossils in shales ranging in age from Middle Ordovician to Late Devonian and found preferred rather than random orientation to be the rule. For such studies many individuals should be measured -- a time-consuming job requiring patience. Some statistics will be needed, but usually only the calculation of the vector mean, well explained by Reymet (1971, Chapter 3) and Potter and Pettijohn (1977, p. 374-376).

There have been numerous experimental studies of fossil orientation in flumes such as that by La Barbera (1977), although most have considered sandy rather than muddy-bottoms.

When fossil debris is small, primary current orientation may be totally disrupted by bioturbation. However, we have often seen fine, invertebrate fossil debris and woody material that lack both orientation

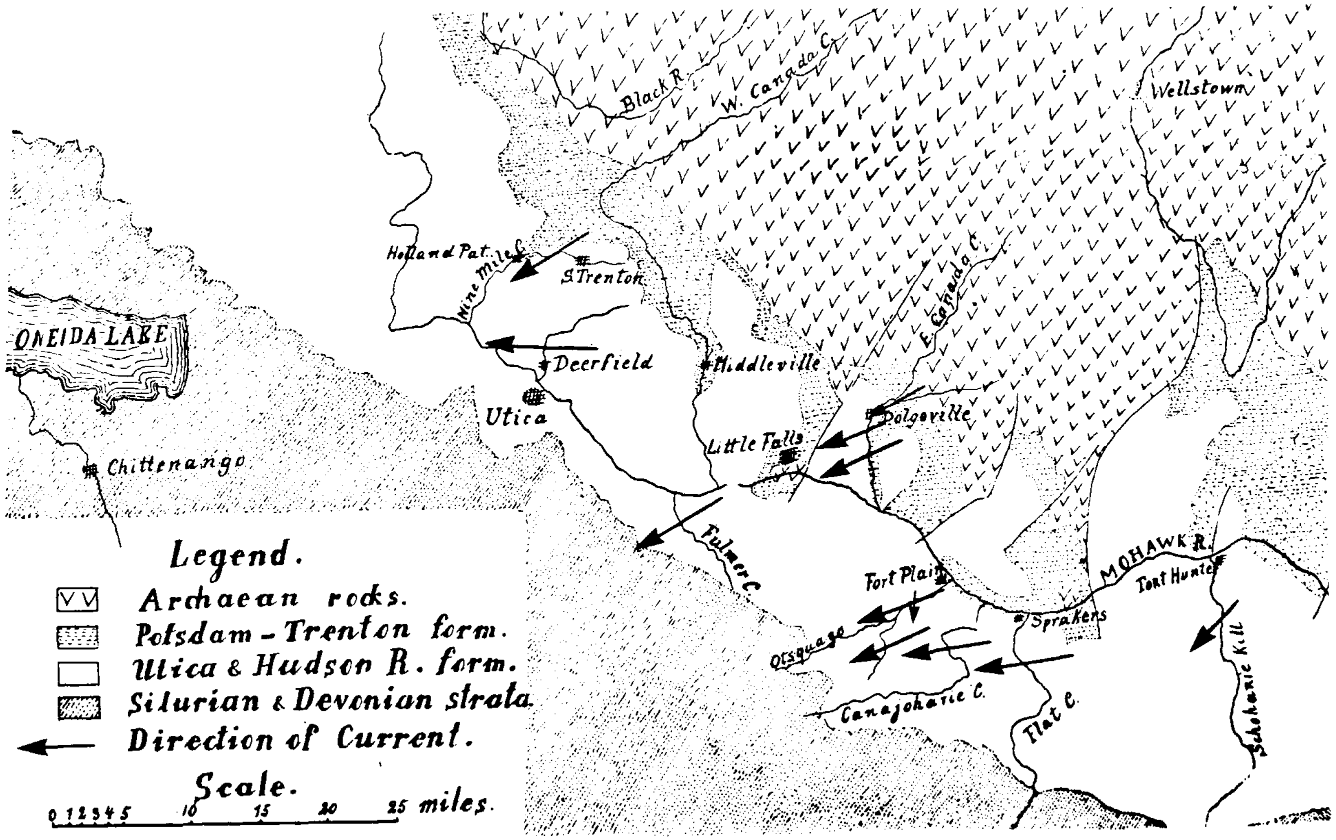

FIGURE 5 Graptolite orientation measured by Rudemann (1897, Pl. 22) in the Utica Shale (Ordovician) of central New York.

and bioturbation. Therefore, bioturbation is not always the cause of the poor orientation. Slumping should also be considered.

Larger body fossils, such as the echinoderms (crinoids, brittle stars, and starfish) with their flexible arms also have provided evidence of current direction in shales. But the evidence is only useful to those skilled in paleoecology, those who can correctly distinguish a transported dead organism from one buried in its life position. Seilacher (1973) provides a brief and excellent summary of fossil orientation and his 1960 paper on current directions in the Hunsrückschiefer, a Devonian black shale in Germany, is a classic, whose beautiful illustrations should be consulted to see how much paleocurrent information can be gathered from some of the large body fossils in shales, when one has the proper skills. An unusual example of the paleocurrent significance of body fossil orientation is provided by Wickwire (1936), who described oriented crinoid stems on a log embedded in the New Albany Shale in Indiana -- the orientation of the stems implying a preferred orientation of currents that deposited the organic-rich muds that finally entombed the log.

What is known about the orientation of fine silt in shales and mudrocks? Because there is appreciable silt in many argillaceous sediments, over 300 claystones averaged 31 percent silt according to Shaw and Weaver (1965, Table 4), it should be possible to measure quartz orientation in the plane of the bedding from low power SEM pictures. We do not know of any such studies and have not yet been successful ourselves, although Piper (1972, Fig. 2) found, using thin sections cut parallel to the plane of the bedding, that scattered grains of silt-sized debris in laminated mudstones had a preferred orientation. Whether or not preferred orientation is present may depend on whether deposition occurred by a slowly decelerating current exerting tractive force on the interface, or by a sudden deceleration wherein all the suspended debris was suddenly dumped on the bottom.

Orientation of fecal pellets (Fig. 6) in the plane of bedding is another possibility, if either compactional distortion or organisms have not totally destroyed it. Fecal pellets are very abundant in many muds and shales.

Another approach is to map the areal variation of scalar properties in a shale: percent silt and spores or percent of specific clay minerals such as kaolinite; or biofacies (the predominance of, say, pelagic to benthonic foraminifers) across a shaly basin; or even its organic mineral facies, in so far as the latter may be related to either provenance or to paleocirculation within the basin. All of these offer most promise when the internal stratigraphy of the shale is well established so that correct lateral comparisons can be made. In the Atlantic and Pacific Oceans, Windom, (1975) has shown how eolian kaolinite and quartz are dispersed oceanward and finally deposited in deep ocean muds by prevailing winds. In a widespread shale, the sedimentologist should try to distinguish the

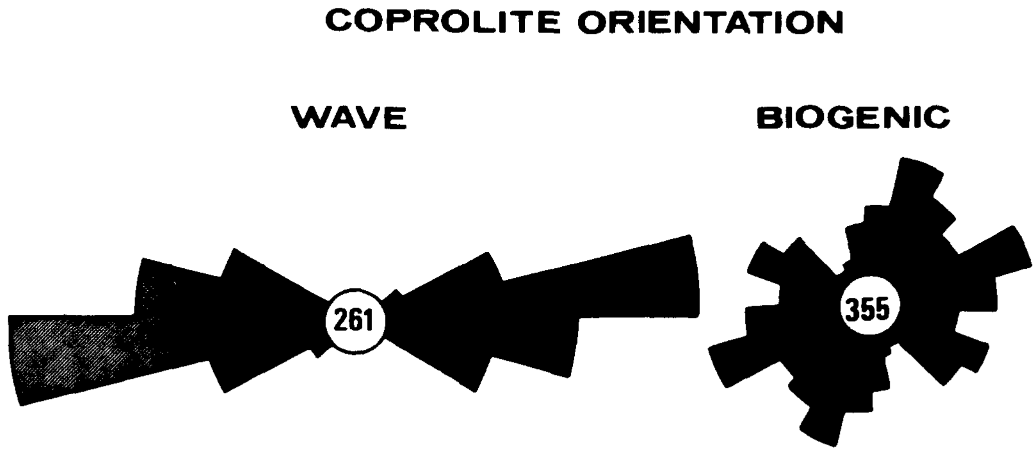

FIGURE 6 Orientation of copralites in Rock Lake Shale (Pennsylvanian) of Kansas (Hakes, 1976, Fig. 11).

dispersal patterns based on eolian contributions from those based on marine circulation. The two may be largely independent, thus yielding different patterns.

Mapping <u>organic mineral associations</u> and relating them to either provenance and/or basin circulation is as yet only in its infancy and few studies have been published. However, based on recent sediments, it seems that it should be possible to trace the proportion of terrestrial carbon in the organic matter of the basin. Most promising is the study of carbon isotopes (Hedges and Parker, 1976; Newman, *et al.*, 1973; Schultz and Calder, 1976). In modern sediments the terrestrial carbon has a ∂C^{13} value of about -25, while marine carbon is about -20. Preliminary work in our laboratory suggests that in some ancient rocks this pattern may be reversed, either by diagenesis or by changes in the isotopic composition of marine carbon with time. For Devonian-Mississippian shales we find terrestrial carbon values of about -25, but the marine carbon is around -31. Detailed study of carbon isotopes in shaly basins, especially when carefully integrated with stratigraphy, should be able to define the proportions and transport directions of the terrestrial carbon (Fig. 7).

For the best results, the study of scalar properties should always be combined with directional structures and/or fabrics.

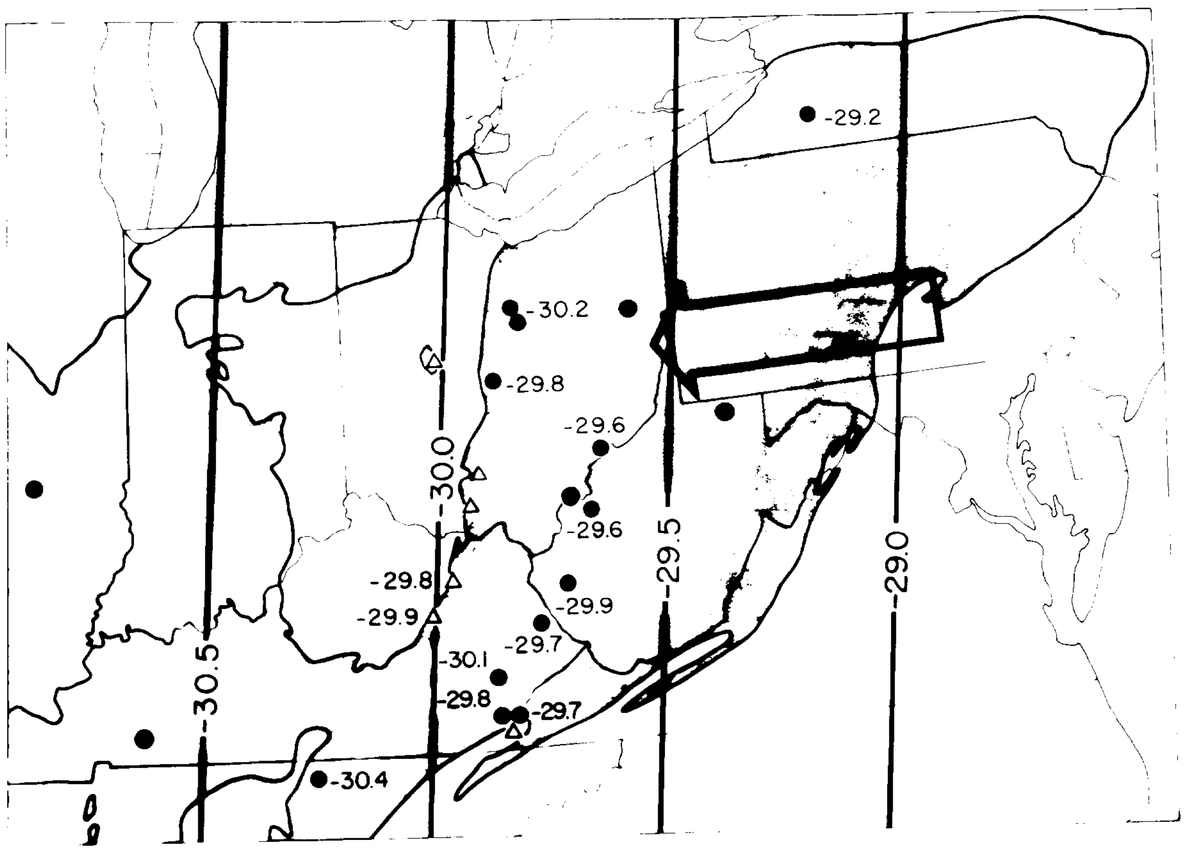

FIGURE 7 Linear trend surface of carbon isotope data (C^{13}/C^{12}) strikes nearly north-south approximately at right angles to paleoslope of basin (arrow from Fig. 1). Linear trend surface accounts for 62 percent of variation in carbon isotopes.

Orientation of concretions in shales has been studied by Colton (1967 b) in the Devonian of New York, who found a general correspondence between their orientation and that of sole marks. Craig and Walton (1962, Fig. 2) also reported on elongate concretions parallel to transport directions in Silurian turbidites in Wales. Orientation of elongate concretions in sandstones is much more common, however, and has been observed to parallel paleocurrent direction, because the sand is believed to have maximum permeability parallel to its transport direction. Along the western outcrop, we have had little success in finding consistent orientation of elongate concretions in the Ohio and Chattanooga Shales.

Both shape and orientation of elongate concretions appear to depend on the time of their formation and on the ratio of maximum to minimum permeability in the plane of the bedding (Fig. 8). Orientation of elongate concretions is always best measured on bedding planes and not on the vertical or near vertical faces of an outcrop.

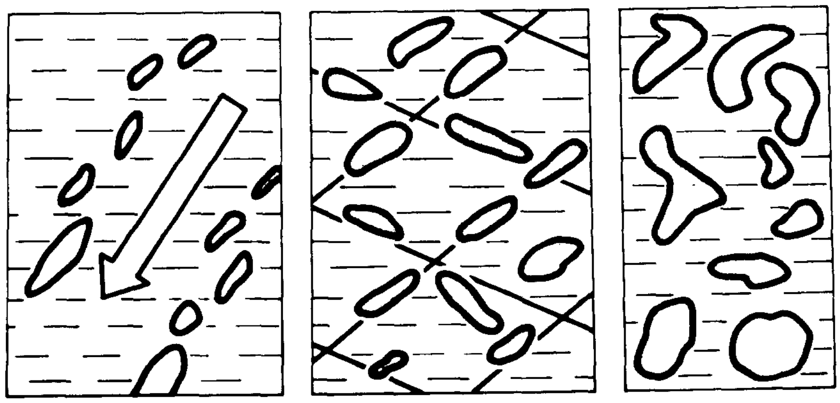

FIGURE 8 Concretions, elongate and non-elongate, and their possible relation to direction of sediment transport and later fractures.

Study of the deep ocean and its shelves with deeply towed side looking sonar and seismic profiles and with bottom photography has revealed mud waves from 10 to 20 meters in wave length and heights of 1 to 2 meters up to giants with wavelengths of 2 to 3 km and heights of 40 to 50 m (Londsdale and Spiess, 1977, p. 67-68). Mud waves with spacings of as much as 20 km and heights of 3 to 5 meters have also been reported on some muddy coasts (see, for example, Alersma, 1971). All of these can be thought of as types of "megasedimentary structures" whose orientation is mappable on the sea bottom by geophysics and whose equivalents should at least be looked for in ancient shales.

Another method is to determine the paleocurrent significance of interbedded and associated facies. For example, linear interbedded sandstone bodies of beach origin define the depositional strike of the basin, which is always an essential step in both a paleocurrent and basin analysis. Or the shape of a bundle of turbidite sandstones may be used to infer, as a first approximation, a down slope direction. In thin shales on cratons, such as the black shales interbedded with coal measures, the geometry of the interbedded fluvial and deltaic sandstones plays a similar role.

METHODOLOGY

The essential methodology for the study of paleocurrent systems in shaly basins is well known and easy to apply and is presented in three parts: discussion of the directional structures most commonly found in shaly basins, how to collect directional information from outcrop and process the resultant data, and how to study paleocurrent data in oriented cores.

Directional Structures

Directional structures are those primary sedimentary structures formed during deposition that show the direction or orientation of currents along the bottom. Such structures are formed by both the traction deposition of silt and sand and by the erosion of cohesive muddy bottoms. These directional structures can be as small as a centimeter and range up to several meters or more and thus are easily observed with the naked eye in both outcrops and cores. Some, such as crossbedding and flute casts, indicate direction of movement but others, such as groove casts and most fine woody debris, only indicate the line of movement.

There is a vast literature on this topic, much of which is summarized in Table 3.

TABLE 3

MAJOR SOURCE MATERIALS FOR PALEOCURRENT ANALYSIS

Angelucci and others, 1967

Most comprehensive documentation of turbidites ever made. Ninety-seven described sections from all over Italy and Sicily plus 65 figures most of which are sedimentary structures. Excellent.

Conybeare and Crook, 1968

Provides many illustrations of sedimentary structures, mostly in sands and sandstones, along with their *description and interpretation plus a short section on how to analyze sedimentary environments. Excellent.*

Dimitrijević, Dimitrijević, and Radosevic, 1967

A small volume with brief descriptions of 52 beautiful line drawings of the inorganic and organic structures of turbidites. Serbian with key ideas also in English, French, and German.

Dzulynski, 1963

Beautifully illustrated treatment of sole marks based on the pioneer work of the Polish school of which Dzulynski is a leader.

Dzulynski and Sanders, 1962

Thirty-seven pages of text and 22 excellent plates dealing mainly with sole marks that occur on the undersides of sandstones.

Dzulynski and Walton, 1965

Devoted mainly to sedimentary structures, most of which are directional. A well illustrated summary.

Gubler, Bugnicourt, Faber, Kubler, and Nyssen, 1966

Contains a short review on stratification and stratigraphic terminology followed by a long section (186 pages) on sedimentary structures. Very systematic and complete. Definition, description, measurement, frequency of occurrence, origin, and utility of each structure. Well illustrated.

Khabakov, 1962

Probably the first comprehensive picture book of sedimentary structures and textures.

Lanteume, Beaudoin, and Campredon, 1967

Sixty-one very good plates, mostly of sole marks, with full captions in French, English, German, Italian, and Spanish. Full cross index and all the previous relevant literature. Essential companion for the field study of turbidite deposits.

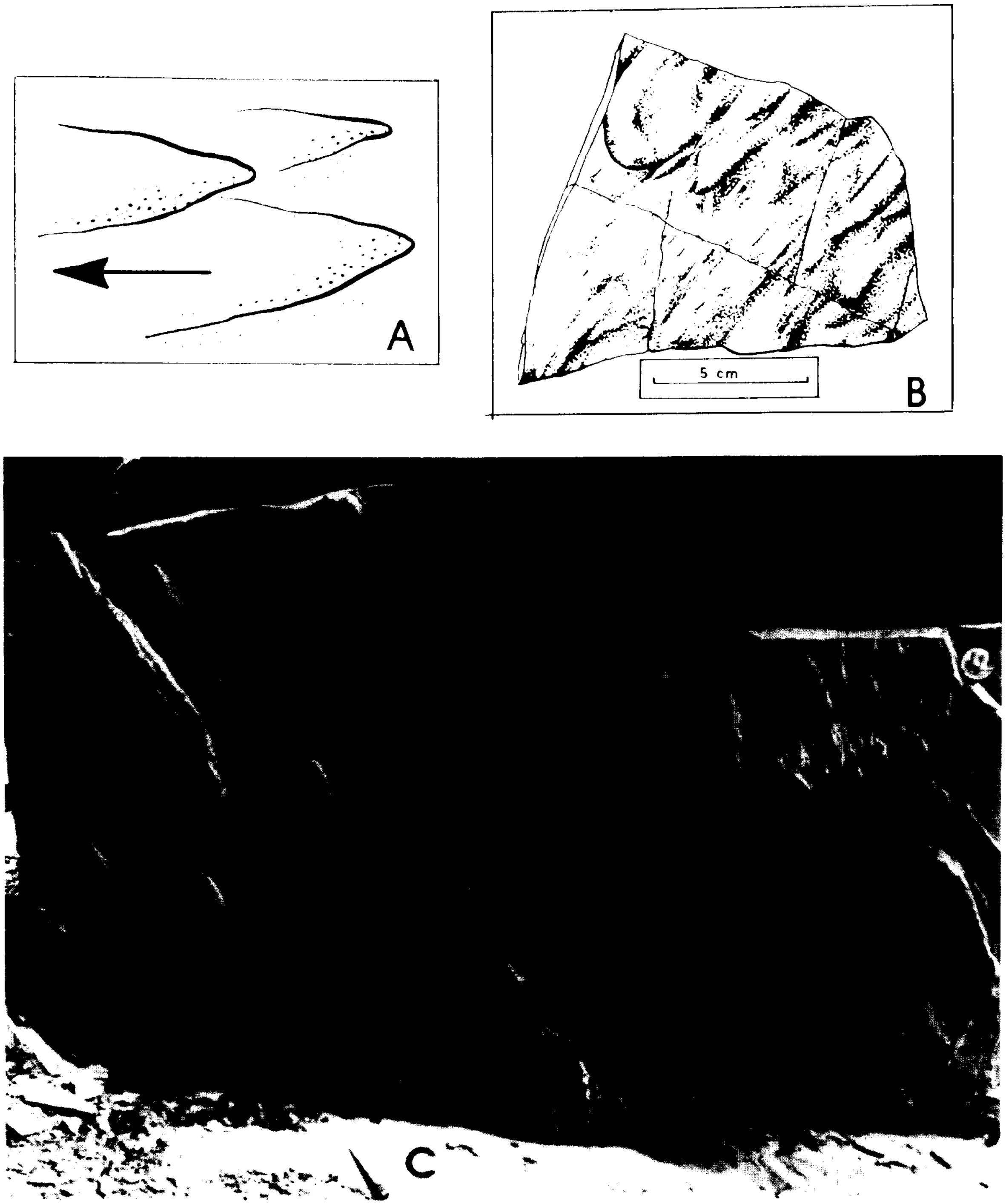

FIGURE 9 Flute casts: A. schematic drawing (arrow indicates direction of flow), B. drawing of actual flute casts (current from lower left to upper right) and C. low relief flute casts on base of siltstone from Olmstead facies of Cleveland Member of Ohio Shale along Rocky River in Cleveland, Cuyahoga County, Ohio (current from top to bottom).

Pettijohn and Potter, 1964

Primarily a picture book prefaced by a short essay on classification and followed by a four-language glossary of 360 entries.

Potter and Pettijohn, 1977

Standard, classic reference on paleocurrents. Updated with over 100 pages of additional text and many illustrations.

Ricci Lucchi, 1970

A beautifully illustrated book of primary sedimentary structures, mainly sole marks of flysch sandstones; 170 plates with marginal text. Italian with English-Italian lexicon.

Many thick shaly basins are probably closely related to distal turbidites, as is the Devonian black shale. Another common environment are the prodelta muds of large deltas deposited on the margins of cratons. Thus in many thick shaly basins, the most common sedimentary structures will be those of turbidites and gravity flow. Widespread thin shales on cratons are probably also commonly of prodelta origin but possibly may even be transgressive lagoonal deposits.

Below, the common directional structures of shaly basins are illustrated and briefly discussed. All the line drawings are taken from the excellent Serbian publication by Dimitrijević and others (1967).

Sole Marks

Sole marks are those structures formed on the bottoms of silt and sand layers interbedded with shale and are formed by the current scouring and sculpting of cohesive mud bottoms followed by infill-casting of sand or silt layers.

Flute casts (Fig. 9) are elongate, blunt ended and fan-shaped and occur on the undersides or soles of sandstone and/or siltstone beds. The blunt end is often bulbous or beaked and is the upcurrent end of the flute.

Longitudinal ridge and furrow casts (Fig. 10) are similar to flute casts, but are narrower and have many bulbous protrusions along their length. The bulbous end points upcurrent.

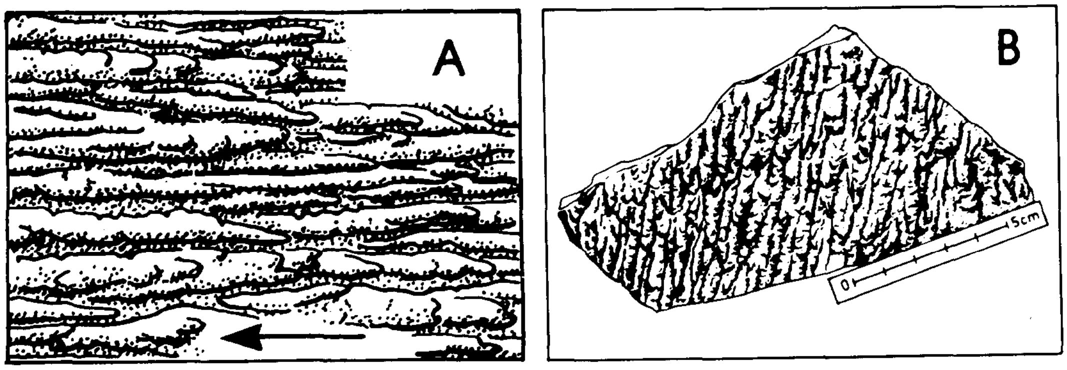

FIGURE 10 Longitudinal furrows and ridge casts: A) schematic drawing (arrow indicates direction of flow) and B) drawing of actual longitudinal furrows and ridge casts (current from bottom to top).

Current crescents (Fig. 11) are formed by the erosional scour around an obstacle on the bottom, such as a pebble, fossil, or a piece of water-logged wood. They also form around worm tubes. The crescent opens down-current.

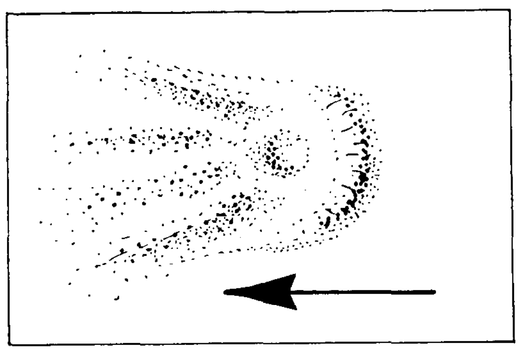

FIGURE 11 Schematic drawing of current crescent (arrow indicates direction of flow).

Channel casts (Fig. 12) are large, long, linear, and hemicylindrical sole marks. They are formed by erosion and commonly deeply truncate laminae of the underlying shale. They indicate line of movement only.

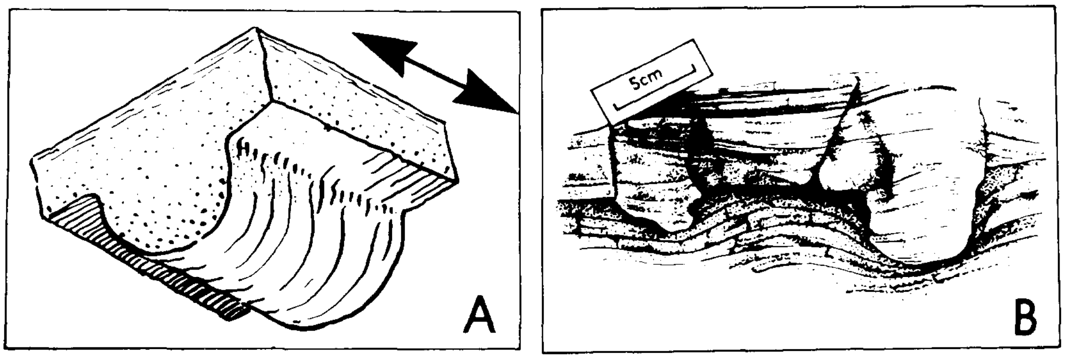

FIGURE 12 Channel casts: A) three dimensional schematic drawing (arrow parallels line of movement) and B) actual channels shown in cross section.

Chevron casts (Fig. 13) are longitudinal ridges with minor systematic transverse ridges produced by the "chattering" action of tools dragged along the mud bottom. The ends of the chevrons are oriented downcurrent.

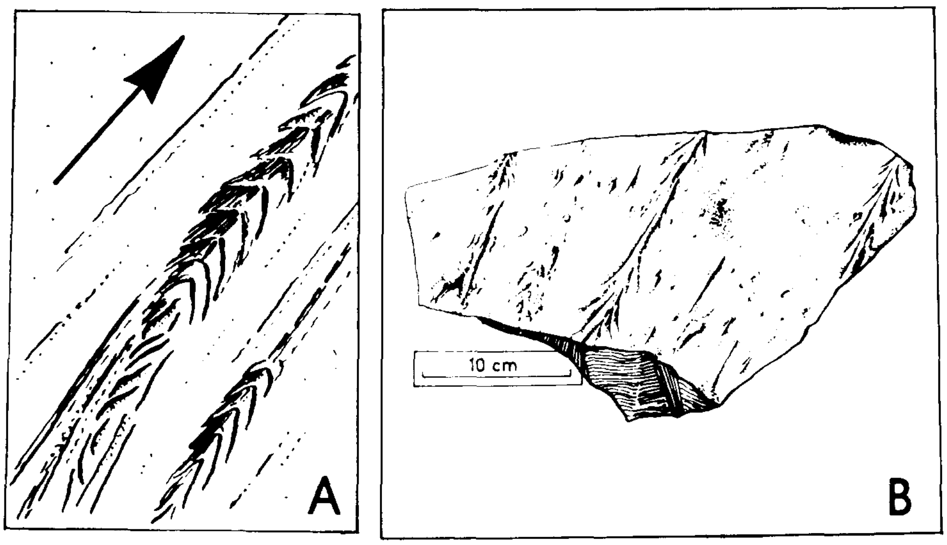

FIGURE 13 Chevron casts: A) schematic drawing (arrow points downcurrent) and B) actual drawing.

Prod, skip, and brush casts (Figs. 14 and 15) are small asymmetrical casts formed by tools impinging upon and brushing against a mud bottom. They have highest relief downcurrent. Skip casts (Fig. 14B) are a repetitive, linear sequence of prod marks. Brush casts (Fig. 14C and D) feather-out upcurrent and have a semi-circular dispression on the downcurrent end. These marks can display many of the surface details of the tool.

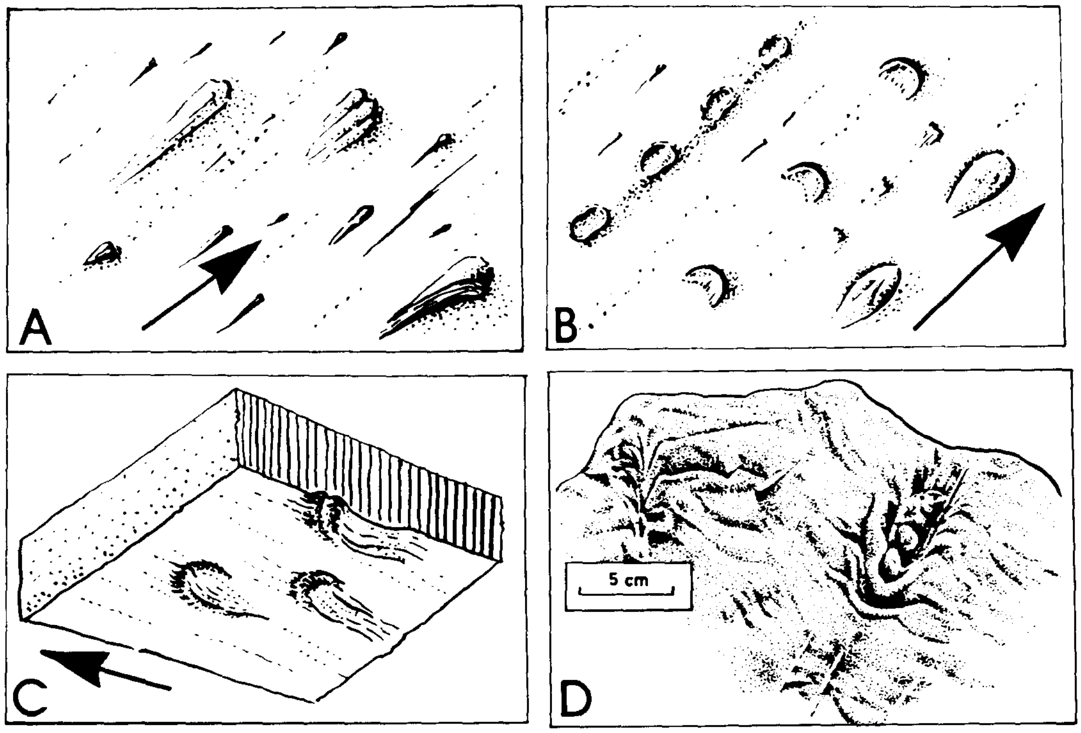

FIGURE 14 Small casts made by tools impinging on muddy bottoms: A) prod casts, B) skip casts, and C) and D) brush casts.

Groove casts (Fig. 16) are narrow, long, and linear ridges commonly with minor ridges. They are formed by hard tools, such as fossils or twigs, dragging along muddy bottoms. They indicate line of movement only.

Load casts, flame structures, and frondescent casts (Fig. 17) are soft sediment deformation structures caused by sands and silts sinking or foundering into underlying muds. Load casts are bulbous ball and pillow structures that range from a few centimeters to tens of meters in diameter. Flame structures are masses of the underlying mud that are squeezed or intruded up around the ball and pillows. When the load casts are formed on a slope, they can become asymmetrical and produce flame structure; the flame points upslope. Frondescent casts (Fig. 17C) are a form of load casting and their thicker, bulbous ends point downslope.

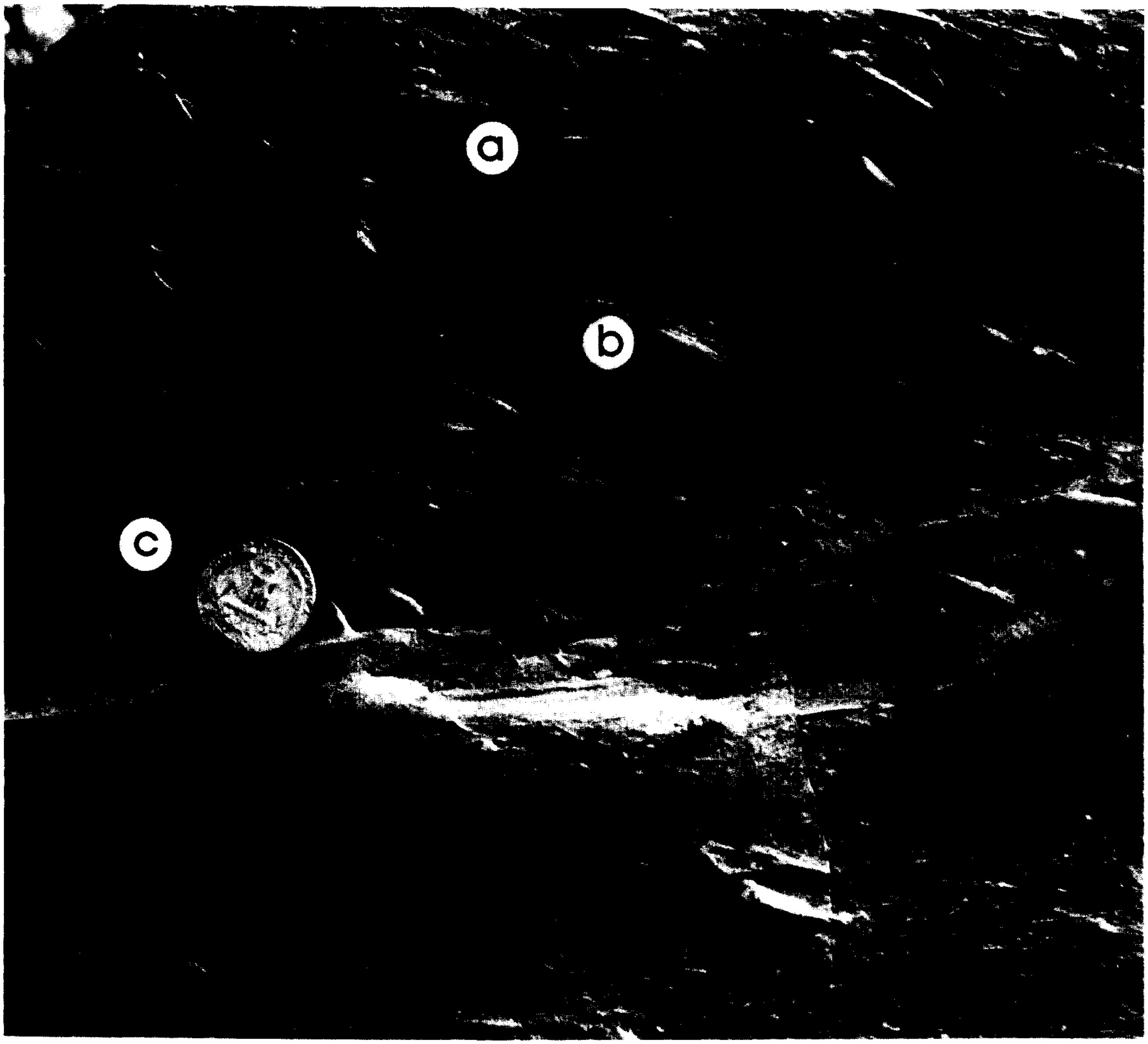

FIGURE 15 Small casts made by tools impinging on muddy bottoms: A. prod casts, B. skip casts, C. and D. brush casts.

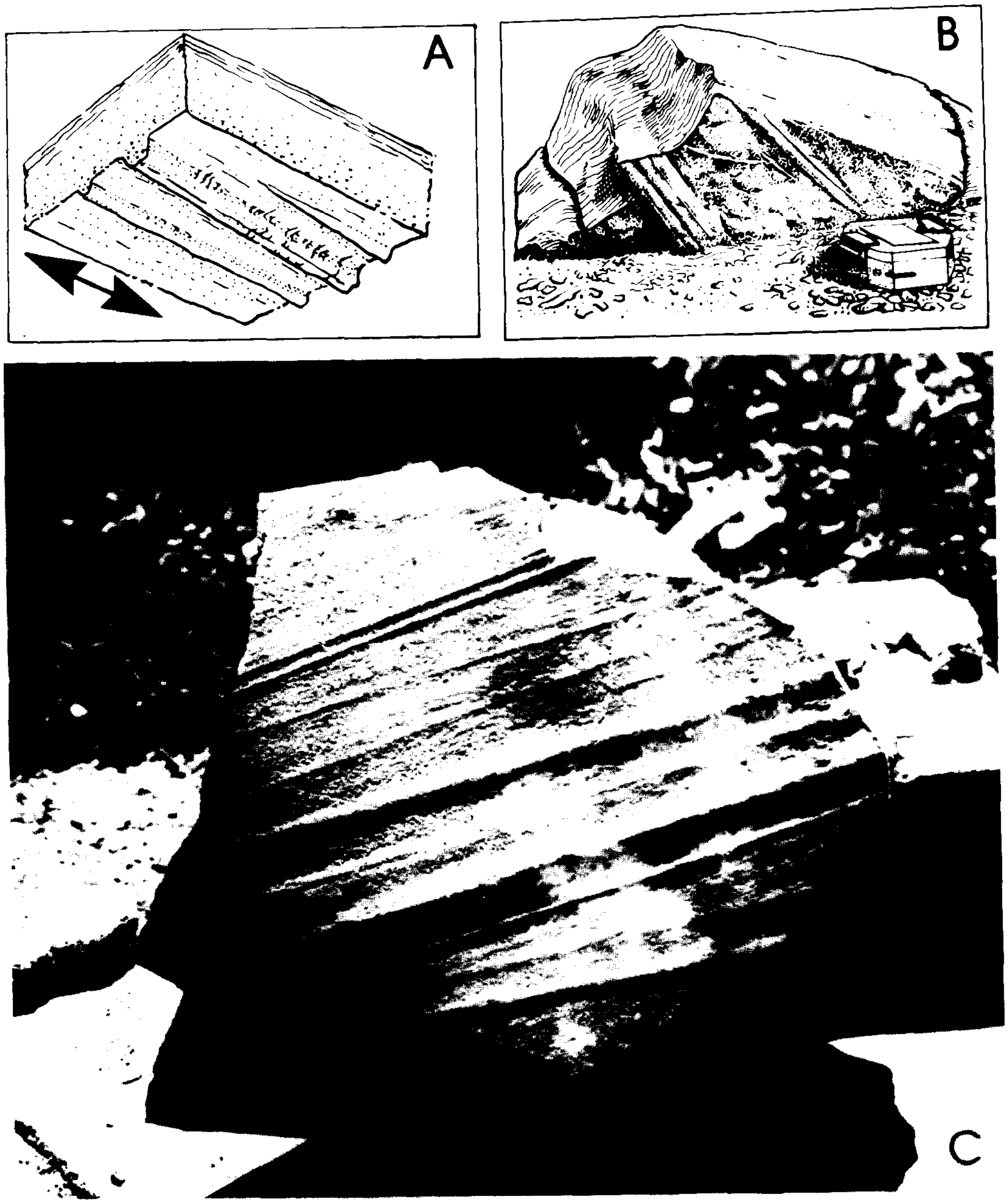

FIGURE 16 Groove casts: A. schematic drawing (arrow parallels line of movement), B. grooves on underside of sandstone bed, and C. siltstone in Chattanooga Shale (northeast side of State Route 31 near Flat Gap, 4.3 miles north of junction with U.S. 11W Hawkins Co., Tennessee).

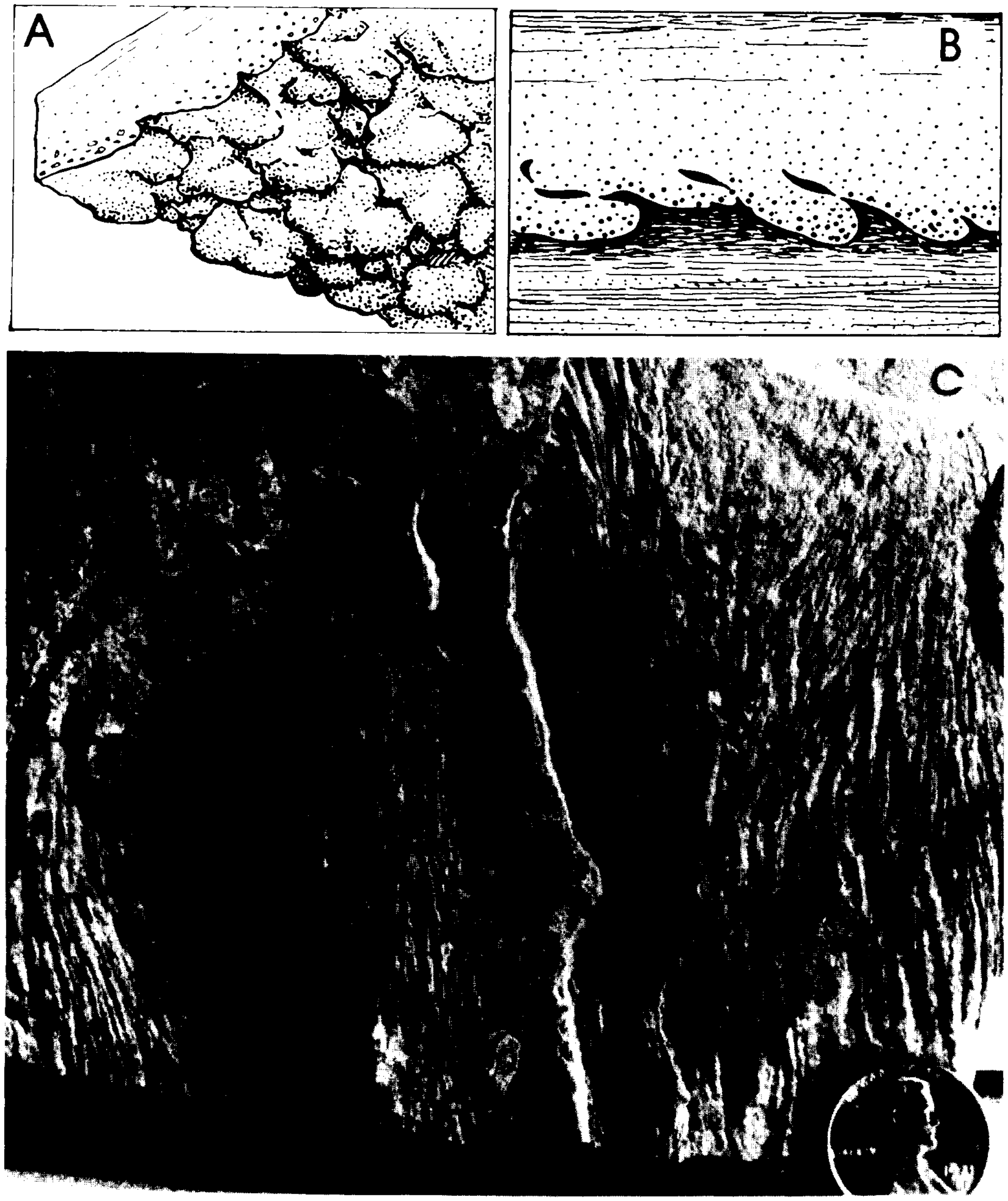

FIGURE 17 A) Load casts, B) flame structure, and C) frondescent casts. Flame (shale intrusion) points up slope. Photograph is from Brallier Formation.

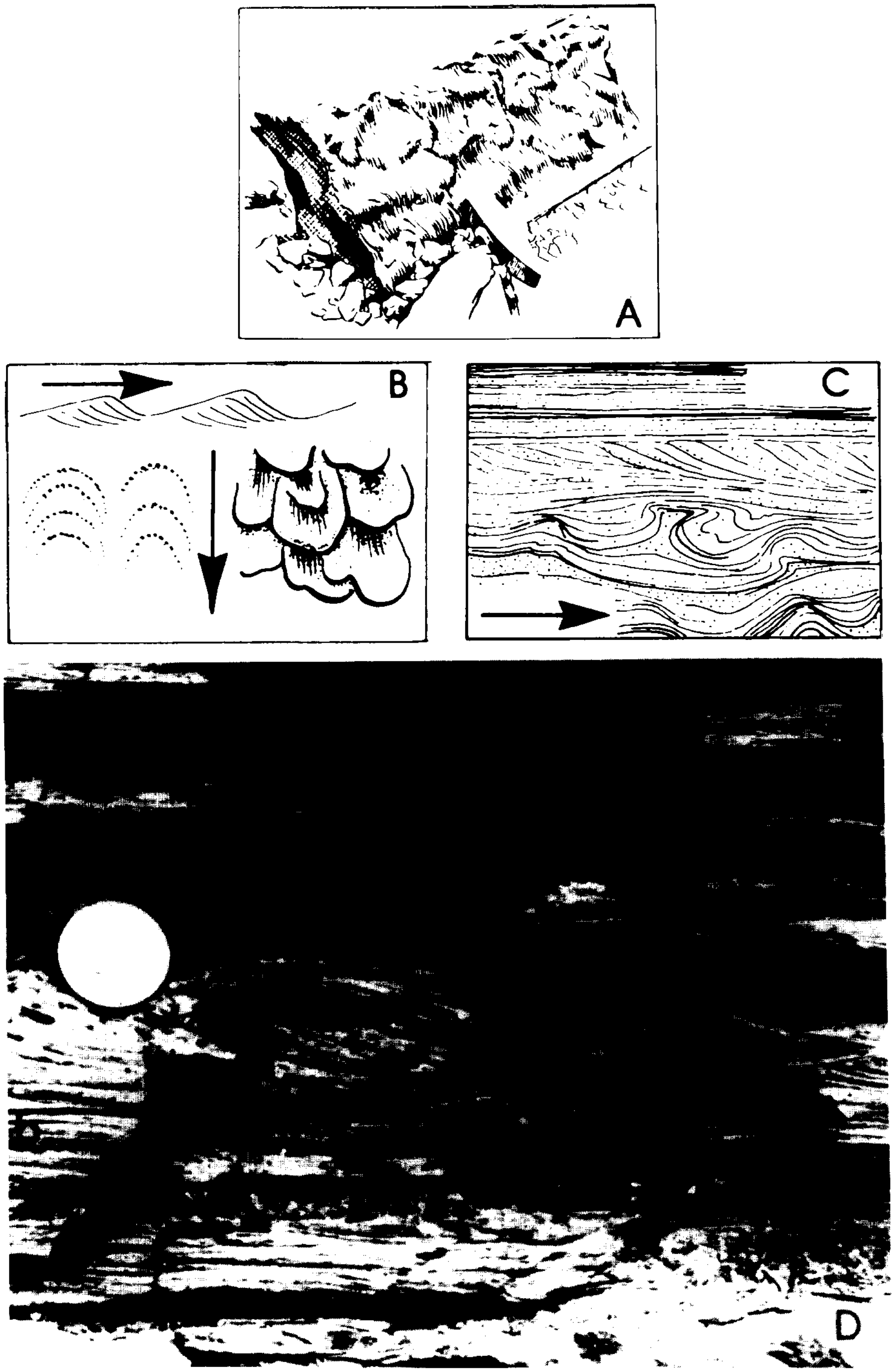

FIGURE 18 Ripplemark and cross lamination: A. drawing of rippled sandstone, B. schematic drawing (arrows) show transport direction, C. schematic drawing of cross lamination and associated convoluted lamination, D. photograph of crosslaminated (a) and flat bedded (b) siltstone from Olmstead facies of Cleveland Member of Ohio Shale, Clifton Club, Lakewood, Cuyahoga County, Ohio.

Ripple Marks, Cross Lamination and Crossbedding

In thin bedded siltstones and sandstones, traction deposition produces many ripple marks (Fig. 18) that have internal small-scale cross lamination. In the Devonian shale sequence of the Appalachian basin rippled and cross-laminated siltstones are very common.

FIGURE 19 Crossbedding from Catskill Formation (Humphreys and Friedman, 1975, Fig. 6). Photograph by permission of the authors and the Houston Geological Society.

Crossbedding (Fig. 19) such as occurs in the Catskill facies of the Devonian, is a larger form of inclined bedding formed by migrating dunes and is commonly found in thicker sandstone found along the margins of shaly basins or in sandstone channels within them.

Parting Lineation

Parting lineation (Fig. 20) is a faint series of linear ridges and depressions that are seen when thinly laminated siltstone and fine sandstone beds are split apart. This structure is the result of grain orientation and shows line of current movement only.

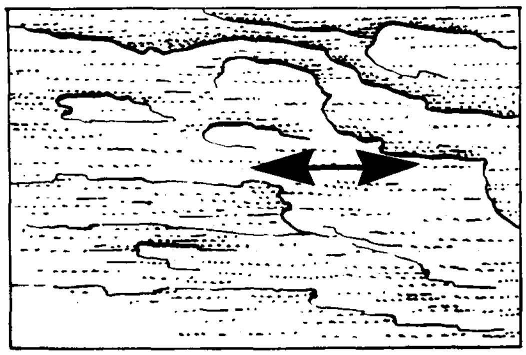

FIGURE 20 Schematic drawing of parting lineation. Currents parallel arrowheads.

Clay clasts (Fig. 21) are commonly found in sandstone and siltstone that are interbedded with shales. They can also occur in shaly slope deposits, but are very rarely seen in the bottom set, distal parts of shaly basins.

Virtually all clay clasts are locally derived by the erosion or pulling apart of cohesive clay layers. Commonly, they are flat and elongate and, in shales, may be oriented in the plane of lamination -- commonly parallel with the depositing currents? In crossbedded sandstones and siltstones, interbedded with shales, they may display some degree of imbrication, inclined in an upcurrent direction. Other elongate particles that can be used to determine current direction are sand grains, woody fragments (Fig. 22) and fossils.

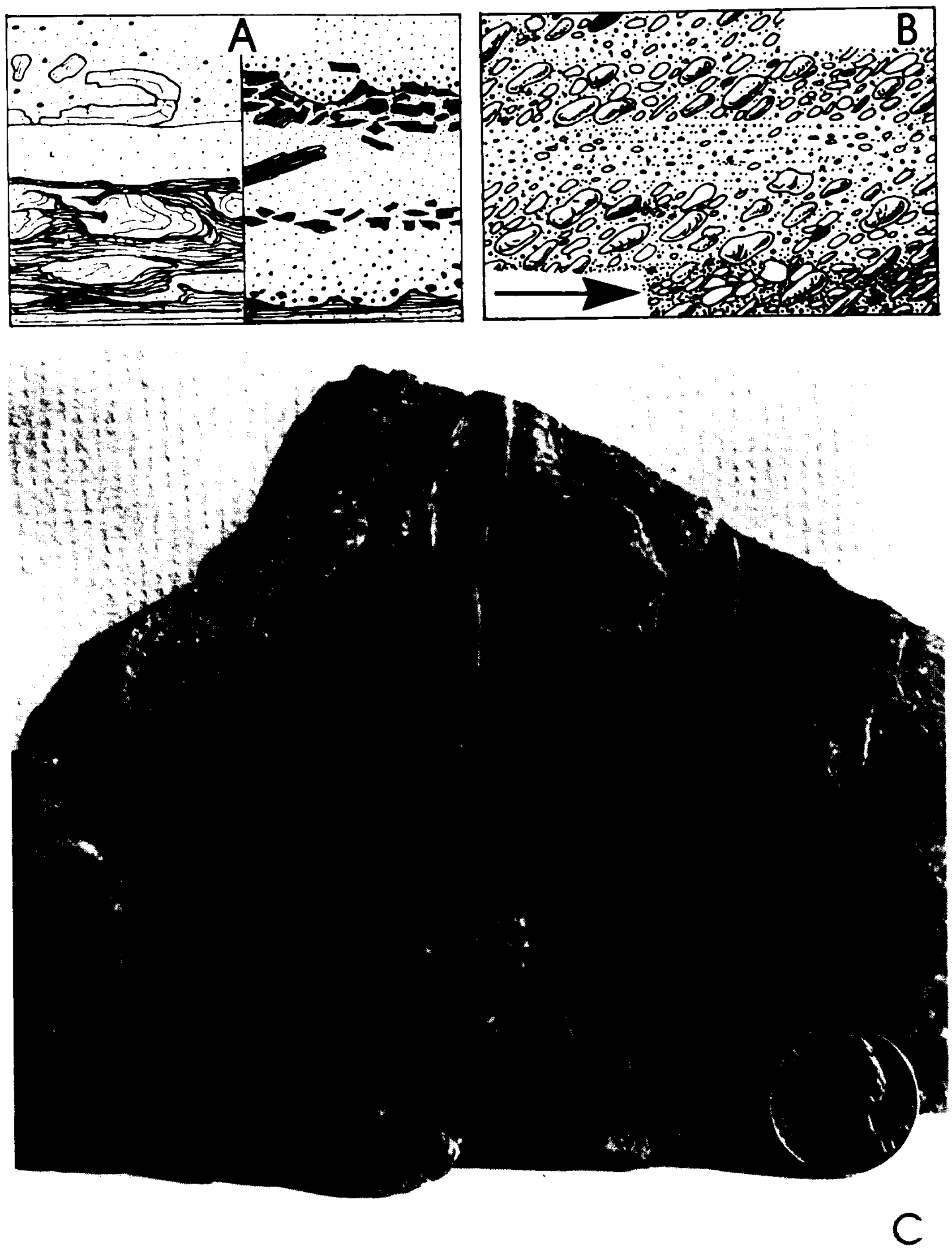

FIGURE 21 Clast orientation: A. how clasts form, B. imbrication seen on a vertical surface parallel to transport direction, and C. oriented elongate clay clasts on bottom of Devonian siltstone (current parallel to long dimension).

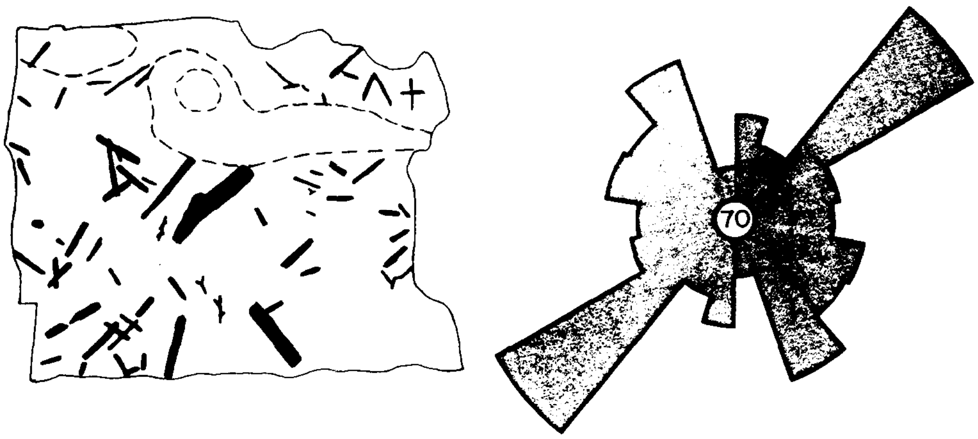

FIGURE 22 Oriented wood with bimodal orientation in Pennsylvanian black shale (Zangerl and Richardson, 1963, Fig. 34). Only larger woody fragments shown.

Graded Beds

A number of the foregoing sedimentary structures are found in graded beds (Fig. 23). Siltstone beds in the Devonian are often graded. Graded siltstones and sandstones may contain cross lamination, parting lineation, and ripple marks, as well as sole marks at their base. Hence the recognition of graded bedding in a shale sequence is an essential step in the mapping of paleocurrent structures -- and in recognizing that turbidity currents played a role. Graded beds change systematically downcurrent, and become thinner and gradually lose their lower subunits. Hence regional mapping of these graded bed properties can help define paleoslope.

Collecting and Processing Outcrop Data

Figure 1 is based on McIver's (1970, Fig. 14) data supplemented by our own examination of outcrops in western New York, Erie County, Pennsylvania, and northern Ohio as well as outcrops in Virginia, West Virginia, Kentucky and Ohio. McIver's map utilized 2400 observations, mostly sole marks and some crossbedding, to which we added 1216 observations from outcrops, of which 636 were sole marks. Other directional structures which we measured included wood fragments, fossils, ripple marks, crossbedding, parting lineation, elongate concretions and nodules, and clay clasts.

The unit of areal sampling was the 7½ minute topographic quadrangle on each of which two to three outcrops were sought. These outcrops were scattered as widely as possible within the quadrangle.

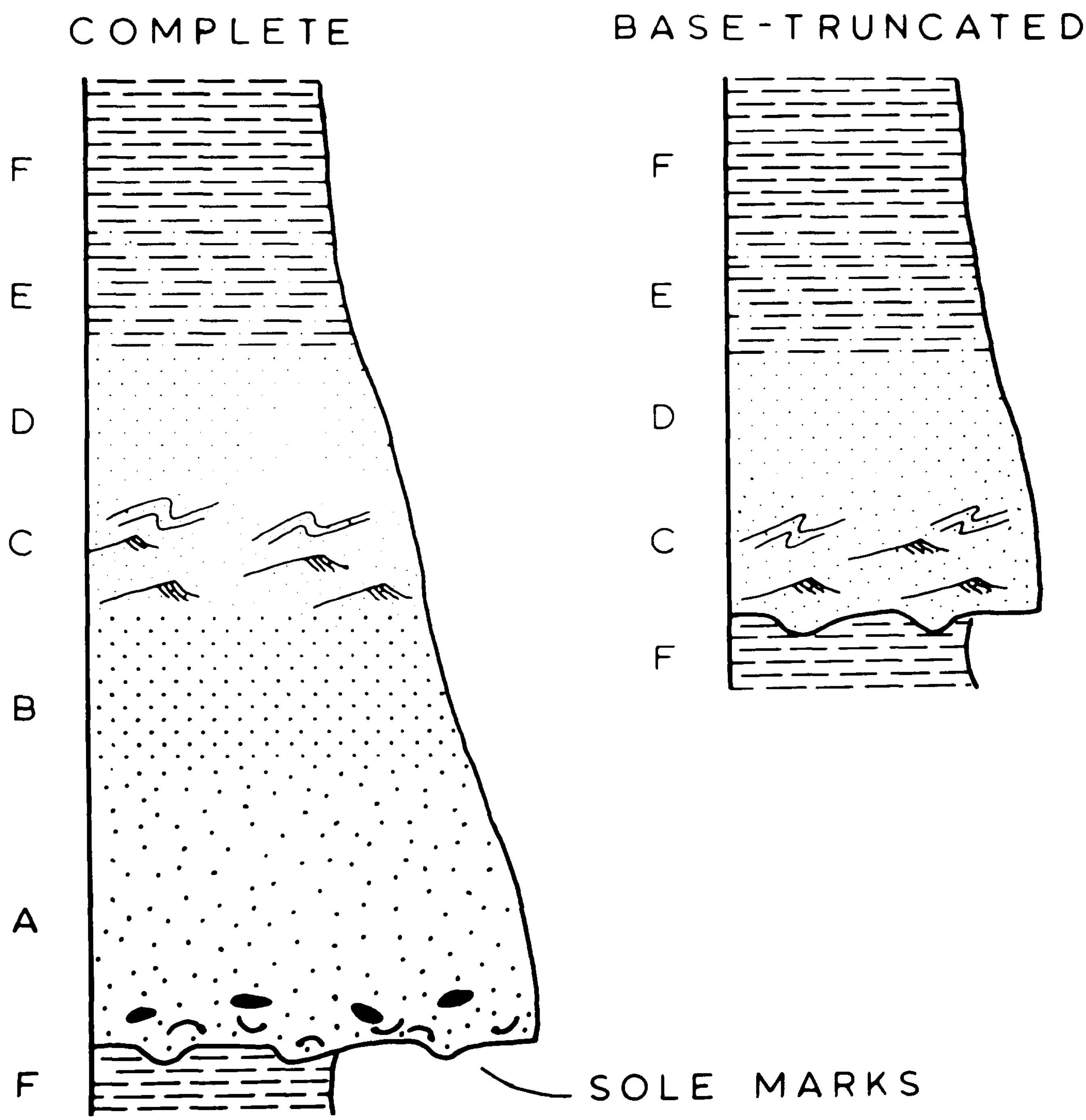

FIGURE 23 Graded beds (Bouma Cycles) typical of the Devonian Brallier Formation in West Virginia and Virginia: complete Bouma cycle at left and a base-truncated cycle at right. Sole marks are at the base, clay clasts are in the A unit, ripple crossbedding and convolute laminae occur in the C unit and parting lineation occurs in unit D.

At each outcrop all the different paleocurrent structures were measured, but special attention was always given to sole marks, because they are most informative and normally have the least variability in direction.

In the laboratory a vector mean of sole mark orientation was calculated for each outcrop and plotted on a basinwide set of 1:250,000-scale maps. Because of the small variability of sole mark orientation, however, an arithmetic average would have served equally as well. Subsequently, all the data were averaged for each 30 minute quadrangle (Fig. 24) to obtain the final basinwide map of Figure 1.

Oriented Cores

Oriented cores are used with increasing frequency to obtain structural dip and fracture orientation in order to solve exploration and engineering problems, but we know of only two published paleocurrent studies based on oriented cores of sandstones (Hewitt and Morgan, 1965, Fig. 9 and Hsu, 1977, p. 142-143) and of <u>no</u> paleocurrent studies of shales from oriented cores.

The oriented cores of the Devonian shale sequence of the Appalachian basin reported herein (Table 4) were obtained by the Christensen Diamond Products Corp. (Rowley and others, 1971) and by Dikor (1977). During coring, reference grooves are inscribed on the core and their down-hole compass orientation is recorded photographically. In the laboratory the known orientation of the inscribed grooves and a goniometer (Fig. 25) are used to mark the four cardinal points of the compass on the core. This done, directional structures are easily measured with a protractor.

The principal paleocurrent structures found in cores are elongate woody debris (Fig. 22), fossils such as <u>Lingula</u> and <u>Tentaculites</u>, and sole marks such as small scale flutes and grooves, and some bounce casts on the base of thin interbedded siltstones and sandstones (Fig. 26). Other oriented structures include small clasts and parting lineation (Fig. 27). Although small-scale cross lamination associated with linguoid ripples is common in many of the siltstones found in the Devonian shales, its orientation is variable and difficult to measure. In some cores, however, ripple crests associated with the cross lamination can be measured after the core is split along the upper surface of cross laminated siltstones.

The best procedure is to examine every siltstone and sandstone laminae or bed, especially its bottom surface, no matter how thin, and carefully separate the core along the bedding planes of its shale to find woody and fossil debris. Three observers examined over 800 ft of core for directional structures in about 10 hours; part of this time a goniometer was used to reorient the core.

TABLE 4

PALEOCURRENT DATA COLLECTED FROM ORIENTED CORES CUT IN DEVONIAN SHALE SEQUENCE OF APPALACHIAN BASIN

Part A Measurements

County	Footage Sampled	Sole Marks	Plant Debris	Parting Lineation	Fossils	Ripples	Vector Mean
Carroll	2100-3200	3	3				94
Lincoln	2700-3000	16	5	1	3		77
Martin	2600-2700		3		4		50
Mason	2700-3400	1	65		4		50[1]
Washington	3490-3500	1		1			90
Wise	4900-5400		8		7	3	91

[1]Midpoint of modal class; only wood considered

TABLE 4 (continued)

Part B

Well Name and Location

Location	Identification	Coordinates
Carroll Co., Ohio	Glen-Gery #5-745 Canton Oil and Gas Co.	600' S.L. & 75 W.L. of S.W. Qtr. of Sec. 29
Lincoln Co., W. Va.	Columbia Gas Trans. #20403 Columbia Gas Transmission Co.	3.1 mi W of ($82^{o}10'00''W$) 4.5 mi S of ($38^{o}10'00''N$)
Martin Co., Ky.	Columbia Gas Trans. #20336 Columbia Gas Transmission Co.	Carter Grid Coordinates 16-P-85 2750' F.N.L. 1650' F.W.L.
Mason Co., W. Va.	Reel Drilling Co., D/K Farm No. 3, Robinson District	$38^{o}55'30''N$, $82^{o}03'45''W$
Washington Co., Ohio	Florence L. House #R-109 River Gas Company	6200'W of ($81^{o}32'00''W$) 8400'S of ($39^{o}25'00''N$)
Wise Co., Virginia	Columbia Gas Trans. #20338 Pennsylvania-Virginia Corp.	$37^{o}00'37''N$; $82^{o}41'41''W$

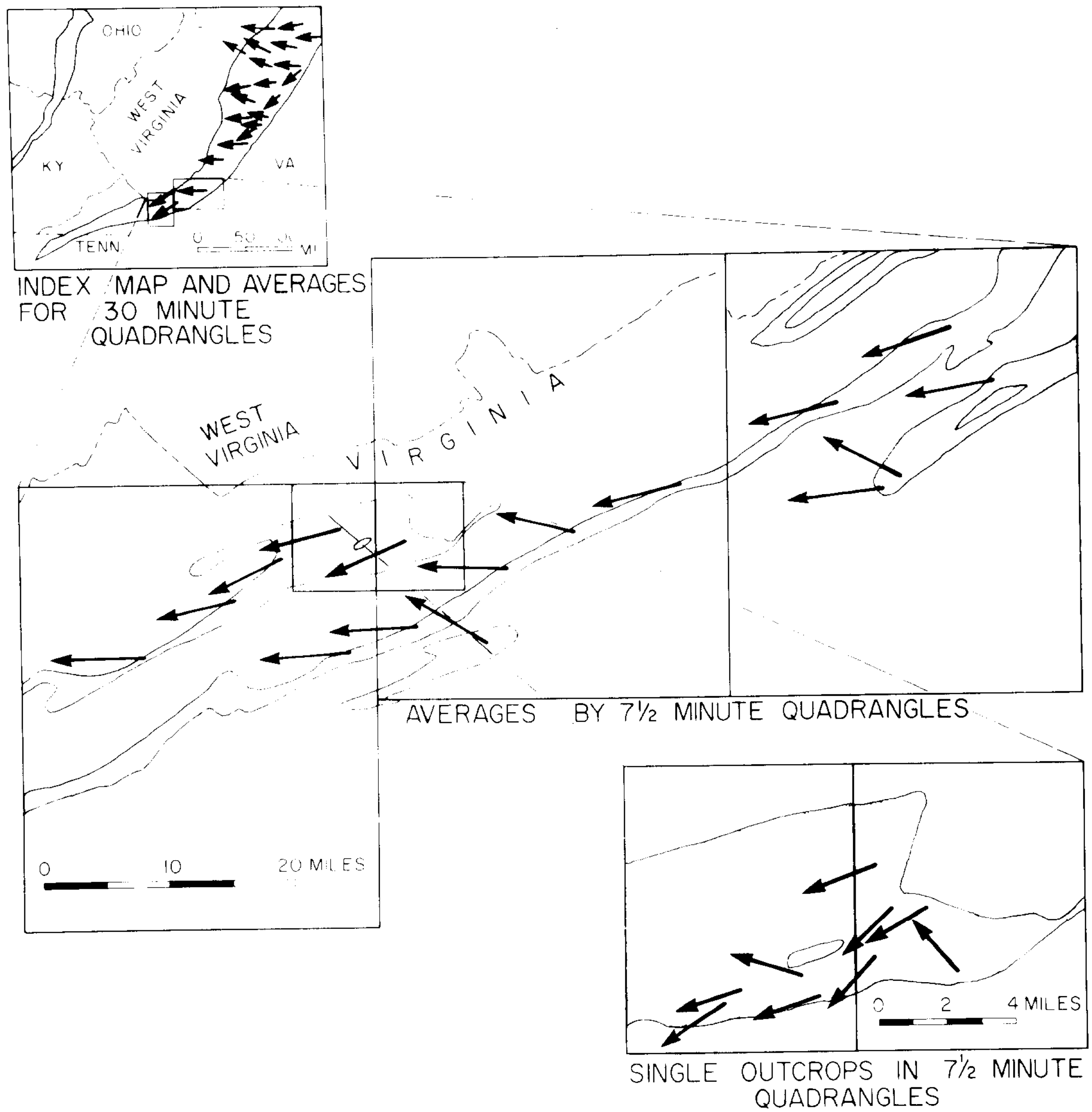

FIGURE 24 Plotting paleocurrent data at different scales alloys determination of variability.

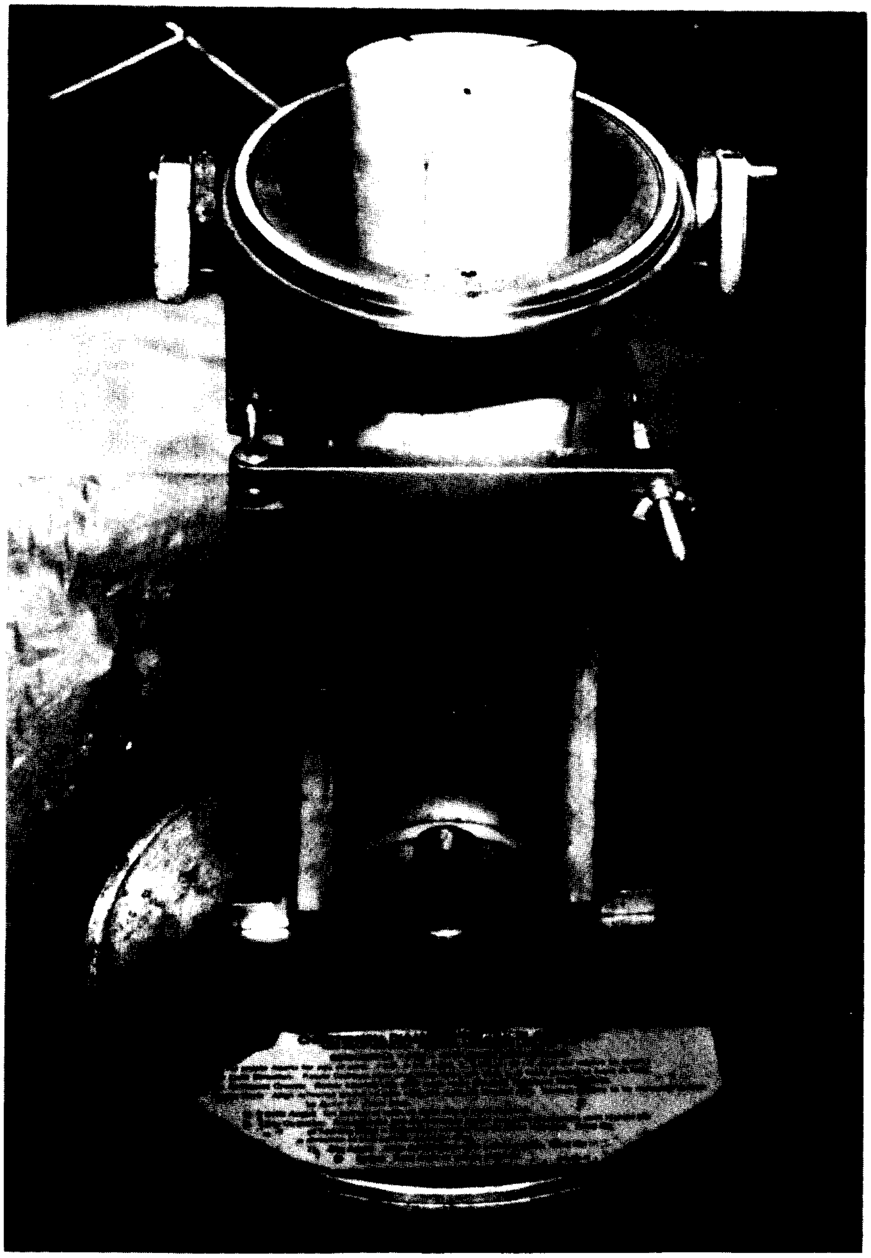

FIGURE 25 Goniometer supplied by the Christensen Diamond Production Company for reorientiion of core in the laboratory.

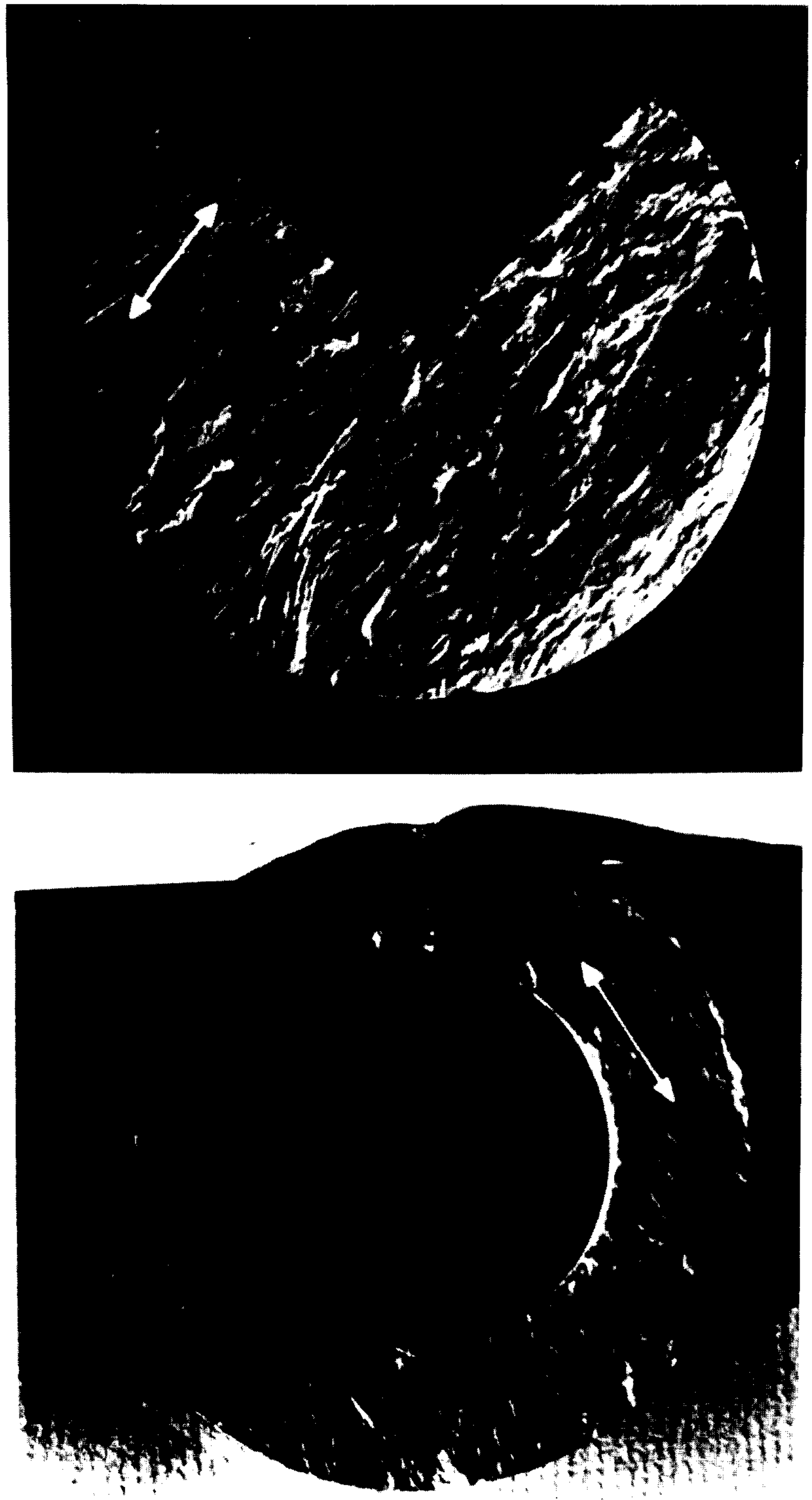

FIGURE 26 Sole marks on underside of thin siltstone from oriented cores of Devonian Shale. Arrows indicate line of current.

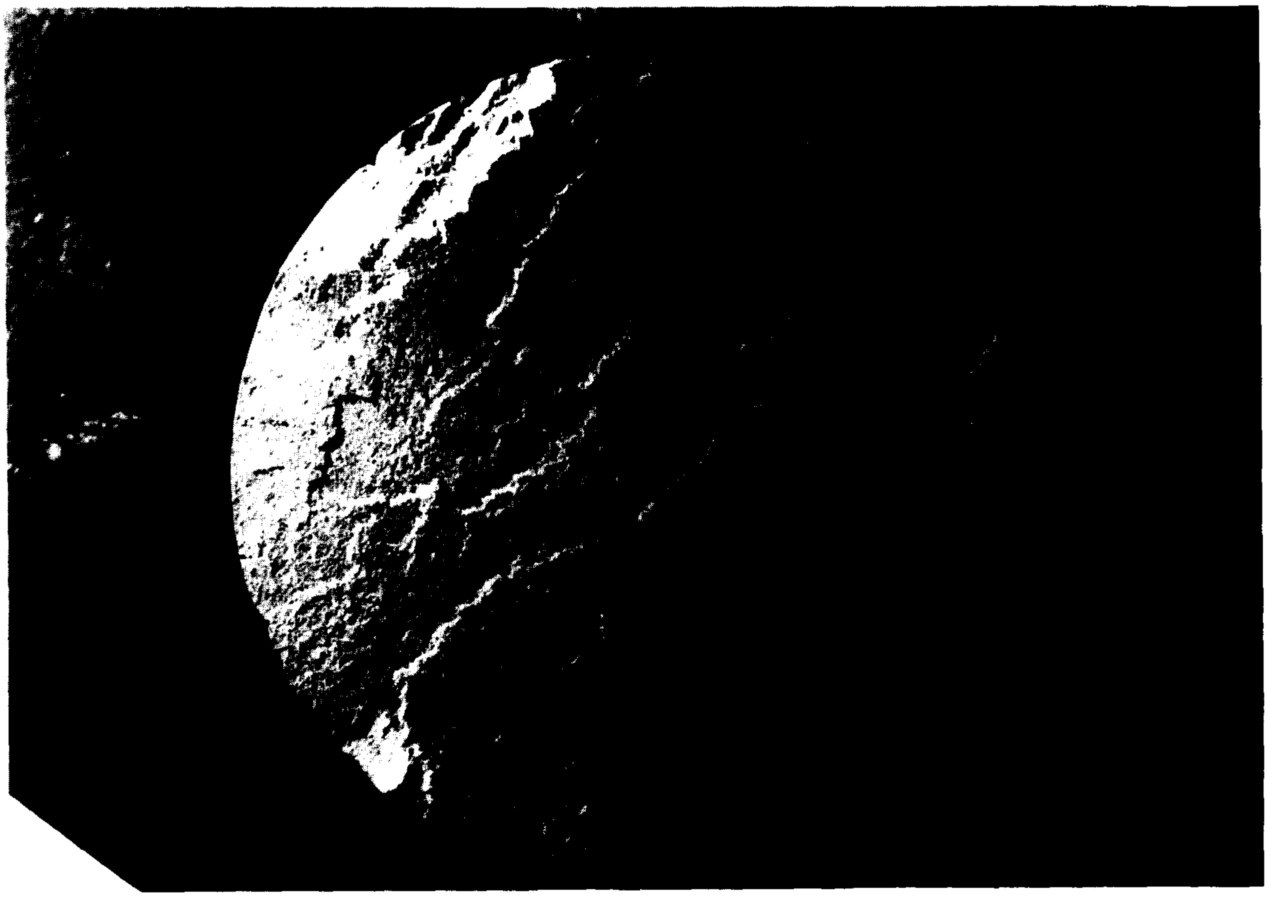

FIGURE 27 Parting lineation from a siltstone in an oriented core cut in the Devonian shales of the Appalachian Basin.

Only one measurement per surface is necessary for grooves, flutes, and parting lineation because their variability is very small. On the other hand, for woody debris and fossils each fragment is measured, because their orientation is generally more variable. For Lingula we recorded the azimuth of the line of symmetry extending through its beak. Tentaculites is another fossil in Devonian shales that can be very well oriented so only one general measurement per bedding plane is usually needed, at least in core materials.

For each of the six cores studied, the types of directional structures and their orientation were recorded, oriented structures were plotted against the gamma-ray log (Fig. 28), and average orientations computed. We considered the sole marks of siltstones the most reliable, in part because their orientation agrees the best with that found in the Devonian

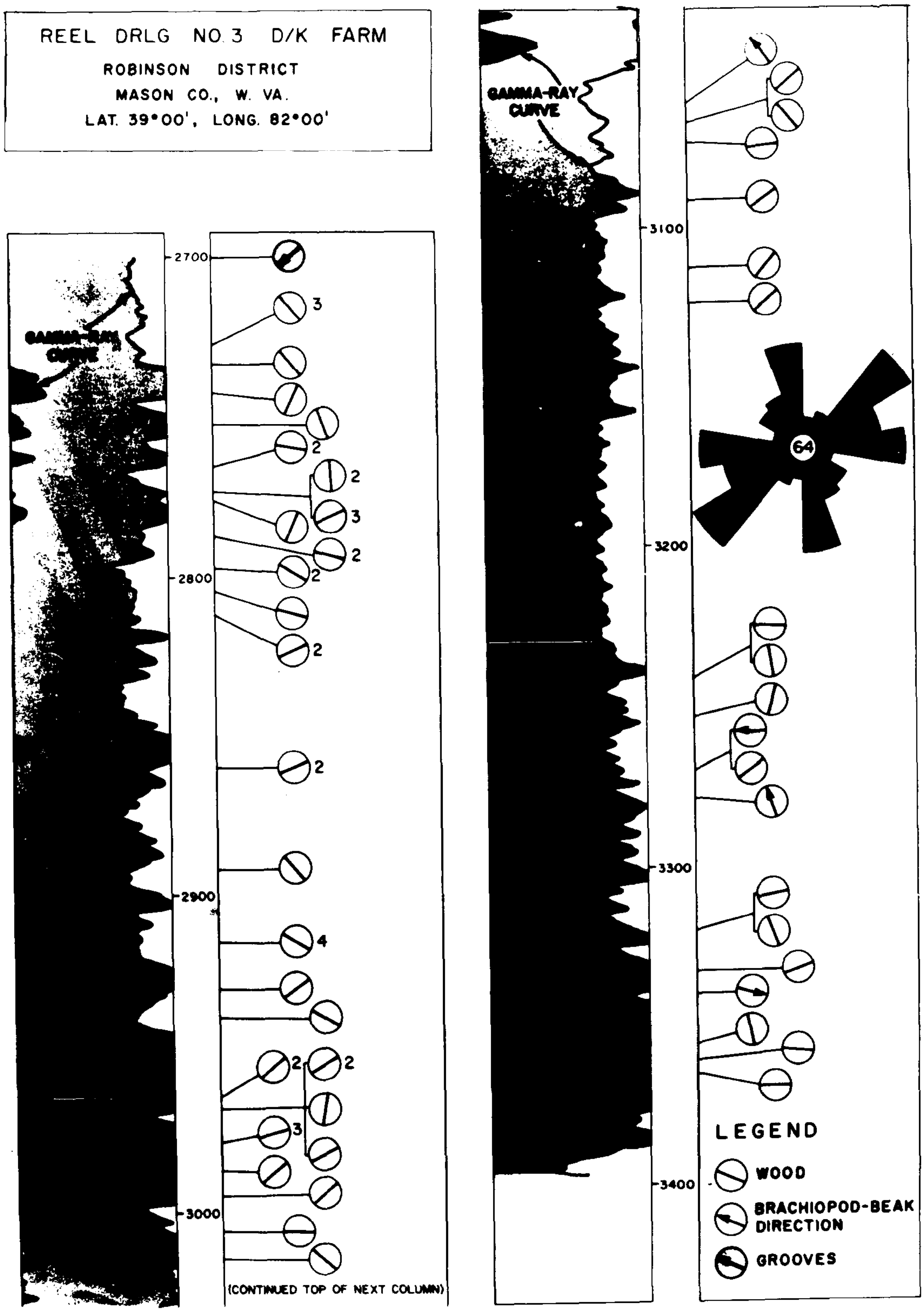

FIGURE 28 Log of Mason County core and orientation of directional structures. Compare distribution of wood orientation with that shown in Figure 20.

outcrop and because of the many successful published studies of sole marks. For woody debris, which tends to have a bimodal orientation, the direction of the major mode seems best.

Our experience suggests that directional structures can almost always be found in the siltstone occurring in a shale sequence and, even when siltstone is absent, careful examination of the shale will reveal oriented woody debris or body fossils. It is our impression that such woody debris tends to be clustered in cores of shales so that when one piece is found careful examination will commonly reveal others above and below. A rose diagram is needed to find the modal directions of either fossil orientation or woody debris and when possible, the orientation of another, better understood directional structure, such as sole marks, should be plotted on the same rose diagram.

UNRESOLVED PROBLEMS

A key question relevant to the study of paleocurrent systems in shaly basins is, to what extent does the paleocurrent system of associated lithologies coincide with that of the shale itself? In the Upper Devonian of the Appalachian Basin this general question has two aspects. First, did the Upper Devonian muds have the same general source as their interbedded siltstones and fine sandstones? And secondly, how many other current systems may have been present that our research has not revealed?

Judging by the vast volume of mud in the Upper Devonian and by the uniformity of both its facies pattern and paleocurrents, it seems most improbable to us that the mud came from a different source than the interbedded silt and sand. Certainly the Upper Devonian deltas of the Appalachian basin were, by comparison with modern deltas, very major ones and in all major deltas, ancient or modern, the mud, silt, and sand have a common source -- a large river system.

The second of the above two questions is more difficult to answer. We recognize, of course, that the marine basin of the Upper Devonian was probably stratified with respect to oxygen and possibly even with respect to density (cf. Heckel, 1977) and that there could have been different circulation cells for these different water masses as has been suggested by Kauffman (1975, Fig. 3) for the Cretaceous inland seaway of North America. Such possible complexity -- and it has never been proven for an ancient basin -- in no way, however, precludes stratified water masses from depositing sediment with well oriented paleocurrent structures in muds, silts and sands.

What actually do field studies of paleocurrent systems in ancient shaly basins show? Many field studies of the medial and distal turbidites of such basins have shown some divergencies in orientation between the base of a distal siltstone or sandstone of turbidite origin and its top (see Pettijohn, et al., 1972, Fig. 4-11; Potter and Pettijohn, 1977, p. 157-195; and Morris, 1974, Fig. 22). There is, however, strong general agreement that the flutes and grooves at the base of turbidite beds represent the initial direction of the turbid flow and are thus the best predictors of its orientation.

What do paleocurrent studies of the Upper Devonian of the Appalachian basin actually show?

In the Upper Devonian slope sequence of New York Colton (1967a, Figs. 5 and 6) suggested a divergence of about 30° between paleocurrents in the shale and their interbedded siltstone. We also noted a divergence of comparable magnitude between the orientation of woody debris in an outcrop and flute casts from nearby (Fig. 29). Thus some differences

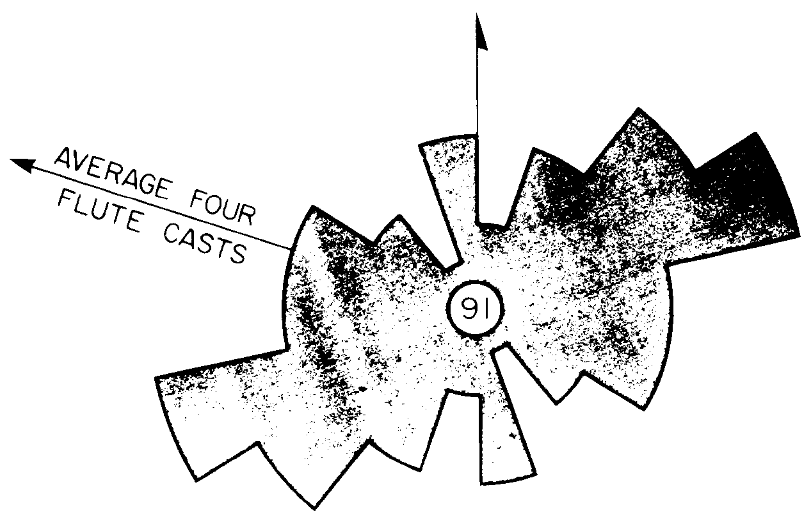

FIGURE 29 Comparison of wood fragment orientation (91 measurements) with flute cast orientation in Brallier Formation in Grant County, West Virginia.

between paleocurrents in shales and their interbedded siltstones and sandstones can be expected and quite possibly 30° may be a good general estimate of this divergence, should it exist. On the other hand, Jones, and Denison (1970, Fig. 6) inferred generally westward paleocurrents in the Chattanooga Shale in Tennessee using fossil orientation, an inference fully confirmed by our own studies of sole marks from interbedded siltstones. Hence we think that the dominant currents that deposited the mud, silt, and sand of the marine fill of the Upper Devonian all had a generally comparable direction -- westward throughout most of the basin but possibly more southwestward along its western margin in Ohio and Kentucky and in the subsurface of central Ohio and in Eastern Kentucky.

We suggest such a possible southwestward deflection for the western, black-shale rich part of the Appalachian basin, because it is fairly common for turbidite basins, both large and small, to have down slope as well as axial directions of flow -- no matter how stratified their water masses may have been. Seilacher and Meischner (1964) effectively illustrated axial, downslope and coastal transport in the Lower Paleozoic shaly basin of southern Norway (Fig. 30). Other examples are the Franklin geosyncline in the Canadian Arctic Islands (Tretten, *et al*., 1972, Fig. 6), the Mesozoic flysch of the Carpathians (Contescu, 1969, Figs. 3 and 4) and the Carboniferous flysch of the Ouachita Mountains (Morris, 1972, Fig. 22). Clearly needed is a rapid and inexpensive method of determining paleocurrent fabric in the purer shales of the deeper, more distal parts of turbidite basins.

What was the depth of water in the basin? Was it uniform or did it systematically shoal westward? We believe it shoaled westward into Ohio and probable maximum depths may have been far less than shown on our cross sections because the actual bathymetry of the black shale is still uncertain. In west central Ohio, for example, Schwietering (1979) has suggested very shallow water depths.

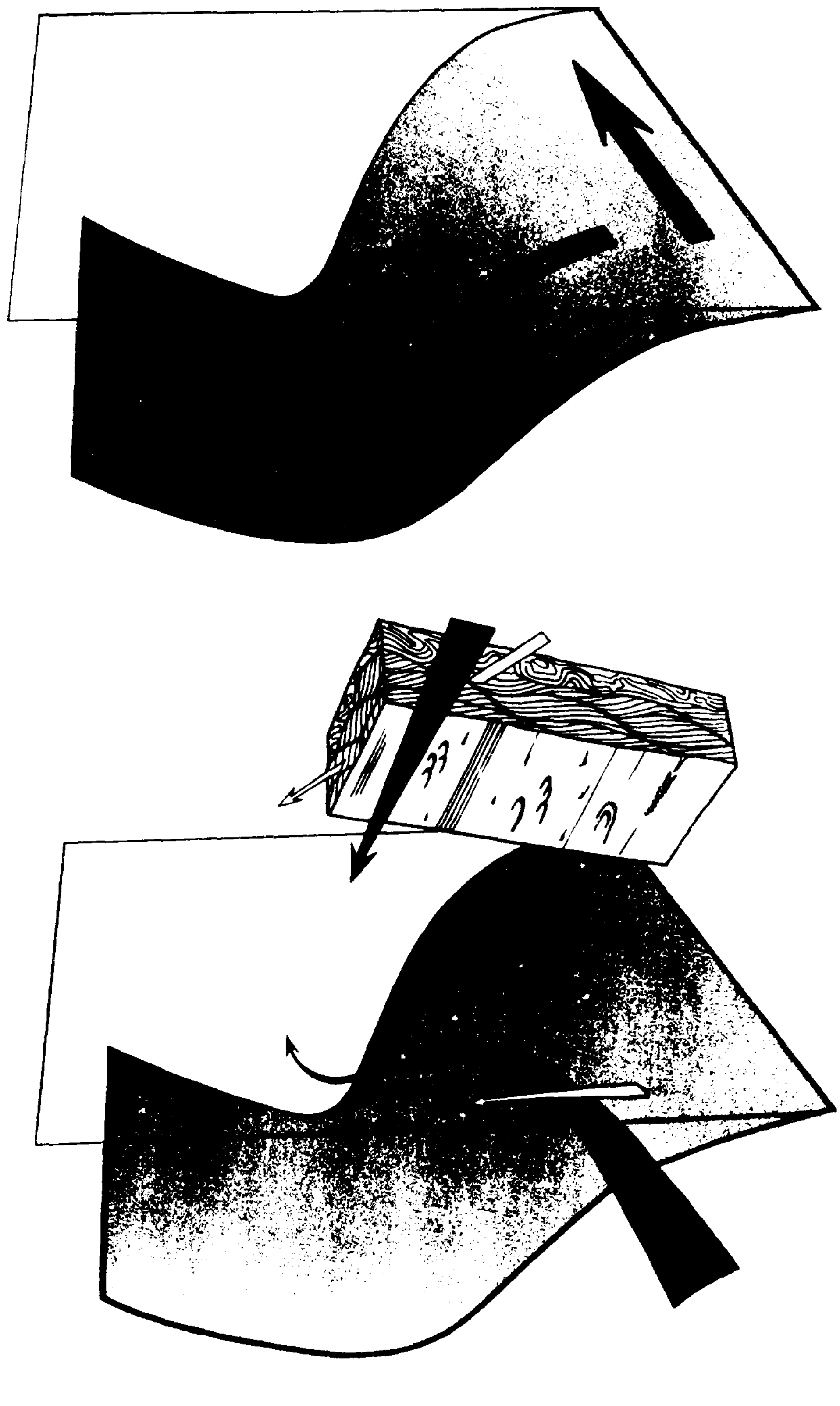

FIGURE 30 Current directions in elongate turbidite basins. Top, coastal, slope and axial currents; bottom, single turbidite bed shows small scale divergence between its initial bottom currents (black arrows) and later ones (white arrows) and how they relate to basin shape.

ANNOTATED BACKGROUND REFERENCES

The references below give a brief, but balanced, overview of the literature of the Devonian of the Appalachian basin and are grouped into Cross Sections and Correlation, Regional Syntheses, Environmental Studies and Black Shale and Gas Production. The list below, while only a small sample of all the available references, should nonetheless be a good introduction to this interesting, complex basin -- one whose economic potential is still to be fully developed, especially with respect to gas production.

Cross Sections and Correlation

We found study of the published cross sections of the Devonian very informative and the most recent are those published in 1977 and 1978 by the U.S. Geological Survey. All of these utilize gamma ray logs, some of which have cuttings and cores and one includes outcrop sections.

Colton, G. W., and W. de Witt, Jr. Stratigraphy of the Sonyea Formation of Late Devonian Age in Western and West-Central New York. U.S. Geol. Survey, Oil and Gas Invest. Chart OC-54, 1958.
Careful outcrop stratigraphy based on 31 sections plus informative text. Figure 8, a diagrammatic east-west cross section, is particularly informative and may well be representative of most of the shelf-slope facies relations in the basin.

Dennison, J. M., and K. O. Hasson. Stratigraphic Cross Section of Hamilton Group (Devonian) and Adjacent Strata Along South Border of Pennsylvania. AAPG, v. 60, 1976, pp. 278-298.
Two cross sections of the Middle Devonian are based on 13 wells and 5 outcrops and extend down depositional dip for 150 miles. The Tioga Bentonite and Tully Limestone are the two best markers in the line of section.

Kepferle, R. C., E. N. Wilson, and Frank R. Ettensohn. Preliminary Stratigraphic Cross Section Showing Radioactive Zones in the Devonian Black Shales in the Southern Part of the Appalachian Basin. U.S. Geol. Survey, Oil and Gas Invest. Chart OC-85, 1978.
One sheet with 13 wells.

Oliver, W. A., Jr., W. de Witt, Jr., J. M. Dennison, D. M. Hoskins, and J. W. Huddle. Correlation of Devonian Rock Units in the Appalachian Basin. U.S. Geol. Survey, Oil and Gas Invest. Chart OC-64, 1969.
General correlation chart shows formations, members and beds plus stratigraphic ranges of ammonites, conodonts and brachiopods. See also Rickard (1964).

Rickard, L. V. Correlation of the Silurian and Devonian Rocks in New York State. Univ. State New York, N. Y. Museum and Sci. Serv., Map and chart Ser. No. 24, 1975, 16 pp.
Very careful outcrop stratigraphy of the Devonian, beautifully summarized in large charts with emphasis on stratigraphic paleontology, especially conodont and brachiopod stratigraphy.

Roen, John B., Laure G. Wallace, and Wallace de Witt, Jr. Preliminary Stratigraphic Cross Section Showing Radioactive Zones of the Devonian Black Shales in Eastern Ohio and West-Central Pennsylvania. U.S. Geol. Survey, Oil and Gas Invest. Chart OC-82 (1978).
One sheet with 7 wells.

Roen, John B., Laure G. Wallace, and Wallace de Witt, Jr. Preliminary Stratigraphic Cross Section Showing Radioactive Zones in the Devonian Black Shales in the Central Part of the Appalachian Basin. U.S. Geol. Survey Oil and Gas Invest. Chart OC-87 (1978).
Two sheets and 27 wells.

Wallace, Laure G., John B. Roen, and Wallace de Witt, Jr. Preliminary Stratigraphic Cross Section Showing Radioactive Zones in the Devonian Black Shales in Southeastern Ohio and West-Central West Virginia. U.S. Geol. Survey Oil and Gas Invest. Chart OC-83 (1978).
One sheet and 9 wells.

Wallace, L. G., J. B. Roen, W. de Witt, Jr. Preliminary Stratigraphic Cross Sections Showing Radioactive Zones in the Devonian Black Shales in the Western Part of the Appalachian Basin. U.S. Geol. Survey, Oil and Gas Invest. Chart OC-80 (1977).
Two sheets and 29 wells.

West, Mareta. Preliminary Stratigraphic Cross Section Showing Radioactive Zones in the Devonian Black Shales in the Eastern Part of the Appalachian Basin. U.S. Geol. Survey, Oil and Gas Invest. Chart OC-86 (1978).
Two sheets and 23 wells.

Regional Syntheses

The papers below all provide a regional view of the basin, or some large part of it, and to varying degree offer interpretations.

Barrell, J. The Upper Devonian Delta of the Appalachian Geosyncline. I. The Delta and Its Relations to the Interior Sea. II. Factors Controlling the Present Limits of the Strata. Am. J. Sci., v. 36, 1913 and 1914, pp. 429-472 and 87-109.
Discussion of depositional environments, paleoclimate, physiography of depositional basin and proximal source plus proven-

ance, all based on carefully measured sections plus a regional thickness and facies map. Compares Catskill delta to the Siwalik series and recognized both as molasse deposits. Also included is a discussion of the present eastern limits of the Upper Devonian. One of the great All American classics still very relevant today.

Caster, K. E. The Stratigraphy and Paleontology of Northwestern Pennsylvania. I. Stratigraphy. Bull. American Paleontology, v. 21, 1934, 185 pp.
Explicit discussion of equivalence of black shale on the west side of the Appalachian basin to gray shales, siltstones and sandstones eastward (regressional overlap) plus introduction of the terms magna- and parvafacies. One of the great classics written on the Upper Devonian of the Appalachian basin, even though detailed descriptions of sections are largely lacking.

de Witt, W., Jr., W. J. Perry, Jr., and L. G. Wallace. Oil and Gas Data from Devonian and Silurian Rocks in the Appalachian Basin. U.S. Geol. Survey Misc. Invest. Ser., Map I-917B, 1975.
Sheet 1 of four is a total Devonian isopach for the Appalachian basin and also includes a diagrammatic cross section along the eastern limit of the basin. Sheet 2 contains a map of total thickness of black shale. Thickness ranges from 0 to more than 12,000 ft. Brief discussion.

Dennison, J. M. Petroleum Related to Middle and Upper Devonian Deltaic Facies in Central Appalachia. AAPG Bull., v. 55, 1971, pp. 1179-1193.
Many cross sections, some maps and a brief description of many of the named units in the Devonian.

Dinley, D. L. North Atlantic Old Red Sandstone--Some Implications for Devonian Paleogeography. In Canada's Continental Margins and Offshore Petroleum Exploration, ed. by C. J. Yorath, E. R. Parker, and D. J. Glass. Canadian Soc. Petroleum Geologists, Mem. 4, 1975, pp. 773-790.
Intercontinental synthesis of Devonian identifies an "Old Red Sandstone Continent".

Oliver, W. A., Jr., W. de Witt, J. M. Dennison, D. H. Hoskins and J. W. Huddle. Devonian of the Appalachian Basin, United States. In International Symposium on the Devonian System, ed. by D. H. Oswald. Alberta Soc. Petroleum Geologists, v. 1, 1967, pp. 1001-1040.
The best single overview and basin analysis of the Devonian of the Appalachian basin, one complete with many thickness and facies maps and cross sections. Start here to learn your regional geology.

Schwietering, Joseph F. Devonian Shales of Ohio and Their Eastern and Southern Equivalents. Dept. of Energy, Morgantown Energy Technology Center, Morgantown, W. Va., METC/CR-79/2, 1979, 68 p.
A regional synthesis of the Ohio shale based on 12 outcrops, 29

sample logs and 132 gamma-ray neutron logs. Basic stratigraphy illustrated by many cross sections.

Shepps, V. C., ed. Symposium on Middle and Upper Devonian Stratigraphy of Pennsylvania and Adjacent States. Pa. Geol. Survey, Ser. 4, Bull. G39, 1963, 301 pp.
Background reading provided by 20 articles ranging from lithofacies to paleocurrents to correlation and paleontology.

Willard, Bradford. Continental Upper Devonian of Northeastern Pennsylvania. Geol. Soc. America Bull., v. 42, 1936, pp. 365-608.
Early classic study.

Wolff, M. P. The Catskill Deltaic Complex-Deltaic Phases and Correlations of the Middle Devonian Marcellus Formation in the Albany Region. In New England Intercollegiate Geol. Conf. Guidebook, sec. 20, 1969, pp. 1-41.
Regional and local stratigraphy of the Marcellus Formation plus discussion of deltaic sedimentation within it at the northeasternmost corner of the Devonian of the Appalachian Basin. Good illustrations, see especially Figure 3, plus road log and photography of many of the stops.

Woodrow, D. L., and F. W. Fletcher. Late Devonian Paleogeography in Southeastern New York and Northeastern Pennsylvania. In International Symposium on the Devonian System, Calgary, Alberta Soc. Petrol. Geologists, v. 2, 1967, pp. 1327-1334.
Four environmental zones - upland alluvial, lowland alluvial, littoral paludal and marine - are recognized.

Environmental Studies

The references below include those that use fossil, lithologic, and facies evidence to define and outline the different depositional environments found in the Devonian of the Appalachian basin. Additional references that contain environmental information are also listed in Table 2.

Ethridge, F. G. Petrology, Transport, and Environment in Isochronous Upper Devonian Sandstone and Siltstone Units, New York. J. Sediment. Petrology, v. 47, 1977, pp. 53-65.
Thin-section petrology of the Sonyea Group shows systematic downdip changes in grain size and mineralogy over a distance of about 200 miles.

Glaeser, J. D. Upper Devonian Stratigraphy and Sedimentary Environments in Northeastern Pennsylvania. Penn. Topographic and Geol. Survey, Gen. Geol. Rept. 63, 1974, 89 pp.
Surface and subsurface data used to develop a three-dimensional picture of depositional environments (pro-delta, coastal margin, and alluvial) of northeastern Pennsylvania. Table 7 lists

occurrence of gas, gas shows, and water in seven different depositional environments and Table 8 gives the characteristics and environmental interpretation of cuttings of the 14 wells studied. Much of general interest.

Heckel, P. H. Nature, Origin and Significance of the Tully Limestone. Geol. Soc. America Spec. Paper 138, 1973, 244 pp.
An anomalous unit in the Catskill delta is carefully examined from almost every viewpoint--detailed petrology, paleoecology and regional facies maps, all of which contribute much to a better understanding of the Devonian. Many cross sections.

Kelley, D. R. Geology of the Red Valley Sandstone in Forest and Venango Counties, Pennsylvania. Penn. Geol. Survey, 4th Ser. Bull. M57, 1967, 49 pp.
Little known study of beach deposits at inner edge of Upper Devonian shelf. Informative cross sections and maps.

LaPorte, L. F. Paleozoic Carbonate Facies of the Central Appalachian Shelf. J. Sedimen. Petrology, v. 41, 1971, pp. 724-740.
Gives criteria to recognize shallow versus deep subtidal facies and applies them to the study of Devonian carbonates, most of which outline an elongate area of deeper water in the central Appalachians. See also LaPorte's earlier papers on the Helderberg Group in New York.

McGhee, G. R., Jr. Late Devonian Benthic Marine Communities of the Central Appalachian Allegheny Front. Lethaia., v. 9, 1967, pp. 111-136.
Paleoecological evidence from brachiopods supports a prograding and shallowing regressive interpretation of the "Catskill Delta". Compare with LaPorte (1971, Figs. 8, 9, 11, 12 and 13).

Thayer, Charles W. Marine Paleoecology in the Upper Devonian of New York. Lethaia, v. 7, 1974, pp. 121-155.
Lateral changes in fauna carefully related to shelf to basin transition. Twenty four informative figures.

Walker, R. G. Upper Devonian Marine-Nonmarine Transition, Southern Pennsylvania. Penn. Geol. Survey Bull. G62, 1972, 25 pp.
Essentially a field guide devoted to the environmental interpretation of the proximal part of the Catskill Delta. Figures 14 and 18 are very informative block diagrams.

Walker, R. G. Nondeltaic Depositional Environments in the Catskill Clastic Wedge (Upper Devonian) of Central Pennsylvania. Geol. Soc. America Bull., v. 82, 1971, pp. 1305-1326.
Analysis of depositional environment suggests that a well defined shelf was absent so that alluvial deposits pass almost directly into slope deposits.

Walker, R. G., and J. C. Harms. The "Catskill Delta": A Prograding Muddy Shoreline in Central Pennsylvania. J. Geol., v. 79, 1971, pp. 381-399.
Detailed sedimentology of the outcropping Irish Valley Member, about 600 m thick, defines a series of sedimentary cycles on a coupled coastal plain- shelf and slope. Figure 12 is an exceptionally good block diagram that suggests that mud and silt were introduced to the basin by turbidity currents and long shore drift.

Walker, R.G., and J. B. Harms. Shorelines of Weak Tidal Activity: Upper Devonian Catskill Formation, Central Pennsylvania. In Tidal Deposits, R. N. Ginsburg, ed. New York, Springer Verlag, 1975, pp. 103-108.
Much as Walker and Harms (1971), but with even more effective illustrations.

Walls, R. A. Late Devonian-Early Mississippian Subaqueous Deltaic Facies in a Portion of the Southeastern Appalachian Basin. Trans. Gulf Coast Assoc. Geol. Soc., v. 23, 1973, pp. 41-45.
Three contemporaneous clastic facies: delta front (siltstone and sandy siltstone), prodelta (clayey siltstone) and offshore marine (pyritic carboniferous, black clay shale). Largely a subsurface study.

Black Shale Gas Production

Although a major gas producer in the basin for many years, there are still very few published studies of the Devonian black and gray shales in the basin and how their gas production is related to either sedimentology, thermal history, fractures, or initial depositional environment.

Board of Mineral Resources. Natural Gas from Unconventional Geologic Sources. Washington, D. C., National Acad. Sciences, Commission on Natural Resources, 1976, 245 pp.
There are four papers (pp. 71-124) on the Devonian shales of the Appalachian basin all by currently active workers plus a short discussion.

Conant, L. C., and V. E. Swanson. Chattanooga Shale and Related Rocks of Central Tennessee and Nearby Areas. U.S. Geol. Survey Prof. Paper 357, 1961, 91 pp.
Still the most definitive publication on the distal Devonian-Mississippian black shales in the Appalachian basin. Much on internal stratigraphy and origin.

Harris, L. D., Wallace De Witt, Jr., and G. W. Colton. What are Possible Stratigraphic Controls for Gas Fields in Eastern Black Shale? The Oil and Gas Journal, Apr. 3, 1978, pp. 162-164.
Isopachs of middle to late Devonian black shales outline two distinct

north-south trending belts; commercial gas production from the shale is mostly obtained from the westernmost of the two belts. Three maps and a diagrammatic cross section.

Hoover, K. V. Devonian-Mississippian Shale Sequence in Ohio. Ohio Geol. Survey Infor. Circ. 27, 1960, 154 pp.
Comprehensive review with virtually all the pre-1960 literature. Topics covered include stratigraphic characteristics of members of Ohio Shale, paleoecology, paleogeography, generalized structure maps plus sedimentary structures (primary and secondary) and fracture systems. Long annotated bibliography which is exceptionally wide ranging and informative and applies to much of the basin rather than only Ohio.

Janssens, A., and W. de Witt, Jr. Potential Natural Gas Resources in the Devonian Shales in Ohio. Ohio Geol. Survey, Geol. Note No. 3, 1976, 12 pp.
The most up-do-date summary for Ohio has a short informative text, small scale structure and thickness maps, and one plate with three gamma ray cross sections plus all the relevant literature for Ohio.

Lewis, T. L., and J. F. Schwietering. Distribution of the Cleveland Black Shale in Ohio. Geol. Soc. America Bull., v. 82, 1971, pp. 3477-3482.
One of the few published maps of a single member of the Ohio Shale shows it to have well defined elongate north-south trends.

Patchen, D. G. Subsurface Stratigraphy and Gas Production of the Devonian Shales in West Virginia. U.S. Energy Research and Development Administration, Morgantown Energy Research Center MERC/CR-77/5, 1977, 35 pp.
The most recent study of the stratigraphy and gas production of the Devonian or "brown" shales in West Virginia contains an isopach map, informative cross sections, a correlation chart and 15 figures.

Rich, J. L. Probable Fondo Origin of Marcellus-Ohio-New Albany-Chattanooga Bituminous Shales. AAPG Bull., v. 35, 1951, pp. 2017-2040.
One of the few papers to address itself to the origin of the Devonian-Mississippian black shales has but one figure--a cross section showing the relation of the black shales to the main body of Devonian clastics. (Please see our Figure 2.)

Schott, G. L., W. K. Overbey, Jr., A. E. Hunt, and C. A. Komar, eds. First Eastern Gas Shales Symposium, October 17-19, 1977. Morgantown Energy Research Center, ERDA, Morgantown, West Virginia, 1977, various paging.
Seven diverse parts including 50 papers with many on stratigraphy and gas occurrence.

Swain, F. M., and M. A. Rogers. Stratigraphic Distribution of Carbohydrate Residues in Middle Devonian Onondaga Beds of Pennsylvania and Western New York. Geochem. et Cosmochim. Acta, v. 30, 1966, pp. 496-509.

The only published geobiochemical map of the Devonian shale sequence shows a very well defined elongate trend oriented north 20° east, very similar to the trend defined by the Cleveland Shale in Ohio (Lewis and Schwiertering, 1971).

Wallace, L. G., and W. de Witt, Jr. Thickness and Extent of Devonian Black Shale Facies, Sheet 2. In Oil and Gas Data from Devonian and Silurian Rocks in the Appalachian Basin, ed. by W. de Witt, Jr., W. J. Perry, Jr. and L. G. Wallace. U.S. Geol. Survey Map I-971B, 1975.

The only published basinwide map of black shale shows as much as 1400 ft. in eastern Pennsylvania, but throughout most of the basin north of Tennessee total black shale thicknesses commonly range between 300 and 900 ft. Major gas fields shown on thickness map.

ACKNOWLEDGMENTS

This study was supported by the Department of Energy in contract with the University of Cincinnati (EY-76-C-05-5201). Ronald Broadhead, Thomas Stenbeck and Fred Schauf assisted in the collection of the paleocurrent data and James D. Williams did much of the drafting. Roy C. Kepferle of the U.S. Geological Survey worked with us collecting data in the field and gave many helpful suggestions during the preparation of the manuscript. Jean Carrol and Wanda Osborne prepared early drafts of the manuscript, and the final draft was prepared by Debbie Moorman. John B. Roen and Wallace de Witt, Jr. reviewed the manuscript for the U.S. Geological Survey. Other reviewers include Donald Streib of Science Associates, Morgantown, West Virginia, and Douglas Patchen of the West Virginia Geological Survey, also of Morgantown. We also thank Attila Kilnic, Head, Department of Geology, University of Cincinnati, for his support of our efforts.

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