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PROJECTION OF FAVORABLE GAS-PRODUCING AREAS FROM PALEOENVIRONMENTAL DATA

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ABSTRACT

Paleoenvironmental biofacies analysis of recent wells in dark Devonian shales in the Appalachian Basin has shown that these facies can be projected to areas with no control points. In particular, the facies distribution in Perry County, Kentucky, were found to be precisely those that were predicted earlier from biofacies and organic geochemical data from the VA-1 well in Wise County, Virginia, and the KY-2 well in Martin County, Kentucky. This demonstrates the importance of these data in assessing the volume of gas in the shale throughout the basin as well as in selecting future test sites.

The recent biofacies and geochemical work together with a review of the tectonics of the basin have contributed to an evolving interpretation of the geologic control of the biofacies.

While a marine environment persisted throughout the Upper Devonian over the Appalachian and Illinois Basins (and probably the Michigan Basin), dynamic emergent areas controlled an intermittent introduction of large amounts of organic matter. Large amounts of non-marine organic matter were periodically transported into the basin from a dynamic source province to the Southeast; massive "blooms" of Tasmanites intermittently spread both east and west from the edges of the emerging Cincinnati Arch. At times one or the other of these organic types swept entirely across the basins; at other times a more normal open marine biota flourished and was deposited, probably under the influence of connections to the open seas to the south and northwest, the north being closed by the collision and suturing of continental plates and the east by the growing Appalachian Mountains.

INTRODUCTION

The Devonian black shales of the Eastern United States once were thought to be uniform in their gas content. This is not the case, thus, a more sophisticated technique is needed for the effective exploration of the Devonian black shales.

Modern geological/geophysical exploration programs primarily depend on an understanding of the environment of deposition of the involved rocks, as well as the concomitant distribution and interrelationships of the various facies patterns. An understanding of the depositional environment of the black shales has not been reached. This has limited the effective development of an exploration program.

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An understanding of the depositional environment is intimately connected with ideas on the origin of deposits. Modern concepts on the origin and environment of deposition of sediments have grown from studies of recent deposits and processes. These studies are used as analogs for ancient sediments and processes. No recent example of black shale deposition has been found that would serve as an analog for the Devonian black shales of the eastern United States.

While much has been learned of the physiochemical nature and regional tectonic setting of black shales, these data have not been synthesized into a convincing story of the origin of the deposits. What is required is to review old data in a new fashion or to acquire new data. Palynology provides us with the new data.

PALYNOLOGY

Palynology, the study of pollen, spores, and other acid resistant microfossils, has proved to be of great value in the exploration for oil and gas. The palynomorphs have very different and distinctive morphologies that make them useful for both correlation and environmental interpretation. They also serve as indicators of the thermal history of sediments after their deposition.

Although some palynomorphs are visible to the naked eye (megaspores), most are very small (less than 200 microns), and may be found in large quantities in many sedimentary rocks. Their abundance in the rock reflects the initial productivity of that palynomorph, their mode of transportation, the rate of sedimentation, and post-depositional chemical or biological changes in the sediments with which they were deposited. Not only do palynomorphs survive both aqueous and aerial transport, but they are resistant to both hydrochloric and hydroflouric acid. These acids will break down most clastic and carbonate rocks, yet leave the palynomorphs unaffected.

A major advantage of using palynomorphs is that a small sample will yield a large quantity and, usually, a variety of palynomorphs. In many instances four or five individual cuttings will together yield enough information to produce an interpretation of both age and environment. The environmental interpretations are strongest in the Tertiary where comparisons can be made with recent palynomorph assemblages. Environmental interpretations in the Mesozoic and Paleozoic are based both on extrapolations from recent sediments and on comparisons with paleoecological studies of the invertebrate fossils in the same strata. No other group of fossils can provide the quantity of information recoverable from the palynomorphs.

The shales and siltstones in the Devonian black shales are ideal for palynologic investigations. All the strata contain palynomorphs, and many contain palynomorphs useful for biostratigraphic studies, which may provide much additional data to enable formulation of depositional models. Comparison of the palynologic data with the gas potential of the black shales may provide a whole new view of what happened in the Middle and Upper Devonian episodes that are reflected in the rock record but not explained by it.

PALYNOLOGIC STUDIES OF OTHER DEVONIAN FORMATIONS

During the time in which the black shales were deposited in much of North America, non-black-shale facies were deposited in adjacent areas. In many of these time equivalent strata, detailed paleoenvironmental and palynologic studies have been carried out, resulting in the working out of relationships between facies and palynomorphs. Most of these studies have been carried out in Europe, where palynology was pioneered.

In Alberta, Canada, the Upper Devonian contains reefs and associated lithofacies. Staplin(1) studied the palynomorphs from those facies and recorded abundant acritarchs from the normal marine, calcareous strata. He was also able to relate different morpho groups of acritarchs to different marine facies. His work established one group of palynomorphs which may be classified as "normal marine."

Another set of time equivalent strata are found in Europe, in northern Spain, in the Cantabrican Mountains, the Vegamian Formation, a 4 to 5 meter thick jet black shale overlies the Eromita Formation, a reddish, calcareous sequence. The Tournaisan Vegamian Formation is "strikingly similar to the Chattanooga shales of the eastern United States, which are about the same age; this is not only true for the lithology and trace elements, but also for the palynology as well."(2)

In time equivalent strata in Belgium, the black shale facies is not present. The strata there, in part, represent barrier island, lagoonal, and open marine facies. A detailed biostratigraphic investigation of those strata(3) provides a reference for the typical palynomorph distributions for those environments. In those near shore and lagoonal facies the concentration of spores with graphnel shaped processes (Anayrospora, Dicrospora and the like) was a considerable percentage of the palynomorphs recovered. No comparable concentrations have been seen in the black shales sampled thus far.

The open marine facies, represented by shallow to deep water shales and siltstones with some carbonates, are well developed in Germany, and in some strata in Belgium. The palynomorphs were deposited within normal marine conditions and well preserved assemblages of Upper Devonian age have been reported by Riegel[4] for the Eifel Region of Germany, by Vangestaine[5] for the region of Tohogne, Belgium and by Stockmans and Williere[6] for various outcrop areas in Belgium.

The clastic Old Red Sandstone localities in Great Britain are in part, time equivalent to the North American black shales. The terrestrial and lacustrine deposits in the Old Red Sandstone contain well developed spore assembleges (studied by Richardson[7] in England and Scotland and by Higgs[8] in Ireland). These spore assembleges are totally lacking in marine palynomorphs and are represented by very diverse assembleges of microspores and megaspores. These terrestrial deposits, in which the organic matter is wholly of terrestrial accumulations were available for transport into adjacent environments.

GENERAL PALYNOLOGY OF THE DEVONIAN BLACK SHALES

The Devonian black shales do not physically resemble the contemporary terrestrial or normal marine lithofacies. There is a monotony associated with the different shale members which is unequaled in contemporaneous strata. There are few lenses rich in diverse invertebrate fossils and few black shale lenses with well preserved megascopic plant remains. Shale facies can be traced from well to well, but correlations are difficult because of a lack of the kinds of fossils more commonly used for correlation.

Palynomorphs are common in all the samples studied to date. The black shale palynomorphs include some palynomorphs known to be of terrestrial origin as well as other palynomorphs known to be marine in origin.

To establish a framework of the kinds of palynomorphs found in the black shales and associated strata, this paper will review the general groups of palynomorphs associated with these sediments.

CHITINOZOANS are relatively large, flask shaped palynomorphs. They are found exclusively in marine rocks and are useful in dating and correlating rocks of Ordovician, Silurian and Devonian (Jansonius and Jenkins[9]). Many chitinozoan workers believe them to of animal origin, although some mycologists argue they are of fungal origin. Chitinozoans (Plate 1, Figsl 1,2) are found sporadically in the black shales and seldom comprise diverse assemblages.

They occur most commonly with the normal marine biofacies, but occasionally form a small part of the Tasmanites - rich biofacies.

SCOLECODONTS are the acid resistant teeth of polychaete worms. They are found either as single isolated elements (Plate 1, Fig. 3) or in apparatuses. Scolecodonts are found associated with the normal marine palynomorph assemblages as well as with some of the Tasmanites rich assemblages.

ACRITARCHS are (Plate 1, Figs., 4-6) are acid resistant palynomorphs believed to have been of algal origin, although precise affinities to extant algal groups have not been established for all acritarch genera. Paleozoic acritarchs are known only from marine environments. In the black shales acritarch assemblages are abundant and diverse, abundant and of limited taxonomic diversity, limited diversity and limited abundance, or absent.

These three groups of palynomorphs comprise the distinctive marine palynomorphs in the black shales.

In some parts of the black shale facies there are large quantities of material derived from land plants. All the vitrinite analyses, for example, are based on land plant debris. The material derived from land plants is distinctive and is summarized in the following paragraphs:

Fragments of woody debris are a major portion of many of the samples analyzed. In some instances the wood is identifiable only by the angular silhouette, but other pieces of "woody" kerogen are identifiable by the distinctive structure of the tracheids (Plate II, Figs. 1, 2, 3, 4).

Land plant spores and prepollen are also abundant in some of the samples.

Megaspores are, by definition, spores greater than 200 microns in size. Although there are some megaspore specimens (Plate II, Fig. 5) in the black shales, they are not common constituents of the palynomorph assemblages. When megaspores are common, the environments are often terrestrial or transitional. Because of their large sizes the megaspores are less prone to aerial or aquatic transport than are other plant spores.

Spores with grapnel shaped processes are among the most distinctive spores found in the black shales. This group includes a number of form genera and species which are currently undergoing taxonomic revision (by a Commission Internation du Microflore du Paleozoique working group). The spores are distinctive in that they have distal processes that look like grappling hooks. In some instances the spores are well preserved (Plate II, Fig. 6) and other specimens have only the hook and the process (Plate II, Fig. 7). This group of spores were found to be very abundant in lagoonal fills behind a barrier island in the Upper Devonian of Belgium.[3] No comparable abundances were found in the black shale samples studied although there are some specimens in the samples interpreted to be more near shore than others.

Spores in Tetrads is another group of spores associated with terrestrial conditions. Miospores are formed in tetrads and then break apart during dispersal. When large quantities of spores in tetrads are found, the tetrads imply that the spores are near to their source.

There are also Zonate and Saccate Spores in the samples (Plate II, Fig. 8). The zona and sacci facilitated aerial dispersal and it is often this sort of spore (or pre-pollen) which are found in samples in which other spores are missing. The saccate Retispora lepidophyta, for example, occurs in large concentrations in the upper samples from the KY-4 and OH-3 wells. Its great concentrations may be due to its having an excellent aid to aerial dispersal.

Other Spores are also common in many of the samples (Plate II, Fig.9). They are distinguished by morphology and are useful for correlation. Their similarity of sizes and their lack of extraordinary ornamentation here precludes detailed discussion of their forms. At present, many of the genera do not appear to be environmentally significant as regards their growth habitat or their propensity for aerial or aquatic dispersal.

The third group of palynomorphs includes specimens of the genus Tasmanites, and specimens informally called leiospheres and sphaeromorphs.

The leiospheres (Plate III, Figs. 5, 8) and sphaeromorphs (Plate III, Fig.6) are thin-walled spherical palynomorphs that are commonly found in marine strata. Their sizes vary and there is very little that is distinctive about any of the forms. Form species have been established for different sizes and for sculptural features, but the form species have little, if any, biostratigraphic significance for correlation. The leiospheres and sphaeromorphs are found in most of the samples run for this black shale proejct, and do not appear to be environmentally significant.

Tasmanites is a very distinctive palynomorph (Plate III, Figs. 1-4, 7). Large specimens can be seen on some black shale bedding planes (and it has sometimes been identified as Sporangites in lithologic description). The specimens are spheres with very thick walls, and specimens may range in sizes from 10-15 microns to several hundred microns in diameter. Some form species have been established for specimens with different openings, different fold patterns and different sizes, but the specimens in the black shale wells are not clarified by such a classification.

Tasmanites specimens occur throughout the stratigraphic column, but most often they are minor constituents of the total palynomorph assemblage. One exception is the Permian-aged "whitecoal" or Tasmanite of Tasmania which is very rich in Tasmanites. A second exception are the Tasmanites concentrations in the Devonian black shales of North America.

KEROGEN FACIES IN THE DEVONIAN BLACK SHALES

This paper discusses four "kerogen facies" and the transitions between them as they are found in conventional cores drilled by the Eastern Gas Shale Project. The term "kerogen facies," in this paper, refers to the kerogen recovered from a sample and will include allocthanous and autocthanous materials which accumulated together in that assemblage. The "kerogen facies" are distinctive in that they represent associations of organic material which were deposited together and represent a replicable and predictable circumstance of accumulation.

Three of the four kerogen facies were deposited in marine environments, but the kerogen types vary greatly. The fourth kerogen facies may have been deposited in a transitional area between marine and non-marine sedimentation. This fourth facies will be referred to here as the transitional-oxidized facies.

Within the black shales there are a few stratigraphically limited zones in which the palynomorphs all appear to have been oxidized and have, in transmitted light, a much more mature appearance than those from surrounding strata. The acritarchs and spores include specimens from above and below stratigraphically. The sample is different in quantity of organic recovery (less than that of adjacent strata) and in the oxidized appearance of the kerogen particles.

The oxidation of material of marine and terrestrial origin may be explained by any of the following hypotheses.

(1) The kerogen was deposited in a marine environment which was subject to a regression and subsequent oxidation, leaving an accumulation of oxidized kerogen.

(2) High tides deposited marine material in a supratidal or intertidal envirnonment and marine and autocthanous materials were oxidized in situ.

(3) Oxidation occurred to both the marine and non-marine materials somewhere else, but at about the same time. Currents transported the oxidized materials into the marine environment as part of the sedimentary bed load.

The second kerogen facies (Plate II) is characterized by large quantities of terrestrial debris and small quantities of marine palynomorphs. Reference to the "Terrestrial facies" is a reference to the dominant constituent which accumulated and overwhelmed the autocthanous marine material.

Samples in the terrestrial kerogen facies contain large amounts of woody debris. This quantity of woody debris encompasses both fresh (first cycle) woody material (telinite and collinite - the two kinds of vitrinite) and also reworked and oxidized woody material. The relative amounts of first cycle and recycled vitrinite can be seen on the vitrinite histograms.

The spore assemblages associated with the woody debris vary in abundance and diversity. In some samples there are very few spores and in other samples they compose a significant volume of the total recovered kerogen. The spore concentration may reflect the importance of aerial versus aqueous transport. It may be that spores are more prone to aerial transport and the woody fragments more prone to transport as part of the sedimentary bed load.

Another point of view would assume a continual and/or time-averaging supply of land plant spores. Thus, if we assume the supply of spores to have been constant over an interval of time, we can relate the accumulation of other types of organic material to a presumed time constant, we may be able to plot the waxing and waning of currents supplying woody debris or conditions favoring the accumulation of other marine palynomorphs.

To call this facies the "terrestrial kerogen facies" accurately reflects the dominant kerogen and also serves to separate it from the gas and oil prone marine kerogen facies. The terrestrial facies was deposited in a marine environment, but the marine environment contributed little to the "terrestrial kerogen facies." The phase "terrestrial kerogen facies" is somewhat misleading in that it does not mean to say that the material was deposited in a terrestrial environment but should be considered a shortened phrase for "kerogen of dominantly terrestrial origin deposited in a marine environment which contributed only a small amount of marine kerogen to the total kerogen accumulation."

The third kerogen facies is referred to as the normal marine facies because it contains palynomorphs typical of normal marine conditions elsewhere in the same time period. Acritarchs, occasional chitinozoans, occasional scolecodonts, leiospheres and sphaeromorphs are found in the samples which have relatively little land plant debris and few *Tasmanites*. In some samples there is a large variety of acritarchs (Plate I, Figure 6) but in normal marine lenses within the black shales there is often a great abundance of the acritarch *Veryhachium trispinosum* and only a limited variety of other acritarchs.

The scarcity of chitinozoans in the upper samples cannot be attributed to changes in marine environments. Inconveniently, chitinozoans became extinct in the Upper Devonian. The distribution of scolecodonts is probably tied both to the availability of food and to the presence of a suitable environment.

The fourth kerogen facies, and the most important in terms of gas potential, is the facies characterized by large accumulations of the green alga Tasmanites. The Tasmanites accumulated in great quantities producing rocks high in total organic carbon content. The environment which favored this accumulation somehow was unfavorable to the accumulation of other marine palynomorphs. Acritarchs are very scarce in the Tasmanites facies and there are no diverse acritarch assemblages associated with the Tasmanites accumulations. Scolecodonts are few, as are chitinozoans. In most samples land plant spores are equally scarce with only saccate or zonate spores present.

The Tasmanites were apparently deposited in marine conditions, but the virtual absence of so-called normal marine palynomorphs strongly implies that Tasmanites were accumulating in a special environment of some sort - one that was biologically or environmentally, or even physically restricted from both the "normal marine" and the "terrestrial" kerogen facies. It was somehow different from the contemporary environments. The Tasmanites environments flourished, were replaced with other environments and flourished again. There are periods of environments changing from Tasmanites to other and back again over twenty foot intervals. Only with further investigations will we be able to define the parameters that governed Tasmanites accumulation and define the factors which favor Tasmanites accumulation to the exclusion of other palynomorphs.

RELATIONSHIP OF KEROGEN FACIES WITH OTHER DEVONIAN BLACK SHALE CHARACTERISTICS

The Devonian black shale intervals can be characterized in terms of the four facies outlined. In the following, only three of the facies (terrestrial, normal marine, Tasmanites-restricted marine) are discussed. The fourth, the transitional-oxidized facies, will be presumed to lie at some distance on either side of the line joining the terrestrial facies with either the normal marine or Tasmanites facies.

Palynologic studies determined the dominant kerogen facies of selected samples from the EGSP cored wells. For several wells these kerogen facies were plotted versus the gamma-ray logs. Also, the organic richness and the rock color of these intervals were evaluated.

These results indicate a consistent relationship between the high gamma-peaks, blacker shale colors (N1-N2's), higher organic richness values and the Tasmanites-restricted marine facies.

The palynomorphs have been shown to be characteristic for certain depositional environments. It would appear that the Tasmanites are characteristics of the black shale depositional facies. Thus, correlation of Tasmanites zones will give correlation of black shale facies, and the Tasmanites palynomorphs will be proved a useful tool in correlation of black shales in the Devonian. A cross-section based on the Tasmanites-restricted marine facies is presented in Figure 1.

The cross-section indicates the general direction of influx of the palynomorph-bearing material. This is derived from a knowledge of the depositional patterns in the Appalachian Basin. The main influx of clastic material during the Middle and, especially, the Upper Devonian is from the Catskill Delta complex. This delta was centered in eastern Pennsylvania spreading material to the west and southwest (Figure 2). Along the western edge of ancient Appalachia other minor fluvial/deltaic systems spread clastic material to the west and northwest into the Devonian Appalachian Basin. On the western side of the Appalachian Basin, periodic emergence of the Cincinnati Arch resulted in small quantities of clastic sediments being deposited to the east. No Devonian sediments in the Appalachian Basin are known to be derived from the north or the south.

There was a general regression of the Tasmanites-restricted marine zones from north to south in the Appalachian Basin with time.

The earlier Tasmanites zones are quite extensive spreading far to the north. Later Tasmanites zones do not extend as far as a result of the prograding of the Catskill Delta complex. This event deposited its clastic sediments and terrestrially derived palynomorphs farther to the southwest with time.

RELATIONSHIP OF THE TASMANITES FACIES TO THE ORIGIN OF THE BLACK SHALES

The Tasmanites seem to be intimately related but not entirely restricted to the black shales. The Tasmanites are at times the only palynomorph present in the Devonian black shales. Thus the occurrence of Tasmanites seems to be related to the origin and nature of the black shales.

Unfortunately, an insufficient knowledge of the life habits of the Devonian Tasmanites inhibits understanding their predominance in the black shales and their environment of deposition. More work needs to be done on this phase.

Other areas of research in connection with this problem involve: investigating modern depositional environments of Tasmanites-like fauna, comparing the Tasmanites black shales of Devonian age with graptolite-bearing black shales of Ordivician and Silurian age, and evaluating the relationship between the high natural radioactivity and Tasmanites zones.

Much data will need to be synthesized to come up with an answer to the question concerning the origin of the black shales and their relationship to the occurrence of Tasmanites.

Tasmanites is considered a green algae. Perhaps one answer to the question of the predominance of Tasmanites in the black shales is in the phenomenon of "algal blooms." This would produce a large biomass of the Tasmanites over a wide area. Upon extinction this would produce the large quantity of organic matter found in the black shales. The "Tasmanites blooms" would also have resulted in the depletion of the oxygen in the Devonian Appalachian waters, leading both to the death and preservation of the Tasmanites.

Conditions leading to the formation of the blooms are unknown. It appears from studies of the distributions of the Tasmanites facies in the EGSP wells that the "blooms" come from the Cincinnati Arch region to the west and from the open ocean area to the south. The generalized environmental-depositional model for a given time during the Upper Devonian is illustrated in Figure 2.

A similar map can be generated for any particular time during the Middle or Upper Devonian, showing the precise facies distributions as interpreted from the EGSP wells. The maps would show a migration of the Tasmanites facies to the west and south as time progressed during the Devonian.

RELATIONSHIP OF TASMANITES TO GAS-PRODUCTION

As mentioned, not all black shales exclusively contain Tasmanites palynomorphs. The relationship of the Tasmanites-rich black shales to gas-production potential needs to be investigated. Are the black shales with exclusive Tasmanites palynomorphs more gas-productive than the black shales with more mixed palynomorph assemblages? This question is currently being addressed.

The gas-production of Tasmanites (restricted marine) black shales relative to black shales comprised of mixed palynomorphic assembledges is being investigated.

CONCLUSIONS

Palynological investigations of the gas bearing Devonian black shales reveal that there are at least three distinctive kerogen facies. One of these, a Tasmanites-restricted marine facies is intimately connected with the black shales. The occurrence can be connected with environmental/depositional models of Appalachian Basin sedimentation. Further studies not only will better define the origin of the black shales but also produce an exploration program for discovering the best gas producing areas and zones.

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PLATE 1
Figure 1

Poorly preserved chitinozoan, PA-2-9 x 390

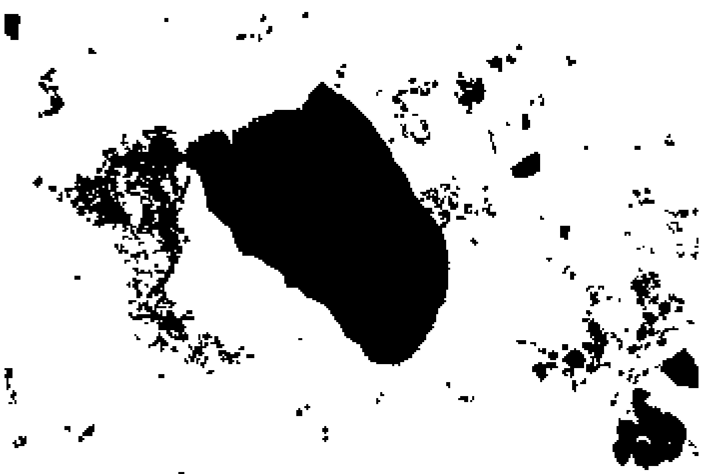


PLATE 1
Figure 2

Well preserved chitinozoan, OH-3-33 x 390

PLATE 1
Figure 3

Scolecodont, some teeth broken off, OH-3-33 x 390

PLATE 1
FIGURE 4

Acritarch Very hachium trispinosum
KY-4-33 x 640

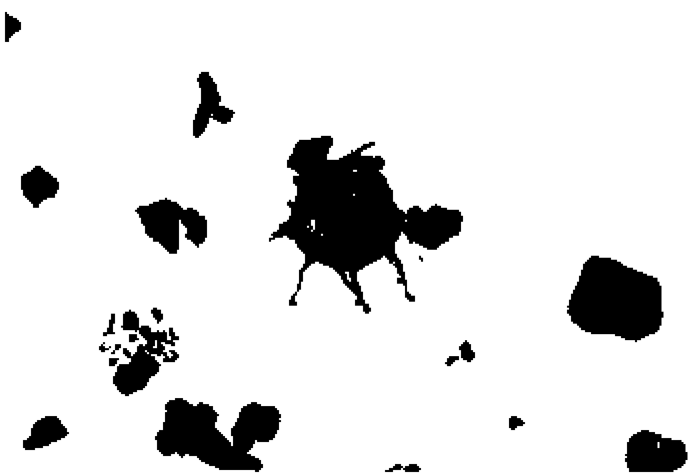


PLATE 1
Figure 5

Poorly preserved Multiplicisphaeridium
sprucegrovensis KY-4-50 x 640

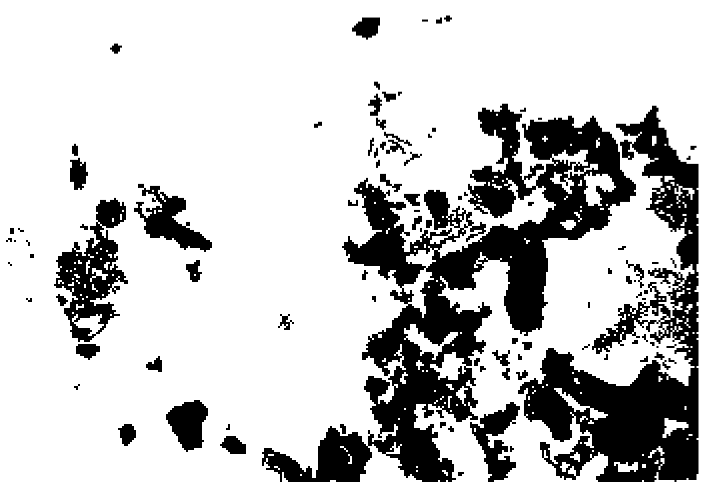


PLATE 1
Figure 6

Normal marine kerogen facies,
rich in acritarchs OH-3-19 x 390

PLATE II
Figure 1

Long sinuous pieces of woody debris PA-2-19 x 640x

PLATE II
Figure 2

Woody debris, one piece with a pitted tracheid, KY-4-1 x 640

PLATE II
Figure 3

Badly corroded pitted tracheids KY-4-3 x 640

PLATE II
Figure 4

Long piece of woody material with well preserved structure KY-4-3 x 640

PLATE II
Figure 5

Fragment of a poorly preserved megaspore, KY-4-3 x 390

PLATE II
Figure 6

Spore with well preserved grapnel-shaped processes WV-7-45 x 640

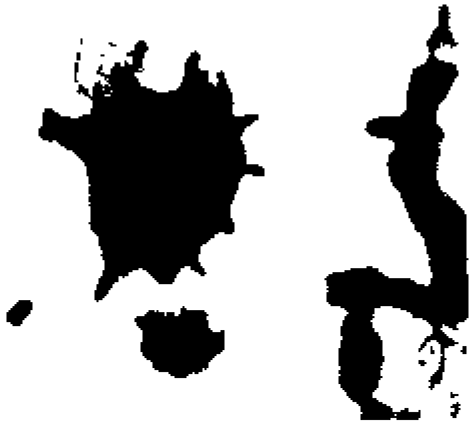


PLATE II
Figure 7

Poorly preserved spore with grapnel-processes, WV-7-45 x 640

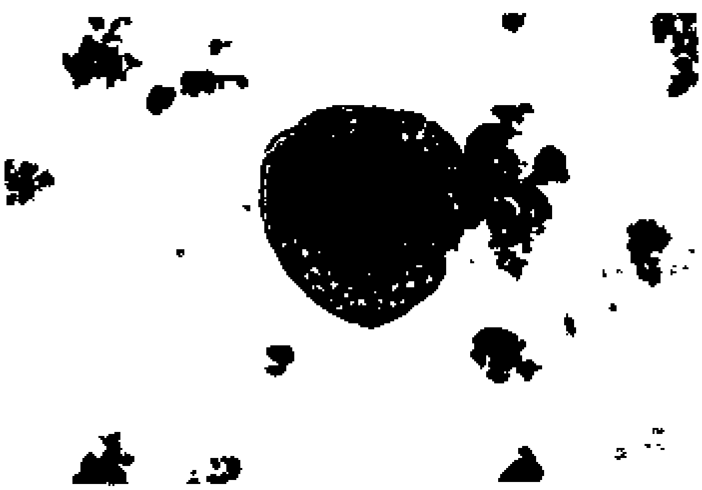


PLATE II
Figure 8

Retispora lepidophyta
KY-4-3 x 640

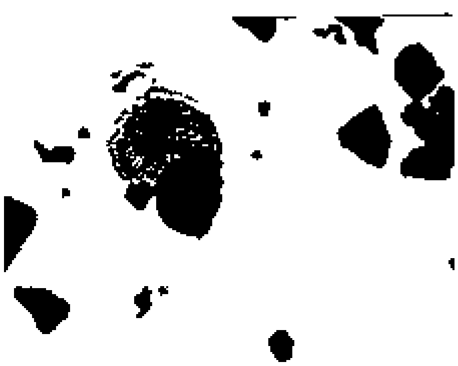


PLATE II
Figure 9

Small trilete spore
KY-4 1 x 640

PLATE III
Figure 1

Fragment of a very large Tasmanites shows broken edge. IND-2-6 x 390

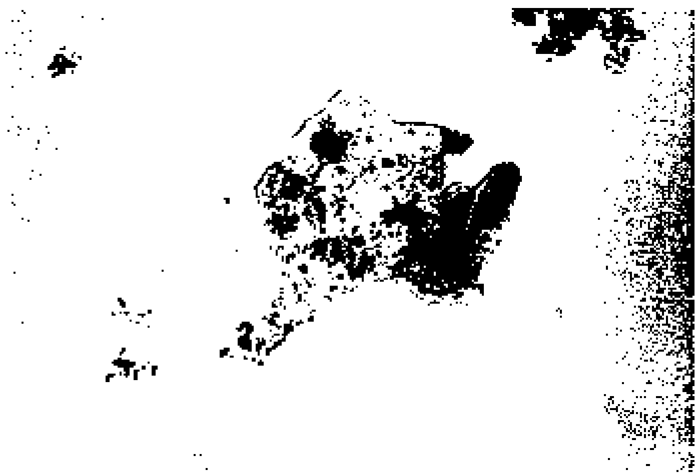


PLATE III
Figure 2

Angular fragment of Tasmanites, KY-4-46 x 640

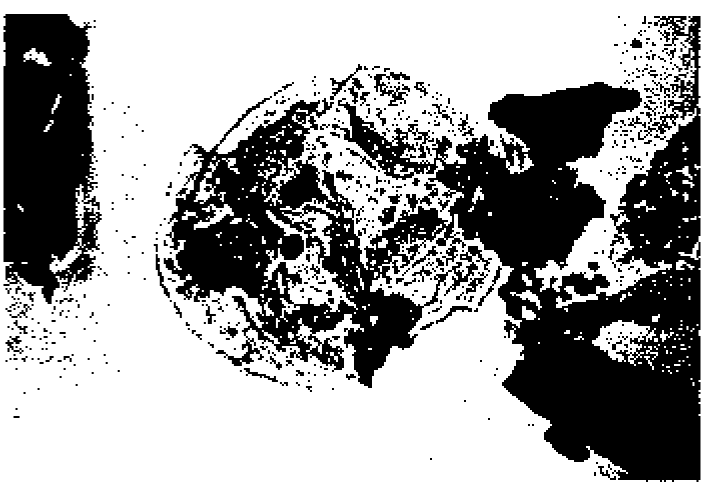


PLATE III
Figure 3

Well preserved Tasmanites with internal pyrite rhombs, WV-7-45

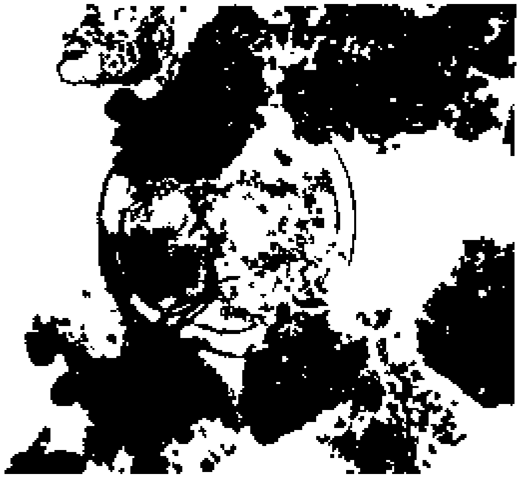


PLATE III
Figure 4

Thick walled Tasmanites surrounded by typical debris, KY-4-30 x 640

PLATE III
Figure 5

Very thin walled leiosphere, KY-4-51 x 640

PLATE III
Figure 6

Sphaeromorph, KY-4-50 x 640

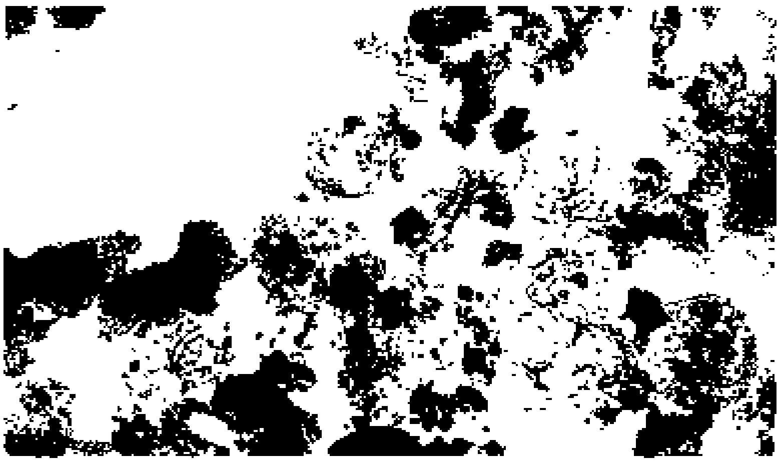


PLATE III
Figure 7

Well preserved assemblage of *Tasmanites*, KY-4-30 x 390

PLATE III
Figure 8

Very poorly preserved oxized leiosphere, PA-2-20 x 640

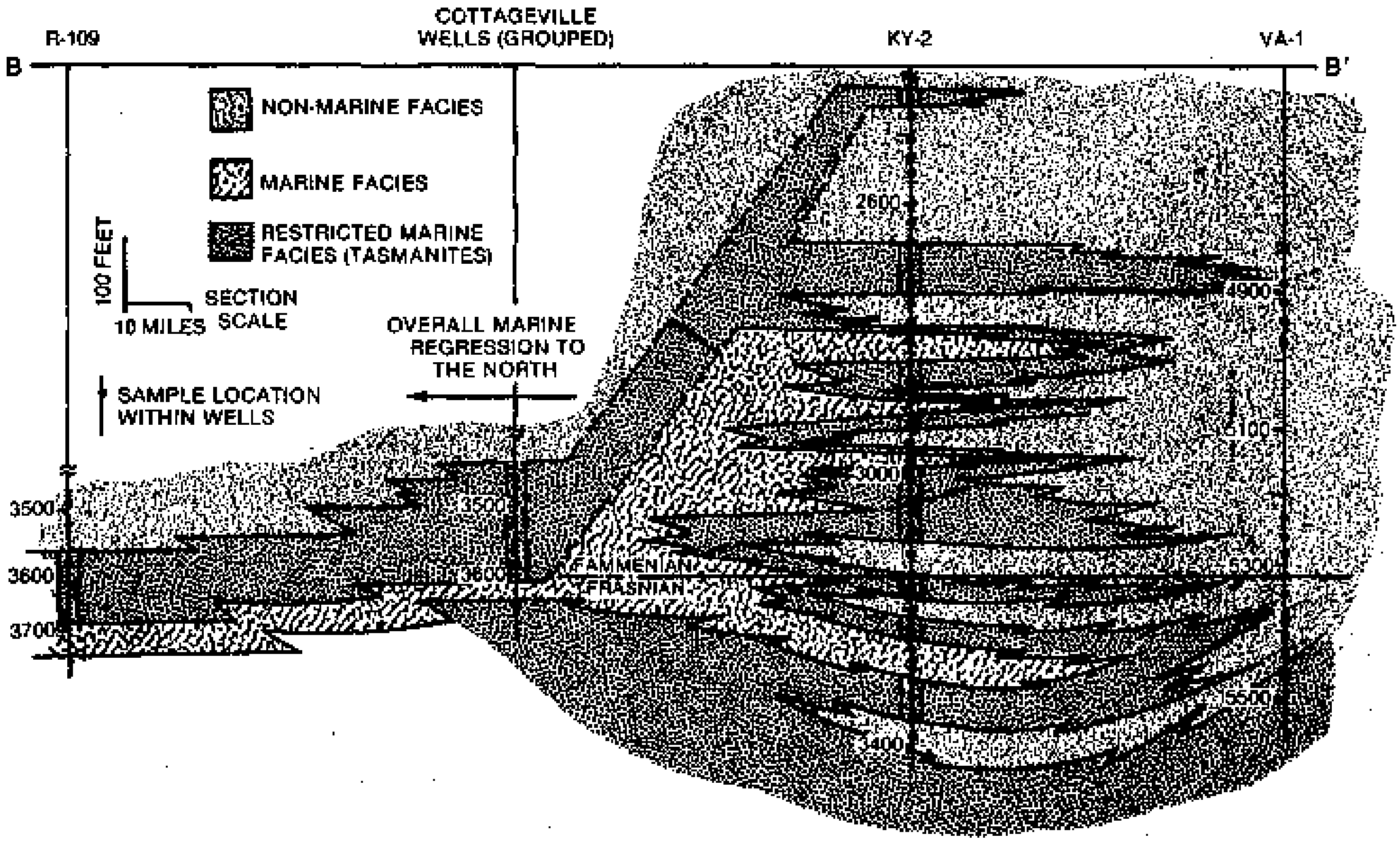
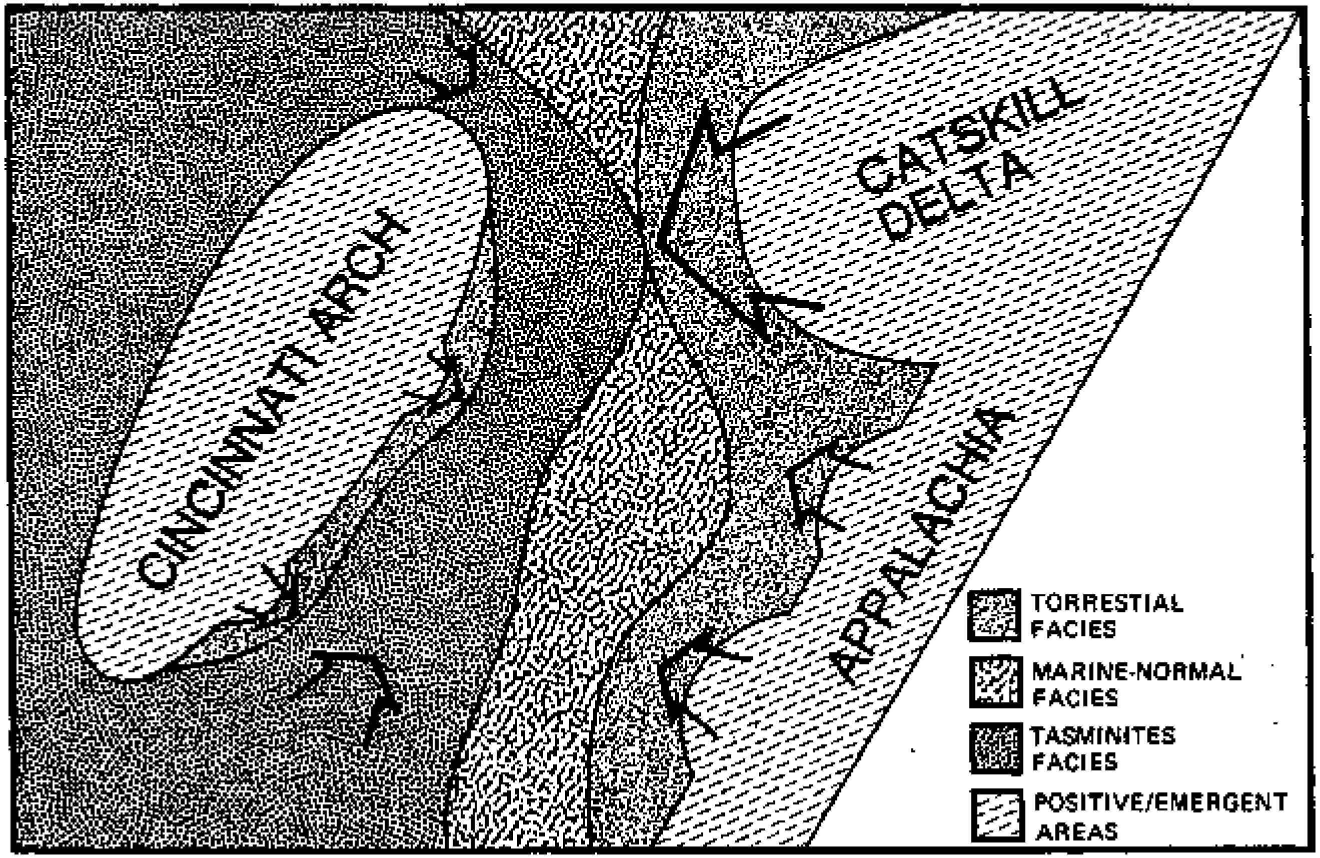


FIGURE 1

Environmental interpretation - Appalachian Basin based on biostratigraphy in Wells KY-2 and VA-1.



Generalized Depositional/Environmental Model for the Appalacian Basin during the Upper Devonian. Arrows indicate general direction of influx.

FIGURE 2