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BLACK SHALE—ITS DEPOSITION AND DIAGENESIS[1]

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Abstract—Black shale is a dark-colored mudrock containing organic matter that may have generated hydrocarbons in the subsurface or that may yield hydrocarbons by pyrolysis. Many black shale units are enriched in metals severalfold above expected amounts in ordinary shale. Some black shale units have served as host rocks for syngenetic metal deposits.

Black shales have formed throughout the Earth's history and in all parts of the world. This suggests that geologic processes and not geologic settings are the controlling factors in the accumulation of black shale. Geologic processes are those of deposition by which the raw materials of black shale are accumulated and those of diagenesis in response to increasing depth of burial.

Depositional processes involve a range of relationships among such factors as organic productivity, clastic sedimentation rate, and the intensity of oxidation by which organic matter is destroyed. If enough organic material is present to exhaust the oxygen in the environment, black shale results.

Diagenetic processes involve chemical reactions controlled by the nature of the components and by the pressure and temperature regimens that continuing burial imposes. For a thickness of a few meters beneath the surface, sulfate is reduced and sulfide minerals may be deposited. Fermentation reactions in the next several hundred meters result in biogenic methane, followed successively at greater depths by decarboxylation reactions and thermal maturation that form additional hydrocarbons. Suites of newly formed minerals are characteristic for each of the zones of diagenesis.

Key Words—Black shale, Deposition, Diagenesis, Organic matter, Syngenetic ores.

INTRODUCTION

The study of black shales has been difficult until a relatively few years ago. Outcrop observations have yielded relatively few kinds of data for interpreting their origin and the factors governing their formation. Recently, however, a growing body of chemical data on the organic as well as the inorganic constituents of black shale has widened the scope of inferences that can be drawn on the genesis of such rocks. Current investigations of eastern black shale, particularly the Chattanooga Shale and its correlatives of Late Devonian and Mississippian ages, as a source of gas (Schott *et al.*, 1978) are producing a new generation of data; and the time is appropriate to review the processes involved in the accumulation of black shale. Recently, data from deep-sea drilling, such as the composition of pore fluids, and new methods applied to the studies of organic matter and the formation of oil and gas have clarified many aspects of the deposition and diagenesis of organic-rich sediments.

This paper summarizes the work of many specialists with emphasis on guides to the study and interpretation of black shale sequences.

DEFINITION OF BLACK SHALE

Black shale is a dark-colored mudrock containing organic matter and silt- and clay-size mineral grains that accumulated together (Swanson, 1961, p. 69). Vine (1966, p. E1–E2) pointed out the compositional variations included in this definition and the ways that these variations can be used to study black shale.

Most shales that immediately meet this color criterion contain 1% or more organic carbon; 2–10% is a common range. A few shales contain more than 20% organic carbon. Pyrolysis yields variable amounts of liquid and gaseous hydrocarbons, the amount depending in part on the nature of the original organic material and in part on subsequent burial history. Minor amounts of authigenic carbonate minerals, either dispersed in cements or in concretions, are characteristic features of many black shale units. Most black shales are marine and may have areal extents of thousands of square kilometers.

Black shale units may have beds enriched in metals by factors greater than 50 for Ag, for example, and greater than 10 for Mo (Krauskopf, 1955, p. 417). Such increased concentrations of Ag, Mo, Zn, Ni, Cu, Cr, V, and less commonly Co, Se, and U are conspicuous features of only some black shales (Vine and Tourtelot, 1970, p. 270).

IMPORTANCE OF BLACK SHALE

Black shales are important to the natural fuel-resource economy of the world because black shales, along with their nonmarine analogue, coal, constitute the most important accessible reservoir of organic compounds in the Earth's crust. The organic matter may have generated liquid and gaseous hydrocarbons found in reservoir rocks in the subsurface into which they

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[1] Invited paper at 1978 Clay Minerals Conference, Bloomington, Indiana.

have migrated. Recently, however, the potential of black shale itself as a reservoir for gaseous hydrocarbons has been recognized, and this potential is being explored intensively. Estimates of the gas content of the Chattanooga Shale, for instance, range from tens to thousands of trillion cubic feet (U.S. Dept. of Energy, 1977, p. 99; Brown, 1976, p. 94).

Hydrocarbons also can be obtained by pyrolysis from thermally immature black shale. Increasing attention will be given to this possibility as demands increase and supplies from conventional sources dwindle.

Black shale units also are important as syngenetic hosts for metal deposits. The Kupferschiefer of Permian age in central Europe is a spectacular example of a metal-enriched black shale, containing a few percent Cu and Pb. Recent lead-isotope data clearly indicate that the metals in the Kupferschiefer were incorporated syngenetically in the shale (Wedepohl *et al.*, 1978). The lead-zinc deposits at Rammelsberg in West Germany are in organic-rich rocks of Devonian age and have a similar origin. The Nonesuch Shale of Proterozoic age has been mined for copper in Michigan (Ensign *et al.*, 1968, p. 464), and at least part of the copper is syngenetic. Oklo, the natural nuclear reactor and uranium deposit in Africa, may represent a maximum concentration of uranium in which the black shale involved may have played an important role in localizing the deposit and in retaining fission products (Brookins, 1976). In Sweden, alum shales of Cambrian age containing about 14% organic carbon have been used as a source of pyrolytic oil and uranium (Armands, 1972).

Only a few metal deposits have been found in black shale units in the United States, but others have not yet been sought systematically. The rich deposits of Rammelsberg occupy less than a square kilometer (Anger *et al.*, 1966). It is still possible that the rocks in a similar small area of the Chattanooga Shale, for instance, are rich enough in metals to constitute an ore deposit. Other metal-rich black shales may eventually serve as metal sources whenever normal sources are depleted (Davidson and Lakin, 1961, 1962; Vine and Tourtelot, 1970).

Metals concentrated syngenetically in a black shale unit either survive metamorphic processes to be retained in graphitic schists (Gammon, 1966; Peltola, 1968) or are released by metamorphic processes to be concentrated elsewhere (Boyle, 1968, p. 838). Conversely, black shale units might be receptor beds for metals released in hydrothermal or metamorphic systems. Exploration strategies in the search for metal deposits are beginning to be based on these concepts (Cox and Curtis, 1977; Gulson, 1977).

Lastly, black shale units seem to excite greatly the intellectual curiosity and imagination of the people investigating them. There is something fascinating about black shale: as Mark Twain said about science, "One gets such wholesale returns of conjecture out of such a trifling investment of fact" (Clemens, 1874, p. 136).

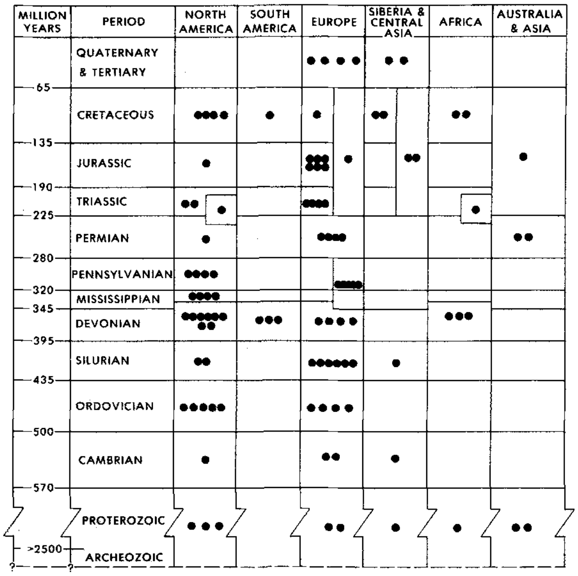

Figure 1. Distribution of black shale units in time and space. Filled circles indicate occurrences. Compiled from Tourtelot (1970) and Fulton (1977). Occurrences differ greatly in areal extent, thickness, and other characteristics.

DISTRIBUTION OF BLACK SHALE IN TIME AND SPACE

Figure 1 was compiled chiefly from the bibliography on black shale prepared by Tourtelot (1970), but the record of some occurrences was taken from Fulton (1977). The symbols do not have equal significance: for instance, the Chattanooga Shale in the Appalachian region and the Houy Formation in Texas are each counted as a single occurrence among black shales of Late Devonian and Mississippian ages in North America despite the great disparity between their areal extent and thickness. The figure indicates that black shale units have formed commonly throughout most of the history of the Earth and in many places. Black shale units are being found also in the ocean basins now being explored by drilling (e.g., Gardner *et al.*, 1977; Dean *et al.*, 1977; Hallam, 1977; Kerr, 1978). This wide geographic distribution of black shale occurrences in itself suggests that a range of geologic settings must be suitable for the accumulation of black shale.

The organic material that gives black shale its distinctive characteristics is derived from living things. Since black shale has accumulated throughout the entire evolution of life on the Earth, the composition of the organic matter in a black shale should reflect evolutionary development of living things at the time the shale was deposited. The importance of biochemical studies of different stages of evolving life, particularly plant material as preserved in black shale, was pointed out by Woodring (1954), but systematic studies still have not been made, and the significance of the evolutionary stage of life available to provide organic material to a black shale has been largely overlooked. For example, land plants did not evolve until the Late Silurian (Arnold, 1969, p. 129). The organic matter in black shales older than that must therefore be derived from aquatic plants and simpler life forms. The parameters widely used to indicate the "marineness" or "nonmarineness" of depositional environments, such as the hydrogen content of kerogen (Breger and Brown, 1962) or carbon isotopic composition, may be misleading or invalid if the interpretation is based primarily on analogies with the present. The assumption that geochemical effects of metabolic processes have been the same from the beginning as they are now probably is not wholly correct.

GEOLOGIC SETTINGS OF BLACK SHALE DEPOSITION

The geologic settings of typical black shales were classified by Vine and colleagues in very broad terms (Vine and Tourtelot, 1970) that can be further generalized into geosyncline, cratonic basin, and shelf, as shown in the following table (asterisks indicate metal-rich units):

Geosyncline	Permian	Western Rocky Mountains (Phosphoria Formation*)
	Upper Paleozoic	SW Midcontinent
	Lower Paleozoic	SW Midcontinent
Cratonic Basin	Pennsylvanian	Colorado Utah (Paradox Formation evaporites)
	Pennsylvanian–Mississippian	Montana
	Upper Mississippian	Wyoming
Shelf (Alternating Marine and Nonmarine)	Pennsylvanian	Midcontinent (Mecca Quarry Shale Member* of Linton Formation) (Zangerl and Richardson, 1963) Midcontinent (other similar shales)
	Proterozoic	Michigan (Nonesuch Shale*)
(Entirely Marine)		
	Cretaceous	Western Interior Texas
	Pennsylvanian	Kansas (Tacket Formation) (Jewett *et al.*, 1965)
	Devonian–Mississippian	Appalachian Region* Midcontinent* Texas* Rocky Mountains*

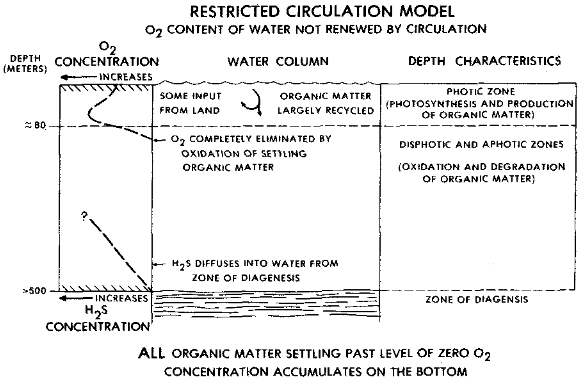

Figure 2. Restricted circulation model for accumulation of organic-rich sediments. Modified from Didyk *et al.* (1978).

In geosynclinal settings, the shales of Paleozoic age form thick deposits the paleogeography of which is not easy to reconstruct because of complex later tectonic history. Black shale in the Phosphoria Formation is the only one of the geosynclinal shales that is enriched in metals (Vine and Tourtelot, 1970). The Phosphoria Formation itself is unusual among sedimentary rocks because of its enrichment in P. The paleogeography of the cratonic basin shales also is difficult to reconstruct. None of those studied by Vine and Tourtelot (1970) are enriched in metals. The black, carbonate-rich shale in the Paradox Formation is unusual because of its association with evaporites.

Classification of a shale as having been deposited in a shelf setting probably would vary from one person to another. All the deposits included here, however, can be viewed broadly as being transgressive. One group includes those deposited in settings in which marine and nonmarine deposition alternated. The other group includes shales that seem to be entirely marine in their associations.

More examples of metal-enriched shales are found among those deposited in the shelf setting than in other settings, but there still is a puzzling variability between some of the shales in the shelf setting. For instance, the Pennsylvanian Mecca Quarry Shale Member (Zangerl and Richardson, 1963) of the Linton Formation is the only one in the Midcontinent region that is enriched in metals. Other marine shales of the same age and lithologic associations in the Midcontinent region are not enriched in metals. Other metal-enriched shelf shales are the Nonesuch Shale of Proterozoic age and shales of Devonian and Mississippian ages.

The interesting metal content of enriched shales is clearly related to the amount of organic matter in the shales. Trace metal adsorption, sulfate reduction, and sulfide precipitation are the chief processes involved (Swanson, 1961; Tourtelot, 1964; Vine and Tourtelot, 1970). A large content of organic matter does not necessarily identify a metal-rich shale. Other factors to be

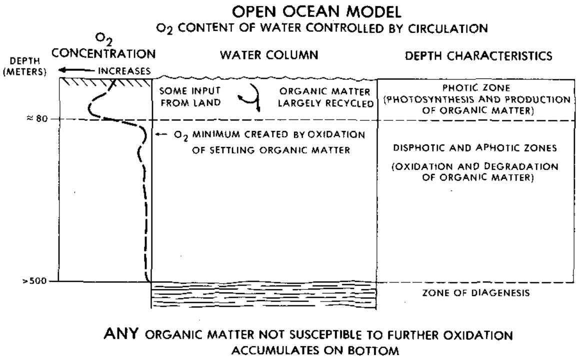

Figure 3. Open ocean model for accumulation of organic-rich sediments. Modified from Didyk *et al.* (1978).

considered include the nature of the organic material and its metal content, the nature of sediments and water in the source areas, volcanic ash, and submarine volcanic exhalations.

The abundances of some elements are related to those of other constituents of black shales. The contents of Si and Al obviously are related to the abundance of detrital minerals, and the Sr content is related to the abundance of diagenetic carbonate minerals. Vine and Tourtelot (1970) discussed the complexities of these and other relations between elemental compositions and mineral or constituent abundance.

The fact that black shale has accumulated in a wide range of geologic settings implies that geologic setting such as geosyncline or shelf is not of prime importance in the formation of black shale deposits compared to what goes on in these settings. Features of depositional environments within geologic settings, such as organic productivity, sedimentation rates, and availability of oxygen, are the important factors in controlling the deposition of the sediments that form black shale.

DEPOSITIONAL ENVIRONMENTS

The range of depositional environments in which black shale may accumulate can be described by three models shown in Figures 2, 3, and 4. The formulation of these models stems directly from similar appearing diagrams presented by Didyk *et al.* (1978). They placed great emphasis on the chemical characteristics of the environment *per se*, such as the distribution of oxygen and hydrogen sulfide in the water column and sediments. Here, however, the role of the amount of organic material in relation to oxygen supply is emphasized. An abundance of organic material depletes oxygen and creates the conditions under which organic-rich sediments can accumulate. Similarly, hydrogen sulfide is produced under the conditions caused by the accumulation of organic material, which favors the further accumulation of organic material. The accumulation of organic material is a cause of conditions, not an effect.

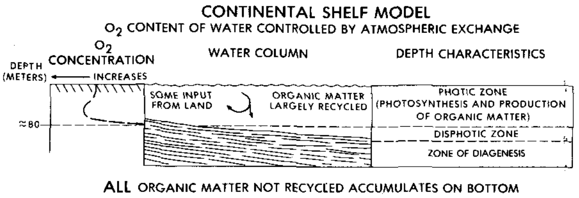

Figure 4. Continental shelf model for accumulation of organic-rich sediments. Modified from Didyk *et al.* (1978).

The restricted circulation model is discussed first because it represents the classic view, and unfortunately often the only view, of the accumulation of organic material in ancient rocks (Figure 2).

Restricted circulation model

The significant feature of the restricted circulation model is that the oxygen content of the water column is not renewed by circulation so that organic-rich sediments can accumulate even if organic productivity is relatively small. Organic material is produced by photosynthesis in the photic zone, mixed with some organic material from land if terrestrial plant life exists, and is largely recycled in the photic zone by chemical and biological processes such as "bigger things eating littler things." The oxygen content of the water may increase towards the bottom of the photic zone because of photosynthesis, but at some point it is completely consumed by the oxidation of the settling organic material. The oxygen depletion did not exist *a priori*, but was caused by the large oxygen demand of the decomposing organic material itself. All the organic matter that settles below the level of zero oxygen content accumulates on the bottom where it can be removed only by anaerobic decomposition. Hydrogen sulfide generated in the bottom sediments may diffuse into the overlying water mass. Both the sedimentational environment and the sediments are anoxic.

This situation prevails because there is too little circulation in the water mass to supply oxygen at a rate fast enough to equal or exceed the oxygen demand of the available organic material. If enough organic material is produced in the photic zone, considerable amounts of oxygen could be supplied and organic matter still would accumulate in the bottom sediments.

The restricted circulation model is represented in part by the Black Sea (the type euxinic setting: see Goldhaber, 1978) or Norwegian and other fjords, which provide good modern examples of the chemical and sedimentational processes outlined above. Organic-rich deposits will accumulate in such restricted basins, including basins formed tectonically such as the Carioco trench or those off the California coast, unless the rate of organic productivity in the photic zone above them is low. However, concepts of fjords and tectonic basins cannot be applied to the origin of widespread black shale units because of the contrast in area and the definite morphologic characteristics of such basins.

Open ocean model

In the open ocean (Figure 3), the oxygen content of the water may be controlled primarily by circulation, but it is also strongly influenced by the amount of organic material that escapes from the photic zone and settles through the water column. The oxygen minimum, just below the photic zone, is created by the oxidation of organic material. Some of the more resistant organic material settling past the oxygen minimum may undergo no further degradation en route to its accumulation on the bottom. Settling rates too rapid for oxidation of organic particles to be complete can be caused by incorporation of organic material in fecal pellets or by aggregation with mineral particles, even if the organic compounds are susceptible to oxidation. Organic-rich sediments thus can accumulate even though the sedimentational environment is completely oxic. In any event, the sediments themselves will become anoxic a few millimeters below the sediment surface because of bacterial processes and the slow replenishment of dissolved oxygen by diffusion below any zone of burrowing that is present.

The balance between organic productivity and available oxygen can shift because of changes in patterns of surface currents in response to tectonic events distant from the depositional site. Or, the depositional site might be carried by seafloor spreading (in the case of younger rocks) from an area of low organic productivity to one of high productivity and then to an area of low productivity again (e.g., White, 1979). The sediments deposited beneath the area of high productivity could be rich in organic matter and form black shales without there necessarily being an anoxic event in the sense of the formation of a barred basin or the cessation of circulation.

Continental shelf model

The continental shelf model (Figure 4) contains the same input factors as the other models, but there is little or no water between the photic zone and the bottom. Organic material is recycled in the photic zone to a lesser extent because of more rapid settling to the bottom. The concentration of oxygen in the water may remain large down to the top of the accumulating sediment because of circulation and the production of oxygen in the photic zone. In this setting also, the sediments become anoxic a very short distance beneath the surface because of bacterial processes.

This kind of sedimentational environment has been deduced for several transgressive black shales in North America, such as those in cyclothems of Pennsylvanian age (Zangerl and Richardson, 1963) and the black shales of Devonian and Mississippian ages (Conant and Swanson, 1961). This model, like the open ocean model, does not require any *a priori* conditions such as a restricted basin, density stratification, hydrogen sulfide in the water, or other characteristics based on analogies with the Black Sea.

RELATIVITY OF FACTORS IN DEPOSITION

Different relations between rates of clastic sedimentation, organic productivity, and the intensity of oxidation result in similar kinds and, perhaps, similar amounts of black shale being deposited. Organic productivity is controlled chiefly by the availability of nutrients, although other factors such as temperature, salinity, and water clarity also are involved. In trying to understand the reasons for the distribution of black shales in time and space, the fundamental concept to be kept in mind is that organic-rich rocks result when and where organic material accumulates because it is produced faster than it can be destroyed.

ZONES OF DIAGENESIS

The characteristics of the environment in which black shales were deposited are more or less imaginary in the sense that the characteristics have to be deduced from very few data of uncertain significance. In contrast, the zones of diagenesis can be fairly well defined on the basis of data on pore fluids and sediments from deep-sea drilling, laboratory experiment, and theoretical considerations. In addition, most of the products of diagenetic processes remain in the rocks and provide a record that can be deciphered. It is important to recognize the products of diagenesis so that data on them are not used misleadingly in the interpretation of conditions of deposition.

Krumbein and Garrels (1952) made clear the role of pH and oxidation-reduction potentials in influencing rock compositions during diagenesis. Postdepositional (diagenetic) changes during the accumulation of sedimentary rocks had, of course, been recognized earlier (Krumbein, 1942). Later, Berner (1964) explored iron and sulfur reactions in early diagenesis. Since then, diagenetic processes have been widely studied. The following discussion is based on four principal papers (Claypool and Kaplan, 1974; Curtis, 1977; Goldhaber and Kaplan, 1974; and Irwin *et al.*, 1977) that review, with some differences in emphasis, the processes of diagenesis of sedimentary rocks containing organic matter.

Figure 5 represents a sequence of diagenetic zones with depth at a particular point in time. The rocks in the zone of hydrocarbon formation already have passed through all of the overlying zones. If sedimentation continues, the sediments in the present zone of sulfate reduction can be expected to pass sequentially in order through the underlying zones. The ultimate nature of the rocks will depend chiefly on the maximum pressure and temperature that they reach during their burial history.

The diagram is only a model, and the boundaries between the zones are not sharply defined. The depths, temperature, and porosity may not be generally agreed to. The numbers in themselves are not important compared to the sequence of zones downwards. In an organic-rich sediment, a zone of oxidation at the top of the sediment column may be absent, thin, or, if present, the accumulating organic material may pass through it so rapidly as to be little affected. A zone of oxidation is not shown on Figure 5, but its presence can be important because in it any remaining free oxygen in the pore water is eliminated, a necessary condition before anaerobic sulfate-reducing bacteria can live. In addition, aerobic bacterial oxidation of part of the organic material may increase the abundance of compounds that serve as a utilizable substrate for the sulfate-reducing bacteria. The thickness of both the zones of oxidation and sulfate reduction depends on the extent of diffusion of oxygen and sulfate into the sediments from the overlying waters. The reduction of sulfate results in the formation of pyrite.

In both the zones of oxidation and sulfate reduction, the carbon dioxide formed is very light in carbon-isotope composition. Carbonate minerals in cements or concretions formed from such carbon dioxide would also be very light.

In the zone of fermentation, methane is produced by the bacterial reduction of carbon dioxide. This process begins when all available sulfate has been reduced. The bacterial population must be a mixed one containing not only methane-producing bacteria but also other bacteria capable of producing carbon dioxide. The fermentive production of biogenic methane causes a large fractionation of the carbon isotopes although the nature of the fractionation process is not well understood. Biogenic methane having the expected very light carbon-isotope composition is being produced commercially from rocks of Cretaceous age in eastern Montana where the fermentation zone represents the zone of greatest diagenesis yet reached by the rocks (Rice, 1975).

Ferroan dolomite, ankerite, and siderite are the carbonate minerals likely to be deposited in concretions and cements because of the depletion of sulfate and complete reaction of sulfide. Iron carbonate does not form in the presence of dissolved sulfide except under unusual circumstances.

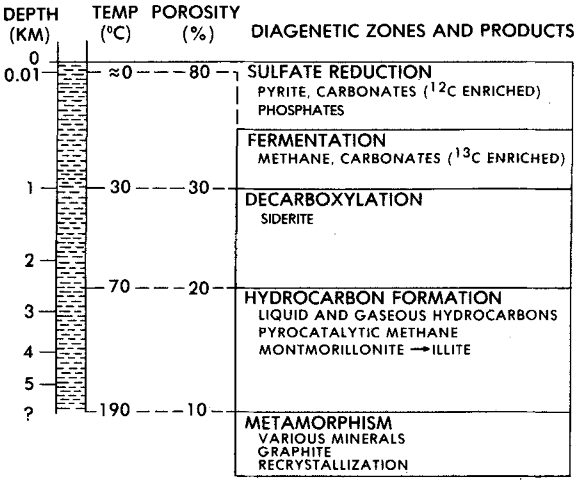

Figure 5. Zones of diagenesis. Modified from Curtis (1977). A zone of oxidation may or may not be present at top of sediment column: see text.

With increasing temperature and depth of burial as sedimentation goes on, the rocks reach the zone of decarboxylation where the organic matter begins to decompose by chemical instead of biologic processes. The carbonate mineral deposited is likely to be siderite, perhaps with a mixed composition, because the higher temperatures promote the reduction of iron compounds that could not be reduced under the milder conditions of the overlying zones.

The remaining organic matter presumably is different in composition than it was when the containing rocks entered the zone of decarboxylation. Such differences have not been detected, perhaps because rocks that have entered the zone of decarboxylation but gone no further have not been recognized.

The gradation from the lower zone of decarboxylation into the upper part of the zone of hydrocarbon formation is particularly broad. Pyrocatalytic formation of methane, for example, can begin at about 50°C, but large amounts may not be produced until much higher temperatures are reached. The carbon in pyrocatalytic methane has a δC^{13} more positive than that in biogenic methane. Organic composition, vitrinite reflectance, and the color alteration index of conodonts are all promising tools for defining the characteristics of this hydrocarbon zone that has such great economic importance. This is also the zone in which montmorillonite is converted into illite through several successive intergrades. The expelled water is a potential force for driving the migration of liquid hydrocarbons. Such expelled water may also carry metals that can be deposited in favorable sites within a black shale, e.g., Cu replacing Fe in pyrite (Tourtelot and Vine, 1976, p. C26).

RELATIVITY OF FACTORS IN DIAGENESIS

Temperature, pressure, and time are the chief factors that control what goes on in each successively deeper zone of diagenesis. The relations between diagenetic factors can be viewed in the same way as the relations of depositional factors. Diagenetic factors may vary regionally within a black shale of great areal extent. The eastern extent of a black shale unit, as a general example, may reach a more advanced zone of diagenesis than the western extent because of greater burial from thicker overlying rocks, tectonism, or igneous intrusions. Variation of this kind is indicated by the distribution of conodont color alteration indices shown by Harris *et al.* (1978). The relations of diagenetic factors can vary between shales, also. A shale of Tertiary age at a depth of 3–5 km in a region of large thermal gradient may have had most of its original montmorillonite transformed to illite. Another shale of Cretaceous age in a region of small geothermal gradient may still retain its original montmorillonitic composition even though at some time during its history it has been buried to a depth of 10 km. Given equal burial depths and thermal gradients, mineral transformations may have gone further in a shale of Paleozoic age than in one of Mesozoic age, simply because of more time having passed. It thus seems likely that a moderate range of relations between pressure, temperature, and time can yield the characteristics of a given diagenetic zone. This relativity of parameters must be taken into account in interpreting data on the chemical and mineralogic composition of black shales.

CONCLUSIONS

In any depositional setting, rates of clastic sedimentation and organic productivity and the intensity of oxidation are the primary controls for the accumulation of organic material.

In zones of progessive diagenesis, the mixture of organic matter and clastic sediment is operated on in rather predictable ways by biologic and chemical processes controlled chiefly by temperature, pressure, and time.

The separate products of the processes operating in the depositional environment and in the zones of diagenesis should be clearly distinguished to avoid misleading interpretations of either setting.

The factors influencing both the amount and composition of organic matter in a black shale can be expressed in an equation of the form sometimes derisively stated as "some of it plus the rest of it equals all of it," as follows:

$$\begin{array}{cccc} \text{BLACK SHALE} & \text{DEPOSITIONAL ENVIRONMENT} & & \text{ZONE OF DIAGENESIS} \\ \begin{array}{l}\text{Organic}\\ \text{matter}\end{array} = & \left\{\begin{array}{l}\text{Organic}\\ \text{productivity}\end{array} - \text{Oxidation}\right\} & - & \left\{\begin{array}{l}\text{Oxidation}\\ \text{Sulfate reduction}\\ \text{Fermentation}\\ \text{Decarboxylation}\\ \text{Pyrocatalytic reactions}\end{array}\right\} \pm \left\{\begin{array}{c}\text{Migration}\\ \text{of}\\ \text{products}\end{array}\right\} \end{array}$$

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Резюме—Чёрные сланец является темно окрашенной глинистой породой, содержащей органический материал, который мог явиться источником углеводородов в недрах или из которого можно получить углеводороды пиролизом. Во многих видах чёрного сланца содержание металлов в несколько раз превышает их содержание в обыкновенных сланцах. Некоторые виды чёрного сланца служат вмещающими породами для сингенетических отложений металлов.

Чёрные сланцы формировались в течение всей истории земли и во всех частях мира. Это указывает на то, что геологические процессы и не геологические условия являются определяющими факторами при формировании чёрных сланцев. Геологические процессы включают отложение, в результате которого накапливаются первичные осадки чёрного сланца, и диагенез, присходящий в результате увеличивающейся глубины захоронения осадков.

Процессы отложения включают целый диапазон отношений между такими факторами как органическая продуктивность, скорость седиментации, интенсивность окисления, разрушающего органическое вещество. Если присутствует достаточное количество органического вещества, чтобы истощить кислород в среде, образуется чёрный сланец.

Диагнетические процессы включают химические реакции, определяемые природой составных частей и режимами давлений и температур, вызванных продолжающимся захоронением. На глубине в несколько метров под поверхностю земли восстанавливается сульфат и могут отложиться сульфидные минералы. На глубине в несколько сотен метров в результате реакций брожения образуется биогенетический метан, а на больших глубинах в результате реакций декарбоксилирования и температурного метаморфизма образуются дополнительные углеводороды. Комплексы вновь образованных минералов характеризуют каждую зону диагенеза.

Resümee—Schwarzschiefer ist ein dunkler Schieferton, der organische Substanz enthält, die durch Überlagerung oder durch Pyrolyse Kohlenwasserstoffe bilden kann. Viele Schwarzschieferschichten zeigen eine Anreicherung an Metallen, sodaß ihre Metallgehalte um einiges höher liegen als die der üblichen Schiefer. Einige Schwarzschieferschichten dienten als Muttergestein für syngenetische Metallablagerungen.

Schwarzschiefer wurden während der ganzen Erdgeschichte und überall auf der Erde gebildet. Daraus folgt, daß geologische Prozesse, nicht geologische Gegebenheiten die ausschlaggebenden Faktoren für die Ablagerung von Schwarzschiefer sind. Diese geologischen Prozesse sind die Ablagerung, durch die das Ausgangsmaterial für den Schwarzschiefer sedimentiert wurde und die Diagenese infolge der zunehmenden Überlagerung.

Ablagerungsprozesse werden durch die Einwirkung mehrerer Faktoren beeinflußt, wie z.B. organische tätigkeit, Absatzgeschwindigkeit klastischer Sedimente, und Intensität der Oxidation, durch die organisches Material zerstört wird. Schwarzschiefer entsteht, wenn genügend organisches Material vorhanden ist, um den Sauerstoff der Umgebung zu verbrauchen.

Diagenetische Prozesse beinhalten chemische Reaktionen, die durch die Art der Komponenten sowie durch die herrschenden Druck- und Temperaturverhältnisse kontrolliert werden, die durch zunehmende Überlagerung entstehen. Denn unter einer Überlagerung von einigen Metern wird Sulfat reduziert, und Sulfidminerale können abgelagert werden. Fermentationsreaktionen in den nächsten hundert Metern führen zur Bildung von biogenem Methan. Ihnen folgen mit zunehmender Tiefe nach und nach Decarboxylierungsreaktionen und thermische Alterung, die weitere Kohlenwasserstoffe bilden. Abfolgen von neu gebildeten Mineralen sind charakteristisch für jede der Diagenesezonen.

Résumé—L'argile shisteuse noire est une roche argileuse foncée contenant de la matière organique qui peut avoir généré des hydrocarbones dans le sous-sol ou qui peut donner des hydrocarbones par pyrolyse. Beaucoup d'unités d'argile shisteuse noire sont enrichies de quantités de métaux plusieurs fois plus importantes que celles aux quelles on s'attendrait dans l'argile shisteuse ordinaire. Certaines unités d'argile shisteuse noire ont servi de roches hôtes pour des dépôts de métal syngénétique.

Les argiles shisteuses noires ont été formées tout au long de l'histoire terrestre et dans toutes les parties du monde. Ceci suggère que ce sont des procédés géologiques et non des lieux géologiques qui sont les facteurs controllants dans l'accumulation de l'argile shisteuse noire. Les procédés géologiques sont: la déposition par laquelle les matières premières d'argile shisteuse sont accumulées et la diagénèse rèpondant à une profondeur d'enterrement croissante.

Les procédés de déposition comprennent une étendue de relations entre des facteurs tels la productivité organique, la vitesse de sédimentation clastique et l'intensité d'oxidation par laquelle la matière organique est détruite. S'il ya assez de matière organique pour épuiser l'oxygène de l'environnement, il en résulte une argile shisteuse noire.

Les procédés diagénétiques comprennent des réactions chimiques contrôlés par la nature des composants et par les régimes de pression et de température imposés par l'enterrement continuel. A une èpaisseur de quelques mètres sous la surface, la sulphate est réduite et des minéraux sulphides peuvent être déposés. Les réactions de fermentation dans les prochaines centaines de mètres résultent en de la méthane biogènique, suivie successivement à de plus grandes profondeurs de réactions de décarboxylation et de maturation thermale qui forment d'avantage d'hydrocarbones. Des suites de minèraux nouvellement formés sont caractèristiques de chacune des zones de diagénèse.