B

BLACK SHALES

Black Shales are fine grained, generally organic carbon-rich sedimentary rocks that primarily consist of a mixture of clay minerals, quartz silt, organic particles (mostly planktonic algae and plant debris), and kerogen. They may also contain variable amounts of disseminated finely crystalline calcite and dolomite, as well as phosphate (commonly as concretions). Most black shales are found in marine sediments (Potter *et al.*, 1980), but they can also form prominent deposits in lacustrine successions (Bohacs *et al.*, 2000). Their black color is due to two constituents: (1) the contained organic matter, and (2) finely disseminated pyrite. The reducing conditions indicated by the latter have long led geologists to believe that ancient black shales required anoxic bottom waters for their formation, and were a typical deposit of the distal, deepest portions of sedimentary basins (via comparisons with the abyssal Black Sea where carbonaceous muds currently accumulate).

The Black Sea is a stratified, silled basin, in which a lower marine water body is overlain by a layer of brackish water due large input of freshwater from rivers. Because of density contrasts a halocline is developed at a depth of approximately 200 m, severely restricting vertical advection of oxygen-rich surface waters. Oxygen demand by decaying and descending organic matter exceeds oxygen replenishment by vertical advection, rendering the water column beneath the halocline anoxic and facilitating the accumulation of organic-rich muds. These observations have suggested to many geologists that organic carbon enrichment in the bottom sediments was basically a result of enhanced preservation (Wignall, 1994).

Although the Black Sea model dominated the study of black shales for many years, it is of limited use when studying ancient black shales. A major difference between the Black Sea and practically all black shales in the rock record is that the substantial depth ($\sim$2000 m) of the former, in conjunction with a stable halocline, greatly restricts circulation, whereas ancient black shales accumulated in much shallower epicontinental seas with a much larger width/depth ratio. Thus, on a geologic time scale at least, storms should have caused frequent mixing of the water column. With continued research into the origin of black shales, many occurrences that were initially interpreted according to the Black Sea model, are now in the process of re-evaluation.

Evolving views of the origin of the Late Devonian Chattanooga Shale of the eastern US may serve as an example for these changing perspectives in black shale deposition. On the basis of well developed fine lamination and apparently little evidence of benthic life, it was initially thought of as a very good representative of a basin with a stratified water column, and enhanced preservation as the primary cause for black shale accumulation. Recent research, however, has uncovered abundant evidence for wave reworking and intermittent erosion (Figure B22) of black shale (Schieber *et al.*, 1998). The observation that erosion surfaces of the type illustrated in Figure B22 can be traced for hundreds of kilometers actually forms the basis for a sequence stratigraphic interpretation of this succession (Schieber, 1998). Careful examination of shale fabrics has also revealed subtle but nonetheless widespread evidence (bioturbation features mostly) for benthic colonization of the seafloor. The high organic carbon contents in the Chattanooga Shale (up to 20 per cent) initially suggest that preservation due to oxygen restriction may have been mainly what controlled its accumulation. Yet, sedimentary and bioturbation features suggest that anoxia, if they indeed occurred, were intermittent, due to frequent water column mixing by storms or seasonal temperature variations. In the case of the Chattanooga Shale, therefore, surface productivity probably was also an important factor for organic carbon enrichment (Schieber *et al.*, 1998).

Although the "deep anoxic basin" model has enjoyed prominence for many years, when we look at black shales more closely we find increasingly that they can actually form in a wide range of depositional settings. Black shales do not constitute a large proportion of the sedimentary rock column,

Figure B22 Erosion surfaces in the Chattanooga Shale (entire exposure consists of black shale).Picture shows truncation of black shale packages by erosion surfaces (dashed white lines marked with large white arrows), and illustrates how succeeding black shale packages are draped conformably over these erosion surfaces. Small white arrows point out truncation of shale beds by erosion surface. In places erosion has removed in excess of 1 m of black shale between successive black shale packages (at a total Chattanooga thickness of less than 10 m).

but they are of great economic interest as the main source rock for hydrocarbon production, as well as containing unusually high metal concentrations (Potter *et al.*, 1980). Estimates suggest that more than 90 per cent of the world's recoverable oil, and gas reserves were generated from black shales (Klemme and Ulmishek, 1991). Equally significant is the fact that the latter are restricted to six stratigraphic intervals that represent a mere one third of Phanerozoic time (Silurian, Upper Devonian-Tournaisian, Pennsylvanian-Lower Permian, Upper Jurassic, Middle Cretaceous, Oligocene-Miocene).

Because organic carbon results from photosynthesis by plants and algae, each atom of carbon buried implies a molecule of oxygen added to the atmosphere. Carbon burial is linked to other global biogeochemical cycles and is a critical variable in our attempts to understand the history and evolution of the oceans and atmosphere, as well as global climate change. Over geologic time, carbon burial probably was responsible for a gradual rise in atmospheric oxygen levels. Also, by reducing the greenhouse effect it can lead to lower global temperatures and even ice ages (Berner, 1997). In that context, considering that the geological record is punctuated by global episodes of widespread black shale formation (Klemme and Ulmishek, 1991), understanding what combinations of variables are required to produce a "black shale world" is of considerable significance.

Three factors control organic matter accumulation in sediments: (1) organic matter input; (2) organic matter decay; and (3) dilution of organic matter by other ingredients. Factor 1, organic matter input, has two components, detrital organic matter washed in by rivers and organic matter from primary production in the water column. The latter is strongly dependent on nutrient availability. Factor 2 relates to breakdown of organic matter, mostly by microbes. Its efficiency and the types of bacteria involved depend on oxygen availability in the water column and the sediment. Factor 3, dilution, has a terrigenous component (fluvial and eolian contributions), and an intrabasinal component of skeletal remains (e.g., coccoliths, radiolaria, foraminifera, diatoms, etc.). The fluvial component is linked to climate and relief in the source region, and to sea level fluctuations. Because the magnitude of this component rises and falls with continental runoff, it is directly linked to the nutrient input that impacts primary production. Relief and sediment supply are linked to tectonism, which in addition can affect subsidence rates, basin geometry, and water depth (Schieber *et al.*, 1998). Because each factor is a function of several other variables that are in part cross-linked to other factors, determining the magnitude of each of these factors in the rock record is far from trivial. Obviously, black shale formation is a multifaceted problem and depending on the interaction of the variables, there are multiple scenarios that are conducive to black shale formation (Tyson and Pearson, 1991). Microbial mats can also promote accumulation, and preservation of organic-rich sediments in a wide range of environments (Schieber, 1999), a currently under appreciated fact (see *Microbially Induced Sedimentary Structures*).

Black shales are not only common in thick, basinal, successions, but also occur as thin tongues within basin-margin successions. The latter are thought to owe their existence to high stands of sea level when terrigenous input was at a minimum, and as such may mark maximum flooding surfaces (Creaney and Passey, 1993). Whether these shallow water black shale tongues, reflect deposition beneath a nearshore zone of oxygen restriction, or simply are the outer edge of an expanding anoxic water body that usually only occupies the basin center (Wignall, 1994), is still being debated. Nearshore oxygen restriction could, for example, be produced by salinity stratification due to freshwater plumes, or by high nearshore productivity fueled by nutrients in continental runoff. Alternatively, rapid sea level rise could have caused expansion of central anoxic water bodies into shallow nearshore waters. Recent efforts to integrate black shales into a sequence stratigraphic context suggest that at the onset of transgression, black shale deposition may commence in the basin interior, that nearshore black shale deposition is possible early in transgressions, and that black shales related to maximum flooding can form during high stands of sea level (Wignall, 1994; Schieber *et al.*, 1998). Sea level variations may also have lead to conditions with recurring water column mixing events and recycling of key nutrients (N, P) to surface waters, making possible a "productivity-anoxia feedback" mechanism to maintain high rates of carbon burial (Ingall *et al.*, 1993).

Black shales are the end product of the complex interplay among a range of geologic variables and processes, and there are no easy answers and no "one size fits all" models. The seemingly drab and uniform nature of many of these rocks poses a considerable challenge and requires us to extract information by all means possible. Sedimentological study includes recognition and tracing of facies changes, sedimentary features, shale fabrics, erosion surfaces and internal stratigraphy, as well as information that can be derived from interbedded non-shale lithologies. Paleontological studies may provide data on paleo-oxygenation, primary production, substrate conditions, paleocurrents, bathymetry, and paleosalinity (Schieber *et al.*, 1998). Petrographic investigations provide the basic inventory of shale constituents, and may yield clues about provenance, compaction history, sedimentary processes (via small scale sedimentary structures), the origin and maturation of organic matter (Taylor *et al.*, 1998), and even paleo-oxygenation (via analysis of pyrite framboid size distribution; Wilkin *et al.*, 1997). Chemical analysis of major and trace elements can provide information on provenance (Roser and Korsch, 1986), and a range of proxies for paleo-oxygenation (Jones and Manning, 1994). Organic geochemistry can furnish information on the source of organic matter, its dispersal, and maturation (Engel and Macko, 1993). Certain organic molecules, such as photosynthetic pigments, may survive as "carbon skeletons" (biomarkers), and may identify the original source of diagenetically altered organic matter and potential indicators of water column anoxia (Brassell, 1992).

Summary

Black shales do not give up their secrets easily. The tools are at hand, however, to extract a wide range of data from them and allow for multiple avenues of inquiry. Past experience shows that interpretation from just one perspective (e.g., petrography, fabric study, trace element geochemistry, or organic geochemistry) leads to conclusions that often are in conflict with those coming from a different line of inquiry. Black shales need to be investigated in a multidisciplinary way and at multiple scales because of the complex interplay of variables that produces them. Conclusions derived from microscopic features must be in agreement with insights coming out of basin scale studies, as well as with findings from all scales in between. Once this is accomplished, patterns are likely to emerge that will not only tell us the critical factors for the formation of a specific example of a black shale, but also reveal the fundamental conditions that make a "black shale world" tick.

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Cross-references

Depositional Fabric of Mudstones
Hydrocarbons in Sediments
Mudrocks
Oceanic Sediments
Sulfide Minerals in Sediments