The Sedimentology of Mudrocks: Organics, Organisms, and Occasional Occurrences
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During his career as a research and exploration geologist, Dr. May found that many geologists had a simplistic idea about shales and mudrocks. Typical descriptions of shales in cores and outcrops were "black, thick, homogeneous, boring, laminar". Actually mudstones are diverse, with varying amounts of clay, silica or carbonate; biogenic or detrital material, or a mix; and are organic-rich to organic-lean. There is also a complex interaction of detrital influx, primary biogenic productivity, the structure of organic material and later diagenesis. This talk provided better descriptors for mud rocks and discussed how the interpretation of processes is important as an exploration tool in assessing TOC and fracability.

Organic matter is a product of primary biogenic productivity, dilution by detrital influx, and what is actually being preserved. Where are we seeing abundant organic matter today? Much is produced at major upwelling systems, especially along the western margins of major continental masses. Abundances are found at low latitudes and in areas of restricted circulation; in terrestrial areas with high runoff but low detrital runoff; and where eustatic rises bring shallow waters over our shelves and cratons. Looking today at modern productivity in our oceans, the highest chlorophyll concentrations, i.e. high phytoplankton productivity, are in circum equatorial upwelling areas where shallow waters move away, replaced by colder oxygenated nutrient rich waters. The nutrients are taken up by phytoplankton followed by zooplankton that feed on it. The degradation takes oxygen out of the sea water and begins producing disoxic and anoxic waters, especially along the margins of the continents in the outer continental shelves and upper continental slope. In restricted basins there is mid-ocean anoxia. Also, major rivers in flood, such as the Mississippi, have high nutrient runoff, creating high biogenic productivity, with phytoplankton blooms, zooplankton, degradation, and removal of oxygen from the waters. The cycle of anoxia produces fish kills, literal dead zones. It is responsible for red tides. Nutrient runoff from farmland can be a component.

High biogenic productivity is present in warm seas, which were present during the Cretaceous and lower Paleozoic and a number of other greenhouse periods. Warm seas produce high calcium carbonate saturation in the ocean waters. The Cretaceous lacked big reef builders, but the phytoplankton and the zooplankton absorbed the calcium carbonate, making skeletal debris that ultimately fell to the bottom of the ocean. This was also a time of sea level rise with flooded continents. There was abundant organic productivity and skeletal matter. One way to preserve the organic material is to overwhelm the degradation system, perhaps by a stratified water column that includes low sea forage, low mixing of waters, low bioturbation, low detrital dilution, and rapid burial.
Today, this is where we have much of our organic accumulations, in basins such as the Black Sea, continental borderlands, or shallow stratified basins such as the Bering or the Baltic sea and the Eastern Mediterranean. Many basins are not truly anoxic, but disoxic. But as oxygen is reduced, the larger burrowing organisms, bivalves, crustaceans, shrimp, crabs disappear, leaving behind smaller worms. Off the shore of central and South America, oxygen levels are low at depths of 100 meters, but abundant organic material is accumulating and being preserved in those localities. Dropping down into the basin off the coast of Venezuela, there is little water circulation at a depth of about 140 meters, and organic matter is accumulating. There are low oxygen conditions and the potential for preservation.

During geologic periods of oceanic anoxia, typically there were warm climates, warm seas, high levels of atmospheric carbon dioxide and methane outgassing. These conditions were complimented by high rates of organic productivity and low levels of dissolved oxygen and tended to occur when there were major eustatic rises. The oxygen minimum zone that was on the outer shelf and continental slope was brought over the cratons.

The Western Cretaceous interior seaway illustrates these conditions with the Mowry, Greenhorn, and Niobrara formations, which were deposited under circumstances of poor circulation and preservation of organic matter. In Niobrara time, there was an abundance of siliciclastics coming from the west, creating a dilution effect. Chalks and carbonates are present farther to the east, away from the major area of influx. The Emery Delta was building out in Utah, producing marls with lower calcium carbonate, higher quartz silt, feldspar silt, higher clay, and higher overall detrital material that diluted the carbonate material. This contrasts with the 60-70 percent calcium carbonate in the chalks. There is high TOC with low dilution, and low TOC with high dilution, a case of dilution versus preservation. But bioturbation also removes the organic material; in bioturbated chalks the organic material is 1 percent or less. The laminations in marls are the result of rapid burial and not as much bioturbation; TOC may range up to 5 percent. The organic process is not just production, dilution, preservation but all three together.

Stratigraphic cycles. What are the components of mudrocks and how do they affect porosity, permeability, mechanical stratigraphy? Stratigraphic cycles are due to the interaction of biogenic productivity. Skeletal and organic material produced in shallow water falls to the ocean bottom. The dilution effect can be either siliclastic or carbonate. There is competition between intrabasinal material and extrabasinal material and competition occurs in multiple frequencies. For example, there is cyclicity in the Niobrara from marls to chalks and back again in 75-110-ft thick cycles. Chalks are composed of foraminifera and fecal pellets. Marls consist of quartz silt, feldspar silt, and clay. The Mowry represents recessive argillaceous intervals, siliceous resistant intervals. Laminations in shales can be due to seasonal cyclicity.

Biogenic material is intrabasinal and it affects very important aspects of shale plays--brittleness, frackability, and organic content. Brittleness and frackability relate to the biogenic skeletal matter--whether it is carbonate or siliceous. Carbonate skeletal material includes foraminifera and coccoliths. Siliceous skeletal material consists of radiolaria, diatoms, and sponge spicules. Organic material includes algae and fecal matter.
Foraminifera are skeletons of amoebic protists <200 microns across, the size of fine-medium grained sand. Foraminifera in the Niobrara increase the brittleness. Coccolithofores are green algae, which produce calcareous disks around themselves. The background material in the Eagleford, Niobrara, and Austin Chalk are coccoliths (2 microns in size). Siliceous protists include radiolarians, which are omnivores. Diatoms are gold-brown algae with skeleton, about 20 microns in size. There are also sponge spicules. All of these are produced in relatively shallow water under high energy conditions before falling out of suspension to the bottom. The sedimentation is not continuous but rather cyclic. The matter may fall down glommed together onto electrostatically charged clay particles to a zone of lower oxygen.

Algal blooms are coccolith spores, seasonal blooms. Tiny shrimp feed on algae and their fecal matter falls to the ocean bottom. At 50-100 microns, this can produce a small sandy layer in a shale. The small matter in seawater visible when diving is largely fecal matter. There are also gelatinous mucous masses - these can be feeding nets of organisms and can reach over a meter in diameter. Their purpose is to catch food for an animal, which releases the net when it becomes clogged (a sinker). In Monterey Bay, 3 or 4 sinkers/sq. meter fall every day.

Much TOC is fecal pellets. Wisps in thin section may be parts of sinkers. Events such as turbidites may dilute organic matter. If there is organic matter it will be eaten, often by small organisms such as polychaete worms (suspension feeders). Other worms move on the seafloor dragging material with them. Laminations can be formed by burrowing. Light gray material can indicate the laminae have been burrowed. Nematodes are the most important organisms moving through sediment, with as many as 100 nematodes in a cubic centimeter. They are 10-20 microns across. They move between silt and sand-sized sediment, ingesting and disturbing the sedimentary structures. Foraminifera hunt for nematodes through the sediment, disturbing the structures. The compressed foraminifera form sand-rich layers, for example in the Barnett Shale.

The predominant processes acting on the seafloor are storm-driven mechanisms and sediment gravity flows. Much of the mud rock reservoirs develop on shallow cratonic basins with periodic high energy storm sedimentation. In one of the type sections of the Chattanooga Shale, a deep dark anoxic black shale, there are silty mud rocks with cross-cutting erosional features. The basin may not have been that deep and dark, but rather still subject to some wave action. Sediment gravity flows can be turbidity flows, slides, slumps, and debris flows. There is the potential for these where there is any topographic high combined with the possibility of releasing material. Not all turbidite deposits are thick--some produce only thin layers. Silt brought in from bedload transport will produce laminations. Clay can be moved as well as sand and silt. Laminations occur from alternating silt and clay. Also, what have been described as burrows may be compacted clay flocculants. There are many processes occurring on the sea floor.

In summary, the old paradigm of mud rock and shale deposition, where grains settle out of suspension to an low energy anoxic sea floor, needs modification. Storm mechanisms and sediment gravity flows
are active. Mud, as well as silt and sand, is transported by flows and currents. Rather than a continual rain of material, much organic material probably falls relatively rapidly as aggregates and pellets. There are variable rates of deposition due to season and climate. Describing a shale as laminated may not be useful unless you know why it is laminated, by gravity flow, or perhaps by burrowing. In addition, the idea that shale basins were anoxic is probably over estimated. Instead, there are subtle high energy events and cryptic bioturbation.

Most of our organic matter that is terrestrial-derived provides gas-prone shales, but volumetrically, it is much less than marine organic material. Marine organic material will go to oil, then will eventually crack to gas. Most of our larger shale gas plays to date are dominated by Type 2 marine organic material, not type 3 terrestrial organic material.