Micro-Textural Analyses of Fine-Grained Sediments and the Roles that Advective Sediment Transport and Suspension Settling Processes Play in the Deposition of Fine-Grained Organic Carbon-Rich Sediments. OR Just How Shaky are the Current Depositional Models that Seek to Explain the Origin of Source Rocks / Shale Gas Reservoirs?

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Introduction and Aims

Black shales are typically interpreted to be the classic basin-center facies association. In these environments varying surface primary production, bottom water anoxia and low energy conditions are typically considered to be the dominant physical, chemical and biological factors responsible for facies variability. This arises because these sediments: (a) are dominated by clay and silt-sized components; (b) appear laminated and contain little obvious evidence of either infaunal colonization or erosion; (c) are commonly organic carbon-rich (>2%); (d) contain fossil assemblages dominated by nektonic organisms (e.g. ammonoids); (e) contain very small populations of pyrite framboids (<10 μm) and, (e) contain high concentrations of biomarkers (e.g. isorenieratene) / trace elements (significantly elevated concentrations of Mo, U, V) that are interpreted to indicate the existence of either bottom water anoxia or photic zone anoxia. These attributes have caused many researchers to argue that these sediments were deposited where: (a) the water column was sufficiently deep to ensure that waves only rarely impinged on either the seafloor or caused overturn; (b) sediment was delivered to the sediment water interface as a continuous rain of fine-grained detritus, and (c) much of the facies variability present was controlled by the changing ratio of primary production to clastic inputs.

In recent years geologists have begun to adopt more sophisticated sampling strategies to investigate the origins of these rocks. These analyses reveal that the monotonous hand-specimen appearance of black shales belies the fact that they are more heterogeneous than earlier researchers have recorded. They also suggest that "full-blown" persistent bottom water anoxia was only a relatively rare phenomenon and that the water column was more likely to be subjected to differing degrees of dysoxia. The basic tenets of much of the underlying paleoenvironmental models used to explain how these rocks formed, however, remain unchanged.

Recently, in order to investigate further the origin of fine-grained organic carbon-rich rocks geologists have started to adopt the latest generation of imaging tools (e.g. backscattered electron imagery), coupled with more traditional methods (optical petrography), to image the microfabrics present. These techniques reveal that these rocks are much more variable than had been previously documented. In particular, they show that mudstone successions are commonly organized into very thin beds (typically < 10 mm thick) and that these thin beds systematically stack into thicker units (parasequences and systems tracts respectively) that can be interpreted within a sequence stratigraphic framework. Crucially, they also show and that internally some of the individual beds preserve their primary sedimentary structures (as documented by the presence of ripple laminae, intraclasts etc.) and / or have been homogenized by the burrowing activities of a diminutive infauna. The presence of these fabrics is very significant as they indicate that at least episodically that while these sedimentary successions were being deposited: a) the sea-floor was being eroded; b) sediment was being transported by advective sediment transport processes, and c) that the bottom waters were rarely persistently anoxic. These data suggest that the models typically used to predict the distribution of organic-carbon rich fine-grained rocks need to be significantly modified to reflect the energetic and dynamic nature of conditions at the sea floor during their formation.

The aim of this contribution is to illustrate, using optical and electron optical methods, some of the micro-fabrics preserved in fine-grained, organic carbon rich sediments. For the purposes of this contribution samples from the Kimmeridge Clay Formation, Posidonia, Jet Rock, Mowry Shale, Mancos Shale, pebble shale unit, Oxford Clay, Ben Bulben Shale, and Second White Specks (Cenomanian / Turonian in Alberta) will be used. With this information I will discuss: a) the likely processes responsible for sediment dispersal in these basins and b) how physical and biological processes combine to contribute to the spatial distribution of lithofacies in organic carbon-rich mud-dominated successions. I shall then consider the implications of these observations for the current generation of facies models that are used to interpret the conditions under which these rocks were deposited and to discuss potential future research directions.

Data

A wide variety of small sedimentary structures are preserved in mudstones, where they have not been homogenized by subsequent bioturbation. These structures are difficult to image in hand specimen because the rocks have been compacted as much as 90% of their original depositional thickness and they are susceptible to weathering. In mudstone-dominated successions, however, individual beds (single events) are commonly thin (<10 mm thick), normally graded and either sharp-based or overlie erosion surfaces. These erosion surfaces may have a vertical relief up to 5 mm. The basal laminae within individual beds may contain silt and very fine sand-sized material composed variously of quartz and feldspar and lithic grains that are organized into thin basal lags. Typically the sediment close to the base of these beds is either (a) homogenized, (b) forms pelleted, discontinuous wavy laminae, or (c) is organized into lamina-sets that comprise thin intercalated layers of silt and clay laminae. The laminae in the basal portions of these beds are wavy, straight or curved and may down-lap onto the underlying bedding planes. Where scale scours are present individual lamina may onlap the margins of the scour features. Small silt and very fine sand-sized composite grains that are composed of reworked clay-sized material may also be present. The latter typically form clay mineral-rich laminae within units otherwise dominated by very fine-grained sand and coarse-silt-sized granular detritus composed mainly of clay minerals.

Some beds contain abundant pellets that are either composed of clay-sized minerals or dominated by nannoplankton-derived debris. In the regions outwith the pellets the sediment is commonly richer in organic carbon than the material within the pellets. The clay and organic matter are commonly organized into wispy organo-minerallic aggregates with diffuse outlines. The top portions of many of the beds are homogenized and the contacts between the homogenized laminae and the underlying intercalated silt and clay-rich laminae are gradational. Within the upper parts of the beds diminutive burrows are common.

Discussion

The common occurrence of thin, sharp-based, normally graded beds with homogenized tops in these organic carbon-rich mudstones is very significant. These beds indicate that even during deposition of these very organic carbon-rich sediments delivery was episodic and that between delivery episodes there was sufficient time for the sediment to be colonized by a diminutive infauna. The sharp / erosion bases, coupled with the presence of intraclasts indicates that the sediment water interface was being reworked by the same processes responsible for later sediment emplacement. The existence of these structures indicates that emplacement of these sediments was commonly a more energetic processes than most geologists have previously argued.

The variety of internal laminae geometries exhibited by these organic carbon-rich sediments indicates that sediment was both delivered by both advective processes and suspension settling from buoyant plumes. The different geometries present and their combined flow nature indicate that sediment was being dispersed by both density flows such as wave-enhanced sediment gravity flows of fluid mud, and turbidites in addition to being reworked and dispersed by wave mixing, presumably by the distal effects of storms and by geostrophic currents. The collected effects of gravity, currents and waves characterize all the products of these processes. The orientations of the sedimentary structures produced by these processes, however, are very difficult to measure because of their very small size, so the exact balance of processes operating in any particularly sub-environments within a basin is currently unknown. What is clear, however, is that mud dispersal in these systems was not just being accomplished by suspension settling from buoyant plumes, and that these depositional systems, at least episodically, were very dynamic.

In addition to deposition from density flows, there is also evidence that at least some of the muddy material was being dispersed as bed-load. In these environments the muddy components were being transported as very fine sand and coarse silt-sized aggregate grains (either pellets or clay floccules) that had been derived by local reworking of the underlying sediment. These clay-mineral-rich aggregate grains are commonly organized into laminae and contribute many of the component grains within some of the ripples and parallel laminated units. The presence of these clay-mineral-rich lithic grains is particularly significant as they indicates that muddy material is not necessarily deposited as a low energy drapes following a period of higher energy deposition. They also indicate that conditions at the sediment water interface were at least occasionally very energetic and mud dispersal is sediment is not always accomplished in density flows.

Where bioturbation has not overprinted the primary fabrics pellets are commonly observed. Pellet-rich laminae are also commonly associated with organo-minerallic aggregates. These aggregates are composed of intimate mixtures of amorphous kerogen, clay minerals and pellets and have diffuse outlines that are difficult to observe unless horizontal thin sections are manufactured from the sediment. These aggregates are interpreted to be the ancient equivalent of marine snow / phytodetritus, that is such a striking components of the water column of recent marine / lacustrine settings. Where organo-minerallic aggregates are present and it seems likely, as in modern environments, that the majority of the sediment in suspension was delivered to the sediment water interface in these aggregates rather than as individual grains. Delivery in these aggregates is important as in this form labile organic carbon can be transported rapidly to the sea floor. In modern oceans marine snow formation particularly occurs below zones of high primary production. The existence of this material in these ancient organic carbon-rich sediments suggests that organic matter was delivered to the sea floor rapidly following phytoplankton blooms and that this high flux of organic carbon coupled with its rapid burial ensured that at least some of the organic carbon was preserved prior to it being oxidized by subsequent sediment colonization between delivery episodes.

Concluding remarks

Petrographic analyses of thin sections provides a great deal of information about the physical, chemical and biological processes that where occurring while fine-grained, organic-carbon rocks were being deposited. This information is neither easily obtained from hand-specimen observations nor by using proxy methods. These data indicate that these sediments are highly heterogeneous on sub-centimeter scales and that conventional analytical methodologies, designed to sample these rocks on hand specimen scales, likely sample more than one event bed. Data generated at a multi-bed scale are difficult to interpret in terms of specific processes operating at the time of deposition.

Petrographic data reveal that a great deal of textural information is preserved in these rocks. These data indicate that in spite of being organic carbon-rich and fine-grained they were deposited in very dynamic environments where much of the sediment was being dispersed by a combination of advective and suspension settling processes. In addition the microfabrics present suggest that a variety of gravity flow mechanisms driven by the combined effects of waves, currents and gravity operated to disperse the sediment. What is perhaps also surprising, particularly given the low energy assertions embedded within the current paradigm for these sediments, is that there is also evidence that during periods when accommodation availability was limited much of the mud was being transported as bed load.

Overall, the models that imply that these rocks are low energy, and boring and that sediment was being deposited as a continuous rain of fine-grained detritus need to be modified. Conditions in the basin centers during deposition of these rocks were much more dynamic than most geologists have previously appreciated. In spite of the complexities of the facies present these sediments do contain a great deal of information that is easily interpretable using existing sedimentological techniques, it is just this information is not present at scales that are easily accessible from conventional field and core-based analyses. In the future will have to work hard to refine our depositional models further – but we do have tools that are readily available to do this work.