A Hierarchy of Current-Produced Bedforms in a Source Rock from the Eastern Carpathians Points to Predominant Bedload Deposition of an Organic-Rich Mudstone

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Abstract

The Oligocene age Bituminous Marl Formation (BMF) of the East Carpathians is a laterally extensive source rock succession in the Moldavide Basin of Romania, and historically was thought of as a rather monotonous lithostratigraphic unit of largely pelagic origin. It contains, however, a wide spectrum of lithofacies that are characterized by sedimentary structures such as intraformational slump folds, clastic dykes, cross-bedding, hummocky cross-stratification, current and wave ripples, and mm-scale fine lamination. Some of these structures are consistent with a slope and deeper water depositional setting, but wave generated features suggest that intermittently the seabed was within the reach of storm waves. On the basis of flume experiments, the pervasive mm-scale fine laminae suggest that a substantial portion of the BMF was deposited and redistributed via floccule ripples by bottom currents, an interpretation that is supported by the presence of ripples wherever sand size particles are available. The BMF contains fish debris, occasional bivalves and isopods on bedding planes, and macroscopic bioturbation features are rare. The most remarkable feature of the BMF are true cross-beds with sigmoidal foresets (10-15 degrees dip).

Cross-bedded marls occur either as thin (5-10 cm) or thick to very thick (1-1.2 m) bedsets. Differential compaction features indicate that surficial sediments had a water content of approximately 70%. When this is taken into account, the decompacted foreset slopes of above bedforms dipped at 30-40 degrees, and the bedforms themselves should have produced from a few dm to
as much as 4-5 meters relief respectively. The BMF shows a full suite of traction-produced muddy bedforms, including cm-scale ripples, dm-scale megaripples, and m-scale mudwaves. Although part of the sediment probably arrived at the seafloor via pelagic settling, reworking and transport of flocculated muds in bedload appears to have been a major factor in producing bedding features from the mm- to m-scale. The observed level of bottom current activity seems incompatible with previous scenarios of anoxic bottom waters as the cause for preservation of lamination and organic matter. Instead, frequent bedload transport of flocculated muds may have prevented the establishment of a burrowing infauna and through formation and rapid burial of organo-mineral aggregates may have promoted organic matter preservation and enhanced source rock potential.
SUMMARY: The Oligocene age Bituminous Marl Formation (BMF) of the East Carpathians is a laterally extensive source-rock succession in the Carpathian-Balkanian Basin Province of Romania, and was long considered a rather monotonous lithostratigraphic unit of largely pelagic origin. When observed carefully, however, it contains a wide spectrum of lithofacies that are characterized by sedimentary structures such as intraformational slump folds, slaty cleavage, cross-bedding, current ripples, and millimeter-scale fine lamination. These structures are consistent with a slope and deeper water depositional setting.

There are potential sedimentary current generated features that would place the succession intermittently within the reach of storm waves, but these features require further verification. In light of recent flume experiments with clay and carbonate mud, the parasequence scale fine lamination suggest that a substantial portion of the BMF was deposited and retransported as mud aggregates in the form of ripples that migrated under the influence of bottom currents. This interpretation is supported by the presence of ripples wherever sand-size particles are available. Microscopic bioturbation features are rare, but bioturbated intervals of the BMF are also consistent with the sedimentary context of the basin.

The most remarkable sedimentary feature of the BMF is the observation of true cross-bedding in outcrops with aggradational foresets that dip at 10-15 degrees. These cross bedded intervals occur either at thin (<0.1 cm) or thick (>1.2 cm) bedsets. Differential compaction of mud around sandy ripples and sand-filled scours indicates that surficial sediments contained ~95% water. When this is taken into account, the decompacted foreset slopes of these bedforms dipped at 30-40 degrees, and the bedforms had from a few dm to as much as 4-5 meter relief.

The BMF shows a full suite of traction-produced muddy bedforms that includes cm-scale ripples, dm-scale megaripples, and m-scale mudwaves. The sediment arrived at the seafloor via pelagic settling, was then reworked and transported (as soft rip-up clasts) in bedload. The observed level of bottom current activity is incompatible with previous scenarios of anoxic bottom waters as the cause for preservation of lamination and organic matter. Instead, frequent bedload transport of aggregated mud interfered with the establishment of burrowing infauna.

GEOLOGIC CONTEXT: Tectonic overview (A) and study site locations (B). The BMF accumulated in the foreland basin of the Eastern Carpathians (the Moldavian Basin). The latter was part of the Alpine Tethys from Cretaceous to Latest Eocene, and of the Paratethys (C, right) from Oligocene to Miocene. During Miocene compressions the basin (D) was detached from the basement and deformed into tectonic nappes (A). The studied area (E) belongs to the most external “Phituk Nappe” (Vrancea Nappe), which accumulated on the eastern slope of the basin (5-10°). BMF deposition coincides with the isolation of the Paratethys from the World Ocean (C) in Tertiary time and goes by a sea of Kanses (right Mantle). Dystric Marls (from the lower Alpine-Moldavian Basin to the Romanian-Southeastern Carpathians).

PALEOGEOGRAPHIC CONTEXT: (D) the location of the study area within the Tethyan realm. (E) Sedimentation realms in eastern Romania during deposition of the BMF.}

GENERAL INFORMATION ABOUT THE BITUMINOUS MARL (BMF):

Marker units that extend from Germany to Romania, of generally accepted Oligocene age (14-16 Ma), belong to a group of marls known to be, generally of pelagic sedimentary facies, but that may include weathered clays within its oultside. In the Eastern Carpathians the unit is named Bituminous Marl (BMF) (southern Romania). The sedimentary succession that includes the BMF is the most important hydrocarbon source rock for Romania, Hungary, and Poland. The TOC varies from 1.2%, whereas 6% and the SW is mostly type I, and it is present in most of the BMF depositional setting. The organic content is dominated by Type I kerogen, with an occasional presence of Type III kerogen. The BMF contains organic-rich mudstone, which is the main source rock for petroleum generation in the Romanian part of the Carpathian-Balkanian Basin Province.
A HIERARCHY OF CURRENT-PRODUCED BEDFORMS IN A SOURCE ROCK FROM THE EASTERN CARPATHIANS POINTS TO PREDOMINANT BEDLOAD DEPOSITION OF AN ORGANIC-RICH MUDSTONE

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SEDIMENTARY FEATURES, BOTTOM CURRENTS, REWORKING, BEDLOAD TRANSPORT, and RIPPLIES

Outcrop View

Sedimentary rhythmites (left) are interpreted as low-angle downlapping laminae (red arrows). Sandy current ripples are the other critical element. They consist of a mixture of: in situ, near bilateral sand ripples, and secondary laminae (yellow arrows). Sandy current ripples are the other critical element. They consist of a mixture of: in situ, near bilateral sand ripples, and secondary laminae (yellow arrows).

Thin Section View

Sedimentary rhythmites (left) are interpreted as low-angle downlapping laminae (red arrows). Sandy current ripples are the other critical element. They consist of a mixture of: in situ, near bilateral sand ripples, and secondary laminae (yellow arrows).

SEM View

Sedimentary rhythmites (left) are interpreted as low-angle downlapping laminae (red arrows). Sandy current ripples are the other critical element. They consist of a mixture of: in situ, near bilateral sand ripples, and secondary laminae (yellow arrows).

COMPOSITION = MUDSTONE, DEPOSITION - JUST LIKE SANDSTONE

OTHER EXAMPLES AND EXPERIMENTAL STUDIES OF LENTICULAR MUDSTONE FABRICS

Experimental setup as follows: Sichel et al., 2018 experimental design. mudstone depositional conditions: a) modern mudstone depositional conditions; b) modern mudstone depositional conditions; c) modern mudstone depositional conditions.

BIOTURBATION AND REDOX STATE

Microfossils in shale can indicate that the redox boundary is anoxic and depositional conditions are oxidizing conditions. For example, microbial mats and microbial communities can form in anoxic conditions. For example, microbial mats and microbial communities can form in anoxic conditions. For example, microbial mats and microbial communities can form in anoxic conditions.
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There is no evidence of shear along foreset planes, and internally the layers within foresets show the same inclination. The bottom and top set boundaries show no evidence of shearing and are sedimentary in nature. Samples from this exposure show some textures as apple laminated and megaripples, with scattered sand grains and soft mud rip-up clasts. The inclination of foresets is the same range as in "normal" laminated BMF, with scattered sand grains separated by fine ground moss mixture.

CONCLUSIONS
The Bituminous Marl Formation (BMF) shows a full suite of traction-produced muddy bedforms, from cm-scale ripples, over dm-scale megaripples, to m-scale mudwaves.

Seafloor erosion of previously deposited pelagic muds provided up to mm-size soft rip-up clasts that acted as "sand" grains during bottom current activity. The exact cause behind the observed hierarchy of traction current bedforms is not fully understood at this time, but probably reflects the combined influences of the amount of available bedload sediment (soft clasts) and the duration of current events. It does not reflect significant differences in flow velocity.

Sedimentary evidence and the presence of marcasite in these sediments suggest bottom waters at the time of deposition were suboxic. The abundance of current activity suggested by these sediments probably was an additional factor that limited bioturbation. Sedile bioturbation by meiofauna and the presence of marcasite in these sediments suggest that the sand grains travelled bedload to mixture of soft mud aggregates and sand grains. Water-rich soft mud aggregates and sand grains strongly suggest that the sand grains traveled in bottom bedload to gather with soft mud rip-up clasts.