# PS 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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Search and Discovery Article #51006 (2014)**
Posted August 29, 2014

*Adapted from poster presentation given at 2014 AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014


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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.

# 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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## 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 intra-formational slump folds, clastic dykes, cross-bedding, current ripples, and mm-scale fine lamination. These structures are consistent with a slope and deeper water depositional setting.

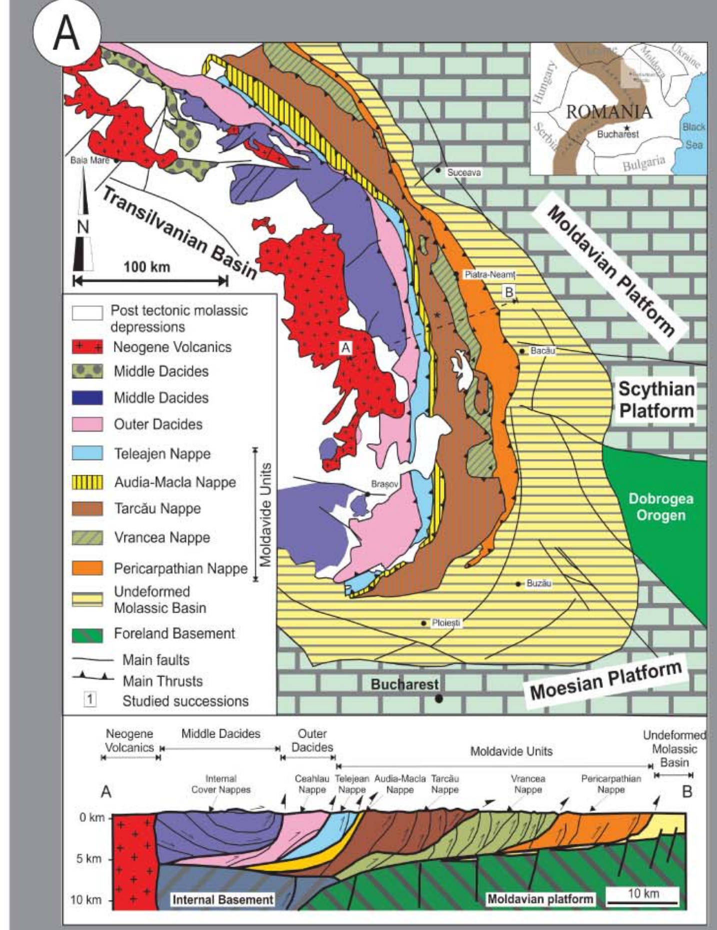
There are potential oscillatory current generated features that would place the succession intermittently within the reach of storm waves, but these featureres require further verification. In light of recent flume experiments with clays and carbonate muds, the pervasive mm-scale fine laminae suggest that a substantial portion of the BMF was deposited and redistributed 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. Macroscopic bioturbation features are rare, but meiofaunal burrowing is evident in thin sections.

The most remarkable sedimentary feature of the BMF is the observation of true cross-bedding in outcrops with sigmoidal foresets that dip at 10-15 degrees. These cross-bedded marls occur either as thin (5-10 cm) or thick to very thick (1-1.2 m) bedsets. Differential compaction of marl around sandy ripples and sand-filled scours indicates that surficial sediments contained ~70% 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 meters relief.

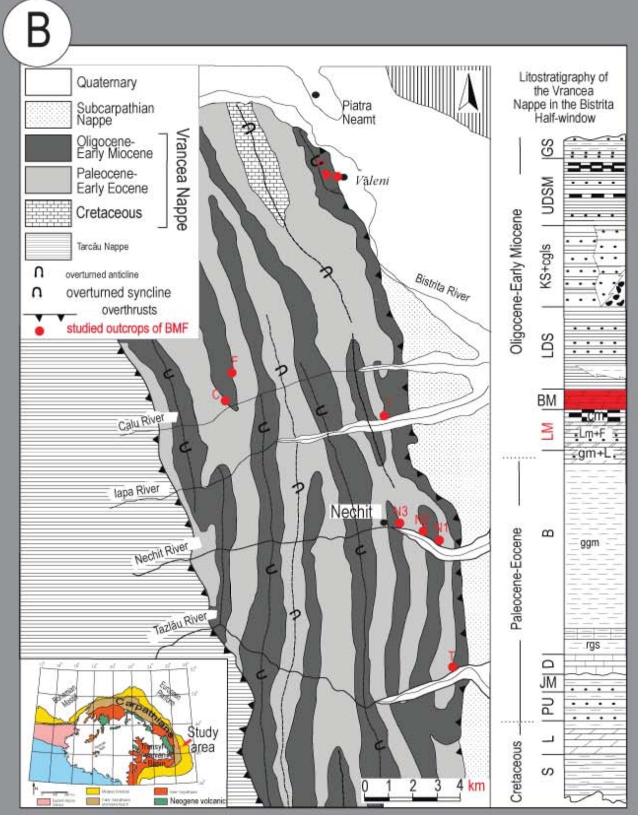
The BMF shows a full suite of traction-produced muddy bedforms that includes cm-scale ripples, dm-scale megaripples, and m-scale mudwaves. The sediment arrived at the seafloor via pelagic settling, was then reworked and transported (as soft rip-up clasts) in bedload. The observed level of bottom current 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 agregated 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 Moldavide 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 fill was detached from its basement and deformed into tectonic nappes (A). The studied area (B) belongs to the most external "Flysch" Nappe (Vrancea Nappe), which accumulated on the cratonic side of the basin (D, right). BMF deposition coincides with the isolation of the Paratethys from the World Ocean (C) in Rupelian times and goes by a variety of names (Bright Marlstone, Dynow Marls) from the Bavarian Alpine Molasse Basin to the Romanian Southeast Carpathians.



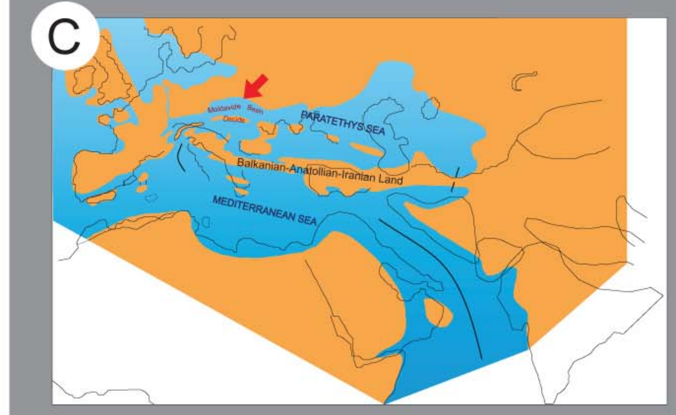
*(A) - Geostructural map of Eastern Carpathians (based on Dumitrescu et al., 1962: Tectonic Map of Romania)*



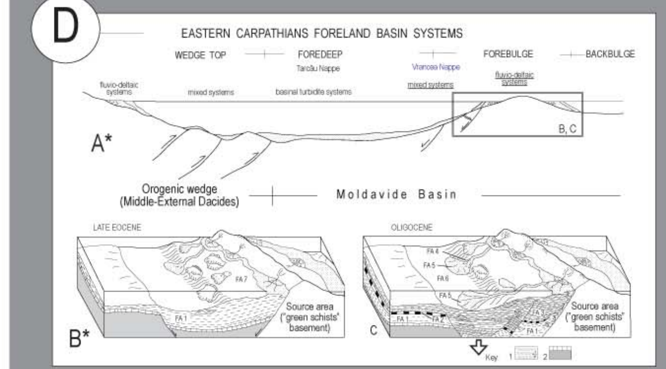
*(B) - Location of study sites on a geostructural detail map of the Bistrita Half-window (based on Micu, 1976, 1987; Grasu et al., 1988). The lithostratigraphic column is shown on the right. S - Sarata Fm, L - Lepsa Fm; PU - Putna Fm; JM - Jgheabu Mare Fm; D - Doamna Fm; B - Bisericani; LMS - Lower Menilite Fm; BM - Bituminous Marls Fm; LDS - Lower Dysodilic Shale Fm; KD+cgls - Kliwa sst with conglomerates, UDSM - Upper Dysodilic Shale and Menilites Fm; GS - Gura Soimului Fm.*

## PALEOGEOGRAPHIC CONTEXT:

(C) the location of the study area within the Tethyan realm. (D) Sedimentation realms in eastern Romania during deposition of the BMF.



*(C) Palaeogeographic context of the sedimentation area of the Oligocene Bituminous Marls Fm (after Rögl, 1998). The red arrow indicates the position of the study area on the cratonic margin of the Moldavide Basin, which is part of the Paratethys Sea.*



*(D) Interpretation of the Vrancea Nappe sedimentation area in the Moldavide Basin (Eastern Carpathians Foreland Basin System). The anomalously large thickness of the BMF and evidence of slumping indicates deposition associated with an active fault system near the external margin of the basin (Miclaus et al., 2009). A* - position of the Vrancea Nappe in the Carpathian Foreland Basin; B* the paleogeographic evolution through time. 1 - deposits of the foreland basin system; 2 - pre-Oligocene deposits; FS 1-7 - Latest Eocene - Oligocene facies associations in the study area; FA3 - Bituminous marls FA.*

## GENERAL INFORMATION ABOUT THE BITUMINOUS MARLS (BMF):

Marker unit that extends from Germany to Romania, of generally acepted Rupelian age (NP23 biozone). Consists mainly of dark brown to brown, variably siliceous (diagenetic silica) marls that weather creamy-white in outcrop. In the Eastern Carpathians the unit thins westward from external (70 m) to internal nappes (2-3 m).

The sedimentary succession that includes the BMF is the most important hydrocarbon source rock in Romania, Ukraine, and Poland. The TOC ranges from 2-20%, average 6%, and the OM is mostly type II, and in places type II-III.

Thoughts on depositional setting have evolved over time. Before the 1950's deposition was supposed to have taken place in shallow marine lagoons (sapropelic muds) during a regression of the sea (Macovei, 1927; Athanasiu et al., 1927; Filipescu, 1933).

After the 1950's the thought was that the BMF was deposited in deep water at the base of a submarine slope and within a deep basin during a highstand (Anastasiu et al., 1994, 1995; Stefanescu et al., 2006) by pelagic of nannoplankton in anoxic waters above the CCD (Anastasiu et al., 2007). A deep water depositional setting was also proposed by Sandulescu and Micu (1989). Badescu (2005) proposed a 400-600 m water depth as likely.

Equivalent units west of the Eastern Carpathians, such as the Heller Meregelkalk in Austria are considered pure nannoplankton ooze deposited on a passive margin slope in an oxygen restricted environment (Wagner, 1998). The basin depth was estimated to be 3000 m at the time of deposition.

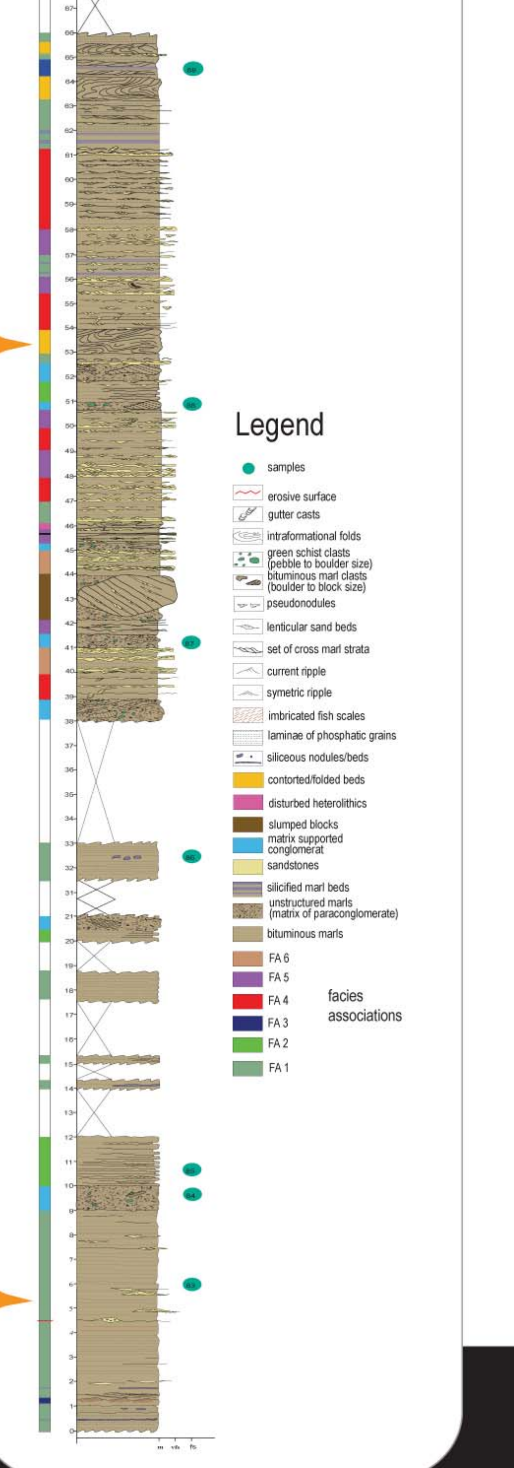
The Heller Mergelkalk in the Bavarian Molasse Basin has been described as a coccolith limestone that was deposited in several hundred meters of water depth in a starved basin (e.g. Zweigel et al., 1998).

In Poland, the Dynow Marl Member (15-20 m) is described as a diagenetically overprinted nannoplankton deposit that was transported via longitudinal weak contour and turbidite currents and sedimented as fine grained contourites and partly as turbidites at the foot of the continental slope in a basin of 1500-2500 m deep. The primary sediments accumulated on the shelf, possibly close to estuaries (brackish-type nanno-fossil association) located at the northern (foreland) margin of the basin (Kotlarczyk, 1985).

*Typical outcrop views of the BMF. Slump fold in the BMF. Folded beds do not show excessive thickness changes at fold noses. This suggests deformation of a stiff sediment, not of a high water content mud.*

*Typical outcrop views of the BMF. Laminated and thinly bedded BMF with wavy sand beds & sand lenses. The latter consist of quartz grains and soft mud rip-up clasts (see next panel) and bear witness to bedload transport during BMF deposition.*

Stratigraphic Column of BMF Tazlau River

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## SEDIMENT INPUT

### *Pelagic Rain*

Coccoliths

Diatoms
mostly dissolved

Fecal Pellets
planktonic

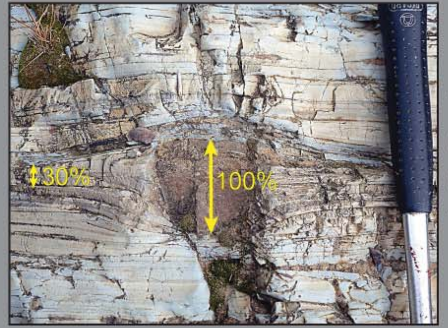
### *Detrital Clastic*

Quartz/Fsp

Clays

MRF's

mid-grade metamorphic source rocks dominate deltaic input, redistribution by bottom currents and gravity flows




"Early" Sediment water-rich differential compaction around gutter casts and sand ripples suggests ~70-75% water content

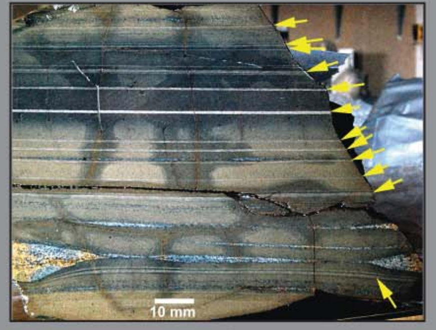
## SEDIMENTARY FEATURES, BOTTOM CURRENTS, REWORKING, BEDLOAD TRANSPORT, and RIPPLES

### *Outcrop View*

*Mud rip-ups are essential for understanding tranport of these muds. These here are large, and rounded by transport. More typical, their size is 0.2-1 mm.*

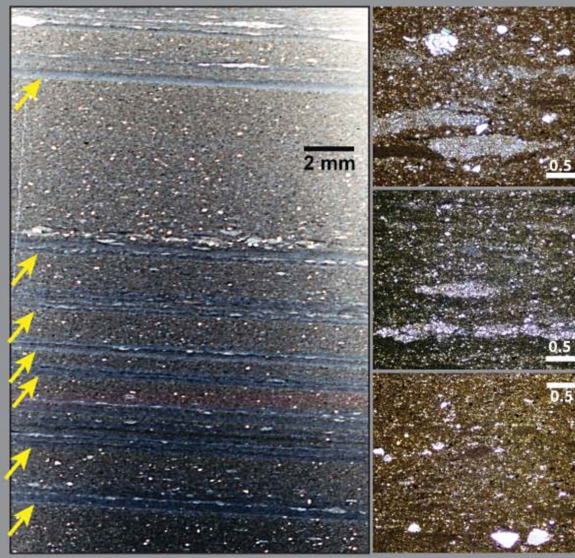
*Sandy current ripples are the other critical element. They consist of a mixture of qtz, fsp, and soft-deformed mud rip-ups (see thin section view at right).*


*Even in absence of sandy ripples, sand grains are common (yellow arrows) at the base of mm-thick mudstone beds. In places they can define low-angle downlapping laminae (red arrows).*



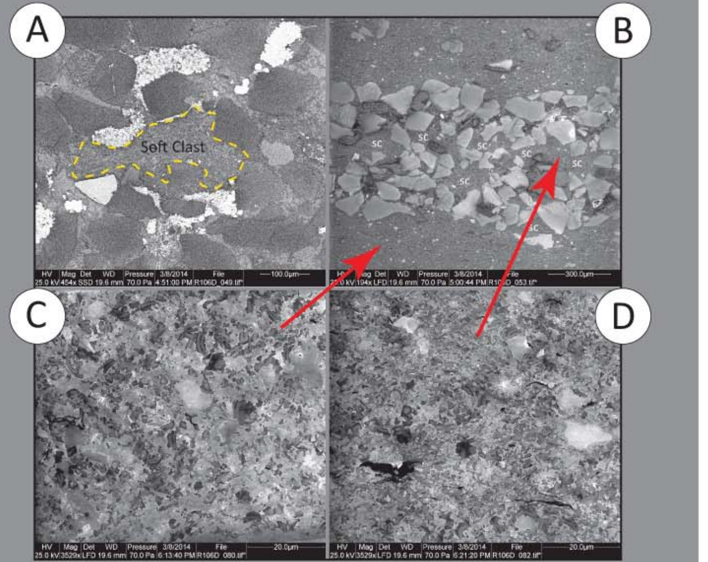

*Laminae consisting of rip-ups and sand grains can be interspersed with lighter laminae that are more carbonate-rich and possibly pelagic (yellow arrows).*

### *Thin Section View*




*Thin sections show distinct carbonate enriched pelagic laminae (yellow arrows) that contrast with mud rip-up and sand grain dominated layers. Enlarged views at right show the flattened and deformed rip-up clasts and the seemingly "suspended" quartz grains. The lenticular fabric suggests erosion and re-deposition of seafloor muds. Panel below shows how this observations relate to experimental work and to other examples in the rock record.*

### *SEM View*

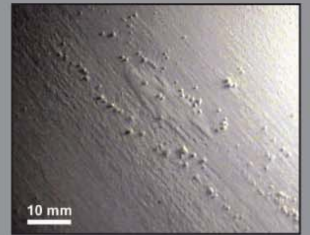



*In the SEM, on argon ion-milled surfaces, we can observe grain relations in detail. (A) shows a soft-deformed mud clast between quartz and other grains. (B) shows the mixing of soft clasts (sc) with sand grains. Image (C) is a close-up view of the fabric of the underlying mudstone, and image (D) shows the fabric of a soft clast. Comparing (C) and (D) strongly suggests that the soft clasts in (A) and (B) were derived by erosion from the underlying substrate.*

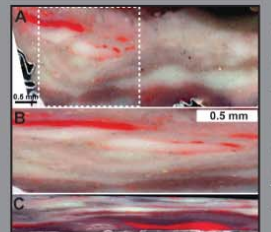
**OUTCROP OBSERVATIONS (RIPPLES, LOW-ANGLE DOWNLAPS) & PETROGRAPHIC RELATIONSHIPS (RIP-UPS, "SUSPENDED" QUARTZ GRAINS) STRONGLY SUGGEST THAT THE BMF WAS LARGELY DEPOSITED IN BEDLOAD FROM MIGRATING RIPPLES. MUD RIP-UPS & QUARTZ GRAINS ARE LIKELY HYDRAULIC EQUIVALENTS. IT IS A MUDSTONE BY COMPOSITION, BUT WAS DEPOSITED AS A "SANDSTONE".**

**COMPOSITION = MUDSTONE, DEPOSITION - JUST LIKE SANDSTONE**

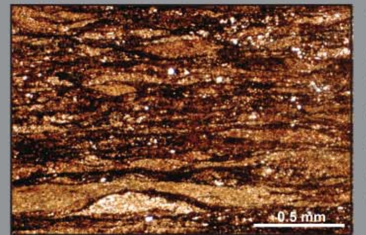
## OTHER EXAMPLES AND EXPERIMENTAL STUDIES OF LENTICULAR MUDSTONE FABRICS




*Experimental erosion of a clay bed (Schieber et al., 2010) produced mm-size rip-up clasts that travelled through the flume channel. The clay bed was water-rich, not unlike the original sediment of the BMF.*

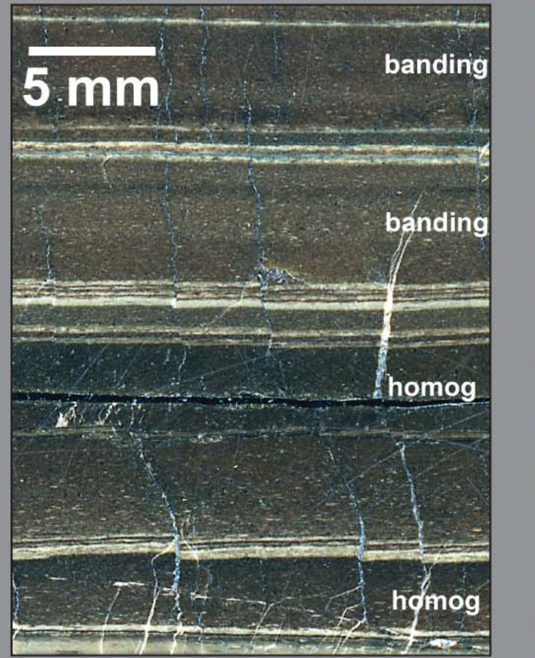


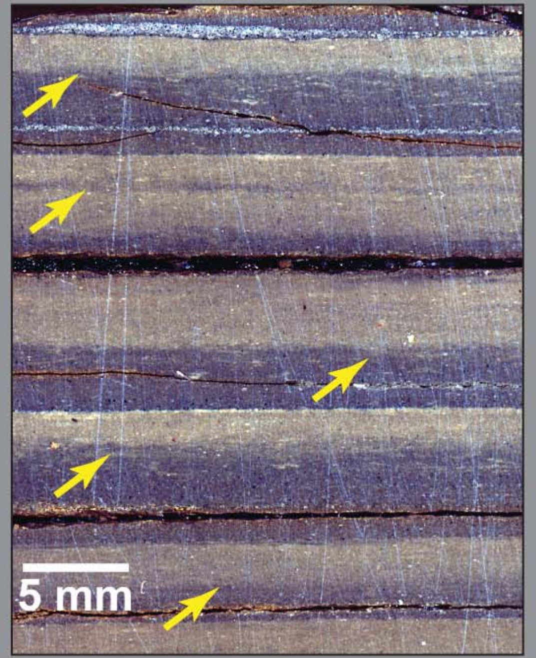

*(A) Capturing these clasts and preserving them with Spurr resin. (B) and (C) shows Photoshop compacted fabrics. The result is a lenticular fabric that resembles that seen in ancient shales.*



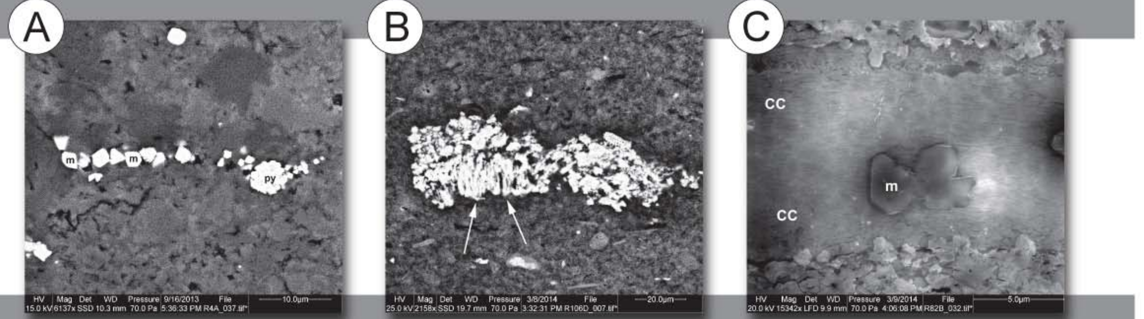

*The experimental fabrics resemble closely lenticular fabrics in ancient shales where it can be demonstrated that the flattened features are indeed mudstone fragments that were eroded from the contemporaneous seabed. By extension, we interpret the lenticular fabrics in the BMF as reflecting erosion of the seabed followed by transport and redeposition of the eroded material.*

## BIOTURBATION AND REDOX STATE




*Detail features within mudstone layers suggest meiofaunal modification (by small worms, nematodes, etc.) of the original sediment. At left, layers dominated by mud clasts and sand grains show "banding" or diffuse boundaries between layers, as well as homogenization. At right, the basal boundaries of dark layers that consist of sand grains and mud rip-ups (see panel to the left) are sharp, whereas their upper boundaries to lighter (carbonate-rich) layers of likely pelagic origin are diffuse (yellow arrows) due to bioturbation by small organisms. This kind of subtle bioturbation has been described from suboxic modern environments (Pike et al., 2001).*




*Marcasite in shales is an indicator that the redox boundary intermittently migrated downwards within the sediment (Schieber, 2011) and that the overlying waters were therefore not anoxic, but at best suboxic. (A) shows marcasite grains (m) next to a pyrite framboid, (B) shows characteristically bladed marcasite (arrows) in an area of replaced fossil debris, and (C) shows marcasite (m) that grew replacively in a calcite (cc) shell.*

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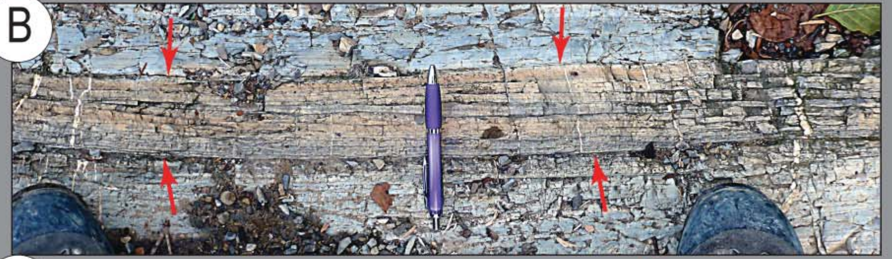
## LARGER- MUDDY MEGARIPPLES

A

B



C

*Within the laminated pelletal shales that are of bedload/small current ripple origin, we find thicker cross-stratified intervals that are 2-12 cm thick and display concave foresets that have dip angles in the 10-15 degree range (in cuts parallel to flowdirection). Yellow arrows in A and B indicate dip direction/angle, and red arrows in C and D mark thickness of bedsets. Assuming an initial water content of 70 vol %, the observed angles translate into foreset slopes in the 30-40 degree range, within the angle of repose range reported for sandstones. It also implies that these bedforms had as much as 40 cm of relief before compaction and qualify as megaripples. Slight oversteepening may reflect cohesiveness of mud aggregates/soft clasts.*

## ANATOMY OF A MUDDY MEGARIPPLE

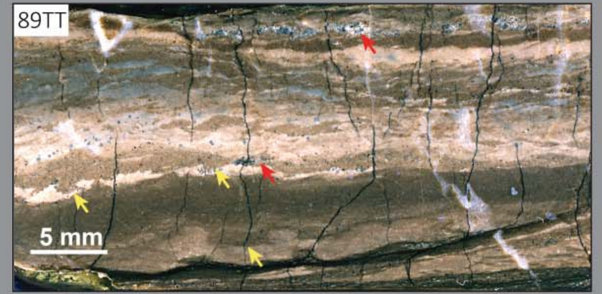
A

B

C


*Given the presence of slumped intervals we wanted to make sure that our perceived megaripples were not simply an artifact that had developed along slide planes. One of the megaripples (see A) was therefore sawed out of the outcrop and stabilized with epoxy and plaster of Paris before removal to the lab. Image (B) above shows this sample, the yellow dashed lines connect reference points between outcrop and sample. Image (C) shows a sawcut surface through the sample and gives a clear view of internal layering. The downlap relations of the foresets are clearly visible, and there is no evidence of any shear relationship between the underlying sediment and the cross-bedded interval. Yellow squares mark locations were samples for microscopic examination were collected.*

89TT




89B

89C

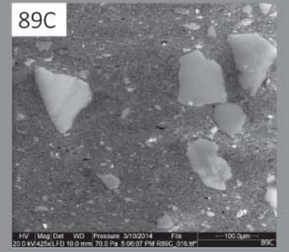


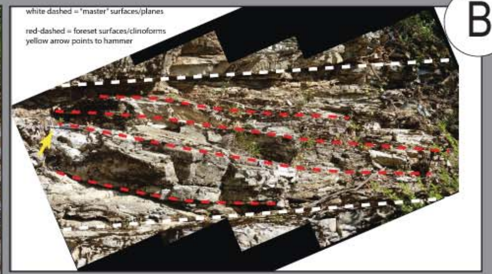
*Image 89TT, thin section view from lower left of (C). Internal layering of same type as in "normal" laminated BMF, with variable amounts of scattered sand (red arrows) suggesting depostion of mixture of soft mud aggregates and sand grains. Water-rich sediment indicated by load casts (yellow arrows).*

*89B and 89C images are from corresponding areas in (C), and show that sand grains are separated by fine ground mass. Like it was explained in the previous panel, these relationships strongly suggest that the sand grains travelled in bedload together with soft mud-rip-up clasts.*

## LARGEST- MUDWAVES

A

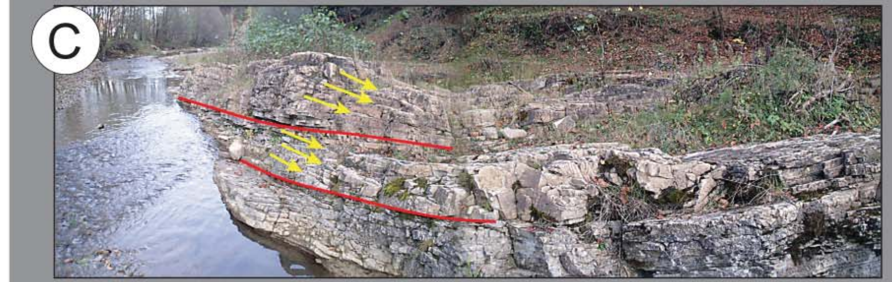
B



*(A) outcrop of BMF with large scale x-bedding. Interval marked with double arrow. (B) Close-up of x-bedded interval that shows foresets and downlapping on common bounding surface. Because there are similar oriented joints in this exposure, the contacts were carefully examined to ensure that the x-beds were genuine.*

*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 the same textures as ripple laminated and megaripple material, with scattered sand grains and soft mud rip-up clasts. The inclination of foresets is in the same range as the megaripples, and when decompacted is at angle of repose for sandstones.*

C



*(C) another example of x-bedded BMF. In this location we see multiple x-bedded intervals. X-beds marked with yellow arrows, basal surfaces marked with red lines.*

D

*(D) a third example of x-beds in the BMF. (D') shows upper set surface with dashed white line, and outlines several foresets with dashed red lines.*

## CONCEPTUAL MODEL

of bedform generation. Because soft mud aggregates tend to deteriorate at shear stresses above 0.2 Pa (~25 cm/sec; Schieber et al., 2010), an increase in flow velocity is not a plausible explanation for size difference (unlike in sandy deposits). The lenght of the flow event can lead to larger and larger bedforms (flume observations in support), as well as the total amount of material that migrated over the bed. In this model, at similar shear and flow velocities, Small Ripples would reflect short lived erosion/transport (days to weeks) and Mudwaves would form when long lived (years to decades) circulation systems are established.


Small Muddy Current Ripples
L=5-60 cm
H=1-6 cm

Large Muddy Current Ripples/ Megaripples (sensu Reineck)
L=0.6-30 m; H=0.06-1.5 m

Mudwaves
L=30-1000 m; H=1.5-15 m

## 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 (mud clasts) and the duration of current events. It does not reflect significant differences in flow velocity.

Subtle bioturbation by meiofauna and the presence of marcasite in these sediments suggest suboxic bottom waters at the time of deposition. The abundance of current activity suggested by these sediments probably was an additional factor that limited bioturbation.

In spite of its likely distal and relatively deep depositional setting, the sedimentary record of the BMF is discontinuous and characterized by intermittent erosion

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