Journal of Sedimentary Research

Journal of Sedimentary Research, 2014, v. 84, 837–838
Discussion
DOI: http://dx.doi.org/10.2110/jsr.2014.73

# TRACES IN THE DARK—SEDIMENTARY PROCESSES AND FACIES GRADIENTS IN THE UPPER DEVONIAN–LOWER MISSISSIPPIAN UPPER SHALE MEMBER OF THE BAKKEN FORMATION, WILLISTON BASIN, NORTH DAKOTA, U.S.A.—DISCUSSION

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I would like to comment on a recent paper by Egenhoff and Fishman (2013) that discusses observations made on cores of the Bakken Shale and presents a methodology to examine and describe these cores. In this contribution I would like to discuss some of their observations and conclusions related to perceived bioturbation features. The authors very eloquently came up with an attractive title for their paper "Traces in the Dark," and it is this darkness that I would like to shine some light on. Some of the burrows that are shown, like the burrow tubes with contrasting fill in their figure 4, are rather clear, and there is no disagreement. Others, like those in their figure 5, may just as well be cross sections of pellets, and probably a thin section parallel to bedding would be required to sort out their actual origin (e.g., Macquaker et al. 2010). The aspects that I found the most troubling are shown in their figure 6 (A and B), where a laminated black shale is shown on which the authors drew white lines to highlight what they interpret to be burrows that penetrate this laminated shale.

And there is the rub: without these white lines I would never have been able to "see" these "burrows," and I have seen plenty of subtle bioturbation in shales before (e.g., Schieber 2003). Having worked on Devonian black shales for two decades, I actually have hundreds of thin sections like this one in my collection. The silt laminae in sections from my collection, especially if only a few grains thick, show gaps and discontinuities in the ten to hundred micron range quite commonly, but I personally would not interpret these gaps in terms of burrows. I have three arguments to present that suggest that the authors overinterpreted in this case. Their perceived burrows are in essence darker features (interpreted as burrows) where coarser silt appears to be "missing," and something like that can for example be a simple artifact of thin-section preparation. Especially in the rather thick and opaque section shown by the authors, subtle damages to the surface of the section, such as grain plucking while smoothing the surface, can in my experience produce features like the ones shown by the authors. On the side of the section that is glued to the glass slide, air-bubble trails or release and coalescing of bitumen (this is, after all, an oil-producing shale) while the slide is cured on a hot plate, can also produce wavy-linear features that affect light transmission and may be misinterpreted as burrows. In my experience it is very helpful in those instances to make a double polished thin section that has been thinned down to as little as 10 microns so that one can recognize artifacts more easily.

But let's for a moment presume that the slides were prepared perfectly and that there are no artifacts. Would burrows make sense in that case? Whereas it is a permissible initial assumption that a discontinuous silt lamina had to suffer disruption by some agent, flume work on mud deposition suggests an alternative. In flume experiments, laminae like those shown in figure 6 (A and B) by the authors are easily produced as muddy suspensions travel across the bed at velocities and shear stresses that are competent to produce ripples in sand (Schieber et al. 2007, 2009, 2013). In these experiments, flocculated mud travels in bedload and forms ripples, and as these ripples migrate over the sediment surface they leave behind a thin veneer of sediment that in essence consists of the toe portions of ripple foresets. As can be seen in images from experiments (e.g., Schieber 2011), the foreset composition can be quite variable due to subtle sorting effects, and the veneer of sediment that is left behind can thus be equally variable laterally. Furthermore, if silt laminae, whether due to ripple migration or to simple winnowing, are only a few grains thick it is easy to imagine that they can develop "holes" if a current that is competent to move sand ripples (Schieber et al. 2007) moves over them. Based on these observations I do not see any need to explain minor discontinuities in silt laminae by the activity of burrowing organisms.

We can also look at the "burrows" from a perspective of where the producers (of the burrows) must have lived and what the sediment must have been like when they did. The burrows outlined by the authors in their figure 6 generally are vertical to subvertical. Given the sizes depicted by the authors, they should have been nematodes or some similar meiofauna, and these creatures typically live in the uppermost millimeters to centimeters of the sediment, depending on the location of the redox boundary (e.g., Cullen 1973; Bernhard and Buck 2004). Surficial muds typically are 80–90% water at the modern seabed (e.g., Schimmelmann et al. 1990; Bennett et al. 1991), and therefore nematodes and other meiofauna in modern sediments tend not to make burrows but rather displace grains and cause a subtle fabric disturbance that does not overtly destroy sediment lamination. Also, due to the high water content (soupground) of surficial muds burrows are difficult to maintain unless stabilized by mucus segregations. Because the latter are biodegradable it is still highly unlikely that even that type of soupground "burrow" has much likelihood to become part of the rock record. Nematode burrows in surficial (uppermost millimeters) muds have been reported as well as pictured from modern environments (Pike et al. 2001), and given that the sediments that they were found in contain on the order of 90–95 vol% water (Schimmelmann et al. 1990), it is instructive to imagine what these burrows would look like once the sediment has been fully compacted (Fig. 1).

In these images (Fig. 1) it is rather clear that subvertical burrows are compressed into the near horizontal, and that vertical burrows are so severely foreshortened as to become nearly unrecognizable. That these burrows in Santa Barbra Basin sediments are visible at all is due to the fact that the infill of the burrows strongly contrasts in color (Fig. 1). Had that not been the case they would not have been recognizable in these modern sediments even prior to compaction. They certainly would not

Published Online: October 2014
 1527-1404/14/084-837/$03.00

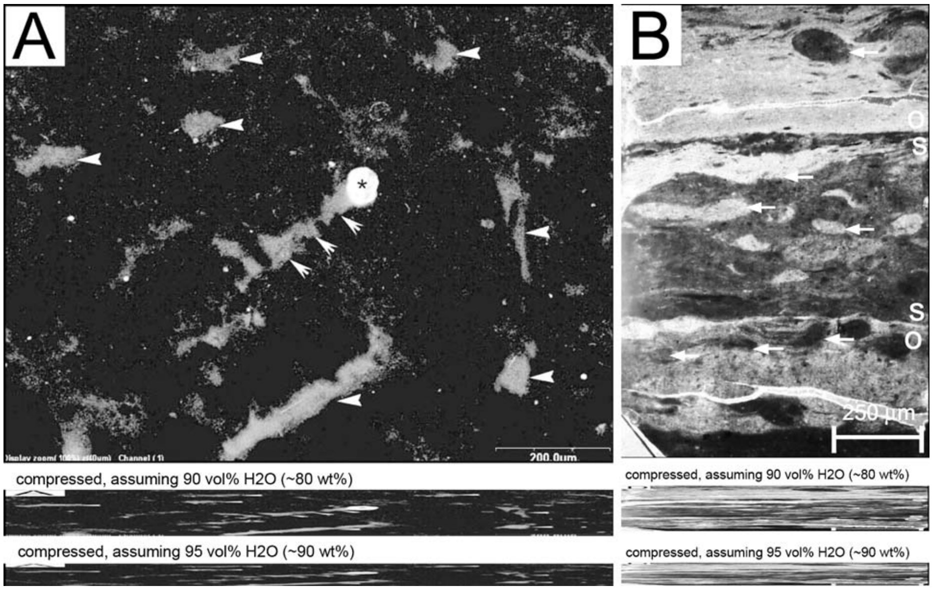


FIG. 1.—**A**, **B)** The top row of images show nematode traces in epoxy-impregnated surface sediments of the Santa Barbara Basin (from Pike et al. 2001). The bottom two rows show the same images after they have been shortened vertically to simulate compaction by 90 and 95% (Lobza and Schieber 1999). The latter is the range of water content of these sediments (e.g., Schimmelmann et al. 1990; recalculated from wt % to vol %).

look like those depicted in figure 6 of the paper by the authors. Their tracings of perceived burrows resemble those that nematodes might make in uncompacted sediments with high initial water content (Pike et al. 2001), but after compaction they could not possibly retain that shape. That these constraints were not considered by the authors indicates that they did not avail themselves of the literature on modern sediments that is quite instructive on the likely impact of meiofauna on the fabrics of freshly deposited muds (e.g., Cullen 1973; Riemann and Schrage 1978; Pike et al. 2001). Given how strongly geometric relations of initial mud fabrics change as compaction proceeds and mud turns into rock, the flawed interpretations presented here highlight the fact that one is indeed ill advised to interpret ancient rocks in isolation. One should always do so with a full understanding of the insights conveyed by research on modern systems, because the present still is a very valuable key to the past and its lessons are ignored at one's own peril. For mudstones probably more so than for sandstones, modern analogs are highly relevant and even indispensable for the interpretation of the rock record.

For the reasons discussed above, I have to conclude that it is doubtful that the "Traces in the Dark" that were heading up the title of the paper are actual relicts of bioturbation. They could simply be artifacts of thin-section preparation, features like it are a plausible by-product of bedload transport processes, and they seem highly unlikely in the context of bioturbation studies on modern muds. In view of all this, and in absence of experimental work to the contrary, I would strongly recommend that the conclusions and interpretations put forth by Egenhoff and Fishman (2013) should not be adopted uncritically by those that work on fine-grained sediments.

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Received 21 February 2014; accepted 26 August 2014.