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Experimental testing of the transport-durability of shale lithics and its implications for interpreting the rock record

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ABSTRACT

Detailed petrographic studies of shales show that they consist of a wide range of components, including a wide spectrum of composite particles that were contributed to the precursor muds in the form of high-water-content suspended floccules, bedload floccules, rip-up intraclasts, pedogenic aggregates, and fully lithified shale clasts. Experimental studies show that shale clasts of sand to silt size (shale lithics) can survive hundreds to thousands of kilometers of bedload transport. Observations of modern river and shelf muds reveal the common presence of shale lithics in these sediments, and suggest that a significant portion of ancient shale formations could potentially consist of reworked shale lithics and not, as commonly assumed, of primary composite particles such as clay floccules and organo-minerallic aggregates. Identification of shale lithics in the rock record presents challenges, but careful petrographic examination (using SEM and ion-milled samples) and case studies will help to develop robust criteria for recognition.

The presented observations have manifold implications for the interpretation of many aspects of shales: mud transport and accumulation, sediment compaction and basin-fill modeling, and geochemical proxies. They emphasize the essential need for petrographic examination of shale samples before more advanced analyses are undertaken.

1. Introduction

The purpose of this study is to evaluate how far shale lithics might travel before they disintegrate, and what their potential contribution to fine-grained successions in the rock record might be. Muds are a very common sediment on the earth surface (Potter et al., 2005) and the precursors of fine grained clastic sedimentary rocks that are commonly known as shales or mudstones (I will use the widely used term shale for the remainder of this article). Shales constitute approximately 2/3's of the sedimentary rock record (Potter et al., 2005) and their constituents are derived from weathering and erosion of the landmasses and transported to the ocean basins by river systems that drain the continents. It is generally thought that the main source of mud constituents are soils where the underlying bedrock has been weathered to a mixture of resistant minerals (quartz, feldspar, etc.), clay minerals, and colloids (submicron size particles). Soil erosion delivers small mineral fragments (<62.5 μm), clay minerals, and colloids to rivers where, due to their small size, they travel in turbulent suspension until they are deposited in lakes and ocean basins (Potter et al., 2005).

Thus, when considering the origin of these rocks, the general assumption is that their constituents arrived at their site of deposition in finely dispersed form, and then were deposited through a combination of gravitational settling and flocculation (from river plumes), redistributed across basin floors by waves and currents (Schieber, 2011), and followed gravitational forces on slopes in the form of liquid muds and mudflows (Potter et al., 2005). Yet, whereas this is the common perception, recent studies of the rock record show instances where fine grained sedimentary successions appear to contain a significant amount of silt size particles that originated through the weathering and erosion of shale outcrops (Plint et al., 2012; Schieber and Bennett, 2013; Plint, 2014; Schieber, 2015). Pieces of other rocks that have been broken down to sand and silt size sedimentary particles have previously been described as "lithics" (Pettijohn, 1954; Williams et al., 1954; Dickinson, 1970), and the particles discussed in this paper are therefore referred to as shale lithics.

Internally, shale lithics are similarly fine-grained as the clays and silt grains (quartz, feldspar) they are deposited together with (Fig. 1). Thus, once a mud with shale lithics has been compacted, the lithics themselves could easily blend in with the clay rich rock matrix. It is therefore plausible to envision a rock that originated as a deposit dominated by sand-size shale lithics, yet would be classified as a shale when encountered in outcrop or drill core millions of years later. Whereas the original sand-size material was likely deposited by strong currents in bedload (like typical sands), the resulting deposit might be interpreted as a bioturbated shale and the overall environment considered of comparatively low energy. Also, unlike typical surface muds that have a high

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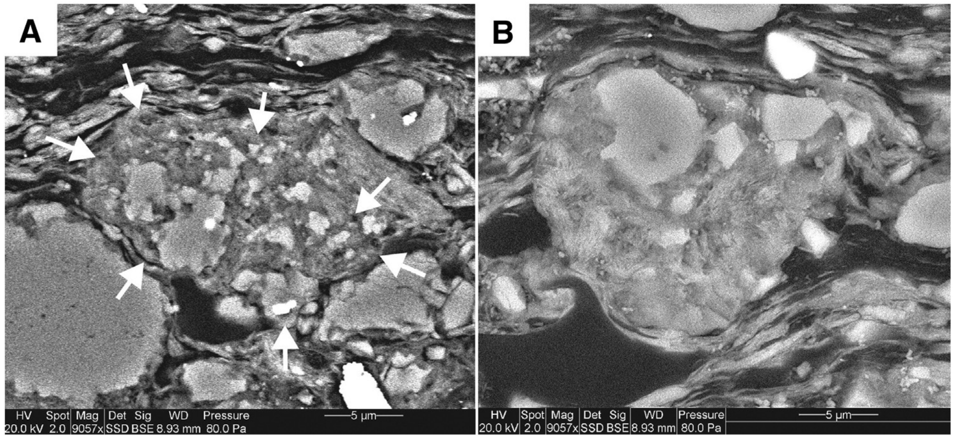

Fig. 1. SEM images (backscatter) of fine grained clasts (shale lithics) in Devonian black shales of the eastern US. (A) Shale clast (marked with arrows) with angular outline in the New Albany Shale of Indiana. Note differential compaction in the surrounding shale matrix. (B) Shale clast with rounded outline from the Chattanooga Shale of Tennessee. Note differential compaction of the surrounding shale matrix. In both cases (A + B) differential compaction indicates that the clasts were solid particles (firm, consolidated) at the time of deposition, and as such are bona fide shale lithics. Given their small size they cannot be detected with a petrographic microscope. A scanning electron microscope (SEM) is needed. In these examples the lithics contrast sufficiently with the matrix to be detectable, but in a matrix with less compositional contrast detection would be more difficult.

initial water content (e.g. Schimmelmann et al., 1990; Bennett et al., 1991) and undergo substantial compaction upon burial (Kominz et al., 2011), shales with abundant shale lithics (with lithics being already fully compacted) would experience much less compaction during burial. Not knowing about the shale lithic component could potentially upset estimates of reconstructed burial depth and lead to strata with “abnormal” thermal maturity that could be of considerable interest in hydrocarbon exploration. Shales with a substantial component of recycled shale lithics may also give erroneous results with regard to geochemical and mineralogical proxies for provenance, environmental parameters, and past climate. The purpose of this study is to evaluate how far shale lithics might travel before they disintegrate, and what their potential contribution to fine-grained successions in the rock record might be.

Shale lithics are composites of smaller mineral grains (clays, quartz, feldspar), and they are just one of a whole spectrum of composite grains that have a part in mud deposition. At the water-rich end of the spectrum are floccules, composite particles that consist of micron size clay minerals and other small particles and are held together by van der Waals forces. These floccules can range in size from a few ten to several hundred microns (Bennett et al., 1991; Schieber, 2011) and have water contents on the order of 85% or more. Organo-minerallic aggregates are common in marine pelagic environments (e.g. Fowler and Knauer, 1986), and depending on size also go by descriptors like “marine snow” (>0.5 mm) and phytodetritus (<0.5 mm). They consist of a mixture of mineral matter, bacteria, microorganisms, fecal pellets, and skeletal debris that is held together by bacterially secreted extracellular polysaccharides. Their water content is similar to that of floccules. Fecal pellets are produced by animals in the water column and within the sediment, can consist of a mixture of organic materials (shell fragments, tissue debris, etc.) and sediment grains (silt, clay etc.), and typically range in size from several ten to several hundred microns (Flügel, 2004). Their water content is lower than that of floccules (~70–75 %) but still rather high. Mud intraclasts, produced from erosion of surficial muds, are irregular shaped to rounded and their size ranges from silt grade (10's of microns) to several centimeters (Schieber et al., 2010). Depending on how deep erosive events remove the substrate, the water content of eroded mud intraclasts can be as high as 85%, although clasts with lower water contents are generally less likely to disaggregate in transport (Schieber et al., 2010). Pedogenic aggregates (Rust and Nanson, 1989; Wright and Marriott, 2007), and reworked alluvial mud crusts (Nanson et al., 1986) have still lower water contents, generally in the 30 to 40% range (Peverill et al., 1999), and are variably shaped particles that range from sub-mm to cm's in size. Composite grains of this origin occur in modern surface environments in association with soil forming processes and desiccation on floodplains (e.g. Nanson et al., 1986; Rust and Nanson, 1989; Wright and Marriott, 2007), and when transported these grains give rise to bedload transported mudstone intervals in fluvial successions (e.g. Wright and Marriott, 2007). These soil and floodplain derived composite grains are rather friable and flume studies suggest that they are not durable enough to survive long-distance transport (Smith, 1972; Maroulis and Nanson, 1996) beyond a few kilometers downstream distance. Shale lithics, solid pieces of fully consolidated rock, form the other (low water content) end of the spectrum. They are derived from weathering of shale outcrops, range in size from microns to mm's, and have low water contents (typically less than 5%).

Water content determines the degree of “flattening” that these particles experience as a consequence of compaction. Water-rich types (floccules, organo-minerallic aggregates, fecal pellets) are flattened to a high degree during compaction, may be squeezed and deformed between other grains, and in many instances can be difficult to differentiate from the shale matrix. The same is true for high water content intraclasts, unless the clasts differ significantly in texture and composition from the shale matrix. Even the relatively low water content soil aggregates are likely to suffer vertical shortening and deformation once buried. Shale lithics on the other hand, being solid rock already, are not likely to compact, although they may show deformation when squeezed between hard grains (quartz, feldspar, etc.) as shown below in Fig. 9. Once a lithic-rich sediment has again been turned into rock, it may not be readily apparent that it is a collection of shale lithics rather than for example a bioturbated shale.

It is the objective of this paper to show (A) that shale lithics should be a common component of fine grained sedimentary rocks; (B) to quantify their ability to be transported over large distances; and (C) to provide some initial criteria to identify them in the rock record. In addition to earlier mentioned criteria (fabric discordance), recognition may be facilitated when a mixture of shale lithics from multiple sources is deposited in the same bed and provides contrast, or if differential compaction around shale lithics points to their already compacted/lithified nature (Schieber and Bennett, 2013; Schieber, 2015).

2. Methods

Shales vary widely in composition and mechanical strength. In order to understand how far shale lithics can travel at a minimum before they disintegrate, it seemed appropriate to select a shale that is at the low end of the mechanical strength spectrum and weathers quickly. Gray, clay-rich, homogenized shales typically fit those criteria. A sample of readily weathering (pieces can be crumbled between fingers, especially when wet) gray, clay-rich, homogeneous shale was collected from an outcrop of the Silurian Crab Orchard Formation in central Kentucky and crushed to sand size. The resulting material was sieved and 650 g of the 700 to 350 μm size fraction was introduced into a racetrack flume (see Schieber et al., 2007 for details) that was running freshwater at 30 cm/s average velocity (water temperature ~20 °C). This velocity was chosen because it is sufficient to keep the sand size particles moving and because it is above the critical velocity of sedimentation (Schieber et al., 2007) for typical clays. Thus, the particles moving over the bottom of the flume channel were largely silt to sand-size fragments of our starting material. The flume was operated at 30 cm/s continuously for 70 days, and the sediment traveling over the flume bottom was recorded daily with a HD camera in macro mode. Particles visible in HD film frames were measured using the Image-J image analysis software, and statistical parameters (mean grain size, mode, standard deviation) and histograms were produced from these data with Microsoft Excel. In our racetrack flumes sediment can build up in the wall region of the drive section (see Schieber et al., 2007), and therefore those areas were swept clean daily with a sponge. After the first 3 weeks of the experiment some sediment buildup was noted just ahead and underneath the drive belt as well, and from then on the entire width and length of the drive section was swept on a daily basis. The averaged sediment coverage for the entire flume channel was 0.01 g per cm^2, purposely kept low so that particles would move continuously and not be "stored" intermittently in slower moving ripples. The flume was equipped with a Campbell OBS-4 turbidity sensor that was calibrated with powdered (~5–60 μm) shale and set to quantitatively record suspended sediment concentrations for the duration of the experiment.

In addition to recording suspended sediment concentration, samples of bottom sediment were collected weekly with a syringe. In addition, samples of suspended sediment were allowed to settle on glass slides for later examination by optical microscope. At the end of the experiment the final suspension was drained, and the residual bedload material was recovered, weighed, and processed further.

One aliquot of the residual sediment was dried and sieved for sand and silt size fractions. For examination by SEM, subsamples of whole residual (all size fractions), sand fraction, and fines fraction (<62.5 μm) were embedded in Spurr resin. Subsamples of the whole residual and the fines fraction were also placed in a hydraulic press at 12,000 PSI (0.83 kbar), a pressure that approximates a burial depth of 3.2 km, and made into powder pellets. Adding a drop of epoxy to these latter two samples resulted in partially epoxy bonded samples that were easier to prepare for ion milling. A GATAN 600 Duomill was used to prepare large format (up to 12 mm diameter) sections for high resolution SEM examination (Schieber, 2013). The samples were examined without coating in low vacuum with an FEI Quanta 400 FEG.

For comparison purposes, available samples of Monongahela River mud (Morgantown, West Virginia), Ohio River mud (collected near Evansville, IN), Mississippi River mud (collected in New Orleans), overbank mud from a small stream near Hanksville Utah, California shelf mud (collected at 105 m water depth, offshore Santa Barbara), and Santa Barbara Basin mud (collected at ~600 m water depth) were examined for the presence of shale lithics. These samples were wet (water content in excess of 50 vol%) and their water was sequentially exchanged for acetone and then for Spurr resin. They were then cured at 60° C, and finally ion milled for SEM examination. In this contribution the emphasis is on the transport of shale fragments, material that is presumed to have originated from erosion of shale outcrops in the watershed of river systems. Such fragments may be single mineral grains, but most commonly are composites of smaller mineral grains (clays, quartz, feldspar), the shale lithics investigated in this study.

3. Observations from experiment

When the sieved sand-size shale debris was added to the flume at 30 cm/s flow velocity, ripples composed of shale debris formed initially and then disappeared within the first 6 hours as sediment particles were dispersed more evenly throughout the flume channel and suspended sediment concentration rose to 150 mg/l. The bed of the flume was no longer visible through the suspension, but sediment movement over the flume bottom was visible with back lighting. Bedload particles moved at an average velocity of approximately 5 cm/s (Schieber et al., 2010). Over the following 2 days suspended sediment concentration continued to rise (Fig. 2) and then leveled out at approximately 190–200 mg/l. Once the sediment sweep procedure was intensified three weeks into the experiment, the suspended sediment concentration rose to approximately 280 mg/l and leveled out at that value (Fig. 2).

Although the initially added shale debris was dominantly 0.5 to 0.7 mm in size, these particles were reduced in size during bedload transport over the 70 day duration of the experiment (Fig. 3), and 26.5% of the dry residue now consisted of silt size particles (<62.5 μm). The rounding of sand size shale lithics increased notably in the course of the experiment (Fig. 3).

Weekly collected sediment samples showed that abundant sand size shale particles (lithics) continued to travel across the flume bottom. HD film clips showed a strong increase in the abundance of silt size particles in the first week of the experiment (Fig. 4), as well as distinct rounding of sand size particles (Fig. 3). It should be noted that disintegration of a single sand size shale lithic of 500 microns diameter could for example produce as many as 1000 silt size lithics of 50 micron diameter. Thus, disintegration of even a small fraction of the original sand size shale lithics is liable to produce an enormous number silt size particles, explaining the preponderance of silt size grains in Fig. 4, even though on a by weight basis the sand size particles clearly dominate through the end of the experiment (Fig. 3).

Microscopic examination of suspended sediment that was collected from the flume channel via syringe and settled on glass slides shows that suspended sediment particles range in size from a few microns to as much as 250 micrometers (Fig. 5). The size range of suspended sediment particles did not change noticeably in the course of the experiment.

Sieving the residual sediment that was recovered from the flume showed 74 wt% sand size shale lithics, and a mixture (26 wt%) of silt size grains (Fig. 3). SEM image analysis of epoxy embedded and ion milled samples (Fig. 6) showed that the silt fraction consists to 70% of

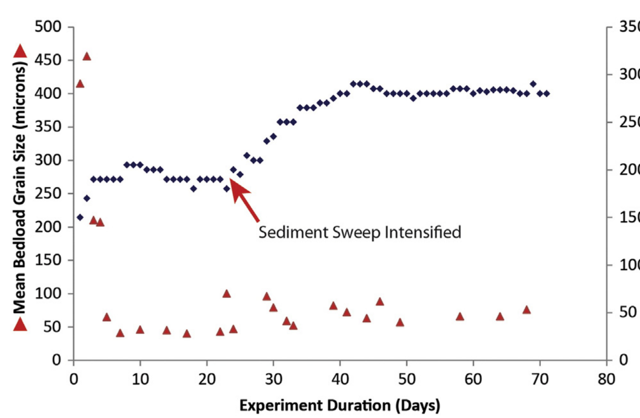

Fig. 2. Change of mean bedload grain size and suspended sediment load over the course of the experiment. Mean grain size was determined from image analysis of HD video frames, and suspended sediment concentration was measured with an OBS (optical backscatter) sensor. Suspended sediment concentration rises after week three because of more aggressive sweeping of sediment from the drive section of the flume. The variability of the mean bedload grain size after week 1 reflects variability in the day to day effectiveness of sweeping accumulating sediment from the drive section.

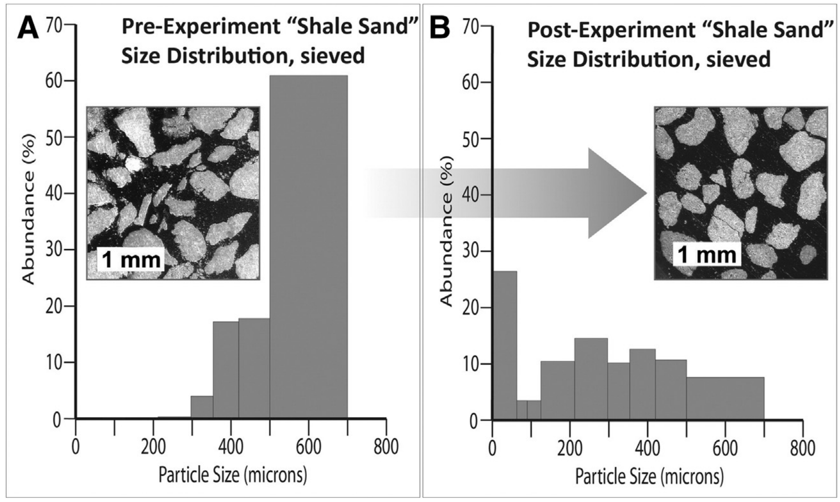

Fig. 3. Sieve data that show the size distribution of shale lithics at start and finish of flume run. (A) Before the experiment most grains are 0.5 to 0.7 mm in size and angular. (B) After the experiment the size distribution is much broader and silt grains are most numerous (although sand grains still dominate by weight). These are sieve data from dry starting materials and residual sediment.

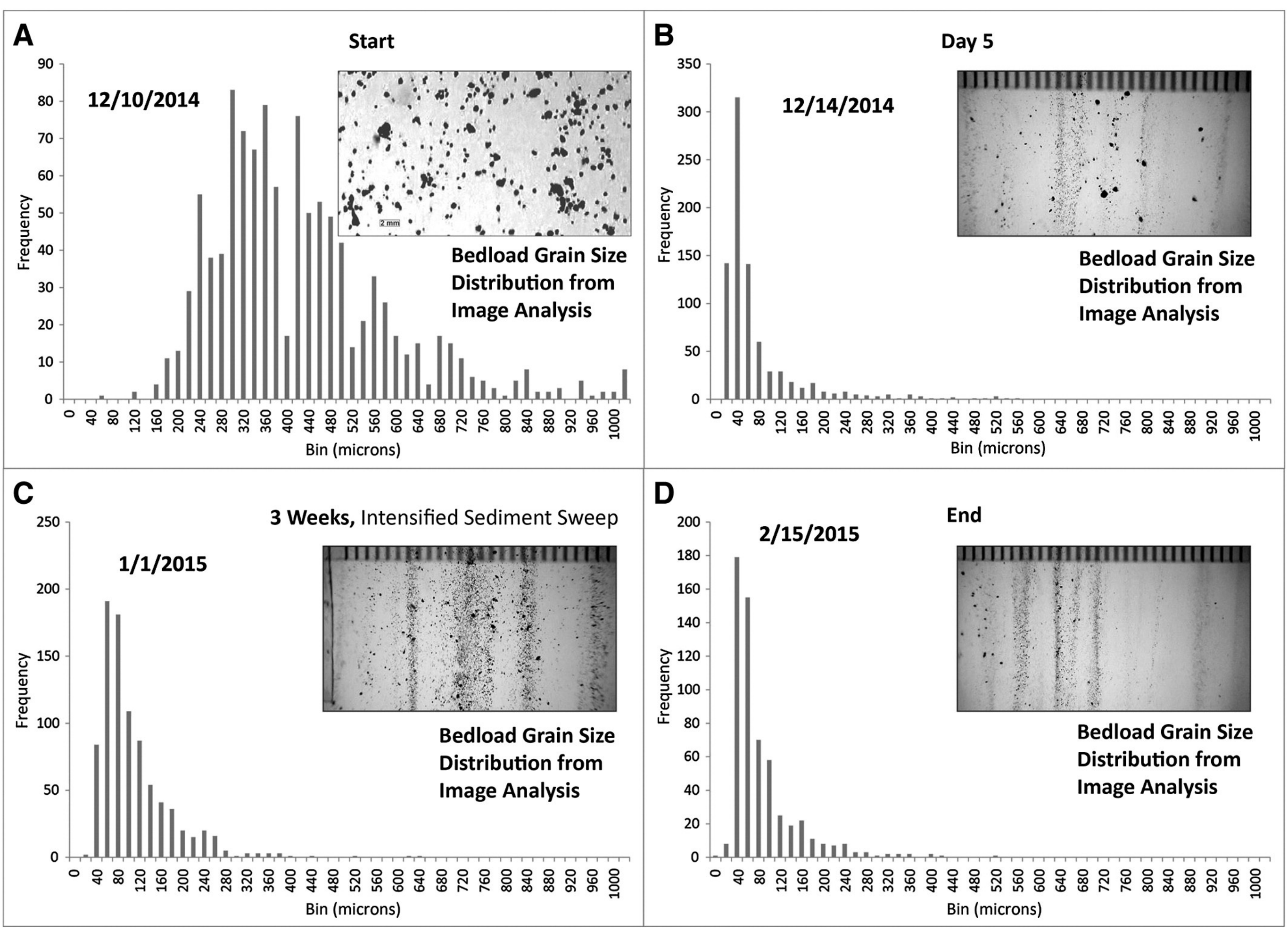

Fig. 4. Comparing grain size distribution by sieving with visual tracking of sediment movement by HD camera in macro-mode. (A) Within a few hours of flume transport, the majority of grains are smaller than 500 μm. Grains in excess of the 700 μm sieve size are "splinters" that got through the sieve lengthwise. (B) After 5 days the bedload sediment is dominated (in numbers of grains, though not in volume) by silt (<62.5 μm) to very fine sand size (<125 μm) particles. (C) In a snapshot after 3 weeks, the dominant bedload sediment grain size has temporarily expanded to include fine sand size (<250 μm) particles, mainly because of more thorough sweeping of the drive section of the flume channel. (D) Until the end of the experiment the bedload sediment remained dominated by silt to very fine sand size particles.

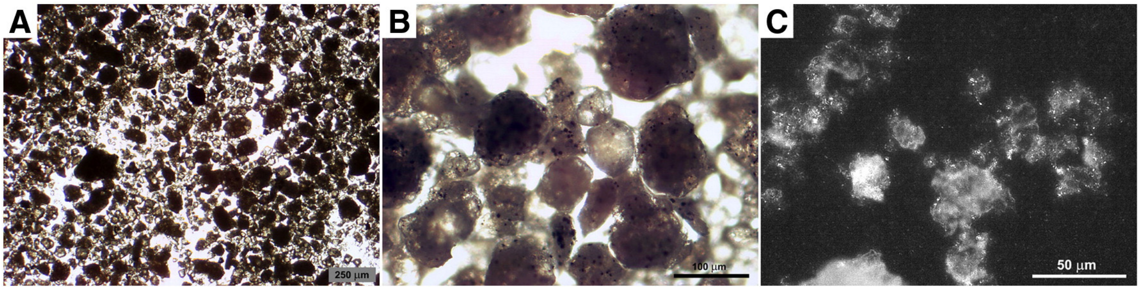

Fig. 5. Petrographic microscope images of shale debris that traveled in suspension load. (A) Grains settled onto glass slide from syringe sample taking from middle of turbulent flow. Suspended grain sizes range to fine sand. (B) Closer view of same sample. Tiny black spots within shale particles are probably pyrite. Note rounding of grains. (C) Example of finer suspended load particles (x-polarized light). Finer grains are generally more angular.

recognizable shale lithics and to 30% of single mineral grains (quartz, feldspar, clay flakes, etc.). The water content of the residual sediment was 50 vol%.

4. Observations from natural sediments

When trying to gauge the significance of these observations, the most obvious question is whether shale lithics, as proposed above, also occur in modern rivers and shelf environments. To that purpose Spurr embedded ion milled sections of modern sediments from a small stream in the Mancos Shale badlands of SW Utah, the Monongahela River at Morgantown, West Virginia, the Ohio River near Mt. Vernon, Indiana, the Mississippi in New Orleans, the California shelf offshore Santa Barbara (105 m water depth), and from the Santa Barbara Basin (~600 m water depth) were examined under the SEM (Fig. 7). All samples contain silt to sand size shale lithics, with the sample from Utah (Fig. 7A) being in effect a shale sandstone, the sample from West Virginia (Fig. 7B) a mud with abundant shale lithics (>50%), and the remaining samples containing 10–20% shale lithics.

Because these modern mud samples have as much as 80% porosity that is filled with epoxy, it is comparatively easy to identify shale lithics within them. However, once any of these muds have been compacted and lithified this task can be quite a bit more challenging, and minute textural details may be the only indication that the sediment in question contains shale lithics.

5. Coming full circle

To better understand how easy or how difficult it might be to detect whether an ancient mudstone is composed of an abundance of shale lithics, samples of post-experiment material were compacted at 0.83 kbar (12,000 PSI), a pressure that approximates a burial depth of 3.2 km. As can be seen in Fig. 8, the textures of ion milled surfaces of the resulting powder pellets (Fig. 8B), examined under the SEM, are not significantly different from the original source shale (Fig. 8A) and could easily pass as rather unremarkable images of a poorly ordered or bioturbated shale (O'Brien, 1987). The powder pellet, due to relaxation after the pressure is removed, does show fine gaps between particles by the time ion milling is completed (Fig. 8C), but had the sample been buried for multiple millions of years these gaps would not exist and would not betray the "artificial" nature of the sample.

6. Discussion and conclusion

6.1. Transport of shale lithics

The focus of this flume study is an evaluation of the transport durability of shale lithics and their potential to contribute to fine-grained successions in the rock record. Given an average bedload travel velocity of 5 cm/s, the bedload transported shale lithics traveled approximately 300 km over a 70 day duration. The suspended load, traveling at an average velocity of 30 cm/s, traversed a distance of approximately 1800 km during the same time interval. Most of the breakdown of sand-size particles to silt grade occurred in the first week of the experiment (Fig. 2) and suspended sediment concentration stabilized halfway through the experiment (Fig. 2). Given that even fine sand size particles traveled at least part of the time in suspension (Fig. 5), observing that most particle breakdown occurred early on in the experiment, and finding that after 70 days more than 90% of the particles could still be identified as shale fragments, suggest that even after an entire year of transport plenty of sand and silt size shale lithics would have been present. With that perspective, and fully acknowledging that most sedimentary particles in nature do not travel continuously, it is nonetheless quite reasonable to expect that silt and sand size shale lithics can survive long distances of river transport, as well as further transport in shelf seas and even into deep sea environments.

This experiment based prediction is validated by the observation of clearly identifiable shale lithics in multiple modern river muds, California shelf mud, and even in deep sea mud (Fig. 7). These examples are clear evidence that shale lithics can indeed survive transport distances on

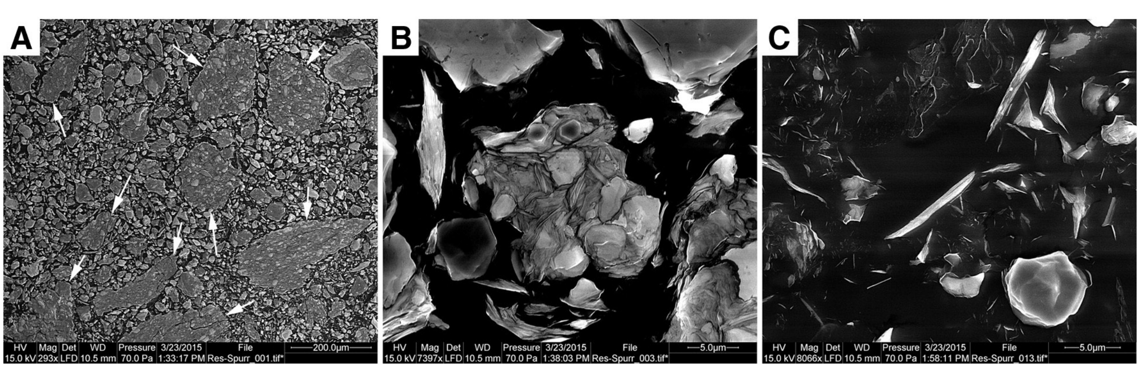

Fig. 6. SEM images of residual sediment from experiments in epoxy resin. (A) At low magnification sand size shale lithics (arrows) are visible in a matrix of silt and epoxy. (B) Clearly identifiable silt size shale lithic in center. Even shale fragments as small as 10 microns are still resolvable as such. (C) Single mineral grains, variably sized clay flakes and quartz grains.

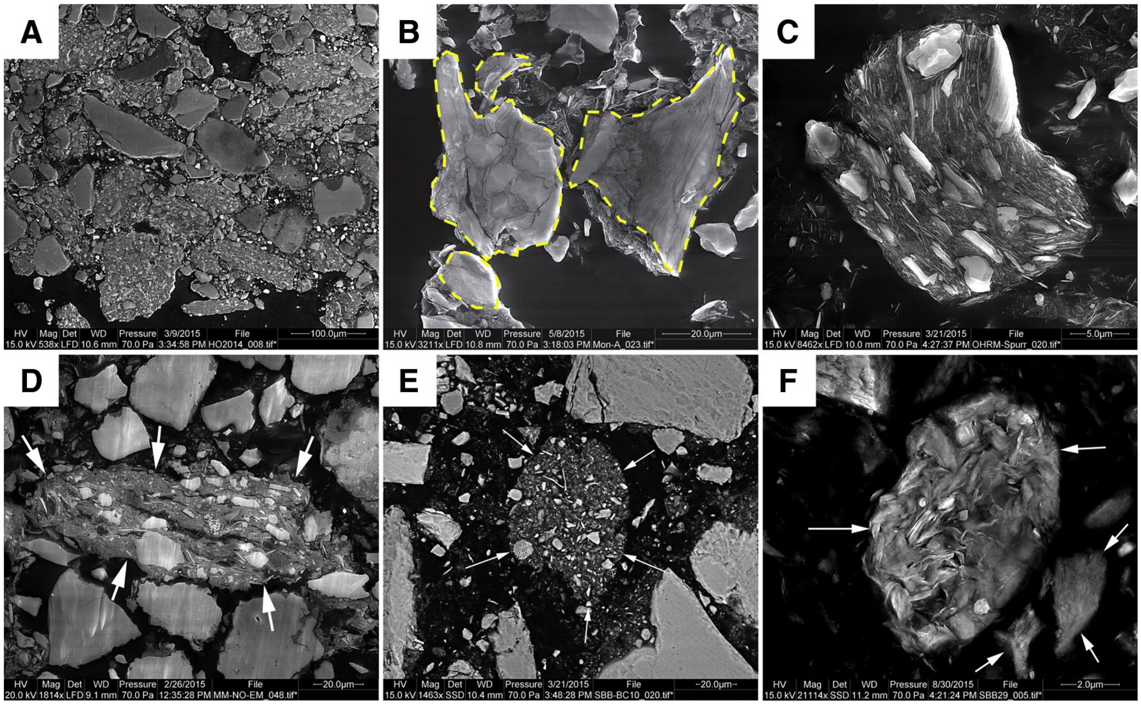

Fig. 7. (A–E) SEM images of shale lithics in modern sediments (E and F are backscatter electron images, all others are secondary electron images). (A) Abundant sand and silt sized shale clasts in a river "mud" from SW Utah. Compared to Fig. 5A from experimental sediments, and note rounding of sand size shale lithics. (B) Mud from the Monongahela River. Shale lithics are marked with yellow dashed lines. The remaining particles are single mineral grains that shriveled together as the mud partially dried prior to collection. Black areas filled with epoxy resin. (C) Shale lithic from the Ohio River. Note rounded outline and aligned clay platelets. (D) Shale lithic from Mississippi River (white arrows). Also shows rounding and alignment of clay particles. (E) Rounded shale lithic in California shelf mud (white arrows). The clast is surrounded with a lower density mixture of small particles (the mud matrix that gives the sample its cohesiveness) and epoxy. (F) Rounded shale lithic (arrows) from the modern muds of the Santa Barbara Basin. The irregular particles in the lower right corner of the image (arrows) are fine grained, and may be shale lithics as well. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the order of thousands of kilometers. Their presence in modern shelf and deep sea muds suggests furthermore that shelf processes as well as deep sea circulation are liable to transport and disperse shale lithics over even larger distances. This apparent common occurrence of shale lithics in modern muds should not be entirely surprising, however, given that most of the continents are covered with sedimentary rocks and a sedimentary rock record that is dominated by shales (e.g. Potter et al., 2005).

6.2. Recognition in the rock record

As Fig. 8 indicates, recognizing shale lithics in consolidated rocks has the potential to be a rather challenging task, and it is likely that multiple detailed case studies are needed to develop widely useable procedures and criteria for their reliable recognition. Probably the fully compacted nature of shale lithics is one of their most helpful properties in that regard. Whereas all other potential aggregates due to their water contents are liable to suffer various degrees of vertical shortening and deformation (Fig. 9), fully consolidated shale lithics will not compact further. Thus, if enclosed in a matrix of water-rich mud they will show differential compaction and laminae wrapping around the "hard" grain (Schieber and Bennett, 2013; Schieber, 2015; Figs. 1, 9), and if occurring in a silt or sand bed they will act as a "supporting" grain instead of collapsing between hard quartz grains (Fig. 9). Given that consolidated shales are softer than typical sands grains (quartz etc.) there is a chance that such supporting shale clasts show indentations and some squeezing and deformation by harder grains (Fig. 9). Shale lithics, coming from a faraway source, are also likely to have textural and compositional attributes that allow differentiation from the enclosing shale matrix. Depending of the orientation of shale lithics, their internal fabric may also show noticeable fabric discordance

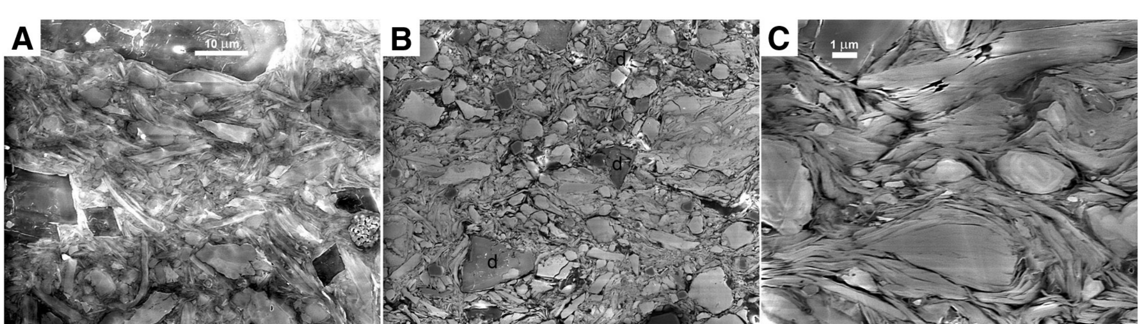

Fig. 8. Comparing compressed sediment collected at end of experiment with fabric of original Crab Orchard Shale. (A) Fabric overview of a sample of Crab Orchard Shale. Dark rhombs are diagenetic dolomite grains. (B) Fabric of dried and compressed (12,000 PSI) sediment collected at end of experiment. Dolomite grains marked with "d". Even though dolomite grains have been transported for as long as 70 days, they show no evidence of either abrasion or dissolution. (C) Closer view of fabric of compressed powder pellet. All images are secondary electron SEM images.

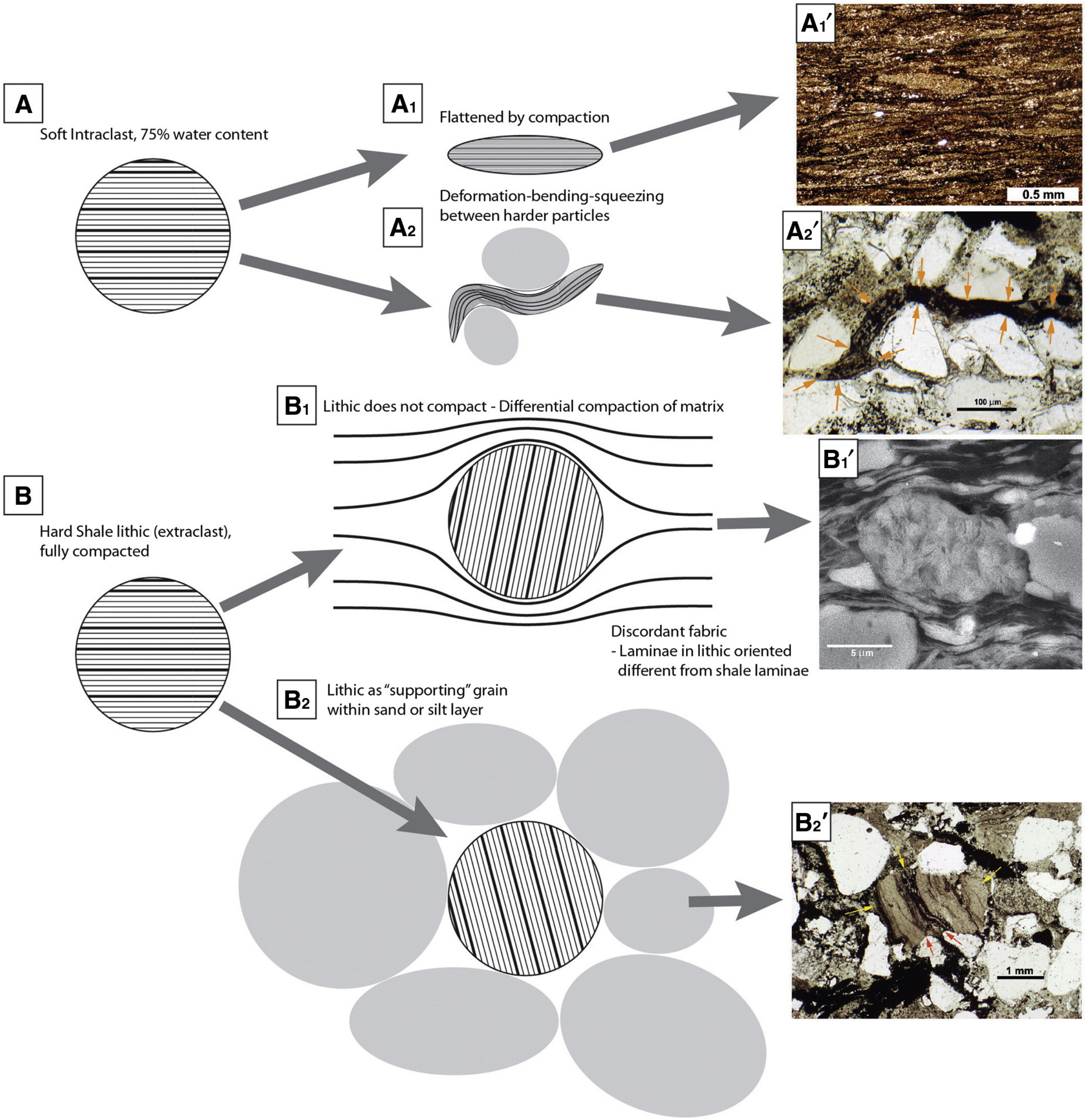

Fig. 9. Conceptual view of shale lithic recognition and rock record examples. (A) Soft, water-rich intraclasts are flattened (A_1) and when abundant may lead to lenticular fabric in the rock record (A_1'; Schieber et al., 2010). They can also show bending and squeezing between compaction resistant (hard) particles (A_2 and A_2'). Orange arrows in A_2' point to deformed intraclast. (B) Shale lithics, because they are already fully compacted, will cause differential compaction when in a water-rich mud (B1) and may also display fabric discordance when found in the rock record (B_1'). When found in the context of a sand or silt matrix they will resist compaction and act as fabric supporting grains (B_2). (B_2') Because of the relative softness of shale lithics they may show some squeezing and indentation by harder grains (red arrows). Yellow arrows in B_2' point to mildly deformed shale lithic in a sand layer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

relative to the surrounding shale matrix (Fig. 9). Especially if the shale lithics are in the silt size range, ion milled surfaces are a prerequisite to see textural contrast with confidence.

6.3. Implications

The potential for long-distance shale lithic transport has manifold implications for the interpretation of many aspects of shales, such as mud transport and accumulation, sediment compaction and basin-fill modeling, and geochemical proxies. For mud transport and accumulation, recognizing and quantifying the presence, distribution, and abundance of shale lithic clasts would give insights into the importance of suspended-sediment and 'fluid-mud' transport relative to bedload movement of newly formed floccules, intraclasts, or shale lithics. The relative abundance of each particle type probably also needs to be an important variable in sediment-transport models for the accumulation of mud and formation of so-called muddy clinothems (e.g., Walsh et al., 2004; Gerber et al., 2008; Slingerland et al., 2008).

In addition, if a shale interval in the rock record were to be composed largely of shale lithics, and if that circumstance were to be missed by geologists, it could cause erroneous outcomes of basin modeling exercises. In petroleum exploration, basin modeling via backstripping (Watts and Ryan, 1976) is a commonly used approach to get information on thermal history and maturity of source rocks. Standard assumptions are that shales and mudstones are deposited at high initial porosities (e.g. 85 vol%; Bennett et al., 1977; Schimmelmann et al., 1990) and gradually dewater as they get buried deeper. Hundred meters of such a mud would compact to approximately 15 m of rock, whereas an initial deposit of a lithics “mud” might start out at 50 vol% porosity, and only compact down to 50 m. If this difference is not recognized, there would be a 35 m error in the presumed burial depth. In a stratigraphic succession of several km thickness, such errors can potentially add up to significant discrepancies in actual vs perceived burial depth and result in “anomalous” thermal maturity in deeper portions of the sedimentary succession.

Another potential problem can arise with the use of geochemical proxies in shale studies. Many geologists use these to derive information on paleoclimate, oxygen availability, sedimentation rates, etc. (e.g. Higginson, 2009), and the underlying assumption is that the rock captured a signal via the circumstances of its accumulation. The geochemical data are usually acquired by grinding up samples and analyzing the powders, without prior microscopic examination. Therefore, if substantial portions of the rock consist of recycled shale lithics, it is quite possible that the signal at deposition is mixed with or overprinted by a different signal recorded in the older shale lithics.

Clearly, being able to recognize whether a shale unit accumulated from clays, silt grains, and organic matter, or whether it is composed of shale lithics derived from older strata, can make an enormous difference not only for the interpretation of such a shale unit itself, but also with regard to mud transport, basin evolution, petroleum systems, and appropriate interpretation of geochemical data. The observations and conclusions presented here, though quite suggestive and potentially paradigm shifting, are based on a small sample set. More work and systematic studies are needed to establish just how common shale lithics are in modern muds and ancient shale successions, as well as understanding their lateral distribution in larger stratal packages. Multiple case studies should also help to develop new and refine existing criteria for shale lithic recognition.

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