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Review article

Mud re-distribution in epicontinental basins — Exploring likely processes

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A R T I C L E I N F O

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A B S T R A C T

Fine grained clastic sediments are very common in the interior deposits of ancient epicontinental seas. Not only do they make up the gross lithology in these basins, but they can also be traced for more than 1000 km offshore from basin margins. Given that epicontinental seas were overall shallow and in many parts most likely less than 100 m deep, basin floor slopes can safely be expected to be in the 0.01 to 0.001° range for much of depositional history. Known processes that bring muds to the basin margin and beyond are hypopycnal river plumes, hyperpycnal fluvial discharge events, storm-setup relaxation flows, and gravity-driven fluidized muds. With the exception of river plumes, all of these processes require the presence of sufficient slope for sustained movement. Due to that constraint, these processes combined might in the majority of situations have been able to move muddy sediments on the order of 100 km offshore. Whereas this is sufficient to distribute mud across marginal shelf seas, it becomes problematic in the case of much larger epicontinental seas. For example, those of Upper Devonian or Upper Cretaceous times extended in places for thousands of kilometers, and thus a process is needed that can move muddy sediments the rest of the way. Flume studies of the bedload transport of mud, combined with observations from the rock record, suggest that wind or tide induced bottom current circulation was most likely essential for moving muddy sediments from the periphery of epicontiental seas to their interiors. Remobilization of seafloor muds during frequently recurring lowering of sea level is likely to have aided in this process.

Contents

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1. Introduction

Historically, a large portion of research in sedimentary geology and paleontology was conducted on sedimentary successions that were laid down in expansive epicontinental (or epeiric) seas (Shaw, 1964; Irwin, 1965; Hallam, 1975), and the processes that operated within them to circulate water and spread sediments are intricately linked to continued evolution of marine organisms and their preservation in the rock record. In addition, these successions constitute an archive of environmental change through time and are critical for understanding earth history. In order to best "read" this archive, understanding how it functions as a sedimentary "recording unit" is clearly desirable.

As defined by Johnson and Baldwin (1996), epicontinental seas are partially enclosed shallow seas within continental areas, and form large expanses when the oceans flood substantial portions of the continents. This happened multiple times over geologic history (e.g. Sloss, 1963), and the minimum to maximum sea level range most likely did not exceed 200 m at the extreme (e.g. Vail et al., 1977). Because there are no good modern analogs of epicontinental seas, much of what we currently know about them is a matter of reading the rock record and extracting process information from the sedimentary structures we observe. Going as far back as Hutton (1788), Hall (1859) and Grabau (1906), geologists had noted that epicontinental marine strata contained abundant evidence of shallow water conditions, such as wave ripples, mud cracks, and shallow water organisms. Because part of the aforementioned depth range (Vail et al., 1977) has to be expended to flood the continental margins (modern shelf seas, marginal seas, pericontinental seas) it stands to reason that the maximum water depth of epicontinental seas is likely only part of that range and probably only tens of meters over large areas (Shaw, 1964). Due to the fact that epicontinental strata are host to significant portions of the world's fossil fuel reserves (coal, natural gas, oil) these rocks have been extensively studied and there are rich data sets on stratigraphic patterns and lateral extent of sedimentary units. The economically driven needs for accurate stratigraphic correlation and the wealth of accumulated data led to geologically very well reasoned accounts of what the epicontinental seas of the past must have been like, notably those of M.L. Irwin (1965) and A.B. Shaw (1964). In his classic book "Time in Stratigraphy", discussing stratigraphic principles and correlation methods, Shaw (1964) compiled a highly useful conceptual view of the likely processes and boundary conditions that determine sedimentation patterns in epicontinental seas, and I shall refer to those repeatedly in the course of this exploration of mud transport across the expanses of ancient epicontinental seas.

Epicontinental seas differ from modern shelf seas by showing great lateral extent that at times must have been on the order of several 1000 km's (Shaw, 1964), and consequently they had comparatively small regional bottom slopes. Whereas modern shelf seas show average bottom slopes in the 0.02–0.1° range, ancient epicontinental seas probably had bottom slopes in the 0.001–0.005° range over large areas (Shaw, 1964; Johnson and Baldwin, 1996), although locally steeper slopes may have occurred. A condition for the formation of extensive epicontinental seas is that there is little topographic relief over large areas prior to sea level rise, because otherwise flooded river valleys and estuaries would result from marine transgression. Therefore, the resulting seabed should not only be shallow, but also rather flat. This is why large stable cratons of the Neoproterozoic and the Phanerozoic era, characterized by large expanses of nearly flat lowlands, were the places where extensive epicontinental sea deposits accumulated in the past (Shaw, 1964; Pratt and Holmden, 2008).

Shallow water deposition and almost negligible bathymetric relief led to accumulation of thin but laterally extensive blankets of sediments in epicontinental seas (Shaw, 1964), although the latter also contained areas of uplift or subsidence that are commonly referred to as domes and basins. Especially during orogenies, thrust loading led to formation of foreland basins (DeCelles and Giles, 1996) with much larger sediment thickness (high rates of subsidence and eventual sediment accumulation) that merged laterally into extensive thin sediment blankets that accumulated in more slowly subsiding portions of the continents. In North America, good examples

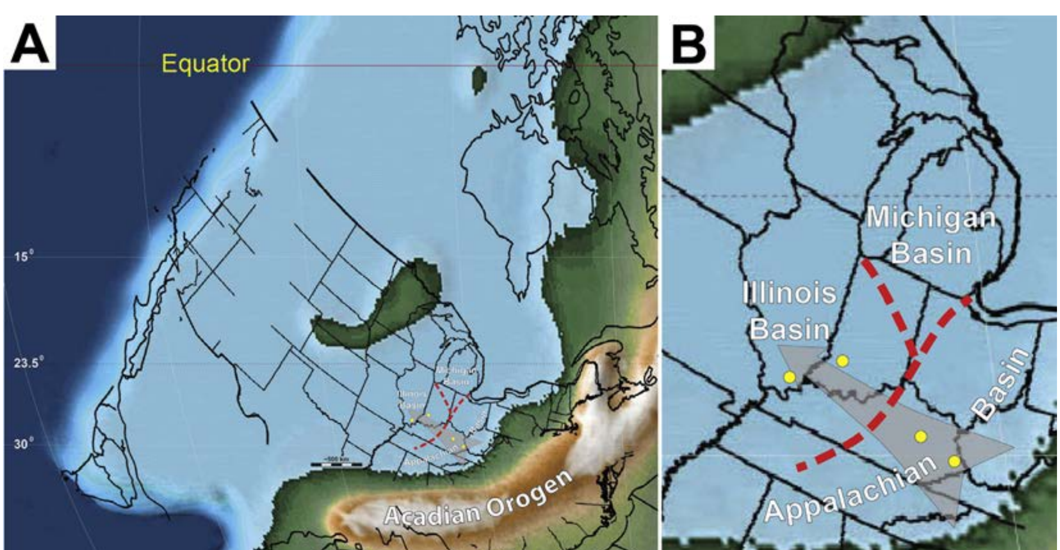

Fig. 1. (A) Paleogeography of North America in the Upper Devonian (Scotese, 2014), showing a wide expanse of shallow shelf (light blue) that extended for 1000's of kilometers. (B) Detail view from the eastern portion of this sea that shows positive elements (arches) as dashed red lines, and the general locations of the Appalachian Basin (foreland basin) and adjacent basins. All these basins contain expanded sections of Upper Devonian strata, with the Upper Devonian section in the Appalachian Basin approaching 2000 m thickness (Milici and Swezey, 2006). The yellow dots mark locations for Fig. 13, and the gray arrow stands for sediment dispersal from the Appalachian Basin, across the Cincinnati Arch, into the Illinois Basin. Scaling information from state outlines and scale bar (approximate). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. A paleogeographic map of the Upper Cretaceous epicontinental sea (light blue) in North America (Blakey, 2014). Scale approximate, outlines of states and provinces provide additional scaling information. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of this would be the Upper Devonian (Fig. 1) where the Appalachian basin contains several kilometers of sediment when compared with tens of meters of sediment in the continental interior (Conant and Swanson, 1961), or the Upper Cretaceous (Fig. 2) where a foreland basin formed east of the Cordilleran fold and thrust belt (Sevier Thrust Belt) and a shallow epicontinental sea (Western Interior Seaway) extended North and South from the Gulf of Mexico to the Arctic Ocean and as far east as the Atlantic Ocean (Kauffman and Caldwell, 1993; Hampson, 2010). There are of course many other examples of epicontinental sea deposits in the rock record, going back at least as far as the Proterozoic, but the Devonian and Cretaceous examples suffice for the objectives of this study.

As can be shown on the example of the Appalachian Basin (Fig. 1), the much thicker sediment fill of foredeeps can give the visual impression of a deep trough when one looks at stratigraphic cross sections and maps of sediment thickness (e.g. Milici and Swezey, 2006), and there is also the assumption that such basins will deepen as a consequence of thrust loading (e.g. Ettensohn, 2008). For these reasons there has been the long standing assumption that for example the Appalachian foredeep had significantly larger water depth (e.g. Broadhead et al., 1982; Ettensohn, 2008) relative to tectonically unaffected portions of continental interiors (Fig. 3).

A similar argument for deepening has also been made for the Cretaceous foreland basin of the Sevier Thrust Belt (Fig. 2), commonly known as the Western Interior Seaway (e.g. Sageman and Arthur, 1994). This greater water depth of foredeeps supposedly allowed them to act as “sediment traps” that prevented terrigenous clastics shed from orogens to “spill out” over the continental interiors (e.g. Heckel, 1973; Tucker, 2001).

The difference between rapidly subsiding foreland basins and the more static continental interiors provides a useful contrast by

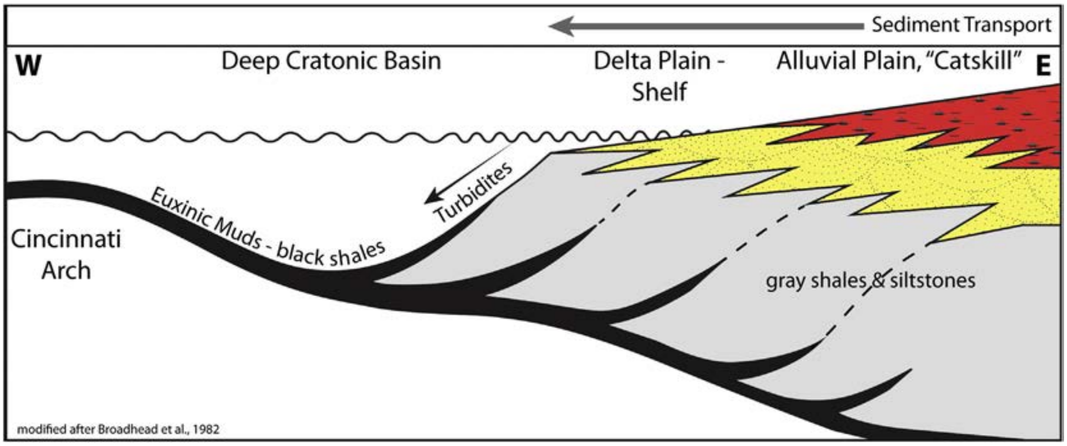

Fig. 3. A widely adopted model of the Upper Devonian Appalachian Basin (Broadhead et al., 1982; Baird and Brett, 1991), characterized by a deep trough to the east of the Cincinnati Arch (Fig. 1). The so called "Euxinic Muds" are the Upper Devonian black shales that are found over wide portions of the North American craton (Conant and Swanson, 1961).

which to examine the role of subsidence on paleobathymetry in epicontinental basins. Whereas there is no question of the significantly higher net sedimentation rates in foredeeps, an exploration of mud transport mechanisms shows that at any given time the water depth in these basins, as well as in other areas of accelerated subsidence (e.g. Illinois Basin, Michigan Basin, Fig. 1), cannot have been significantly different from adjacent areas of the submerged craton. Sediment delivery mechanisms were capable to keep up with subsidence and the synoptic basin floor relief was rather flat and did not form deep troughs like implied in Fig. 3. As will be shown in the course of this discussion, even during comparatively sediment starved initial subsidence, the accumulating black shales show sedimentary features (Section 3) suggestive of bottom currents that moved muddy sediments across largely level seafloor towards the craton. Reviewing the various currently proposed mechanisms for modern cross-shelf mud transport (gravity driven liquid muds, tempestites, hyperpycnites) suggests these mechanisms, while plausible for present day marginal shelf seas, are unlikely to have carried sediment far into the expanses of ancient epicontinental ic seas. Wind and tide driven currents, possibly assisted by intermittent storms and lowering of sea level, were probably the main agents that spread thin blankets of muddy sediments across wide stretches of epicontinental seas.

Whereas shale and mudstone are both widely used terms for fine-grained terrigenous clastics, I will primarily use the term shale, with the understanding that it includes what some prefer to identify as mudstones. Also, when quoting literature where authors used the term mudstone, I will adhere to their designation.

2. Delivering mud to an epicontinental sea

2.1. Eolian input — dust storms and volcanic ash

Strictly speaking, dust storms and volcanic fallout are not processes that redistribute mud in epicontinental seas. They do, however, have the potential to enhance far offshore sedimentation rates of muds. Strong winds can mobilize dust from desert surfaces and glacial outwash plains, such as seen today in the central Atlantic where Saharan dust storms carry eolian material for 1000's of km's offshore (Middleton and Goudie, 2001). Because of this well known modern example, geologists may at times suggest eolian input to explain unusual amounts and types of silt grains (e.g. Werne et al., 2002; Sageman et al., 2003; Gabott et al., 2010) within shale successions. One thing to keep in mind in that context is the need for a large eolian source region (such as the Sahara) and appropriate wind patterns (trade winds) to allow transport to the basin of choice. In general however, because large epicontinental seas mark times of high sea levels, flat lying areas on the continents are more likely flooded by the sea instead of being covered by deserts, and therefore eolian source areas of significant size are probably not very common. Thus, evaluation of the potential eolian input to a shale succession requires examination of paleogeography, paleoclimate, and paleowind patterns. Doing so should greatly lessen the temptation to call upon significant eolian sediment supply for a good many shale successions, including the Upper Devonian (Fig. 1) and Upper Cretaceous (Fig. 2) ones that I will use as examples in this report.

Volcanic ash beds are made up of finely fragmented volcanic rock, glass, and minerals of sand size and finer that are the product of powerful volcanic eruptions (Rose and Durant, 2009). They are a common occurrence in many shale successions, like for example those of the Upper Cretaceous Western Interior Seaway (Fig. 2), where they form laterally extensive beds of now altered ash (bentonite) that are very useful marker beds (Obradovich and Cobban, 1975; Zelt, 1985). Yet, just as material derived from dust storms, volcanic ash falls settle from above through the water column, and do not require a distribution mechanism that operates in the sea itself. Nonetheless, though initially laid down in a blanket-like fashion, being clastic in nature they are subject to reworking by bottom currents (Fig. 4).

2.2. Mud getting deposited at basin margin — hypopycnal plumes

As rivers enter the sea, river borne muddy suspensions tend to float on more saline and denser marine waters (Bates, 1953; Orton and Reading, 1993) and flocculate through the combined effects of flow expansion (reduction of velocity and turbulence) and mixing with saline basin waters (Potter et al., 2005). These buoyant river plumes, dependent in size on the given output of a river system, can extend offshore for tens of kilometers (e.g. Warrick et al., 2007; Falcieri et al., 2014), and in the case of large rivers may be spread along the coast for hundreds of kilometers (Fig. 5) by longshore currents (Weight et al., 2011).

The example of river issued hypopycnal sediment input in Fig. 5 is largely due to input from a very large river (the Mississippi) that drains a large portion of the North American continent. Most likely any rivers that entered into the epicontinental seas of the past were at a comparative "disadvantage" with regard to drainage area and

Fig. 4. A bentonite (altered volcanic ash) layer in the Cretaceous Tropic Shale of Utah (coin for scale). The entire sample is part of a thick bentonite deposit. Yellow arrows and heavy dashed black lines show internal truncation surfaces. Thin dashed lines mark cross-lamina orientations. Note variable dip of cross-lamina sets. This style of cross-lamination is reminiscent of hummocky cross-stratification, suggesting that the ash bed was reworked by storms repeatedly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

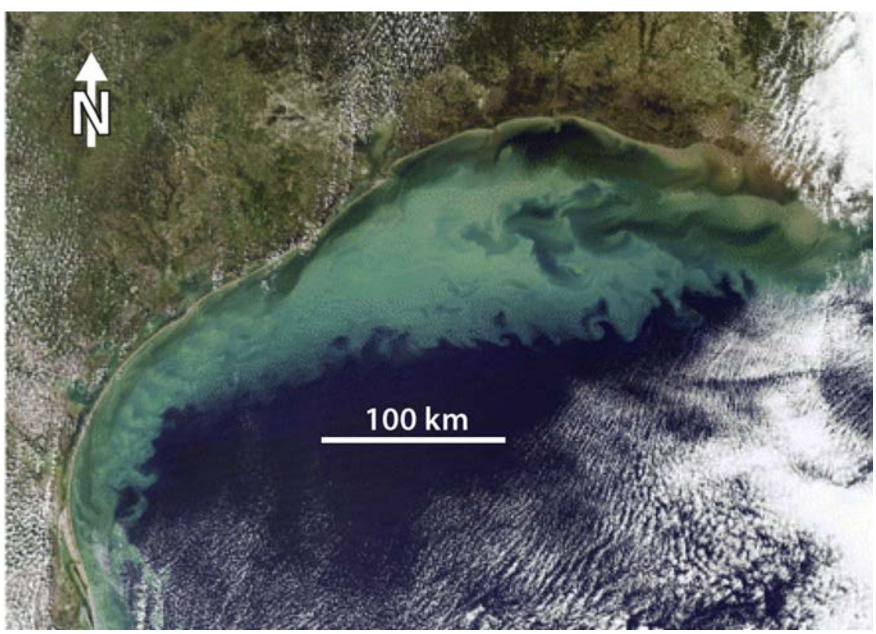

Fig. 5. Satellite image that shows westward spread of suspended sediment in the northern Gulf of Mexico (Louisiana and Texas coast) by westward flowing shore parallel currents (Weight et al., 2011). Most of the suspended sediment is a westward extension of the Mississippi River surface plume, with smaller contributions from the Colorado and Brazos Rivers.

potential sediment supply because much of the continent was under water (e.g. Figs. 1 and 2). Therefore the observed offshore reach of sediment bearing surface waters that we see in Fig. 5, about 100 km's at its maximum, is probably far in excess of what we should expect from the smaller rivers that were the norm during times of continental flooding. For the sake of argument, however, let us assume that on rare occasions hypopycnal plumes were able to spread suspended sediment as far as 100 km's offshore in epicontinental seas.

2.3. Gravity driven transport processes

Once delivered to the margins of epicontinental seas, these sediments have to continue their offshore journey for large distances. No matter what process we envision, be it in bedload or suspension, these sediments are transported by moving fluids, and for these fluids to move energy is required. On the earth surface the requisite energy is generated as these fluids follow gravity and move from higher to lower elevations. Because transport consumes

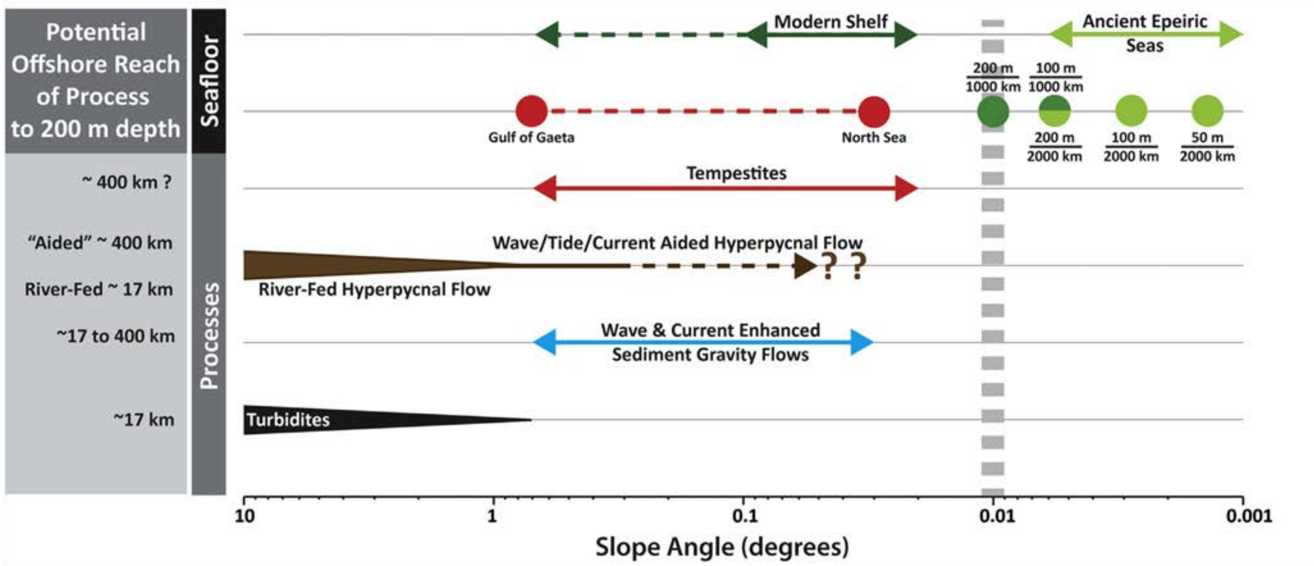

Fig. 6. Processes discussed in text in relation to required slope angles (note that scale is logarithmic). The slope limits for the bottom half of the diagram follow the usage of Friedrichs and Wright (2004), Bhattacharya and MacEachern (2009), and Macquaker et al. (2010). For tempestites (in red) the data are from studies by Reineck and Singh (1971) and Aigner and Reineck (1982), and the slope ranges for modern shelves and epeiric (or epicontinental) seas are from Shaw (1964) and Johnson and Baldwin (1996). The green circles mark average slope angles for a given offshore water depth and distance from shore. On the left, an approximate "offshore" reach for each process is given if a maximum water depth of 200 m and the minimum necessary slope is assumed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

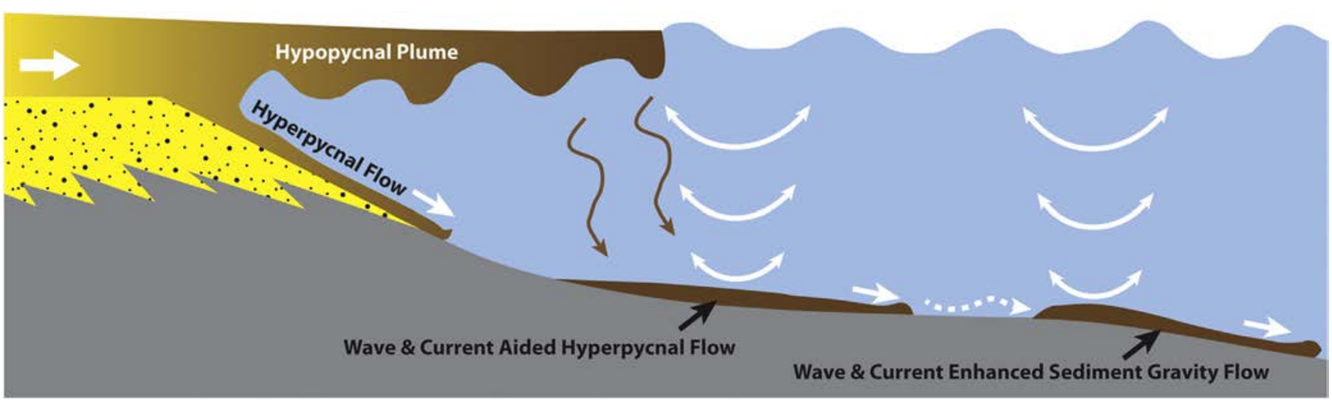

Fig. 7. Definition sketch for hyperpycnal flows and wave-current enhanced sediment gravity flows. At left a modified version of a figure from Bhattacharya and MacEachern (2009) that relates hypopycnal plumes and hyperpycnal flows (0.7° minimum slope, Fig. 6). In areas of gentler slopes (as little as 0.03°, Fig. 6) waves and currents keep sediment in suspension (instead of inertia and slope driven turbulence) and allow a liquid mud layer to propagate further. At right, water rich muds that may or may not be related to direct deltaic input can be remobilized by subsequent wave and current activity and propagate to deeper water provided there is some surface slope (0.03° minimum, Fig. 6).

energy, the associated slopes cannot be infinitely small. In the following paragraphs we will explore the processes that have been suggested in past studies as conveyors of mud in shelf seas. The slope requirements of these various processes are summarized in Fig. 6.

2.3.1. *Turbidity currents associated with river deltas*

Ultimately, river mouth regions are the place where the bulk of clastic sediments enter the marine realm and start to build out a delta with comparatively steep prodelta slopes (Bhattacharya, 2010). Slope failure can initiate surge-type turbidity currents that carry short lived pulses of sediment multiple kilometers offshore into deeper water (Pattison, 2005). In order for these turbidites to support their sediment load in autosuspension (Pantin, 1979) a minimum slope angle of approximately 0.7° is required (Friedrichs and Wright, 2004), significantly limiting the offshore reach of these flows (Fig. 6).

Direct fluvial input of sufficiently dense suspensions into marine waters can also produce sustained turbidity currents, so called hyperpycnal flows (Fig. 7). These turbulent suspensions move down the prodelta slope and carry mud in an offshore direction (Mulder and Alexander, 2001). Complete hyperpycnites are sedimentologically characterized by a symmetrical grain size profile due to waxing and waning discharge, where a basal coarsening upwards unit is overlain by a fining upwards succession with indications of decreasing flow velocity (Bouma sequence). Not uncommonly, maximum flood discharge may be accompanied by erosion of initial deposits and lead to incomplete (asymmetrical) deposits that are difficult to differentiate from other graded beds (Mulder and Alexander, 2001; Mulder et al., 2003), such as turbidites and tempestites (Bhattacharya and MacEachern, 2009; Wilson and Schieber, 2014). Examples of muddy hyperpycnites from the rock record are shown in Fig. 8.

Because river-fed hyperpycnites (Fig. 7) require high sediment

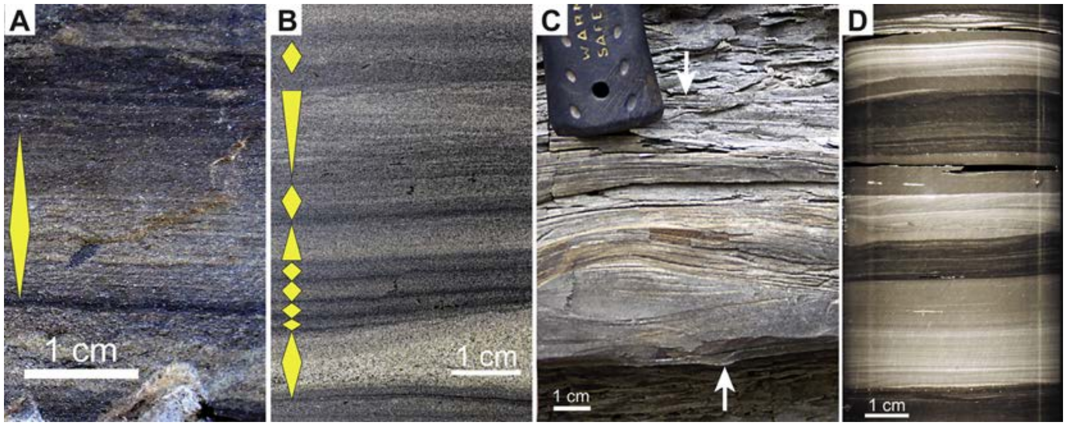

Fig. 8. Rock record examples of hyperpycnites. (A) Symmetrical, inverse-normal graded silt bed in mudstone interval (marked yellow) of Ferron Sandstone (Cretaceous of Utah). (B) image of slabbed Ferron mudstone with multiple thin inverse-normal graded hyperpycnite layers. The one normal graded layer could have other origins, although in the larger context it is probably a hyperpycnite as well. See Li and Bhattacharya (2015) for more information. (C) Thick, mostly normal graded hyperpycnite (between arrows) in the Devonian Geneseo Formation of New York. (D) Drill core from the same unit that shows closely stacked hyperpycnal layers, that can be variably silt-rich (light colored) and mud-rich (dark), amalgamated, and rarely show the symmetrical development common to the hyperpycnites seen in (A) and (B). See Wilson and Schieber (2014) for more information. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concentrations to overcome buoyancy in marine waters, they are more likely during exceptional river floods, and also seem more commonly associated with smaller (in terms of drainage area) "dirty" rivers that drain high-relief mountain areas in humid climates (Mulder and Syvitski, 1995). It appears that such rivers have good potential to issue hyperpycnal flows in association with large seasonal floods, whereas large rivers such as the Mississippi or Amazon are much less likely to turn hyperpycnal (Mulder and Syvitski, 1995; Bhattacharya and MacEachern, 2009). The conditions under which hyperpycnal flows are initiated can also be influenced by the salinity of the receiving basin (brackish water helps), climate fluctuations ("wet" cycles), and the intensity of weathering (mud generation), but as a general rule the bottom slope for river-fed hyperpycnites needs to be 0.7° or steeper (Fig. 6) for the flow to maintain autosuspension (Bhattacharya and MacEachern, 2009).

2.3.2. Sediment gravity flows that are enhanced by waves and currents

Many rivers can produce both hypopycnal plumes (Fig. 7) and hyperpycnal flows (e.g. Kineke et al., 2000). Sediment that settles out from hypopycnal plumes in prodelta and shelf areas with gentler slopes (Fig. 7) has the potential to become remobilized by waves and currents that induce bottom turbulence and hinder settling. The liquid mud layers that are produced as a consequence (Fig. 7) can follow gravity on slopes as shallow as 0.03° (Friedrichs and Scully, 2007; Ogston et al., 2008; Bentley, 2003) and transport sediment further offshore.

When located close to a delta, the deposits of these kinds of flows have been described as wave and current aided (Fig. 7) hyperpycnal flows (Bhattacharya and MacEachern, 2009), although they do not differ in terms of process from the criteria (Fig. 6) that are applied to the wave and current enhanced sediment gravity flows (Fig. 7) described from elsewhere on continental shelves (Friedrichs and Wright, 2004; Traykovski, 2007; Ogston et al., 2008).

The latter have been recognized in various recent studies of modern cross-shelf mud transport, for example on the northern California shelf (Eel River, Traykovski et al., 2000), the Amazon shelf (Kineke et al., 1996) and the Louisiana shelf (Jaramillo et al., 2009). Whereas these examples may differ in the exact way by which various physical processes interact, the common denominator appears to be that near bed currents or wave orbital motion help to maintain a bottom layer of fluid mud (e.g. Kineke et al., 1996) that can continue to move on slopes as small as 0.03° (Friedrichs and Wright, 2004; Traykovski, 2007; Ogston et al., 2008). A rather awkward and unpronounceable acronym, "WESGFs", has recently been suggested (Macquaker et al., 2010) for the wave enhanced variety of these flows, but given that in most shelf settings waves and currents probably operate simultaneously to produce them, one should hope that a more serviceable naming convention is not too far off. The slope limits for these flows and their potential offshore reach are the same as for wave and current aided hyperpycnal flows (Fig. 6).

Given that these flows are initiated by wave and/or current reworking of surficial muds, move downslope as long as the suspension (fluid mud) can be maintained, and then settle as energy dissipates, normal grading is a generally observed feature (e.g. Stow and Bowen, 1980; Martin et al., 2008; Bhattacharya and MacEachern, 2009). Thin graded beds, however, are a common feature of many muddy shelf successions (e.g. Schieber, 1989, 1999; Lazar et al., 2015), and whereas there appear to be multiple "flavors" of these (Schieber, 2011a), it is currently not known whether these subtle differences can be used to assign them to different processes (e.g. turbidite, tempestite, wave aided hyperpycnite, wave enhanced sediment gravity flow etc.).

Macquaker et al. (2010) proposed that wave-generated fluidized muds show a diagnostic "triplet" succession (i.e., scoured base with current ripple cross-laminated silts, planar-parallel-laminated silts and muds) of sedimentary features. Results from flume studies (Schieber, 2011a), however, show that triplets of the same appearance can be deposited from continuous as well as decelerating flows of muddy suspensions with significantly lower suspended sediment concentrations than the 10 g per liter threshold (Winterwerp and van Kesteren, 2004) for fluidized muds. The multiple processes that can transport mud and generate graded beds are overlapping in their reach on modern shelves, and appear tightly intermingled in the rock record (e.g. Pattison, 2005; Bhattacharya and MacEachern, 2009; Wilson and Schieber, 2014; Li and Bhattacharya, 2015). It appears therefore that more work is required before the deposits of various shelf mud transport processes can be identified and differentiated with confidence.

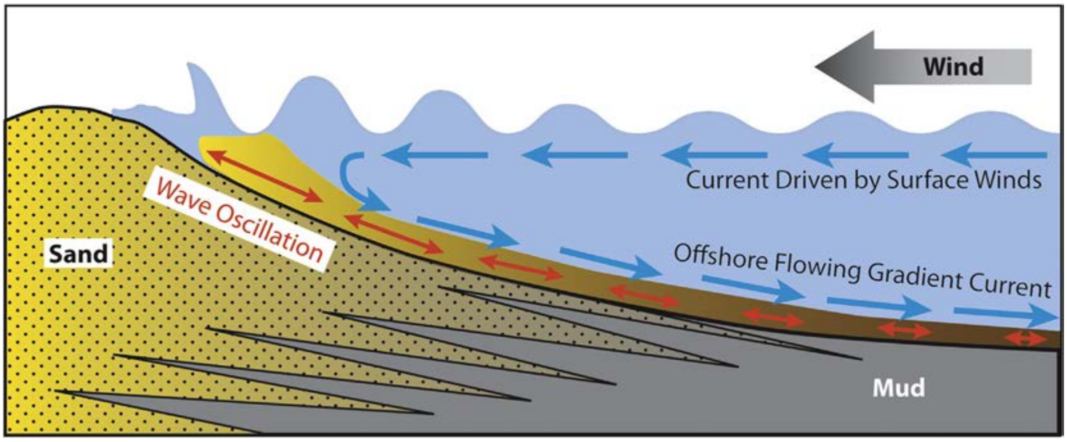

Fig. 9. Schematic model for offshore flowing bottom currents due to wind-set up at the coast (after Allen, 1985). Sediment is brought into suspension by wave action, and driven basinward by bottom hugging offshore flowing compensation currents. This process also results in distal mud deposition (Aigner and Reineck, 1982).

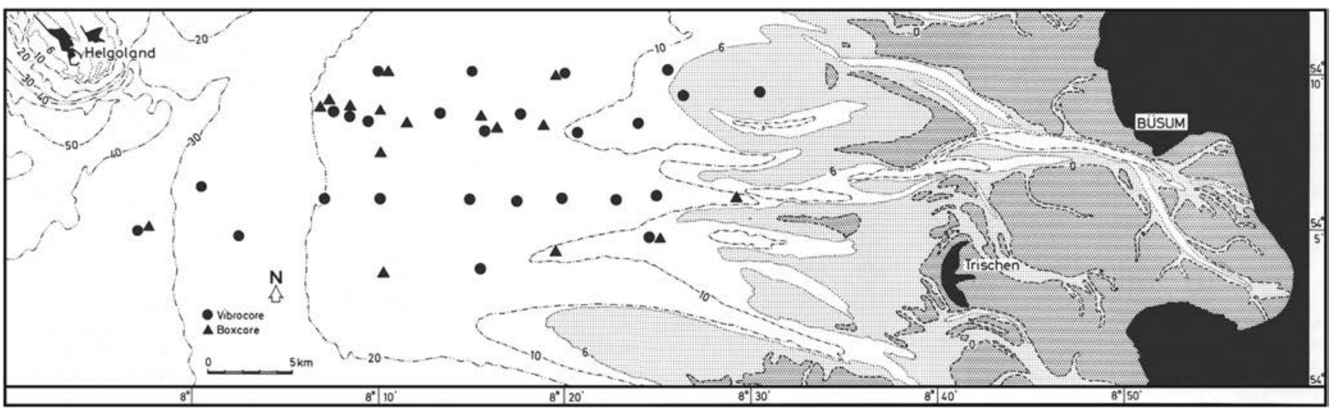

Fig. 10. Gently sloping North Sea shelf between German coast and the island of Helgoland (figure from Aigner and Reineck, 1982). The black dots and triangles are sampling locations for the tempestite study of Aigner and Reineck (1982). Sea bed contour lines are dashed and marked in meters, and bottom slopes in E–W direction are in the 0.07–0.33° range.

2.3.3. Storm induced offshore transport

Detailed studies of shelf seas in various parts of the world have established quite convincingly that storms are capable of moving sediment in offshore direction (e.g. Hayes, 1967; Gadow and Reineck, 1969; Reineck and Singh, 1971; Aigner and Reineck, 1982; Nelson, 1982), and also that distal storm deposits can be rather muddy or even consist entirely of mud (Aigner and Reineck, 1982). Because the shallow marine realm is an area where a variety of current generating processes can overlap, such as wind-drift currents, rip-currents, density currents initiated by storm wave reworking, storm surge ebb currents, combined storm wave action and density currents, wave-induced currents, and storm driven bottom currents combined with storm-wave induced sediment liquefaction (for more background see Aigner and Reineck, 1982), resulting current patters can be complex. Current patterns can be further complicated by Coriolis forces and Ekman transport (Pond and Pickard, 1983), but there is usually an offshore component due to coastal wind set-up that induces offshore flowing gradient currents (Fig. 9) that move sediment basinwards (Gienapp and Tomczak, 1968; Gienapp, 1973; Aigner and Reineck, 1982; Allen, 1985). Thus, unlike in the sediment gravity flows from Section 2.3, the flow moves because of coastal downwelling rather than due to gravity pulling on a suspension. Yet, because this type of flow will decelerate as it moves away from the shoreline, normal grading is a typical characteristics (Gadow and Reineck, 1969; Aigner and Reineck, 1982) and thus the distinction to turbidites, normal graded hyperpycnites, and other sediment gravity flows is not an easy one to make in fine grained end members.

The slope angles in locations where tempestite transport of this type was studied (Reineck and Singh, 1971; Aigner and Reineck, 1982) can vary from wide and semi-sheltered shelf areas like the North Sea (Fig. 10) where the average slope angle is around 0.03°, to more open and narrow shelves like the Gulf of Gaeta in the Mediterranean (Reineck and Singh, 1971) where slope angles may be as steep as 0.7°.

The distal muddy tempestites in these studies are characterized by a sharp and in part erosive base, and grade upwards from laminated silts to mud that tends to be bioturbated from the top (Aigner and Reineck, 1982). Some examples from the rock record are shown in Fig. 11.

2.4. Physical reach of processes – summary

As seen in Fig. 6, even by assuming an epicontinental sea that gets as deep as 200 m, and using the smallest presumed slope angles for the envisioned processes (storm-induced coastal downwelling, hyperpycnites assisted by waves and currents, wave and current enhanced sediment gravity flows, turbidites) muds could not have been transported more than approximately

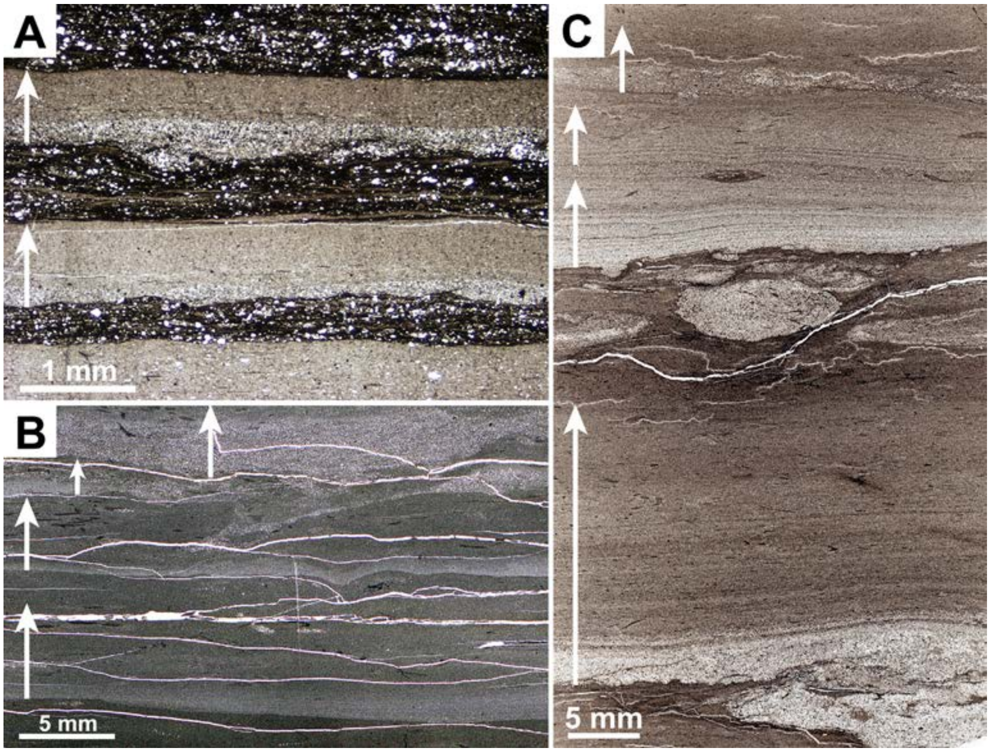

Fig. 11. Rock record examples of tempestite event beds. (A) Graded silt-mud couplets (arrows) in the Mid-Proterozoic Belt Series of Montana that alternate with carbonaceous background sedimentation of benthic microbial mats (Schieber, 1986). (B) Sharp-based silt-mud couplets (arrows) in the Devonian Sonyea Group of New York (Schieber, 1999). Tops of graded beds are bioturbated and thus the distinction between even beds and background sedimentation is less clear. (C) Sharp based graded silt-mud couplets (arrows) in the Cretaceous Blackhawk Formation of Utah. Event beds are separated by bioturbated intervals and bioturbated from the top. The low angle dipping laminae in these muddy beds suggests a lateral transport component, possibly because storm induced currents transported flocculated mud in bedload (Schieber et al., 2007; Schieber and Yawar, 2009).

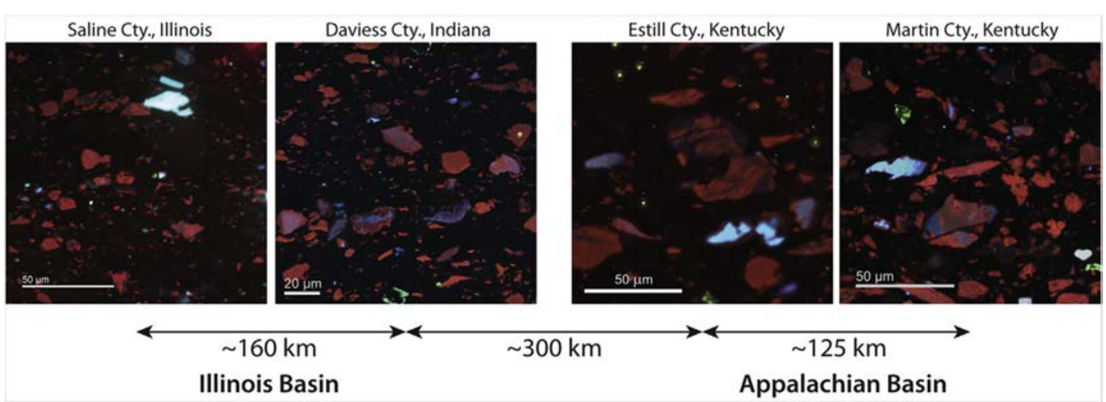

Fig. 12. Continuity of fine clastic sediment source from Appalachian to Illinois Basin. The images show SEM-CL images of the quartz fraction of Late Devonian shales along an east-west transect. The dominant reddish-orange colors suggest a low grade metamorphic source rock, probably a slate dominated provenance (Schieber and Wintsch, 2005). The locations for the samples correspond to the yellow circles in Fig. 1, and show an east to west comparison. From right to left the character of the quartz grains in terms of color and textural details does not change, only the average grain size is decreasing. This strongly suggests that Late Devonian black shales in the Illinois Basin received sediment from the same source as the Appalachian Basin. SEM-CL images were acquired with a GATAN Chroma II system, attached to an FEI Quanta FEG SEM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

400 km's offshore. Furthermore, because wave interaction with the sea bed and wave induced currents are critical for the operation of distal hyperpycnites and sediment gravity flows (Fig. 6), storm wave base is a critical variable. Whereas storms may reach as deep as 200 m on narrow continental shelves that face the open ocean, storm wave base is typically shallower than that extreme in most shelf areas (Johnson and Baldwin, 1996). For example, in the case of a sheltered ocean area like the Gulf of Mexico, the expected depth of wave penetration is approximately 50 m (at 10% probability of wave encounter, Peters and Loss, 2012) in shelf regions. In the North Sea, another partially enclosed and comparatively wide shelf sea, lateral distribution of modern tempestites suggests a storm wave base of approximately 30 m (Aigner and Reineck, 1982). This basic limitation was also pointed out by Shaw (1964), who argued that in epicontinental seas the smaller wave fetch and energy loss by bottom friction should have kept the interaction of storm waves with the seabed at considerably shallower depth than in the case of marginal shelf seas. Taking our cues from the Gulf of Mexico (Peters

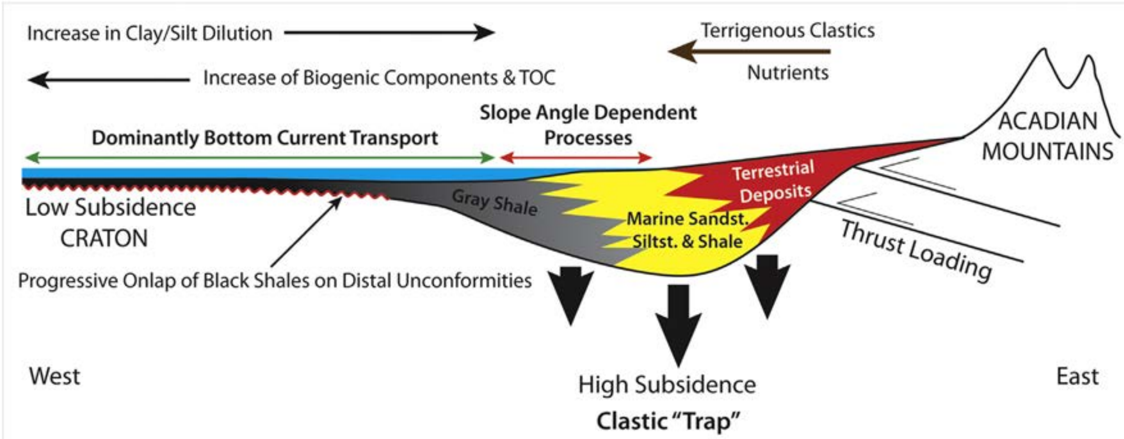

Fig. 13. Schematic view of bathymetry in the eastern portion of the Late Devonian epicontinental sea of North America (Fig. 1), as adapted from Smith and Leone (2010). In contrast to Fig. 3, there is no deep trough in the Appalachian basin, and sediment can travel over a largely flat basin floor from the Appalachian basin to the Illinois Basin, located further to the west of the diagram.

and Loss, 2012) and the North Sea (Aigner and Reineck, 1982), suggests that assuming a 50 m effective depth for storm wave penetration is quite a bit more likely than 200 m, although most likely still overly optimistic for epicontinental seas of the past (Figs. 1 and 3).

Under assumption of a 50 m average storm wave base, wave aided processes like distal hyperpycnites and sediment gravity flows would barely make it 100 km's offshore before they reach 50 m water depth at minimum slope (0.03°). Thus, these processes, as well as storm induced flows can at best be expected to spread mud offshore within a 100 km wide fringe along the margins of the epicontinental seas shown in Figs. 1 and 3. Nonetheless, as can be shown with the example of the Upper Devonian of the eastern USA, fine grained clastic material from the Acadian orogen in the south (Fig. 1) was evidently deposited along the margins of the Appalachian Basin and subsequently carried across the Cincinnati Arch into the Illinois Basin (Fig. 13). Had the Appalachian Basin indeed shown a morphology like in Fig. 3, this would not have been possible. Neither water nor sediment has a habit of traveling upslope, and thus the clastics would have been trapped in a deep trough and could not have traveled up the western side of that trough to cross the Cincinnati Arch and to reach the Illinois Basin.

That such a trough most likely did not exist in the Upper Devonian is supported by multiple lines of reasoning that suggest that over wide areas the water was only tens of meters deep (Conant and Swanson, 1961). On the basis of the grain size of storm wave reworked beds water probably was rarely deeper than 50 m (Schieber, 1994). Recent basin analysis and sequence stratigraphic analysis (Smith and Leone, 2010) also indicates that a transgressive onlap model, where shales occur on the cratonward side of the basin and onlap and are time-equivalent to unconformities, agrees much better with observed stratigraphic relationships than the deep downlap model that is implied in Fig. 3.

3. Moving mud the rest of the way

In the case of the Upper Devonian epicontinental sea (Fig. 1), where a black shale blanket extends from the Appalachian to the Illinois Basin and beyond (Conant and Swanson, 1961), petrographic features of detrital quartz grains (Fig. 12) provide strong evidence that Upper Devonian fine grained terrigenous clastics were carried from the Acadian Mountains to the Illinois Basin over a distance of 800 km's or more (Fig. 1), and that presumed basin

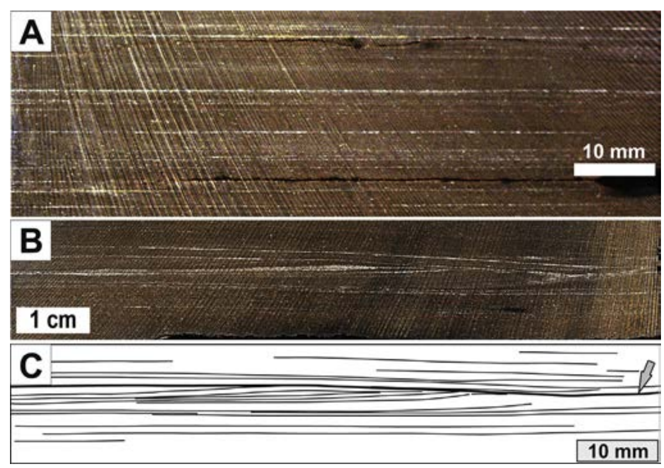

Fig. 14. (A) Finely laminated black shale from the Devonian New Albany Shale (Indiana). The lighter laminae contain coarse silt. (B) Photo from different location in same sample as shown in (A). Here we see clear cross-lamination, and structure is highlighted by silt-rich laminae. Most of the laminae in this ripple consist of a mixture of organic matter, clay, and silt. (C) Tracing of silt laminae visible in B. Arrow marks top of ripple, and we see inclined (to the left) and truncated laminae that form the outline of a compacted and mud-dominated ripple. The synoptic relief of this ripple is 3 mm, but its original relief would have been on the order of 20 mm (assuming 85% water content), the same magnitude as observed in experiments (Schieber et al., 2007).

topography (Fig. 2) posed no obstacle to westward sediment transport (Fig. 13). Whereas the initial 100 km of the journey are readily explained with sediment transport processes known from modern shelf seas (Fig. 6), the far offshore regions require a process (or processes) that does not rely on slope for propulsion.

Clues with regard to the likely processes come from petrographic observations of these black shales and flume experiments on the bedload transport of mud. Thin sections from various locations within the Upper Devonian black shale succession show as a typical feature that these shales are laminated and that fine laminae of coarse silt are interspersed with laminae that contain abundant clays and organic matter. Whereas generally these laminae are nicely parallel (Fig. 14A), in places they can show low angle downlapping of laminae and show geometries that are suggestive of cross-laminated ripples that have undergone substantial vertical shortening (Fig. 14B), or they can show thickening of coarse silt laminae into thin lenses (Fig. 14C).

Laminae like those shown in Fig. 14 have been produced in flume experiments with muddy suspensions (Schieber et al., 2007; Schieber and Southard, 2009). In these experiments it was demonstrated that muds as well as pure clays can be deposited from swift flows in the 15–30 cm/s range (5 cm flow depth). Muds and clays will flocculate in these flows, sand size floccules transfer into bedload, form migrating floccule ripples, and the final deposits have a laminated appearance (Schieber and Yawar, 2009). Whether simple laminae are observed (Fig. 14A) or whether we see preserved (though compacted) current ripples (Fig. 14B) may reflect sedimentation rates, analogous to what can be observed in fluvial deposits. In the latter case, sand bars that migrate through a channel may be half a meter or more in thickness, but typically only leave decimeter thick cross-bedded deposits behind. Fully preserved sand bars are rare, require burial without preceding erosion, and thus imply higher sedimentation rates (Reineck and Singh, 1980; Leeder, 1982; Allen, 1985). An additional factor that can produce intermingled silt-rich and clay-rich laminae is the observation that in mixed suspensions of clay and silt, coarse silt segregates from the finer components that form bedload floccules (Schieber, 2011b). As a result, ripples made of coarse silt and ripples that consist of flocculated muds migrate over the bottom simultaneously (Schieber et al., 2013), resulting in deposits where laminae of coarse silt are interspersed with laminae of finer components (Schieber, 2011b). On the basis of these considerations we can therefore interpret laminated shales (Fig. 14A) as the product of bedload transport in muddy suspensions, even if there is no immediate evidence of subtle cross-lamination (Schieber et al., 2007; Schieber, 2011c).

In the context of a foredeep–craton association (Fig. 13), the seafloor is largely flat except for the area of rapid sediment accumulation near the shoreline. Although the foredeep does act as a clastic "trap" (Fig. 13), sediment supply in proximal areas is sufficient to keep pace with the comparatively large subsidence rates in the foredeep. Such assessments do largely rely on presumed sediment delivery for coarse clastics (e.g. DeCelles, 2004) and tectonic reconstructions of ancient foreland basins, and derived maximum sedimentation rates for foreland basins are probably on the order of a few tenths of a mm per year (Yonkee and Weil, 2015). Knowing from experiments and observations of modern shelves that muddy suspensions that carry either flocculated mud in bedload (e.g. Schieber et al., 2007; Schieber, 2011c) or move as liquid muds (e.g. Macquaker et al., 2010) can readily deposit a mm (in compacted state) or more of mud in a week, it seems likely that even the mud dominated portions of foreland basins received sufficient sediment to keep pace with subsidence. Depending on the timing between thrust loading, erosion of mountain ranges, and sediment transport to the basin, one can of course not completely exclude the possibility for short interludes of a supply shortage and deeper water in the foredeep. Yet, given the overall stratal architecture of foredeep successions (e.g. Asquith, 1970; Kauffman, 1977; Van Wagoner, 1995; Taylor and Lovell, 1995; Lazar, 2007; Hampson, 2010), where shale rich parasequences thin gradually in offshore direction and, when not too badly bioturbated, show current generated sedimentary features that suggest bedload transport of mud (Fig. 14), the situation depicted in Fig. 13 should dominate over time.

In both the Cretaceous and the Devonian epicontinental sea deposits (Figs. 1 and 3), shales with laminae that suggest bedload transport of flocculated mud by bottom currents (Schieber et al., 2007) can be found across the extent of the foredeep as well as in the distal deposits that onlap and cover the craton (Figs. 14 and 15).

In addition, examination of laminated shales from my collection of thin sections, as well as examples from the literature (Ulmer-Scholle et al., 2015; Lazar et al., 2015), ranging in age from Precambrian to Tertiary and including material from several continents, suggest that the type of shale lamination that can be attributed to bedload transport by bottom currents (Schieber et al., 2007; Plint et al., 2012; Trabucho-Alexandre et al., 2012) is widespread in epicontinental sea successions (Fig. 16).

Given how common this current produced type of shale lamination appears to be in epicontinental shale successions (Fig. 16), one has to wonder about likely mechanisms that could produce near bottom currents in the 10–25 cm/s range (Schieber et al., 2007). Two mechanisms that come to mind are tidal and wind driven circulation.

In his discussion of the characteristics of epicontinental seas,

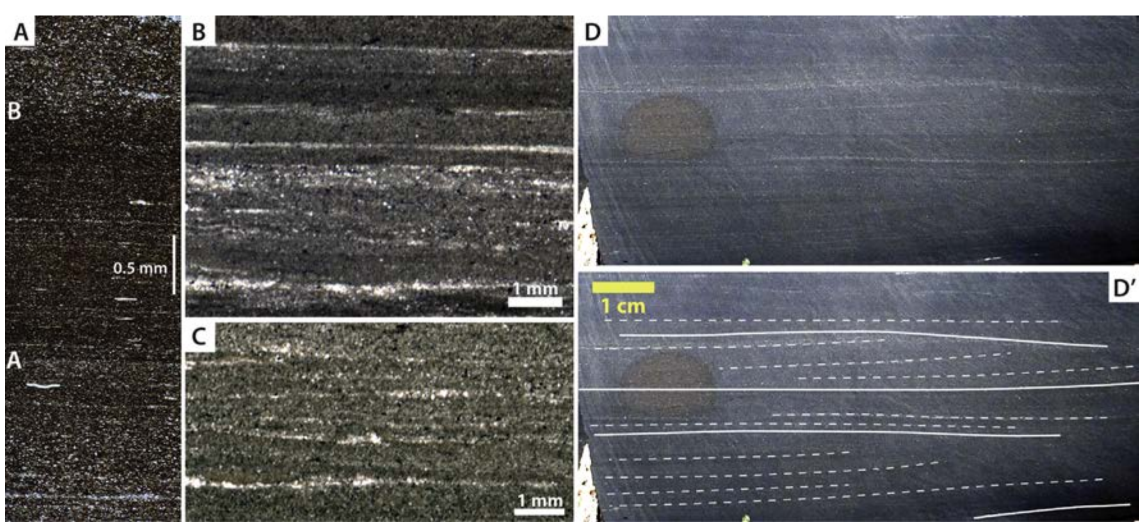

Fig. 15. Laminated shales and bedload transport. (A) Thin section image of Upper Devonian Ohio Shale from the west flank of the Appalachian Basin. Interval A–B shows finely laminated black shale that most likely reflects bedload transport of mud (Schieber et al., 2007; Schieber and Southard, 2009; Schieber, 2011c; Schieber and Wilson, 2013). The shale below A and above B shows only relict lamination because of fabric disruption by meiofaunal burrowing (Pike et al., 2001; Riese, 2014). (B) and (C) show fine scale lamination in the Upper Cretaceous Mancos Shale of the Book Cliffs, Utah (foredeep, proximal). Although there is fabric disruption by meiofauna, the laminae are clear enough and in places show low angle inclination (to the right), an indicator of bedload transport of flocculated mud (Schieber et al., 2007; Schieber and Yawar, 2009). (D) Photo of drill core from Upper Cretaceous Niobrara Shale in the Denver Basin (foredeep, distal). (D′) Line drawing highlights the presence of stacked and compacted muddy ripples. These ripples were most likely produced as bottom currents transported flocculated mud in bedload (Schieber et al., 2007).

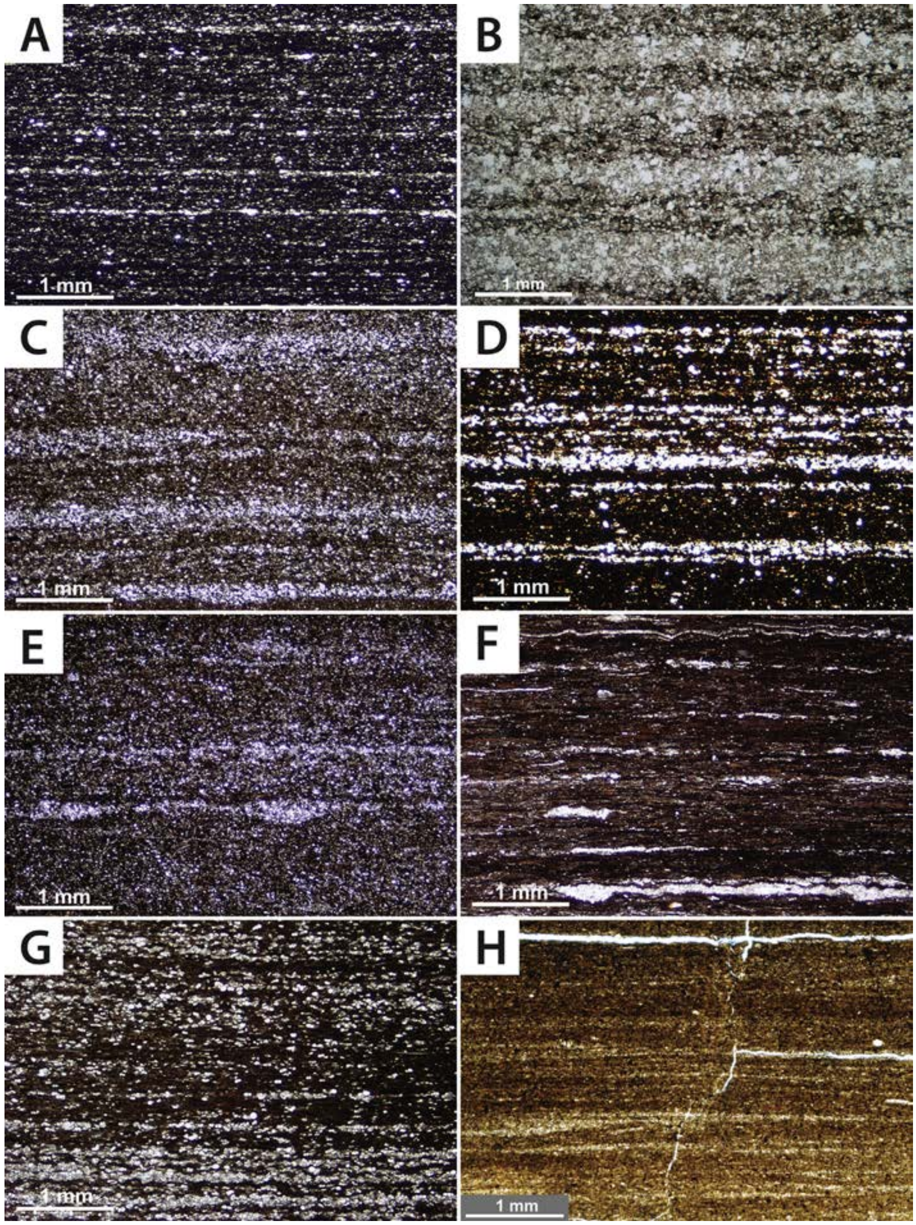

Fig. 16. Current laminated shales from various times and places. (A) Mt. Isa Group, Mid-Proterozoic, Australia. (B) Belt Supergroup, Mid-Proterozoic, Montana, USA. Shows Thinning and thickening of coarse silt laminae. (C) Maquoketa Shale, Ordovician, Indiana, USA. Shows lenticular nature of coarse silt laminae. (D) New Albany Shale, Devonian, Indiana, USA. Looks nicely parallel laminated in this view, but may show low angle cross-lamination in nearby samples. (Fig. 15). (E) Dunkirk Shale, Devonian, New York, USA. Note lenticular nature of coarse silt laminae. (F) Jet Rock, Jurassic, Yorkshire, Great Britain. Note lenticular thickening of coarse silt laminae. (G) Niobrara Formation, Colorado, USA. Parallel laminated in this image, but may show low angle cross-laminae in other samples. (Fig. 16). (H) Mowry Shale, Wyoming, USA (image courtesy of Joe Macquaker). Shows low-angle cross-laminae. In all of these units, interspersed clay and silt rich laminae are the norm, but samples that show lenticular thickening of coarse silt laminae and low angle cross-laminae provide hints that the shales were deposited by currents that carried flocculated mud in bedload (Schieber et al., 2007; Schieber, 2011c).

Shaw (1964) suggested that because of the shallow depth and wide extent of the latter, tidal currents should be dampened to the point that diurnal tides should not be expected to operate in the interior of epicontinental seas (Keulegan and Krumbein, 1949). Yet, whereas this point of view can safely be considered the majority opinion among sedimentary geologists, there are probably circumstances when tides can be a factor in sediment transport in epicontinental seas (e.g. Klein and Ryer, 1978; Kvale et al., 1989). Today, the combination of Coriolis effect, gravitational forces of Moon and Sun, and the geometry of ocean basins forces their water masses to rotate around a number of amphidromic points, a phenomenon first recognized by Whewell in 1836. These rotating tidal currents are strong enough to move sandy sediment across the North Sea (Houbolt, 1968; Kenyon and Stride, 1970), and would also suffice to move flocculated muds in bedload (Schieber et al., 2007). Thus, given the right orientation relative to the migration of tidal bulges and paleoshorelines, epicontinental seas of the past may well have experienced tidal circulation that contributed to the spreading of muddy sediments across their expanse. At this point in time, however, there are no established criteria for recognition of tidal currents in ancient shales that do not contain substantial amounts of sand or silt and thus might record flaser bedding and related tidal facies (Reineck and Singh, 1980). Nonetheless, if tidal currents were active they most likely moved flocculated muds or water rich mud rip-ups in bedload (Schieber et al., 2007, 2010), and would have been a supporting element for redistributing and spreading muds across epicontinental seas.

With regard to wind-driven circulation, storms do intermittently interact with the seabed in shallow seas (e.g. Swift, 1970; Reineck and Singh, 1971; Aigner and Reineck, 1982; Nittrouer et al., 2007), and there is abundant evidence that they also have done so in the past (e.g. Reineck and Singh, 1980; Schieber, 1989; Prothero and Schwab, 2004; Datillo et al., 2008; Plint et al., 2012). In proximal areas or in areas of some bottom slope storms appear to be able to facilitate lateral transport of mud (Aigner and Reineck, 1982; Macquaker et al., 2010), but in the wide and low-slope expanses of epicontinental seas (Figs. 1 and 2) they are probably too short in duration to have, on their own, much of an effect on long distance lateral transport.

Interaction of seasonal winds with the water cover of modern shelf seas has been examined in a variety of studies (e.g. Beardsley and Boicourt, 1981; Stabeno et al., 1999; Di Lorenzo, 2003; Lentz, 2008; Danielson et al., 2014), and even though they are poor analogs to epicontinental seas of the past, what we can learn about wind-water column interaction is nonetheless instructive. For example, Beardsley and Boicourt (1981), using multi-year instrument records, were able to show that wind driven circulation in the Mid-Atlantic Bight caused bottom currents of approximately 20 cm/s for multi-day and even week-long time periods. Wind-driven currents of that kind should be capable to move and redistribute reworked surface muds in bedload as well as suspension (Schieber, 2011c), and may have been an important agent of mud re-distribution in epicontinental seas of the past. The wide expanses of such seas should enable trade winds to interact with large portions of the sea surface and drive current systems that continue for multiple months or longer (e.g. Lloyd, 1982; Scotese, 2014). Whether the near-seabed component of such currents would have sufficed to move significant quantities of muddy sediments is uncertain of course, but in conjunction with tidal currents and strong storms that intermittently resuspended seafloor muds they should have been a powerful agent of mud-redistribution.

Another factor that probably helped mud redistribution in distal settings of epicontinental seas is the fact that sea level fluctuates at multiple time scales, as evident by the subdivision of the stratigraphic record into depositional sequences that are bounded by erosion surfaces (e.g. Vail et al., 1977; Bohacs, 1998). Changes in the shape and dimension of epicontinental seas can be a by-product of sea level change and may result in the amplification of tidal currents and enhanced redistribution of mud. Also, as sea level drops the sea bed experiences more erosional energy by currents and waves, and lags and scours are the consequence, even in very distal settings (Schieber, 1998). As such the sedimentary record of shales and mudstones is not continuous, but rather is riddled with gaps that mark erosional removal at the mm, cm, dm, and meter scale (Schieber, 1998; Plint et al., 2012; Trabucho-Alexandre, 2015). The removed material is either disintegrated and resuspended or forms rip up clasts of variable water content and size (Schieber et al., 2010), and is then available for transport by any available current, be it fueled by tidal forces, wind shear, or a combination thereof. Furthermore, systematic changes of sedimentation rates in the course of parasequence buildup allow for considerable reworking by storm waves on flooding surfaces and in the basal portions of distal parasequences (Bohacs et al., 2014) because relative to energy input sedimentation rates are very small.

4. Conclusion

In the context of expansive epicontinental seas, gravity assisted sedimentary processes that on modern shelves are thought of as the main conveyors of mud are unlikely to carry mud more than 100 km's from the shoreline. Even under the most optimistic assumptions more than a few hundred kilometers of offshore mud transport seems highly unlikely. On the other hand, petrography, stratigraphic patterns, and sedimentary features strongly suggest that the mud blankets of continental interiors were sourced from surrounding land areas and that their terrigenous component was carried to distal locations without the benefit of gravity. For the interiors of epicontinental seas, in most instances measuring 1000 or more kilometers in width, mud was probably carried in by bottom currents that carried silt as well as flocculated mud in bedload. This much we can say from comparing ancient epicontinental laminated shales to flume produced modern analogs. These currents were likely driven by seasonal winds, and may have been aided by tidal currents, intermittent storm reworking of the muddy substrate, and lowering of sea level. How one would recognize the imprint of storm waves and tidal currents in distal mudstones and shales is currently not known with any degree of certainty. However, it will soon be possible to model these processes with muddy suspensions, and look for textures that may help to identify them in the rock record.

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