Carbonate mud deposited below storm wave base: A critical review

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INTRODUCTION

As it pertains to carbonate mud generation, there are both neritic and open water, pelagic carbonate mud factories. The origin of carbonate mud is well documented (Appendix A). With the exception of whitings in select modern locations, carbonate mud has a biogenic origin. As it pertains to carbonate mud transport, existing carbonate facies models emphasize suspension settling. Literature on off-bank sediment gravity flow transport is well established (e.g., Goldstein et al., 2012), and there is a growing amount of current literature on carbonate slope processes and the reworking of sediment via contour currents (e.g., Betzler et al., 2014). Even so, existing literature on sediment gravity flows and contour currents are bias toward the documentation and interpretation of coarser-grained carbonate facies, with limited focus on carbonate mud transport.

Here, we focus on a critical review of carbonate mud deposited below storm wave base in modern and ancient carbonate settings. We use storm wave base as an indicator of marine offshore deposition, beyond the majority of wave influence, with the caveat that storm wave base is likely not a feature found at one fixed water depth and can vary significantly with sea floor morphology (e.g. carbonate platform versus ramp), through time, and with storm strength (Peters and Loss, 2012).

Pelagic carbonate deposits are commonly associated with type II, oil-prone organic matter and can be exceptional source rocks (e.g., Miceli Romero et al., 2018). They are also proving to be important reservoir rocks in unconventional hydrocarbon plays, for example the Eagle Ford and Niobrara of North America (Sonnenberg, 2011; Hentz et al., 2014). Because coarser-grained carbonates have historically been important hydrocarbon reservoirs, they have been the focus of decades of research. As a result, there are some significant knowledge gaps pertaining to the deposition of thick, ancient carbonate mudstone successions deposited below storm wave base.

Researchers have long assumed that carbonate mud was deposited through suspension settling below storm wave base. However, a modern understanding of carbonate mud deposition contends that depositional mechanisms are not limited to suspension settling. In fact, flume experiments have demonstrated that, like terrigenous mud, carbonate mud forms floccules and is transported in bedload, forming ripples (Schieber et al., 2013).

The assumption that carbonate mud, mostly pelagic in origin, was deposited through suspension settling alone is largely based on the fine grained nature of carbonate mud and the fact that there is no sedimentary fabric preserved to suggest otherwise. This apparent lack of sedimentary fabric arises from a few common obstacles in regards to the sedimentologic examination and interpretation of carbonate mudstones. Properly identifying sedimentary structures, like ripples for instance, in mudstones requires detailed cm-scale description of carbonate mudstone successions from outcrop and core coupled with careful petrographic analysis using ultra-thin, thin sections and scanning electron microscopy, all with a trained eye. Not many research studies have set out to do this specifically in carbonate mudstone successions deposited below storm wave base. Furthermore, carbonate mudstone facies are difficult to image through scanning electron microscopy (SEM) due to the lack of grain size and compositional contrast. Carbonate mudstone successions deposited below storm wave base are commonly burrowed, obscuring the majority of the original depositional fabrics and sedimentary structures. Quantifying the volume of depositional versus diagenetic micrite in carbonate mudstones can be challenging, particularly in successions that have experienced significant burial diagenesis. Existing studies on periplatform deposits suggests the presence of aragonite leads to early cementation that preserves primary structures. However, during burial diagenesis calcareous tests in marls are more easily lost to dissolution and overgrowth than in purer carbonate mudstones, like chalks or pelagic limestones (e.g., Frank et al., 1999; Frank and Bernet, 2000; Westphal et al., 2004). At greater depth and through interaction of basinal fluids micro- and nannofossil features may be lost, in some cases, making it difficult to quantify the original

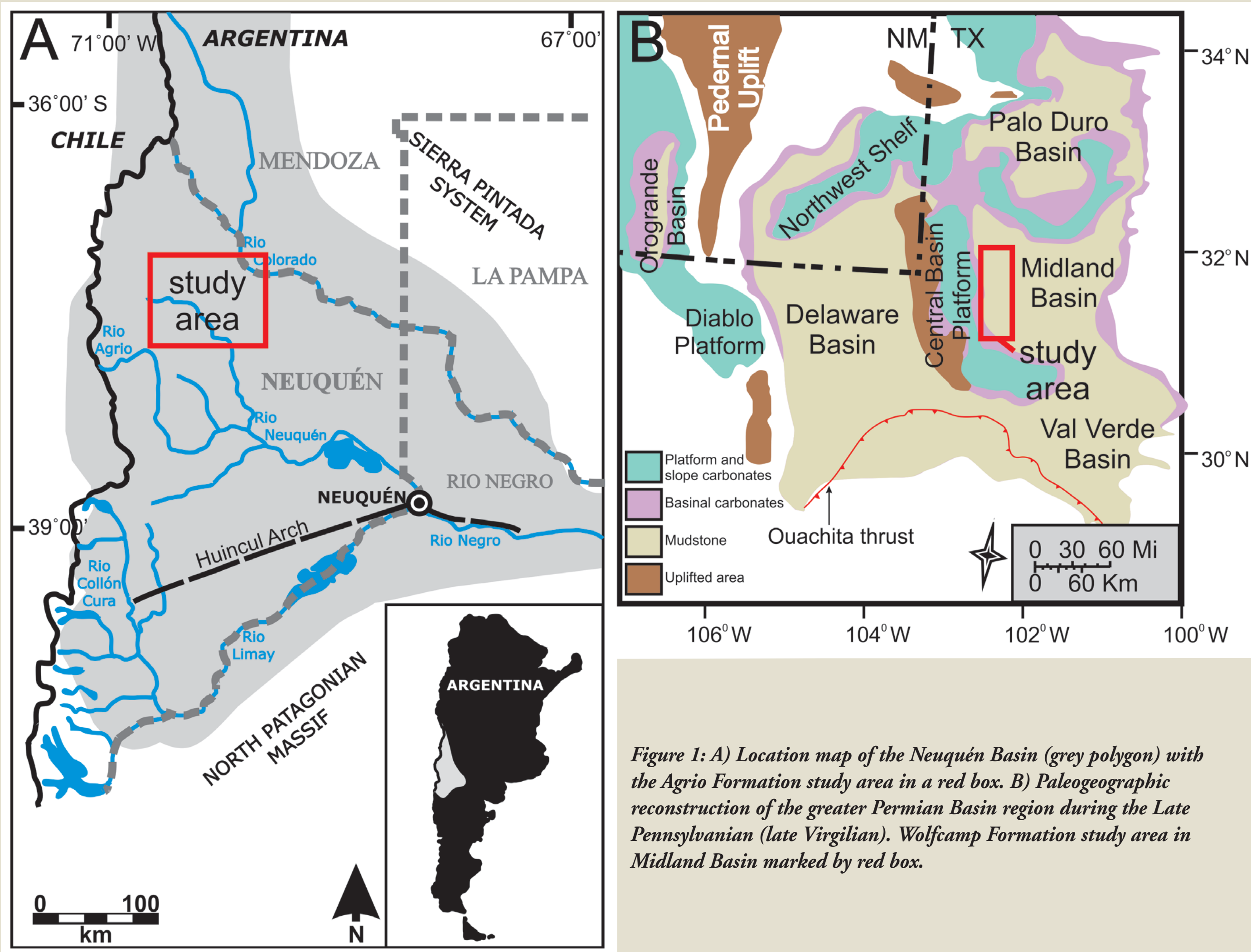

Figure 1: A) Location map of the Neuquén Basin (grey polygon) with the Agrio Formation study area in a red box. B) Paleogeographic reconstruction of the greater Permian Basin region during the Late Pennsylvanian (late Virgilian). Wolfcamp Formation study area in Midland Basin marked by red box.

volume of nanno- and microfossils that make up the carbonate mudstone.

The carbonate mud transport problem is brought into particular focus in interpreting the depositional origin of thick successions of carbonate mudstone deposited below storm wave base in an ancient marine environment. Estimated sedimentation rates from thick carbonate mudstone-dominated successions deposited below storm wave base challenge the notion that suspension settling was the only depositional mechanism. Additionally, a handful of classical chalk successions, like the Eagle Ford Group and upper Cretaceous Danish Chalks, have recently been re-interpreted to contain evidence of current-influenced mud deposition, not just pelagic biogenic production followed by suspension settling (Rasmussen and Surlyk, 2012; Minisini et al., 2018). Minisini et al. (2018) interpret several carbonate-rich mudstone facies in the Eagle Ford Group to have been deposited by bottom currents. Rasmussen and Surlyk (2012) interpret upper Cretaceous Danish Chalks as contourite deposits.

In light of this more recent sedimentologic understanding, the transport of carbonate mud in the context of carbonate facies models needs to be re-visited and re-evaluated. The carbonate facies models we teach in geology classrooms in University and industry settings across the country need to be updated to incorporate a broader range of carbonate mud depositional mechanisms.

A REVIEW OF CARBONATE MUD TRANSPORT

Here we focus on a review of carbonate mud transport mechanisms. For a review of both neritic and pelagic carbonate mud generation, see Appendix A. In carbonate platforms with steep slopes that descend to a deep basin floor, platform and/or slope-derived carbonates are re-suspended and deposited on the slope and basin floor (e.g., Eberli et al., 2004). Re-suspended carbonate slope deposits represent a significant volume of sediment deposited on the carbonate platform and have been the focus of renewed research interest, given their relevance for new hydrocarbon targets (Reijmer et al., 2015a). In general, upper slope settings are connected to sediment producers at the platform edge, dominated by high slope angles, coarse-grained deposits, cementation and platform margin failure. Mid slope settings are characterized by a decrease in slope angle, an increase in mud percentage, mud onlap, coarse-grained deposits as a result of re-sedimentation and slope failure, and channel levee development. The lower slope displays similar features with the added impact of contour currents. And finally basin deposits are characterized by high pelagic input, drift deposits and periplatform ooze (Reijmer et al., 2015a). Periplatform oozes occur on modern carbonate platform slopes, like the Bahama platform slopes, and consist of platform-derived neritic mud and sand mixed with pelagic carbonate material, like micro- and nannofossil tests. Recent studies highlight the complexity of Bahama slope processes through time, during sea level lowstand and highstand conditions, with the interaction of slope failure, turbidity and contour currents (Wunsch et al., 2017). Fundamentally, Bahama bank slopes, where periplatform drift sediment is found, reflect the interaction between off-platform sediment export as debris flows and basin-derived contour currents (Betzler et al., 2014).

Channel-levee systems that have long been documented in deepwater siliciclastic systems have only recently been documented on the western carbonate slope of the Great Bahama Bank (Mulder et al., 2014). Their discovery has implications for sediment transport, including carbonate mud, from shallow to deep water carbonate systems.

Study of carbonate turbidite systems is well established. Classical examples are found from the Cretaceous to Paleogene succession of the European Alps and Appenines (e.g., Goldstein et al., 2012). In general, carbonate debris flow deposits are poorly sorted with grains up to cobble or boulder size and include floatstone and packstone facies. Carbonate debris flow deposits, like those from the Miocene of Spain, are mostly defined as carbonate breccias (e.g. Goldstein et al., 2012). Normally graded, skeletal and foraminiferal wackestones to packstones with scoured bases are interpreted to have been deposited by turbidity currents (Goldstein et al., 2012). Sharply based, fining-upwards packages of grainstones to packstones and/or packstones to wackestones, (carbonate mudstones exclusive) interpreted as calcareous turbidites can display incomplete Bouma sequences

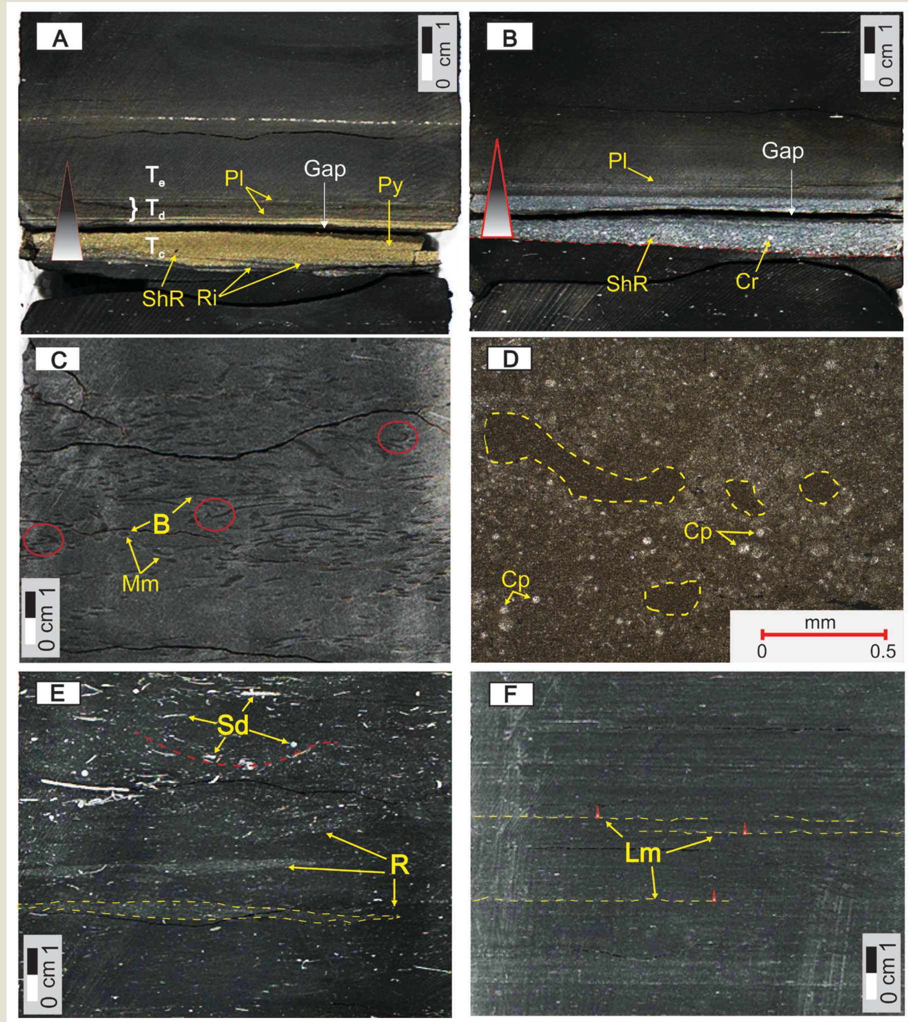

Figure 2: A and B) Partial Bouma sequence in calcareous mudstone of the Wolfcamp Formation (contrast enhanced) interpreted as turbidite deposits. A) Normally graded bed displaying tripartite fining upward succession (grey triangle): coarse siltstone to medium siltstone to fine siltstone. Bouma sequence elements are labeled Tc-Te (after Bouma, 1962). Ri= rippled interval, Pl= planar laminations, Py= pyrite, and ShR=shale rip up clast. B) Same normally-graded bed (grey triangle) as shown in A showing the highly sharp and erosive basal contact (red dashed line) of the base of the turbidite bed. Very faint planar laminations (Pl) occur towards the top of this bed. C and D) Key feature in facies tan, bioturbated, calcareous, medium siltstone (contrast enhanced) interpreted as contourite deposits. C) Example of low diversity high-intensity bioturbation. Burrow traces are largely horizontal ovoid to elongated and sub-horizontal. Red circles mark "fish-hook" structure interpreted as Phycosiphon incertum. *B= bioturbation (yellow arrows), Mm= mantle material (light-gray material surrounding burrow traces). D) Example of bioturbation in contour currents in thin section. Burrow traces are delineated by dashed yellow lines. Burrows are filled with argillaceous material. Cp= calcispheres. E) Example of ripples (R) and horizontal to wavy lamations in hand sample in calcareous mudstone deposits interpreted as contourites. The preferential wavy fabric of skeletal debris (Sd) is delineated by red dashed line. F) Discontinuous laminae in calcareous mudstone. Lm = laminations. Notice the slightly erosive bottom contacts (a few bottom contacts have been marked by a dashed yellow line). Red triangles mark fining upward trends of laminae. Laminations are at a slight low angle to one another, suggesting they may record mud ripples. Interpreted as distal contourite.*

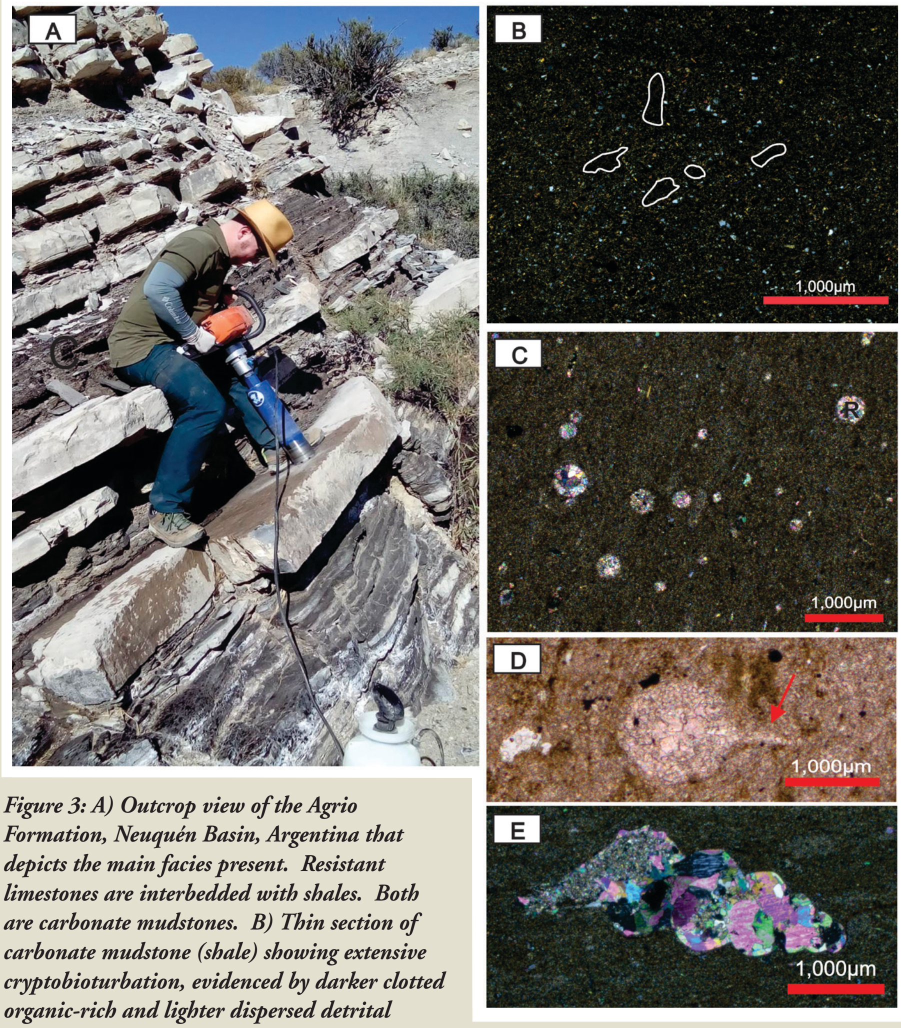

Figure 3: A) Outcrop view of the Agrio Formation, Neuquén Basin, Argentina that depicts the main facies present. Resistant limestones are interbedded with shales. Both are carbonate mudstones. B) Thin section of carbonate mudstone (shale) showing extensive cryptobioturbation, evidenced by darker clotted organic-rich and lighter dispersed detrital silt-rich domains. Several examples of the darker silt-free domains are outlined in white. C) Thin section of carbonate mudstone (resistant limestone) showing blocky spar calcite replaced radiolarians (R). Mottled and massive texture suggests extensive cryptobioturbation. D) Sparry calcite replaced radiolarian with preserved spine (red arrow). E) Blocky spar calcite recrystallized or replaced benthic foraminifera. Note both larger grained sparry calcite and smaller grained micritic cement within the foram, indicating multiple diagenetic events.

with Ta, Tb, and sometimes Tc subdivisions (Eberli, 1991; Playton et al., 2010). There is also a wealth of literature on modern carbonate turbidite deposits in the Bahamas (e.g., Bernet et al., 2000; Swart et al., 2000; Reijmer et al., 2015b).

CASE STUDIES

Here we present two case studies from thick carbonate mudstone dominated successions deposited below storm wave base (Figure 1). Both formations provide evidence that existing carbonate facies models that emphasize suspension settling below storm wave base are insufficient to account for mud deposition. In fact, when both of these carbonate mudstone successions are properly sedimentologically examined, there is ample evidence for current-influenced, rather than suspension settling dominated, deposition.

The first case study from the Upper Pennsylvanian to lower Permian Wolfcamp Formation preserves a deep water carbonate-dominated turbidite system deposited downdip from the shallow marine Central Basin Platform in the Midland Basin of West Texas, a sub-basin of the greater Permian Basin (Handford, 1981; Mazzulo and Reid, 1989). The second, the Lower Cretaceous Agrio Formation, of the Neuquén Basin of Argentina, was deposited on a mixed siliciclastic-carbonate ramp where proximal shoreface sandstone bodies transition to offshore siltstones to distal carbonate mudstones (Schwarz et al., 2018). These two successions represent two different types of deep water carbonate mudstone depositional systems.

Case study 1: Wolfcamp Formation, Midland Basin, TX

Carbonate platform to slope successions from the Permian Basin have been heavily studied (e.g., Tinker, 1998; Kerans and Tinker, 1999). Lower Permian debris flow and turbidite deposits from the Permian Basin in West Texas are cited as a type example a mud-dominated gullied foreslopes associated with broad and/or protected platform interiors (Playton et al., 2010). Slope to basin floor deposits in this Permian system are quantified as roughly half debris- and grain-dominated and half mud-dominated deposits (Playton et al., 2010).

The mudstone-dominated Wolfcamp Formation was deposited well below storm wave base, with published Midland Basin water depth estimates ranging from between 120 and 490 m (Hobson et al., 1985; Mazzulo and Reid, 1989). Wackestones and packstones, interpreted as debris flow deposits on the platform slope, and grainstones that exhibit Bouma sequences, interpreted as carbonate turbidites, have long been recognized in the Wolfcamp Formation (Handford, 1981). Organic-rich shales or carbonate mudstones in the Wolfcamp Formation have previously been interpreted as deposited from suspension settling (Handford, 1981).

The Wolfcamp Formation also preserves many examples of carbonate mudstone deposits with sedimentary structures, like ripples, that indicate bedload transport. Normally graded calcareous siltstone deposits preserve partial Bouma sequences in a tri-partite succession. A sharp, erosive basal contact is overlain by 1) current ripple-laminated coarse siltstone which grades upwards into 2) plane parallel-laminated medium siltstone, grading into 3) massive fine siltstone (Figure 2A, B). In thin section, plane-parallel laminated siltstones preserve reverse grading between laminations indicative of mud ripples. Based on the sedimentary structures present, these tri-partite layers may be interpreted as the Tc, Td, and Te portions of a Bouma sequence, respectively, even though they are all composed of mud-sized grains. This interpretation diverges from a classical Bouma sequence in which the Tc layer is rippled sandstone, Td is plane parallel laminated siltstone, and Te is massive mudstone (Bouma, 1962). Because mud flocculates, it acts like a coarser-grained particle. Therefore, both the ripple-laminated coarse siltstone (Tc) and plane parallel-laminated medium siltstone (Td) are interpreted as being deposited by active currents. This is in contrast to a traditional Bouma sequence interpretation in which plane parallel-laminated siltstone (Td) is interpreted to represent suspension settling. Thin section petrography reveals silt-size carbonate grains are composed largely of disarticulated bioclasts, like shell fragments, crinoids and fish bones.

A subset of calcareous mudstone deposits in the Wolfcamp Formation are interpreted to have been deposited by contour currents. Variably bioturbated medium to fine siltstone displays ripples, low angle laminations, scours and normally graded lags (Figure 2C - F). Bioturbation is considered a hallmark feature of contour currents, as they provide continuous circulation and oxygenations of the sea floor (Shanmugam, 2008). The presence of ripples, scours and normally graded lags within are consistent with current deposition. Interlaminated claystone and siltstone within these deposits suggests migration of silt and clay floccule ripples during multiple low flow velocity (< 25 cm/s) episodes (Yawar and Schieber, 2017).

Non-laminated massive mudstone deposits that lack petrographic evidence of bioturbation are also found in the Wolfcamp Formation. These facies are interpreted to record classical suspension settling deposition. Importantly, massive mudstone only represents a small fraction of the thickness of the Wolfcamp. Because current indicators in the Wolfcamp Formation are dominant, sedimentation rates were likely much higher than previous suspension-settling dominated models suggested (e.g., Handford, 1981).

Case study 2: Agrio Formation, Neuquén Basin, Argentina

The Lower Cretaceous Agrio Formation contains a total of ~600 m of carbonate mudstone in its lower Pilmatué and upper Agua de Mula Members in outcrop localities from the central to northern Neuquén Basin. These deposits record paleogeographically distal marine environments in the basin (Spalletti et al., 2011; Schwarz et al., 2018). Limestones that are resistant in outcrop are interbedded with shales (Figure 3A) (Spalletti et al., 2011). Both limestones and shales are carbonate dominated and consist of mud-sized grains, hence are carbonate mudstones.

In the Agrio Formation of Argentina, cryptobioturbation, only visible in thin section, obscures original sedimentary structures in carbonate mudstone deposits, making depositional mechanisms difficult to interpret (Figure 3B). Bioturbation is evident from a mottled texture that includes silt-free domains. Furthermore, a complex diagenetic history is evident in the Agrio Formation. Silica tests of radioloaria, which likely underwent Opal A to Opal CT to microcrystalline quartz transformations have been dissolved and replaced with drusy calcite (Figure 3C, D). Similarly, benthic foraminifera tests have been dissolved and replaced with drusy calcite (Figure 3E). Though radiolarian and benthic forams are present in the carbonate mudstone, they do not represent the bulk of the mudstone by volume. Instead, the majority of the mudstone is composed of micrite. Given that many Cretaceous age distal marine carbonate mudstone deposits are chalks composed of coccolithophore tests, it is reasonable to hypothesize a chalk origin for muddy limestones of the Agrio Formation. However, burial diagenesis has also destroyed nannofossil tests in some localities, precluding nannofossil identification and quantification of coccolithophore abundance by sediment volume. And a lack of mineralogical contrast within samples yields poor SEM imaging results. As a result, the origin of the micrite is ambiguous. Due to bioturbation and significant burial diagenesis, direct evidence of current influence from sedimentary structures is largely lacking in this carbonate mudstone succession.

It is unlikely that pelagic biogenic mud deposition alone was responsible for carbonate mud or micrite deposition in the Agrio Formation. There are robust age constraints on the deposition of the Agrio Formation from extensive biostratigraphy studies that are tied to radiometric tuff dates on the succession. These known age constraints combined with the stratigraphic thicknesses of carbonate mudstone successions suggest 8 cm/ ky sedimentation rates, almost an order of magnitude greater that average calcareous ooze deposition rates from Cretaceous-aged chalks (1.84 cm/ ky, Locklair et al., 2011). Therefore, pelagic carbonate sedimentation was likely not the only mud depositional mechanism at work in the sub-storm wave base portion of the ramp. Bottom currents were likely a prominent feature in the basinal environment. A documented shallow water carbonate factory on the eastern margin of the Neuquén Basin may have sourced carbonate mud (Spalletti et al., 2011). Offshore-directed bottom currents may have transported carbonate mud from proximal to distal portions of the basin.

DISCUSSION

Though we know that carbonate mud can be transported as floccules in bedload as demonstrated by Schieber et al. (2013), we don't know how common bedload transport is as compared to suspension settling across a variety of modern and ancient carbonate settings. This is partly because many ancient thick successions of carbonate mudstone, nominally deposited below storm wave base, have yet to be sedimentologically re-evaluated with an updated understanding of mudstone depositional processes.

There has been a significant advancement in recent years regarding sediment transport, depositional processes, and resulting facies and stratigraphic architecture on platform slopes (e.g., Betzler et al., 2014; Reijmer et al., 2015a; Wunsch et al., 2017). Because the slope is the main environment where neritic mud can be transported to deep water environments, this is valuable research. Yet still, with so many modern case studies from the Bahama platform slope settings, is our understanding of carbonate mud depositional processes in ancient systems bias? What aspects of the depositional mechanisms in modern systems are actually analogous to Mesozoic and younger carbonate systems?

Armed with the knowledge that carbonate mud can be transported as floccules in bedload, ocean currents below storm wave base, like contour currents, should be reconsidered as capable of transporting large volumes of carbonate mud, not just sand, in bedload. Recently emerging studies focused on contour current deposition will help us toward that goal (e.g., Betzler et al., 2014). Assuming contour currents are significant carbonate mud transport agents, is all the mud below storm wave base pelagically sourced? Is some fraction originally neritically sourced and transported via the slope to deep water environments? How do those transport mechanisms vary across different modern and ancient settings?

The realization that carbonate mud can be carried in bedload is significant to the long-standing interpretation that mud only settles out of suspension during the waning phases of a turbidity current. Existing literature on fine-grained turbidites, like Bouma and Stone (2000), focuses heavily on the sand fraction and interprets mud as settling out of suspension, predating most publications in the last decade on mud transport in bedload. This interpretation should be re-visited in light of advances in sedimentologic understanding.

CONCLUSIONS

Carbonate mudstone deposited in sub-storm wave base marine settings are common and can be high quality source rocks and unconventional reservoir rocks. We now understand current-influenced deposition of carbonate mud, even below storm wave base, is significant. As a community, let's challenge ourselves to incorporate a modern sedimentological understanding of carbonate mud deposition and update classical carbonate facies models accordingly.

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APPENDIX A

A review of carbonate mud generation

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Carbonate settings have historically been subdivided into platform-slope-basin floor or ramp systems. Within these systems, carbonate mud has either a neritic or pelagic origin. In modern neritic tropical to sub-tropical environments, like the Great Bahama Bank and Florida Shelf, green codiacean algae, like *Penicillus*, are thought to be responsible for much of the shallow water mud generation since these algae break down into micron-sized aragonite needles (Stockman et al., 1967; Neumann and Land, 1975). Secondarily, biomicritization of grains by boring organisms, as well as fecal pellet production, play a role in shallow water micrite generation. There is a long standing debate over the organic versus inorganic origin of Bahamian mud (Shinn et al., 1989). Milky water column events consisting of suspended aragonite needles, termed whitings, are a common occurrence in both the Bahamas and Florida Shelf (Robbins et al., 1997). Whitings may be inorganic precipitation events or biologically induced and may be responsible for a significant volume of shallow water mud generation over time (Shinn et al., 1989; Robbins and Blackwelder, 1992; Purkis et al., 2017). Recent studies link precipitation events to ocean circulation patterns, specifically off-platform ocean currents that periodically reach the platform (Purkis et al., 2017).

Temperate carbonate seafloors host coarse-grained carbonates and generally lack mud producing organisms. The origin of carbonate mud in temperate, non-tropical settings is less common and more enigmatic. Studies of modern settings like South Australia suggest mud is composed of macerated shell fragments, rather than from aragonite precipitation in seawater documented from tropical to sub-tropical settings (O'Connell and James, 2015).

Pelagic biogenic production is an important source of carbonate mud. In Mesozoic and younger open water systems, pelagic biogenic production by calcareous organisms has resulted in the deposition of micro- and nannofossil tests and calcareous ooze deposition, preserved as pelagic limestones and chalks in the sedimentary record (Ekdale, 1984). Microfossils, like foraminifera, make up pelagic limestone units, like those found in the Cretaceous aged Eagle Ford, which are interbedded with organic and clay-rich shale beds (Denne et al., 2014; Hentz et al., 2014; Denne et al., 2016; Denne and Breyer, 2016; Fairbanks et al., 2016). Nannofossils, specifically coccololithophores, make up chalk deposits. Jurassic-age chalks preserved in the North Sea and across portions of Europe are among the most heavily cited geologic examples (Herrington et al., 1991). Chalks deposited in the Cretaceous Western Interior Seaway, like the Niobrara represent typical pelagic biogenic coccolithophore-rich mud deposition (Longman et al., 1998; Sonnenberg, 2011). Average calcareous ooze deposition rates from Cretaceous-aged chalks is 1.84 cm/ ky (Locklair et al., 2011). Where clay dilution was locally high, marls instead of chalks are preserved (Longman et al., 1998; Sonnenberg, 2011).

Large volumes of carbonate mud also occur in mud mounds. Mud mounds are carbonate buildups with depositional relief that are composed dominantly of carbonate mud, peloid mud, or micrite (Bosence and Bridges, 1995). Mud mounds may be microbial or biodetrital in nature (Bosence and Bridges, 1995). Microbial mounds are relatively in-situ features, constructed from the trapping and baffling of sediment by microbial mats (Bosence and Bridges, 1995; Lees and Miller, 1995; Monty, 1995), whereas biodetrital mud mounds are composed of broken and transported skeletal debris (Bosence, 1995; Bosence and Bridges, 1995; Bridges, 1995; Taberner and Bosence, 1995). In biodetrital mud mounds, mud may be generated locally or transported significant distances (Bosence and Bridges, 1995). These two types of mounds may or may not be mutually geographically exclusive. In some cases, microbial facies transition to biodetrital facies within one mound (Bosence and Bridges, 1995). Mud mounds can be found in a variety of settings ranging from deep basinal, to lower slope, to shelfal or lagoonal environments (Bosence and Bridges, 1995; Pratt, 1995).

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