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Lazar, O. R., K. M. Bohacs, J. Schieber, J. H. S. Macquaker, and T. M. Demko, 2022, Laminae, laminasets, beds, and bedsets, *in* K. M. Bohacs and O. R. Lazar, eds., Sequence stratigraphy: Applications to fine-grained rocks: AAPG Memoir 126, p. 89–106.

Laminae, Laminasets, Beds, and Bedsets

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No problem of geology compares in importance with the question of the origin of bedding.
—Walther, 1894, p. 623, cf. Campbell, 1967

ABSTRACT

This chapter discusses the smaller scales of the stratal hierarchy—from lamina to bedset. In mudstone, these typically range from less than a millimeter to hundreds of millimeters in thickness. This is the scale of strata that records individual depositional events and environmental changes in bottom energy, biogenic production rates, and redox conditions. Recognition and description of this scale of strata enables recognition of repeated patterns and associations of rock-property variation (facies), their distribution in three dimensions, and interpretation of the proximate causes of variation (to enable prediction away from sample control).

In this chapter, we define essential stratal elements from laminae (the smallest units) to bedsets (larger units) and provide key recognition criteria and examples of these elements in cores, outcrops, and thin sections. Bohacs et al. (2022, Chapter 5 this Memoir) discusses how beds and bedsets stack into parasequences and how to synthesize this next larger scale of strata into an overall picture of a depositional environment (in terms of sediment supply; dominant erosional, transport, and depositional processes; and oceanographic conditions)—and make the tie with the well-log response.

Bedding is a key characteristic of sedimentary rocks (as introduced in Lazar et al., 2022a, Chapter 2 this Memoir); it records variations in sediment input and accumulation, as well as benthic energy and the effects of sediment disruption by organisms. Our approach

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DOI:10.1306/137122993860

to describing bedding builds upon Campbell's (1967) work, which emphasizes the genesis of the bed's characteristics that reveal depositional conditions and history. Bedding is described by two sets of essential attributes: (1) the shape and geometry of bed bounding surfaces and (2) the continuity, shape, and geometry of laminae between the bounding surfaces (in this context, "shape" denotes the spatial configuration of a lamina or surface, whereas "geometry" signifies the spatial arrangement of bedding elements with respect to the surrounding bedding elements, i.e., parallel or nonparallel).

LAMINAE, LAMINASETS, BEDS, AND BEDSETS: DEFINITIONS AND KEY RECOGNITION CRITERIA

These small-scale stratal units and their bedding attributes are commonly visualized in mudstone successions by close inspection of fresh surfaces of core or hand specimens and in digital scans of thin sections (see Lazar et al., 2022a, b, Chapters 2 and 3 this Memoir; Schieber, 1989, 1994, 1998, 1999; Bohacs and Schwalbach, 1992; Macquaker and Gawthorpe, 1993; Macquaker and Taylor, 1996; Macquaker et al., 1998; Plint et al., 2012; Könitzer et al., 2014; Lazar et al., 2015a, b). The main attributes of laminae, laminasets, beds, and bedsets are reviewed in the sections that follow and summarized in Figure 1B of Lazar et al. (2022a, Chapter 2 this Memoir).

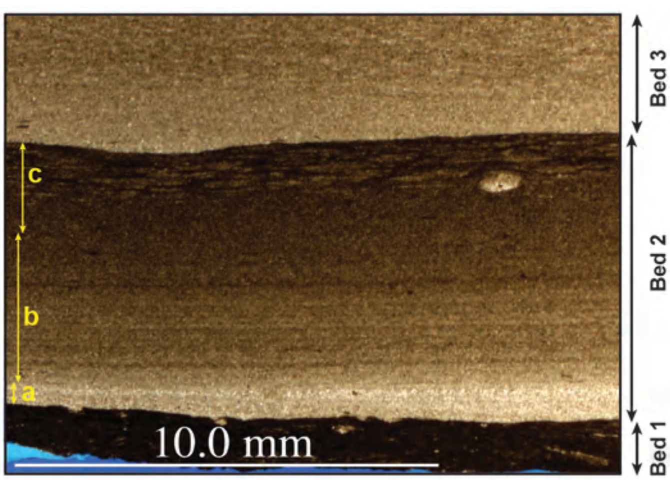


Figure 1. Careful examination of the Mowry Shale in a thin section reveals the presence of individual beds with scoured bases and burrowed tops indicating episodic, discontinuous sedimentation. Notice that Bed 2 consists of three laminasets (a, b, and c; after Macquaker et al., 2010; see Figure 5 for their detailed description).

Laminae

A lamina is the smallest megascopic layer (typically ≥0.1 mm in thickness) without internal layers (Campbell, 1967). It is bounded at base and top by lamina surfaces formed by erosion or nondeposition. Lamina surfaces are analogous to bedding surfaces, but are of smaller areal extent and shorter time of formation, because they are contained within beds.

In a genetic sense, a lamina is very similar to a bed. It does, however, differ from a bed in four significant aspects.

- It is relatively uniform in composition and texture.
- It is never internally layered at megascopic scale (i.e., ≥~0.1 mm).
- It has a smaller lateral extent than the enclosing bed (on the order of centimeters in current ripples to tens of meters in abyssal deposits).
- It forms during a shorter span of time than the encompassing bed.

Lamina continuity, shape, and geometry are the three key attributes for describing lamination (Figure 1B of Lazar et al., 2022a, Chapter 2 this Memoir). Within their relatively small lateral extent, laminae can be *continuous* or *discontinuous*; *planar*, *curved* (single variation), or *wavy* (multiple variation); and *parallel* (laminae do not intersect) or *nonparallel* (laminae intersect). Description of these laminae attributes is essential to the identification of primary sedimentary structures, such as planar, ripple, and trough cross-bedding, as well as of secondary disruption by burrowing or reworking, which informs the interpretation of the paleo-environments of deposition. They are equally important for relating the permeability, porosity, and seal capacity to reservoir engineering.

Laminae are interpreted to form in a shorter span of time than the encompassing beds, typically in a few seconds to one or more years, in an "instant of geological time" (Campbell, 1967, table 1, p. 17). Laminae commonly form in response to small-scale fluctuations within a single flow or depositional event at the rates of the controlling processes (e.g., boundary layer bursts and sweeps under currents, wave oscillation currents, seasonal growth of planktonic or benthic organisms, or deposition by dilute hemipelagic suspensions or wind).

Most textbooks consider lamination to be a primary characteristic of "shale." Lamination is commonly interpreted to indicate predominantly continuous sediment accumulation by suspension settling under relatively calm and persistently anoxic bottom water depositional conditions (e.g., Tyson et al., 1979;

Demaison and Moore, 1980; Schlanger et al., 1987). Differentiating laminae from very thin beds is therefore important for discerning whether sediment accumulation was predominantly continuous or episodic. "Parallel-laminated mudstone" implies continuous sediment accumulation during a single depositional event, whereas "parallel-bedded mudstone" implies discontinuous sediment accumulation under repeated depositional events of similar character. Closer examination of a mudstone, for example, may reveal the presence of individual beds with scoured bases and burrowed tops indicating episodic, discontinuous sedimentation (with breaks in sediment accumulation sufficient to allow biogenic colonization; Figure 1). We heartily recommend a close reading of Campbell (1967), Van Wagoner et al. (1990), and Lazar et al. (2015a, b) for a full introduction to the above concepts and their implications.

Fissility is another widely used defining attribute of "shale" and has been commonly ascribed to lamination. Fissility, however, is not identically equal to lamination—fissility is a by-product of weathering and unloading, and not a unique property of a rock or its original depositional fabric. Fissility develops along the weakness planes of many origins (including consolidation, compaction, and diagenesis) and is mostly attributed to the nature and amount of cement (Ingram, 1953). Fissility is not very useful for classification. For example, a fresh piece of nonfissile mudstone (from either an outcrop or a core) can develop well-defined fissility during weathering over short timescales—so what went into a storage box as a "mudstone" would later be called a "shale" although there was no change in texture, bedding, or composition. (We have witnessed a newly drilled and slabbed core of Wealden Shale change from a continuous, coherent slab into a mass of "poker chips" because of salt crystallization and unloading effects over the course of three weeks.) Thus, fissility is not a fundamental property of a mudstone.

Laminasets

A laminaset is a conformable succession of genetically related laminae that are bounded by laminaset surfaces (Campbell, 1967). Commonly, laminasets consist of a group of laminae that exhibit similar texture, geometry, and composition within a bed (Figure 1). Typical thicknesses of laminasets range from millimeters to centimeters in mudstone. The lateral extent of laminasets is smaller than that of the enclosing beds and varies from a few centimeters in current ripples to hundreds of meters in some turbidite beds. Laminasets are particularly common in current- and wave-ripple beds formed in fine-grained sedimentary rocks. Other common types of laminasets are associated with turbidite beds (e.g., Bouma a, b, c, d, e). Laminasets are interpreted to form in a shorter amount of time than the enclosing beds.

Beds

A bed is a relatively conformable succession of genetically related laminae or laminasets bounded at base and top by bedding surfaces of erosion, nondeposition, or correlative conformity (after Campbell, 1967). Beds are typically thin in fine-grained sedimentary rock, may range from millimeters (Figure 1) to tens of centimeters in thickness, and do not have a minimum or maximum absolute thickness. Beds can extend laterally on the order of meters to kilometers. Adjacent beds do not have to differ in lithofacies or composition, and a single bed can contain one or more lithotypes.

Recognition of beds depends on the identification of the surfaces that separate adjacent beds. Bed surfaces have no thickness, but they have lateral extents equivalent to the beds they bound. Bed surfaces can be planar, curved, or wavy. These surfaces thus terminate where the bed under examination ends, but the depositional surfaces can continue as bounding surfaces for adjacent beds or lose their physical expression across lateral lithological changes and become quite difficult to recognize (Campbell, 1967). Bed surfaces run the gamut from the obvious to the relatively obscure. Where the lithofacies of adjacent beds differ, bedding surfaces in the outcrop are distinct because weathering commonly etches these surfaces into relief. Where lithotype and sedimentary structures do not change substantially from bed to bed, bedding surfaces are revealed by patterns of internal features of the beds. Terminations of laminae or laminasets by truncation below a surface, or onlap or downlap above, are key criteria for identifying bedding surfaces as are colonization horizons or subjacent burrowing (Figures 1–5). Bounding surfaces between groups of repetitive or quasiperiodic successions of laminae are bed surfaces.

Not all beds, however, exhibit internal sedimentary features. This situation can be a result of bed deposition without internal layering or subsequent homogenization of sediment by burrowing organisms. Internal layering can also be hard to distinguish when the texture and composition of a bed vary within a very small range or when the size distribution of silt is very homogeneous. A modifier such as "homogeneous-looking" can be applied to describe these beds (Lazar et al., 2015a, b).

Some readers might wonder whether the prevalence of diagenesis in mudstone makes impossible the recognition of bedding. Diagenetic changes can, in some cases, make it challenging to see the original depositional bedding. Such changes, however, do not mean that the bedding did not exist. Extensive rearrangements are not common because mudstone has very low permeability; hence, practically all diagenetic changes are set by the starting character of the sediment. In our experience, careful examination of strata can commonly reveal sufficient clues to allow interpretation of the original bedding attributes.

To reiterate, this particular concept of a bed includes the following four distinct attributes:

- Beds have no minimum or maximum absolute thickness.
- Adjacent beds do not necessarily differ in texture or composition.
- A bed does not have to comprise only a single lithotype (indeed many beds show distinct systematic changes in composition).
- Beds record time-stratigraphic units of limited areal extent and relatively short times of deposition (minutes to hours to years, in “many moments of geological time”; Campbell, 1967, p. 17).

That last attribute is key for the application of sequence-stratigraphic concepts in that the stratification within a bed is genetically related and represents the product of a significant depositional episode or event. The bed, in the realm of sequence stratigraphy, is considered to be the building block of such larger scale stratal units as bedsets and parasequences. These concepts and their implications are discussed further in Bohacs et al. (2022, Chapter 5 this Memoir).

To summarize, beds record single flows or depositional events, whereas laminae record fluctuations within a single event. Minimal breaks occur in sediment accumulation during the formation of lamina, but potentially significant hiatuses in sediment accumulation between beds allow for biogenic colonization or reworking of sediment by current or wave activity.

Bedsets

A **bedset** is defined as a relatively conformable succession of two or more genetically related beds bounded by surfaces of erosion, nondeposition, or their correlative conformities (called bedset surfaces; Campbell, 1967). Bounding surfaces of a bedset are the bottom bedding surface of the lowest bed in the bedset and the upper bedding surface of the highest bed in the bedset (Figures 3–5; Campbell, 1967). These bounding surfaces typically mark the changes in depositional conditions within a particular depositional environment (e.g., scour surfaces, starvation surfaces, significant increase or decrease in energy level or sedimentation rate). The key characteristics of the bedset boundaries are that they separate beds that have distinct physical or genetic associations.

A bedset typically contains beds that have similar texture, sedimentary structures, and composition (Figures 3–5). A bedset may also consist of a succession of beds that exhibit a repetitive pattern of texture and structures, such as a stack of thin turbidite beds. Bedsets commonly found in mudstone successions include stacked wave ripples from a single storm, Bouma bcde muddy turbidites, stacked planar-parallel beds, stacked graded beds, and stacked current ripples from a single flood event. Bedsets are interpreted to record related or repeated flow episodes or events and form in “many moments of geological time”—usually hours to years (Campbell, 1967, p. 17).

Bedsets exhibit most of the characteristics of beds but differ in the following key aspects:

- Beds above and below the bedset typically differ in sedimentary structures, texture, and composition from those beds composing the bedset.
- Beds within a bedset are similar or repetitive.
- The thickness of a bedset consists of the total thickness of stacked beds.

Applications

The approach discussed above, initially codified by Campbell (1967) and Van Wagoner et al. (1990), and expanded to mudstone by Bohacs and Schwalbach (1992), Bohacs (1993), Macquaker and Gawthorpe (1993), Macquaker et al. (1998), and Lazar et al. (2015a, b), requires detailed and consistent description of stratal geometry, stratal surfaces, and the rocks bounded by those surfaces. This scale of observation is useful for capturing detailed information about the distribution of rock properties and depositional conditions. It is also essential for the construction of facies models and calibration to well-log responses that enable prediction of rock properties away from sample control. The stacking of laminae, laminasets, and beds into bedsets is important for the recognition of facies and facies associations. Additionally, our extension of Campbell’s (1967) nomenclature provides a standard for organization and comparison of observations that enables quantitative comparison of thickness, length, or areal extent of small-scale stratal units by different members of the same work group as well as between groups.

Analysis of the vertical stacking of beds and bedsets is essential for the interpretation of depositional facies in sedimentary rock successions in cores or outcrops. This approach is an outgrowth of Walther's observations (cited in Grabau, 1913, 1924) and is elaborated in numerous reports (e.g., Shaw, 1964; Allen, 1965; Harms et al, 1982; Walker and James, 1992). Vertical and lateral changes in bedding typically reflect a change in processes within depositional environments. A summary of vertical successions is presented in facies summary texts (e.g., Harms et al, 1982; Walker and James, 1992; James and Dalrymple, 2010). The stacking of bedsets forms other stratal elements, such as parasequences described in Bohacs et al. (2022, Chapter 5 this Memoir) and analogous parasequence-scale packages (storeys [*sic*]; e.g., Sprague et al, 2002), channel belts (e.g., Patterson et al., 2010), and submarine channel complexes (e.g., Zelt et al., 1995; Campion et al., 2005; Sprague et al., 2005).

COMMONLY OCCURRING SEDIMENTARY FEATURES AT LAMINA-TO-BEDSET SCALE IN MUDSTONES

This section provides the key recognition criteria and examples of commonly occurring sedimentary features in mudstone successions. It also includes some considerations regarding the continuity of the mudstone record, with a focus on the formation of lag deposits and diagenetic products.

Common Sedimentary Structures in Mudstones

Figures 2–6 and Tables 1 and 2 present examples of the 15 most common sedimentary structures and features at the lamina-to-bedset scale in mudstone (e.g., Bohacs et al., 2014; Lazar et al., 2015b), along with detailed recognition criteria. Figure 2 presents three types of ripples, Figure 3 illustrates the bed types associated with higher deposition rates (convolute lamination, parallel and graded beds), and Figure 4 shows features associated with erosion and reworking—scours, gutter casts, and lags. Figure 5 compares and contrasts common types of event beds: wave-enhanced-sediment-gravity-flow (WESGF) beds, tempestites, and turbidites. Figure 6 illustrates three common composite grain types in mudstone (floccules, organic-mineralic aggregates, and intraclasts).

Table 1 addresses "lag" beds *sensu lato*, that is, beds that contain concentrations of outsized particles: shells, bones, phosphate grains, and detrital silt. Finally, Table 2 summarizes the variety of commonly observed early (precompaction) cements and nodules along with their typical conditions of formation in marine mudstone. This topic is elaborated in Bohacs et al. (2022, Chapter 5 this Memoir).

The Discontinuity of the Mudstone Record

In our experience, based on the examination of a variety of Paleozoic to Cenozoic fine-grained rock successions, mudstone strata typically record discontinuous and unsteady sediment accumulation in between major time gaps. Calculated sedimentation rates must, therefore, be adjusted for these gaps, and we recommend calculation of sedimentation rates for each systems tract and depositional sequence, for time spans that are less than 5–10 million years in total duration. As discussed in Bohacs et al. (2005), based on the approach of Gardner et al. (1987), rate calculations should be converted to a year basis to allow direct comparison with modern oceanographic data (and models based upon them) using the following equation:

$$\text{Corrected sedimentation rate} = (\text{Reported rate}) \times (\text{Time interval of measurement (in years)})^{0.185} \tag{1}$$

On longer time intervals, sedimentation rates can be inferred based on paleontological data and isotopic ages. On shorter time intervals, sedimentation rates can be inferred based on the degree of bioturbation and presence and type of burrows (e.g., Wetzel and Aigner, 1986; Wetzel and Uchmann, 1998; Pemberton et al., 2001). For example, horizontal burrows indicate relatively slower sedimentation rates, whereas vertical burrows tend to indicate faster sedimentation rates (e.g., Seilacher, 2007).

Lag deposits are another indicator of the discontinuity of the mudstone record. Lags are residual accumulations of coarser particles produced when the underlying units were eroded and winnowed (e.g., Schieber, 1998). Recognition criteria and the sequence-stratigraphic implications of residual accumulation of coarser particles, such as shell beds following erosion and winnowing of the underlying strata, are presented in Table 1. Sparsely to abundantly

Sedimentary Structures	Recognition Criteria
Current ripple	• Asymmetric crest • Truncation or toplap below the top • Discontinuous, curved, nonparallel lamina geometry, more steeply inclined foresets upward • Downlap onto basal scour surface • Typically 0.5–30 mm thick in mudstone
Wave ripple	• Symmetric crest • Curved truncation with closely spaced onlap or concordant below, toplap or concordant above • Discontinuous, curved to wavy, nonparallel lamina geometry, flattening upward • Laminae lap onto basal surface in all orientations • Laminae dip at less than the angle of repose • Typically 0.5–30 mm thick in mudstone
Combined-flow ripple	• Curved to planar truncation with dominantly downlap below, wavy surface with toplap or concordant above • Discontinuous, curved, nonparallel lamina geometry • External form of wave ripple, internal form of current ripple, with one dominant direction of downlapping lamina (foresets indicating direction of bedform migration)

Examples

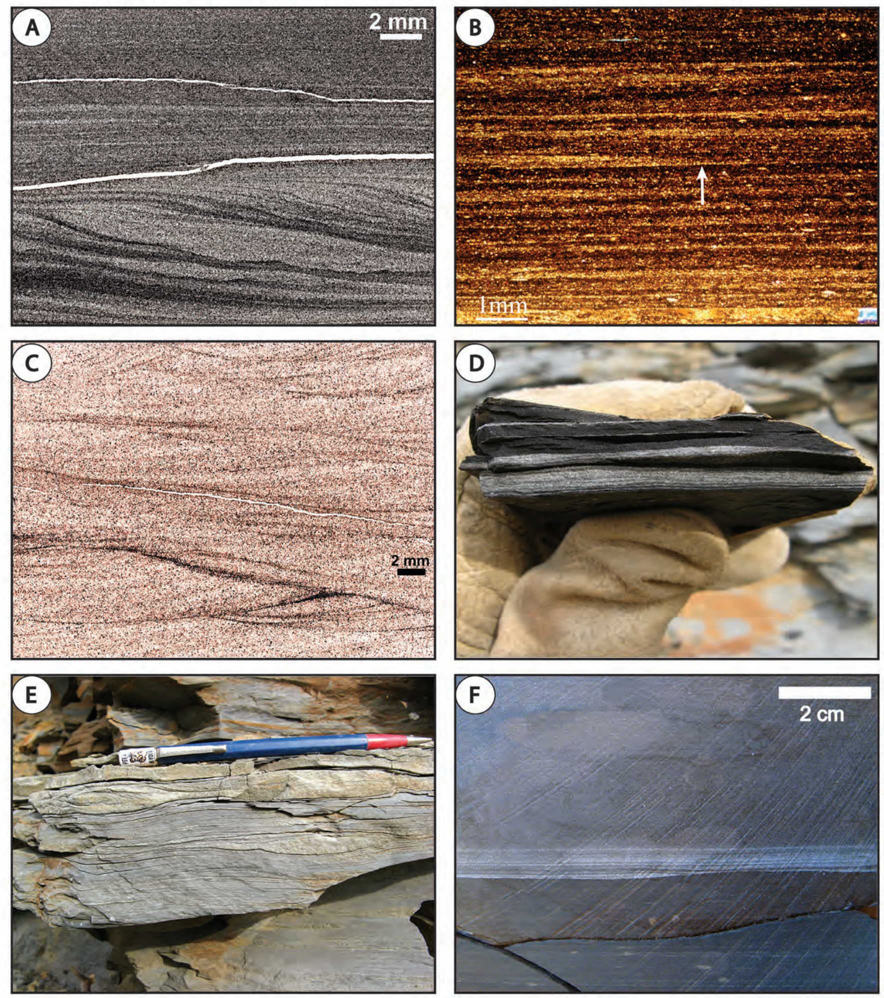


Figure 2. Key recognition criteria and examples of commonly occurring sedimentary features in mudstone successions: current ripple, wave ripple, and combined-flow ripple. (A) Sonyea–Middlesex, Devonian, New York; (B) Mowry Shale, Cretaceous, Utah (arrow pointing to downlapping laminae); (C) Ankareh Formation, Triassic, Utah; (D) New Albany Shale, Devonian, Kentucky; (E) New Albany Shale, Devonian, Kentucky (pencil is 15 cm long); (F) New Albany Shale, Devonian, Indiana (A–D; after Lazar et al., 2015b).

Sedimentary Structures	Recognition Criteria
Planar lamination	• Concordant below, concordant above • Planar parallel lamina geometry
Graded bed	• Sharp base, truncation of concordant below, concordant above • Continuous or discontinuous, planar- or wavy-parallel or structureless lamina geometry • Distinct, systematic changes in composition (mineralogy, organic-matter content/type, biogenic taxa, etc.) • The term normal grading is used to describe beds that display gradations from coarser particles at the base of each bed to finer particles at the top
Convolute lamination	• Discontinuous, wavy, nonparallel laminae geometry • Laminasets folded, stretched (necked), or both • Type of soft-sediment deformation structure developed syndepositionally or shortly after sediment deposition

Examples

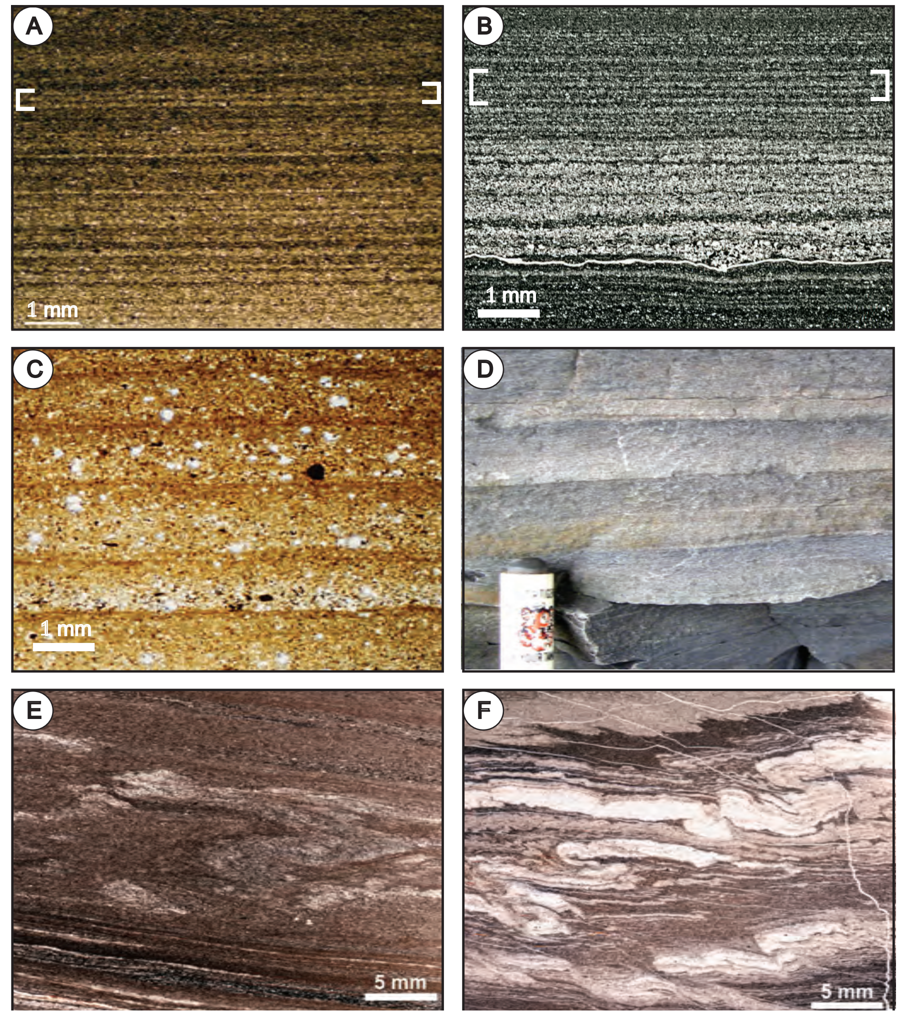


Figure 3. Key recognition criteria and examples of commonly occurring sedimentary features in mudstone successions: planar lamination, graded bed, and convolute lamination. (A) Cleveland Ironstone Formation, Jurassic, UK (brackets highlighting an example of parallel lamination); (B) Gunpowder Formation, Proterozoic, Australia (brackets highlighting an example of parallel lamination); (C) Chattanooga Shale, Devonian, Tennessee; (D) Chattanooga Shale, Devonian, Tennessee (pencil head is 1 cm wide); (E) Green River Formation, Eocene, Colorado; (F) Green River Formation, Eocene, Colorado (A–D; after Lazar et al., 2015b).

Sedimentary Structures	Recognition Criteria
Scour	• Erosional surface formed as a result of sediment removal under the action of a current of water or air • Truncation below, onlap or concordant above
Gutter cast	• Curved, narrow and deep scour with truncation below (aspect ratio of 1:1-3), with discrete onlapping laminasets • Concordant above (typically planar surface and burrowed); straight to curved, bifurcated planform • Planar to curved, parallel lamina geometry
Lag deposit	• Residual accumulations of coarser particles that are produced when underlying units are eroded and winnowed • Lags have been categorized by the estimated depth of erosion into the underlying strata (e.g., Schieber, 1998) • See Table 1 and Lazar et al. (2015b) for details on recognition criteria, interpretation, and implications of various types of concentrations of outsized particles

Examples

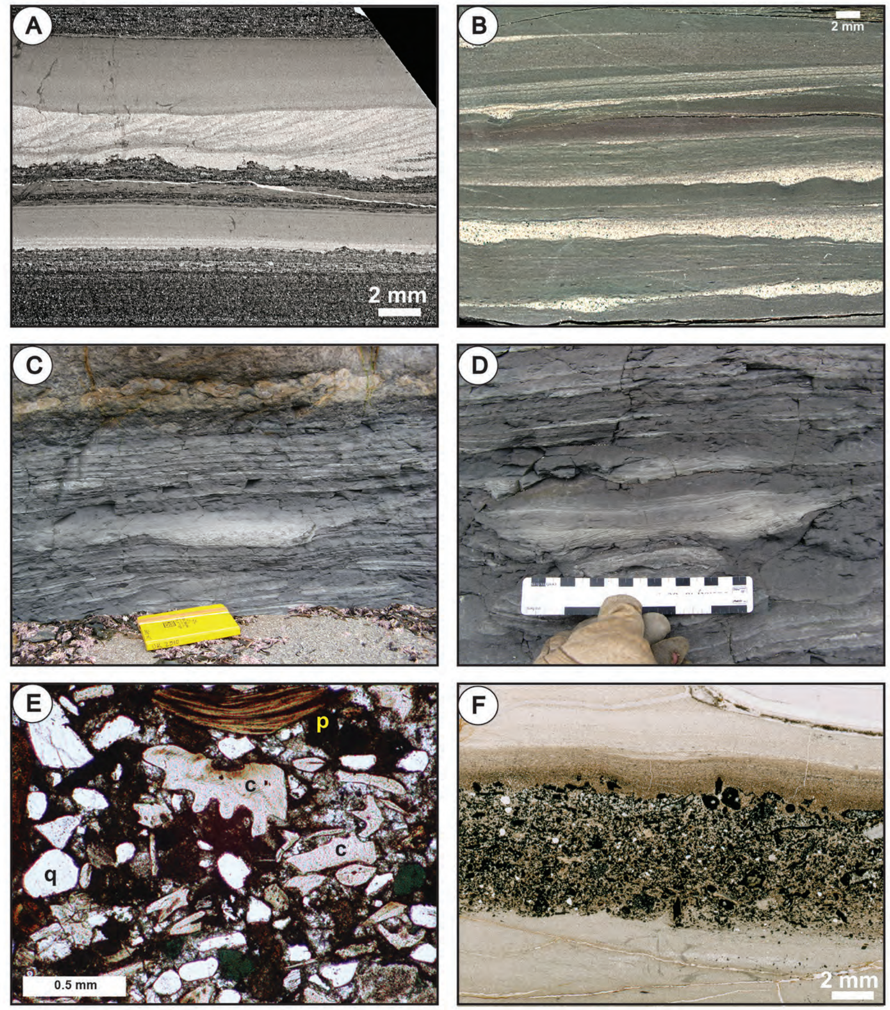
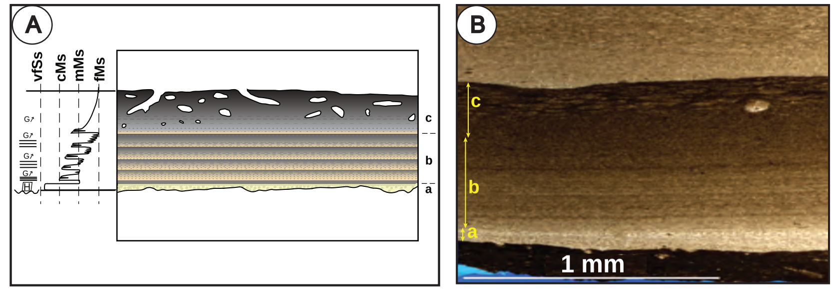


Figure 4. Key recognition criteria and examples of commonly occurring sedimentary features in mudstone successions: scour, gutter cast, and lag deposit. (A) Gunpowder Formation, Proterozoic, Australia; (B) Eau Claire Formation, Cambrian, Indiana; (C) Cleveland Ironstone Formation, Jurassic, U.K. (notebook is 19 cm wide); (D) Cleveland Ironstone Formation, Jurassic, UK (scale in cm); (E) Conodont-rich (c), quartz-rich (q), and pyrite-rich (p) lag, New Albany Shale, Devonian, Kentucky. (F) Pyritic lag, Ohio Shale, Devonian, Kentucky (A, B, E, and F after Lazar et al., 2015b).

Sedimentary feature | **Recognition criteria** | **Examples**

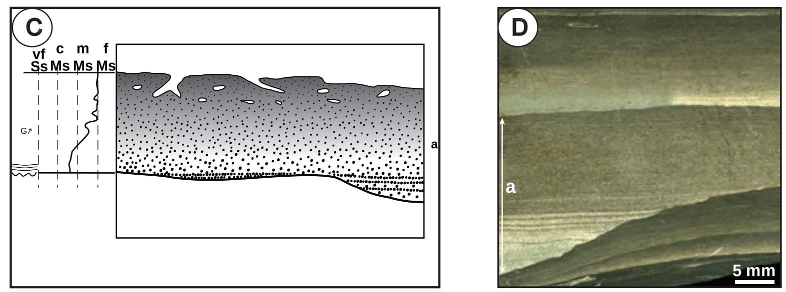
WESGF (wave-enhanced-sediment-gravity-flow bed)

- Rel. conformable, typically burrowed top
- Internally contains three laminasets:
  - c: clay-rich, fines upward
  - b: multiple, very thin, broadly curved to wavy laminae of silt grading into clay; has gradational top
  - a: silt-rich and largely homogenous to slightly graded; ± very fine-grained sand; ± continuous; has sharp to abruptly gradational top
- Scoured base, broadly curved with rel. low relief and some localized narrow, mod. 'deep' high aspect ratio incisions



Tempestite

- Rel. conformable, typically burrowed top, ± wave reworked
- Internally, fines upward smoothly throughout its thickness; laminae tend to be broadly curved near base to planar upwards; basal laminasets typically lap onto basal scour and fill in scour relief; overlying lamina tend to be more poorly defined and diffuse
- Scoured base, curved to wavy, with rel. high local relief, ± enhanced by sediment loading and deformation
- Commonly associated with the offshore end of gutter casts



Turbidite

- Rel. conformable, typically burrowed top
- Internally, fines upward in distinct steps; a complete bed comprises five laminasets:
  - e: graded; finest grained sediment
  - d: continuous to discontinuous planar-parallel laminaset
  - c: discontinuous, curved, nonparallel laminaset (current ripples); dominated by silt or coarser grains
  - b: continuous, planar-parallel laminaset with conformable base and top; dominated by rel. coarse grains
  - a: basal homogenous laminaset with gradational conformable top; tends to contain the coarsest grains
- Scoured base, curved to wavy, with mod. to high local relief and some localized narrow, deep scours

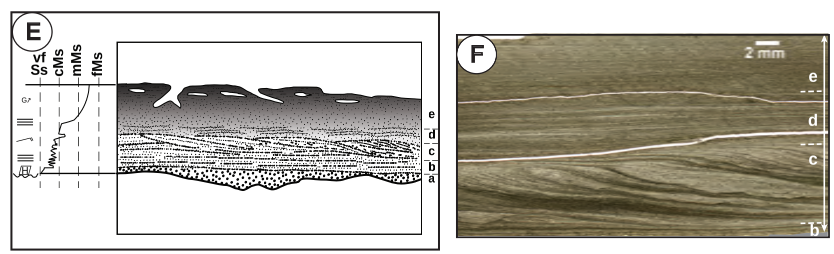


Figure 5. Key recognition criteria and examples of commonly occurring sedimentary features in mudstone successions: WESGF (wave-enhanced-sediment-gravity-flow bed), tempestite, and turbidite. (A, C, E) Schematic illustrations of WESGF, tempestite, and turbidite beds. (B) Mowry Shale, Cretaceous, Wyoming (after Macquaker et al., 2010). (D) Mowry Shale, Cretaceous, Utah. (F) Sonyea Group, Devonian, New York (A–F after Lazar et al., 2015b). vfSs = very fine sandstone; cMs = coarse mudstone; mMs = medium mudstone; fMs = fine mudstone.

Composite grains	Recognition Criteria
Floccules	• 80%–90% water content • Travel in bedload and suspended load • Flattens significantly during sediment burial
Organo-mineralic aggregates	• Diffuse, irregular-shaped aggregates mostly composed of organic-derived material clumping in the water column; detrital particles more common on the rim • Identifiable under electronic and optical microscope in thin sections manufactured parallel to bedding • Described as "marine snow" in modern settings
Intraclasts	• Angular, subangular, subrounded, or even rounded especially when small size (medium to coarse mud size) • Sharper outline than that of organo-mineralic aggregates and floccules (especially visible when high composition contrast with the surrounding material) • Form within a basin by erosion of cohesive mud by currents and waves • Differential compaction common when eroded mud was precompacted significantly • More common at the bottom of beds (burrows are more common at the top of beds)

Examples

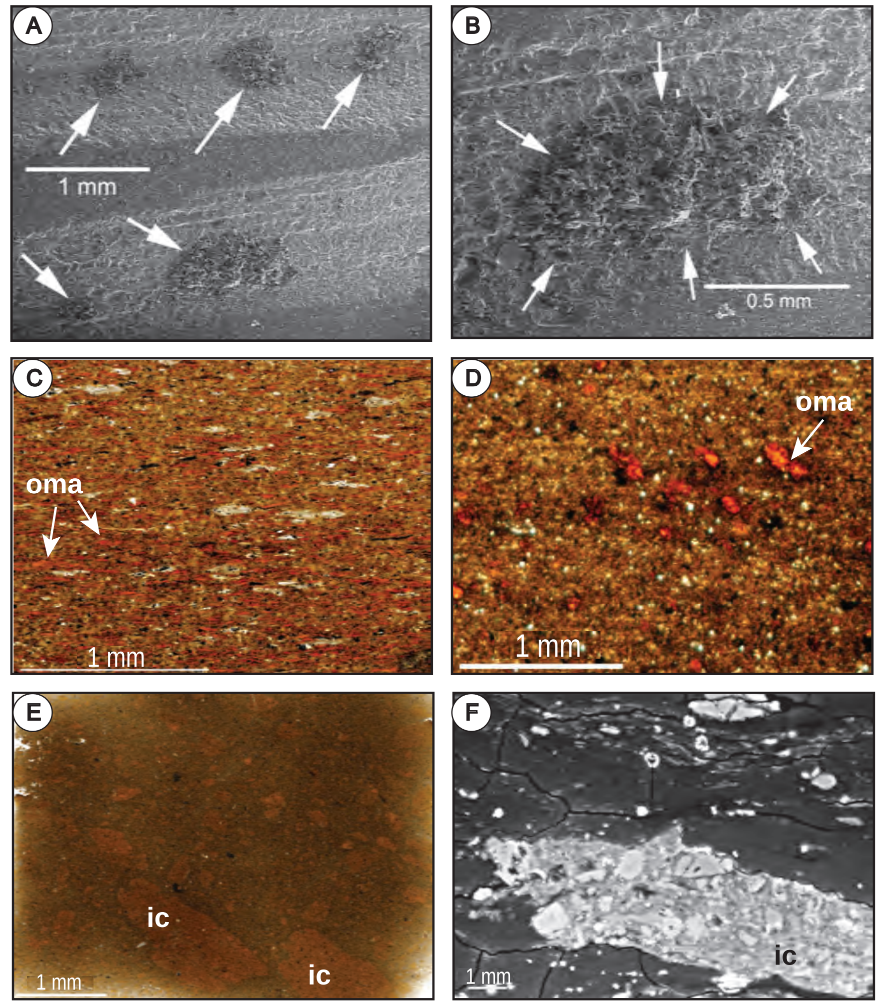


Figure 6. Key recognition criteria and examples of commonly occurring composite grains in mudstone successions: floccules, organo-mineralic aggregates (oma), and intraclasts (ic). (A) SEM image of dried kaolinite floccules (arrows), flume experiments. (B) Close-up of a floccule from A (bottom row, right). (C) Bedding-perpendicular thin-section view of organo-mineralic aggregates (oma) in the Kimmeridge Clay Formation, Jurassic, UK. (D) Bedding-parallel thin-section view of organo-mineralic aggregates (oma) in the same mudstone sample as shown in C. (E) Bedding-parallel thin-section view of compacted intraclasts (ic) in the Kimmeridge Clay Formation, Jurassic, UK. (F) Backscattered electron image of an intraclast composed of quartz and clay minerals from E (A–F after Lazar et al., 2015b). SEM = scanning electron microscope.

Table 1. Recognition and Differentiation Criteria for Various Types of Concentrations of Outsized Particles: Interpretation and Implications (from Lazar et al., 2015b, used with permission).

Shell Beds	Shell Packing				Orientation				Taphonomy					Recognition Criteria	- Interpretation § Sequence stratigraphic association
	Gs	Ps	Ws	Ms	Aligned			Random	6	5	4	3	2/1		
Transported (*"advected"*)	■					■	■		■	■				- Rel. densely packed, mostly broken shells in current stable position (aligned/convex up/shingled). - Shells from different habitat than underlying strata.	- Shells advected from different habitats (typically more proximal) and concentrated by currents or waves. § above SB, TS
Winnowed (*"in place"*) (*"lag"*)	■	■			■					■	■			- Mod. densely packed, rel. unbroken shells associated with outsized quartz grains, phosphatic debris, pyritized burrows. - Shells from underlying strata.	- Shells concentrated by intermittent erosion from underlying strata. § above FS, TS, MFS
Condensed	▒	■	▒			■	■			■	■	■	■	- Variably, rel. densely packed shells with variable orientation. - Shells encrusted/bored. - Associated with phosphatic debris and crusts, and underlying nodules. - Shells from different biozones if long-term condensation.	- Shells concentrated through lack of other sediment input. § above (TS), MFS
Midden	■	■					■	■	■	■				- Predation marks (drill holes, bite marks, crushed). - Broken, mostly randomly aligned, in clusters or burrows.	- Shells concentrated by feeding activities of predators. § above FS, TS, MFS
Drowned		▒	■				■	■				■	■	- Rel. sparsely packed, mixed orientation and taphonomy. - Bivalve molluscs mostly open, both articulated and disarticulated. - Patchy distribution, with vague alignment into layers. - Shells from within habitat of surrounding strata.	- Shells concentrated by migration upward from underlying strata in attempt to escape rising redox boundary. Anoxic conditions overtook biota and killed them. (*well preserved articulated skeletons due to sudden death and rapid burial—see below*) § at/near bedset boundary (*not particularly diagnostic of sequence stratigraphy)*

Table 1. (continued)

Shell Beds		Shell Packing				Orientation				Taphonomy						
		Gs	Ps	Ws	Ms	Aligned			Random	6	5	4	3	2/1	**Recognition Criteria**	- Interpretation § Sequence stratigraphic association
	Obrution *("rapid in-situ burial")*														- Wide variety of packing, typically patchy; represents biocoenosis. - Shells in life position, trilobites rolled up. - Geopetal/sparry fill of shells.	- Shells concentrated by intermittent erosion from underlying strata. § above SB in LST; (below SB in upper HST)
	NOTE: Barren well bedded/laminated mudstone beds tend to be event beds due to floods or storms…															
Bone Beds		As above, but with Articulated Skeletons in Drowned and Obrution beds. Well-preserved articulated skeleton = sudden death and rapid burial; moderate articulated skeleton = persistently hostile bottom conditions and/or moderate burial rates; fair articulated skeleton = mod./intermittently hostile bottom conditions and rel. slow burial rates; poor articulated skeleton = persistently benign bottom conditions and slow to very slow burial rates.														
Phosphatic beds		This series represents increasing amounts of concentration, typically under progressively slower net sediment accumulation rates: Isolated grains → peloids (type P) → concentrated peloids → scattered nodules → aligned nodules (type F) → aligned & cemented nodules (type D) → reworked nodules → hardgrounds (type D)														
Siltstone beds	Transported *("advected")*														- Dominantly detrital grains (weathered from lithified rocks) with signs of significant lateral transport. - Underlain by surface of erosion or non-deposition.	- Silt grains advected by traction and deposited during waning phase of flow (river floods, hyperpyncnal flows, storm-induced currents, etc). § above SB in LST; in upper portions of parasequences.
	Winnowed *("in place")*														- Mixture of grain types and compositions—derived from rock weathering, glacial grinding, early diagenesis (within algal cysts, pores), biogenic. - Underlain by surface of erosion	- Silt grains concentrated by intermittent erosion of underlying strata over long period. § above MFS, TS, FS; in lower portions of parasequences.

Shell packing: Gs = grainstone; Ps = packstone; Ws = wackestone; Ms = mudstone.
Taphonomic states: 6: comminuted; 5: broken; 4: disarticulated & aligned; 3: disarticulated & randomly scattered; 2: articulated brought together (Thanatocoenosis); 1: articulated, living together (Biocoenosis).
PO_4 types: P = peloids, F = friable, D = dark and dense (Garrison et al., 1994).
SB = sequence boundary, FS = flooding surface, TS = transgressive surface, MFS = maximum flooding downlap surface, LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract.

Lag deposits: Commonly used for residual accumulations of coarser particles that are produced when underlying units are eroded and winnowed (see "winnowed" above).

Lags have been categorized by the estimated depth of erosion into the underlying strata as (e.g., Schieber, 1998):
- **High-energy lags** (bone beds, sand, pyritic, and thick silt lags). Interpreted as a result of infrequent and exceptionally strong storms (recurrence on the order of 10^2–10^4 years?), possibly connected to intensified reworking during relative fall of sea level.
- **Low-energy lags** (silt, conodont, and Lingula lags). Interpreted as a result of more typical and more frequently occurring storms (recurrence on the order of 10–10^2 years?).

Tip: Not all erosion surfaces are marked by a lag deposit.

Table 2. Typical Conditions for Formation of Precompaction (high intergranular volume) Cements or Nodules in Marine Mudstone Settings (after Lazar et al., 2015b, used with permission).

Cement/ Nodule type	Eh[1]	OM[2]	Terrigenous Components	Sediment Accumulation Rate	Oxidant/ Respiratory Paths	Depth in Sediment[4]	Most Common Near[5]	Summary of Typical Conditions for Formation
Calcite	High	Bioavailable	Variable	Low	O_2	Shallow	SB, (TS)	Oxic conditions
Calcite / Dolomite (Nonferroan) + pyrite*	Low, persistently	Abundant, bioavailable	Abundant	Low, persistently	SO^4, Fe^{3+} [3]	Shallow	**FS**[6], MFS, (TS)	Reducing sulfidic conditions with abundant bioavailable organic matter and available iron (derived typically from detrital or aeolian inputs); no sulfate poisoning of dolomite
Ferroan Dolomite	Low, persistently	Abundant, bioavailable	Variable	Low, persistently	Methano-genesis	Moderate to relatively deep	**FS**, MFS, (TS)	As above, but deeper in a "stable" sediment column below zone of SO_4 reduction, that is, minimal sediment reworking or relatively distal
Phosphate**	Low, intermittently	Abundant to Common, bioavailable	Very Low	Low to Very Low Net accumulation	O_2/H_2S interface	Mostly shallow (to deep)	FS, **MFS**, TS	Distal areas rich in fresh OM, but starved of terrigenous input *(PO_4 comes from OM degradation)* Larger, more concentrated PO_4 nodules indicate slower net sediment accumulation rates *(see note)*.
Siderite	Low, intermittently	Sparse, not bioavailable (refractory)	Abundant	Low Net accumulation *(reworking common)*	Fe^{3+} *(no SO^4 reduction)*	Shallow	**SB**, (TS), (within LST)	In marine environments of deposition = Low oxygen conditions with poorly preserved OM and low net accumulation at or near bypass surface (significant sediment reworking). *NOTE: controls on siderite are complex and siderite is commonly a burial cement…*
Silica (bio-opal to quartz chert)	Low to Moderate	Common to Abundant (high production rates)	Very Low to Low	Moderate to Low	*(no Fe reduction)*	Moderate to very deep	FS	Glassy chert indicates low pH, low terrigenous input (biogenic opal to cristobalite to quartz proceeds by dissolution and re-precipitation, so it results in most pure chert in the absence of terrigenous input of Al and Fe [which tend to cause clay mineral authigenesis])

*Pyrite morphology = *f* (sulfide production rate), that is, supersaturation of sulfate and iron (= *f* (OM, SO_4)): framboid > euhedral > coatings/replacements.

**PO_4 morphology with decreasing net sediment accumulation rate: isolated peloids -> concentrated peloids -> isolated nodules -> concentrated nodules -> cemented nodules -> reworked cemented nodules.

[1]Eh = oxidation state = *f* (oxygen supply/oxygen demand); low Eh = reducing conditions, typically because of limited oxygen diffusion (restriction, stratification) and high demand due to high OM content.

[2]OM = organic matter; bioavailable = fresh, hydrogen rich; refractory (less bioavailable) = weathered, reworked, hydrogen poor.

[3]Fe = bioavailable iron; most iron is supplied to marine shelves by river or aeolian transport of iron oxides and hydroxides from soils or rock weathering products; a proxy for terrigenous clastic input.

[4]Depth in sediment: in general, shallow < 0.3 m, deep > 1 m.

[5]FS = flooding surface; MFS = maximum flooding surface; SB = sequence boundary; TS = transgressive surface (top of lowstand systems tract [LST]).

[6]bold font = most common; regular font = normal; in parentheses = sometimes.

distributed shell beds in mudstone strata also suggest intermittent increase of oxygen levels leading to colonization (e.g., Kidwell, 1989, 1991a, b; Brett, 1995; Brett and Allison, 1998; Brett et al., 2003; Dattilo et al., 2008). Although some shell beds record single events, most shell beds record relatively long periods and background sedimentation. In contrast, many barren mudstone beds represent event beds (rapid sedimentation).

Development of a typical shell-bed "lag" follows this evolution (e.g., Kidwell, 1991a, b; Brett and Allison, 1998):

1. Mud deposition
2. Colonization of mud by shelly taxa adapted to soft substrates
3. Winnowing and concentration of soft-substrate shelly taxa
4. Colonization of concentrated soft-substrate shelly taxa ("shell pavement") by shelly taxa that prefer hard substrates
5. Repeat winnowing and colonization until deposition of a new mud bed that buries the shells, as in step 1, and then start over again

Types of physical concentration of shell beds, as a function of time span of accumulation, include the following (e.g., Kidwell, 1991a, b; Brett and Allison, 1998):

a. "Census" sample (essentially instantaneous)
b. Within a single habitat or environment of deposition conditions (10^1–10^2 years)
c. Environmental condensation, which refers to multiple habitats or environments of deposition over time (10^2–10^3 years)
d. Biostratigraphic condensation, which refers to multiple habitats or environments of deposition or both and multiple biozones (10^3–10^6 years)

In our experience, the frequency of occurrence of these types of shell beds in the rock record is b > c > a > d.

The formation of *diagenetic cement and nodules* in marine settings is related to pauses in sediment accumulation, which allow time for the by-products of microbial respiration to accumulate and become a significant component of the rock volume. The *forms* and *extent* of the diagenetic components are functions of the duration of the pause in sediment accumulation (see Bohacs et al., 2022, Chapter 5 this Memoir for a detailed discussion of early diagenesis processes and products). The *mineralogy* of cement or nodules or both is a function of specific microbial metabolic pathways that are controlled by the supplies of oxidants, reductants, and buffers or auxiliary reactants in the environment of deposition and in the sediment column (e.g., Berner, 1971, 1980, 1981, 1985; Irwin et al., 1977; Froelich et al., 1979; Canfield et al., 1993; Aplin and Macquaker, 2010; Taylor and Macquaker, 2014). Typical conditions for the formation of cement and nodules in marine mud are summarized in Table 2.

Other diagenetic products, such as "beef" and "cone-in-cone" structures, commonly seen in mudstone strata, however, are related to later, deeper diagenetic processes. "Beef" refers to a bedding-parallel vein with fibrous mineral growth that is oriented perpendicular to the vein walls (commonly calcite, but also gypsum, quartz, dolomite, halite, various borates, and other minerals). Carbonate "beef" in mudstone has been interpreted to be associated with overpressure and tensile failure linked to hydrocarbon generation and to dehydration reactions (Cobbold et al., 2013). A "'dual' beef" has a darker central pair of fibrous growth that is surrounded by lighter zones of fibrous growth above and below (e.g., Cobbold and Rodrigues, 2007). The central pair contains perpendicular antitaxial fiber growth (center outward) that is gray because of fluid inclusions of hydrocarbons and records growth in the oil window; the surrounding pair contains fibers oblique to the fracture wall that are white with minimal fluid inclusions, and probably records later growth in the gas window (e.g., Cobbold and Rodrigues, 2007). A "cone-in-cone" structure has multiple nested cones of fibrous calcite or other minerals in which the fibers have grown vertically on average, within horizontal-to-inclined fractures (e.g., Cobbold and Rodrigues, 2007). These structures are attributed to dilatant shear failure as a response to overpressure.

CONCLUSIONS

Characterizing mudstone strata at lamina-to-bedset scale provides insights into the patterns and causes of rock-property variation. These insights can be used to construct process-based models and make predictions away from sample control. To understand the variation at this small scale is also essential because most analytical samples used to calibrate well logs and seismic response are of this millimeter-to-centimeter scale.

With this understanding firmly established, we are ready to examine how beds and bedsets stack into parasequences and characterize the depositional conditions and environments, as discussed in Bohacs et al. (2022, Chapter 5 this Memoir).

> *By the agitation of water and silt, and their gradual accumulation and consolidation … the rocks were formed gradually by the evolution of sediments in water.*
>
> —Ye Zi-qi, 1378, p. 342

ACKNOWLEDGMENTS

We thank ExxonMobil for support and permission to release this information. We thank Dr. Jennifer Eoff, Dr. Jon Kaufman, and Professor Paul Potter for their constructive reviews and insightful input.

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