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CAPTURING KEY ATTRIBUTES OF FINE-GRAINED SEDIMENTARY ROCKS IN OUTCROPS, CORES, AND THIN SECTIONS: NOMENCLATURE AND DESCRIPTION GUIDELINES

O. REMUS LAZAR[1], KEVIN M. BOHACS[1], JOE H.S. MACQUAKER[1], JUERGEN SCHIEBER[2], AND TIMOTHY M. DEMKO[1]

[1]ExxonMobil Upstream Research Company, 3120 Buffalo Speedway, Houston, Texas 77252, U.S.A.
[2]Department of Geological Sciences, Indiana University, 1001 East 10th Street, Bloomington, Indiana 47405, U.S.A.

ABSTRACT: An integrated nomenclature scheme is proposed to capture the inherent heterogeneity of fine-grained sedimentary rocks at the 10_{2} to 10_{23} mm scale and to assist the evaluation of these rocks as sinks of organic carbon, barriers to fluid flows, and reservoirs of oil and gas. This scheme incorporates previous knowledge and the latest field, petrographic, and laboratory observations. We propose to name fine-grained sedimentary rocks using a root term based on their texture (grain size), which is modified by description of bedding, composition, and grain origin. Regarding texture, we suggest the use of ''mudstone'' as a class name for the entire spectrum of fine-grained sedimentary rocks. We define mudstone as a rock in which more than fifty percent of its grains are mud (clay and silt) size (< 62.5 mm). Similar to the approach used for the description of sandstone texture, mudstone texture can be refined by a ''coarse,'' ''medium,'' or ''fine'' size-range term. Regarding bedding, we follow Campbell's (1967) genetic approach to define laminae, laminasets, and beds, and describe lamina geometry, continuity, and shape. Regarding composition, we propose terms such as ''siliceous,'' ''calcareous,'' ''argillaceous,'' and 'carbonaceous'' to capture differences in rock composition. The name of a mudstone can be further modified by additional attributes that detail the form and origin of the rock components. Application of this approach to the Cretaceous Eagle Ford Shale illustrates the variability typically present in mudstone successions and demonstrates how our detailed characterization can be used to decipher and predict rock properties of economic interest.

INTRODUCTION

Most of the sedimentary record contains rocks dominated by grains smaller than 62.5 mm (e.g., Picard 1971; Wedepohl 1971; Stow 1981; Blatt 1982). These fine-grained sedimentary rocks serve as sources, reservoirs, and seals of hydrocarbons; influence the flow of groundwater; and can be rich in metals. Investigation of these rocks provides insight into the global carbon cycle and associated climate and oceanography through geologic time.

Fine-grained sedimentary rocks are commonly referred to as ''shale,'' ''mudrock,'' ''mudstone,'' or ''claystone,'' and are traditionally described as ''homogeneous,'' ''structureless,'' ''massive,'' and/or ''laminated.'' ''Shale'' has been commonly interpreted to form under a narrow range of processes (e.g., continuous mud deposition from suspension settling under minimal benthic energies, and in the case of organic-carbon-rich examples, under persistently anoxic conditions). Describing these rocks in outcrops and cores can be a challenge because they are very fine grained, weather easily, and generally do not exhibit large-scale sedimentary features. A lack of a widely used, consistent nomenclature (in spite of the best efforts of a number of authors; e.g., Macquaker and Adams 2003; Potter et al. 1980, 2005) has restricted our ability to compare mudstone strata, and has limited our interpretation of depositional processes responsible for the formation of these rocks.

Examination of a variety of Paleozoic to Cenozoic fine-grained rock successions in cores, outcrops, and thin sections over the last three decades has revealed that these rocks are typically heterogeneous at many scales and likely formed via a range of processes (e.g., Schieber 1989, 1999, 2011a; Bohacs 1990, 1998; Macquaker and Gawthorpe 1993; Macquaker and Howell 1999; Bohacs et al. 2005, 2011, 2014; Schieber et al. 2000, 2010a, 2010b; Schieber and Lazar 2004; Lazar and Schieber 2006; Lazar 2007; Macquaker et al. 2007, 2010a, 2010b, 2014; Taylor and Macquaker 2014). This body of work also demonstrates that traditional descriptors used for these rocks do not capture the range of variability observed in their physical, biogenic, and chemical attributes, and do not facilitate interpretations of depositional processes. The need for a simple, integrated descriptive scheme is timely, because interest in the processes responsible for their accumulation, stratigraphy, and resource potential has expanded rapidly in the last few years as new drilling and completion technologies have unlocked significant amounts of hydrocarbons in these rocks.

In this contribution, we discuss the utility of some of the existing nomenclature, provide context for the information that is required to fully characterize mudstone strata, and recommend guidelines that facilitate consistent, repeatable, and efficient capture of key attributes needed to evaluate, interpret, and compare fine-grained sedimentary rocks. In the following sections, with these aims in mind, we:

1. Discuss some of the issues associated with terms commonly used to refer to, and describe, fine-grained rocks.
2. Propose a naming scheme based on three key rock attributes: texture, bedding, and composition. In this scheme, the rationale for rock descriptors and specific guidelines are provided to enable the textural, bedding, compositional, and grain origin attributes to be captured and compared consistently for the entire spectrum of fine-grained sedimentary rocks.
3. Provide an example based on our integrated investigations of the Cenomanian–Turonian Eagle Ford Shale of south Texas to illustrate how the proposed approach helps us maximize the extraction of information recorded in fine-grained rocks by capturing key aspects of their vertical and lateral variability in physical, biological, and chemical properties at millimeter to

meter scales. The Eagle Ford Shale is an ideal example because it exhibits significant textural, bedding, and compositional variability that likely impacts the quality and distribution of hydrocarbon source, seal, and reservoir intervals in this ''shale'' succession.

4. Discuss some of the challenges geologists face when describing the texture, bedding, and composition of fine-grained sedimentary rocks, in light of recent experimental results on mud transport, deposition, and erosion, and propose some potential solutions.

GUIDELINES FOR THE NOMENCLATURE OF FINE-GRAINED SEDIMENTARY ROCKS

There has been significant variation in how some of the terms have been used to describe fine-grained sedimentary rocks (e.g., Ingram 1953; Shepard 1954; Folk 1965, 1968; Tourtelot 1960; Picard 1971; Pettijohn et al. 1973; Blatt et al. 1980; Lundegard and Samuels 1980; Potter et al. 1980, 2005; Spears 1980; Stow 1981; Stow and Piper 1984; Flemming 2000; Macquaker and Adams 2003). There has been particular misunderstanding concerning terms like shale, claystone, and fissility. Shale, for example, has been widely used as a class name for all fine-grained sedimentary rocks. It has also been used as a field term for any fissile fine-grained sedimentary rock. Fissility, in some instances, is incorrectly used interchangeably with lamination. Fissility, however, is a byproduct of weathering and not a unique property of a rock. For example, a fresh piece of non-fissile fine-grained rock (either from an outcrop or a core) can develop well-defined fissility during weathering over short time scales and then be called ''shale.'' Shale has also been equated with a claystone, which, in turn, has been characterized either as a clay-mineral-rich fine-grained rock or as a clay-size-dominated fine-grained rock. In the last few years, shale-gas and oil researchers have argued increasingly that the fine-grained sedimentary rocks they studied were not ''shale.'' It is likely that shale, a term so entrenched in the literature, will continue to be used as a class name for all kinds of fine-grained sedimentary rocks. We prefer to use ''shale'' only as a field term for fine-grained, indurated, fissile sedimentary rocks. We also recommend the use of ''mudstone,'' a ''stone'' term similar to other sedimentary-rock descriptors such as sandstone and limestone, as the generic name for all fine-grained sedimentary rocks (e.g., Macquaker and Adams 2003; Potter et al. 2005; Lazar et al. 2010).

The accumulation of mud is governed by the rate and character of the mud supply and the energy levels in the depositional environment (e.g., Einstein and Krone 1962; Owen and Odd 1970; Wheatcroft and Borgeld 2000; Bentley 2002; Bentley and Nittrouer 2003; Trincardi et al. 2004; Wheatcroft and Drake 2003; Schieber et al. 2007; Hovikoski et al. 2008; Macquaker et al. 2010b, 2010c; MacKay and Dalrymple 2011; Schieber 2011a; Bohacs et al. 2014). Typically, mudstone contains fine-grained material of different grain sizes and composition derived from terrigenous and biogenic input to the basin, primary biogenic production in the basin, and diagenetic overprinting. Fine-grained material is delivered to a basin by a variety of transport processes (e.g., bed load, suspension) and is subsequently modified by postdepositional processes (e.g., bioturbation, diagenesis). It is particularly important to recognize the effects of diagenesis because it is so pervasive in mudstone. The resulting beds exhibit characteristic textures, sedimentary structures, and compositions that can be linked to these processes (e.g., Schieber 1999, 2003, 2011a; Macquaker et al. 2010b, 2010c, 2014; Bohacs et al. 2011, 2014; Taylor and Macquaker 2014). We argue that a nomenclature scheme of fine-grained sedimentary rocks needs to reflect these attributes and be applicable across scales from hand specimens to thin sections to enable interpretations of these processes. With these aims in mind, we propose here to name these rocks using a root term based on texture (grain size), which is then modified by terms describing bedding and composition (Lazar et al. 2010). The full name can be further modified by attributes such as degree of bioturbation, type and abundance of fossils, physical sedimentary structures, diagenetic components, and color. In the following sections, we discuss the texture, bedding, and composition of fine-grained sedimentary rocks.

Guidelines for the Nomenclature of Fine-Grained Sedimentary Rocks: Texture (Grain Size)

Texture analysis (grain size, shape, orientation of individual grains, and overall sorting) has provided insights into sediment provenance, water column energy level, and rock properties such as porosity and permeability. Grains can be simple or composite (e.g., floccules, pellets, or intraclasts). Grain size has been a commonly used attribute in classifications of fine-grained sedimentary rocks (e.g., Trefethen 1950; Ingram 1953; Shepard 1954; Folk 1965, 1968; Tourtelot 1960; Picard 1971; Pettijohn et al. 1973; Blatt et al. 1980; Lundegard and Samuels 1980; Potter et al. 1980, 2005; Spears 1980; Stow 1981; Flemming 2000; Macquaker and Adams 2003; Lazar et al. 2010).

Fine-grained rocks can be represented within the full spectrum of clastic sedimentary rocks on a ternary diagram with percent of sand, coarse mud, and fine mud as end members (Fig. 1; Folk 1965, 1968; Picard 1971; Macquaker and Adams 2003; Stow 2005; Lazar et al. 2010). We define the following grain-size boundaries in this ternary space: fine mud (clay and very fine silt) is less than 8 μm, medium mud (fine and medium silt) ranges from 8 to 32 μm, coarse mud (coarse silt) ranges from 32 to 62.5 μm, and sand ranges from 62.5 to 2000 μm. The proposed grain-size boundaries (i) maximize continuity with published classification schemes; (ii) recognize the existence of a size-sortable silt fraction that reflects the role of different dispersal mechanisms (e.g., McCave et al. 1995); (iii) incorporate recent insights from flume experiments on mud transport, deposition, and erosion that show a distinct change in transport behavior among these grain-size classes (e.g., Schieber et al. 2007; Schieber and Southard 2009; Schieber and Yawar 2009; Schieber 2011a); (iv) are relatively easy to follow at hand-specimen to thin-section scales (10^{-2} to 10^{-6} m); and (v) provide useful information for grain-size trends. In addition, the proposed grain-size range for the fine mud fraction recognizes that, in practice, it is difficult to distinguish the clay size fraction (variously reported as 4, 2, or 1 μm) from the very fine silt grain fraction without resorting to special analytical methods (e.g., laser particle size analysis or differential settling). In this ternary space, a ''mudstone'' is a fine-grained sedimentary rock that has more than fifty volume percent of the grains of mud size (Fig. 1). Analogous to the approach used for sandstone grain size, a mudstone that has less than a quarter sand-size grains can be further differentiated by a size-range term, ''coarse,'' ''medium,'' or ''fine'' (Fig. 1; Lazar et al.

2010). In this scheme, a ''coarse mudstone'' has more than two-thirds of the mud-size grains as coarse mud, a ''fine mudstone'' has more than two-thirds of the mud-size grains as fine mud, whereas a ''medium mudstone'' has neither coarse or fine mud as more than two-thirds of the mud-size grains (Fig. 1). A mudstone that has between 25 and 50% sand-size grains can be further modified by a ''sandy'' size-range term (Fig. 1). Figure 1 illustrates one way of displaying mudstone texture based on our description approach (Appendix 1). We recognize that ternary diagrams have limitations for depicting these rocks because they can contain as many as four grain-size fractions. (One possible approach for display purposes would be to divide the medium mud fraction equally between the coarse and fine mud fractions.) Despite these limitations, plotting mudstones in ternary space can reveal significant groupings and enables comparison of mudstones with different grain-size distributions. It is important that texture is described as accurately as possible so that, no matter what classification or display scheme is used, other geologists can understand what was observed. Worth mentioning in this context is also the fact that the term mudstone has been widely used by carbonate geologists as a rock class name. In this usage, it describes a carbonate rock that mostly comprises mud (defined as any component , 20 μm in size) and less than 10% grains of varying composition and larger than 20 μm (Dunham 1962). We prefer to use the textural definition and grain-size boundaries we propose here for mud instead of the narrower Dunham's usage.

Siltstone and claystone are terms well entrenched in the literature of fine-grained sedimentary rocks but, as discussed earlier for claystone, have somewhat variable definitions and their use has generated confusion in the past. Following the proposed grain-size boundaries (Fig. 1) and making a distinct separation of textural and compositional meaning, one could use, however, the siltstone, mudstone, and claystone terms as an alternative to the coarse, medium, and fine mudstone terms. In this alternative scheme, a claystone, for example, is a rock composed of more than two thirds fine mud-size grains, less than a third coarse mud-size grains, and less than a quarter sand-size grains. The use of these alternative terms has, however, the disadvantage of using the term mudstone both as a general term for all fine-grained sedimentary rocks and as a specific term for a subclass of fine-grained rocks.

We recognize that it might be challenging to quantify visually the proportions of the grain sizes when describing fine-grained sedimentary rocks in cores or outcrops. We provide a practical, proxy method, the ''scratch test,'' to determine the dominant grain size at hand specimen scale in Appendix 1. The pluses and minuses of this test are discussed in the section titled ''Challenges.''

Guidelines for the Nomenclature of Fine-Grained Sedimentary Rocks: Bedding

Bedding is a key characteristic of sedimentary rocks that records variations in (i) sediment input and accumulation, and (ii) benthic energy, as well as (iii) the effects of sediment disruption by organisms. Bedding here includes laminae, laminasets, and beds. Bedding is described by two sets of essential attributes: the geometry and shape of bed bounding surfaces, and the continuity, shape, and geometry of laminae between the bounding surfaces. These bedding attributes are commonly visualized in mudstone by close inspection of fresh surfaces of core or hand specimens and in digital scans of thin sections (e.g., Macquaker and Taylor 1996; Macquaker et al. 1998; Schieber 1999; Könitzer et al. 2014). The main attributes of laminae, laminasets, and beds are reviewed below (Fig. 2).

Following the usage of Campbell (1967), a **lamina** is the smallest megascopic layer (commonly, fractions of millimeters to millimeters in thickness) without internal layers in a sedimentary succession. It is bounded at base and top by lamina surfaces formed by erosion or nondeposition. A lamina is relatively uniform in composition and texture. A lamina has a smaller lateral extent than the enclosing bed (on the order of centimeters in current ripples to tens of meters in abyssal deposits). Lamina continuity, shape, and geometry are three key attributes for describing lamination (Fig. 2). 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 and capture of these laminae attributes are 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 interpretation of paleo-environments of deposition.

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

A **laminaset** is a genetic association of laminae that are bounded by laminaset surfaces (Campbell 1967). Commonly, laminasets consist of a group of conformable laminae that exhibit similar geometry, texture, and composition within a bed. The thickness of laminasets ranges from millimeters to centimeters in a mudstone. The lateral extent of laminasets is smaller than that of the enclosing bed, and varies from a few centimeters in current ripples to hundreds of meters in some turbidite beds. Current- and wave-ripple laminasets commonly occur 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.

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 (Campbell 1967). Beds are typically thin in fine-grained sedimentary rocks, may range from millimeters 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 can be composed of one or more lithotypes. Recognition of beds depends on identification of the surfaces of separation between 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, and can be recognized by stratal terminations (truncation below a surface or onlap or downlap above it), presence of colonization above or subjacent burrowing, and changes in lithofacies. Not all beds, however, exhibit internal sedimentary features. This situation can be a result of bed deposition without internal layering or homogenization 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. A modifier such as ‘‘homogeneous-looking’’ can be applied to describe these beds.

In the realm of sequence stratigraphy, beds are the building blocks of larger-scale stratal units such as bedsets and parasequences. They are interpreted to record a single depositional episode or event of limited areal extent, and form in ‘‘a few minutes’’ ‘‘to years’’ or longer time spans, in ‘‘many moments of geological time’’ (Campbell 1967, table 1, page 17).

Guidelines for the Nomenclature of Fine-Grained Sedimentary Rocks: Composition

The composition of fine-grained sedimentary rocks is strongly controlled by the interaction of physical, chemical, and biological processes that operate during and after mud deposition. The materials that are delivered to the basin are typically composed of the products of weathering, and include clay minerals and a resistant fraction of fine-grained quartz, feldspars, and heavy minerals (e.g., rutile, zircon), as well as debris of higher plants. To these are added materials produced by production within the basin including organic material (e.g., algal, bacterial, and archaeal), and mineralized skeletal parts of calcareous, siliceous, and phosphatic tests of organisms. Once buried, this mix of fine-grained material undergoes chemical transformations (both mineral dissolution and authigenesis) and compaction. Typical products of diagenesis include quartz, carbonate (e.g., calcite, dolomite, ankerite, and siderite), clay (e.g., illite, kaolinite, chlorite, and berthierene), and sulfide minerals (e.g., pyrite, marcasite). Volcanic ash may be a significant component in mudstone successions. Because composition is strongly controlled by the various processes responsible for mud deposition and diagenesis, geologists have used compositional variability of grains with different origin to distinguish fine-grained rocks (e.g., Bramlette 1946; Blatt et al. 1980; Isaacs 1981; Stow 1981; Williams 1982; Shipboard Scientific Party 1984; Macquaker and Adams 2003; Lazar et al. 2010; Stow 2012).

The compositional characteristics of a fine-grained sedimentary rock can be represented on a ternary diagram with percent of total quartz, total carbonate (e.g., calcite, dolomite, etc.), and total clay (e.g., illite, smectite, etc.) minerals as end members Fig. 3; Lazar et al. 2010). Following our proposed nomenclature, the compositional name reflects which component is greater than 50% or the two most common components if no single component is more than 50% of the rock. For example, a rock composed of 60% carbonate minerals is a calcareous mudstone, whereas a rock composed of 45% carbonate minerals, 40% clay minerals, and 15% quartz is a calcareous-argillaceous mudstone (Fig. 3). The ternary compositional diagram (Fig. 3) should be modified to reflect the cases when a mudstone is dominated by other components such as organic matter, phosphates, feldspars, or sulfides. There are widely used terms for fine-grained sedimentary rocks dominated by certain forms of their compositional components. Varieties of siliceous mudstone include, for example, radiolarite, diatomite, and porcellanite. Radiolarite is composed of more than 70% remains of radiolarians (e.g., Shipboard Scientific Party 1984), diatomite is composed of more than 80% frustules of diatoms, whereas porcellanite has between 50% and 80% silica (e.g., Isaacs 1981; Williams 1982). Tonstein, an example of an argillaceous mudstone, is composed mainly of kaolinite following the alteration of volcanic ash deposited in coal swamps (e.g., Blatt et al. 1972; Potter et al. 2005). Chalk, an example of a calcareous mudstone, is composed of more than 80% remains of calcareous pelagic grains such as coccoliths and foraminifera (e.g., Pettijohn 1975).

Another term used as a class name for carbonate rocks is wackestone. It was defined as a mud-supported carbonate rock that comprises more than 10% grains of varying composition and origin (Dunham 1962). Dunham (1962) designated ‘‘grains’’ as material $>$ 20 μm and ‘‘mud’’ as $<$ 20 μm. As such, the term ‘‘wackestone’’ encompasses a broad range of possible grain mixtures, and those grains can have different origin and composition. We recognize that the term wackestone has great utility in many carbonate-dominated deposits. We suggest, however, that the scheme proposed here provides a more useful subdivision of this broad range; for example, a more detailed description of a wackestone would be: calcareous coarse or medium mudstone, calcareous sandy mudstone, or calcareous muddy sandstone, with grain-origin modifiers as appropriate.

Fine-grained sedimentary rocks may also be composed of significant amounts of phosphate minerals or feldspars (Blatt et al. 1980; Garrison et al. 1987, 1990; O’Brien and Slatt 1990; Milliken 1992, 2004; Blatt and Tracy 1996; Föllmi 1996; Land 1997; Land et al. 1997). A phosphatic fine-grained rock contains a 0.2–20% mixture of primary and secondary phosphate, whereas a phosphorite is a fine-grained sedimentary rock that contains more than 20% phosphate (Blatt and Tracy 1996). By analogy with the sandstone nomenclature, one can use the term arkosic to refer to a mudstone that contains more than 25% feldspars, and the term subarkosic to refer to a mudstone that contains between 5 and 25% feldspars.

Total organic carbon (TOC) content ranges significantly, from essentially zero to approximately 50 wt. %, and commonly a mudstone has a TOC content of less than 1 wt. % (e.g., Blatt et al. 1980; ExxonMobil in-house analyses of hundreds of thousands of samples collected from Paleozoic to Cenozoic fine-grained rock successions). Based on these data, and to both recognize the importance of the organic-carbon content, and to maintain continuity with commonly used classifications of source rocks, a mudstone with a TOC content between 2 and 25 wt. % is considered to be enriched beyond background values and is here defined as ‘‘carbonaceous’’ (cbMs). In addition, when the nature of the organic material is known, a mudstone with TOC content between 25 and 50 wt. % can be referred to as ‘‘kerogenous’’ (keMs) when its composition is dominated by aquatic algae, or ‘‘coaly’’ (coMs) when its composition is dominated by land plants. We also propose ‘‘muddy kerogenite’’ (mKe) or ‘‘muddy coal’’ (mCo) terms for fine-grained rocks with TOC contents ranging from 50 to 75 wt. %, and ‘‘kerogenite’’ (Ke) or ‘‘coal’’ (Co) terms for rocks with TOC contents greater than 75 wt. %. More detailed terms such as ‘‘alginitic,’’ ‘‘peaty,’’ or ‘‘lignitic’’ can be used when information on the type or thermal maturity of organic material is available (e.g., Tyson 1995; Taylor et al. 1998).

We provide a few guidelines on making compositional observations and interpretations in cores and outcrops in Appendix 1. Bulk composition determined by sample or well-log analyses is useful for understanding bulk-rock behavior and well-log response. It is essential, however, to determine the form and origin of each compositional component (e.g., detrital, biogenic, authigenic) for insights into depositional conditions and prediction away from sample control (Fig. 4). Examination of polished thin sections, particularly using a scanning electron microscope equipped with combined energy-dispersive, cathodoluminescence, and backscattered-electron detectors, is useful in distinguishing the composition of individual grains and cement (e.g., Macquaker and Gawthorpe 1993; Macquaker et al. 1998; Schieber 1999, 2011b; Schieber et al. 2000; Schieber and Baird 2001; Schieber and Riciputi 2004; Milliken et al. 2012; Milliken 1994, 2013; Milliken and Day-Stirrat 2013).

To summarize, the name of a fine-grained sedimentary rock has three main parts: texture, bedding, and composition. The name of a mudstone can be further modified, especially with terms that provide insight into the detrital, biogenic, and diagenetic form, provenance, and causes of its texture, bedding, and composition. For example, a moderately bioturbated, discontinuous, wavy-nonparallel-laminated, calcareous medium mudstone could contain detrital limestone fragments, or coccolith tests, or in-place microbial laminae, or interparticle calcite cement, with the discontinuous bedding due to disruption by bioturbation (the degree of bioturbation can be assessed using a 0 to 5 scale; Appendix 1; from Lazar et al. 2010; after Reineck 1963; Potter et al. 1980; Droser and Bottjer 1986; Taylor and Goldring 1993; Aplin and Macquaker 2010). Other attributes useful to record can include, for example, information on fracturing, deformation, and/or color.

After all observations are made, a mudstone may be described, for instance, as a ‘‘gray, moderately bioturbated, discontinuous, wavy-nonparallel-laminated, calcareous medium mudstone with abundant foraminifera and sparse pyrite nodules.’’ The same rock can be also referred to using a shortened, readily usable phrase such as a ‘‘bioturbated, calcareous medium mudstone.’’ We recommend the use of such phrases only after the variability in the studied mudstone succession has been characterized.

APPLICATION

In previous sections, we developed the concept that mudstone strata are heterogeneous both vertically and laterally at outcrop to thin-section scales. An example from the Cretaceous Eagle Ford Shale in the gas maturity window is given next to illustrate how we can take full advantage of the information recorded in fine-grained sedimentary rocks by carefully capturing key aspects of their variability (Fig. 5). This, in turn, helps us to (i) recognize genetically related strata, (ii) interpret depositional conditions and environments in which mud accumulated, and (iii) predict mudstone properties of interest such as TOC, porosity, and permeability in stratigraphic context.

The Eagle Ford Shale of southern Texas accumulated during the Cenomanian–Turonian in a series of shelfal basins regionally isolated from major siliciclastic influx (e.g., Adams and Carr 2010; Dawson and Almon 2010; Donovan and Staerker 2010; Bohacs et al. 2011; Hentz and Ruppel 2011; Bryer et al. 2013). Mudstone character and distribution was influenced at the local scale by evolving paleobathymetry due to salt movement and syndepositional faulting (Bohacs et al. 2011). The Eagle Ford Shale has been interpreted to be a transgressive and highstand sequence set with significant onlap at the base and variable truncation at the top (e.g., Bohacs et al. 2011).

We recorded facies attributes at the millimeter scale in cores that penetrated the Eagle Ford Shale in southern Texas. Significant vertical variability in grain size; bedding; composition; type and abundance of physical sedimentary structures; degree of bioturbation; type, abundance, and diversity of body and trace fossils; type and distribution of nodules; and color were observed and recorded. Recurring, representative, and diagnostic facies attributes were aggregated into three facies associations, summarized below (Fig. 5).

The basal facies association comprises very dark to dark-gray, continuous, wavy-parallel to discontinuous, wavy-parallel-laminated, argillaceous fine mudstone to calcareous fine to medium mudstone (Fig. 5). Few wave ripples and scours are present, whereas graded beds, wave-enhanced-sediment-gravity-flow (WESGF) beds (Macquaker et al. 2010b), current ripples, and planar beds are very sparse to sparse. Bioturbation index is commonly 1 (to 2); trace fossils include *Planolites* and *Chondrites*. Biodeformational structures referred to as ‘‘mantle and swirl’’ (sensu Lobza and Schieber 1999) are present in some intervals. Additional components of this facies association include a low to moderately diverse fauna with few fragments of *Inoceramidae*, scattered fish scales and pyritized fish bones, as well as scattered foraminifera, calcispheres, and sparse to common fecal pellets; common to abundant pyrite nodules and pyritized burrows also exist in some intervals.

The middle facies association consists of medium to medium-dark gray, discontinuous, wavy-parallel to discontinuous, curved-nonparallel to discontinuous, wavy-nonparallel-laminated, coccolith-pellet-rich coarse mudstone interbedded with calcareous medium to fine mudstone (Fig. 5). WESGFs and scours are few, whereas wave ripples, current ripples, and graded beds are sparse. Bioturbation index typically varies between 1 and 2; trace fossils include *Planolites*, *Chondrites*, and *Helminthopsis*. Faunal diversity is moderate and includes fragments of *Pectinidae*, *Pteriidae*, and *Inoceramidae*. Minor amounts of disarticulated and scattered fish debris, and few pyritized burrows and phosphatic nodules are present in some intervals. Coccolith-rich pellets and aggregates, foraminifera, and calcispheres are few to abundant in some beds and laminae; foraminifera show various degrees of transport and reworking, and their chambers are typically filled with organic material and/or early diagenetic calcite, clay minerals, or pyrite (Fig. 5).

The upper facies association contains light-gray, discontinuous, wavy-nonparallel to discontinuous, curved-nonparallel-laminated, calcareous coarse mudstone to sandy mudstone with thick- and thin-wall bivalves, and horizontal to inclined burrows (Fig. 5). Scours are common, wave ripples are few, and graded beds are sparse. Bioturbation index typically varies between 2 and 4; trace fossils include *Planolites*, *Anconichnus*, and *Teichichnus*. Foraminifera, calcareous fecal pellets, and calcispheres are common to abundant in some beds, whereas radiolaria are sparse. Early cements are common in this upper facies association. Chambers of foraminifera are typically filled with organic material and/or early diagenetic calcite, clay minerals, or pyrite (Fig. 5).

The observed variability in the rock character of the three facies associations translated into significant variability in rock properties such as TOC, porosity, and permeability (e.g., Cusack et al. 2010; Robertson 2010; Workman 2013), which, in turn, controls the quality and distribution of the intervals that are optimum source and gas reservoir in the Eagle Ford Shale (Fig. 5; Bohacs et al. 2011; Schieber et al. 2012). The three facies associations form a succession that has a characteristic stacking pattern that we interpret to represent a parasequence (Fig. 5). All attributes within a facies-association succession record an upward increase in sediment grain size and sediment reworking, sedimentation rates, and oxygenation level (Fig. 5). We interpret the three facies associations to be a result of mud accumulation under variable depositional conditions on the distal, medial, and proximal parts of a storm-wave-dominated shelf (Fig. 5; Bohacs et al. 2014). Capturing rock heterogeneity was facilitated by the recognition and detailed description of texture, bedding, and composition, as well as of additional attributes such as physical sedimentary structures, degree of bioturbation, fossils, diagenetic components, grain origin, or color. Identification and recording of rock heterogeneity then assisted us in deciphering past depositional conditions and environments. With stratigraphic context throughout a depositional basin, understanding of rock spatial heterogeneity facilitates predictions of the quality and distribution of mudstones as sources, reservoirs, and seals of natural resources.

CHALLENGES

Geologists face challenges when describing the texture, bedding, and composition of mudstone. These challenges arise from the textural modification through physical, biological, and chemical processes, the difficulty of distinguishing beds from laminae, and the presence of materials of similar composition in different size fractions.

Texture

Texture is one of the primary attributes that enables description and comparison of mudstone specimens. It is critical to determine not only the present-day grain size but also to obtain insights on the original grain size and type (simple versus composite). Such information is key for interpreting provenance and bottom-energy levels and subsequent diagenetic transformations. Quantification and interpretation of original grain size in mudstone at core and outcrop scale can be challenging, however, because grains are typically modified after deposition by physical disruption, biological activity, or diagenetic processes.

Composite grains are common in mudstone and include floccules, pellets, organo-mineralic aggregates, and intraclasts. Recent research on mud (clay and silt) transport and deposition has revealed that most mud travels as silt or larger-size composite grains (floccules) in bed load and suspended load (Fig. 6; e.g., Schieber et al. 2007; Schieber and Southard 2009; Schieber and Yawar 2009). To complicate matters further, composite grains also form by erosion of weakly consolidated mud by storms (intraclasts), or through clumping during marine-snow formation (organo-mineralic aggregates; Fig. 6; e.g., Macquaker et al. 2010a; Schieber et al. 2010a; Plint et al. 2012). Outcrop and modern sediment observations together with flume experiments have also shown, for instance, that erosion may generate millimeter- to centimeter-scale intraclasts (Fig. 7). Intraclasts form because biochemical processes rapidly stabilize mud shortly after deposition (within hours to days), which increases sediment cohesion and minimizes re-entrainment of mud as individual component particles.

The full extent of the role of aggregation in mud transport has not been fully recognized, for two main reasons. First, grain-size determination in ''shale'' has been commonly measured by disaggregating samples and then analyzing texture using sieving or particle-size-analyzer techniques. This inevitably modifies the original particle size and affects interpretations of the depositional hydrodynamic attributes. Second, as discussed below, the present-day grain size can reflect the overprint of physical, biological, and chemical alteration which can obscure the original depositional grains. For example, compaction of grains with high water content modifies original grain outlines. Bioturbation can both form and destroy sediment fabrics; for instance, in situ pelletization may occur, or grain outlines may be disrupted (Fig. 7). Diagenesis may further modify particle-size distribution, particularly where cement nucleation sites develop in association with breaks in sediment accumulation. Early diagenesis, particularly the precipitation of cements such as quartz, carbonate, kaolinite, and pyrite at nucleation sites that are either dispersed or localized within a bed, may lead to apparent grain-size increase or generation of new material (e.g., Macquaker and Taylor 1996; Schieber 1996; Schieber et al. 2000; Schieber and Baird 2001). Conversely, dissolution of certain grains (e.g., silicate minerals) may cause grain-size diminution (e.g., Milliken 1992; Schieber 1996). Many mud components (e.g., detrital clay minerals) are highly susceptible to diagenetic alteration because they are chemically unstable and have high surface areas. Upon burial they are subjected to very different pore-water composition and pressure-temperature conditions that differ substantially from those under which they originally formed. This means that diagenetic processes overprint depositional mineralogy to various degrees (e.g., Hower et al. 1976; Curtis 1977; Aplin and Macquaker 2010; Macquaker et al. 2014). Where the resulting cement crystals are very small ($< 2\ \mu m$) it may be difficult to unequivocally differentiate them from hydrodynamically sorted grains. The presence of euhedral crystal terminations, cement zonation, and either cements infilling grain dissolution pores or intragranular porosity facilitates this distinction (e.g., Milliken and Day-Stirrat 2013; Taylor and Macquaker 2014). These observations illustrate the difficulty of relating present-day grain size to depositional conditions, especially of the argillaceous grains. Even when overprinting is pervasive, more stable components (e.g., quartz grains) can still be recognized in hand specimens and thin sections, however, and grain-size estimates can be made to place a rock within particular fields of a ternary diagram (Fig. 1; Appendix 1).

A scratch test can be applied to determine the dominant grain size in core and outcrop samples. The scratch test is underpinned by the observation that fine-grained rocks are commonly composed of clay, quartz, feldspars, and carbonate minerals in addition to organic material. These components typically reside in different grain-size fractions. For instance, in successions like the Kimmeridge Clay Formation (Macquaker and Gawthorpe 1993), the fine fraction is dominated by relatively soft clay minerals and the coarse fraction is dominated by harder components such as quartz and carbonate minerals. Thus, as grain size varies, so does the response of the rocks to the scratch test. It is important to interpret the results from the scratch test critically, however, because of the presence of cement (which can lead to apparent coarser interpretations of grain size), aggregate grains (which can lead to underestimation of grain size especially when argillaceous aggregate grains are present), and microcrystalline quartz (which can lead to overestimates of grain size, e.g., Milliken et al. 2012; Milliken 2013). The scratch test has been tested in such mudstone successions by comparison with thin-section grain-size determinations (e.g., Dunham and Blake 1988; Bohacs 1990, 1993; Schwalbach 1992; Schwalbach and Bohacs 1992), and we found it useful and consistent for both field and core textural studies. More precise and accurate grain-size assessments can be made in thin sections, when available. Examination of thin sections is particularly useful for calibration of the scratch test because it enables the identification of the presence of composite grains (e.g., flocs, fecal pellets, and intraclasts) and facilitates evaluation of the effects of cementation, dissolution, and bioturbation on grain size.

Bedding

Differentiating laminae from very thin beds is important for discerning whether sediment accumulation is dominantly continuous or episodic. ‘‘Parallel-laminated mudstone’’ implies continuous sediment accumulation under a single depositional event, whereas ‘‘parallel-bedded mudstone’’ implies discontinuous sediment accumulation under repeated depositional events of similar character. Most textbooks consider lamination to be a primary characteristic of ‘‘shale.’’ Lamination is typically interpreted to indicate dominantly continuous sediment accumulation by suspension settling under relatively still and mostly anoxic bottom-water depositional conditions (e.g., Tyson et al. 1979; Demaison and Moore 1980; Schlanger et al. 1987). Field and core observations (e.g., Bohacs 1990; Macquaker and Gawthorpe 1993; Schieber 1994, 1998, 1999; Lazar 2007; Bohacs and Lazar 2010; Macquaker et al. 2010a, 2010b; Schieber et al. 2010b) combined with recent experimental data (e.g., Schieber et al. 2007; Schieber and Southard 2009; Schieber 2011a) demonstrate, however, that what many have described as ‘‘laminated mudstone’’ is not always a result of continuous deposition from suspension. Instead, it is commonly the product of discontinuous sediment accumulation by lateral transport in bed load or dense suspension (Fig. 8), under intermittently energetic conditions, and, at most, intermittent anoxia. Under such circumstances what have been described as laminae are, in fact, very thin beds. Beds in mudstone strata are typically 1 to 4 mm thick and composed of genetically related laminae. Bed surfaces are identified by stratal terminations, presence of colonization horizons or subjacent burrowing, and changes in lithofacies (e.g., Campbell 1967). These attributes might result from changes in flow conditions and pauses in sediment accumulation that allow for biogenic colonization and/or sediment reworking by current or wave activity (Fig. 8). To reiterate, misidentification of bedding can lead to misinterpretations of depositional conditions, and therefore it is critical to identify and differentiate between laminae and beds during characterization and interpretation of mudstone successions.

Composition

Mudstone composition varies significantly (e.g., Blatt et al. 1980; O’Brian and Slatt 1990; Potter et al. 2005). The inherent variability in mudstone composition reflects the interactions of physical, chemical, and biological processes that operate as fine-grained material is delivered to or produced within basins and diagenetically changed during and after deposition.

Researchers have used compositional information to distinguish one mudstone from another (e.g., Bramlette 1946; Blatt et al. 1980; Isaacs 1981; Stow 1981; Williams 1982; Shipboard Scientific Party 1984; Macquaker and Adams 2003; Lazar et al. 2010; Stow 2012). A comparison of four mudstone deposits based only on X-ray-diffraction derived average composition of total quartz, total carbonate (calcite and dolomite), total clay minerals, and TOC content (Fig. 9A), reveals that such comparison neither captures the wide compositional ranges and overlap present (Fig. 9B), nor does it include information on the different origins of the compositional material (grains versus cements). Interpretation of composition and grain origin can be refined when mudstones are examined under the microscope. For instance, chalk and calcite concretions may have similar composition but obviously formed by different processes. To clarify this point, it might be necessary to comment specifically on the origin of the various grain types seen in a fine-grained rock (Fig. 4). A chalk, for example, would then be a coccolith- or foram-rich calcareous mudstone. In contrast, a calcite concretion could be a calcite-cemented mudstone. Similarly, silica can be in the form of detrital quartz grains, tests of organisms (e.g., opaline diatom frustules), cements (microcrystalline quartz located in the tests of organisms or in the matrix), or grain replacements. A fine-grained rock with 55% detrital quartz in the coarse mud fraction would be described as a detrital siliceous coarse mudstone, whereas a fine-grained rock composed of 55% silica cement would be a cemented, siliceous mudstone. Clay minerals can also be present in either the detrital or diagenetic fractions. For instance, kaolinite can be a direct weathering product or an authigenic precipitate in pore spaces or fossil tests. When kaolinite contributes more than 50% to a fine-grained rock, the former could be described as a detrital-argillaceous mudstone, whereas the latter should be described as a cemented, argillaceous mudstone. Feldspars as well can be detrital or diagenetic. A fine-grained rock with 26% detrital feldspar would be described as a detrital-arkosic mudstone, whereas a fine-grained rock composed of 12% feldspar as both detrital grains and overgrowths would be called a detrital and cemented, subarkosic mudstone.

Composition varies at lamina to parasequence scale in mudstone successions. This variability reflects the composition of individual grain-size fractions, and is produced by the varying input, sorting processes and diagenetic overprints in different reaches of the basin. This is illustrated, for example, in the Gothic Shale of the Middle Pennsylvanian Paradox Formation in the Paradox Basin of southeastern Utah, where the original TOC content varies in the same bed from 1 wt. % to 4 wt. % over a distance of 3 km (Guthrie and Bohacs 2009).

To summarize, geologists face significant challenges when describing mudstone texture, bedding, and composition because fine-grained sedimentary rocks are heterogeneous at many scales. In our opinion, mudstone descriptions that reflect the inherent genetic variability of grain size and origin, as well as bedding and compositional attributes, have predictive value. Primary rock attributes can be described directly by integrating careful observations in outcrops and cores, and be supplemented with information from thin sections. We can use the nomenclature and guidelines we recommend here to describe and capture mudstone variability to make interpretations of the processes that control the formation of these rocks (see the integrated workflow for mudstone description in Appendix 1). Inevitably, this vocabulary and the recommended guidelines will be refined as our knowledge about mudstone continues to evolve.

CONCLUSIONS

Mudstone is typically heterogeneous at many scales. There is currently no naming scheme that captures the inherent heterogeneity of this rock. Our contribution tackles this situation by providing recommendations for naming, describing, and quantifying the variability present in fine-grained sedimentary rocks. Our approach enables information to be captured at different scales of observations (hand specimen to thin section) in a way analogous to the approach used for other sedimentary rocks (sandstone, carbonate). Our scheme is deliberately designed to incorporate previous knowledge as well as the latest field, laboratory, and subsurface observations and insights, so that a solid foundation for interpretations of the primary controls (physical, biological, and chemical) on the formation of these rocks can be achieved. It also addresses many of the challenges geologists face when describing these rocks, and it can be used to help decipher past environmental conditions.

In our scheme, we propose to name fine-grained sedimentary rocks using a root term based on texture (grain size), and modifying it using bedding and composition descriptors. The name can be further modified by adding attributes that specify types of grains and primary and secondary alteration. In terms of texture, we suggest the use of ''mudstone'' as a class name for the entire spectrum of fine-grained sedimentary rocks. Texture information is critical because it provides insights into the relative location of sediment source and water-column energy level. The utility of grain-size information may be enhanced when careful observations reveal that aggregation, flocculation, precipitation, or dissolution has occurred. Similarly, bedding is important for understanding variations in sediment input and accumulation, as well as benthic energy and oxygenation levels. Distinguishing beds from laminae is crucial to identifying genetically related stratal units and evaluate the completeness of the rock record. Composition is strongly controlled by the interaction of physical, chemical, and biological processes that operate during and after mud deposition, and therefore compositional description needs to be supplemented by information about the form and origin of the compositional components. Variations in texture, bedding, and composition, as well as in other attributes including bioturbation and diagenetic overprint, affect rock properties (e.g., porosity and permeability). The heterogeneity of mudstone is captured during an integrated description of all of the above rock attributes in outcrops, cores, and thin sections. This, in turn, enhances the understanding of past depositional conditions and environments under which mudstone strata formed, as well as the prediction of rock properties away from sample control.

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REFERENCES

Adams, R.L., and Carr, J.P., 2010, Regional depositional systems of the Woodbine, Eagle Ford, and Tuscaloosa of the U.S. Gulf Coast: Gulf Coast Association of Geological Societies, Transactions, v. 60, p. 3–27.

Aplin, A.C., and Macquaker, J.H.S., 2010, Getting started in shales: American Association of Petroleum Geologists/Datapages, Getting Started Series GS20.

Bentley, S.J., 2002, Dispersal of fine sediments from river to shelf: process and product: Gulf Coast Association of Geological Societies, Transactions, v. 52, p. 1055–1067.

Bentley, S.J., and Nittrouer, C.A., 2003, Emplacement, modification, and preservation of event strata on a flood-dominated continental shelf: Eel shelf, Northern California: Continental Shelf Research, v. 23, p. 1465–1476.

Blatt, H., 1982, Sedimentary Petrology: San Francisco, Freeman, 564 p.

Blatt, H., and Tracy, R.J., 1996, Petrology Igneous, Sedimentary, and Magmatic, Second Edition: New York, Freeman, 529 p.

Blatt, H., Middleton, G., and Murray, R., 1972, Origin of Sedimentary Rocks, Englewood Cliffs, New Jersey, Prentice-Hall, 634 p.

Blatt, H., Middleton, G., and Murray, R., 1980, Origin of Sedimentary Rocks, Second Edition: Englewood Cliffs, New Jersey, Prentice-Hall, 782 p.

Bohacs, K.M., 1990, Sequence stratigraphy of the Monterey Formation, Santa Barbara County: integration of physical, chemical, and biofacies data from outcrop and subsurface: SEPM, Core Workshop 14, p. 139–200.

Bohacs, K.M., 1993, Source quality variations tied to sequence development in the Monterey and associated formations, southwestern California, in Katz, B.J., and Pratt, L.M., eds., Petroleum Source Rocks in a Sequence-Stratigraphic Framework: American Association of Petroleum Geologists, Studies in Geology 7, p. 177–204.

Bohacs, K.M., 1998, Contrasting expressions of depositional sequences in mudrocks from marine to nonmarine environs, in Schieber, J., Zimmerle, W., and Sethi, P., eds., Shales and Mudstones, Volume I: E. Schweizerbart'sche Verlagsbuchhandlung, Nägele u. Obermüller, p. 33–78.

Bohacs, K.M., and Lazar, O.R., 2010, Sequence stratigraphy in fine-grained rocks at the field to flow-unit scale: insights for correlation, mapping, and genetic controls: Applied Geoscience Conference of U.S. Gulf Region, Mudstones as Unconventional Shale Gas/Oil Reservoirs: Houston Geological Society, Annual Meeting.

Bohacs, K.M., Grabowski, G.J.J., Carroll, A.R., Mankiewicz, P.J., MiskellGerhardt, K.J., Schwalbach, J.R., Wegner, M.B., and Simo, J.A., 2005,
Production, destruction, and dilution: the many paths to source-rock development, in Harris, N.B., ed., The Deposition of Organic-Carbon-Rich Sediments: Models, Mechanisms, and Consequences: SEPM, Special Publication 82, p. 61–101.

Bohacs, K.M., Ottmann, J.D., Lazar, O.R., Dumitrescu, M., Klimentidis, R., Schieber, J., Montelli, R., Liu, C., and Shamrock, J., 2011, Genetic controls on the occurrence, distribution, and character of reservoir-prone strata of the Eagle Ford Group and related rock: Houston Geological Society, Annual Meeting.

Bohacs, K.M., Lazar, O.R., and Demko, T.M., 2014, Parasequence types in shelfal mudstone strata: quantitative observations, lithofacies stacking patterns, and a conceptual link to modern depositional regimes: Geology, v. 42, p. 131–134.

Bramlette, M.N., 1946, The Monterey Formation of California and the origin of its siliceous rocks: U.S. Geological Survey, Professional Paper 212, 57 p.

Bryer, J.A., Denne, R., Funk, J., Kosanke, T., and Spaw, J., 2013, Stratigraphy and Sedimentary Facies of the Eagle Ford Shale (Cretaceous) between the Maverick Basin and the San Marcos Arch, Texas, USA: American Association of Petroleum Geologists, Search and Discovery Article, #50899.

Campbell, C.V., 1967, Lamina, laminaset, bed and bedset: Sedimentology, v. 8, p. 7–26.

Curtis, C.D., 1977, Sedimentary geochemistry: environments and processes dominated by involvement of an aqueous phase: The Royal Society of London, Philosophical Transactions A, v. 286, p. 353–372.

Cusack, C., Beeson, J., Stoneburner, D., and Robertson, G., 2010, The discovery, reservoir attributes, and significance of the Hawkville Field and Eagle Ford Shale Trend, Texas: Gulf Coast Association of Geological Societies, Transactions, v. 60, p. 165–179.

Dawson, W.C., and Almon, W.R., 2010, Eagle Ford Shale variability: Sedimentologic influences on source and reservoir character in an unconventional resource unit: Gulf Coast Association of Geological Societies, Transactions, v. 60, p. 181–190.

Demaison, G.J., and Moore, G.T., 1980, Anoxic environments and oil source bed genesis, American Association of Petroleum Geologists, Bulletin, v. 64, p. 1179–1209.

Donovan, A.D., and Staerker, T.S., 2010, Sequence stratigraphy of the Eagle Ford (Boquillas) Formation in the subsurface of South Texas and outcrops of West Texas: Gulf Coast Association of Geological Societies, Transactions, v. 60, p. 861–899.

Droser, M.L., and Bottjer, D.J., 1986, A semiquantitative field classification of ichnofabric: Journal of Sedimentary Petrology, v. 56, p. 558–559.

Dunham, J.B., and Blake, G.H., 1987, Guide to Coastal Outcrops of the Monterey Formation of Western Santa Barbara County, California: SEPM, Pacific Section, p. 1–36.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, in Hamm, W.E., ed., Classification of Carbonate Rocks: American Association of Petroleum Geologists, Memoir 1, p. 108–121.

Einstein, H.A., and Krone, R.B., 1962, Experiments to determine modes of cohesive sediment transport in salt water: Journal of Geophysical Research, v. 67, p. 1451–1461.

Flemming, B.W., 2000, A revised textural classification of gravel-free muddy sediments on the basis of ternary diagrams: Continental Shelf Research, v. 20, p. 1125–1137.

Folk, R.L., 1965, Petrology of Sedimentary Rocks: Austin, Texas, Hemphill Publishing, 159 p.

Folk, R.L., 1968, Petrology of Sedimentary Rocks: Austin, Texas, Hemphill Publishing, 170 p.

Fo¨ llmi, K.B., 1996, The phosphorous cycle, phosphogenesis and marine phosphate-rich deposits: Earth-Science Reviews, v. 40, p. 55–124.

Garrison, R.E., Kastner, M. and Kolodny, Y., 1987, Phosphorites and phosphatic rocks in the Monterey Formation and related Miocene units, Coastal California, in Ingersoll, R.V., and Ernst, W.G., eds., Cenozoic Basin Development of Coastal California: Rubey, Volume VI, New Jersey, Prentice-Hall, p. 349–381.

Garrison, R.E., Kastner, M., and Reimers, C.E., 1990, Miocene phosphogenesis in California, in Riggs, S.R., and Burnett, W.C., eds., Phosphate Deposits of the World: Volume 3, Genesis of Neogene to Modern Phosphorites: Cambridge, U.K., Cambridge University Press, p. 285–299.

Guthrie, J.M., and Bohacs, K.M., 2009, Spatial variability of source rocks: a critical element for defining the petroleum system of Pennsylvanian carbonate reservoirs of the Paradox Basin, SE Utah, in Houston, W.S.,Wray, L.L., and Moreland, P.G., eds., The Paradox Basin Revisited: New Developments in Petroleum Systems and Basin Analysis: Rocky Mountain Association of Geologists, Special Publication, p. 95–130.

Hentz, T.F., and Ruppel, S.C., 2011, Regional stratigraphic and rock characteristics of Eagle Ford Shale in its play area: Maverick Basin to East Texas Basin: American Association of Petroleum Geologists, Search and Discovery Article #10325.

Hovikoski, J., Lemiski, R., Gingras, M., Pemberton, G., and MacEachern, J.A., 2008, Ichnology and sedimentology of a mud-dominated deltaic coast: Upper Cretaceous Alderson Member (Lea Park Fm), Western Canada: Journal of Sedimentary Research, v. 78, p. 803–824.

Hower, J., Eslinger, E.V., Hower, M.E., and Perry, E.A., 1976, Mechanism of burial metamorphism of argillaceous sediment. 1. Mineralogical and chemical evidence: Geological Society of America, Bulletin, v. 87, p. 725–737.

Ingram, R.L., 1953, Fissility of mudrocks: Geological Society of America, Bulletin, v. 64, p. 869–878.

Isaacs, C.M., 1981, Field characterization of rocks in the Monterey Formation along the coast west of Santa Barbara, in Isaacs, C.M., ed., Guide to the Monterey Formation in the California coastal area, Ventura to San Luis Obispo: American Association of Petroleum Geologists, Pacific Section, v. 52, p. 39–54.

Ko¨ nitzer, S.F., Davies, S.J., Stephenson, M.H., and Leng, M.J., 2014, Depositional controls on mudstone lithofacies in a basinal setting: implications for the delivery of sedimentary organic matter: Journal of Sedimentary Research, v. 84, p. 198–214.

Land, L.S., 1997, Mass transfer during burial diagenesis in the Gulf of Mexico sedimentary basin: an overview, in Montan˜ ez, I., Gregg, J.M., and Shelton, K.L., eds., Basin-Wide Diagenetic Patterns: Integrated Petrologic Geochemical and Hydrologic Considerations: SEPM, Special Publication 57, p. 29–39.

Land, L.S., Lynch, F.L., Mack, L.E., and Milliken, K.L., 1997, Burial metamorphism of argillaceous sediment, Gulf of Mexico sedimentary basin: a re-examination: Geological Society of America, Bulletin, v. 109, p. 2–15.

Lazar, O.R., 2007, Redefinition of the New Albany Shale of the Illinois basin: an integrated, stratigraphic, sedimentologic, and geochemical study [unpublished Ph.D. thesis]: Indiana University, Bloomington, 336 p.

Lazar, O.R., and Schieber, J., 2006, Stratigraphic insights into Late Devonian black shales of the Illinois and Appalachian basins: outcrop to subsurface examples [abstract]: American Association of Petroleum Geologists, Annual Meeting, Houston, Abstract Volume, 38 p.

Lazar, O.R., Bohacs, K.M., Macquaker, J.H.S., and Schieber, J., 2010, Fine-grained rocks in outcrops: classification and description guidelines, in Schieber, J., Lazar, O.R., and Bohacs, K.M., eds., Sedimentology and Stratigraphy of Shales: Expressions and Correlation of Depositional Sequences in the Devonian of Tennessee, Kentucky, and Indiana: American Association of Petroleum Geologists, Annual Convention, Field Guide for SEPM Field Trip 10, p. 3–14.

Lobza, V., and Schieber, J., 1999, Biogenic sedimentary structures produced by worms in soupy, soft muds: observations from the Chattanooga Shale (Upper Devonian) and experiments: Journal of Sedimentary Research, v. 69, p. 1041–1049.

Lundegard, P.D., and Samuels, N.D., 1980, Field classification of fine-grained sedimentary rocks: Journal of Sedimentary Petrology, v. 50, p. 781–786.

MacKay, D.A., and Dalrymple, R.W., 2011, Dynamic mud deposition in a tidal environment: the record of fluid-mud deposition in the Cretaceous Bluesky Formation, Alberta, Canada: Journal of Sedimentary Research, v. 81, p. 901–920.

Macquaker, J.H.S., and Adams, A.E., 2003, Maximizing information from fine-grained sedimentary rocks: an inclusive nomenclature for mudstones: Journal of Sedimentary Research, v. 73, p. 735–744.

Macquaker, J.H.S., and Gawthorpe, R.L., 1993, Mudstone lithofacies in the Kimmeridge Clay Formation, Wessex Basin, Southern England: implications for the origin and controls of the distribution of mudstones: Journal of Sedimentary Petrology, v. 63, p. 1129–1143.

Macquaker, J.H.S., and Howell, J.K., 1999, Small-scale (, 5.0 m) vertical heterogeneity in mudstones: implications for high-resolution stratigraphy in siliciclastic mudstone successions: Geological Society of London, Journal, v. 156, p. 105–112.

Macquaker, J.H.S., and Taylor, K.G., 1996, A sequence-stratigraphic interpretation of a mudstone-dominated succession: the Lower Jurassic Cleveland Ironstone Formation, U.K.: Geological Society of London, Journal, v. 153, p. 759–770.

Macquaker, J.H.S., Gawthorpe, R.L., Taylor, K.G., and Oates, M.J., 1998, Heterogeneity, stacking patterns and sequence-stratigraphic interpretation in distal mudstone successions: examples from the Kimmeridge Clay Formation, UK, in Schieber, J., Zimmerle, W., and Sethi, P., eds., Shales and Mudstones, Volume I: Stuttgart, Schweizerbart'sche Verlagsbuchhandlung, Nägele u. Obermüller, p. 163–186.

Macquaker, J.H.S., Taylor, K.G., and Gawthorpe, R.L., 2007, High-resolution facies analyses of mudstones: implications for paleoenvironmental and sequence-stratigraphic interpretations of offshore ancient mud-dominated successions: Journal of Sedimentary Research, v. 77, p. 324–339.

Macquaker, J.H.S., Keller, M.A., and Davies, S.J., 2010a, Algal blooms and ''marine snow'': mechanisms that enhance preservation of organic carbon in ancient fine-grained sediments: Journal of Sedimentary Research, v. 80, p. 934–942.

Macquaker, J.H.S., Bentley, S.J., and Bohacs, K.M., 2010b, Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: reappraising sediment transport processes operating in ancient mudstone successions: Geology, v. 38, p. 947–950.

Macquaker, J.H.S., Bentley, S., Bohacs, K.M., Lazar, O.R., and Jonk, R., 2010c, Advective sediment transport on mud-dominated continental shelves: processes and products: American Association of Petroleum Geologists, Annual Meeting, New Orleans, LA, Search and Discover Article #50281.

Macquaker, J.H.S., Taylor, K.G., Keller, M.A., and Polya, D., 2014, Compositional controls on early diagenetic pathways in fine-grained sedimentary rocks: implications for predicting unconventional reservoir attributes of mudstones: American Association of Petroleum Geologists, Bulletin, v. 98, p. 587–603.

McCave, I.N., Manighetti, B., and Robinson, S.G., 1995, Sortable silt and fine sediment size composition slicing parameters for paleocurrent speed and paleoceanography: Paleoceanography, v. 10, p. 593–610.

Milliken, K.L., 1992, Chemical behavior of detrital feldspars in mudrocks versus sandstones, Frio Formation (Oligocene), south Texas: Journal of Sedimentary Petrology, v. 62, p. 790–801.

Milliken, K.L., 1994, Cathodoluminescent textures and the origin of quartz silt in Oligocene mudrocks, south Texas: Journal of Sedimentary Research, v. 64, p. 567–571.

Milliken, K.L., 2004, Late diagenesis and mass transfer in sandstone–shale sequences, in Holland, H.D., and Turekian, K.K., eds., Treatise on Geochemistry: Sediments, Diagenesis, and Sedimentary Rocks, Volume 7: Oxford, U.K., Elsevier Pergamon, p. 159–190.

Milliken, K.L., 2013, SEM-based cathodoluminescence imaging for discriminating quartz types in mudrocks: Unconventional Resources Technology Conference, no. 1582467.

Milliken, K.L., and Day-Stirrat, R.J., 2013, Cementation in mudrocks: brief review with examples from cratonic basin mudrocks, in Chatellier, J., and Jarvie, D., eds., Critical Assessment of Shale Resource Plays: American Association of Petroleum Geologists, Memoir 103, p. 133–150.

Milliken, K.L., Esch, W.L., Reed, R.M., and Zhang, T., 2012, Grain assemblages and strong diagenetic overprinting in siliceous mudrocks, Barnett Shale (Mississippian), Fort Worth Basin, Texas: American Association of Petroleum Geologists, Bulletin, v. 96, p. 1553–1578.

O'Brian, N.R., and Slatt, R.M., 1990, Argillaceous Rock Atlas: New York, Springer-Verlag, 141 p.

Owen, M.W., and Odd, N.V.M., 1970, A mathematical model of the effect of tidal barrier on siltation in an estuary: International Conference on Utilization of Tidal Power, Halifax, Canada, Department of Energy, Mines and Resources, 36 p.

Pettijohn, F.E., 1975, Sedimentary Rocks: New York, Harper and Row, 628 p.

Pettijohn, F.E., Potter, P.E., Siever, R., 1973, Sand and Sandstones: New York, Springer-Verlag, 618 p.

Picard, D.M., 1971, Classification of fine-grained sedimentary rocks: Journal of Sedimentary Petrology, v. 41, p. 179–195.

Plint, A.G., Macquaker, J.H.S., and Varban, B.L., 2012, Bedload transport of mud across a wide, storm-influenced ramp: Cenomanian–Turonian Kaskapau Formation, Western Canada Foreland Basin: Journal of Sedimentary Research, v. 82, p. 801–822.

Potter, P.E., Maynard, J.B., and Pryor, W.A., 1980, Sedimentology of Shale: Study Guide and Reference Source: Berlin, Springer-Verlag, 303 p.

Potter, P.E., Maynard, J.B., and Depetris, P.J., 2005, Mud and Mudstones: Introduction and Overview: Berlin, Springer, 297 p.

Reineck, H.-E., 1963, Sedimentgefüge im Bereich der südlichen Nordsee: Senckenbergische Naturforschende Gesellschaft, Abhandlungen 505, p. 1–138.

Robertson, G., 2010, From first idea to 10TCF in 10 months: discovery of Eagle Ford Shale in Hawkville Field: American Association of Petroleum Geologists, Search and Discovery Article #110137, p. 1–17.

Schieber, J., 1989, Facies and origin of shales from the Mid-Proterozoic Newland Formation, Belt basin, Montana, U.S.A.: Sedimentology, v. 36, p. 203–219.

Schieber, J., 1994, Evidence for episodic high energy events and shallow water deposition in the Chattanooga Shale, Devonian, central Tennessee, U.S.A: Sedimentary Geology, v. 93, p. 193–208

Schieber, J., 1996, Early diagenetic silica deposition in algal cysts and spores: a source of sand in black shales?: Journal of Sedimentary Research, v. 66, p. 175–183.

Schieber, J., 1998, Developing a sequence stratigraphic framework for the Late Devonian Chattanooga Shale of the southeastern U.S.A.: relevance for the Bakken Shale, in Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L., eds., Eighth International Williston Basin Symposium, Saskatchewan Geological Society, Special Publication 13, p. 58–68.

Schieber, J., 1999, Distribution and deposition of mudstone facies in the Upper Devonian Sonyea Group of New York: Journal of Sedimentary Research, v. 69, p. 909–925.

Schieber, J., 2003, Simple gifts and buried treasures: implications of finding bioturbation and erosion surfaces in black shales: The Sedimentary Record, v. 1, no. 2, p. 4–8.

Schieber, J., 2011a, Reverse engineering mother nature: shale sedimentology from an experimental perspective: Sedimentary Geology, v. 238, p. 1–22.

Schieber, J., 2011b, Marcasite in black shales—a mineral proxy for oxygenated bottom waters and intermittent oxidation of carbonaceous muds: Journal of Sedimentary Research, v. 81, p. 447–458.

Schieber, J., and Baird, G., 2001, On the origin and significance of pyrite spheres in Devonian black shales of North America: Journal of Sedimentary Research, v. 71, p. 155–166.

Schieber, J., and Lazar, R.O., 2004, eds., Devonian Black Shales of the Eastern U.S.: New Insights into Sedimentology and Stratigraphy from the Subsurface and Outcrops in the Illinois and Appalachian Basins: SEPM, Great Lakes Section, Annual Field Conference, Field Guide, Indiana Geological Survey Open File Study 04-05, 90 p.

Schieber, J., and Riciputi, L., 2004, Pyrite ooids in Devonian black shales record intermittent sea-level drop and shallow-water conditions: Geology, v. 32, p. 305–308.

Schieber, J., and Southard, J.B., 2009, Bedload transport of mud by floccule ripples: direct observation of ripple migration processes and their implications: Geology, v. 37, p. 483–486.

Schieber, J., and Yawar, Z., 2009, A new twist on mud deposition: mud ripples in experiment and rock record: The Sedimentary Record, v. 7, no. 2, p. 4–8.

Schieber, J., Krinsley, D., and Riciputi, L., 2000, Diagenetic origin of quartz silt in mudstones and implications for silica cycling: Nature, v. 406, p. 981–985.

Schieber, J., Southard, J.B., and Thaisen, K.G., 2007, Accretion of mudstone beds from migrating floccule ripples: Sciences, v. 318, p. 1760–1763.

Schieber, J., Southard, J.B., and Schimmelmann, A., 2010a, Lenticular shale fabrics resulting from intermittent erosion of water-rich muds: interpreting the rock record in the light of recent flume experiments: Journal of Sedimentary Research, v. 80, p. 119–128.

Schieber, J., Lazar, O.R., and Bohacs, K.M., 2010b, Sedimentology and Stratigraphy of Shales: Expressions and Correlation of Depositional Sequences in the Devonian of Tennessee, Kentucky, and Indiana: American Association of Petroleum Geologists, Annual Convention, Field Guide for SEPM Field Trip 10, 172 p.

Schieber, J., Lazar, O.R., Bohacs, M.K., Klimentidis, R., Ottmann, J., Dumitrescu, M., 2012, A scanning electron microscope study of porosity in the Eagle Ford Shale of Texas: American Association of Petroleum Geologists, Search and Discovery Article #90142.

Schlanger, S.O., Arthur, M.A., Jenkyns, H.C., and Scholle, P.A., 1987, The Cenomanian–Turonian oceanic anoxic event, I. Stratigraphy and distribution of organic carbon-rich beds and the marine delta (super 13) C excursion, in Brooks, J., and Fleet, A.J., eds., Marine Petroleum Source Rocks: Geological Society of London, Special Publication 26, p. 371–399.

Schwalbach, J.R., 1992, Stratigraphic and sedimentological analysis of the Monterey Formation: Santa Maria and Pismo basins, southern California [Ph.D. dissertation]: University of Southern California, Los Angeles, 360 p. Schwalbach, J.R., and Bohacs, K.M., 1992, eds., Sequence Stratigraphy in Fine-Grained Rocks: Examples from the Monterey Formation: SEPM, Pacific Section, Field Guide, v. 70, 80 p.

Shepard, F.P., 1954, Nomenclature based on sand-silt-clay ratios: Journal Sedimentary Petrology, v. 24, p. 151–158.

Shipboard Scientific Party, 1984, Introduction and explanatory notes, in Hay, W.W., Sibuet, J.-C., etc., Initial Reports Deep Sea Drilling Project, Leg 75, p. 3–25.

Spears, D.A., 1980, Towards a classification of shales: Geological Society of London, Journal, v. 137, p. 125–129.

Stow, D.A., 1981, Fine-grained sediments: terminology: Quarterly Journal of Engineering Geology and Hydrology, v. 14, p. 243–244.

Stow, D.A.V., 2012, Sedimentary Rocks in the Field: A Color Guide: New York, Academic Press, 320 p.

Stow, D.A.V., and Piper, D.J.W., 1984, Deep-water fine grained sediments: history, methodology and terminology, in Stow, D.A.V., and Piper, D.J.W., eds., Fine-Grained Sediments: Deep-Water Processes and Facies: Geological Society of London, Special Publication 15, p. 3–16.

Taylor, A.M., and Goldring, R., 1993, Description and analysis of bioturbation and ichnofabric: Geological Society of London, Journal, v. 150, p. 141–148.

Taylor, K.G., and Macquaker, J.H.S., 2014, Diagenetic alterations in a silt- and clay-rich mudstone succession: an example from the Upper Cretaceous Mancos Shale of Utah, USA: Clay Minerals, v. 49, p. 245–259.

Taylor, G.H., Teichmuller, M., Davis, A., Diessel, C.F.K., Linke, R., Robert, P., Glick, D.C., Smyth, M., Swaine, D.J., Vanderbroucke, M., and Espitalie, J., 1998, Organic Petrology: Berlin, Gebrüder Borntraeger, 704 p.

Trefethen, J.M., 1950, Classification of sediments: American Journal of Science, v. 248, p. 55–62.

Trincardi, F., Cattaneo, A., Correggiari, A., Ridente, D., 2004, Evidence of soft sediment deformation, fluid escape, sediment failure and regional weak layers within the late Quaternary mud deposits of the Adriatic Sea: Marine Geology, v. 213, p. 91–119.

Tourtelot, H.A., 1960, Origin and use of the word ''shale'': American Journal of Science, v. 258A, p. 335–343.

Tyson, R.V., 1995, Sedimentary Organic Matter: Organic Facies and Palynofacies: London, Chapman and Hall, 615 p.

Tyson, R.V., Wilson, R.C.L., and Downie, C., 1979, A stratified water column environmental model for the type Kimmeridge Clay: Nature, v. 227, p. 377–380.

Wedepohl, K.H., 1971, Environmental influences on the chemical composition of shales and clays: Physics and Chemistry of the Earth, v. 8, p. 307–333.

Wheatcroft, R.A., and Borgeld, J.C., 2000, Oceanic flood layers on the northern California margin: large-scale distribution and small-scale physical properties: Continental Shelf Research, v. 20, p. 2163–2190.

Wheatcroft, R.A., and Drake, D.E., 2003, Post-depositional alteration and preservation of sedimentary event layers on continental margins, I. The role of episodic sedimentation: Marine Geology, v. 199, p. 123–137.

Williams, L.A., 1982, Lithology of the Monterey Formation (Miocene) in the San Joaquin Valley of California, in Williams, L.A., and Graham, S.A., eds., Monterey Formation and Associated Coarse Clastic Rocks, Central San Joaquin basin, California: SEPM, Pacific Section, Publication 25, p. 17–36.

Workman, S.J., 2013, Integrating depositional facies and sequence stratigraphy in characterizing unconventional reservoirs: Eagle Ford Shale, South Texas [Master's Thesis]: Western Michigan University, 141 p.

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APPENDIX 1:
INTEGRATED WORKFLOW FOR DESCRIBING MUDSTONES IN OUTCROPS AND CORES

Fine-grained sedimentary rocks weather significantly in outcrops and cores due to their commonly large content of reactive minerals (e.g., clay, pyrite). Describing these rocks in outcrops and cores can therefore be a challenge, and, at first sight, one may argue that not much more than color variations can be observed. After getting a fresh surface, detailed and systematic examination reveals, however, much about rock texture, bedding, and composition, vertical and lateral variation, and modes of accumulation. It also enables acquisition of appropriate and representative samples in their sedimentologic and stratigraphic context. Some of the steps we recommend taking when examining mudstones in outcrops and cores are (note: this is not an exhaustive list):

Make Observations:

I. Establish stratigraphic context. In the field, step back, examine and photograph the entire exposure walking the section several times; obtain and examine a fresh face of rocks from each potential stratigraphic package. In a core, check core depths and core box order; clean the core; photograph the entire cored interval; then step back and examine the cored interval several times with well logs in hand.

II. Start at the base, identify, examine, and describe stratigraphic packages and surfaces as you proceed up-section.

A. Describe the rocks: **texture**, **bedding**, and **composition**.

1) Assign a **texture** name (coarse, medium, or fine mudstone; Fig. 1): estimate the percentage of sand-size grains with visual comparison to percentage charts. If less than 50% are sand-sized grains, the rock is a mudstone and a **scratch test** can be performed to determine the dominant grain size. The scratch test is performed by scratching the fresh face of outcrop rocks or the clean back of the core with a sharp steel probe and then observing the luster of the scratch and the color of powder generated:

- Distinctly waxy luster and dark color generally indicates more than two thirds fine-mud-size material (termed a ‘‘fine mudstone’’).
- Distinctly dull luster and light color indicates more than two thirds coarse-mud-size material (termed a ‘‘coarse mudstone’’).
- Mid-lustrous scratch and intermediate colored powder indicates medium-mud-size material between two thirds and one third (termed a ‘‘medium mudstone’’).
  - The results from the scratch test need to be critically interpreted, however, because of the presence of cement (which can lead to apparent coarser interpretations of grain size), aggregate grains (which can lead to underestimation of grain size especially when argillaceous aggregate grains are present), and microcrystalline quartz (which can lead to overestimates of grains size, e.g., Milliken et al. 2012; Milliken 2013).
  - Grain-size assessments can be further enhanced if thin sections are available (e.g., recognize the effects of diagenesis and bioturbation on grain size). We do recommend that conventional thin sections are prepared early on in the investigation to compare scratch-test estimates of texture with microscopic textural determinations. If there are no sample-size limitations, it is particularly valuable to make large polished thin sections (76 mm x 48 mm; ~ 3 in x 2 in).

2) Describe **bedding** (Fig. 2). How are the strata packaged at the millimeter- to centimeter- to decimeter-scale?

- Identify and describe laminae and beds. Bed surfaces can be distinguished by stratal terminations (e.g., truncation below a surface or onlap or downlap above it), presence of colonization horizons or subjacent burrowing, and changes in lithofacies. Beds in mudstones are millimeter to centimeter thick (typically 1 to 4 mm thick), and composed of genetically related laminae and laminasets.
- Describe physical sedimentary structures.
- Describe biogenic sedimentary structures. The **degree of bioturbation** varies from no visible burrows to no remnant bedding left when a rock interval is fully homogenized. The degree of bioturbation can be assessed using a 0 to 5 scale (Table A1). Bioturbation tends to be subtle in mudstone strata; don’t expect too many textbook-style ichnofossils, because burrows tend to be obscure where matrix and fill do not differ in composition and rheology. Prior to mud compaction, benthos does not burrow but swims through muddy sediment with high water content (70–90%) and disturbs the sediment fabric, producing deformational structures (e.g., Lobza and Schieber 1999; Schieber 2003).
- Describe body-fossil type, size, diversity, distribution, and taphonomy.

3) Assign a **composition** modifier to texture name (e.g., siliceous, calcareous, argillaceous, carbonaceous, etc.; Fig. 3):

- After performing the scratch test, drop dilute HCl on scratch, powder, and adjacent fresh face or back of core and observe vigor of reaction to estimate the presence and types of carbonates.
- Observe general fracture character, luster, color (function of composition but not unique and heavily modified by weathering), and identify dominant minerals.
- Describe detrital, biogenic, and authigenic components (Fig. 4).
- Describe organic-matter type (e.g., amorphous, algal, herbaceous, woody, coaly; migrated liquids might contribute to the organic-carbon component in mature mudstones) and distribution.
  - Compositional assessments can be further enhanced if thin sections are available (e.g., distinguish the composition of individual grains and cement).

B. Aggregate recurring, representative, and diagnostic facies attributes into facies associations.

C. Record all information consistently and take samples. See Figure A10 for an example of a description of mudstone in core.

Make Interpretations:

III. Integrate outcrop/core observations with thin-section descriptions, analytical, well-log, and seismic data as available. Make a hierarchical interpretation of stratal units (beds, bedsets, parasequences, parasequence sets, sequences; significant stratal boundaries).

IV. Make interpretations on (Figure 5; e.g., Bohacs et al. 2005, 2014):

A. Dominant sediment provenance.
B. Dominant input mode.
C. Dominant current mode.
D. Physical reworking.
E. Sediment accumulation rate.
F. Completeness of sedimentary record.
G. Bottom-water redox conditions.
H. Environment of deposition.

TABLE A1.—Classification of bioturbation (from Lazar et al. 2010; after Reineck 1963, Potter et al. 1980, Droser and Bottjer 1986, Taylor and Goldring 1993, and Aplin and Macquaker 2010).

Bioturbation Index, BI	Verbal BI	Description
0	*not bioturbated*	No visible burrows; all original sedimentary structures preserved
1	*weakly bioturbated*	Beds continuous, a few burrows
2	*sparsely bioturbated*	Beds discontinuous, some burrows
3	*moderately bioturbated*	Remnant bedding, common burrows, individual burrows mostly recognizable
4	*strongly bioturbated*	Minimal bed continuity, abundant burrows, some distinct burrows
5	*churned*	No remnant bedding, fully homogenized, difficult to recognize individual burrows

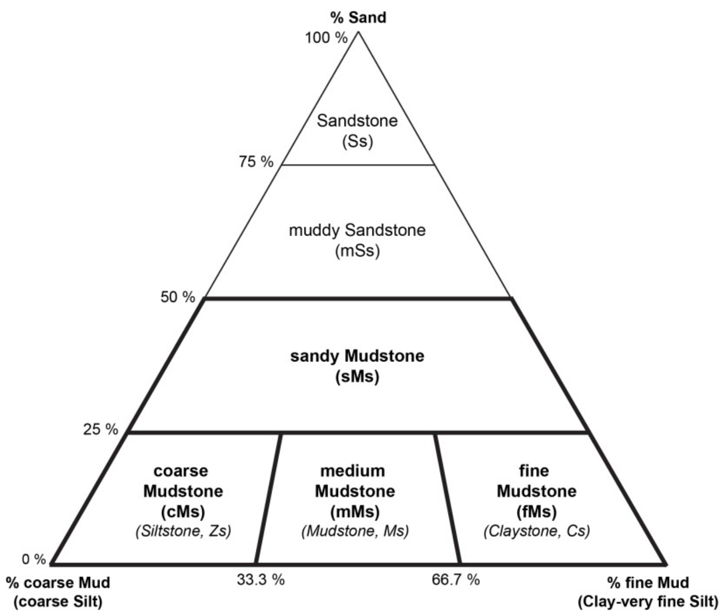

FIG. 1.—Nomenclature guidelines for fine-grained sedimentary rocks: texture (grain size). See discussion in text for details and limitations of this representation.

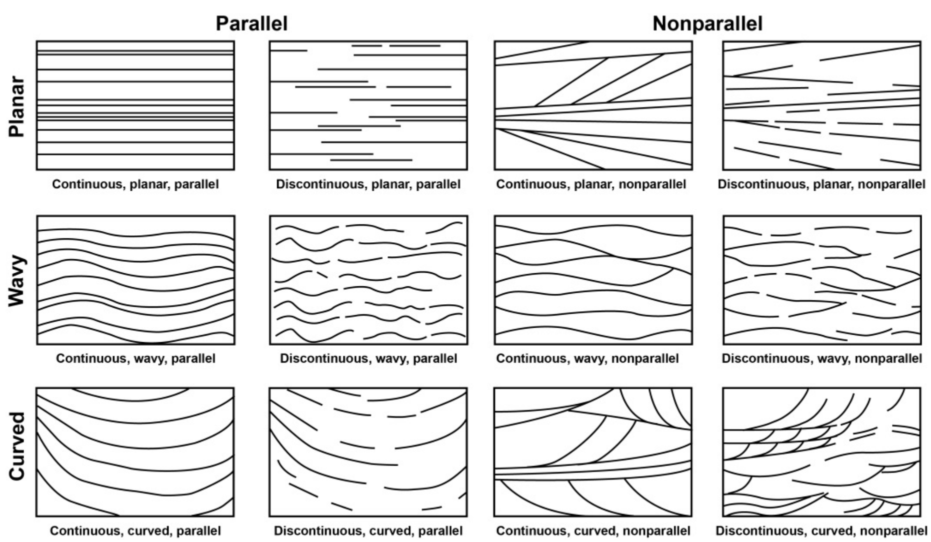

FIG. 2.—Descriptive terms for lamina continuity, shape, and geometry (after Campbell 1967). These terms are useful for all levels of stratification (e.g., laminae, laminasets, beds, bedsets).

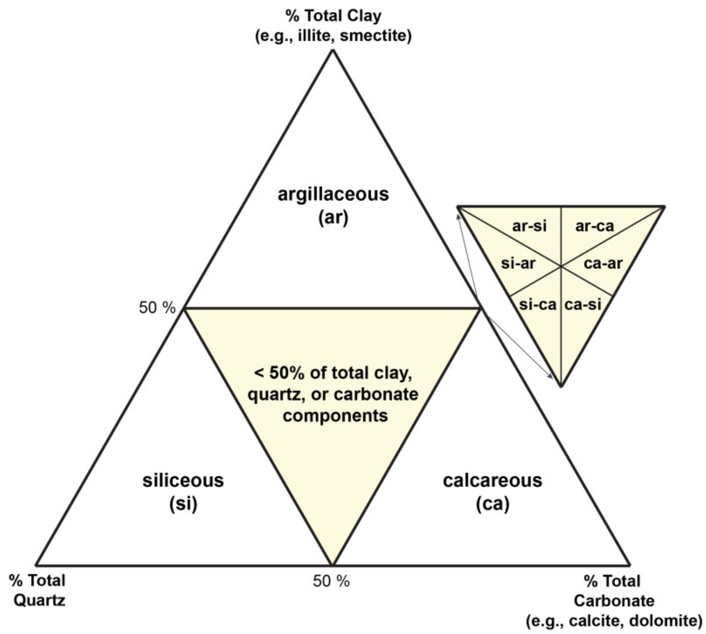

FIG. 3.—Nomenclature guidelines for fine-grained sedimentary rocks: composition (e.g., calcareous coarse mudstone).

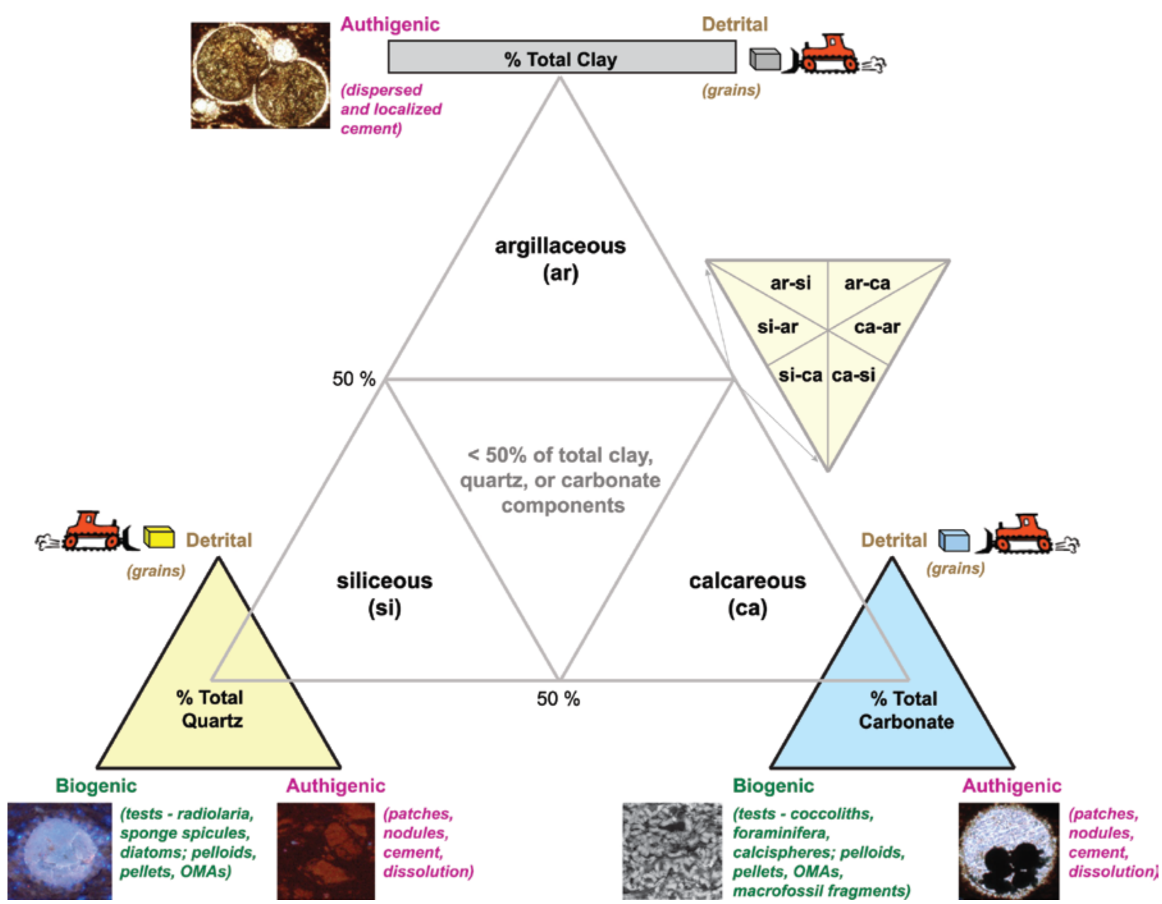

FIG. 4.—Nomenclature guidelines for fine-grained sedimentary rocks: compositional forms of siliceous, calcareous, and argillaceous mudstone (OMAs, organo-mineralic aggregates).

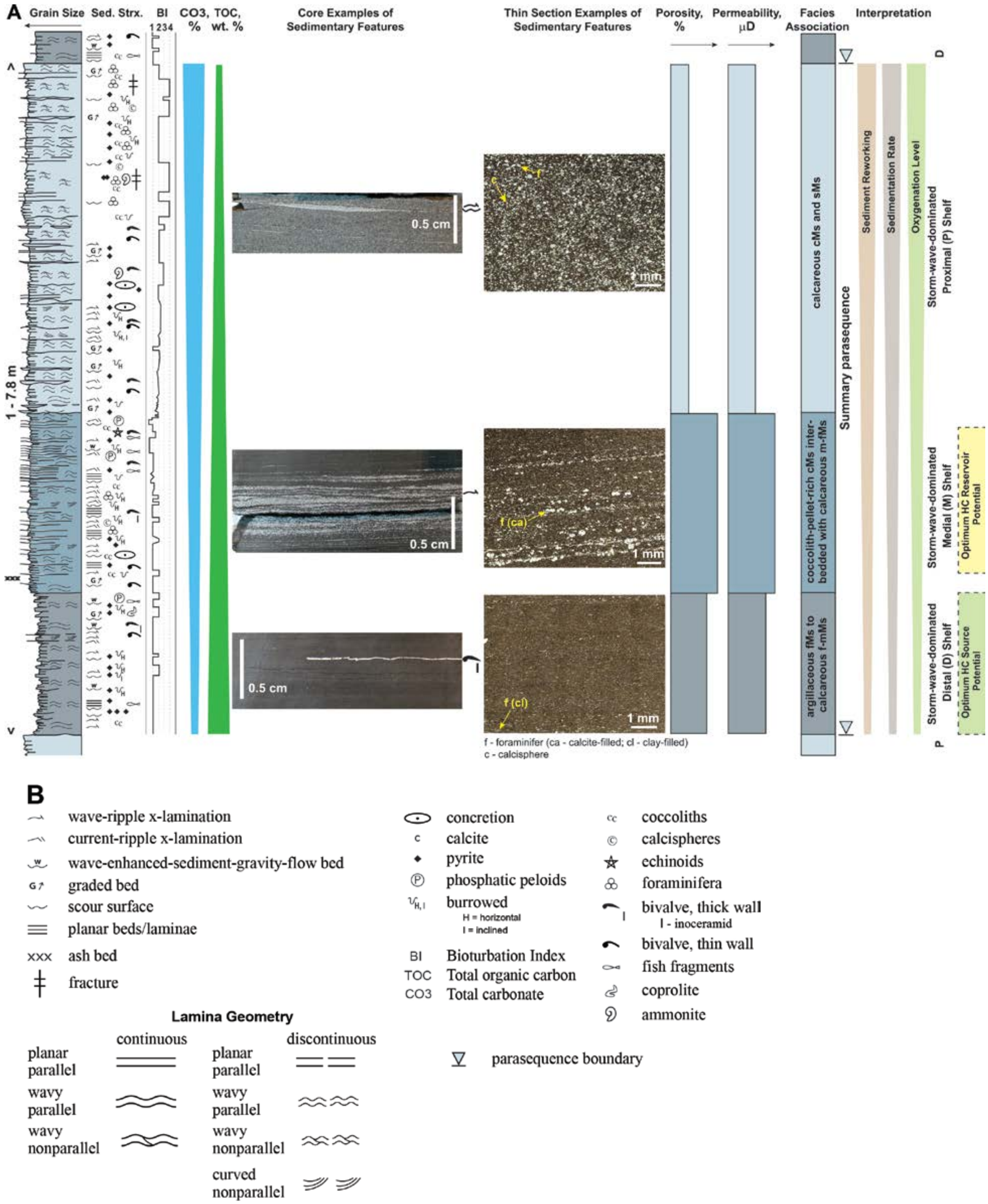

FIG. 5.—Schematic summary of parasequence expression in the Cretaceous Eagle Ford Shale, south Texas, illustrating vertical variability in texture, bedding, composition, physical sedimentary structures, degree of bioturbation, body and trace fossils, type and distribution of nodules, and color. Facies attributes were grouped into three facies associations that form a succession with a characteristic stacking pattern that we interpret as a distinct parasequence. All attributes in this facies-association succession record an upward increase in grain size and sediment reworking, sedimentation rates, and oxygenation level. We interpret the three facies associations as a result of deposition on the distal, medial, and proximal parts of a storm-wave-dominated shelf. Note also that we have hypothesized the vertical distribution of facies associations with the most promising source and gas reservoir potential based on published data of total organic carbon, porosity, and permeability (e.g., Cusack et al. 2010; Robertson 2010; Workman 2013).

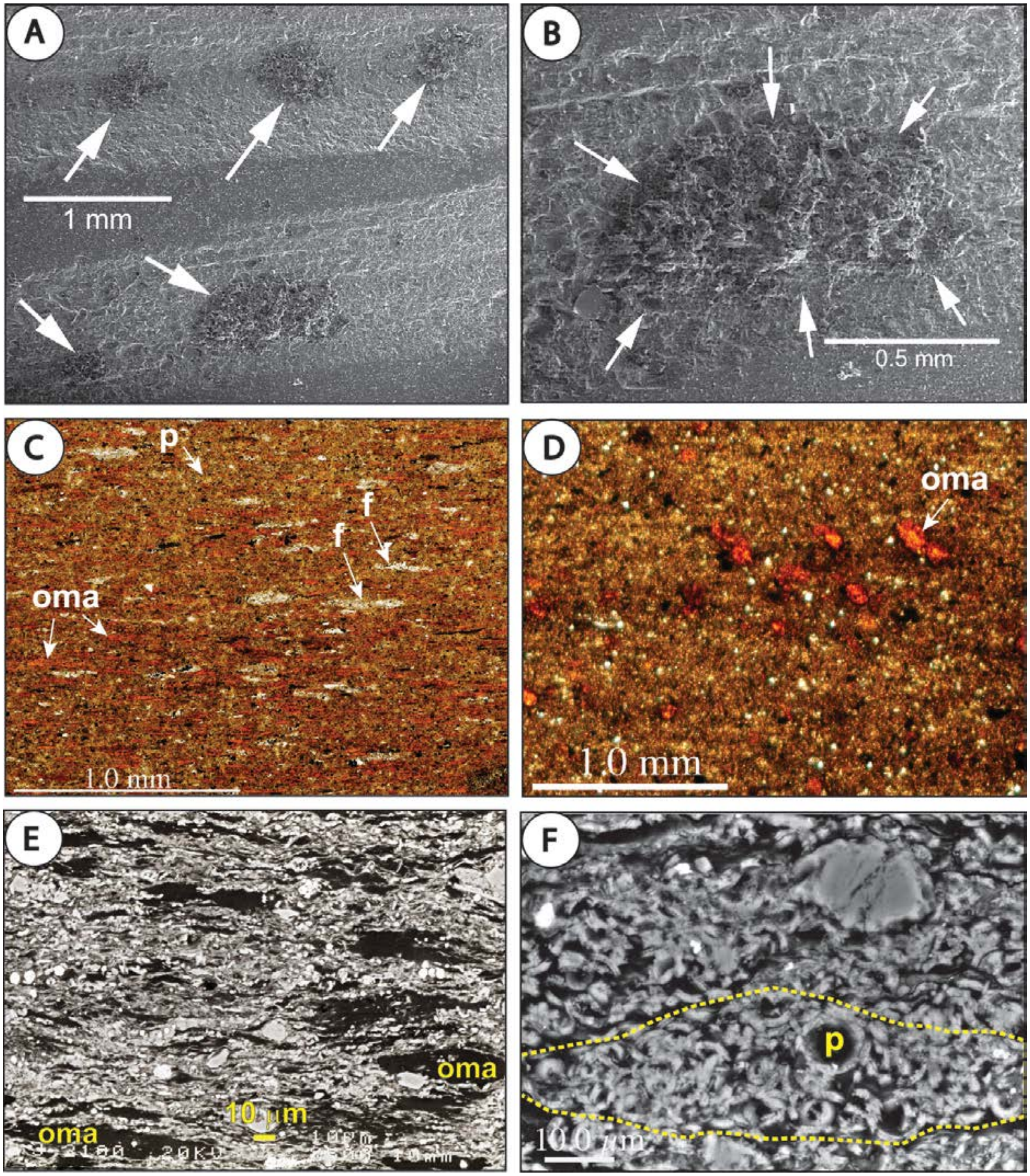

FIG. 6.—Examples of composite grains. **A)** Secondary electron image of dried kaolinite floccules (arrows) captured with a grooved glass slide placed on the flume bottom during an experiment on mud transport (after Schieber 2011a). **B)** Close-up of a floccule from Part A, bottom row, right (after Schieber 2011a). **C)** Organo-mineralic aggregates (oma), pellets (p), and benthic agglutinated foraminifera (f) in a carbonaceous, calcareous-argillaceous mudstone from the Upper Jurassic Kimmeridge Clay Fm., U.K. **D)** Bedding-parallel thin section in the same carbonaceous, calcareous-argillaceous mudstone from Part C with examples of organo-mineralic aggregates (oma). Individual oma contain mixtures of amorphous organic material, clay and carbonate minerals, and pyrite. **E)** Detail of organo-mineralic aggregates (oma) captured in a backscattered electron image (Jeol 6400 operating at 15 kV at a working distance of 15 mm) in the same sample illustrated in Part C. **F)** Detail, captured in a backscattered electron image of a coccolith-rich pellet (p, outlined in yellow) in the same sample illustrated in Part C (Jeol 6400 operating at 15 kV at a working distance of 15 mm).

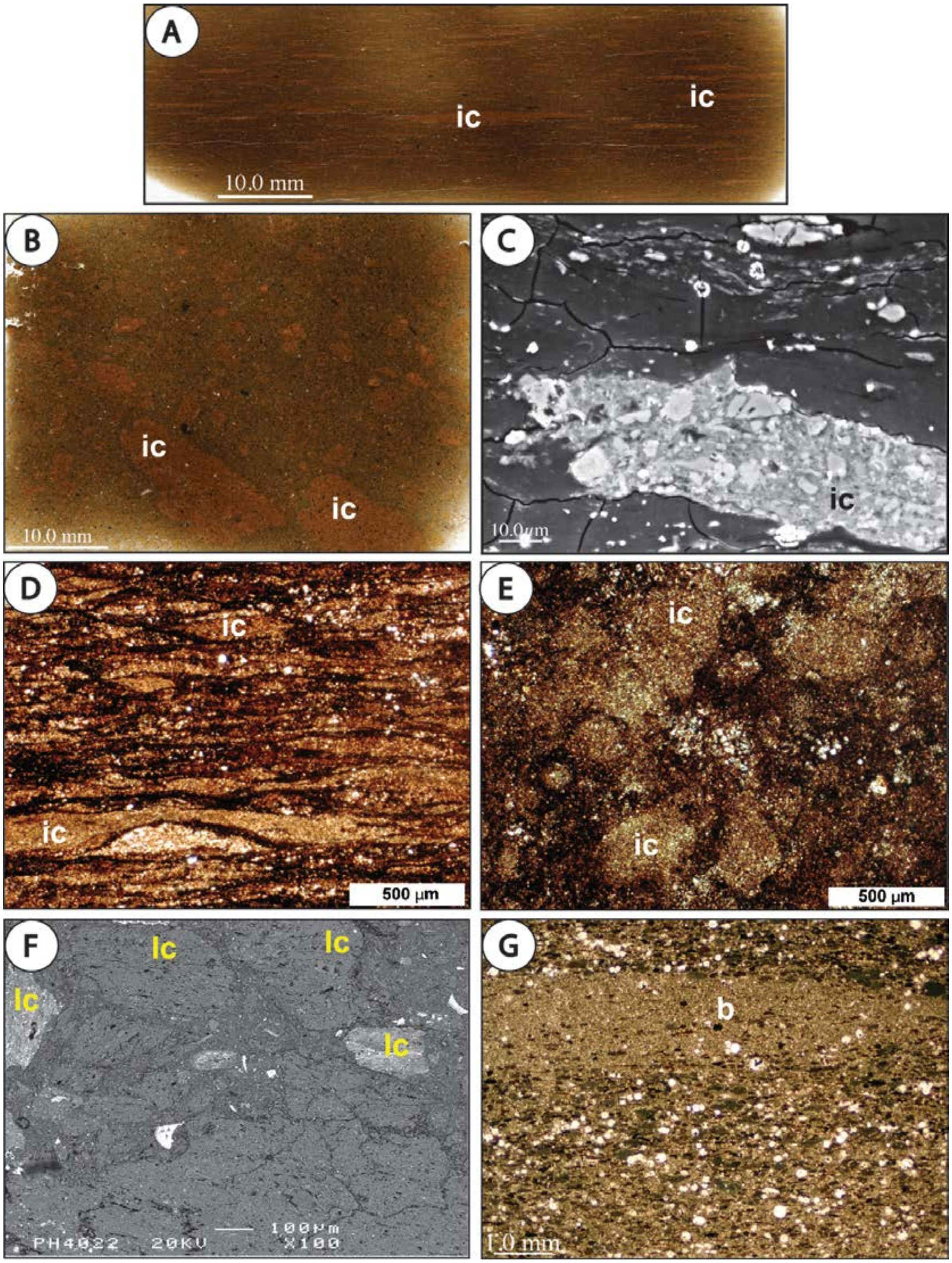

FIG. 7.—Examples of erosion-generated mud clasts. **A)** Compacted intraclasts (ic) in a kerogenous, argillaceous coarse mudstone from the Upper Jurassic, Kimmeridge Clay Fm., U.K. These clasts are mostly composed of partially consolidated algal-rich kerogenous mud and range from 1 to 20 mm in length. **B)** Bedding parallel thin section in the same kerogenous, argillaceous coarse mudstone shown in Part A. Note the presence of well-defined intraclasts (ic). **C)** Backscattered-electron image of an intraclast composed of quartz and clay minerals from Part A. **D)** Compacted intraclasts (ic) in the lenticular laminated Proterozoic Rampur Shale, Vindhyan, India (after Schieber et al. 2007, 2010a). **E)** Bedding-parallel thin section in the same lenticular mudstone shown in Part D. **F)** Backscattered-electron image of sand-size lithoclasts (lc) in an argillaceous matrix. Lithoclasts are composed of clay minerals, quartz, pyrite, and organic material, and range from hundreds of micrometers to millimeters in length. Lower Pennsylvanian Marsdenian Mudstone, U.K. **G)** Bioturbation (b) overprint of depositional fabric in a pellet- and foraminifera-rich, calcareous, medium mudstone from the Upper Cretaceous Greenhorn Fm., U.S.A.

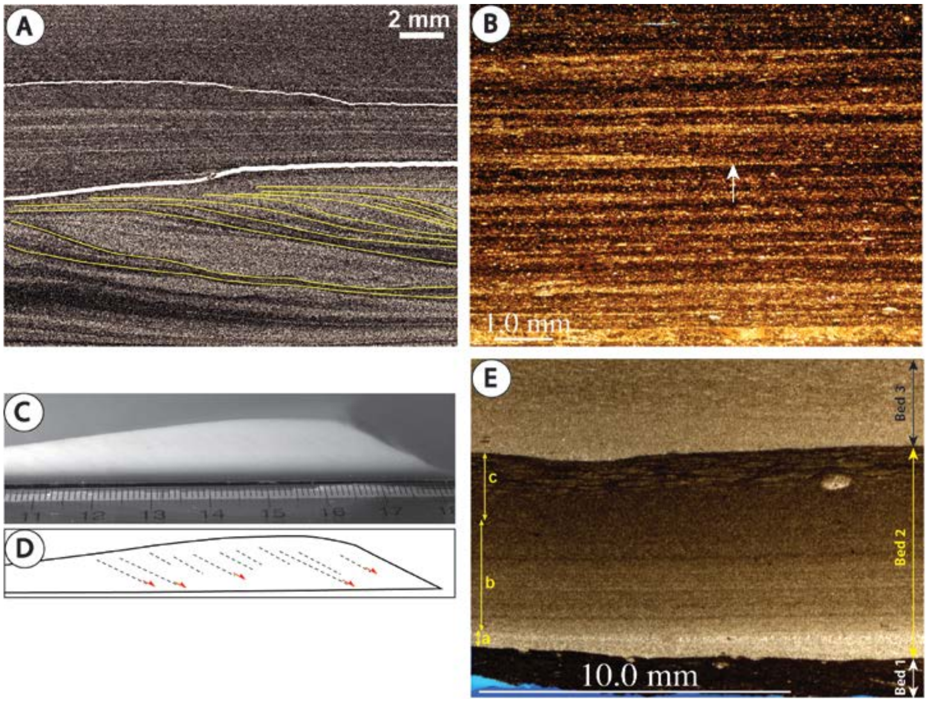

FIG. 8.—Laminated and thin-bedded mudstone is commonly the result of discontinuous sediment accumulation by lateral transport under intermittently energetic conditions that allow biogenic colonization and or sediment reworking. **A)** Current ripple, Upper Devonian Sonyea Group, NY (after Schieber 1999). **B)** Current ripple, Cretaceous Mowry Shale, UT. **C, D)** Flume experiments on mud transport and deposition (after Schieber and Southard 2009; Schieber and Yawar 2009). Cross section of floccule ripple of 90% water and 10% material that consists of > 80% grains finer than 10 μm. Flow velocity is 0.2 m/s at 5 cm effective flow depth. **C)** Ripple has an asymmetrical profile and shows faint internal cross laminae. **D)** Cross laminae highlighted in line drawing. **E)** Thin beds in the Cretaceous Mowry Shale, Wyoming (after Macquaker et al. 2010b): long-term mudstone consolidation and erosion of bed 1; deposition, bioturbation, consolidation, and erosion of bed 2 (interpreted to be produced by wave-enhanced sediment-gravity flow; a, silt-rich basal laminaset; b, laminasets composed of intercalated clay minerals and quartz-rich layers; c, laminaset that fines upward into mostly clay-size material, subsequently burrowed); deposition of bed 3.

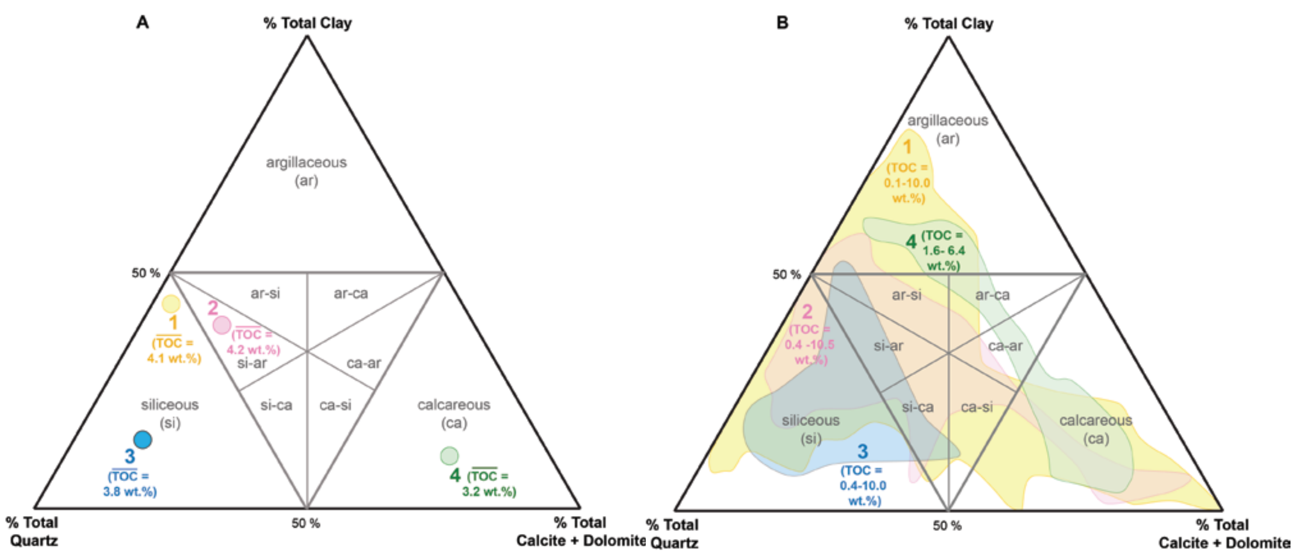

FIG. 9.—**A)** Comparison of four mudstones (1 to 4) based on average composition of total quartz, total carbonate (calcite and dolomite), total clay, and total organic carbon (TOC) content. **B)** Comparison of the four mudstones from Part A illustrating significant compositional ranges and overlap.

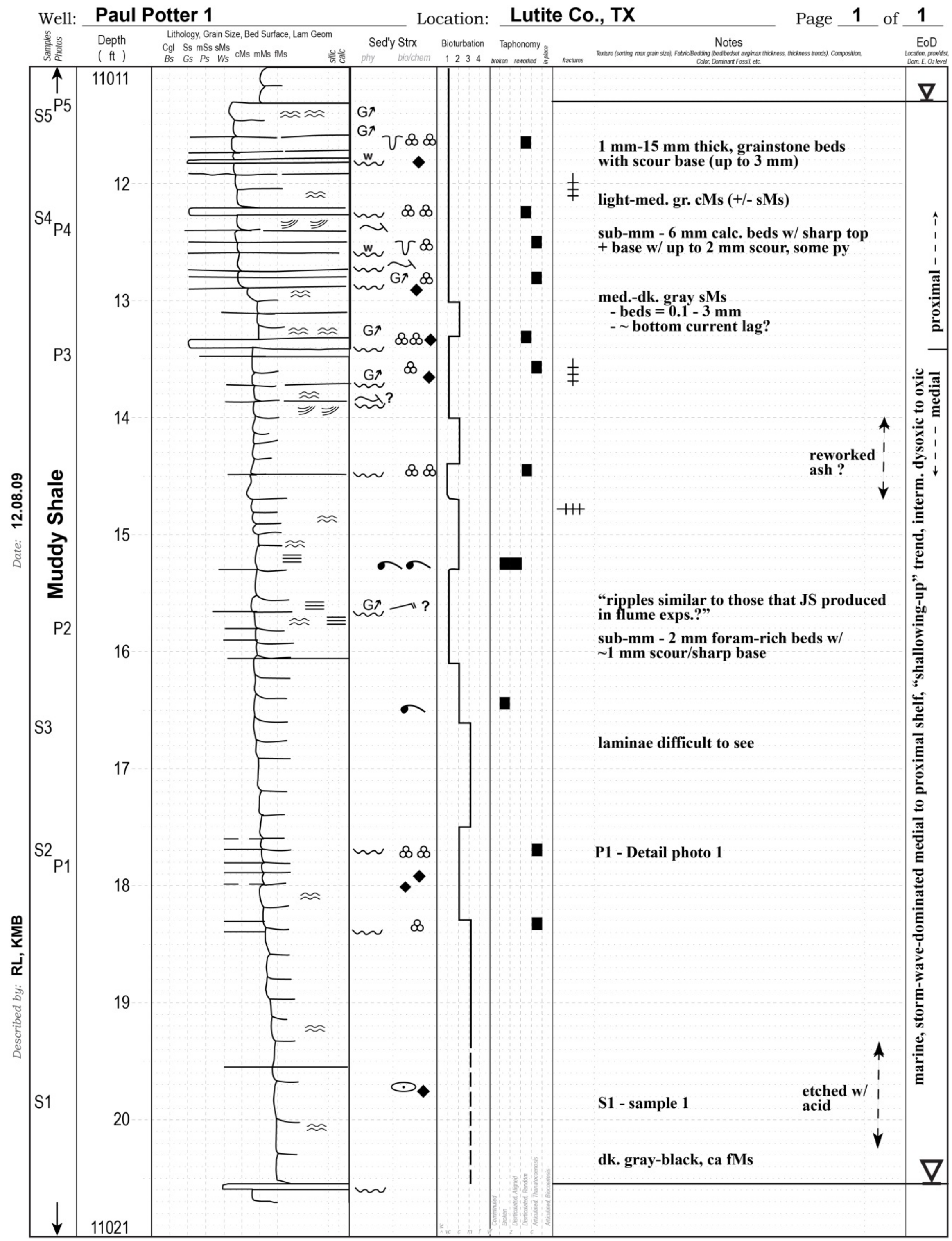

FIG. A10.—Example of mudstone description in core. See Figure 5B for explanation of symbols.