Juergen Schieber, 2011, Shales, Encyclopedia of Geobiology, Springer Verlag, J. Reitner & V. Thiel (Eds.), p. 785-791.

SHALES

Definition

Historically, the term shale has been used to describe fine-grained sedimentary rocks of largely terrigenous derivation, dominated by mud-size particles (0.06 mm and smaller) and containing appreciable quantities (several ten percent) of clay minerals. The definition of the term has been a subject of debate (Potter et al., 2005) because of the closely allied terms mud and clay for which competing definitions may emphasize grain size, mineralogy (clay dominated), or physical properties (plasticity). In place of shale, the term mudstone is also used widely and describes the same compositional spectrum of sedimentary rocks. Because shales span the clay-silt boundary, a good many rocks that are identified as siltstones in the literature also qualify as shales (and vice versa). Although the term shale traditionally had a “terrigenous” connotation, shales that accumulated in sediment starved settings may to more than 50 percent consist of microbially induced early diagenetic cements (calcite, dolomite, ferroan carbonates, silica, authigenic clays, iron sulfides), organic matter, and biogenic debris (fish bones, microfossils) upon close inspection. One could argue that the term “biogenic” would be more appropriate for these rocks.

Thus, categorizing shales is by no means a trivial exercise and the various classification schemes in existence (e.g. Ingram, 1953; Dunbar and Rodgers, 1957; Folk, 1965; Picard, 1971; Lewan, 1979; Blatt, Middleton, and Murray; 1980; Lundegard and Samuels, 1980; Potter et al, 1980; Stow and Piper, 1984; Macquaker and Adams, 2003) leave much to be desired. Many fine grained sedimentary rocks contain variable amounts of a fine grained carbonate component and it is common practice to use the terms shale and mudstone for rocks with less than 50% carbonate (Potter et al., 2005). Beyond that arbitrary cut-off the terms marl, micrite, limestone, and dolostone are most commonly used. The classification scheme proposed by Macquaker and Adams (2003), however, also includes fine grained materials of non-terrigenous origin. The books by Potter et al. (1980; 2005) and Schieber et al. (1998) provide further information on this, as well as other topics concerning shales.

Fundamentally, shales span such a large compositional and textural spectrum that a comprehensive and meaningful classification will only be possible when we can build on a much larger body of case studies than currently available. At present it is probably pointless to agonize over the actual names given to shale types encountered in a given study. What matters primarily is that the rocks be dominantly fine grained, and that we report as accurately as possible their composition, texture, and fabric. The latter two are indispensable for meaningful descriptions of shales because they convey key insights into their transport and deposition (Schieber, 1999a; Schieber et al., 2007).

Significance of shales for geobiology

Although still understudied when compared to sandstones and carbonates (Schieber and Zimmerle, 1998), shales nonetheless are geologically important for multiple reasons.

They constitute by volume two thirds of the sedimentary rock record and once examined systematically will contribute much to a better understanding of earth history and the evolution of life. Because overall they accumulate slower than sandstones or carbonates, as much as 90% of geologic time recorded in sedimentary rocks may be preserved in shales.

Shales are an excellent matrix for fossil preservation, and contained fossils are comparatively easy to extract for study. Because their low permeability limits chemical exchange and access by oxygen, metastable skeletal minerals (e.g. aragonite) and even soft tissues may be preserved. It is not by accident that many of the worlds most scientifically significant sites of fossil preservation (Fossil Lagerstätten; Seilacher et al., 1985) are found in shale successions. Notable examples are the Cambrian Burgess Shale (Conway Morris, 1998), the Devonian Hunsrück Slate (Bartels et al., 1998), the Jurassic Posidonia Shale (Kauffman, 1978), and the Messel oil shale deposit (Wuttke, 1983). Preservation of fossils carries much valuable information, particularly in the case of marine shales. Fossils are useful because taphonomy (the study of organismal decay over time), spatial distribution of fossils, fossil diagenesis, morphological attributes of fossils (e.g. reflecting adaptation to substrate conditions), fossil assemblages and comparison to modern counterparts, and paleocommunities (paleoecology) all can provide a wealth of information about the deposition of a shale succession (e.g. Brett and Allison, 1998).

Freshly deposited muds, the sediments destined to become shales after compaction, have an enormous internal surface area. Depending on the assumptions about particle geometry and water content, one can readily estimate that a liter of watery mud should have an internal surface area on the order of several hundred square meters (e.g. Fenchel, 1970). That is enough space to provide habitat for trillions (10^{12}) of microbial cells (Fig. 1).

Juergen Schieber, 2011, Shales, Encyclopedia of Geobiology, Springer Verlag, J. Reitner & V. Thiel (Eds.), p. 785-791.

Image File: Schieber-Shale-Fig-1.tif

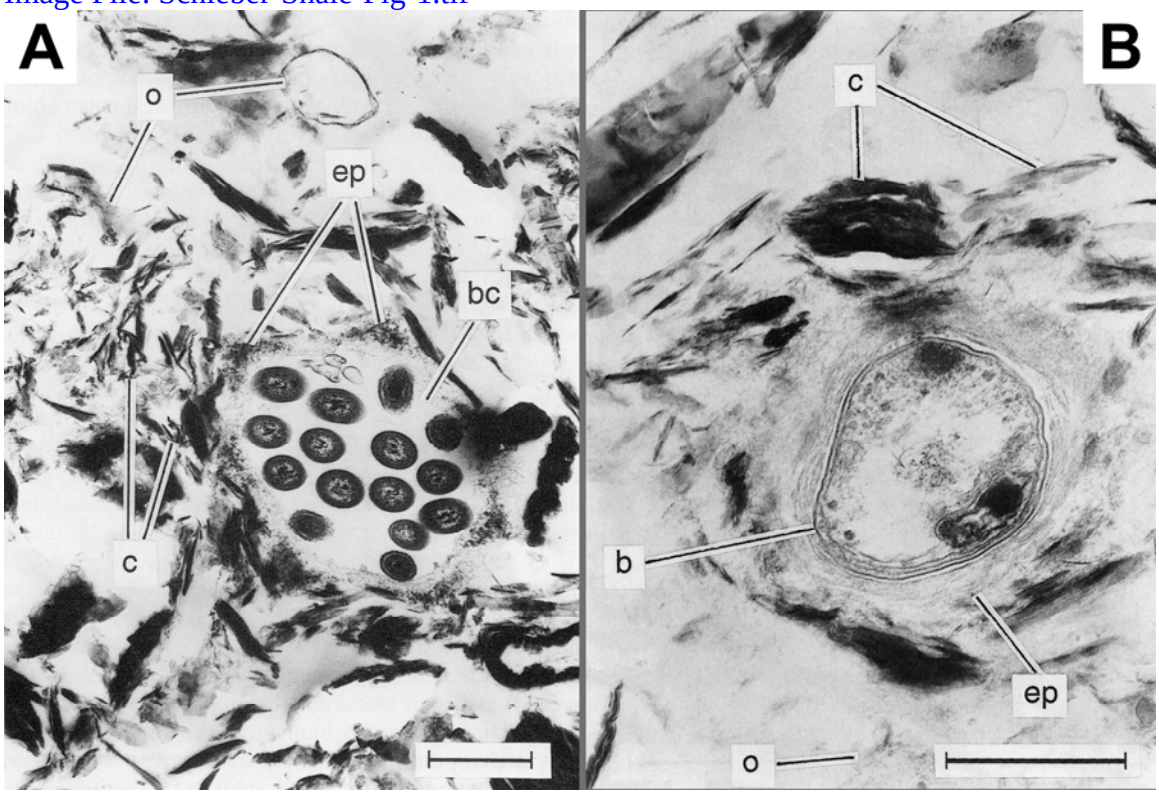

Figure 1: (A) TEM micrograph of modern mud from the continental slope off northern California at a burial depth of 5 cm. Illustrates the spatial relationships of a colony of bacteria (bc), its exocellular polysaccharide secretions (ep), and the surrounding sediment matrix of clay (c) and organic matter (o). Scale bar represents one micrometer. (B) TEM micrograph of a modern mud from Eckernförde Bay, Germany. Shows the relationships between bacteria (b), their exocellular polysaccharide secretions (ep), and the surrounding sediment matrix of clay (c) and organic matter (o). Scale bar represents 0.5 micrometers. Images from Ransom et al., 1999.

Juergen Schieber, 2011, Shales, Encyclopedia of Geobiology, Springer Verlag, J. Reitner & V. Thiel (Eds.), p. 785-791.

Deposition of shales

The sedimentology of shales has made progress over the past decades (Potter et al., 2005), and sedimentologists are gradually learning to appreciate the utility of the many small scale sedimentary structures observable in shales (e.g. Schieber, 1989; 1990a; 1990b; 1999a; O'Brien and Slatt, 1990). When studied in polished slabs and petrographic thin sections, a wealth of information about depositional conditions and history can be gleaned from most shales (Fig. 2).

Image File: Schieber-Shale-Fig-2.tif

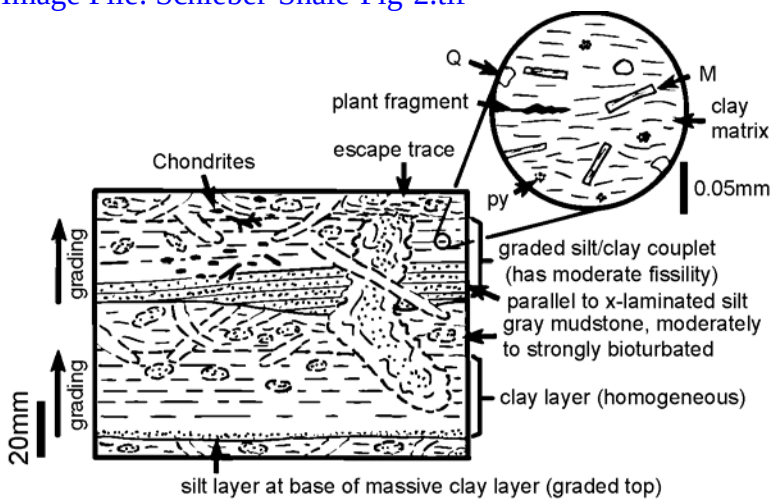

Figure 2: Line drawing that summarizes features observed in a mudstone from the Late Devonian Sonyea Group in New York (Schieber, 1999a). M = mica; Q = quartz; py = pyrite.

Laminae are the most typically observed sedimentary feature in shales. They show a large range in thickness and lamination styles (even, discontinuous, lenticular, wrinkled etc.), and these may represent conditions that include quiet settling, sculpting of the sediment surface by bottom currents, and growth of microbial mats respectively (Schieber, 1986; 1999b). Internal lamina features, e.g. grading (a), random clay orientation (b), preferred clay orientation (c), sharp basal contacts (d), and sharp top contacts (e) may be interpreted as indicative of (a) event-sedimentation (e.g. floods, storms, turbidites), (b) flocculation or sediment trapping by microbial mats, (c) settling from dilute suspension, (d) current flow and erosion prior to deposition, and (e) current flow and erosion/reworking after deposition (Schieber, 1990a, 1990b). Due to somewhat larger grain size, silt laminae are the most readily observed lamina type in shales and may imply somewhat more energetic conditions. Examples are density currents (grading, fading ripples), storm reworking and transport (graded rhythmites), wave winnowing (fine even laminae with scoured bases), and bottom currents (silt layers with sharp bottom and top). Gradual compositional changes between e.g. clay and silt dominated laminae are another commonly observed feature, and are suggestive of continuous (although slow) deposition, possibly from deltaic sediment plumes and shifting nepheloid flows.

For many years conventional wisdom has held that parallel laminae in shales are the result of settling from slow moving or still suspensions, and the common assumption was that this reflects distal deposition in comparatively deep water with only minor current activity. Recent flume experiments, however, have demonstrated conclusively that muds can be deposited from swift moving currents that are competent enough move sand in bedload (Schieber et al., 2007). This occurs because muds have a strong tendency to flocculate, regardless of exact particle mineralogy and water composition. The floccules travel in bedload and form migrating ripples (Fig. 3) that build up a contiguous mud bed if sediment supply is sufficient. In spite of accumulation via lateral accretion, after compaction these muds have a parallel laminated appearance, just like many shales in the rock record (Fig. 4; Schieber et al., 2007). Obviously, it will be difficult from now on to ascribe a quiet, deep water setting to a laminated shale without corroborating evidence (e.g. paleoecology, trace fossils).

Image File: Schieber-Shale-Fig-3.tif

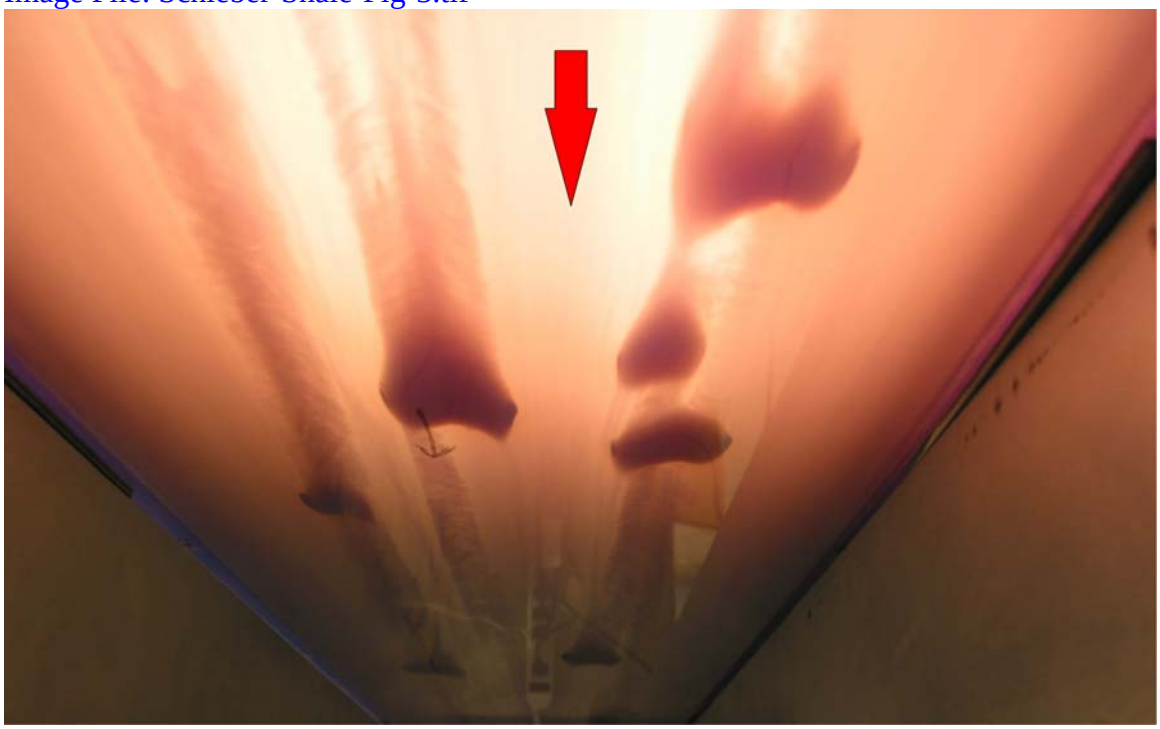

Figure 3: Migrating ripples of flocculated kaolinite in seawater, photographed through the bottom of a flume. Width of flume channel is 25 cm, flow direction indicated by red arrow. From Schieber et al. (2007). The ribbed “tails” behind the ripples are the eroded remains of foreset laminae.

Image File: Schieber-Shale-Fig-4.tif

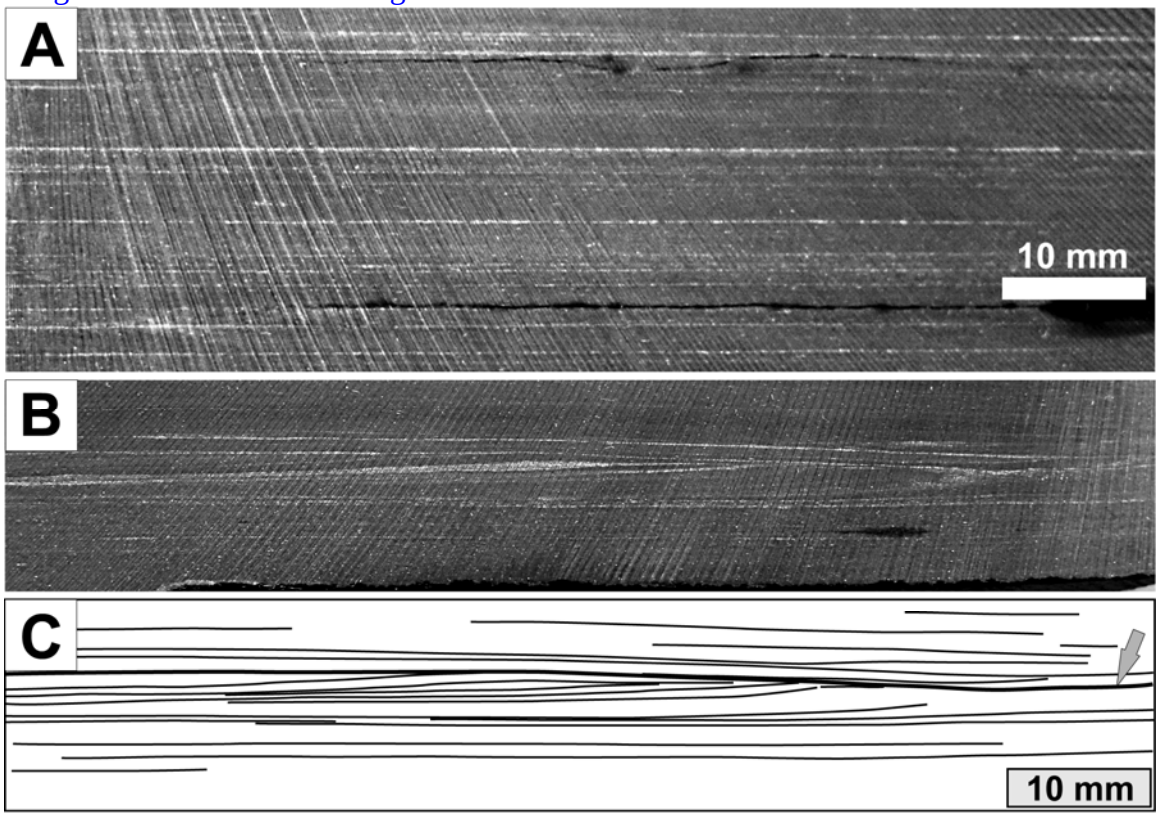

Figure 4: (A) Parallel-laminated black shale, New Albany Shale, Devonian, Indiana. Lighter laminae are silt enriched (the steeply inclined and slightly curved lines are saw marks). (B) A sample from the same core interval as seen in (A). In the center we see inclined (to the left) truncated laminae, forming the outline of a compacted mud-dominated ripple. (C) Tracing of silt laminae visible in (B). Arrow marks an internal erosion surface. This is a fossil equivalent of migrating mud ripples observed in flume experiments (Schieber et al., 2007).

A variety of other small scale sedimentary features also occurs in shales, including mudcracks, load casts, flame structures, dewatering structures, graded rhythmites (Reineck and Singh, 1972), cross-lamination, loop structures (Cole and Picard, 1975), bioturbation (Wetzel and Uchmann, 1998), fossil concentrations and lags, all of which carry information about conditions of sedimentation. Among the more subtle sedimentary features are clay-filled mud cracks, brecciation due to desiccation, and sands or conglomerates that consist entirely of shale particles (Schieber, 1985). The latter can for example form as a result of soil erosion (pedogenic particles; Nanson et al., 1986; Rust and Nanson, 1989), erosion of cracked mud crusts, and submarine scouring of mud substrates by strong currents.

Biologic agents may produce microbial laminae and protection of mud surfaces from erosion (e.g. Schieber, 1986; O'Brien, 1990), or may manifest themselves as bioturbation and via destruction of primary fabrics (Wetzel and Uchmann, 1998). Infaunal activity that

took place early in depositional history, when the muds had a high water content, may be exceedingly subtle and hard to detect after compaction (Schieber, 2003). In many instances of bioturbation sufficient proportions of primary features survive and can still be interpreted in terms of depositional processes. Careful examination of bioturbation features can provide additional information about substrate firmness, event deposits (escape traces), and rates of deposition. Fecal pellets and pelletal fabrics are another by-product of organic activity, and they are probably more abundant in mudstones and shales than commonly recognized (Pryor, 1975; Potter et al., 1980; Cuomo and Rhoads, 1987). Best seen in thin section, pellets typically differ from the shale matrix with respect to texture, color, and organic content. They range in size from 0.2-2mm, are generally of elliptical outline, and flattened by compaction. If matrix and pellets are similar in composition and composed of particles of similar grain size, pellet identification can be challenging. Pellets of benthic vs. planktonic organisms may be differentiated on the basis of composition (Cuomo and Bartholomew, 1991; Schieber, 1994).

Early diagenesis of shales

It is due to the abundance of endosedimentary microbes (Fig. 1) that surficial muds are very active sediments from a geochemical perspective. Much of the initially buried organic material is remineralized in these water-rich sediments (80-90% initial water content), prompting the description of surficial muds as “fluidized bed reactors” (Aller, 1998). The microbial breakdown of buried organic matter requires electron acceptors (oxidizing agent) and due to limitations by diffusion, overall abundance, and differences in energy yield for the various oxidation reactions, we observe a systematic exhaustion of available electron acceptors (e.g. oxygen, nitrate, iron (III), manganese (IV), sulfate, carbon dioxide) as we move downwards from the sediment-water interface. For these reasons closely comparable microbial decay profiles (Brett and Allison, 1998; Curtis et al., 2000) are observed in many marine sediments (Fig. 5).

Image File: Schieber-Shale-Fig-5.tif

“Oxic” zone organic matter oxidation

(1) $CH_2O + O_2 = H^+ + HCO_3^-$ ~530 kJ/mol C_{org}

“Suboxic” zone manganese and iron reduction

(2) $CH_2O + 2MnO_2 + H_2O = 2Mn_2^+ + 3OH^- + HCO_3^-$ ~500 kJ/mol C_{org}

(3) $CH_2O + 2Fe_2O_3 + 3H_2O = 4Fe_2^+ \; 7OH^- + HCO_3^-$ ~230 kJ/mol C_{org}

“Anoxic” zone sulfate reduction

(4) $2CH_2O + SO_4^{2-} = HS^- + 2HCO_3^- + H^+$ ~65 kJ/mol C_{org}

Microbial methanogenesis

(5) $2CH_2O + H_2O = CH_4^+ + H^+ + HCO_3^-$ ~60 kJ/mol C_{org}

Figure 5: Idealized sequence of microbial decay reactions in marine sediments, using carbohydrate as a starting material. The number at the right is the energy gain for the reaction (after Curtis et al., 2000). A similar set of reactions can be written with proteins

as a starting material (e.g. Allison, 1988). See Figs. 6 & 7 for examples of early diagenetic cements and the insights that one can derive from careful petrographic observation of these cements.

Image File: Schieber-Shale-Fig-6.tif

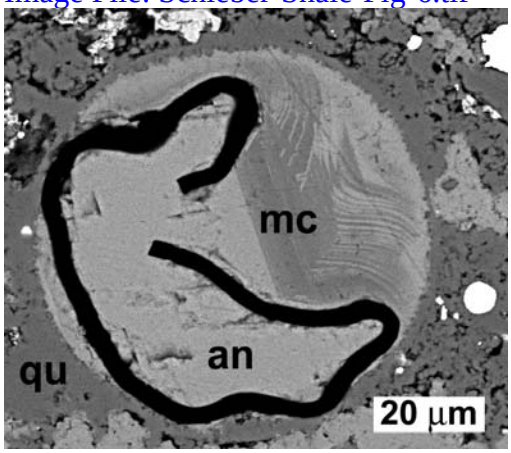

Figure 6: SEM photomicrograph (backscatter image) of a pore space in the Devonian New Albany Shale (Indiana, USA), illustrating suboxic to anoxic diagenesis. Light gray mineral **an** is ankerite (Fe-Mg-Ca-carbonate) that initially grew in the interior of a *Tasmanites* cyst (dark black line), a locally reducing and anoxic microenvironment. Very early growth is indicated by the uncompacted *Tasmanites* wall and the overall circular growth of carbonate (**an** + **mc**) cement. Outside of the protected microenvironment of the cyst we see growth of manganoan calcite (**mc**, darker grey), indicating suboxic conditions in the sediment and oxygenated bottom waters (Calvert et al., 1996). The carbonate cement is surrounded by fine crystalline quartz (**qu**), derived from dissolution of radiolarian opal (Schieber et al., 2000). The image suggests that pore waters were initially alkaline, allowing for precipitation of carbonates and dissolution of biogenic opal, and that this was followed by a lowering of pH that led to precipitation of quartz.

Image File: Schieber-Shale-Fig-7.tif

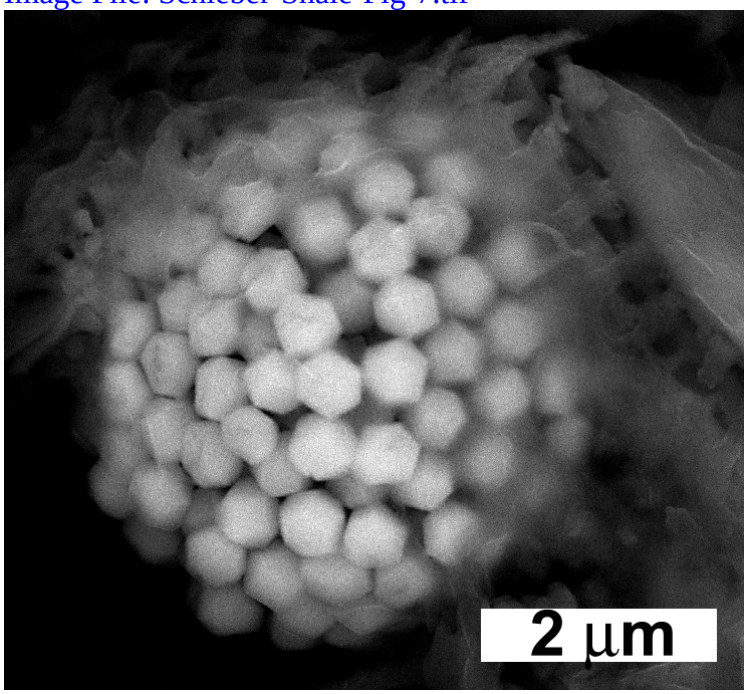

Figure 7: Pyrite framboid from bottom muds of the Santa Barbara Basin. Note regular arrangement of euhedral subcrystals. The sediment layer in which this framboid occurs is only a few years old. Pyrite formation is associated with the activity of anaerobic bacteria that utilize seawater sulfate (SO_4) as an oxygen source and generate hydrogen sulfide as a byproduct. They are among the most common and familiar of early diagenetic mineral formations in shales.

Not all observed early diagenetic mineral formations are covered by the decay-reaction scheme of Fig. 5, although associated pH shifts can be instrumental for their precipitation. For example, early diagenetic silica (quartz) precipitation is not uncommon in shales. In Phanerozoic shales it is derived from the dissolution of biogenic opal (radiolarian, diatoms, sponge spicules) and fills pore spaces that range from tens of microns to as much as a millimeter in size (Fig. 7). Quite frequently these pore fills (in situ quartz) are mistaken for detrital quartz (Schieber, 1996; Schieber et al., 2000).

Juergen Schieber, 2011, Shales, Encyclopedia of Geobiology, Springer Verlag, J. Reitner & V. Thiel (Eds.), p. 785-791.

Image File: Schieber-Shale-Fig-8.tif

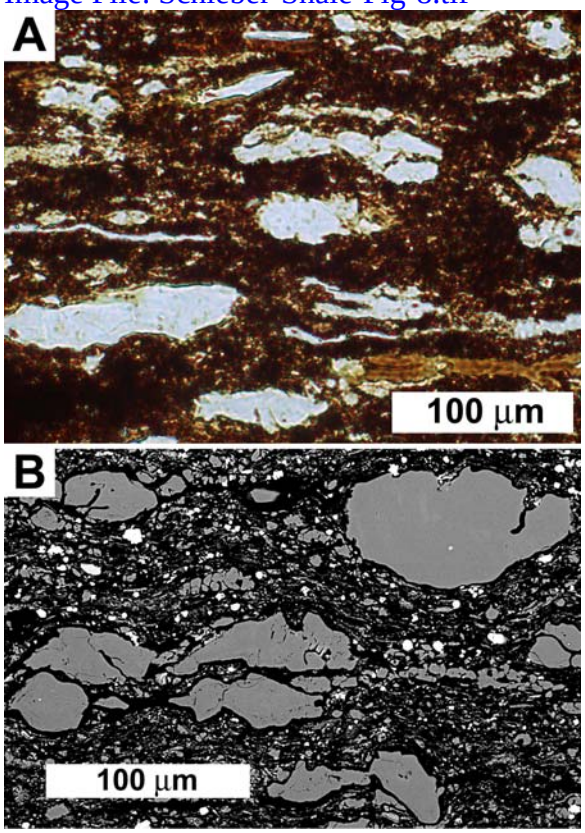

Figure 8: Authigenic quartz (chalcedony) in the Late Devonian Chattanooga Shale (Kentucky, USA). (A) Photomicrograph in transmitted light. The clear/bright grains are chalcedonic infills of algal cysts (*Tasmanites*). (B) SEM image (backscatter) from the same specimen, showing more clearly the rounded-lobate outlines of the quartz grains and the enclosing cyst walls (black rim). For a detailed discussion of these features see Schieber (1996) and Schieber et al. (2000).

If phosphorous is abundant in the initial mud, such as due to accumulation of phosphatic skeletal material, phosphatic concretions, ranging in size from less than a mm to more than 100 mm's, may form (Fig. 8). An early diagenetic phosphate matrix seems to be an excellent medium for preserving minute details of soft tissues, such as in the Neoproterozoic Doushantuo Formation of China (Shen et al., 2000).

Image File: Schieber-Shale-Fig-9.tif

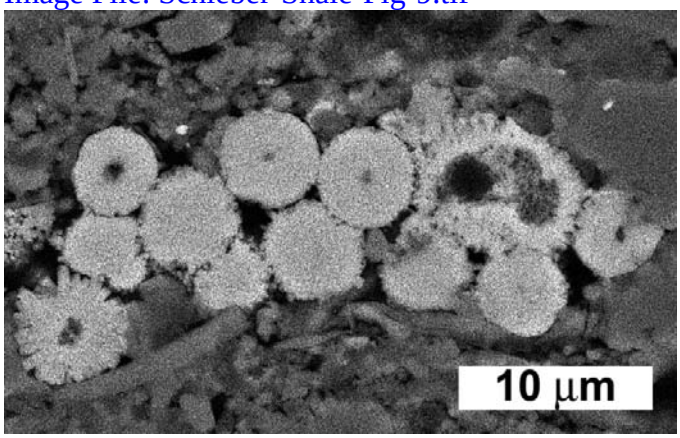

Figure 9: SEM photomicrograph (backscatter image) of an example of early diagenetic phosphate precipitation. The image shows what appears to be a colony of phosphate encrusted bacteria (Mid-Proterozoic Bijaigarh Shale, India).

Due to the rapid and systematic expulsion of pore waters and decrease of porosity during compaction, early diagenetic minerals in shales are preferentially preserved. For this reason shales contain a rich record of geochemical processes that relate closely to the chemistry of the overlying ocean waters and paleoceanographic conditions. When studied systematically, the authigenic component of shales holds the promise to capture a snapshot of seawater and/or porewater chemistry. With the necessary age constraints, this may enable us to develop a much more detailed record of ocean geochemical changes than currently available.

Conclusion

Shales result from the complex interplay of a range of geologic variables and processes, and there are no easy answers and no “one size fits all” models. Although these rocks have an (undeserved) reputation for being drab, uniform, and un-interesting, the repay the investigative challenges they pose by being a rich storehouse of information about the geologic past. Sedimentological study includes recognition and tracing of facies changes, sedimentary features, shale fabrics, erosion surfaces and internal stratigraphy, as well as information that can be derived from interbedded non-shale lithologies. Paleontological studies may provide data on paleo-oxygenation, primary production, substrate conditions, paleocurrents, bathymetry, and paleosalinity (Schieber et al., 1998). Petrographic investigations provide the basic inventory of shale constituents, and may yield clues about provenance, compaction history, chemical conditions, sedimentary processes (via small scale sedimentary structures), and the origin and maturation of organic matter (Taylor et al., 1998). Chemical analysis of major and trace elements can provide information on provenance (Roser & Korsch, 1986), and a range of proxies for paleo-oxygenation (Jones and Manning, 1994). Organic geochemistry can furnish information on the source of organic matter, its dispersal, and maturation (Engel and Macko, 1993). Certain organic molecules, such as photosynthetic pigments, may survive as “carbon

skeletons" (biomarkers), and may identify the original source of diagenetically altered organic matter and potential indicators of water column anoxia (Brassell, 1992).

Fundamentally, shales do not give up their secrets easily. The tools are at hand, however, to extract a wide range of data from them and allow for multiple avenues of inquiry (Schieber et al., 1998). Interpretations that rely on just one perspective (e.g. petrography, fabric study, trace element geochemistry, or organic geochemistry) typically do not match conclusions derived from a different line of inquiry. Shales need to be investigated in a multidisciplinary way and at multiple scales because of the complex interplay of variables that produces them. Conclusions derived from microscopic features must be in agreement with insights coming out of basin scale studies, as well as with findings from all scales in between.

Juergen Schieber

Bibliography

Aller, R.C. (1998): Mobile deltaic and continental shelf muds as suboxic, fluidized bed reactors. Marine Chemistry, 61, 143-155.

Allison, P.A., (1988): The role of anoxia in the decay and mineralization of proteinaceous macr-fossils. Paleobiology, 14, 139-154.

Bartels, C., Briggs, D.E.G., AND Brassel, G. (1998): The fossils of the Hunsrück Slate - Marine Life in the Devonian. Cambridge University Press, 309 pp.

Blatt, H., Middleton, G., and Murray, R. (1980): Origin of Sedimentary Rocks. Prentice Hall, 782 pp.

Brassell, S.C. (1992): Biomarkers in sediments, sedimentary rocks and petroleums. In Pratt, L.M., Brassell, S.C., and Comer, J.B. (eds.), Geochemistry of Organic Matter in Sediments and Sedimentary Rocks. SEPM Short Course Notes 27, 29-72.

Brett, C., and Allison, P.A. (1998): Paleontological approaches to the environmental interpretation of marine mudrocks. In: J. Schieber, W. Zimmerle, and P. Sethi (editors), Shales and Mudstones (vol. 1): Basin Studies, Sedimentology and Paleontology, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, p. 301-349.

Calvert, S. E., Bustin, R. M., Ingall, E. D. (1996): Influence of water column anoxia and sediment supply on the burial and preservation of organic carbon in marine shales. Geoch. Cosmoch. Acta, 60, 1577-1593.

Cole, R.D., and Picard, M.D. (1975): Primary and secondary sedimentary structures in oil shale and other fine-grained rocks, Green River Formation (Eocene), Utah and Colorado. Utah Geology, 2: 49-67.

Conway Morris, S. (1998): The Crucible of Creation: The Burgess Shale and the Rise of Animals. Oxford University Press, Oxford, 276 pp.

Cuomo, M.C., and Rhoads, D.C. (1987): Biogenic sedimentary fabrics associated with pioneering polychaete assemblages: Modern and ancient. J. sediment. Petrol., 57: 537-543.

Juergen Schieber, 2011, Shales, Encyclopedia of Geobiology, Springer Verlag, J. Reitner & V. Thiel (Eds.), p. 785-791.

Cuomo, M.C., and Bartholomew, P.R. (1991): Pelletal black shale fabrics: their origin and significance. In: R.V. Tyson and T.H. Pearson (eds.), Modern and Ancient Continental Shelf Anoxia. Geol. Soc. London Spec. Publ. No. 58: 221-232.

Curtis, C.D., Cope, J.C.W., Plant, D., and Macquaker, J.H.S., (2000): "Instantaneous" sedimentation, early microbial sediment strengthening and a lengthy record of chemical diagenesis preserved in Lower Jurassic ammonitiferous concretions from Dorset. J. Geol Soc. London, 157, 165-172.

Dunbar, C.O., and Rodgers, J. (1957): Principles of Stratigraphy. Wiley, New York, 356 pp.

Engel, M.H., and Macko, S.A., 1993. Organic Geochemistry: Principles and Applications. Plenum Press, New York, 861 pp.

Fenchel, T. (1970): Studies on the decomposition of organic detritus derived from the turtle grass *Thalassia testudinum*. Limnol. Oceanogr., 15, 14-20.

Folk, R.L., (1965): Petrology of Sedimentary Rocks. Hemphill's Bookstore, Austin, 170 pp.

Ingram, R.L. (1953): Fissility in mudrocks. Geol. Soc. Amer. Bull., 65, 869-878.

Jones, B., and Manning, D.A.C., 1994. Comparisons of geochemical indices used for the interpretation of paleoredox conditions in ancient mudstones. Chemical Geology, 111, 111-129.

Kauffman, E. G. 1978. Benthic environments and paleoecology of the Posidonienschiefer (Toarcian). Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, **157**, 18-36.

Lewan, M.D. (1979): Laboratory classification of very fine-grained sedimentary rocks. Geology, 6, 745-748.

Lundegard, P.D., and Samuels, N.D. (1980): Field classification of fine-grained sedimentary rocks. J. Sediment. Petrol., 50, 781-786.

Macquaker, J.H.S., and Adams, A.E., (2003): Maximizing information from fine-grained sedimentary rocks: an inclusive nomenclature for mudstones. J. Sediment. Research, 73, p. 735-744.

Nanson, C.G., Rust, B.R., and Taylor, G. (1986): Coexistent mud braids and anostomosing channels in an arid-zone river: Cooper Creek, central Australia. Geology, 14: 175-178.

O'Brien, N.R. (1990): Significance of lamination in Toarcian (Lower Jurassic) shales from Yorkshire, Great Britain. Sedimentary Geology, 67: 25-34.

O'Brien, N.R., and Slatt, R.M. (1990): Argillaceous Rock Atlas. Springer Verlag, New York, 141 pp.

Picard, M.D. (1971): Classification of fine grained sedimentary rocks. J. Sediment. Petrol., 41, 179-195.

Potter, P.E., Maynard, J.B. and Pryor, W.A. (1980): Sedimentology of Shale. Springer Verlag, New York, 303 pp.

Potter, P.E., Maynard, J.B. and Depetris, P.J. (2005): Mud and Mudstones. Springer Verlag, New York, 297 pp.

Pryor, W.A. (1975): Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments. Geol. Soc. Amer. Bull., 86: 1244-1254.

Juergen Schieber, 2011, Shales, Encyclopedia of Geobiology, Springer Verlag, J. Reitner & V. Thiel (Eds.), p. 785-791.

Ransom, B., Bennett, R.H., Baerwald, R., Hulbert, M.H., and Burkett, P.-J. (1999): In situ conditions and interactions between microbes and minerals in fine-grained marine sediments; a TEM microfabric perspective. American Mineralogist, 84, 183-192.

Reineck, H.-E. and Singh, I.B. (1980): Depositional Sedimentary Environments. Springer Verlag, Berlin, 549 pp.

Roser, B.P., and Korsch, R.J., 1986. Determination of tectonic setting of sandstone-mudstone suites using SiO2 content and K2O/Na2O ratio. Journal of Geology, 94, 635-650.

Rust, B.R., and Nanson, G.C. (1989): Bedload transport of mud as pedogenic aggregates in modern and ancient rivers. Sedimentology, 36: 291-306.

Schieber (1985): The Relationship between Basin Evolution and Genesis of stratiform Sulfide Horizons in Mid-Proterozoic Sediments of Central Montana (Belt Supergroup). Ph.D. Dissertation, University of Oregon, Eugene, 811 pp.

Schieber, J. (1986): The possible role of benthic microbial mats during the formation of carbonaceous shales in shallow Proterozoic basins: Sedimentology, 33: 521-536.

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

Schieber, J. (1990a): Sedimentary structures, textures, and depositional settings of shales from the Lower Belt Supergroup, Mid-Proterozoic, Montana, U.S.A. In: Bennett, R.H., Bryant, W.R., and M.H. Hulbert (eds.), Microstructure of Fine-Grained Sediments, New York, Springer Verlag, 101-108.

Schieber, J. (1990b): Significance of styles of epicontinental shale sedimentation in the Belt basin, Mid-Proterozoic of Montana, U.S.A.: Sedimentary Geology, 69: 297-312.

Schieber, J. (1994): Reflection of deep vs shallow water deposition by small scale sedimentary features and microfabrics of the Chattanooga Shale in Tennessee. Canadian Society of Petroleum Geologists, Memoir 17: 773-784.

Schieber, J. (1996): Early diagenetic silica deposition in algal cysts and spores: A source of sand in black shales? Journal of Sedimentary Research, 66, 175-183.

Schieber, J. (1999a): Distribution and deposition of mudstone facies in the Upper Devonian Sonyea Group of New York. Journal of Sedimentary Research, 69, 909-925.

Schieber, J. (1999b): Microbial Mats in Terrigenous Clastics: The Challenge of Identification in the Rock Record. Palaios, 14, 3-12.

Schieber, J. (2003): Simple gifts and hidden treasures – Implications of finding bioturbation and erosion surfaces in black shales. The Sedimentary Record, 1, 4-8.

Schieber, J., and Zimmerle, W. (1998): The history and promise of shale research. In: J. Schieber, W. Zimmerle, and P. Sethi (editors), Shales and Mudstones (vol. 1): Basin Studies, Sedimentology and Paleontology, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1-10.

Schieber, J, Zimmerle, W., and Sethi, P., 1998 (eds.). Shales and Mudstones (vol. 1 & 2). Stuttgart, Schweizerbart'sche Verlagsbuchhandlung.

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

Schieber, J., Southard, J.B., and Thaisen, K.G. (2007): Accretion of mudstone beds from migrating floccule ripples. Science, 318, 1760-1763.

Juergen Schieber, 2011, Shales, Encyclopedia of Geobiology, Springer Verlag, J. Reitner & V. Thiel (Eds.), p. 785-791.

Seilacher, A., Reif, W.-E., Westphal, F., Riding, R., Clarkson, E.N.K., and Whittington, H.B. (1985): Sedimentological, Ecological and Temporal Patterns of Fossil Lagerstatten [and Discussion]**.** Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, Vol. 311, No. 1148, Extraordinary Fossil Biotas: Their Ecological and Evolutionary Significance (Oct. 17, 1985), 5-24.

Shen, Y., Schidlowski, M., and Chu, X. L. (2000): Biogeochemical approach to understanding phosphogenic events of the terminal Proterozoic to Cambrian. Palaeogeography, Palaeoclimatology, Palaeoecology, 158, 99-108.

Stow, D.A.V., and Piper, D.J.W. (1984): Deep-water fine-grained sediments: facies models. In: Stow, D.A.V., and Piper, D.J.W. (Eds.), Fine-Grained Sediments: Deep-Water Processes and Facies. Geol. Soc. Spec. Publ. London, 15, 611-645.

Taylor, G.H., Teichmüller, M., Davis, A., Diessel, C.F.K., Littke, R., and Robert, P. (1998): Organic Petrology. Borntraeger, Stuttgart, 704 pp.

Wetzel, A., and Uchmann, A. (1998): Biogenic sedimentary structures in mudstones – an overview. In: J. Schieber, W. Zimmerle, and P. Sethi (editors), Shales and Mudstones (vol. 1): Basin Studies, Sedimentology and Paleontology, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, p. 351-369.

Wuttke M. (1983): 'Weichteil-Erhaltung' durch lithifizierte Mikroorganismen bei mittel-eozänen Vertebraten aus en Ölschiefern der 'Grube Messel' bei Darmstadt. Senckenbergiana Lethaea, 64: 509– 27.

Cross references

Mudstone, clay, mudrock, sedimentology, depositional environment, facies, early diagenesis, microbial diagenesis, fossil preservation