Stratigraphy and Mapping of Shale Formations

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Abstract

Shale is one of the most important rocks in geoscience from applied perspective. Commonly shale is considered to be deposited in quiet water condition in deep basins. Shales in sequence stratigraphy have been discussed in geoscience that enables us to understand the large-scale perspective of exploration. Shales have been studied also for chemostratigraphy, chronostratigraphy, and by geophysical means to correlate and map regionally.

1. General information

The terms claystone, mudstone/mudrock, argillaceous rocks and shale have been used almost interchangeably (Paul et al. 2025). About two-third of the stratigraphic record on the Earth is of shale. Shale rocks are important globally as source, reservoir and cap rocks, and have been targeted for CO_2 storage (e.g., Kar et al., 2022; Paul et al., 2025). For these reasons, research on shale is one of the most prolific topics in geoscience. A litho-unit recognized by a geologist as a *"shale member"* can have sandstone-siltstone alteration at the base and dominantly mud at the top (Mondal et al. 2025). The term turbidite can include different kinds of mud- *(i)* mud with silt laminae, *(ii)* graded mud, and *(iii)* ungraded (Piper and Stow 1991). Mud-dominated successions can reveal different disposition of turbidites and grain-coarseness (Piper and Stow 1991).

Shales can deposit by "hemipelagic rain" in deep marine environments, or can come from hyperpycnal flows, turbidity currents, storm and wave reworking (tempestite deposits) and bottom-hugging slope oceanic currents (contourites) (Slatt and Abousleiman 2011). Depositional geometries of mudstones can be *(i)* continuous, *(ii)* discontinuous, *(iii)* wedge (uniform and non-uniform varieties), *(iv)* drapes, *(v)* mounds and *(vii)* random (see fig. 8.8 of Potter et al. 2005).

Black shales are usually layered, consisting of less fauna, with high TOC, and with or without (arseno)pyrite. Greenish grey mudstones are less layered, bioturbated and much less pyrite-bearing (Potter et al. 2005). Black shales are sometimes covered by bones, phosphatized fecal pellets and glauconites. Hot shales, common in Silurian, Devonian and Ordovician, are shales enriched with organic matter and uranium (Slatt and Abousleiman 2011). Black shales can develop in *(i)* epicontinental basins in deep water, and *(ii)* during quick transgression whereby depositional area also included basin margin areas (Wignall 1991). The former situation can arise due to subsidence, rise in sea level and decreased supply of sediments during transgression.

Shales or mudstones are to be studied along with other branches of geoscience. This is because from mudstone facies alone, one cannot decipher the complete tectonic settings of the past (Potter et al. 2005).

2. Sequence stratigraphy

Being homogeneous and fine grained, establishing sequence stratigraphy from mudrocks is difficult (Ver Straeten et al. 2011). Mud-mounds can be located deep ramps / slopes (Catuneanu et al. 2009). Mudflow deposits revealing chaotic internal facies connotes initial stage of forced regression and deposition related to late transgression (Catuneanu et al. 2009). Sequence stratigraphy of shales in different locations can be found several publications (e.g., fig. 6 of Barnett shale in Slatt and Abousleiman 2011). See fig. 8.6 of Potter et al. (2005) for the sequence stratigraphy involving carbonates, sand and mud. **Fig. 1** represents the sequence stratigraphy of gas shales.

Accommodation governs the geometry of the mudstone bodies inside basins. Quicker subsidence can create overpressure leading to mud diapirs. From mudstone facies alone, one cannot decipher tectonic settings of the past (Potter et al. 2005). A flooding surface can be defined by sandstone below and shale above (Emby 2009). At least two levels of predictable relative sea level cyclicity was deciphered from several shale formations (Slatt 2015). Sequence stratigraphic intervals can be mapped based on sequence stratigraphy of shales (Slatt 2015). The transgressive systems tract (TST)/condensed sections (CS) are usually clay and organic matter-rich (Slatt 2015). Carbonates and quartz are more common in the highstand systems tract (HST). Hydrofracturing is augmented therefore in the HST (Phaye et al., 2021). Both in the TST and in the early-HST (EHST), shales can be present that were deposited in anoxic condition (Jiang et al. 2017).

Transgresive black shales constitute few of the best source rocks worldwide. Black shales lying on a hiatus indicates the beginning of the transgression. On other hand, black shales can also deposit at peak transgression during maximum retreat of shoreline (review in Wignall 1994).

Sequences and systems tracts in the deep-water anoxic environments in deep basins can be characterized by TOC and Mo. Bioturbation can show negative correlation with TOC and Mo.

Al concentration, as an indicator of fine rained sediments, can distinguish EHST and LHST (Van Straeten et al. 2011). Van Straeten et al. (2011) in their figs. 9 and 10 presented sequence stratigraphic models of mud dominated deposits. More such models are required from different terrains, so that general models can come up.

Carbonate-rich shales in the TST and in the EHST can show lower magnitudes of TOC, lower gamma ray and quartz content than the siliciclastic shales found in those portions of sequences (Jiang et al. 2017). From few locations, TST has been identified as the most favourable shale gas interval (Chen et al. 2015). Water depths during highstands in basins inside (super)cratons rarely exceeded ~ 100 m. Few dm of siliceous mud deposited during a long time connotes a starved basin (Potter et al., 2005). How to identify sequence boundary and flooding surface in muddy basins is presented in table 8.3 of Potter et al. (2005).

Several Paleozoic and Mesozoic gas shales have a common sequence stratigraphy. Upwards, these are *(i)* combined sequence boundary/erosive transgressive surface (SB/ETS), *(ii)* organic-rich TST, and *(iii)* regressive systems tract or a *"cleaner gamma-ray"* highstand systems tract (RST/HST) (Slatt and Rodriguez 2012). Several organic material-dominated mudstones have recently been re-interpreted to be of more proximal environments (LaGrange et al. 2020). In deep basins, maximum flooding black shale, generally condensed, pass into much thicker facies of nearshore deposits (Wignall and Maynard 1993).

Few of the sequence stratigraphic units (e.g., maximum flooding surface, maximum regressive surface, transgressive systems tract, and regressive systems tract) of mudstones can be identified chemostratigraphycally (table 4 of LaGrange et al. 2020). However, not all sequence stratigraphic units can be identified based on chemostratigraphy.

3. Chronostratigraphy

Since K is mobile, K-Ar dating of (clay part of) shale may be problematic to explain. K-Ar dates of illites in successions can show younger ages down the depth. This is because K fixation increase with depth (review in Meunier 2005). Dating of K-rich micas can yield late diagenetic ages using K-Ar and Ar-Ar methods (Potter et al. 2005). Shale dating can be done by either Sm-Nd (review in Meunier 2005) or by Rb-Sr method (Clauer and Chaudhuri 1995). U-Pb dating of zircon grains found from shales indicate the age of provenance of shale samples (Xu et al., 2025). If in a basin two generations of illites are there and they have been dated, dates of such illite samples can provide little value in the basin's stratigraphy. Further, the ^{40}Ar retention capability of very small illite particles is debated (e.g. Clauer 2020). Zircon grains found within ash bds can be dated using isotopes of Pb to find out the depositional age of the surrounding rocks.

4. Chemostratigraphy

$\delta^{13}C$ has been studied in detail for black shales from several places in the world. $\delta^{13}C$ minima has been linked with mass extinction events (Sial et al. 2015). Si/Al ratio for shale is usually < 5 (Craige 2018). Chemical Index of Alteration (CIA) of shale is 70-75 (Craige 2018). K/Al, Mg/Al, Zr/Nb, Rb/K and Ti/K plotted for shale or clay samples have been used to discriminate different sequences of sediments (Craige 2018). Deep sea mud has been studied for REEs, and different stratigraphic division of such sediments can be made (e.g., Tanaka et al. 2020).

Sulphides and iron oxides have been used to correlate shales (Kuroda and Ohkouchi, internet reference).

5. Mapping

Mapping/tracing continuity of mudstones can be easier since *(i)* these are easy to identify in gamma ray profiles, and *(ii)* thin mudstone units are prone to continue much longer distance than the other rocks units (Potter et al. 2005).

6. Well log studies

Since shale's geomechanical properties have been well studied, mapping of shales leads to understand reservoir geomechanics (Slatt and Abousleiman 2011). Radioactive elements tend to concentrate in fine-grained sediments such as clays/shales. On other hand, carbonates and clean sands have low radioactivity. Gamma log can therefore determine lithology. See gamma ray logs of different shale formations in Slatt et al. (2015). Interpretation of the gamma ray neutron log is presented in fig. 8.14 of Potter et al. (2005). Liu's (2017) fig. 4.5 is a simpler version of the curve for different lithologies. Using gamma ray integrated error filter analysis, different parasequences with shale formations can be identified (Li et al. 2022). Ash can deposit along omission surfaces thereby defining the margins of parasequences in some cases (Potter et al. 2005). Bentonites can aid in identifying the geometry of the clinoform in few mudstone clinothems. Gamma logs give kicks at hot shales. If bentonites consist of K-feldspar and illite, the gamma ray deflection is most striking and is easily identifiable. Marine basins and swamps are places of best preservations for tonsteins (kaolinite-rich sedimentary rocks) and bentonites.

Gamma-ray measurements have been used quantitatively. 20 API units or above of gamma-ray intensity has been used as the grey-shale baseline demarcating the boundary between organic-poor and organic-rich facies (the 20-API method). A 230 API units is taken as the shale's threshold value for its high gas content, therefore can also be considered as an alternate definition of the organic-poor, organic-rich boundary (the 230-API method) (Schmoker 1980). Schmoker (1980) considered 2% by vol. of organic matter (0.8% by wt.) to be the *"best definition of the organic-rich, organic-poor boundary"* (the 2-percent method). As per the gamma ray response, 20 American Petroleum Institute (API) above the shale baseline is considered to represent a high clay content (review in Hennissen et al. 2024).

With the help of the "shale baseline" in SP and gamma ray logs, one can deduce lithology. Once signals from a mudrock body is obtained, a vertical line can be drawn that defines the shale baseline or the 100% shale line (fig. 2.15 of Brenner and McHargue 1988). Maximum deflection from this line indicates that the rock is devoid of clay. Just like the shale base line, one can also define the 100% carbonate or the 100% sandstone lines, and further the 50% sandstone line. The clean sandstone line is taken as the 75% sandstone line (Brenner and McHargue 1988). The clean sandstone line can indicate 25% of clay materials. Similarly, for carbonate-shale, similar lines can be defined.

Shale volume can also be determined from SP and gamma ray logs. How far the curve deflects from the shale base line in SP log can connote relative salinities of mud filtrate and the formation water (Liu 2017). The gamma ray technique can be applied in case the SP readings are distorted (Mondol 2015). However, well logging techniques may miss cm-scale layers

(Slatt and Abousleiman 2011). Cryptic hiatus can be present inside deep-water shales that can be difficult to detect.

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Abbreviations

API	American Petroleum Institute
CIA	Chemical Index of Alteration
CS	Condensed section
EHST	Early highstand systems tract
ETS	Erosive transgressive surface
HST	Highstand systems tract
LHST	Late highstand systems tract
RST	Regressive systems tract
SB	Sequence boundary
TST	Transgressive systems tract
TOC	Total organic carbon

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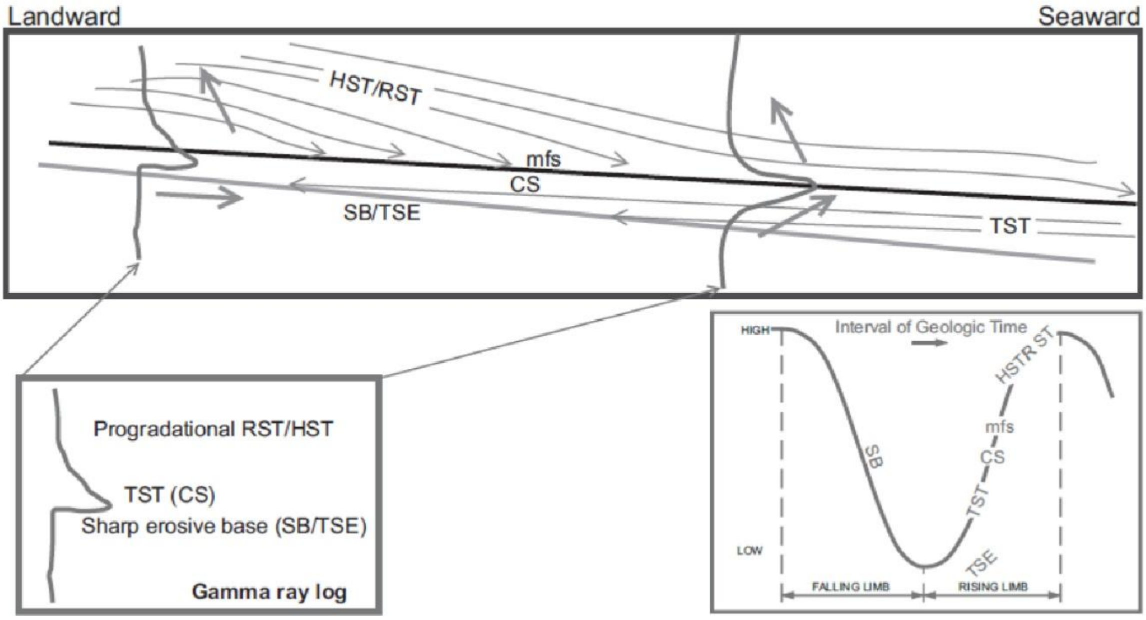

Fig. 1. Model of sequence stratigraphy for gas shales. Reproduced from fig. 22 of Slatt and Rodriguez (2012).