



Overview of Stratigraphy and Mapping of Shale Bodies

Soumyajit Mukherjee^{1,*}, Ajoy Kumar Bhaumik² and Puloma Chakrabarty³

¹Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai 400076, India

²Department of Applied Geology, Indian Institute of Technology (Indian School of Mines) Dhanbad, Dhanbad 826004, India

³Department of Earth and Environmental Sciences, University of California, Los Angeles, CA 90095, United States

Abstract

Shales and mudstones are fine-grained sedimentary rocks of global extent and considerable economic importance. Dating them is not straightforward, because clay minerals such as illite can reset isotopic systems during diagenesis. K-Ar, Ar-Ar and Rb-Sr dates of shales therefore often record diagenetic events rather than deposition. Sm-Nd and detrital-zircon U-Pb data mainly constrain provenance, whereas Re-Os data from organic-rich mudrocks can give depositional ages, and Re-Os data from oils constrain hydrocarbon generation. U-Pb dating of zircon from interbedded volcanic ash provides the most direct depositional age. Carbon-isotope excursions, elemental ratios, redox-sensitive trace metals, rare earth elements and iron-sulfide systematics can be used to correlate shale successions. Fossils such as trilobites, graptolites, conodonts, cephalopods, foraminifera and calcareous nannoplankton help to date, and hence correlate, shales. Shale bodies can be mapped in the field by conventional methods. In the subsurface, gamma-ray and spontaneous-potential

(SP) logs identify shale intervals, unless the beds are very thin, and allow shale volume to be estimated.

Keywords: shale, mudstone, chronostratigraphy, chemostratigraphy, biostratigraphy, well logs.

Abbreviations

Abbreviation	Definition
API	American Petroleum Institute (gamma-ray unit)
CIA	Chemical index of alteration
DSDP	Deep Sea Drilling Project
FAD	First appearance datum
IODP	Integrated Ocean Drilling Program (2003–2013) / International Ocean Discovery Program (2013–present)
LA-ICP-MS	Laser ablation inductively coupled plasma mass spectrometry
LAD	Last appearance datum
LIP	Large igneous province
Ma	Mega-annum (age)
MTD	Mass-transport deposit
Myr	Million years (duration)
ODP	Ocean Drilling Program
REE	Rare earth element
RSTM	Redox-sensitive trace metal
SP	Spontaneous potential
TOC	Total organic carbon
T_{max}	Temperature of maximum S2 hydrocarbon yield during Rock-Eval pyrolysis
XRD	X-ray diffraction



Submitted: 06 August 2026

Revised: 12 September 2026

Accepted: 12 October 2026

Published: 19 October 2026

Vol. 3, No. 1, 2026.

10.62762/RS.2026.712719

*Corresponding author:

✉ Soumyajit Mukherjee

soumyajitm@gmail.com

Citation

Mukherjee, S., Bhaumik, A. K., & Chakrabarty, P. (2026). Overview of Stratigraphy and Mapping of Shale Bodies. *Reservoir Science*, 3(1), 26–37.



© 2026 by the Authors. Published by Institute of Central Computation and Knowledge. This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

1 Introduction

The terms claystone, mudstone (mudrock), argillaceous rock and shale have been used almost synonymously [1]; see [2] for a detailed discussion. Shales and mudstones make up about two-thirds of the stratigraphic record [3]. They act as source, reservoir and seal rocks; the accumulation of organic carbon in shale successions is governed by the interplay of primary production, decomposition and dilution [1, 4], which is why shale research matters in geoscience. A lithological unit described as a “shale member” may consist of siltstone-sandstone alternations at its base and mainly mud at its top [5]. Fine-grained (mud) turbidites may comprise mud with silt laminae, graded mud or ungraded mud, so that mud-dominated successions can contain several types of turbidite and a range of grain sizes [6].

Shales may accumulate from “hemipelagic rain” in deep-marine settings, or be supplied by hyperpycnal flows, turbidity currents, storm and wave reworking (tempestites) and bottom-hugging slope currents (contourites) [7]. Flume experiments have further shown that mud can be deposited from migrating floccule ripples under currents strong enough to move sand [8]. Mudstone bodies may be continuous or discontinuous, and may form wedges, drapes and mounds [3].

Black shales are commonly laminated and rich in total organic carbon (TOC) [9]. “Hot” shales, which are commonly of Ordovician, Silurian or Devonian age, are enriched in both TOC and uranium [7]. Black shales form not only in deep-water epicontinental basins but also during rapid transgressions [10] and during episodes of widespread oceanic anoxia, as in the Cretaceous [11].

This review summarises the chronostratigraphy, chemostratigraphy and biostratigraphy of shale bodies, and the field and geophysical (well-log) methods used to map them.

2 Importance of shale in hydrocarbon geoscience: the fossil angle

Mudstones and shales are essential components of the petroleum system, together with reservoir rocks and traps [12]. Shales have prominent bedding and lamination, with well-developed fissility along which they split into thin sheets parallel to bedding [13]. The platy habit, large surface area and small pore size of clay minerals favour the preservation and retention of organic carbon, making mudstones and

shales potential source rocks. Small pores also hold little oxygenated pore water, which protects the stored organic carbon from oxidation and alteration. Organic matter therefore becomes concentrated in shales deposited in anoxic settings. Organic carbon preservation in shales is controlled mainly by the depositional setting (primary productivity, bottom- and pore-water oxygen concentration, the oxygen minimum zone, the supply of very fine particles and a high sedimentation rate), by the type of clay mineral and by the available mineral surface area [14, 15]. Clay minerals also hold structural water in their lattices. On heating, this water is released as vapour and can build up overpressure, which fractures the rock and opens migration pathways for oil [16].

Knowledge of fine-grained clastic sediments, both consolidated and unconsolidated, has grown rapidly since the mid-twentieth century. This growth was driven by international scientific drilling—the Deep Sea Drilling Project (DSDP), the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program (IODP, 2003–2013) and the International Ocean Discovery Program (IODP, 2013–2024)—as well as by rising energy demand and research on source rocks.

The fine grain size, small pores and possible deposition in calm environments make shales and mudstones an ideal medium for preserving fossils. Klemme and Ulmishek [17] showed that effective source rocks are concentrated in the Phanerozoic and are unevenly distributed through it. Six stratigraphic intervals, which together span only ~30% of Phanerozoic time, generated 91.5% of the world’s discovered original oil and gas reserves (Table 1). The oldest of these six intervals is the Silurian, which accounts for ~9% of the reserves. The next is the Upper Devonian–Tournaisian (lower Carboniferous), with 8%, followed by the Pennsylvanian (upper Carboniferous)–Lower Permian, with ~8%. The largest share (~54%) comes from Mesozoic source rocks: the Upper Jurassic accounts for ~25% and the middle Cretaceous (Aptian–Turonian) for ~29%. The youngest interval, Oligocene–Miocene, contains ~12.5%.

The remaining 8.5% is distributed as follows: Upper Proterozoic (0.2%), Cambrian–Ordovician (1%), Lower–Middle Devonian (0.3%), Middle–Upper Mississippian (0.4%), Permian–Middle Jurassic (1.2%), Lower Cretaceous (2.6%) and Upper Cretaceous–lower Paleogene (2.8%). The oldest effective source rocks are therefore Upper Proterozoic (Neoproterozoic). Most of these source rocks are shales or mudstones.

Table 1. Shares of effective source rocks through geological time. Only the six major intervals, which together account for 91.5% of the world's discovered original oil and gas reserves, are listed (after Klemme and Ulmishek [17]).

Interval	Share (%)	Basin/province [source rocks]
Oligocene-Miocene	12.5	East Venezuela-Trinidad, Maracaibo [Oficina Fm and equivalents; deltaic and prodeltaic shales]; Niger Delta [Akata and Agbada Fms; deltaic shales]; Mackenzie Delta [Tertiary deltaic shales]; Mahakam Delta [Miocene deltaic shales]; Californian basins [Monterey Fm; diatomaceous shale]; Gulf Coast and Mississippi Delta [Tertiary marine and deltaic shales]; Indonesian basins [Pematang Brown Shale and Banuwati Shale, lacustrine shales; Talang Akar Fm, fluviodeltaic shale]; North Kalimantan (Baram Delta) [Miocene deltaic shales]; North China, Biyang, Nanxiang, Jiangnan [lacustrine shales]; South Caspian and North Caucasus [Maykop Series and middle Miocene marine shales]; Suez [Rudeis Fm; marine shales]; Carpathians (Ploiesti and western Ukraine) [Menilite Shale; marine shale]
Aptian-Turonian	29	Arabian-Iranian [Kazhdumi Fm; marine shales and limestones]; Maracaibo [La Luna Fm; marine shales and limestones]; East Venezuela, Middle Magdalena, Llanos Orientales [Querecual and La Luna Fms; marine shales and limestones]; Alberta, Overthrust, Green River [Mannville Fm; marine shales and equivalents]; Gulf Coast [marine shales]; Amu Darya, North Caucasus, Crimea [Aptian-Albian marine shales]; North Atlantic basins [upper Neocomian-Aptian lacustrine and marine shales; Turonian marine shales]; West Siberia (northern) [Pokur Fm (Albian-Cenomanian); continental clastic rocks]; North Slope [HRZ shale; Hue Shale; marine shales]; Songliao [Qingshankou and Nenjiang Fms; deep lacustrine shales]
Upper Jurassic	25	Arabian-Iranian [Hanifa, Diyab/Dukhan and Sargelu Fms; marine shales, marls and limestones]; West Siberia [Bazhenov Fm; marine siliceous shales and carbonate rocks]; North Sea, Greenland Sea [Kimmeridge Clay Fm and equivalents; marine siliceous shale]; Gulf of Mexico (Gulf Coast, Reforma-Campeche, Tampico-Chicontepic) [Kimmeridgian-Tithonian marine shales and carbonate rocks]; North Caucasus, Amu Darya [Khodzhaipak Fm; Upper Jurassic sub-salt rocks; marine shales and limestones]
Pennsylvanian-Lower Permian	8	Anadarko, Permian [Pennsylvanian-Guadalupian basinal facies; marine shales]; southern North Sea [Westphalian Coal Measures]; North Caspian [Carboniferous-Lower Permian basinal facies; marine shales and carbonate rocks]; Bighorn, Powder River, Wind River, Uinta, Piceance [phosphatic shale members of the Phosphoria Fm; marine shale]; Vilyuy [Permian continental clastic rocks]; Sichuan [Yangxin Fm; argillaceous limestones]; Cooper [Gidgelpa Group (Permian); coal measures]
Upper Devonian-Tournaisian	8	Volga-Ural, Timan-Pechora, North Caspian [Domanik Fm and facies equivalents; marine shales and carbonate rocks]; Alberta [Duvernay, Ireton and Exshaw Fms; marine shales]; Anadarko, Permian [Woodford Shale; marine shales]; Appalachian [Chattanooga Shale; marine shales]; Williston, Michigan, Illinois [New Albany Shale, Antrim Shale, Bakken Fm]; Pripyat, Dnieper-Donets [Upper Devonian-Tournaisian marine shales and carbonate rocks]; Illizi [Upper and Middle Devonian marine shales]
Silurian	9	Arabian-Iranian [Gahkum and Tabuk Fms; graptolitic shales]; Erg Oriental, Erg Occidental [Silurian graptolitic shale]; Permian, Anadarko [Silurian marine shale]; Michigan [Niagara Fm; off-reef carbonate rocks]
Total	91.5	

3 Chronostratigraphy

Dating shale successions directly is difficult. The minerals most commonly analysed-clay minerals,

particularly illite and mixed-layer illite-smectite-are largely diagenetic products and do not behave as closed systems from the time of deposition [18]. The main problem is the mobility of potassium (K), which

is redistributed during burial diagenesis. K-Ar dates of shale clay fractions are therefore much harder to interpret than K-Ar dates of unaltered igneous minerals [19–21].

Perry [19] showed that K-Ar ages of mixed-layer illite/smectite in Gulf Coast shales become progressively younger with burial depth, the opposite of what a closed-system model would predict. The cause is now well understood: during burial, detrital illite and K-feldspar dissolve and supply K to newly forming diagenetic illite, and this addition of K without accumulated radiogenic ^{40}Ar lowers the apparent age of the bulk clay fraction. Meunier [18] showed that K fixation in the clay fraction increases with depth. For this reason, K-Ar dates of shale clay separates may decrease downhole, an artefact of progressive illitisation rather than a stratigraphic signal.

A second problem is argon retention in the finest illite fractions. Very small illite crystals ($< 0.02\ \mu\text{m}$) may lose some radiogenic ^{40}Ar by recoil during ^{40}K decay, although the net loss is expected to be small [20–22]. Whether very fine illite retains all of its ^{40}Ar therefore remains open, and apparent ages from the smallest size fractions should be treated with caution, particularly where several generations of illite are mixed.

Where a basin contains several generations of illite formed during separate diagenetic episodes, or has experienced local hydrothermal or fault-related fluid flow, a date from a bulk sample may represent a mixture of populations and correspond to the true age of none of them. Such mixed dates have no direct stratigraphic meaning. Size-fraction separation and petrographic and XRD characterisation of the illite populations [23, 24] are needed before any age is given a stratigraphic interpretation.

K-rich micas dated by K-Ar and Ar-Ar likewise tend to record late diagenetic rather than depositional ages, reflecting the same resetting problem [3]. Where provenance information is needed, isotopic systems that are less sensitive to K mobility are preferred. Whole-rock or clay-fraction Sm-Nd is one such system [18]: Sm and Nd are comparatively immobile during diagenesis, so the data record the average signature of the detrital source rather than the time of deposition. The Rb-Sr method [23] can also be applied to shales and pelitic sediments. However, Rb-Sr ages of clay separates are affected by the same illitisation and K-Rb redistribution as K-Ar ages, and their reliability depends on separating authigenic clay

from detrital grains [25, 26].

U-Pb dating of detrital zircon gives a different and complementary line of evidence, because zircon is highly resistant to diagenetic and metamorphic resetting. U-Pb ages of zircon grains recovered from shales do not date deposition; they constrain sediment provenance, that is, the crystallisation ages of the source rocks from which the zircons were derived, and they provide a maximum depositional age [27].

A more direct route to a depositional age exists where volcanic ash beds are interbedded with the shale, as in the Eagle Ford black shales of South Texas. Zircon in an ash fall crystallised shortly before eruption and deposition, so U-Pb ages of ash-bed zircon give precise depositional ages for the enclosing shale, free of the diagenetic complications of clay-based methods. Where datable ash horizons are present, this is the preferred method. In the Cenomanian-Turonian Eagle Ford Shale, LA-ICP-MS U-Pb dating of zircon from ash beds in five subsurface cores gave ages of 95.5–93.2 Ma, consistent with the Cenomanian-Turonian boundary and limiting the sampled depositional interval to ~ 2.3 Myr [28]. The same study found that zircon from outcrop “black shale” samples of similar appearance did not yield Eagle Ford ages but matched the younger, overlying Austin Chalk. Lithological similarity alone is thus an unreliable guide to chronostratigraphic position, and ash-bed geochronology should be used wherever possible.

Whole-rock Re-Os isotope systematics is a further, less widely applied tool. Allègre and Luck [29] established the framework for Os isotopes as petrogenetic and geological tracers. In organic-rich mudrocks, whole-rock Re-Os isochrons commonly yield depositional ages [30], whereas Re-Os data from oil and bitumen can constrain the timing of hydrocarbon generation and migration [31]. In practice the results can be disturbed by post-depositional mobility of Re and Os, by thermal maturation and by later tectonic or impact-related events. Re-Os ages from shales should therefore be cross-checked against independent maturity indicators (e.g. vitrinite reflectance, Rock-Eval T_{max}) before they are given geological significance.

In summary, the isotopic method must be matched to the question being asked. K-Ar, Ar-Ar and Rb-Sr data from clay minerals are best interpreted as records of diagenetic and thermal history, not of deposition. Sm-Nd data give detrital (provenance) signatures that are less affected by diagenesis, and

detrital-zircon U-Pb ages constrain provenance and a maximum depositional age. Whole-rock Re-Os can date organic-rich mudrocks and, applied to oils, the timing of hydrocarbon generation. Zircon from primary ash horizons gives the most direct depositional age. The different sensitivities of these methods to diagenetic overprinting should guide which one is applied to a given shale succession.

4 Chemostratigraphy

Chemostratigraphy uses systematic changes in elemental and isotopic composition through a succession to identify chemofacies, correlate sections and reconstruct palaeoenvironmental and palaeoclimatic conditions. Geochemical data can help to identify sequence-stratigraphic surfaces that are difficult to recognise from lithology alone [32, 33]. The approach is particularly useful in shale and mudstone successions, which are often visually homogeneous and lack the sedimentary structures used for facies analysis in coarser clastic rocks [34].

4.1 Carbon isotopes ($\delta^{13}\text{C}$) and mass extinction events

The carbon-isotope composition ($\delta^{13}\text{C}$) of black shales is a sensitive record of major perturbations to the global carbon cycle. Negative $\delta^{13}\text{C}$ excursions in particular are repeatedly associated with mass extinctions and environmental crises [34]. They reflect large-scale changes in organic carbon burial, volcanic CO_2 release during the emplacement of large igneous provinces (LIPs), or release of methane from gas hydrates [35]. Because the mixing time of the ocean ($\sim 10^3$ yr) is much shorter than the residence time of carbon in the ocean-atmosphere system ($\sim 10^5$ yr), such excursions are recorded nearly synchronously worldwide. This makes them useful for high-resolution correlation between basins that lack biostratigraphic markers.

4.2 Elemental ratios and weathering/provenance indices

Major- and trace-element ratios are used alongside isotopic data to characterise shale and mudstone successions. The Si/Al ratio reflects mineralogical variability; in shales it is generally < 5 , reflecting the dominance of aluminosilicate clay minerals over detrital quartz. Departures from this baseline indicate changes in detrital quartz input, biogenic silica or diagenetic silicification.

The chemical index of alteration (CIA) is defined

as [36]:

$$\text{CIA} = \left[\frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O}} \right] \times 100, \quad (1)$$

where all oxides are expressed in molar proportions and CaO^* is the CaO in the silicate fraction only (i.e. corrected for carbonate and apatite).

Average shales have CIA values of 70-75 [36]. Vertical departures from this range record changes in the intensity of continental weathering driven by palaeoclimate, as shown for Lower Cambrian black shales of the Yangtze Block [37]. In addition to the CIA, vertical changes in element/Al ratios (e.g. K/Al, Mg/Al), in Rb/K and Ti/K, and in ratios of immobile trace elements such as Zr/Nb are used as high-resolution chemostratigraphic markers [38]. Because these elements are distributed differently among detrital aluminosilicates, heavy minerals and authigenic clays, their vertical profiles respond to subtle changes in provenance, hydrodynamic sorting and depositional energy. Plotting these ratios through a shale succession can therefore reveal depositional sequences and boundaries that are not visible in the bulk lithology.

4.3 Redox-sensitive trace metal (RSTM) systematics

A well-established set of redox proxies complements the detrital indices. Concentrations of Mo, U, V, Ni, Cr and Co, normalised to immobile terrigenous elements (Al, Ti), are used to reconstruct bottom- and pore-water redox conditions [39]. These metals differ in solubility and uptake pathway along oxygen gradients, and their authigenic enrichment patterns are standard tools for distinguishing oxic, suboxic, anoxic and euxinic chemofacies in black shales. Mo-U covariation additionally tracks the degree of basin restriction, distinguishing open-marine settings from strongly restricted silled basins [40].

4.4 Rare earth element (REE) systematics in pelagic successions

In deep-sea and hemipelagic mudstone successions, REE systematics help to define stratigraphic divisions. Total REE concentrations, shale-normalised REE patterns (e.g. $\text{La}_\text{N}/\text{Yb}_\text{N}$, where the subscript N denotes normalisation to average shale) and anomalies of the redox-sensitive lanthanides, especially cerium (Ce/Ce^*) and europium (Eu/Eu^*), where the asterisk denotes the value interpolated from neighbouring REE, respond to ancient seawater

chemistry, continental runoff and early diagenetic remobilisation [41, 42]. Horizons defined by REE patterns allow correlation across deep-water basins in which carbonate microfossils are absent because of dissolution below the lysocline [43].

4.5 Iron speciation and sulfide systematics

Iron and sulfide mineral systematics can be used to test elemental redox indices when correlating shale successions between distant sections. Iron speciation (e.g. highly reactive iron relative to total iron) and the amount of diagenetic pyrite help to locate the chemocline and to track changes in bottom-water redox state. This mineralogical approach complements the RSTM proxies described above [39]. Because trace-metal uptake and iron-sulfide precipitation are linked during early diagenesis, combining mineralogical and trace-element data gives a stronger basis for identifying fine-scale sequence-stratigraphic surfaces in mudstones.

5 Biostratigraphy

Fossils are found mostly in shales and limestones. Exceptionally preserved soft-bodied biotas of Burgess Shale type are known chiefly from the early to middle Cambrian, with rare Ediacaran occurrences [44]. The Burgess Shale biota itself was discovered by Walcott in 1909 in the middle Cambrian (~508 Ma) shale on Fossil Ridge near Field in the Canadian Rockies of British Columbia, and was first described shortly afterwards [45]. Rapid burial of soft-bodied organisms in fine-grained sediment left little time for decay, and early diagenetic conditions in the clay-rich mud further limited degradation [46]. As a result, these deposits preserve soft tissues as carbonaceous compressions, not merely as impressions. More than 50 Burgess Shale-type deposits are now known [44, 47], mainly from lower to middle Cambrian strata in Australia, Canada, China, Poland, Spain and elsewhere in Laurentia and Gondwana [47, 48].

After the Ediacaran, invertebrate, vertebrate and microfossil groups diversified, producing successive new species while others became extinct. The first appearance (first occurrence) and last appearance (last occurrence) of each species are key stratigraphic markers: biostratigraphers refer to them as the first appearance datum (FAD) and last appearance datum (LAD) [49, 50]. Marine invertebrates, corals, amphibians and insects were prominent in the Paleozoic, reptiles dominated the Mesozoic and mammals the Cenozoic [51]. Although a group

of organisms may range through a long interval, individual species within it can still be precise markers, and the overall range of a group determines the interval for which it is useful.

FADs and LADs are widely used in biostratigraphy and in building the geological time scale, and advances in radiometric dating have since given more accurate and precise ages for the stage boundaries. As noted above, six intervals account for ~91.5% of global source-rock-generated reserves, and most of these source rocks are shales and mudstones. The boundaries of these intervals are well defined, mostly by FADs of graptolites, conodonts, ammonites and foraminifera.

Trilobites are the principal index fossils of the Cambrian [52]; graptolites are used for Ordovician-Silurian shales [53, 54], together with conodonts in the Silurian [55]; placoderm fishes characterise some Devonian black shales [56]; conodonts are used for Carboniferous-Permian siliceous mudstone and chert successions [57]; ammonites and other cephalopods for Triassic-Cretaceous shales [58]; and foraminifera and calcareous nannoplankton for Cenozoic shales [59, 60].

5.1 Organic carbon

Organic carbon is the key component of a source rock; its bacterial or thermal cracking ultimately yields oil and gas. Shales with 0.5-1% TOC are considered fair, 1-2% good, 2-4% very good and > 4% excellent source rocks [61]. Terrestrial organic input is largely confined to the shelf, whereas marine phytoplankton supply organic carbon throughout the ocean basin. Continental-margin sediments, including deltas, account for most (of the order of 90%) of organic carbon burial in the ocean [62]. Preservation of organic carbon depends on primary productivity, dissolved-oxygen concentration in the water column, the abundance of organic-carbon consumers, water depth, sedimentation rate and grain size. Marine phytoplankton (calcareous nannoplankton, diatoms, etc.) are the main primary producers.

Seaweeds, bacteria and faecal pellets are minor additional sources of organic carbon. Counts of calcareous nannoplankton, diatoms, radiolarians, acritarchs and dinoflagellate cysts give both biostratigraphic information and an indication of primary productivity. An increase in nannoplankton abundance reflects blooms and a higher flux of organic carbon to the sea floor. Only about 1% of

the organic carbon exported from the surface ocean reaches ~1000 m water depth [63]. Foraminiferal census counts and their carbon-isotope values are useful tools for estimating palaeoproductivity. The planktic foraminifer *Globigerina bulloides* is an important palaeoproductivity indicator associated with upwelling [64, 65]. An assemblage of the benthic species *Cassidulina carinata* and *Bulimina marginata* indicates a supply of labile organic carbon to the sea floor [66], and *Alabaminella weddellensis* is an opportunistic taxon that increases rapidly in fresh phytodetritus [67]. *Uvigerina peregrina*, *Hoeglundina elegans*, *Sphaeroidina bulloides*, *Bolivina albatrossi*, *Cibicides pseudoungerianus*, *Globobulimina* spp. and similar species are regarded as high-organic-flux taxa on the continental slope to abyssal plain, whereas a high abundance of shelf species such as *Trifarina fornasinii* and *Uvigerina mediterranea* indicates high organic flux on the shelf [68]. More negative $\delta^{13}\text{C}$ values in foraminiferal tests generally indicate higher productivity. When using foraminiferal $\delta^{13}\text{C}$, however, three factors must be considered: the habitat of the species (epifaunal, shallow infaunal or deep infaunal), since deep-infaunal species have much lower $\delta^{13}\text{C}$ [69]; diagenesis, since diagenetic calcite further lowers $\delta^{13}\text{C}$; and methane flux [70, 71].

5.2 Dissolved oxygen

Dissolved oxygen plays a key role in the preservation of organic carbon, which a shale needs in order to become a source rock. Oxygen-rich bottom water oxidises organic carbon, so sediments deposited under low-oxygen conditions commonly have source-rock potential. Upwelling areas combine high organic production with the development of an oxygen minimum zone [72]. Benthic foraminifera are good indicators of bottom-water oxygen. Shallow- and deep-infaunal species generally indicate an organic-rich, low-oxygen environment [73], and elongate benthic taxa likewise indicate oxygen depletion [74, 75]. A high abundance of bolivinids, buliminids, uvigerinids, *Cassidulina*, *Fursenkoina*, *Melonis* and similar taxa points to poorly oxygenated bottom water [66, 76].

5.3 Depositional depth and sediment grain size

Most shale source rocks were deposited in relatively shallow water on the continental shelf and slope. These settings receive large volumes of clastic sediment at high sedimentation rates, have high organic production, and the path for organic particles to reach the sea floor is short. Several

benthic foraminiferal genera (*Ammonia*, *Amphistegina*, *Asterorotalia*, *Calcarina*, *Elphidium*, *Heterostegina*, *Operculina* and some bolivinids) are key markers of the shelf, whereas others (*Bolivina*, *Bulimina*, *Cassidulina*, *Cibicides*, *Nonionella*, *Pullenia*, *Uvigerina*, etc.) mark the continental slope to abyssal zone. Abundant shallow-water benthic species in a deep-water setting can indicate a mass-transport deposit (MTD). In the Krishna-Godavari Basin, Bhaumik et al. [77] found an intermediate sediment layer containing shelf benthic foraminifera (*Ammonia* spp., *Bolivinita subangularis*, *Loxostomum amygdalaeformis* and *Quinqueloculina seminulum*) at ~1038 m water depth, overlain and underlain by sediment with deep-water species including *Cassidulina carinata*. From these assemblages and the seismic reflection profile, they identified an MTD within the deep-water succession and explained the nucleation and saturation of gas hydrates within it.

Many benthic foraminifera are also distributed according to grain size. Shallow-water genera (*Ammonia*, *Elphidium*, *Amphistegina*, etc.) are associated mostly with coarse sediment (sand and coarse silt), whereas deep-water taxa (bolivinids, *Nonionella*, etc.) are associated with fine sediment (fine silt and clay).

6 Mapping

Mudstones can be traced and mapped geophysically with relative ease, because (i) they are readily identified on gamma-ray logs and (ii) even thin shale units commonly extend over long distances [3]. Field mapping of shale together with other lithologies is described in many works, and standard schemes exist for describing fine-grained rocks in outcrop and core [78–80]. Field mapping of shale uses the classical methods, such as chain-and-compass mapping; no technique is specific to shale. Section 7 reviews geophysical (well-log) mapping of shale.

7 Well-log studies

Shale mapping is needed in reservoir geomechanics, where the well-known geomechanical properties of shale are useful [7]. Radioactive elements are concentrated in fine-grained sediments, whereas clean sandstones and carbonates have low radioactivity, so gamma-ray logs can be used to identify lithology (e.g. Fig. 8.14 of [3]; Fig. 4.5 of [81]) and to identify parasequences [82]. Ash may accumulate on omission surfaces and can sometimes mark parasequence boundaries [3]. Bentonites can help to define

clinoform geometry. Gamma-ray logs show kicks at hot shales, and bentonites, which consist of K-feldspar and illite, are readily identified by their gamma-ray response. Tonsteins (kaolinite-rich altered ash beds) and bentonites are best preserved in marine basins and coal swamps.

Gamma-ray measurements are also used quantitatively in shales. Schmoker [83] compared three ways of defining the boundary between organic-rich and organic-poor facies in the Devonian shale of the Appalachian Basin. In the “20-API method” the boundary is placed at a gamma-ray intensity 20 API units above the grey-shale baseline. In the “230-API method” it is placed at 230 API units, a value associated with high gas content. In the “2-percent method”, which Schmoker regarded as the best definition, the boundary is an organic-matter content of 2% by volume (0.8% by weight). A cut-off of 20 API units above the shale baseline has also been applied to the Bowland Shale [84].

Lithology can be inferred from the “shale baseline” on SP and gamma-ray logs. Once the response of a shale body has been obtained, the “shale baseline” or “100% shale line” can be drawn (Fig. 22 of [85]). Maximum deflection from this line indicates absence of clay. In the same way, 100% carbonate, 100% sandstone and 50% sandstone lines can be defined. The 75% sandstone line is regarded as the “clean sandstone line” and corresponds to 25% clay [86]. Similar lines can be defined for carbonate-shale successions.

The volume of shale can also be estimated from gamma-ray and SP logs. Deflection of the SP curve from the shale baseline depends on the relative salinity of the mud filtrate and the formation water [81], and the gamma-ray method can be used where SP readings are distorted [87]. However, well logs may fail to resolve very thin (centimetre-scale) beds [7] and can obscure hiatuses within deep-water shales.

Classic studies of shale identification from logs include [88–91].

8 Synthesis

Shales and mudstones are fine-grained sedimentary rocks found worldwide, and their study is important for hydrocarbon geoscience. Dating them is difficult because clay minerals such as illite alter during diagenesis and can reset isotopic systems. K-Ar, Ar-Ar and Rb-Sr data commonly record diagenetic events, not deposition. Sm-Nd and detrital-zircon U-Pb data provide information on provenance, whereas

U-Pb dating of zircon from interbedded volcanic ash gives depositional ages. Whole-rock Re-Os can date organic-rich mudrocks, and Re-Os data from oils can constrain the timing of hydrocarbon generation. Among chemostratigraphic tools, carbon-isotope excursions, elemental ratios, redox-sensitive trace metals, REEs and iron-sulfide systematics help to correlate shale successions. Trilobites, graptolites, conodonts, cephalopods, foraminifera and calcareous nannoplankton are useful for shales of different ages. Conventional field mapping establishes the continuity of shale bodies. Gamma-ray and SP logs identify shale, allow its volume to be estimated, and help to recognise organic-rich intervals and bentonites, although very thin beds and subtle breaks may be missed.

Data Availability Statement

Not applicable.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

References

- [1] Paul, A., Mukherjee, S., & Biswas, M. (2025). Global review on shale: Focus on hydrocarbon geoscience & carbon sequestration. *Results in Earth Sciences*, 3, 100088. [CrossRef]
- [2] Ilgen, A. G., Heath, J. E., Akkutlu, I. Y., Bryndzia, L. T., Cole, D. R., Kharaka, Y. K., ... & Suarez-Rivera, R. (2017). Shales at all scales: Exploring coupled processes in mudrocks. *Earth-Science Reviews*, 166, 132-152. [CrossRef]
- [3] Potter, P. E., Maynard, J. B., & Depetris, P. J. (2005). *Mud and Mudstones: Introduction and Overview*. Springer, Berlin. [CrossRef]
- [4] Sageman, B. B., Murphy, A. E., Werne, J. P., Ver Straeten, C. A., Hollander, D. J., & Lyons, T. W. (2003). A tale of shales: the relative roles of production, decomposition, and dilution in the accumulation

- of organic-rich strata, Middle–Upper Devonian, Appalachian basin. *Chemical Geology*, 195(1–4), 229–273. [CrossRef]
- [5] Mondal, I., Choudhuri, A., Choudhury, T. R., Srimani, S., Koner, A., Mandal, S., & Sarkar, S. (2025). Sedimentology, sequence stratigraphy and geochemical reappraisal of the Mesoproterozoic Rampur Shale, Vindhyan Basin, India: Implications for paleoenvironment and basin evolution. *Journal of Palaeogeography*, 14(3), 100259. [CrossRef]
- [6] Stow, D., & Smillie, Z. (2020). Distinguishing between deep-water sediment facies: Turbidites, contourites and hemipelagites. *Geosciences*, 10(2), 68. [CrossRef]
- [7] Slatt, R. M., & Abousleiman, Y. (2011). Merging sequence stratigraphy and geomechanics for unconventional gas shales. *The Leading Edge*, 30(3), 274–282. [CrossRef]
- [8] Schieber, J., Southard, J., & Thaisen, K. (2007). Accretion of mudstone beds from migrating floccule ripples. *Science*, 318(5857), 1760–1763. [CrossRef]
- [9] Wignall, P. B. (1994). *Black Shales* (Oxford Monographs on Geology and Geophysics 30). Clarendon Press, Oxford. <https://mitpressbookstore.mit.edu/book/9780198540380>
- [10] Wignall, P. B. (1991). Model for transgressive black shales? *Geology*, 19(2), 167–170. [CrossRef]
- [11] Ohkouchi, N., Kuroda, J., & Taira, A. (2015). The origin of Cretaceous black shales: a change in the surface ocean ecosystem and its triggers. *Proceedings of the Japan Academy, Series B*, 91(7), 273–291. [CrossRef]
- [12] Aplin, A. C., & Macquaker, J. H. S. (2011). Mudstone diversity: Origin and implications for source, seal, and reservoir properties in petroleum systems. *AAPG Bulletin*, 95(12), 2031–2059. [CrossRef]
- [13] Tucker, M. E. (2003). *Sedimentary Rocks in the Field* (3rd ed.). John Wiley & Sons, Chichester. https://usuarios.geofisica.unam.mx/cecilia/CT-SeEs/Tucker_Sedimentary%20Rocks%20in%20the%20Field.pdf
- [14] Kennedy, M. J., Pevear, D. R., & Hill, R. J. (2002). Mineral surface control of organic carbon in black shale. *Science*, 295(5555), 657–660. [CrossRef]
- [15] Srivastava, H., Bhaumik, A. K., Tiwari, D., Mohanty, S. P., & Patil, D. J. (2018). Characterization of organic carbon in black shales of the Kachchh basin, Gujarat, India. *Journal of Earth System Science*, 127, 93. [CrossRef]
- [16] Selley, R. C. (1998). *Elements of Petroleum Geology* (2nd ed.). Academic Press, San Diego. <https://raregeologybooks.wordpress.com/wp-content/uploads/2014/10/elements-of-petroleum-geology.pdf>
- [17] Klemme, H. D., & Ulmishek, G. F. (1991). Effective petroleum source rocks of the world: Stratigraphic distribution and controlling depositional factors. *AAPG Bulletin*, 75(12), 1809–1851. [CrossRef]
- [18] Meunier, A. (2005). *Clays*. Springer, Berlin. [CrossRef]
- [19] Perry, E. A., Jr. (1974). Diagenesis and the K-Ar dating of shales and clay minerals. *Geological Society of America Bulletin*, 85(5), 827–830. [CrossRef]
- [20] Clauer, N. (2013). The K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ methods revisited for dating fine-grained K-bearing clay minerals. *Chemical Geology*, 354, 163–185. [CrossRef]
- [21] Clauer, N., & Lerman, A. (2022). A kinetic explanation for combined potassium gains and radiogenic ^{40}Ar losses of diagenetic illite-rich clay separates. *Geosciences*, 12(5), 186. [CrossRef]
- [22] Szczerba, M., Derkowski, A., Kalinichev, A. G., & Środoń, J. (2015). Molecular modeling of the effects of ^{40}Ar recoil in illite particles on their K-Ar isotope dating. *Geochimica et Cosmochimica Acta*, 159, 162–176. [CrossRef]
- [23] Clauer, N., & Chaudhuri, S. (2012). *Clays in crustal environments: isotope dating and tracing*. Springer Science & Business Media. [CrossRef]
- [24] Liewig, N., Clauer, N., & Sommer, F. (1987). Rb-Sr and K-Ar dating of clay diagenesis in Jurassic sandstone oil reservoir, North Sea. *AAPG Bulletin*, 71(12), 1467–1474. [CrossRef]
- [25] Clauer, N., Cocker, J. D., & Chaudhuri, S. (1992). Isotopic dating of diagenetic illites in reservoir sandstones: Influence of the investigator effect. In D. W. Houseknecht & E. D. Pittman (Eds.), *Origin, Diagenesis, and Petrophysics of Clay Minerals in Sandstones* (SEPM Special Publication 47, pp. 5–12). SEPM, Tulsa. [CrossRef]
- [26] Compston, W., & Pidgeon, R. T. (1962). Rubidium-strontium dating of shales by the total-rock method. *Journal of Geophysical Research*, 67(9), 3493–3502. [CrossRef]
- [27] Gehrels, G. (2014). Detrital zircon U-Pb geochronology applied to tectonics. *Annual Review of Earth and Planetary Sciences*, 42, 127–149. [CrossRef]
- [28] Chakrabarty, P., & Basu, A. R. (2026). Calc alkaline volcanism-aided phytoplankton growth and organic matter production of the Cenomanian-Turonian Eagle Ford Formation of South Texas. *International Geology Review*, 68, 1185–1206. [CrossRef]
- [29] Allègre, C. J., & Luck, J. M. (1980). Osmium isotopes as petrogenetic and geological tracers. *Earth and Planetary Science Letters*, 48(1), 148–154. [CrossRef]
- [30] Selby, D., & Creaser, R. A. (2003). Re-Os geochronology of organic rich sediments: An evaluation of organic matter analysis methods. *Chemical Geology*, 200(3–4), 225–240. [CrossRef]
- [31] Selby, D., & Creaser, R. A. (2005). Direct radiometric dating of hydrocarbon deposits using rhenium-osmium isotopes. *Science*, 308(5726), 1293–1295. [CrossRef]
- [32] LaGrange, M. T., Konhauser, K. O., Catuneanu, O., Harris, B. S., Playter, T. L., & Gingras, M. K. (2020). Sequence stratigraphy in organic-rich marine

- mudstone successions using chemostratigraphic datasets. *Earth-Science Reviews*, 203, 103137. [CrossRef]
- [33] Ver Straeten, C. A., Brett, C. E., & Sageman, B. B. (2011). Mudrock sequence stratigraphy: A multi-proxy (sedimentological, paleobiological and geochemical) approach, Devonian Appalachian Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 304(1-2), 54-73. [CrossRef]
- [34] Sial, A. N., Gaucher, C., Ferreira, V. P., Pereira, N. S., Cezario, W. S., Chigilino, L., & Lima, H. M. (2015). Isotope and elemental chemostratigraphy. In *Chemostratigraphy* (pp. 23-64). Elsevier. [CrossRef]
- [35] Schobben, M., Van De Schootbrugge, B., & Wignall, P. B. (2019). Interpreting the carbon isotope record of mass extinctions. *Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology*, 15(5), 331-337. [CrossRef]
- [36] Nesbitt, H. W., & Young, G. M. (1982). Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature*, 299, 715-717. [CrossRef]
- [37] Xu, H., Shen, J., Yang, F., Hu, Q., Yu, Y., Xiong, L., ... & He, J. (2025). Provenance, sedimentary paleoenvironment and organic matter accumulation mechanisms in shales from the Lower Cambrian Qiongzhusi Formation, SW Yangtze Block, China. *Marine and Petroleum Geology*, 181, 107520. [CrossRef]
- [38] Craigie, N. (2018). *Principles of Elemental Chemostratigraphy: A Practical User Guide*. Springer, Cham. [CrossRef]
- [39] Tribouillard, N., Algeo, T. J., Lyons, T., & Riboulleau, A. (2006). Trace metals as paleoredox and paleoproductivity proxies: An update. *Chemical Geology*, 232(1-2), 12-32. [CrossRef]
- [40] Algeo, T. J., & Tribouillard, N. (2009). Environmental analysis of paleoceanographic systems based on molybdenum-uranium covariation. *Chemical Geology*, 268(3-4), 211-225. [CrossRef]
- [41] Wright, J., Schrader, H., & Holser, W. T. (1987). Paleoredox variations in ancient oceans recorded by rare earth elements in fossil apatite. *Geochimica et Cosmochimica Acta*, 51(3), 631-644. [CrossRef]
- [42] Shields, G. A., & Webb, G. E. (2004). Has the REE composition of seawater changed over geological time? *Chemical Geology*, 204(1-2), 103-107. [CrossRef]
- [43] Tanaka, E., Nakamura, K., Yasukawa, K., Mimura, K., Fujinaga, K., Iijima, K., ... & Kato, Y. (2020). Chemostratigraphy of deep-sea sediments in the western North Pacific Ocean: Implications for genesis of mud highly enriched in rare-earth elements and yttrium. *Ore Geology Reviews*, 119, 103392. [CrossRef]
- [44] Dornbos, S. Q., Oji, T., Kanayama, A., & Gonchigdorj, S. (2016). A new Burgess Shale-type deposit from the Ediacaran of western Mongolia. *Scientific Reports*, 6, 23438. [CrossRef]
- [45] Walcott, C. D. (1911). Cambrian geology and paleontology II. No. 2-Middle Cambrian Merostomata. *Smithsonian Miscellaneous Collections*, 57(2), 17-40. <https://repository.si.edu/server/api/core/bitstreams/7387f961-257b-426d-a03b-0efab8e9391d/content>
- [46] Gaines, R. R., Hammarlund, E. U., Hou, X., Qi, C., Gabbott, S. E., Zhao, Y., ... & Canfield, D. E. (2012). Mechanism for Burgess Shale-type preservation. *Proceedings of the National Academy of Sciences*, 109(14), 5180-5184. [CrossRef]
- [47] Gaines, R. R. (2014). Burgess Shale-type preservation and its distribution in space and time. *The Paleontological Society Papers*, 20, 123-146. [CrossRef]
- [48] Morris, S. C. (1989). The persistence of Burgess Shale-type faunas: implications for the evolution of deeper-water faunas. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 80(3-4), 271-283. [CrossRef]
- [49] Armstrong, H. A., & Brasier, M. D. (2005). *Microfossils* (2nd ed.). Blackwell Publishing, Malden, MA. [CrossRef]
- [50] Haq, B. U., & Boersma, A. (Eds.). (1998). *Introduction to Marine Micropaleontology* (2nd ed.). Elsevier, Amsterdam. https://archive.org/details/introductiontoma0000unse_g911
- [51] Ogg, J. G., Ogg, G. M., & Gradstein, F. M. (2016). *A Concise Geologic Time Scale 2016*. Elsevier, Amsterdam. [CrossRef]
- [52] Peng, S. C., Babcock, L. E., & Ahlberg, P. (2020). The cambrian period. In *Geologic time scale 2020* (pp. 565-629). Elsevier. [CrossRef]
- [53] Churkin, M., Jr., Carter, C., & Eberlein, G. D. (1970). Graptolite succession across the Ordovician-Silurian boundary in south-eastern Alaska. *Journal of the Geological Society*, 126(1-2), 319-330. [CrossRef]
- [54] Štorch, P. (2023). Graptolite biostratigraphy and biodiversity dynamics in the Silurian System of the Prague Synform (Barrandian area, Czech Republic). *Bulletin of Geosciences*, 98(1), 1. [CrossRef]
- [55] Kleffner, M. A. (1989). A conodont-based Silurian chronostratigraphy. *Geological Society of America Bulletin*, 101(7), 904-912. [CrossRef]
- [56] Lelièvre, H., & Goujet, D. (1986). Biostratigraphic significance of some uppermost Devonian placoderms. *Annales de la Société géologique de Belgique*. <https://popups.uliege.be/0037-9395/index.php?id=2382>
- [57] Muto, S., Takahashi, S., & Murayama, M. (2023). Conodont biostratigraphy of a Carboniferous-Permian boundary section in siliceous successions of pelagic Panthalassa revealed by X-ray computed microtomography. *Frontiers in Earth Science*, 11, 1162023. [CrossRef]
- [58] Fürsich, F. T., Alberti, M., Pandey, D. K., Chaskar, K., & Bhosale, S. (2021). Facies analysis and palaeoecology of the Jurassic Spiti Shale Formation in the Spiti

- area, Northern India. *Journal of Palaeogeography*, 10(4), 438-462. [CrossRef]
- [59] Khanolkar, S., & Saraswati, P. K. (2019). Eocene foraminiferal biofacies in Kutch Basin (India) in context of palaeoclimate and palaeoecology. *Journal of Palaeogeography*, 8(1), 21. [CrossRef]
- [60] Gómez, V. M. G., Beik, I., Podlaha, O. G., & Mutterlose, J. (2017). The micropaleontological record of marine early Eocene oil shales from Jordan. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 485, 723-739. [CrossRef]
- [61] Peters, K. E., & Cassa, M. R. (1994). Applied source rock geochemistry. In L. B. Magoon & W. G. Dow (Eds.), *The Petroleum System-From Source to Trap* (AAPG Memoir 60, pp. 93-120). AAPG, Tulsa. [CrossRef]
- [62] Walsh, J. J., Dieterle, D. A., & Pribble, J. R. (1991). Organic debris on the continental margins: a simulation analysis of source and fate. *Deep Sea Research Part A. Oceanographic Research Papers*, 38(7), 805-828. [CrossRef]
- [63] Martin, J. H., Knauer, G. A., Karl, D. M., & Broenkow, W. W. (1987). VERTEX: Carbon cycling in the northeast Pacific. *Deep-Sea Research Part A*, 34(2), 267-285. [CrossRef]
- [64] Naidu, P. D., Babu, C. P., & Rao, C. M. (1992). The upwelling record in the sediments of the western continental margin of India. *Deep Sea Research Part A. Oceanographic Research Papers*, 39(3-4), 715-723. [CrossRef]
- [65] Naidu, P. D., & Malmgren, B. A. (1996). A high-resolution record of late Quaternary upwelling along the Oman Margin, Arabian Sea based on planktonic foraminifera. *Paleoceanography*, 11(1), 129-140. [CrossRef]
- [66] Bhaumik, A. K., Gupta, A. K., & Thomas, E. (2011). Blake Outer Ridge: Late Neogene variability in paleoceanography and deep-sea biota. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 302(3-4), 435-451. [CrossRef]
- [67] Gooday, A. J. (1988). A response by benthic foraminifera to the deposition of phytodetritus in the deep sea. *Nature*, 332(6159), 70-73. [CrossRef]
- [68] Gooday, A. J. (2003). Benthic foraminifera (Protista) as tools in deep-water paleoceanography: Environmental influences on faunal characteristics. *Advances in Marine Biology*, 46, 1-90. [CrossRef]
- [69] McCorkle, D. C., Keigwin, L. D., Corliss, B. H., & Emerson, S. R. (1990). The influence of microhabitats on the carbon isotopic composition of deep-sea benthic foraminifera. *Paleoceanography*, 5(2), 161-185. [CrossRef]
- [70] Hill, T. M., Kennett, J. P., & Valentine, D. L. (2004). Isotopic evidence for the incorporation of methane-derived carbon into foraminifera from modern methane seeps, Hydrate Ridge, Northeast Pacific. *Geochimica et Cosmochimica Acta*, 68(22), 4619-4627. [CrossRef]
- [71] Rathburn, A. E., Levin, L. A., Held, Z., & Lohmann, K. C. (2000). Benthic foraminifera associated with cold methane seeps on the northern California margin: Ecology and stable isotopic composition. *Marine Micropaleontology*, 38(3-4), 247-266. [CrossRef]
- [72] Helly, J. J., & Levin, L. A. (2004). Global distribution of naturally occurring marine hypoxia on continental margins. *Deep Sea research part I: Oceanographic research papers*, 51(9), 1159-1168. [CrossRef]
- [73] Jorissen, F. J., de Stigter, H. C., & Widmark, J. G. V. (1995). A conceptual model explaining benthic foraminiferal microhabitats. *Marine Micropaleontology*, 26(1-4), 3-15. [CrossRef]
- [74] Saalim, S. M., Saraswat, R., Suokhrie, T., & Nigam, R. (2019). Assessing the ecological preferences of agglutinated benthic foraminiferal morphogroups from the western Bay of Bengal. *Deep Sea Research Part II: Topical Studies in Oceanography*, 161, 38-51. [CrossRef]
- [75] Corliss, B. H., & Chen, C. (1988). Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology*, 16(8), 716-719. [CrossRef]
- [76] Kaiho, K. (1994). Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen levels in the modern ocean. *Geology*, 22(8), 719-722. [CrossRef]
- [77] Bhaumik, A. K., Kumar, S., Chaudhuri, S., Mohanty, S., Mukherjee, M. K., Sain, K., ... & Kumar, P. (2024). Accumulation of gas hydrates in mass transport deposits at Krishna-Godavari Basin, Bay of Bengal: Foraminiferal, sedimentologic, and seismic evidence. *AAPG Bulletin*, 108(9), 1687-1703. [CrossRef]
- [78] Macquaker, J. H., & Adams, A. E. (2003). Maximizing information from fine-grained sedimentary rocks: An inclusive nomenclature for mudstones. *Journal of Sedimentary Research*, 73(5), 735-744. [CrossRef]
- [79] Lazar, O. R., Bohacs, K. M., Macquaker, J. H. S., Schieber, J., & Demko, T. M. (2015). Capturing key attributes of fine-grained sedimentary rocks in outcrops, cores, and thin sections: Nomenclature and description guidelines. *Journal of Sedimentary Research*, 85(3), 230-246. [CrossRef]
- [80] Schieber, J. (1999). Distribution and deposition of mudstone facies in the Upper Devonian Sonyea Group of New York. *Journal of Sedimentary Research*, 69(4), 909-925. [CrossRef]
- [81] Liu, H. (2017). *Principles and Applications of Well Logging*. Springer, Berlin, Heidelberg. [CrossRef]
- [82] Li, G., Lin, C., Dong, C., Ma, P., Du, X., Jiang, L., & Guo, F. (2022). Sequence stratigraphy, depositional environment and associated lithofacies of lacustrine shale: A case from the upper fourth member of Shahejie Formation, Dongying Depression, Bohai Bay

- Basin. *Frontiers in Earth Science*, 10, 906987. [CrossRef]
- [83] Schmoker, J. W. (1980). *Defining Organic-Rich Facies in the Devonian Shale in the Western Part of the Appalachian Basin* (U.S. Geological Survey Open-File Report 80-707). [CrossRef]
- [84] Hennissen, J. A., Emmings, J. F., Raine, R., Hough, E., Vane, C. H., Page, M., ... & Leng, M. (2024). The Bowland Shale Formation in the Blacon Basin: Palaeoecology and resource potential. *Geological Society, London, Special Publications*, 534, 91-121. [CrossRef]
- [85] Brenner, R. L. (1989). Stratigraphy, petrology, and paleogeography of the upper portion of the Cherokee Group (Middle Pennsylvanian), eastern Kansas and northeastern Oklahoma. *Kansas Geological Survey Bulletin* (Geology Series 3), 1-70. [CrossRef]
- [86] Brenner, R. L., & McHargue, T. R. (1988). *Integrative Stratigraphy: Concepts and Applications*. Prentice Hall, Englewood Cliffs, NJ. https://openlibrary.org/books/OL2393222M/Integrative_stratigraphy
- [87] Mondol, N. H. (2015). Well logging: principles, applications and uncertainties. In *Petroleum geoscience: From sedimentary environments to rock physics* (pp. 385-425). Berlin, Heidelberg: Springer Berlin Heidelberg. [CrossRef]
- [88] Poupon, A., & Gaymard, R. (1970, May). The evaluation of clay content from logs. In *SPWLA Annual Logging Symposium* (pp. SPWLA-1970). SPWLA. <https://onepetro.org/SPWLAALS/proceedings-abstract/SPWLA-1970/All-SPWLA-1970/SPWLA-1970-G/18376>
- [89] Poupon, A., Clavier, C., Dumanoir, J., Gaymard, R., & Misk, A. (1970). Log Analysis of Sand-Shale Sequences A Systematic Approach. *Journal of Petroleum technology*, 22(07), 867-881. [CrossRef]
- [90] Heslop, A. (1974). Gamma-ray log response of shaly sandstones. *The Log Analyst*, 15(5), 16-21. <https://onepetro.org/petrophysics/article-abstract/171640/Gamma-ray-Log-Response-Of-Shaly-Sandstones>
- [91] Serra, O., & Sulpice, L. (1975, June). Sedimentological analysis of shale-sand series from well logs. In *SPWLA Annual Logging Symposium* (pp. SPWLA-1975). SPWLA. <https://onepetro.org/SPWLAALS/proceedings-abstract/SPWLA-1975/SPWLA-1975/SPWLA-1975-W/19893>
- Soumyajit Mukherjee** is with the Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai 400076, India. (Email: soumyajitm@gmail.com; smukherjee@iitb.ac.in)
- Ajoy Kumar Bhaumik** is with the Department of Applied Geology, Indian Institute of Technology (Indian School of Mines) Dhanbad, Dhanbad 826004, India.
- Puloma Chakrabarty** is with the Department of Earth and Environmental Sciences, University of California, Los Angeles, CA 90095, United States.