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Depositional processes of black shales in deep water

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Abstract

With deep-water exploration for and production of hydrocarbons becoming progressively more extensive and successful, it is clearly important to understand the processes of deposition and organic matter preservation of black shale source rocks in the deep sea. This short contribution aims to summarize the current state of knowledge in this area and to suggest directions for future research. Black shales are defined as generally fine-grained sediments or sedimentary rocks that contain >1% total organic carbon (TOC). Deep water in the marine environment is taken as any depth in excess of storm wave base (i.e. approximately 200 m). Much of this synthesis is based on previous work by the authors on deep-water processes (*Sediment transport and depositional processes* (1994) 257; *Sedimentary environments: processes, facies and stratigraphy* (1996) 395) and black shales (*Fine grained sediments: deep-water processes and facies* (1984) 527; *AAPG studies in geology no. 40* (1995); Geol. Soc. Spec. Publ., 26 (1987) 287), as well as on general black shale/source rock compilations (*Marine petroleum source rocks* (1987); *Black shales* (1994)). © 2001 Published by Elsevier Science Ltd.

Keywords: Black shales; Deep water; Depositional processes

1. Depositional processes

The first important contention of this paper is that black shales can be deposited by any one or by a combination of the processes that typically control fine-grained sedimentation in deep water. These are briefly described below.

Pelagic settling is a process of vertical settling under the influence of gravity, by which primary biogenic material and very fine-grained terrigenous or other detritus in the surface waters falls slowly to the seafloor. The rate of fall and hence of sediment accumulation is increased by both flocculation and by organic pelletization, especially in high productive areas. In oligotrophic open-ocean systems, the process is quite continuous and accumulation is typically very slow — i.e. <1 cm/ky (2.5 g/cm^2 ky). However, in highly productive margin areas, the process can occur as pulsed blooms, or be seasonal (Shannon & Nelson, 1996). In this case, sediment is mainly deposited during the onset of eutrophic periods where flocculation of blooming primary producers and production of large fecal pellets by the growing zooplankton are favored. Rates of accumulation locally can exceed 8 cm/ky (20 g/cm^2 ky).

Hemipelagic deposition (Stow & Tabrez, 1998) is a complex process involving both vertical settling and slow lateral advection through the water column. The driving forces behind this lateral advection include the inertia of river plumes (both within the water column and at the surface), glacial meltwater diffusion, turbid layer plumes, internal tides and waves, and other slowly moving mid-water currents. Cross-shelf and/or shelf-to-slope advection of selected fine or low-density particles has been described as contributing to this process (Biscaye, Flagg, & Falkowski, 1994). Between 1000 and 2000 m water depth, modern slope sediments are generally enriched in organic carbon older than 1000–2000 y. Hemipelagic deposition is a continuous process with very variable rates depending on the nature of biogenic and terrigenous inputs — e.g. 2 cm/ky (5 g/cm^2 ky) on continental margins with little terrigenous input, 10 cm/ky (25 g/cm^2 ky) for black shale hemipelagites in areas of high upwelling, and over 20 cm/ky (50 g/cm^2 ky) for high-latitude glaciomarine hemipelagites.

Hemiturbiditic sedimentation (Stow & Wetzel, 1990) involves negative buoyancy and upward dispersion from a dilute turbidity current (Sparks et al., 1993) during its final stages of deposition and/or following interaction with a positive topographic obstacle. The fine-grained material carried by the turbidity current disperses above and beyond the final deposit of the normal turbidite, mixes with any

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background pelagic or hemipelagic material and deposits slowly by vertical settling. Deposition is episodic (geologically an event deposit) but accumulation is sufficiently slow that a restricted ichnofaunal bioturbation continues throughout. Insufficient data exist to estimate mean rates of accumulation.

Contouritic sedimentation refers to deposition that occurs under the influence of variable intensity bottom currents (e.g. Hollister & Heezen, 1972; Stow, Reading, & Collinson, 1996). These currents are driven by normal thermohaline circulation including the deep-water influence of major wind-driven current systems. Weak bottom currents will only slightly affect the nature of the background pelagic or hemipelagic sedimentation, moderate currents can transport fine-grained material long distances and construct large contourite drifts, whereas the strongest currents can winnow sands and gravels or cause widespread hiatuses and erosion surfaces in the deep sea. Rates of contourite accumulation are clearly, therefore, very variable, but typically lie between 10 and 20 cm/ky (25–50 g/cm^2 ky) for the major drifts. Other bottom-current processes are not discussed here.

Hyperpycnal flow involves the near-bottom discharge of suspended sediment plumes from the mouth of a river during periods of flood (Mulder, Savoye, Syvitski, & Parize, 1997) or from high-latitude glacially fed systems (Syvitski, LeBlanc, & Cranston, 1990). Underflow is caused by the excess density of the sediment load. In most cases this will dissipate and the sediment settle out relatively close to the river mouth, but hyperpycnal flow can continue further into deep water across the pro-delta slope. Such flows can also directly generate a low-density turbidity current and contribute to hemipelagic advection via suspension cascading, for example. Insufficient data exist to allow good estimates of mean rates of accumulation due to hyperpycnal flow.

Turbidity currents are one of the most important ways by which fine-grained (as well as medium- and coarse-grained) material is transferred from shallow to deep water — carried in a generally dilute turbulent suspension that is propelled by the downslope component of gravity. Much higher concentration flows also occur, which are capable of carrying sand and gravel grade material as well as large volumes of mud. For a good overview of turbidity current and related downslope processes, see Pickering, Hiscott, and Hein (1989), Pickering, Stow, Watson, and Hiscott (1986), Stow (1994) or Stow et al. (1996). Individual flows are discrete events with very variable recurrence intervals (10^0–10^5 y) and of very different sizes that can deposit beds from <1 cm to >10 m thick. Mean accumulation rates, therefore, are also very variable, typically from 10 cm to >1 m/ky (25 to >250 g/cm^2 ky).

Debris flows (mudflows) are high-concentration sediment–water mixes that can move very large amounts of material downslope in single (though often complex) events (Masson, Kenyon, & Weaver, 1996; Masson, van Niel, & Weaver, 1997). They move mainly by plastic flow as a thick slurry of fine cohesive matrix that can support much larger clasts (e.g. rock boulders, shale clasts, soft-sediment clasts). Individual deposits typically range from 1 to >50 m in thickness.

Slides and slumps are processes of mass gravity transport that can transport even larger volumes of sediment downslope as single events. They are very widespread on all deep marine slopes (Hampton, Lee, & Locat, 1997; Mulder & Cochonat, 1996).

Each of the processes summarized above is capable of depositing organic-rich sediments or otherwise influencing black shale sedimentation. They may operate singly or together (Fig. 1). Process interaction can occur sequentially by means of flow transformation, as in a slide becoming a slump, then a debris flow, a high- to low-concentration turbidity current and finally, a hemiturbiditic plume. Alternatively, several of the processes may operate at the same time, as in the numerous processes that together influence hemipelagic sedimentation.

2. Organic matter preservation

Whereas over 90% of the organic matter that enters the marine realm, either from terrigenous input or primary marine productivity, is destroyed by oxidation and bacterial degradation prior to its incorporation into the sediment, some is preserved (Huc, 1995). This preservation is due to several independent and interacting variables, the most important of which are the following (Fig. 2).

Organic matter supply: Where the rate of supply of organic matter through the water column to the sediment surface is sufficiently high that input outstrips degradation, then some will be preserved. This typically occurs beneath upwelling zones of high primary productivity, seaward of rivers that are carrying large amounts of organic detritus and/or nutrients, and in cases of rapid downslope resedimentation from organic-rich shelf sediments. Gallois (1976) put forward a *productivity model* for the Kimmeridge Clay black shales, invoking the repetition of phytoplankton blooms. Other authors favor enhanced supply of organic matter by turbidity currents (e.g. Dean, Arthur, & Stow, 1984).

Organic matter type: Depending on the genetic type of organic matter, the relative proportion of resistant biopolymers can be different. This can lead to enhanced preservation through the selective preservation model described by Derenne, Largeau, Casadevall, Berkalon, and Rousseau (1991).

Bottom-water anoxicity: Where the oxygen content of the bottom waters is extremely low or nil, then the rate of anaerobic bacterial degradation of organic matter is, at least, slightly retarded. More significantly, the lack of oxygen inhibits macro and meio benthic activity in favor of microbial activity. The consequent absence of (macro) burrowing decreases the amount of time organic matter

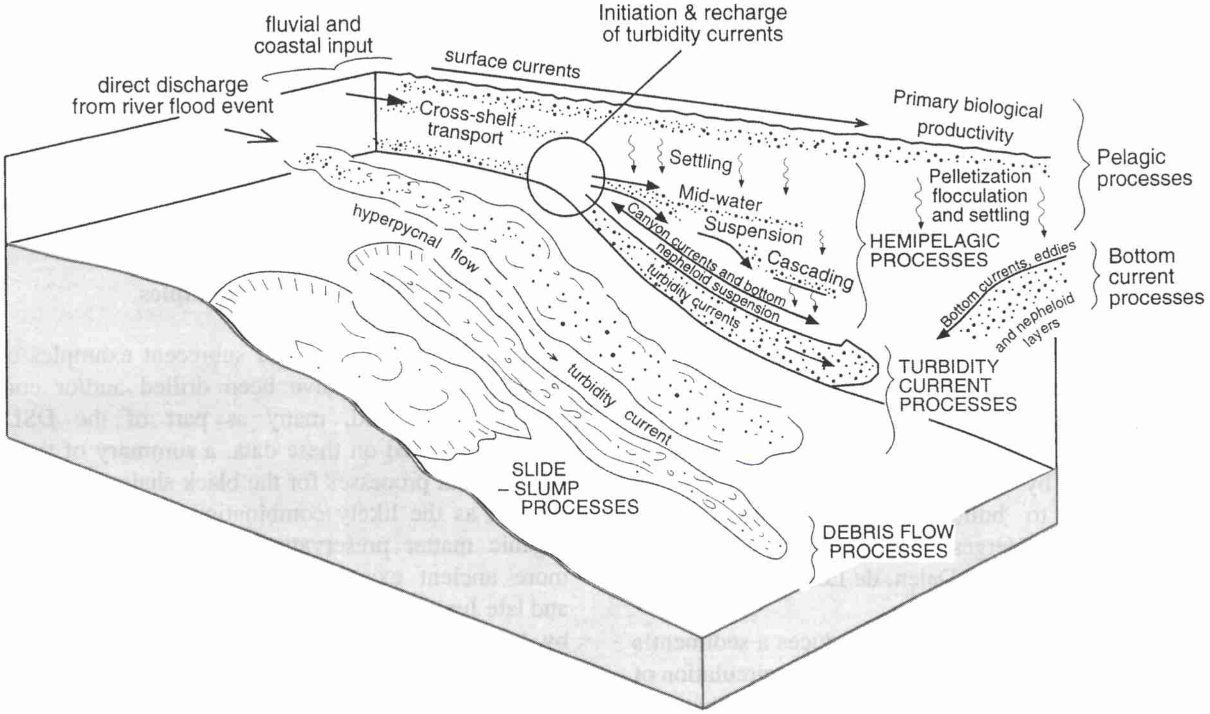

Fig. 1. The principal processes operating in the deep-water marine environment that affect the transport and deposition of sedimentary materials and organic matter in deep water (modified from Stow et al., 1996; Stow & Tabrez, 1998).

resides near the sediment surface in any of the oxidant zones, prevents deep-penetration pore-water circulation and inhibits gut microbial activity. Several oceanographic and topographic factors can conspire to reduce oxygen content, including topographic restriction of bottom-water circulation, elevated bottom-water temperatures and salinities, and increased organic matter supply. Numerous authors have recognized the importance of bottom-water anoxicity in a *preservation model* for black shales (e.g. Tyson, 1987; Miller, 1990; and review in Arthur, Dean, & Stow, 1984).

Rapid burial: High sedimentation rates lead to the rapid

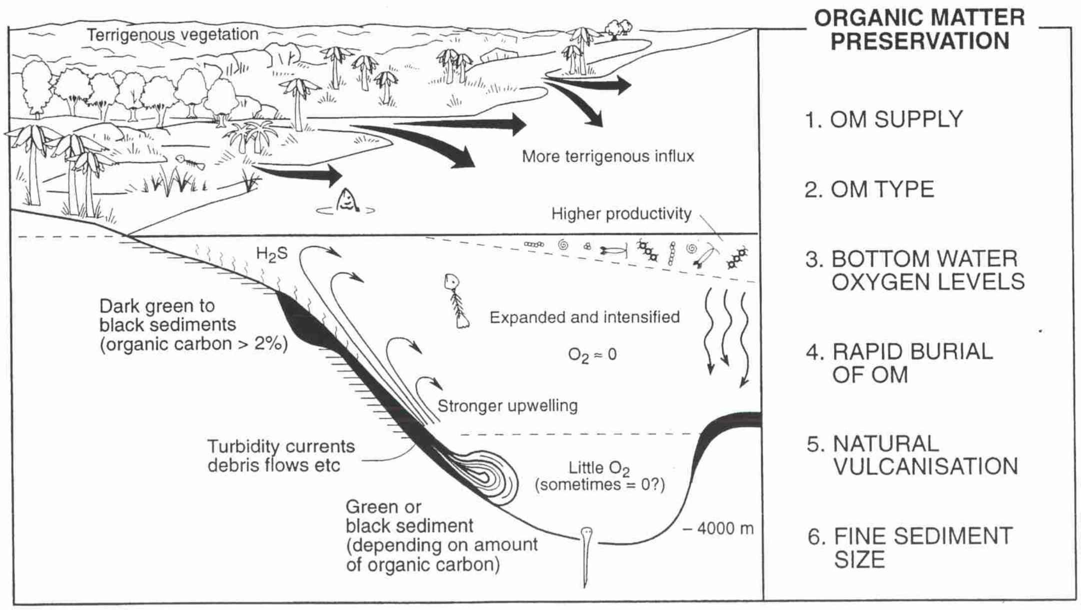

Fig. 2. Schematic illustration of the principal factors that affect the preservation of organic matter (OM) in the deep marine environment (modified from Arthur et al., 1984).

burial of any included organic matter and therefore quickly remove these organics both from the upper oxygenated part of the sediment column, where aerobic degradation is particularly aggressive, and from the underlying oxidant levels (i.e. nitrate and sulfate reducing zones). Such high rates are typical of rapid hemipelagic and hyperpycnal sedimentation, as well as of downslope resedimentation processes such as turbidity currents, debris flows and slides (e.g. Dean et al., 1984).

Natural vulcanization: In areas where a significant flux of metabolizable organic matter reaches the bottom, sulfate reduction can occur at or some centimeters below the sediment–water interface. This anaerobic process oxidizes organic matter using sulfate as oxidant. However, at the same time, it can favor organic matter preservation by releasing H_2S and by using this reduced sulfur to link biomolecules and to build vulcanized resistant geobiopolymers (Lallier-Vergès et al., 1996; Sinninghe-Damsté, Rijpstra, Kock-Van Dalen, de Leeuw, & Schenck, 1989).

Fine sediment size: Fine grain size reduces a sediment's permeability and hence inhibits the downward circulation of any oxygen-charged seawater. Organic matter that has survived to become incorporated into a fine-grained sediment thus has a greater chance of preservation than organic matter in, for example, sand or gravel grade sediment. Additionally, some organic matter is possibly preserved through adsorption on mineral surfaces (Keil, Montluçon, Prahl, & Hedges, 1994). The quantitative importance of such a process is still controversial (Ransom, Bennett, Baerwald, & Shea, 1997), but, if significant, it should be enhanced by fine sediment size.

Although some authors have favored one or other of these variables as the most important for any particular case study, most workers now accept that a complex combination of factors is the norm (e.g. Arthur et al., 1984; Ogg, Robertson, & Jansa, 1983; Stow, 1987; Wignall, 1994). Furthermore, black shales most commonly occur in cyclic alternation with non-organic-rich facies. In these instances, the environment may be poised at conditions close to those favoring preservation of organic matter (e.g. low-oxygen but not anoxic bottom waters), and then external factors periodically tip the balance in favor of preservation. Variations in climate (with Milankovitch cyclicity) can be one external factor (Bertrand, Lallier-Verges, & Boussafir, 1994; Hallam, 1987; Jacquin & de Graciansky, 1988; Oschmann, 1988); episodic turbidity current input can be another (Dean et al., 1984).

Because of the great variability in the depositional process, the proportion of any given section that comprises black shale facies, and in the factors that influence organic matter preservation, it is difficult to generalize about the rates of accumulation of organic matter in deep-water settings. Under conditions of slow pelagic/hemipelagic sedimentation in which bottom-water anoxicity was a principal cause of preservation, rates of TOC accumulation may average 0.025–0.075 g/cm^2 ky. Higher rates of sedimentation in higher productivity zones may yield TOC accumulation of 0.25–1.5 g/cm^2 ky. Rapidly deposited organic-rich turbidites can accumulate TOC at similar or even higher rates, up to about 3.5 g/cm^2 ky locally, although the average rates are very much dependent on turbidite thickness and frequency.

3. Deep-water black shales: examples

A number of modern and subrecent examples of deep-water black shales have been drilled and/or cored and extensively studied, many as part of the DSDP/ODP programs. Based on these data, a summary of the inferred depositional processes for the black shale facies recovered, as well as the likely combination of factors that favored organic matter preservation is given in Table 1. Other more ancient examples from Miocene, mid-Cretaceous and late Jurassic intervals worldwide have been summarized by Arthur et al. (1984), Brooks and Fleet (1987), Klemme and Ulmishek (1991), North (1979), and Wignall (1994). We have not considered Paleozoic black shales in this review (but see, for example, Thickpenny & Leggett, 1987).

Two examples of deep-water black shales from different settings are shown in Figs. 3 and 4. These serve to illustrate the range of TOC values to be expected in shallow to deep-water transects where a combination of factors favorable to organic matter preservation has been operative. Several important points can be derived from these various studies.

1. Black shale facies typically make up between 10 and 20% (more rarely up to 50%) of the succession in which they are present, and occur in cyclic alternation with the more dominant organic poor facies. The cycle period is different for different systems, but a Milankovitch signal has been noted in a number of examples.
2. The black shale depositional processes most commonly involved are pelagic settling, hemipelagic sedimentation and turbidity currents. Debris flows and slides are also noted in some cases, and hyperpycnal flood events seem likely to have influenced others. For any one location, and even for any single black shale interval, two or more of these processes may have contributed to deposition. In other cases, black shale deposition is controlled by a single process. Subtle sedimentary characteristics including lamination style, fabric type, organic content and distribution, primary sedimentary structures, bioturbational features, textural attributes, composition and color, can be used to determine the depositional processes involved.
3. In some cases the depositional process has been the key factor in organic matter preservation (e.g. turbidity current and debris flow input into the deep oxygenated Angola Basin during the Pliocene to Recent). In other cases, the black shale event is externally triggered and the

Table 1
Deep-water black shales: modern and subrecent examples

Walvis Ridge, SE Atlantic Ocean (DSDP Site 532)
Pliocene–Recent, open ocean, margin of Namibian upwelling zone, 1330 m water depth
Processes: hemipelagic, 2.5–8 cm/ky
Organics: marine OM, mean 4.5%, max. 8%, cyclicity 24 and 41 ky mean period
Preservation: upwelling, mid-water O-min, high productivity and supply, rapid burial

Angola Basin, SE Atlantic Ocean (DSDP Site 530B)
Pliocene–Recent, open-ocean basin adjacent to Walvis Ridge Site 532, 4600 m depth
Processes: black shales — turbidity currents, debris flows, slide-slumps; background — pelagic and hemipelagic; mean rate 2–3 cm/ky
Organics: marine OM, mean 3.5%, max. 6%, cyclicity 25 ky mean period
Preservation: high rate of organic matter supply and burial via downslope processes

Orca Basin, Gulf of Mexico (DSDP Site 618)
Pleistocene–Recent, inter-diapiric slope basin, 2400 m water depth
Processes: hemipelagic, turbidity currents and (?) muddy debris flows, 85–170 cm/ky
Organics: marine OM, (?) approx 1% (few data), no regular cyclicity
Preservation: high sedimentation rate and burial of OM, episodic anoxicity below brine layer

East Mediterranean Sea (DSDP Site 378, ODP Sites 964, 966, 967, 969)
Pliocene–Recent, partially silled marginal ocean basin, 600–4100 m water depths
Processes: mainly hemipelagic, some turbidity currents and rare debris flows, 1–20 cm/ky
Organics: mainly marine OM, >2%, max. 27%, sapropel (black shale) layers show overall mean periodicity of 40 ky, comprising intervals with approximately 25-ky cycles
Preservation: restricted circulation, high OM supply, episodic anoxicity

Black Sea (DSDP Sites 379, 380, 381)
Pleistocene–Recent, silled basin with strong salinity stratification, 200–2500 m depths
Processes: hemipelagic, turbidity currents
Organics: mainly marine, some terrestrial, max. 6%, irregular cyclicity
Preservation: restricted circulation, strong salinity stratification, episodic anoxicity

Oman margin, NW Indian Ocean (ODP Sites 723, 728, 730)
Pliocene–Recent, slope basins, 810–1430 m water depths
Processes: hemipelagic and pelagic, 3.5–17 cm/ky
Organics: marine OM, range <1–7% (max. 723), cyclicity 40–70-ky period
Preservation: upwelling zone, mid-water O-min, high productivity and supply

Peru margin, SE Pacific Ocean (ODP Sites 680B, 686B)
Pleistocene–Recent, shelf basins beneath upwelling zone, 250 and 450 m water depths
Processes: mainly hemipelagic, 6.6 (680) to 17.1 cm/ky (686)
Organics: mainly marine, some terrestrial OM, mean 3–5%, max. 12% (680), irregular cycle period — mean approximately 40 ky
Preservation: upwelling zone, mid-water O-min, high productivity and supply, rapid burial episodic anoxicity

Table 1 (*continued*)

Santa Barbara Basin, NE Pacific Ocean (ODP Site 893)
Pleistocene–Recent, shelf basin beneath upwelling zone, 580 m water depth
Processes: hemipelagic dominant, some turbidity currents and (?) hyperpycnal flood events, mean rate 120 cm/ky
Organics: marine and terrestrial OM, mean 1.8%, max. 5%, cyclicity 23 ky mean period, plus higher frequency signal
Preservation: upwelling zone, mid-water O-min, high productivity and supply, very high rates of sedimentation and OM burial, episodic anoxicity

Baja California Margin, E Pacific Ocean (DSDP Sites 474, 475, 476)
Pliocene–Recent, open slope setting within Gulf of California, 2400–3020 m depths
Processes: hemipelagic, turbidity currents, debris flows and slumps, 22.5 cm/ky mean rate
Organics: mainly marine, some terrestrial OM, mean 1.8%, max. 3.7%
Preservation: relatively high productivity and low oxygen values, rapid burial of OM

Guyamas Basin, E Pacific Ocean (DSDP Sites 477, 478, 481)
Pleistocene–Recent, silled narrow spreading basin, Gulf of California, 1900–2000 m depth
Processes: hemipelagic, turbidity currents, debris flows, slumps, 100 cm/ky mean rate
Organics: mixed marine and terrestrial OM, mean 1.6%, max. 3.6%
Preservation: relatively high productivity and low oxygen values, rapid burial of OM

Mexican Margin, E Pacific Ocean (DSDP Sites 479, 480)
Pleistocene–Recent, open-ocean slope setting beneath upwelling zone, 650–750 m depth
Processes: mainly hemipelagic, (?) hyperpycnal flood events, 38 cm/ky mean rate
Organics: mainly marine, some terrestrial OM, mean 2.5%, max. 3.8%
Preservation: upwelling zone, high productivity/supply, mid-water O-min, rapid burial

Makassar Strait, Indonesia (MISEDOR II Cruise, Site KS 12)
Late Quaternary, abyssal plain between Borneo and Celebes islands, 2229 m depth
Processes: turbidity currents, 27 cm/ky mean rate
Organics: terrestrial organic matter including macro and micro plant detritus, sometimes concentrated in organic-rich layers at the base of the turbiditic sequences, TOC range: 1–2%
Preservation: high rate of terrestrial organic supply by downslope processes

Japan Sea (ODP Sites 794, 795, 797, 798, 799)
Late Pliocene–Recent, semi-enclosed marginal sea, back arc basin, 900–3100 m depth
Processes: hemipelagic, turbidity currents, slumps and slides, 11–19 cm/ky
Organics: mainly marine, some terrestrial OM, range 1–7%, cyclicity at several distinct Milankovitch periods (including 100 and 41 ky) and at 10.5 ky
Preservation: restricted circulation leading to suboxic and anoxic conditions, some turbidity current input and rapid burial

depositional process only of secondary importance (e.g. Cretaceous black shales of the Angola Basin, or the mixed processes involved in deposition of eastern Mediterranean sapropels).

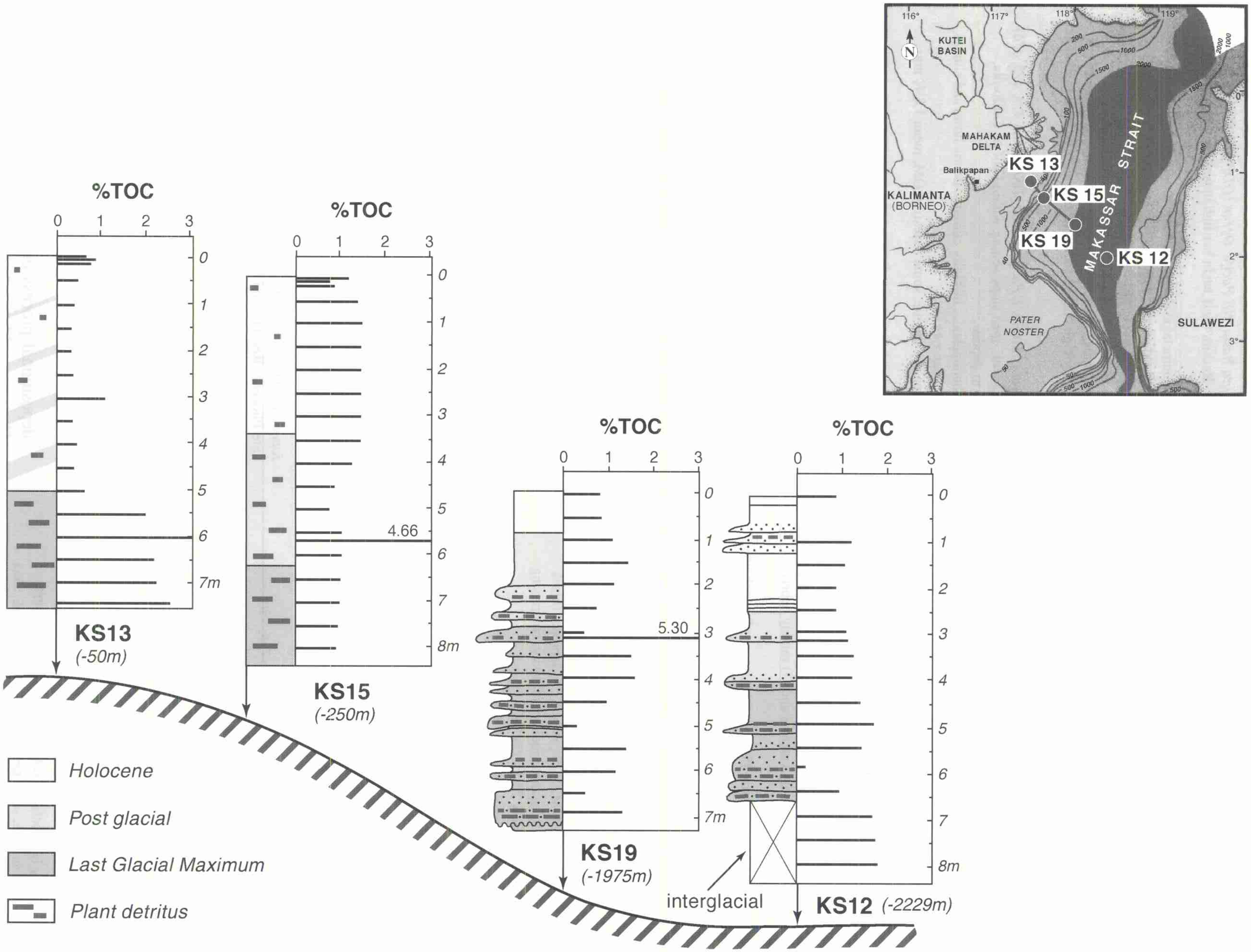

Fig. 3. An example of the variation in sediment facies and organic carbon content in piston cores recovered from a partial transect across the Makassar Strait, between Borneo and Sulawesi.

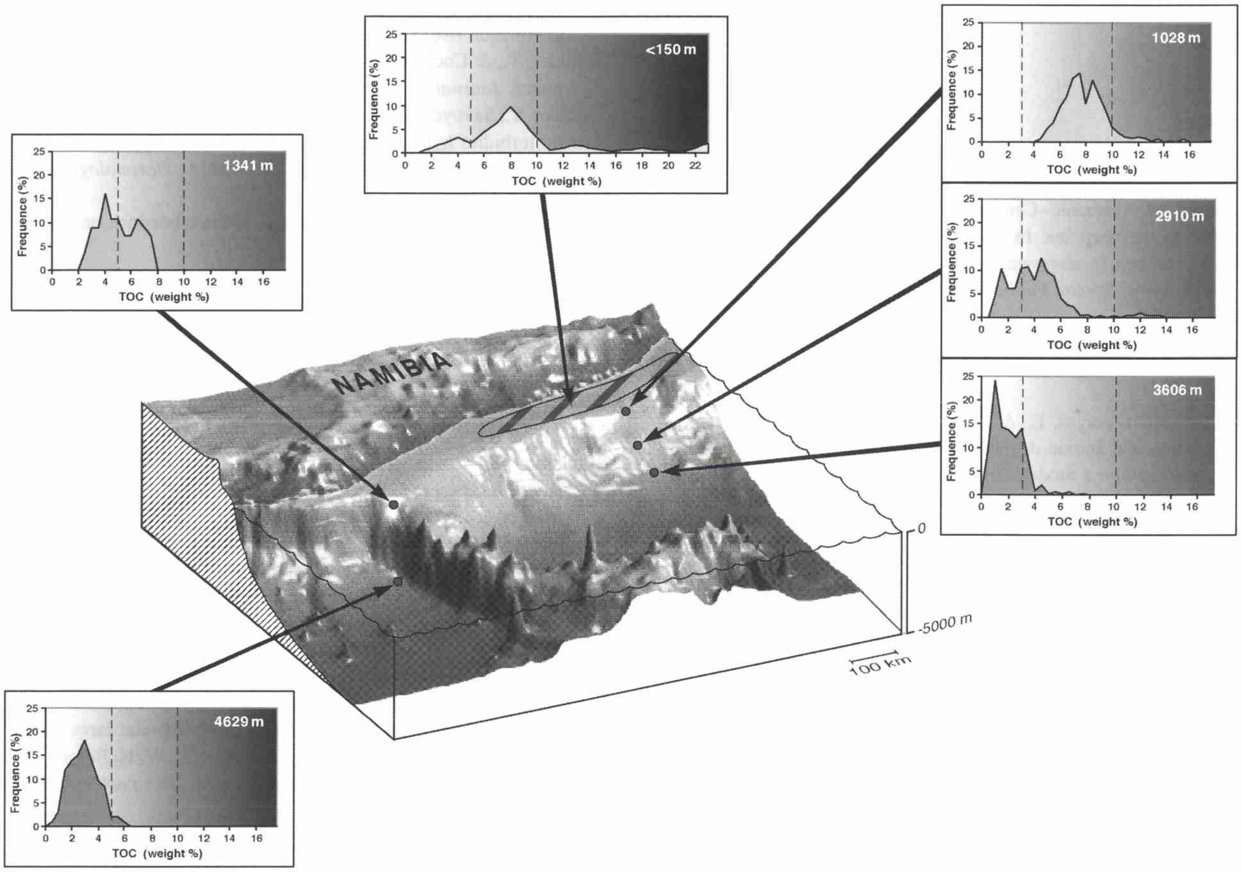

Fig. 4. Illustration of variation in total organic carbon (TOC) at various depths and locations on the Namibian continental margin.

4. A deep-water slope, basin or other setting in which bottom waters are poised at relatively low oxygen values is then highly susceptible to periodic black shale events. These events occur as the result of external factors, such as changes in climate, productivity or sediment input, tipping the balance in favor of anoxicity and organic matter preservation (Bertrand & Lallier-Verges, 1993; Bertrand et al., 1994).

4. Research directions

In the context of both basic research and hydrocarbon interests, the deep water is clearly a prime target as we move into the next century. Within the spectrum of deep-water issues and questions, the slope systems of continental margins must be our key concern for at least the next decade. This is clearly recognized in a number of national and international research programs that have been launched recently.

With respect to deep-water black shale source rocks in particular, the following topics must be addressed:

1. The nature, distribution and depositional processes of fine-grained sediments. Particular attention should be paid to the role of process in black shale origin, the importance of hyperpycnal flows and bottom currents, and the interaction of different processes.
2. Organic matter type and budget in different deep-water black shales, and the relationship of this to depositional process and setting, to the controlling factors and to the biotic framework.
3. External and internal controls on black shale deposition and preservation in deep water, and their influence on cycles and budgets. Particular attention should be paid to high-resolution stratigraphy and chronostratigraphy, and to correlation and distribution of black shale facies.

Significant advances in our understanding are most likely to be achieved by a research methodology that allows for a multidisciplinary approach to the problems, inter-laboratory as well as international cooperation, close liaison between the academic and industrial community and the full utilization of the very large databases that already exist within both sectors.

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