CHAPTER ELEVEN

Organic-rich Facies and Hydrocarbon Source Rocks

11.1 Introduction

Sequence stratigraphy provides a useful geological framework for considering the distribution of organic-rich facies (source-rocks*). It can allow a seismic, well or outcrop section to be subdivided into systems tracts in which the factors controlling source-rock deposition can be considered. Understanding the sequence stratigraphic context of a source-rock is necessary in order to predict its lateral extent and variability. However, it should be emphasized that source-rocks cannot be predicted from stratal geometries alone because there are too many variables involved (Fig. 11.1). This chapter first explores the controls on deposition of organic-rich facies and to what extent these can be predicted from sequence stratigraphic analysis. It then considers in detail the sequence stratigraphic context of coals and transgressive. marine black shales and concludes by describing stratigraphic models for organic-rich carbonate facies.

11.1.1 Controls on organic richness and source potential

Enhanced organic matter preservation is a function of many factors, the most important being the physiogeography of the basin, climate, terrestrial organic productivity, marine aquatic organic productivity, oceanic circulation, sedimentation rate and water depth (Fig. 11.1). A number of these factors clearly are not predictable from systems tract analysis alone, e.g. climate and oceanic circulation.

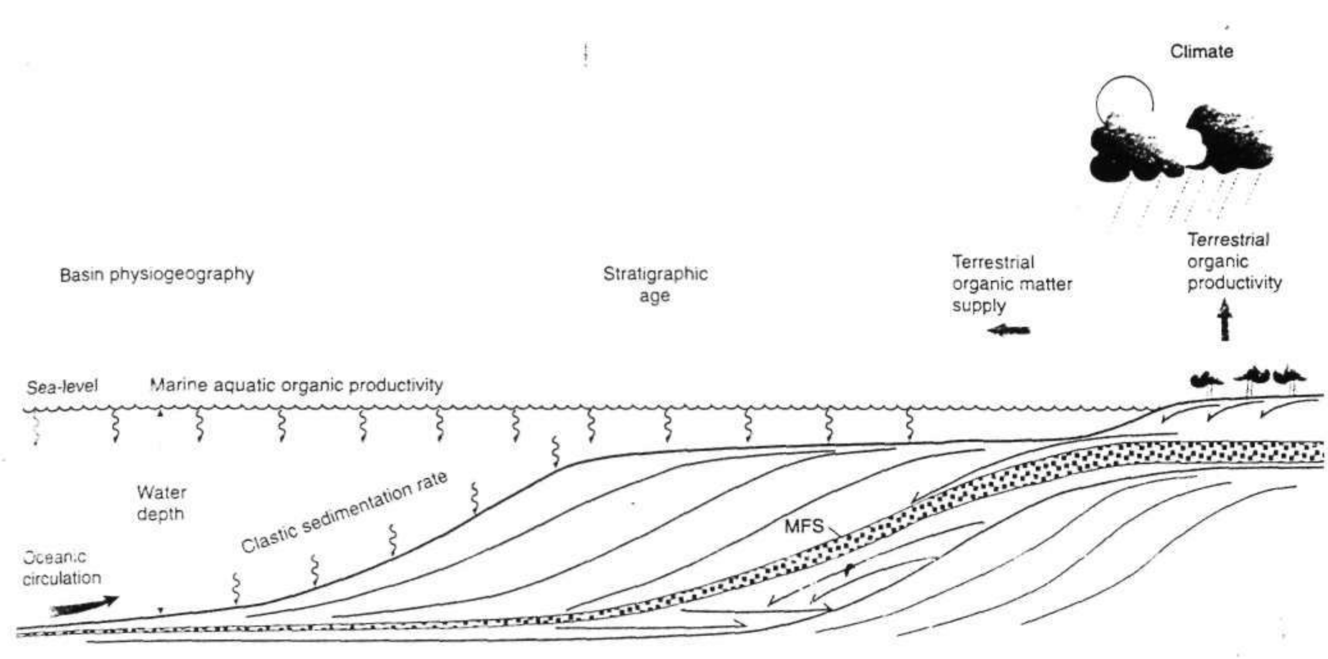
* An oil-prone source-rock comprises sediments that arc rich in organic carbon and contain organic material sufficiently hydrogen-rich to convert mainly to oil on maturation (Tissot *et al*., 1974).

Terrestrial organic productivity

Terrestrial organic productivity is a primary influence or the development of coals and coaly sediments deposited in coastal/delta-plain environments. McCabe (1984) considers that the potential for modern peat accumulation is a complex function of climate, which controls the balance between the rates of plant production and decay. Hot. humid climates favour plant production and cool climates favour plant preservation. The nature of the plant ecosystem has a strong influence on the type of organic matter preserved and hence the potential for oil- or gas-prone source-rock development (section 11.2.2).

Terrestrial organic matter supply

The rate of terrestrial organic matter supply to marine sediments is controlled principally by the nature of the floral ecosystem in the hinterland, the grain size of **the** sediment and the distance from the shoreline (Schlesinger and Mellack, 1981). Terrestrial organic productivity was negligible in pre-Devonian times and therefore little preserved in marine sediments. Terrestrial organic matter will, because of its low density and grain size, tend to be concentrated in the fine-grained mud and silt facies of the systems tract. Terrestrial organic matter supply rates will be highest in fine-grained sediments in close proximity to well-vegetated deltas. Swamp and marsh areas are particularly important sources of terrestrial organic matter. Supply decreases exponentially with increasing distance from the shoreline and increasing water depth. However, shelf-edge deltas potentially may deliver high terrestrial organic matter fluxes to the upper slope, and submarine canyons may **tap**



Fie. 11.1 The the organic: richness and source potential of sediments in clastic depositional systems. Note that most marine petroleum rocks were deposited under anoxic bottom water conditions. The development of anoxic conditions is controlled by the factors shown. Stippled zone highlights the transgressive systems tract. MFS, maximum flooding surface

sources of terrestrial organic matter in the coastal plain and transport it directly into deep water settings.

Primary productivity

Oil-prone kerogen in marine source-rocks originates predominantly from marine phytoplankton. The flux of alga! organic matter to marine sediments is a function of primary organic productivity in the photic zone and water depth Calvert, 1987; Schwartzkopf, 1993;. Zones of high organic productivity usually occur in the vicinity of continents. Zones of particularly high productivity are located in areas of coastal upwelling, where shore-parallel winds result in upwelling of nutrient-rich deep water. Modern upwelling areas are concentrated on the western margin of modern continents (Pelet, 1987). Note, however, that palaeoproductivity prediction in the geological record is difficult. Palaeoclimatic models can allow prediction of prevailing wind patterns and hence upwelling areas in the geological record. The accuracy of these predictions of upwelling areas is very variable (R. Miller, pers. comm.).

Water depth

The flux of carbon from surface productivity to bottom sediments is strongly influenced by water depth. Degradation and recycling of organic matter in the water column (whether oxic or anoxic) sharply reduces the carbon flux at shallow water depths. At 1000 m water depth, the carbon flux is < 10% of the value at 100m water depth (Suess, 1980; Betzer *et* a/., 1984). As a general rule-of-thumb, the supply of marine algal organic matter to bottom sediments is likely to decrease with increasing water depth and distance from the shoreline, owing to lower surface productivity and remineralization in the water column (Schwartzkopf, 1993).

Organic matter preservation

Aquatic organic matte: derived from phytoplankton- is the main precursor of oil-prone kerogen. Preservation of oil-prone organic matter in sediments is greatly enhanced under anoxic bottom-water conditions (Demaison and Moore, 1980) which develop where oxygen demand from decaying organic matter exceeds supply. Anoxic conditions result from restricted vertical circulation of sea-water and/ or high biological productivity.

Physiogeographic restriction helps limit the water column circulation, and hence the resupply of oxygen to bottom waters. It is a favourable element for predicting anoxic environments. Physiogeographic restriction may take several forms and occur at a variety of scales. Examples include classic silled or intra-shelf basins; geographically restricted oceanic basins, such as the Gulf of Mexico and Arctic basins in Cretaceous times; and geographically enclosed epeiric seaways, such as the Cretaceous Western Interior Seaway, USA, the Jurassic of the North Sea and the Holocene Black Sea.

Anoxia is used here to cover both truly anoxic and oxygen depleted, dysaerobic (< 0.5 ml oxygen) bottom-waters under which organic matter preservation is enhanced.

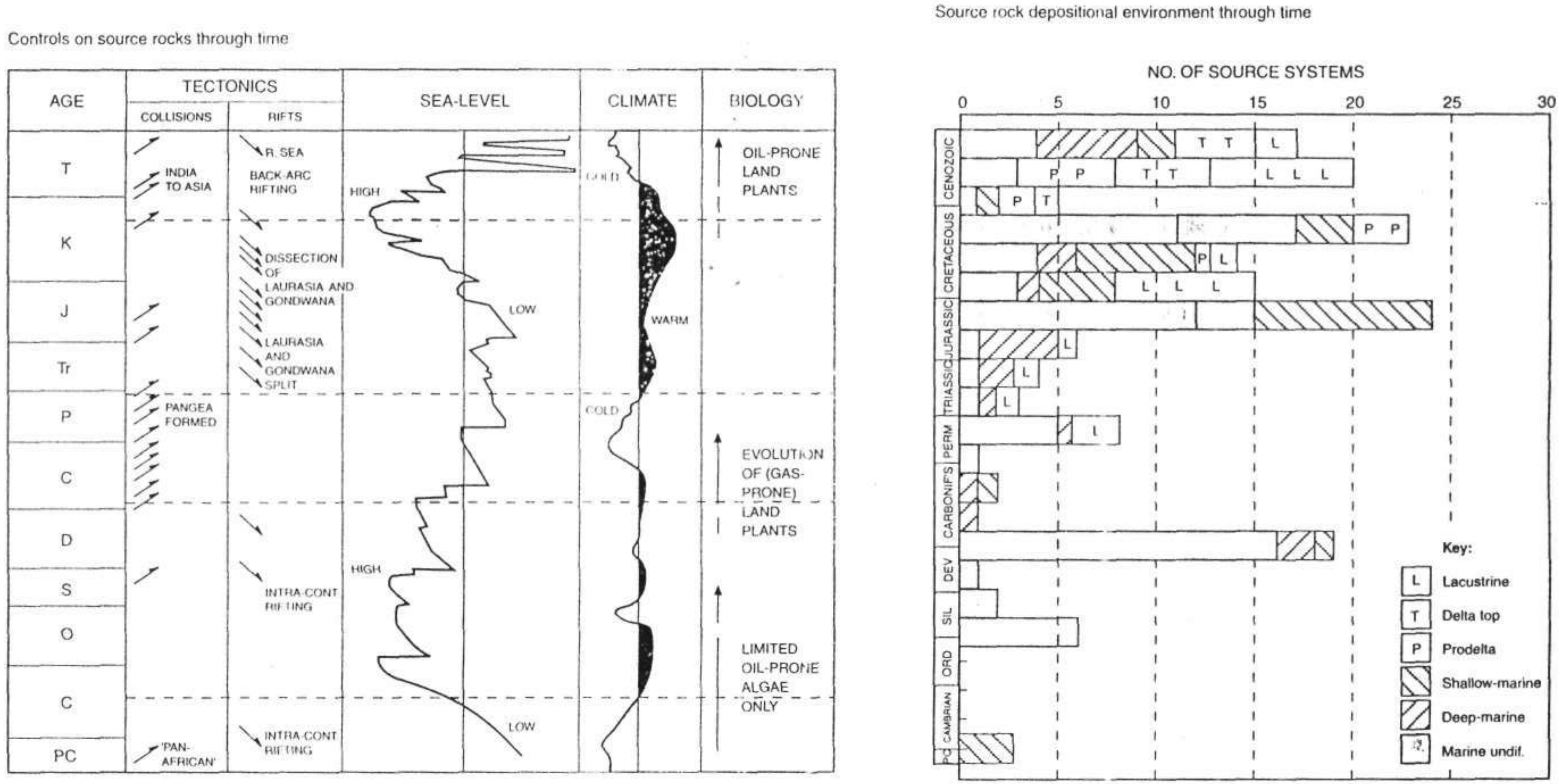


Fig. 11.2 The distribution of source rocks through geological time compiled from published literature and internal BP data bases. The column on the right contains source rocks that have been demonstrated to have generated a minimum of 500 million barrels of oil. These are classified into different environments of deposition. Peaks in marine source-rock deposition occur in the Late Devonian, Late Jurassic and Cretaceous, at times of continental break-up and rising first-order sea-level.

Water column stratification enhances the probability of anoxic conditions developing by inhibiting bottom-water replenishment. A positive water balance occurs where run-off from land and rainfall exceeds evaporation. A less dense freshwater cap forms over more saline marine water, and restricted circulation may lead to episodically anoxic conditions in basins of limited extent (see Fleet *et al.'s* (1987) discussion of the Lower Jurassic of Southern England). A negative water balance means that evaporation exceeds supply by runoff and rainfall. Dense saline water sinks to feed the bottom waters, which may become anoxic as oxigen is used by the degradation of organic matter. This is the model commonly used to explain anoxia in Jurassic-aged intrashelf basins in the Middle East (e.g. Droste, 1990). Stratification and hence anoxic conditions can persist only below the surface mixing layer, i.e. effectively below storm wave base. The surface mixing layer thickness varies with wind and tide energy in the basin, and usually is within the range 50-200 m.

Oceanic circulation

Water column oxygen profiles are key factors in predicting anoxic conditions and hence source potential in deep-water sediments of the continental slope and rise. In present-day oceans, the dissolved oxygen minimum is at depths of 100—1000 m because most oxidation of sinking organic matter occurs at these depths. However, at present the oxygen minimum is rarely sufficiently intense to give anoxic conditions and enhance organic matter preservation. Oxygen contents rise below the oxigen minimum zone because deep ocean water today is supplied by cold, oxygen-rich polar waters. The oxygen content of ocean bottom-water therefore decreases with increasing distance from [he poles. The oxygen minimum (and hence anoxic conditions) is presently most intense in areas of high surface productivity, i.e. upwelling areas. Where the oxygen minimum is intense, anoxic conditions may occur on the upper slope and outer continental shelf.

Although it is understood that oceanic circulation patterns must have changed dramatically through geological time, prediction of ancient water-column oxygen profiles is difficult. For example, at times of high global sea-level and mote extensive continental shelves, the oxygen minimum '-one may have covered large areas of the continental shelf. In an ice-free Earth, sources of deep water may have been die warm and saline waters from low latitudes rather than the present-day cold and less saline polar waters. This could have resulted in an expanded oxygen minimum zone 'Brass et *al.*, 1982). Palaeogeography is a pointer to past areas of intense oxygen minima. Intense minima seem to have occurred in physiogeographically restricted areas of the oceans, distant from the main body of the oceans (e.g. Cretaceous Arctic Ocean, Cretaceous Gulf of Mexico).

Sedimentation rate

Changes in sedimentation rate and, in particular, intervals of condensed sedimentation can be predicted from sequence stratigraphic analysis. It has been suggested that condensed sections are likely candidates for source-rock intervals (Loutit *et al.,* 1988). However, sedimentation can have either a positive or negative effect on organic carbon preservation (see review in Schwarzkopf, 1993). The relationship between organic preservation and sedimentation rate is complex because it is a delicate balance between enhanced preservation through rapid burial and dilution of organic matter by clastic material during rapid sedimentation (Schwartzkopf, 1993). Nevertheless, there are increasing numbers of case studies demonstrating the correlation between enhanced organic preservation and regional transgression and, in particular, anoxic condensed facies (Hallam and Bradshaw, 1979; Demaison and Moore, 1980; Jenkyns, 1980; Loutit *et al,* 1988; Leckie *et al.,* 1990; Palscy *et al.,* 1991; Creaney and Passey, 1993).

11.1.2 Source-rocks, tectonics and sea-level change

Figure 11.2 shows the distribution of the world's ma|or source rocks for oil through geological time (based on an in-house compilation). Certain plate tectonic configurations in the past were favourable for source-rock deposition. Peaks of marine source-rock development in late Devonian and in the Late Jurassic to Cretaceous coincide with continental break-up and peaks in extensional activity in the Wilson Cycle' of global plate tectonic movements. These periods also coincide with peaks in the first-order sea-level cycle.

The vast majority of source-rocks form in extensional tectonic settings, particulary, passive margins, and intra-cratonic and back-arc basins. A low in marine source-rock development occurs in the Permo-Carboniferous interval, at a time of predominantly contractual tectonic activity and widespread glaciation.

Note also the influence of stratigraphic age. Gas-prone, land-plant-derived, source rocks are present only since the Devonian. Delta top oil-prone source-rocks are restricted to the late Mesozoic and Cenozoic times, coincident with the evolution of the flowering angiosperms.

11.2 Delta/coastal plain organic-rich facies and source rocks

11.2.1 Sequence stratigraphic significance of coals

Coals can form in a variety of basin settings. For example. Tertiary coals in southeast Asia formed predominantly in extensional basins, whereas the widespread Upper Cretaceous coal deposits in western USA formed in a foreland basin setting. Autochthonous coals are an important component of delta/coastal plain deposits because they represent vertical accumulation of sediment and hence pure aggradation of the delta/coastal plain. Controls on coal formation are many and varied, but given favourable factors, such as a hot and wet climate, a stable, high groundwater table and no clastic influx to the peat forming mire, coals can accumulate rapidly on the delta/coastal plain (McCabe, 1984). Recently, it has been proposed that coals can be used for regional correlation in non-marine basins (Hamilton and Tadros, 1994).

Peat accumulation rates in modern Arctic climates are very slow compared with modern tropical climates, where rates of 2.5 m per 1000 years are typical and where rates up to 5 m per 1000 years have been recorded (Fig. 11.3). In ancient coal deposits it is worth considering the time required for the accumulation of thick coals. After allowing for compaction, a 3 m coal seam deposited at 1.8 m per 1000 years may have required favourable conditions to persist for perhaps 16 000 years. Rates of coal accumulation therefore can be rapid but ultimately are limited by the rate of base level (relative sea-level) rise. Modern coal swamps are unlikely to be able to keep pace with the most rapid rates of Holocene eustatic sea-level rise of 20 m per 1000 years (Fairbanks, 1989).

Coals accumulate at or close to base level, and it follows that for a thick coal to accumulate, aggradation of the delta/coastal plain must occur. In other words, the rate of coal accumulation and the rate of creation of sediment accommodation must balance. In addition the coal swamp must be effectively sheltered from clastic input in order for low-ash coals to accumulate. It is suggested that the development of raised mires on the coastal plain is necessary for this to occur (e.g. McCabe and Shanley, 1993). Raised mires occur where the build-up of waterlogged peat elevates the surface of the mire above regional ground-water tables. In southeast Asia, raised mires tens of kilometres across can be elevated up to 7 m above adjacent flood plains (Cameron *et al.*, 1989).

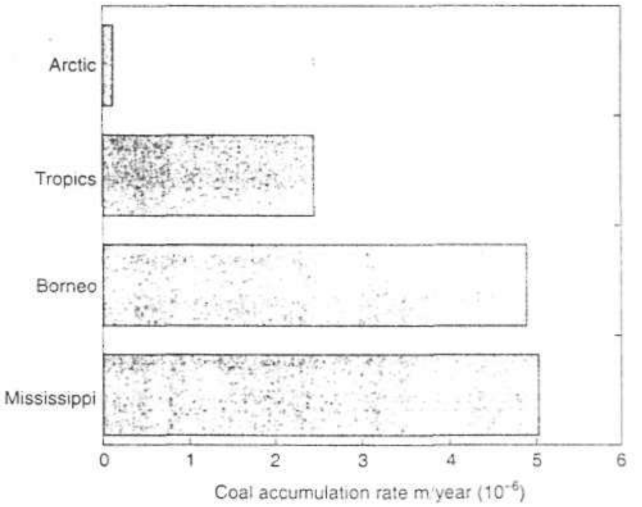


Fig. 11.3 Modern coal (peat) accumulation rates in different geographical settings

The development of coals during progradation and abandonment of a delta lobe will now be considered (Fig. 11.4 Coals can form in local depocentres on the delta plain during active delta progradation. These coals are likely to be thin owing to low delta-plain aggradation rates, are discontinuous owing to erosion by active alluvial channels and dilution by clastic sediment. Thick regionally extensive coals are more likely to form during abandonment of the delta lobe. The abandoned delta lobe will subside at a rate governed by subsidence and eustasy. If the abandonment phase persists, sediment starvation can ensue and a thick coal may accumulate. Eventually, either through a drop coal accu sea-level rise, the delta plain is flooded by transgressive marine sediments and the cycle begins again.

Workers in the Cretaceous Western Interior Seaway USA have related the stratigraphic position of coals to parasequence stacking patterns (Ryer, 1984; Levey, 1988 Cross, 1988; Shanley and McCabe, 1993). Coals developed in coastal plain mires extending several tens of kilometres landward of coeval shorelines (Fig. 11.5). Coals are thicker, landward of aggradational parasequence sets, i.e. when the shoreline stacks vertically. Coals associated with basin ward and landward stepping parasequences are thinner (Cross, 1988). Ryer (1984) specifically relates the larger coal fields in Utah with extensive aggradational stacking parasequences (fourth-order cycles) developed at the transgressive and regressive maxima of third-order cycles. The inference from these observations is that thick coals correlate with ever, the fact that coals can form up to 45% of the coastal plain succession in these deposits, and that low-ash coal accumulate only 4 km from a clastic shoreline, require further thought. Shanley and McCabe (1993' suggest that the formation of raised mires in the coastal plain stabilize the shore rise, inhibiting transgression and encouraging vertical stack ing of facies belts in much the same way as a carbonate platform margin might behave (Chapter 10).

11.2.2 Geochemistry of delta plain organic-rich facies

The controls on the oil- or gas-prone nature of organic-rich delta/coastal plain sequences are still debated. It is known that some late Cretaceous and Tertiary delta/coastal plain source-rocks have sourced significant quantities of oil, can oil-pr This is a complex subject for which generalized rules-of thumb can sometimes be misleading (Fig. 11.6).

Oil-prone terrigenous kerogen is derived from pla- cuticles and resins. It is thought that only in post-Jurassic times have plants had sufficient foliage to yield significant amounts of oil-prone kerogen (there is uncertainty of late Triassi plants would yield gas-prone kerogen.

Hot, wet climates are conducive to the production

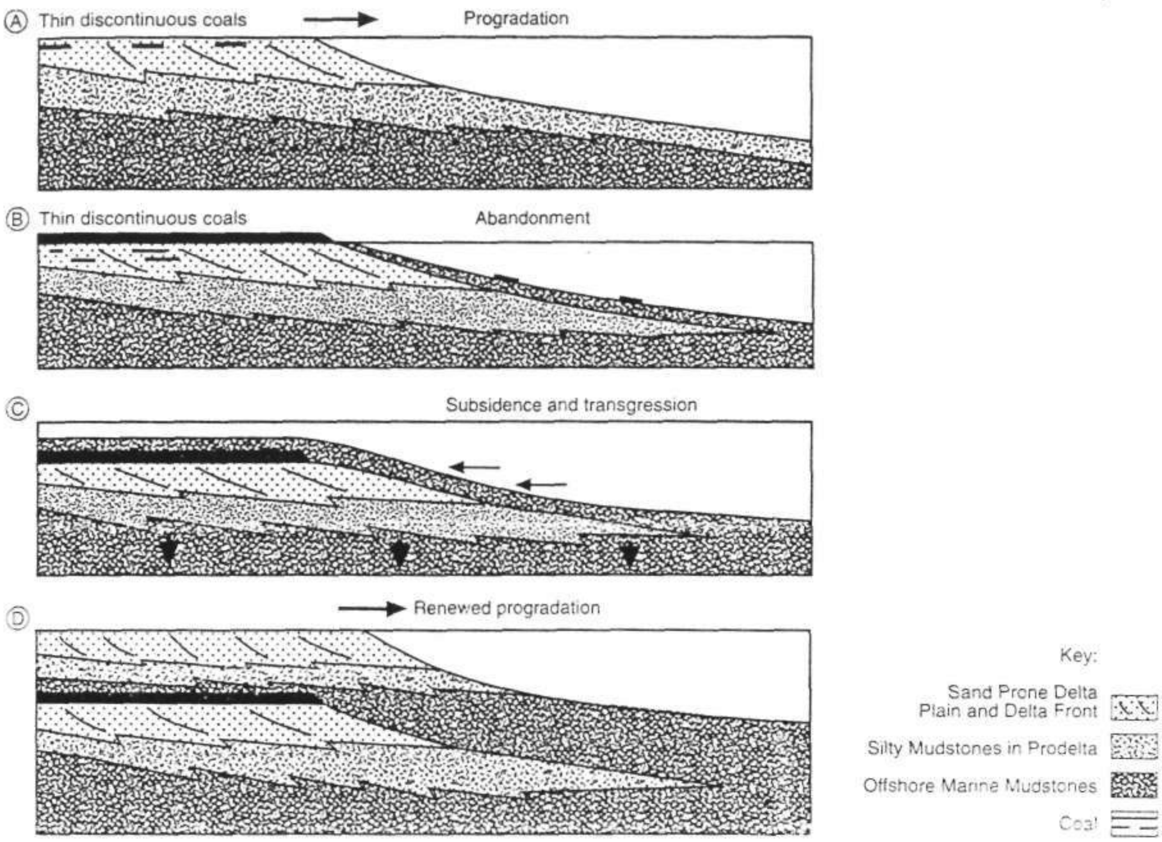


Fig. 11.4 Cartoons illustrating coal formation during progradation and abandonment of a delta lobe (after Allen and Mercier, 1988)

high foliage : wood ratio plant communities with potentially high yields of oil-prone kerogen. Cool, wet climates with gymnosperm (coniferous) dominated plant communities have yielded prolific resiniferous oil-prone kerogen in some Cretaceous delta/coastal plains in Australasia. Dry climates result in predominantly gas-prone kerogen.

Preservation of oil-prone terrigenous kerogen is thought to be enhanced in the brackish to saline conditions of the lower delta/coastal plain. Upper delta-plain (freshwater influenced) coals and coaly sediments are considered mainly to be gas-prone.

It sometimes may be possible to map coal distributions using techniques such as seismic attribute and seismic Abies analysis given well calibration. However, the prediction of relative oil- or gas-prone potential of delta/coastal plain sediments in a seismic package is very difficult, if not impossible. Firstly, the differentiation of lower and upper delta plain settings within the top sets of a seismic sequence is unlikely. Secondly, the relative oil- and gas-prone potential of coals can vary laterally both within and between individual coal seams. Finally, there is presently no con--ensus over the relative potential of coals and associated carbonaceous shales.

11.3 Organic-rich fades and systems tracts in clastic systems

The following section attempts to integrate some of the controls on clastic source-rock development described earlier within a sequence stratigraphic framework. Source-rock development is discussed within a series of systems tracts developed during a cycle of changing relative sea-level. The systems tract block diagrams are adapted from those published by Posamentier and Vail (1988).

11.3.1 Lowstand systems tract

Significant coal accumulation on the coastal plain is unlikely in the early lowstand systems tract and terrestrial organic matter is likely to be highly oxidized. The shelf and upper slope are considered to be zones of sediment bypass and hence source potential there is negligible (Fig. 11.7). Terrestrial organic matter supply is limited to locally reworked material in basinal fan deposits. If anoxic conditions persist in the basin a condensed basinal source-rock facies may occur away from the sediment entry points. The lowstand prograding wedge has some potential for coal development during the aggradational phase but the areal extent of the

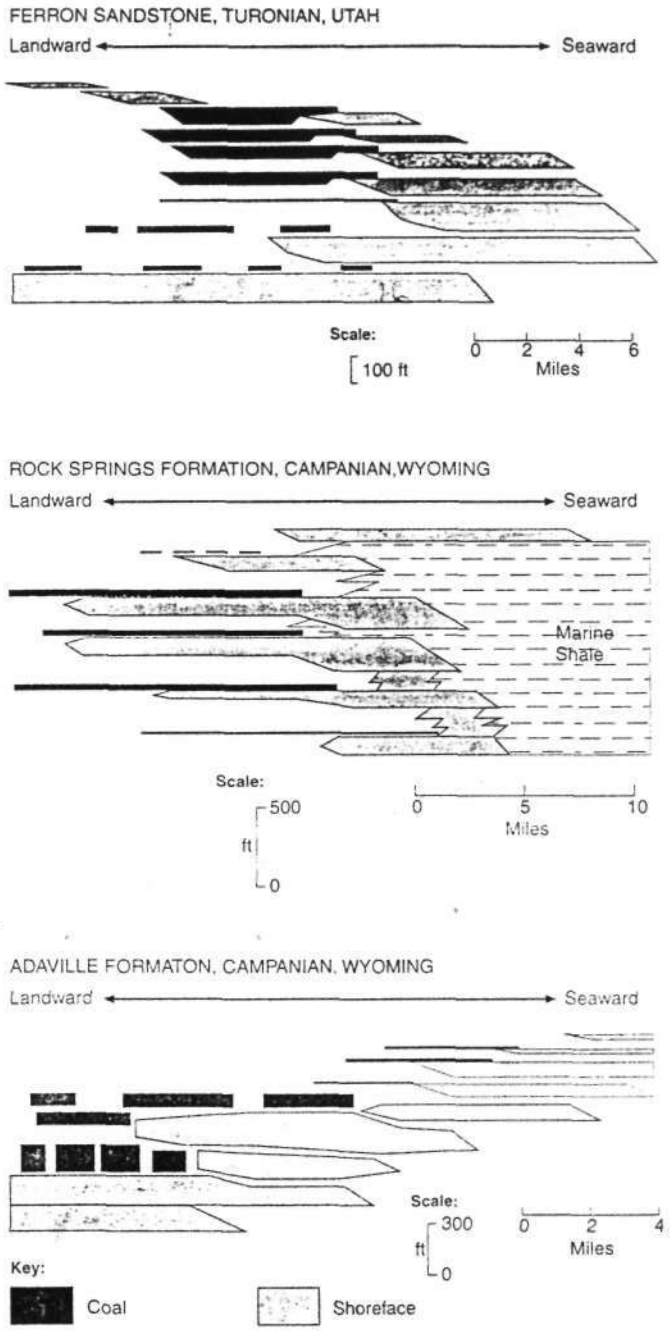


Fig. 11.5 Diagrammatic cross-sections illustrating the distribution of coal relative to the position of the shoreline in different srratigraphic intervals of the Cretaceous, Western Interior Seaway, USA. Shorelines steppingbasinward indicate progradation, whereas shorelines stacking vertically indicate aggradation and shorelines stepping landward indicate retrogradation (from Cross, 1988)

organic-rich facies will be restricted to the incised valleys and associated canyons. Marine organic-rich slope and basinal facies are unlikely owing to the rapid sedimentation rates. Although marine source-rocks could occur, overall this appears to be the least prospective systems tract for source-rock development.

11.3.2 Transgressive systems tract

This is the most important systems tract for the development of marine oil-prone source rocks. Many authors have noted the correlation between the occurrence of organic rich facies and regional transgression (Hallam and Bradshow 1979; Demaison and Moore, 1980; Jenkyns, 1980; Loutit *et al.*, 1988; and see Fig. 11.2). However, not all transgress systems tracts result in deposition of organic-rich facil The link is complex and is explored in some detail in this section.

General features of the transgressive systems tract

In the transgressive systems tract the shoreline retret landward, resulting in a progressive increase in the geo graphical extent of shallow-marine shelf deposition, reaching a maximum at the maximum flooding surface. Increasing distance from the contemporary shoreline results in reduced clastic sediment supply and reduced terrestrial organic matter supply to the outer shelf and slope. Very low sedimentation rates on the shelf and slope can result in deposition of a condensed facies (Fig. 11.8).

However, reduced sedimentation rates alone will not result in deposition of organic rich facies. Enhanced preser vation of organic matter in poorly oxygenated benthic environments is a common characteristic of transgressive black shales (e.g. Demaison and Moore, 1980; Oschman 1988; Miller, 1990; Wignall, 1991a,b). Shallow water depths on the shelf result in high organic fluxes and therefore high oxygen demand. The higher the surface productivity, the higher is oxygen demand in the bottom waters. In the surface mixing layer above storm wave bars storms and tidal currents can effectively mix the water column and reoxygenate the bottom waters. It follows the sediment -water interface will have to remain below the surface mixing layer for oxygen deficient/depleted conditions to persist for significant periods of time. The depth (H) will vary depending on storm and tide energy For example, *H* may be shallower on wide shelves compared with narrow shelves owing to reduced tidal and wave activity (Hallam and Bradshaw, 1980). Development *of* stratified water column and physiogeographic restriction will increase the chances of anoxic conditions and organic-rich facies development during transgression.

Models for source-rock development

In the model shown (Fig. 11.9), the basin is permanent anoxic below a certain water depth, marking the base of the surface mixing layer. A distal deep-water, relatively condensed, source-rock facies occurs in an anoxic basin centre in the distal toe-sets of both lowstand and highstand systems tracts, which would be manifested as a downlap surface on seismic sections. The transgressive systems tract results in landward translation of this facies belt until

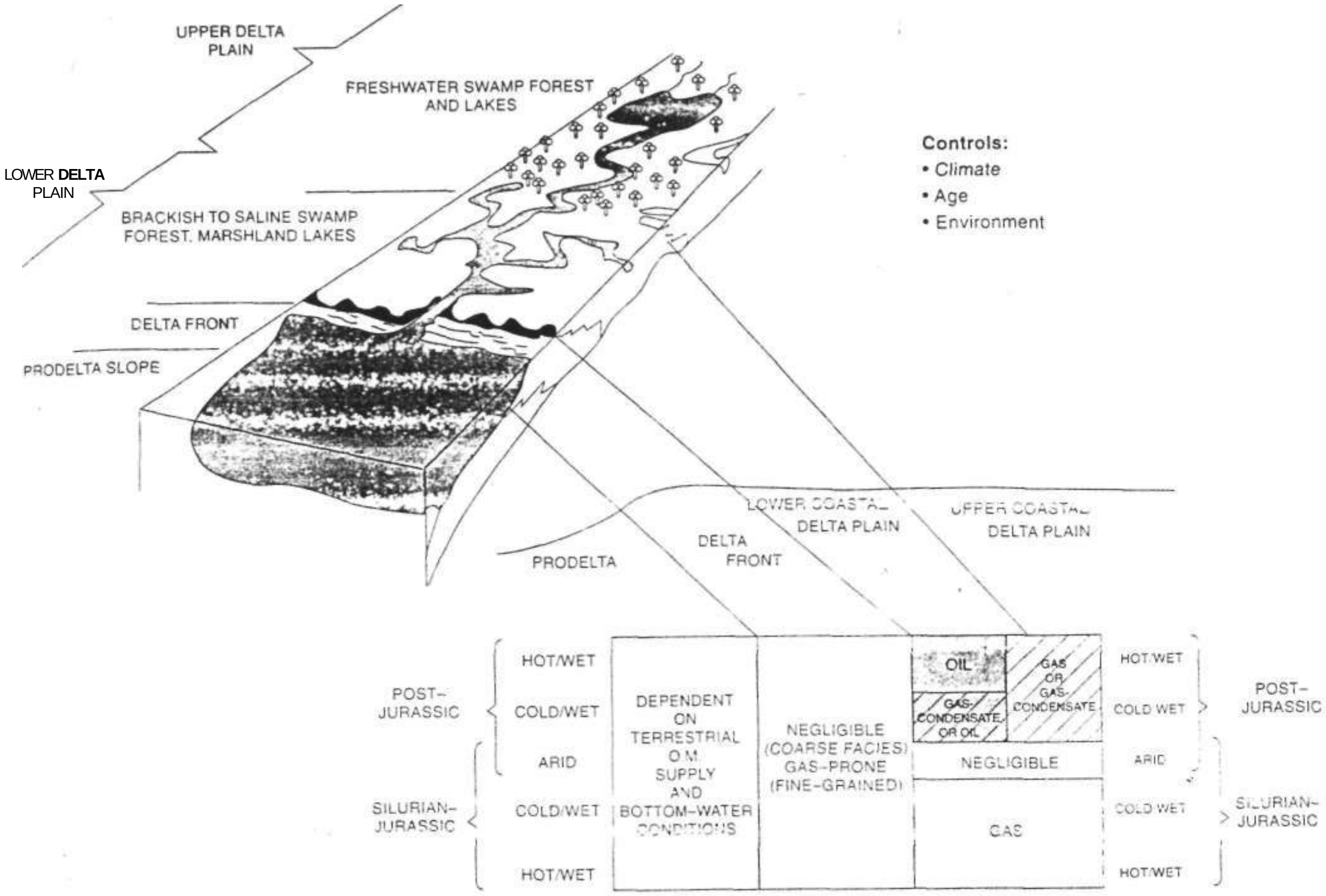
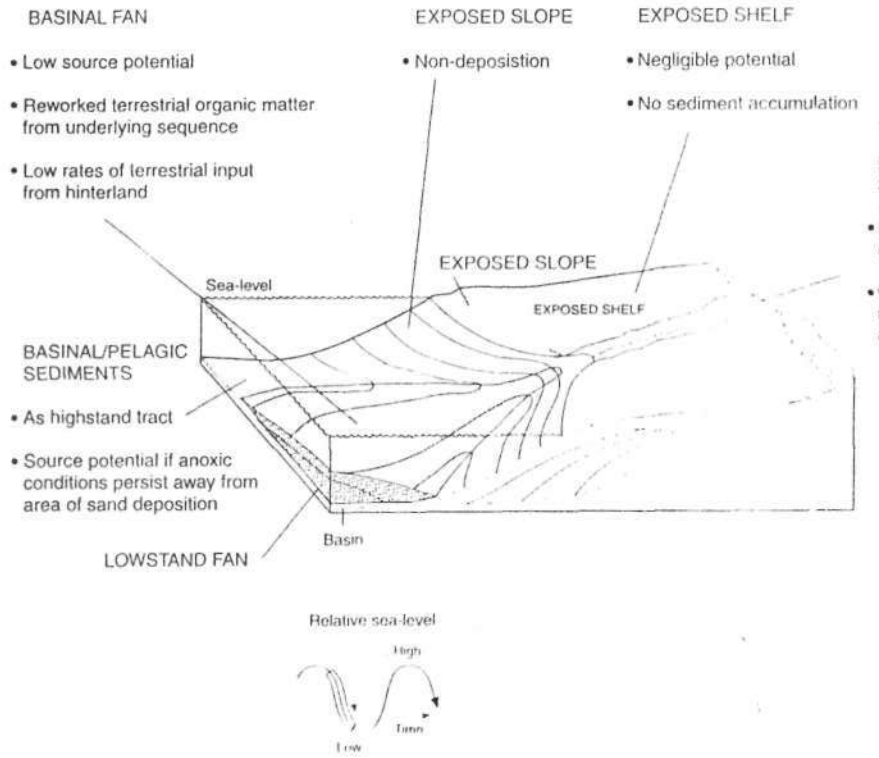


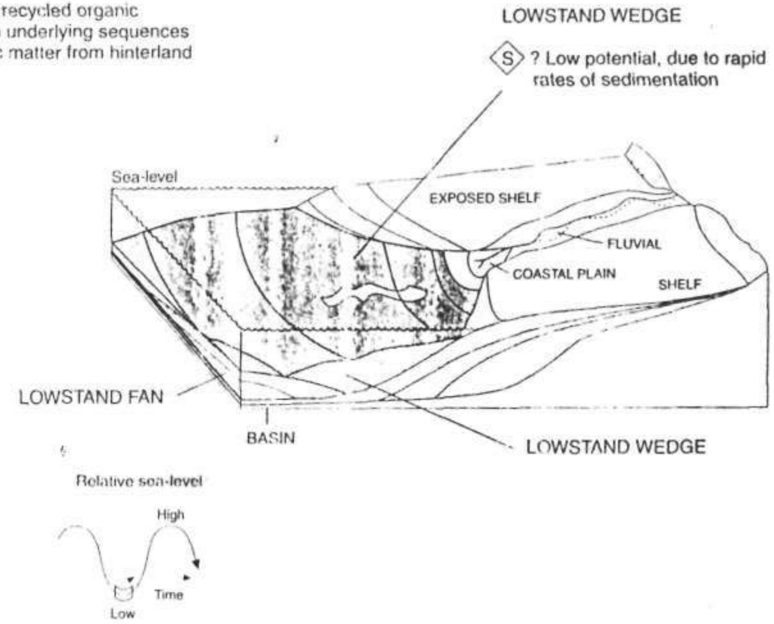
Fig. 11.6 Cartoon illustrating different types of source-rock setting on a typical modern delta plain from southeast Asia (based on the Klang Delta). Lower delta-plain environments are thought to he areas where the preservation of oil-prone (organic matter likely to generate oil) is enhanced in brackish alkaline environments. Hot humid climatic regimes in the post-Cretaceous era are the most favourable for generating high foliage-to-wood ratio plant communities, which, given favourable preservation, can result in deposition of oil-prone coal source rocks

deeper water condensed source-rock facies impinges on the transgressed shelf. In this model the greatest extent of source-rock facies will coincide with the time of maximum flooding. During subsequent highstand progradation, water depths decrease and the area of source-rock deposition gradually shrinks. Thus source rocks are not restricted to a particular systems tract but expand to a maximum during the transgressive systems tract. This model is similar to the 'expanding puddle'model of Wignall (1991a), derived from the study of black shale deposits in epicontinental shelf seas Tig. 11.10). It is less applicable to passive continental margins, where the deep ocean may be well-oxygenated.

Wireline logs are particularly useful in characterizing source rocks (Passey *et a!.,* 1990; Myers and Jenkyns, 1992). Creaney and Passey (1993) noted that many marine oil-prone source rocks are characterized by an initially abrupt upward increase in organic richness, against back-ground values, and a subsequent gradual decrease in rich-ness (Fig. 11.11). They attributed this pattern to the control of organic carbon contents by clastic sedimentation rate under anoxic bottom water conditions. The initially rapid increase in TOC total organic carbon) results from a rapid decrease in the rate of clastic sediment supply to the shelf during transgression. The subsequent gradual decrease in TOC reflects increasing clastic sediment supply and dilution of organic carbon during highstand progradation. In this model, the source interval would thicken from the basin margin into a series of stacked source intervals in the basin centre. Wignall (1991a) interprets the Toarcian black shales of England to be of this type.

An alternative model is where the anoxic conditions develop only in the transgressive systems tract itself (Fig. 11.12). Basinal areas will have interbedded source facies deposited in the TST, with non-source facies deposited in the HST and LST. Shelfal source-rocks are restricted to the TST. This model implies that the palaeogeographic con-ditions necessary for anoxia to develop are unique to the transgressive systems tract. Leckie *et al.* (1990) document an example from the Cretaceous Shaftsbury Formation of Canada, where a nearshore organic-rich zone deposited during rapid transgression passes basinward to more nor-mally oxygenated sediments. In this case, a nearshore zone


BASINAL FAN
• Low source potential
• Reworked terrestrial organic matter from underlying sequence
• Low rates of terrestrial input from hinterland
EXPOSED SLOPE
• Non-deposistion
EXPOSED SHELF
• Negligible potential
• No sediment accumulation
INCISED FLUVIAL SYSTEM
• Erosion of underlying coastal plain
• Conduit for recycled organic matter from underlying sequences and organic matter from hinterland
Sea-level
EXPOSED SLOPE
EXPOSED SHELF
BASINAL/PELAGIC SEDIMENTS
• As highstand tract
• Source potential if anoxic conditions persist away from area of sand deposition
Basin
LOWSTAND FAN
Relative sea-level
High
Time
Low


LOWSTAND WEDGE
S ? Low potential, due to rapid rates of sedimentation
Sea-level
EXPOSED SHELF
FLUVIAL
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BASIN
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Relative sea-level
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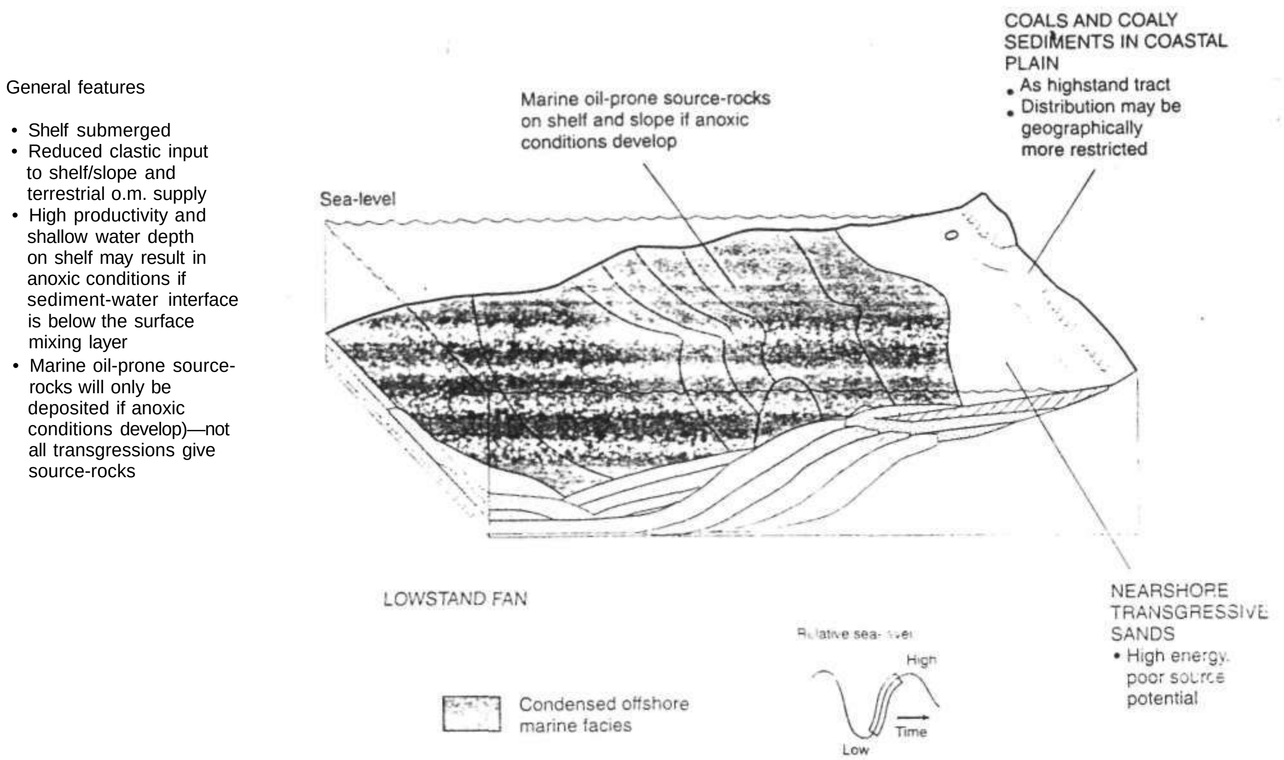


Fig. 11.8 Schematic cartoon of a transgressive systems tract on a shelf-break margin adapted to show the potential for organic-rich facies development after Posamentier and Vail, 1988)

of high productivity is assumed to be localized in the transgressive systems tract.

It should be clear from the above that although there is a general relationship between source rocks and transgression, the stratigraphy of organic facies is complex in detail. This complexity is shown by the work of Curiale *ct al.* (1991) and Palscy *ct al. 1991*' in the Cretaceous Western Interior Seaway. Curiale *c:* .. .199 1 show maximum organic richness occurring in the early highstand systems tract *above* the condensed section associated with maximum flooding in the Cenomanian—Turonian interval they studied. Palsey *et al.* (1991), in contrast, show that in the overlying Coniacian strata, maximum organic richness occurs in the transgressive systems tract below the condensed section associated with maximum flooding.

Organic richness will vary from the proximal to distal portions of the systems tract and should not be considered to he uniform. A common problem tor the petroleum geologist is to extrapolate a source-rock proven in the shelfal portion of a transgressive systems tract into the

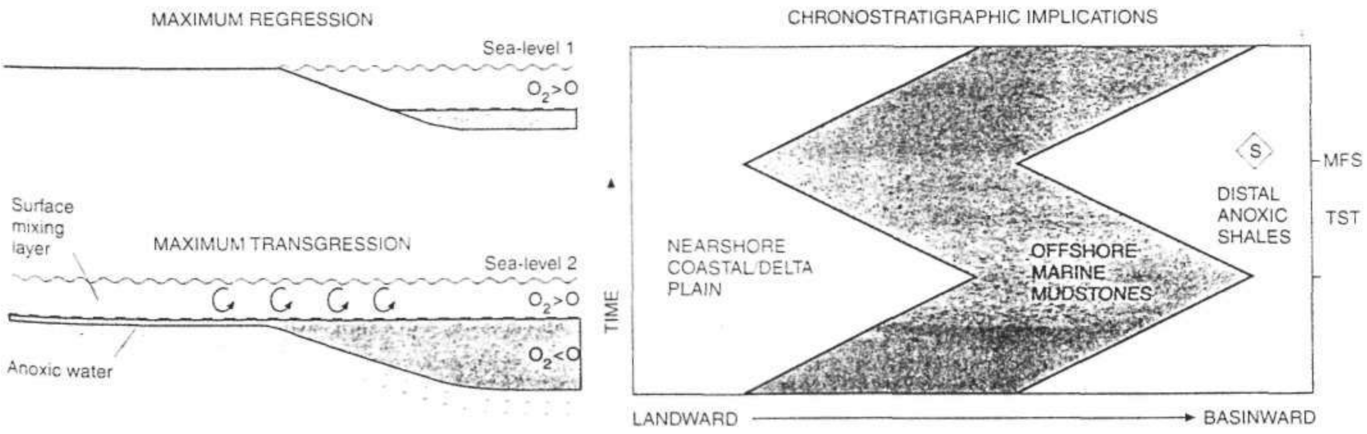


Fig. 11.9 Chronostrangraphic implications of a source-rock model where organic-rich rocks are developed in a distal facies in the basin at times of both maximum transgression and regression. Transgression serves only to spread the area covered by organic-rich facies landward. MFS, maximum flooding surface; TST, transgressive systems tract

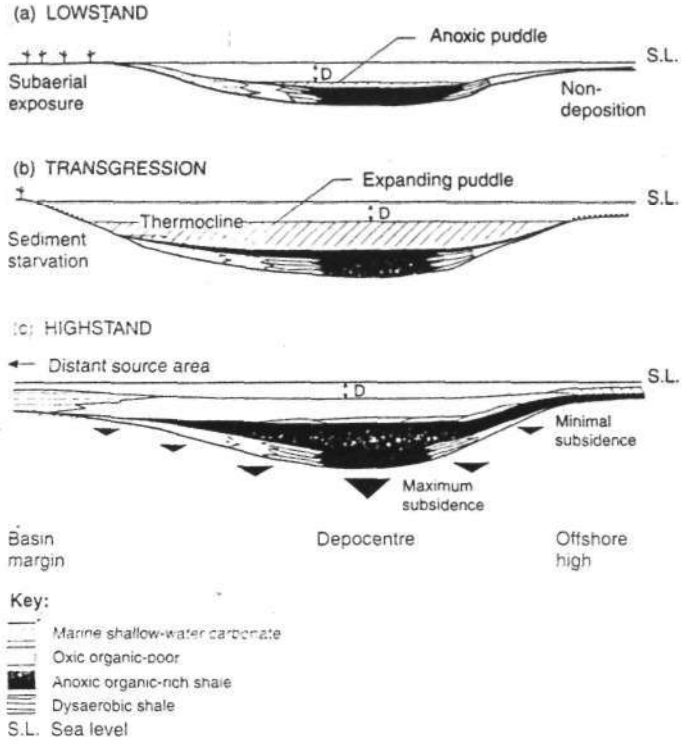


Fig. 11.10 The expanding puddle model proposed by Wignall (199la) to explain the distribution of Lower Toarcian organic-rich fades in a shallow epeiric basin. D is the depth of the surface mixing layer below which anoxic bottom waters are trapped, (a) During lowstand organic facies accumulate only in the basin depocentres. *(b)* A combination of sediment starvation, sea-level rise and continuing subsidence during transgression causes marked expansion in the area of deep water and thus the areal extent of organic-rich facies deposition, (c) During highstand, progradation results in shallowing of the water column and a shrinkage in the area of organic-rich facies

basin. The first question to consider is whether anoxia is developed in the basin as well as on the shelf. Figure 1 1.13 shows models where (i) anoxia develops on both the shelf and in the basin, (ii) anoxia and source rocks develop on the slope and basin but not on the shelf, and (iii) high productivity and source rocks develop on the shelf but not in the basin. Many other permutations are possible.

The thickness of the anoxic organic-rich interval will be a function of sedimentation rate and the duration of the interval. Richness of the anoxic organic-rich interval (if only marine aquatic organic matter is considered) will be a function of surface productivity, water depth, sedimentation rate and bottom-water oxygenation.

11.3.3 Highstand systems tract

Thick coastal plain successions are most likely in the topsets of aggradational systems (Fig. 11.14). Coals **and** coaly sediments may occur if climate and other factors are favour-**able. Where rates of progradation are high, coastal plain aggradation rates are low, and thick delta/coastal-plain source rocks are less likely.**

High sedimentation rates and oxygenated environments on actively prograding slopes will dilute organic carbon contents. Slope mudstones are usually, at best, sources for gas. However, where coal swamps are accumulating on **an** aggrading coastal plain, high rates of terrestrial **organic** matter may **be** supplied **to** interdistributary **bay or upper** slope mudrocks.

Basinal facies in the bottomsets of the prograding clino forms may be organic-rich if the basin is anoxic at **depth** (Curiale *et al.,* **1991).** Where submarine canyons tap into coastal plain sediments, terrestrial organic matter **can** be transported rapidly to deepwater areas by density currents

11.4 Marine Carbonate Source Rocks

Many of the world's most prolific source rocks are **developed** in marine carbonate depositional systems. The depositional controls on organic carbon accumulation in carbonate systems are similar to clastic systems (Fig. 11.1), with the development of anoxic bottom-water conditions being critical, eithe surface productivity. A terrigenous organic matter contribution tend which many carbonate systems develop.

Carbonate systems differ from clastic systems in **that_** they can create the physiogeographic restriction **necessary** for the development of anoxia and enhanced preservation of organic matter by their response to rapid relative sea-level rise. The carbonate depositional geometries **outlines** are discussed in detail in Chapter 10.

11.4.1 Genetic classification scheme

The following section will consider four genetic types of carbonate source rock defined on depositional geometry. The intercarbonatc build-up source rock develops **pre**dominantly in bonate platforms and platform margins. The intraplatform depression source rock develops when an isostatically sagged platform interior is drowned. These source rocks ar| characteristic of high carbonate productivity systems. The unrestricted carbonate-margin type develops on low **car**-bonate pro and/or oceanic anoxia. Finally, deep-ocean-basin source rocks develop in bathyal water depths in long-lived, tectonically silled, carbonate fringed anoxic basins.

11.4.2 Intercarbonate build-up

Rapid relative sea-level rise may result in the differentiation of an antecedent platform into a series of isolated build-ups (Fig. 11.15, based on Stoakes, 1980). Build-ups may nucleate on topographic highs such as the platform margin. Restri

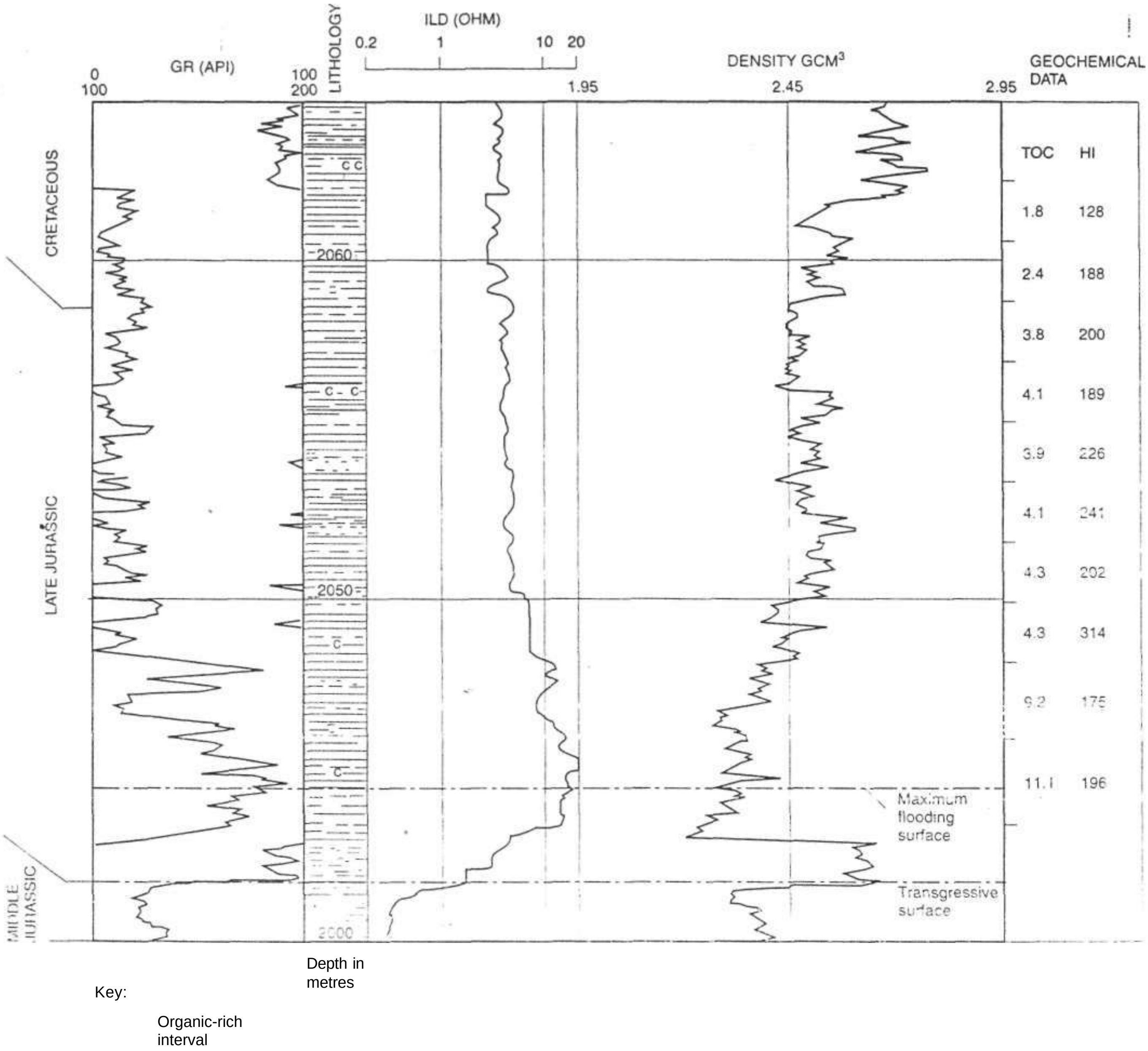


Fig. 11.11 A typical wireline log response of the organic-rich Kimmeridge Clay Formation in the North Sea. The log shows an abrupt upward increase in organic carbon content above a transgressive surface, as shown by the rapid upward decrease in density (Passey *et al.*, 1990). The high gamma radioactiviry is due to enrichment of the shales in uranium, which indicates deposition under anoxic bottom-water conditions (Myers and Wignall, 1987). Organic carbon contents decrease upward more gradually, which can be explained by increasing clastic sedimentation rates and dilution of organic matter during highstand progradation. In this case organic-rich facies are deposited under anoxic bottom-water Conditions, both in the transgressive and early highstand systems tracts, with the highest organic contents correlating with the lowest rates of clastic dilution

ted circulation in the inter-build-up area results in the development of anoxia below the surface mixing layer. Organic-rich carbonates are deposited in the transgressive systems tract at the time of maximum bathymetric relief, coeval with the rapidly aggrading carbonate build-ups. Organic carbon contents may be enhanced further by low rates of carbonate dilution. In the highstand systems tract, prograding systems gradually infill the topography developed during earlier transgression.

The Devonian Douvernay Formation is the type example of this type of source rock (Fig. 11.16). Organic-rich carbonates of the Douvernay Formation overlie the extensive antecedent Cooking Lake platform and are time equivalent to up-building pinnacle reefs of the Leduc Formation

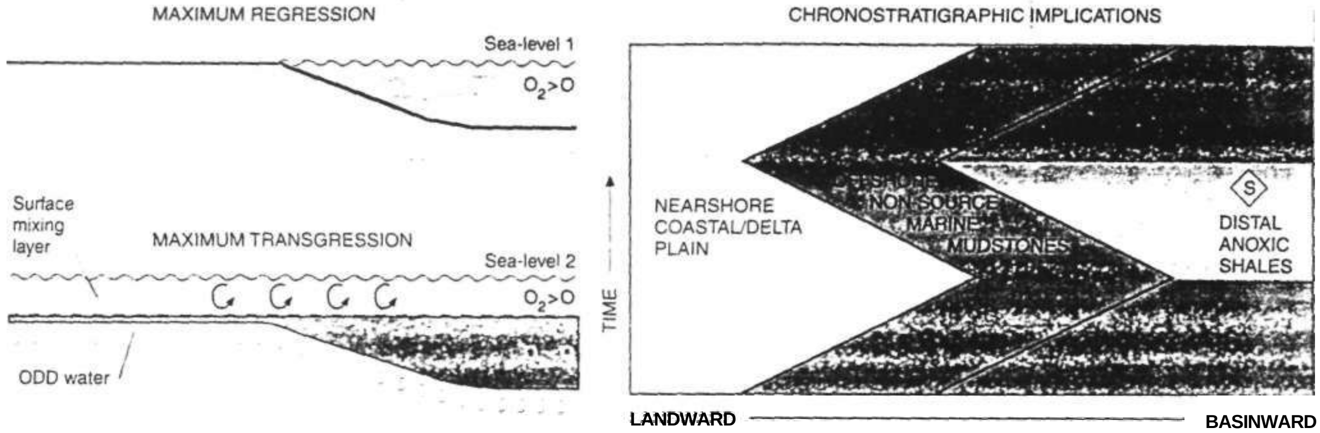


Fig. 11.12 Chronostratigraphic implications of a source-rock model where organic-rich rocks are developed in a distal facies the basin only in the transgressive systems tract. During both lowstand and highstand systems tracts the basin is well aerated a l l there is a causal link between transgression (T) and the development of anoxic conditions, e.g. owing to the development of high surface productivity on the flooded shelf. ODD. oxygen deficient/depleted (conditions); MFS, maximum flooding surface; TST. rransgressive systems tract

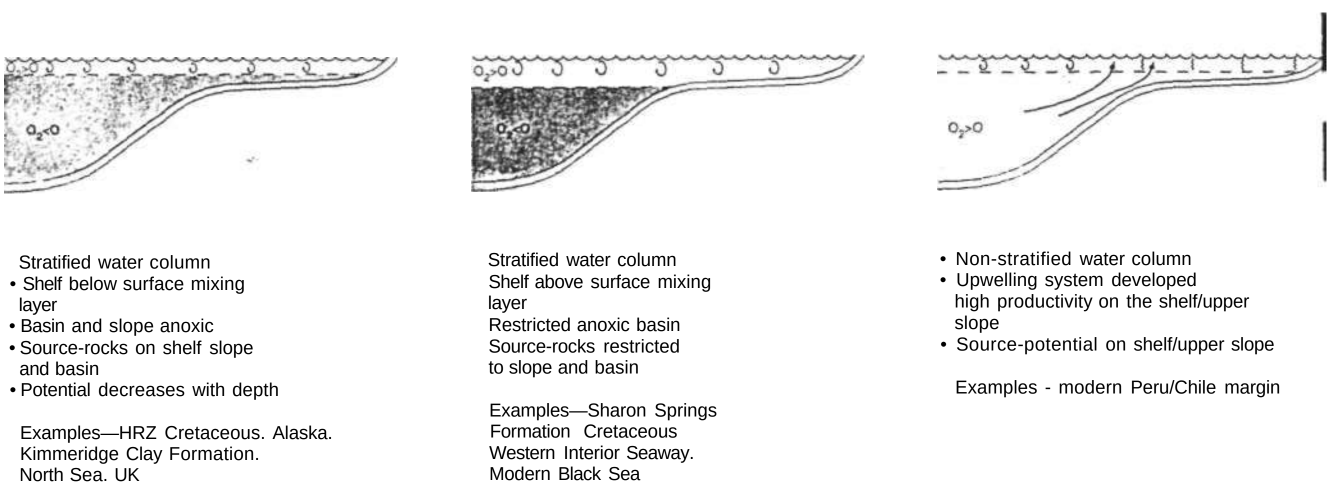


Fig. 11.13 Three models for rransgressive systems tract variability and possible ancient analogues

(Stoakes, 1980; Fig. 11.15). Calcareous mudstones of the Ireton Formation form the prograding highstand deposits that infill the Lcduc— Douvernay topography. Net thickness of the organic-rich facies varies from 10 to 20 m, with total organic carbon contents in the 4 — 7% range. The source rock is estimated to have been deposited over a period of 2 — 3 million years, during a 'second order' sea-level rise.

11.4.3 Intraplatform depression

In this case differential subsidence in the platform interior results in the formation of a long-lived depression during rapid sea-level rise (Fig. 11.17). No convincing mechanism tor the isostatic sagging has been demonstrated bur salt withdrawal has been suggested (Burchette and Britton, 1985; Aigner and Lawrence, 1990). The sequence stratigraphic model in Fig. 11.17 is based largely on Drosre's (1990) work on the Late Jurassic Hanifa Formation Saudi Arabia. Duri the platform generates enough sediment to fill accommodation space ac are maintained. During rapid sea-level rise in the transgressive systems tract the whole platform cannot keep pace and a shallow intraplatform depression forms. Restricted circulation results in anoxia and organic-rich sedimentation. Aggradation of the margins of the basin result in minimal carbonate dilution in the basin centre. In the following' highstand systems tract the topography is wholly or par? infilled as the margins of the basin prograde into the depression. There also may be a close association with evaporites if the basin becomes isolated and drawdown

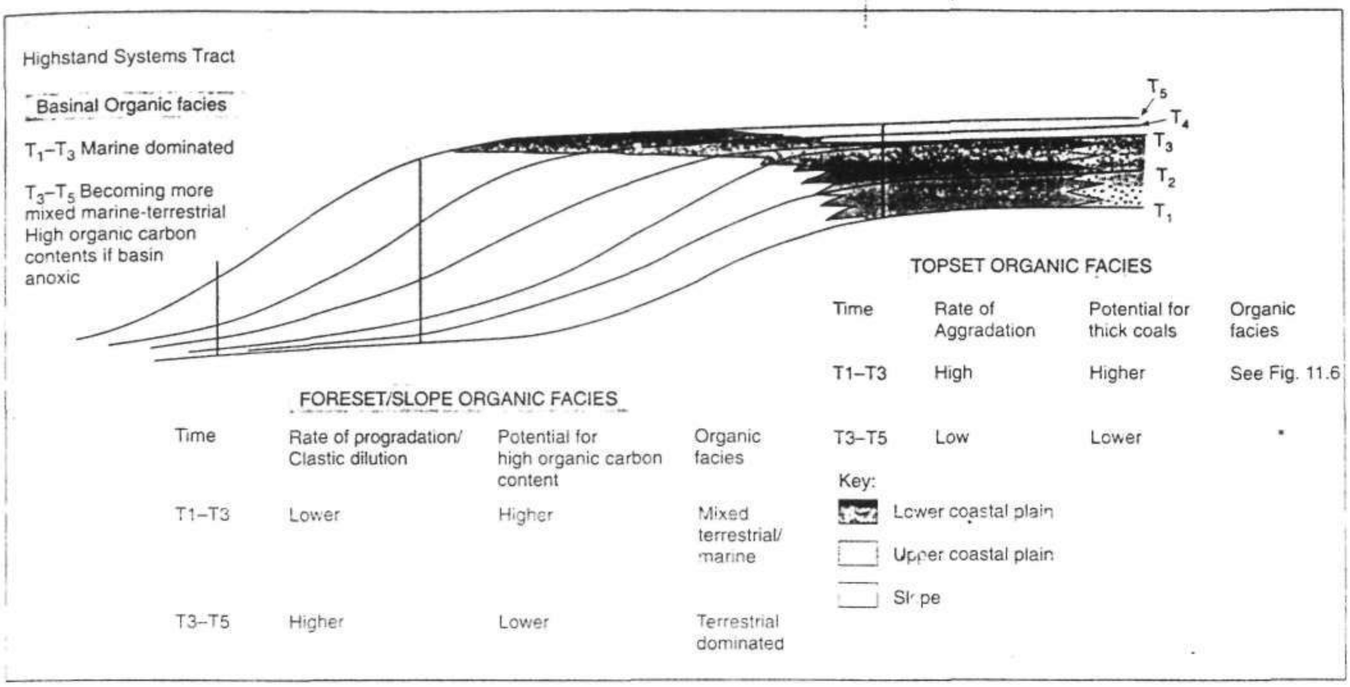


Fig. 11.14 The potential for source-rock development in a hypothetical highstand systems tract. It considers probability of organic-rich facies occurring in basinal, slope and topset settings. Times 1—3 represent aggradation during early high stand and times 3 — 6 represent pro gradation during lace high stand

ensues. This can happen in any systems tract but may be more likely during low stand (Chapter 10).

The Haifa Formation described by Droste1990; is one of a chain of intraplatform-depression source rocks deposited in the Gulf of Arabia area in Oxfordian—Kimmeridgian times (Murris, 1980). The thickness of the organic-rich interval reaches 30—50 m in the centre of the depression, with TOC of 5-10% (Droste, 1990). The Haifa Formation was deposited in Oxfordian—Kimmeridgian times during a second-order sea-level rise and shows an internal cyclicity reflecting higher order sea-level changes (Fig. 11.18).

11.4.4 Unrestricted basin margin

The unrestricted-basin-margin source rock has a similar depositional geometry to the transgressive marine clastic source rocks described in section 11.3.2. This type of source rock occurs in low-productivity carbonate systems, when transgression results in sediment starvation of the outer shelf or deep ramp and deposition is dominated by Pelagic carbonate (Fig. 1 1.19). Low carbonate productivity inhibits up-building and deep-water environments develop across the shelf or ramp. Source rocks will be deposited if anoxia and/or high phytoplankton productivity is developed. As the rate of sea-level rise decreases, high stand pro gradation of the clastic or carbonate ramp proceeds and source-rock deposition ceases.

i here are a number of examples of this type of source rock: the Upper Jurassic Smackover Formation, Gulf Coast, the Upper Cretaceous La Luna Formation, South America and the Upper Cretaceous Brown Limestone Formation, Gulf of Suez. Figure 11.19 shows the typical stratal geometry of this type of source rock, with the organic-rich facies located in the transgressive systems tract underlying the low-angle clinoforms. Figure 11.20 is a typical well-log through the Brown Limestone Formation. The high radioactivity unit is an organic and phosphate-rich pelagic limestone interpreted as a distal ramp carbonate deposited following rapid transgression of the underlying clastic Matulla Formation. The organic-rich interval is 20—50 m thick and contains *3— 6%* TOC. Its precise age range is not well controlled, although it may represent 4—5 million years of deposition in the early Campanian.

11.4.5 Deep ocean basin

The deep-ocean-basin type carbonate source rock is controlled more by palaeo-oceanographie factors than relative sea-level changes because it is deposited at 100s to 1000s of metres water depth in silled basins. The type example of

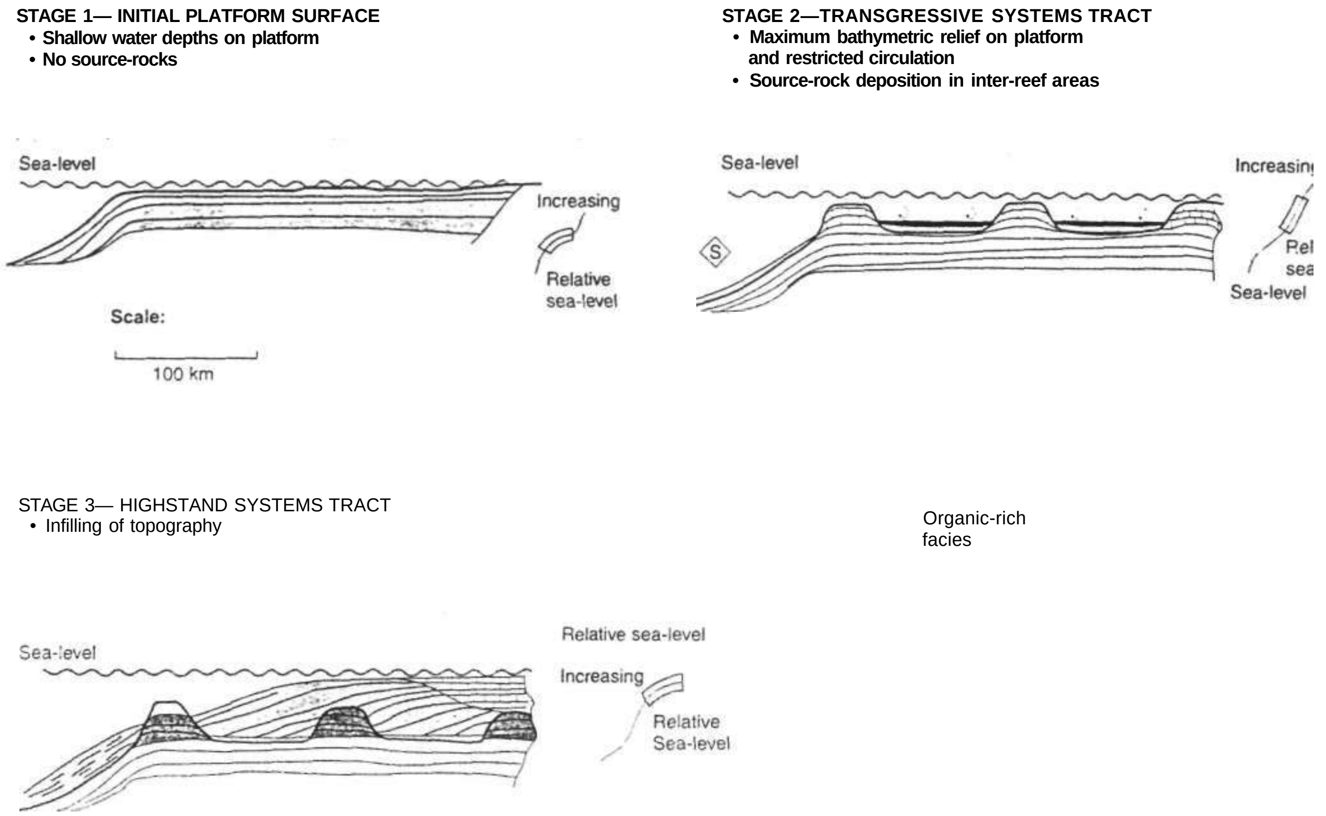


Fig. 11.15 lntercarbonate build-up source rock. The hypothetical two-dimensional cross-section illustrates depositional geometries at three stages: (1) prior to rapid relative sea-level rise with the platform at keep-up stage; (2) transgressive system tract with platform at catch-up stage; (3) highsrand systems tract with platform at keep-up stage. Cross-section is based on StoaHl (19X0) interpretation of the Devonian Leduc —Douvernay Formations of the Western Canada Basin

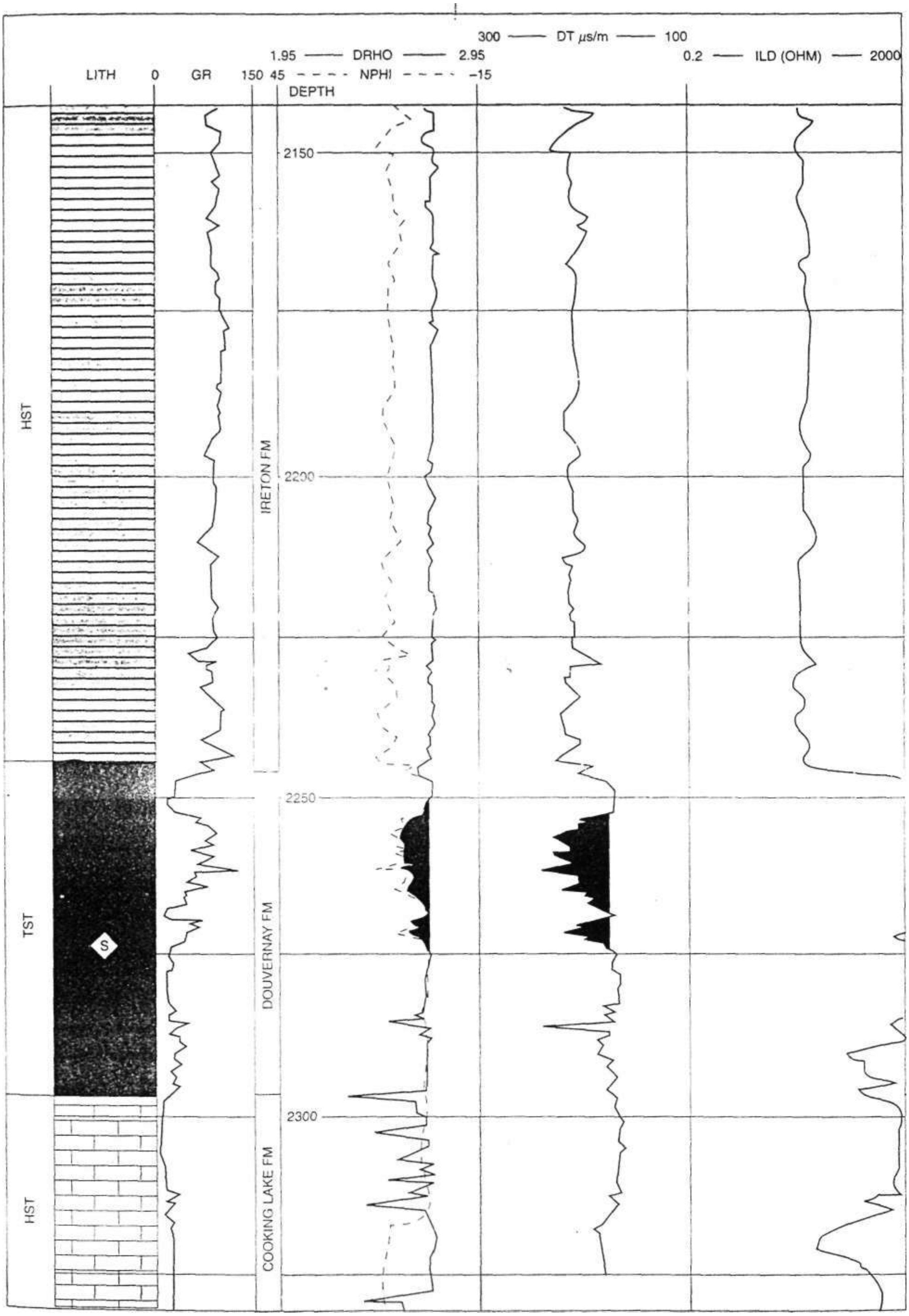
this source rock is the early to middle Cretaceous pelagic carbonates of the deep water Gull of Mexico (Katz, 1984). These were deposited periodically over 43 million years in water depths of around 1500-2000 m. In DSDP boreholes *535* and 540 they attain up to 250 m in thickness and contain an average of 1.4 ± 1.8% TOC (Katz, 1984).

11.5 Conclusions

Sequence stratigraphy clearly has an important role to play in the study of organic-rich facies. Prediction of source rocks in an undrilled frontier basin using seismic stratigraphy-alone will not be possible, because factors such as climate, oceanic circulation and bottom-water anoxia cannot be interpreted from seismic data. However, by identifying likely transgressive svstems tracts and condensed facies, the most prospective intervals of the basin fill can be highlighted Sequence stratigraphy will be particularly useful in predicting the lil away from well control, by constraining palaeobathymetry and lateral changes in sedimentation rate. Coals are import ant facies as they represent periods of coastal plain aggradation and

This chapter has presented very much an overview of a complex topic and to a large extent has considered orgJ richness only in terms of total organic carbon. Howel the type of organic matter controls the potential of the organic facies to generate oil or gas on maturation. Publis case studies integrating sequence stratigraphy and deta| geochemistry ate rare at present (e.g. Palsey *ct cil.,* 1' Curiale *et a!.,* 1991) and future work must continue to study the link between organic facies and systems trac^M

Fig. 11.16 (opposite) A typical wireline-log profile through the Devonian Douvernay Formation, the type example of an intercarbonate build-up source rock. The organic-rich interval is shown by the shaded low-density (DRHO gm/cc) and high soiBJ_ travel-time (DT) zone, which together with the high resistivity (ILD) indicates a mature source rock (e.g. see Passey *et* <i/., 1990). The Douvernay overlies the highstand carbonates of the Cooking Lake Formation and is time equivalent to the Leduc pinna^? reefs (Stoakes, 1980). The calcareous mudstones of the Ireton Formation represent the overlying highstand systems tract (H^l TST, transgressive systems tract; S, indicates source rock potential; GR, gamma ray log; NPHI, neutron porosity (%)


300 — DT μs/m — 100
1.95 — DRHO — 2.95
0.2 — ILD (OHM) — 2000
LITH
0 GR 150
45 - - - NPHI - - - -15
DEPTH
2150
2200
2250
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TST
HST
IRETON FM
DOUVERNAY FM
COOKING LAKE FM
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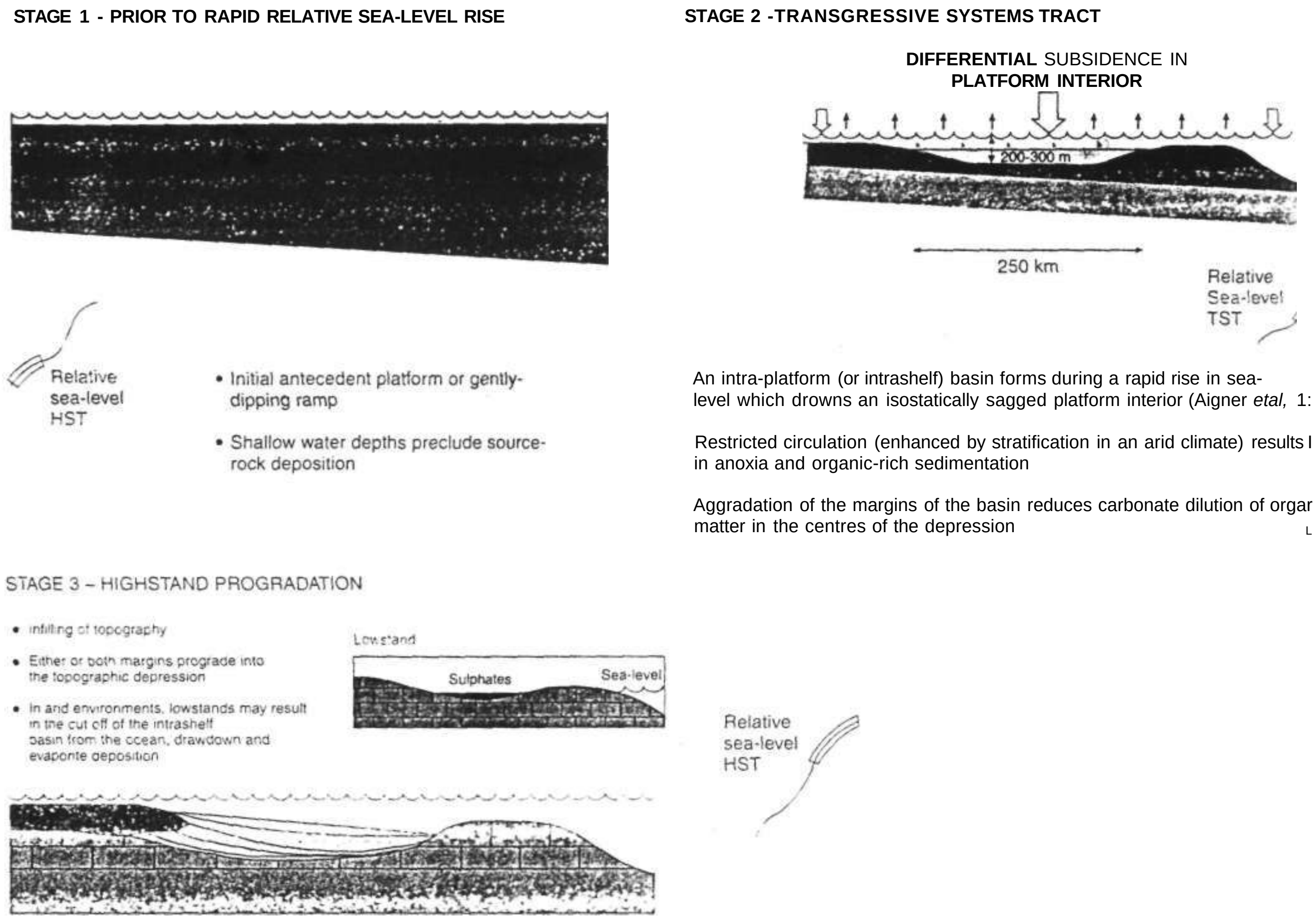
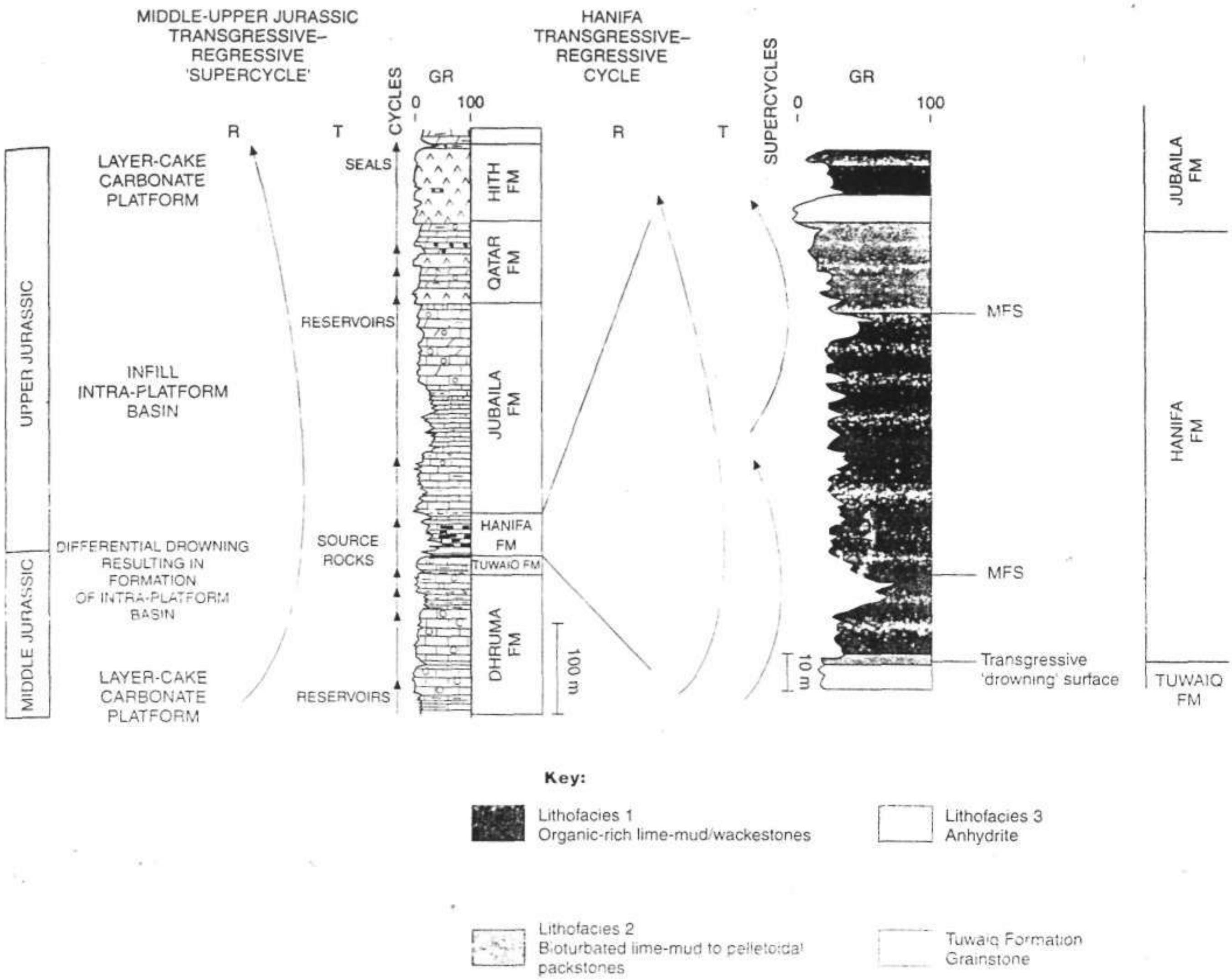


Fig. 11.17 Intrapl.itform depression source-rock. The hypothetical two-dimensional cross-section illustrates depositional geometries at three stages: (1) prior to rapid relative sea-level rise, with the platform or ramp at keep-up stage; (2) in the transgressive systems (1ST) tract during rapid relative sea-level rise; *(3)* during highstand progradation (after Droste. 1[4]S)()) HST. hiuhstand svstems tract



tig. I 1.1 S A r. pical \\ ireline log response through the Hanifa Formation, the rvpc evenHi of .ir irtraplattomi-ilcpri'ssH rock from Drosrc. |4V()i. MFS, maximum Hooding surface; R, regressive; T, transgressive; CIR, (iamma-Rav log

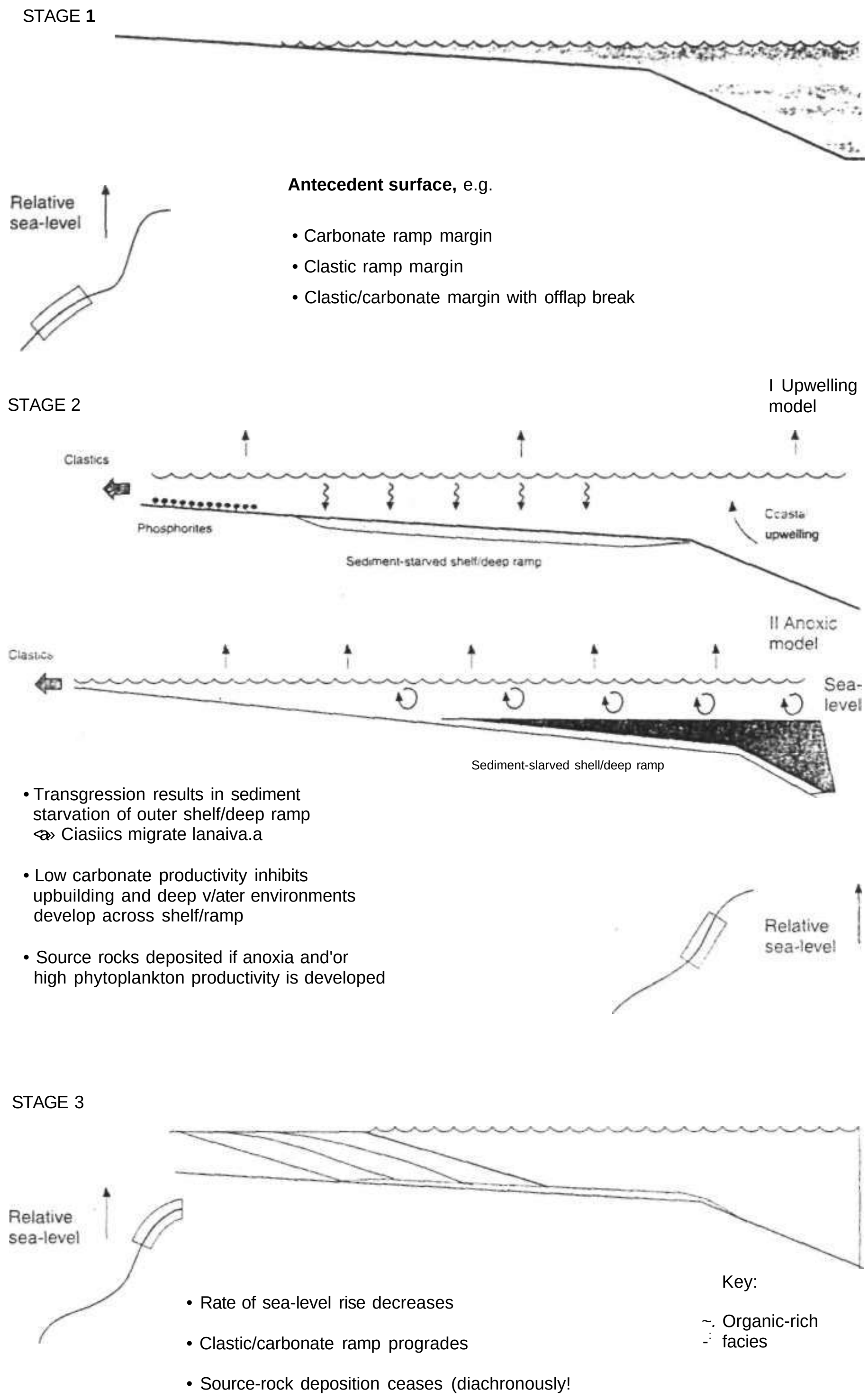


Fig. 11.19 Unrestricted-hasin-margin source ruck. The hypothetical two-dimensional cross-section illustrates typical depositional geometries at different stages of the sea-level cycle. Geometries are similar to clastic souro rocks

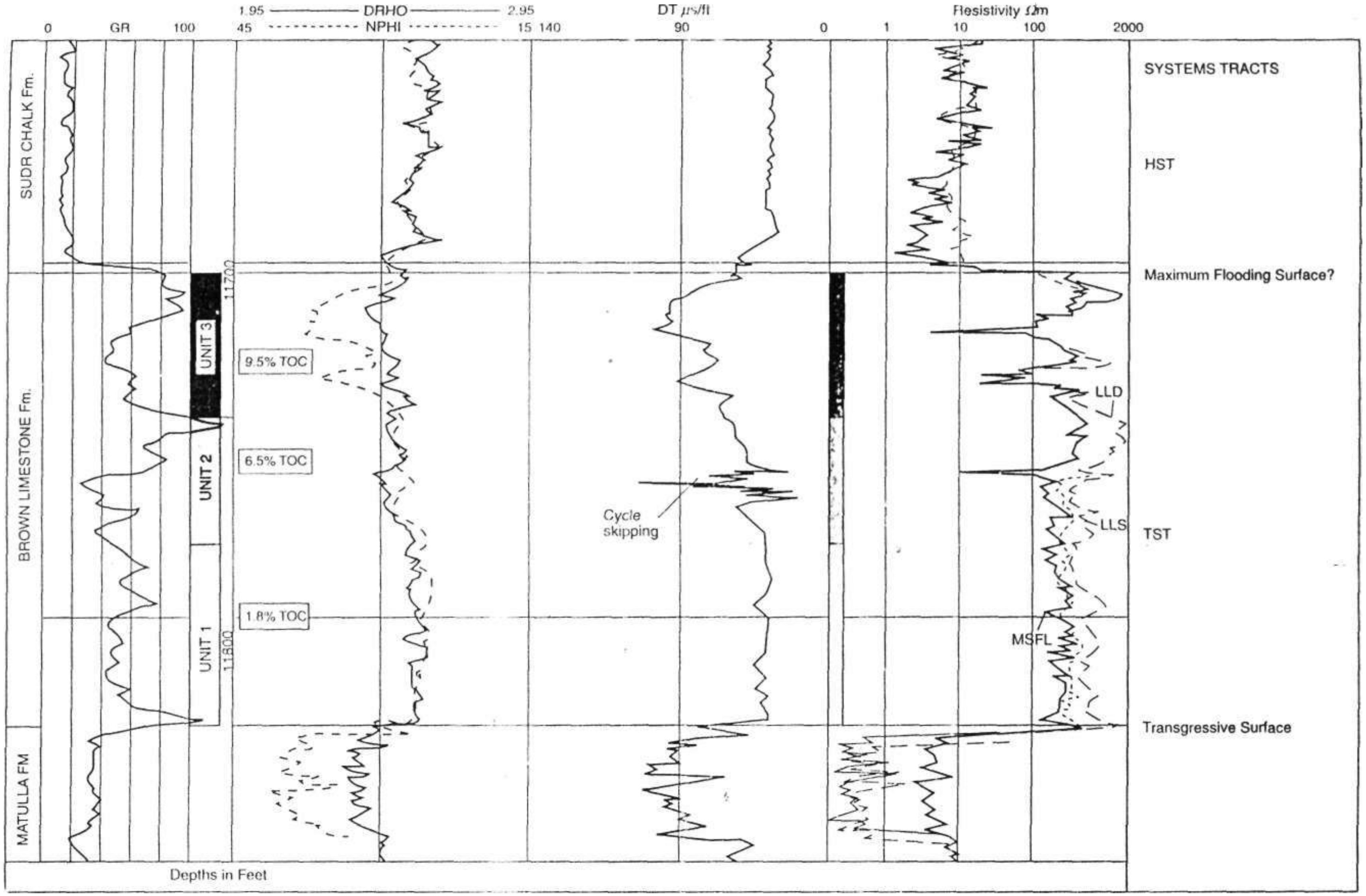


Fig. 11.20 A typical wireline log profile through the Upper I retaceous Brown Limestone, Gulf of Sue/, 1-gypt. The organic-rich carbonate is shown by **the** low density and high sonic travel limes together with the high resistivity, (leochernicai parameters refer to the results of geochemical analyses of cuttings samples. The Brown Limestone is separated from the underlying clastic Manilla !<>: mation by a transgressive surface, and is an organic- and phosphate-rich pelagic limestone considered to be upwelling related. However, the high radioactivity is due lo uranium enrichment, indicating that anoxic conditions also prevailed during deposition. The overlying Sudr Chalk Formation is organic-poor and probably represents the overlying highstand systems tract