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Production, preservation and prediction of source-rock facies in deltaic settings

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Abstract

This article hypothesizes that production and preservation of source-rock type facies in deltaic systems, both landward and seaward of a coastline, is mutually exclusive, time-successive and related to the dynamics of relative sea level. Sedimentologic research in the Holocene Mississippi and Rhône delta complexes suggests that rheotrophic peats and associated organic-rich beds preferably accumulate in the accommodation space created behind landward stepping shorelines in a transgressive systems tract (TST). Such a setting also allows for a sufficient supply of recharging fresh nutrient-rich groundwater into the peat forming mires [Kosters, E.C., Suter, J.R., 1993. Facies relationships and systems tracts in the late Holocene Mississippi Delta Plain. Journal of Sedimentary Petrology 63 (4) 727–733.]. Independently carried-out quantitative paleoecological studies in the same delta systems (and in addition in the Orinoco and Po deltas) suggest that in a progradational setting (highstand systems tract/HST), seasonally discharged nutrient- and sediment-laden river waters on the shelf may give rise to anoxia or dysoxia. Subsequent overfertilization of the shelf leads to accumulation of organic-rich mud belts on the shelf [VanderZwaan, G.J., Jorissen, F.J., 1991. Biofacial patterns in river-induced anoxia. In: Tyson, R.V., Pearson, T.H. (Eds.), Modern and Ancient Continental Shelf Anoxia. Geological Society of London, Special Publication no. 58, pp. 65–82.]. Thus, production and preservation of source-rock type facies

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landward of a shoreline (as peats and related sediments) is preferred in a TST, when accommodation space and nutrient supply are landward of the shoreline. Vice versa, production and preservation of such facies seaward of a shoreline (as organic-rich shelf muds) occurs preferentially in a highstand systems tract. In that situation, accommodation space is on the shelf, where river-fed nutrients are supplied as well. This hypothesis suggests further potential for application of sequence stratigraphic concepts for improved understanding of the occurrence of source-rock type facies.

Keywords: peat; coal; source rock; delta; sequence stratigraphy; Mississippi; Rhône; Po; Orinoco

1. Background

This article combines the outcome of two independent lines of research in Holocene delta systems of the Mississippi and Rhône rivers. Partly together with others, the senior author presented new insights in the origin and preservation of the late Holocene peats of the Mississippi Delta (Kosters, 1987, 1989; Kosters and Suter, 1993; Kosters et al., 1987). She subsequently analyzed the classic Rhône delta core collection, first interpreted by Oomkens (1967); re-interpreted by Kosters et al. (in review).

VanderZwaan and Jorissen (1991) and VanderZwaan (1999) studied the benthic foraminifera of the present-day shelves of the Po, Orinoco, Rhône and Mississippi deltas and concluded that organic-rich shelf muds accumulate in the present-day highstand setting. Thorough discussions on our independently reached findings led us to formulate the ideas presented here.

Sequence stratigraphic concepts were important in enabling us to put our data in context. The original objective of the sequence stratigraphic method is to improve prediction of reservoir facies "ahead of the drill". In recent years, a growing number of authors have attempted to apply these concepts to improve understanding of non-framework, source-rock type facies (e.g., Vail, 1987; Cross, 1988; Arditto, 1991; Kosters and Suter, 1993; Pasley et al., 1993;Hart et al., 1994; Yancey, 1997; Petersen et al., 1998).

In paralic settings, these facies are represented by peats and coals landward of a shoreline and as organic-rich shales and muds on the shelf seaward of a shoreline. Improved insight in the conditions that drive production and preservation of these facies increases our understanding about their occurrence in the geologic record, and thus about the source-rock potential of certain stratigraphic intervals.

Vail (1987) first stated that, within large depositional systems, thick coals preferentially occur within a transgressive systems tract (TST). The main argument for this idea was the increased accommodation space available landward of the shoreline of each backstepped parasequence. That such a relationship between framework and non-framework facies should exist was suggested earlier by Frazier (1974) and Ryer (1981), and later again by Cross (1988), Arditto (1991) and Petersen et al. (1998). Accommodation space, however, only drives the quantity of peat that can accumulate, not the quality (ash content).

The discussion regarding stratigraphic positioning of organic facies, the focus of this article, has been somewhat occluded because of a parallel and intertwined discussion on modern-day coal-analogues (see for a representative summary of this discussion Calder and Gibling, 1994). Coal geologists have tended to focus on a search for Holocene peats that are — in terms of quantity *and* quality [3] — good coal analogues. The best modern-day coal analogues are the ombotrophic [4] raised mires of Malaysia and Kalimantan (e.g., Cecil, 1990; Cecil et al., 1985; Esterle, 1990; Phillips and Bustin, 1998). These studies have led to increased understanding of tropical peat formation and related insight in coal formation. Stratigraphic setting and preservation potential of these peats, however, is not necessarily comparable to that of the well-documented paralic coals of many parts of the Paleozoic Euramerican coal province (e.g., Cecil et al., 1985; Calder and Gibling, 1994), the Mesozoic Rocky Mountain coal province (e.g., Ryer, 1981; Cross, 1988) and the Cenozoic Gulf of Mexico Lignite province (e.g., Raymond et al., 1997; Yancey, 1997). Many of these coals are thought to have originated in ombotrophic mires, although recent work suggests that certain Gulf Coast lignites, of which the depositional system is unquestionably deltaic, are rheotrophic in origin (Raymond et al., 1997; Yancey, 1997).

Peat quality depends on floral origin, (lack of) clastic influx, nutrient availability and possibly on atmospheric CO_2: ombotrophic peats require nutrient-poor water (rainwater), whereas rheotrophic peats require nutrient-rich water. The modern high quality, thick southeast Asian peats are mostly ombotrophic mires (Esterle, 1990). Many of the world's modern large, well-studied deltas are located in temperate climate zones and therefore support rheotrophic mires.

Floral evolution, atmospheric CO_2, climate, mire hydrology, sedimentary processes and sea level dynamics are the dominant factors influencing peat formation, independent of its rheotrophic or ombotrophic condition. Of these, only mire hydrology and sedimentary processes are time-independent, although to some extent interrelated (Calder and Gibling, 1994; Bohacs and Suter, 1997). It is therefore unlikely to find perfectly matching Holocene analogues for ancient coal-forming environments. Whereas the importance of the abovementioned studies is unquestioned, it remains equally important to attempt to understand the occurrence of a broad range of organic facies within their (sequence) stratigraphic setting.

Katz (1994) lists four primary depositional settings for source-rock type facies: (a) broad, flooded continental shelves; (b) areas on the shelf where the oxygen minimum zone impinges on the sediment–water interface; (c) regions of active upwelling; (d) structurally isolated basins. This article addresses the findings on some Holocene broad, flooded continental shelves.

[3] Peat quality is here defined consistent with earlier articles by Kosters (see list of references), that is, in terms of ash content: high quality peats have a low ash content and vice versa.

[4] Consistent with other literature, we define our terms as follows.

- A *mire* is a peat-forming wetland.
- *Oligotrophic* means "requiring few nutrients". Most oligotrophic mires eventually form *ombotrophic* (*raised*) bogs, that is, the groundwater table becomes perched.
- "*Rheotrophic*" is defined as "requiring significant amounts of nutrients".

2. Peats of the Mississippi and Rhone deltas

2.1. Mississippi Delta

The Holocene Mississippi Delta Complex contains rheotrophic peat mires. Kosters (1987; 1989), Kosters and Suter (1993) and Kosters et al. (1987) showed that both quantity and quality of peats landward of the youngest backstepping TST shoreline (Shoreline of Maximum Transgression, SMT) are higher than that of peats landward of the first Highstand shoreline (Figs. 1 and 2). The authors suggested that the difference could be explained by the changing dynamics of river-supplied nutrient-rich groundwater, together with the change in accommodation space. Nutrient-rich groundwater may be recharged into the delta plain landward of the shoreline, which is where the accommodation space is in a retrogradational (TST) setting. This groundwater 'feeds' the nutrient-dependent rheotrophic peats. In a highstand setting (such as at present), groundwater and river water are discharged onto the shelf, which holds the accommodation space.

2.2. Rhône delta

The present climate in the northwestern Mediterranean, the location of the Rhône delta, does not favor peat formation. On the contrary, there is a salt evaporation plant in the present-day active delta lobe. Some organic matter preservation, however, did take place during the Holocene. Remarkably, the only clearly autochthonous organic bed in the entire Holocene Rhône wedge occurs immediately behind the SMT (Fig. 3) (Kosters et al., in review). The radiocarbon date of this bed, 6400 BP, places it more or less at the time of maximum rate of sea level rise. The fact that the organic-rich bed is insignificant as a modern coal analogue, is irrelevant. What is relevant is that the conditions for organic matter production and preservation were optimal under the same conditions and at the same time in the Mississippi Delta and in the Rhône delta. These conditions are: a fresh water setting landward of a well-established transgressive barrier shoreline.

2.3. Hydrology and nutrients

Both the Holocene Mississippi and the Rhône deltas display similar time-stratigraphic relationships with respect to their organic facies. The idea that changing groundwater behavior in combination with sea level dynamics drives this stratigraphy remains somewhat speculative, but appears supported by evidence from elsewhere.

Salt water intrusion is limited behind a barrier shoreline, due to what is commonly known as the Ghyben Herzberg relationship (Fig. 4), which shows that a large fresh-water reservoir develops beneath a sandy coastline, especially when it has an elevated relief in the form of dunes. Chapman (1987) showed that coastal plains are dominated by fresh water as long as a strandplain/barrier system is present. Apparently, tide range is of minimal influence. This relation is indicated by the observation that the meso- to macro-tidal back-barrier coastal plain of the Rhine/Meuse delta plain of the Netherlands contained almost exclusively fresh-water marshes during the early to

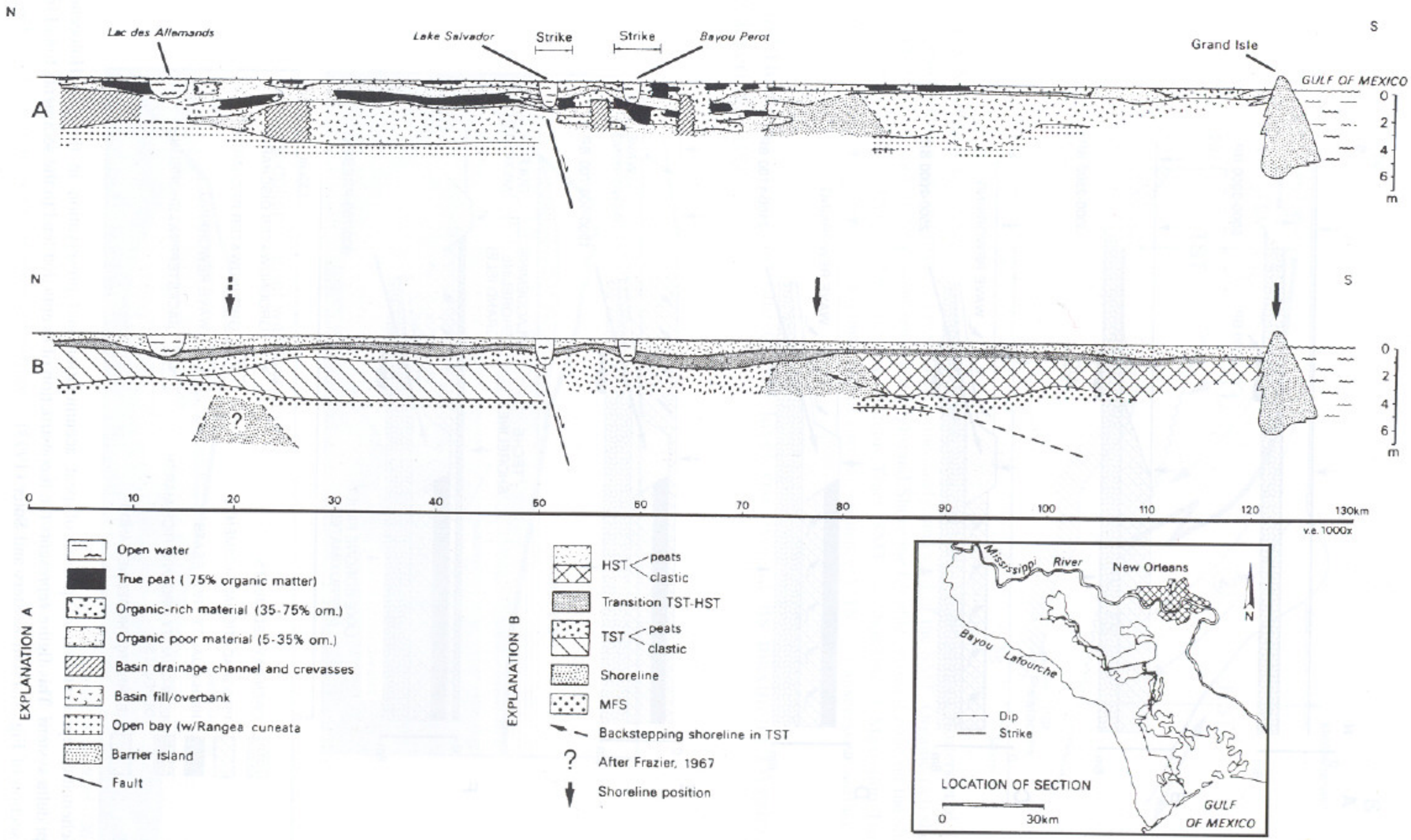

Fig. 1. Dip-oriented cross-section through sediments of the late Holocene Mississippi delta; upper part of figure shows sedimentology, lower part of figure shows interpretation in terms of sequence stratigraphy. The highest quality and thickest peats occur landward of the Shoreline of Maximum Transgression, indicated by the central arrow on the lower part of the figure. From Kosters and Suter (1993).

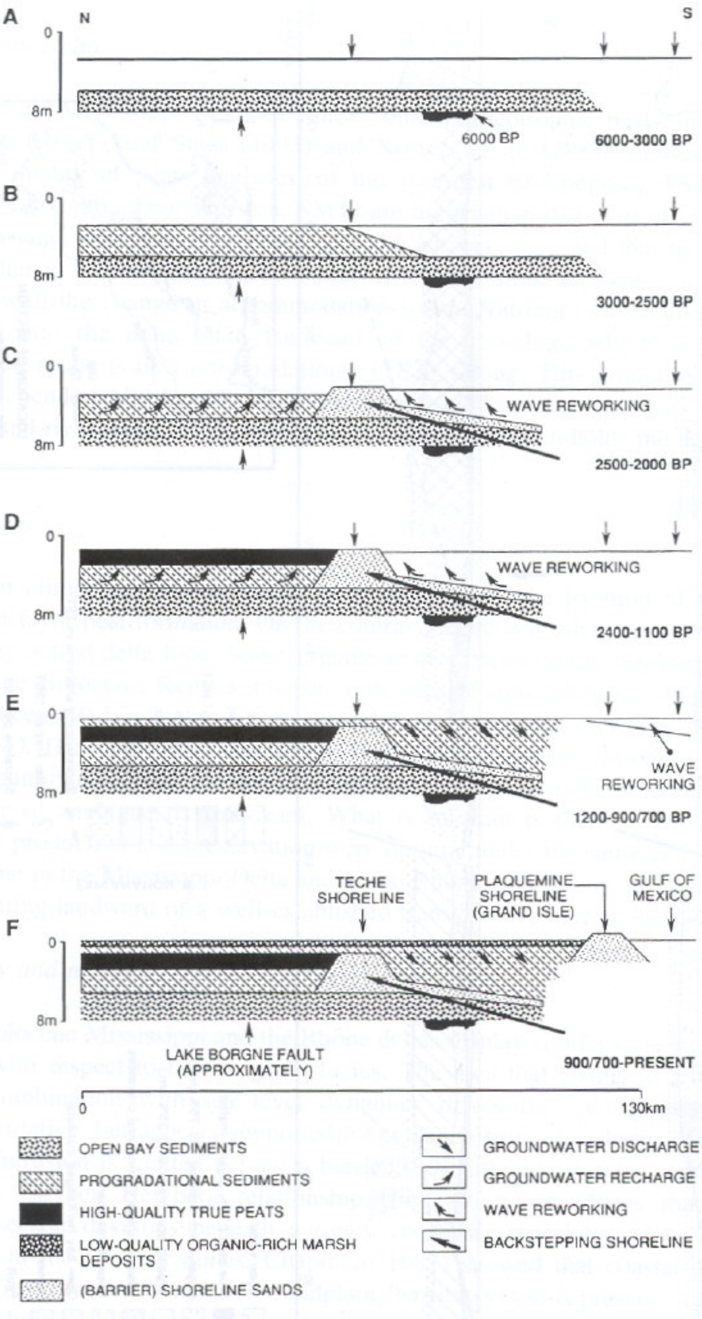

Fig. 2. Schematic representation of phases of peat accumulation and preservation in the late Holocene Mississippi delta system. This figure represents the reconstruction of events that lead to the sediments found in the cross-section of Fig. 1. From Kosters and Suter (1993).

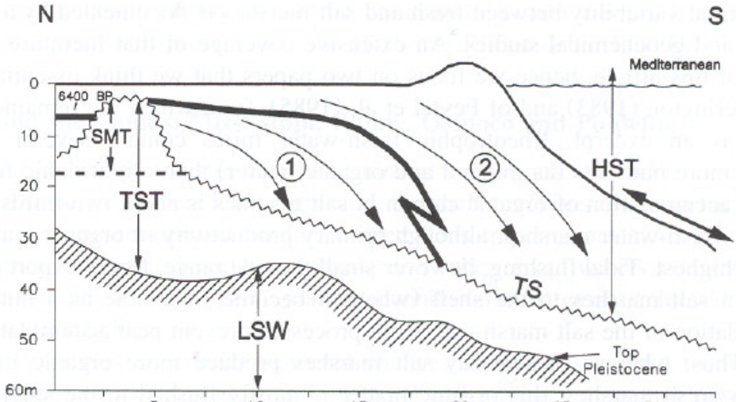

Fig. 3. Simplified dip-oriented cross-section Rhone delta and shelf. Modified from Kosters et al. (in review). One autochthonous organic-rich bed is situated immediately landward of the SMT. Organic-rich shelf mud has accumulated seaward of the present reworked Highstand Shoreline (double-arrowed zone on the shelf). LSW — lowstand wedge. TST — Transgressive Systems Tract. SMT — Shoreline of Maximum Transgression. HST — Highstand Systems Tract (consisting of two parasequences). TS — transgressive surface.

mid-Holocene, when the rate of sea level rise was at its maximum (Westerhoff and Cleveringa, 1990).

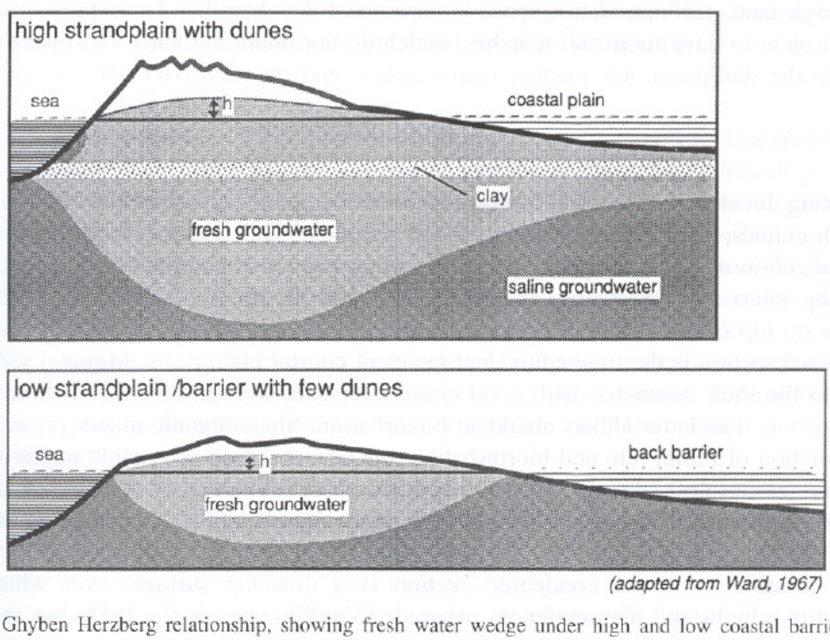

Fig. 4. Ghyben Herzberg relationship, showing fresh water wedge under high and low coastal barrier. The thick black line represents the sediment surface. ''h'' — hydraulic head.

The nutrient variability between fresh and salt marshes is documented by a wealth of ecological and geochemical studies. An extensive coverage of that literature is beyond the scope of this article, hence we focus on two papers that we think essential, namely that of Etherington (1983) and of Feytel et al. (1985), from which the remainder of this paragraph is an excerpt. Rheotrophic fresh-water mires contain several orders of magnitude more nutrients (as mineral and organic matter) than oligotrophic fresh-water mires. Net accumulation of organic carbon in salt marshes is about two-thirds of that in rheotrophic fresh-water marshes, although primary productivity of organic matter in salt marshes is highest. Tidal flushing, however small the tide range, forces export of organic matter from salt marshes to the shelf (where it becomes available as a nutrient) and causes oxidation of the salt marsh soil. Both processes prevent peat accumulation in salt marshes. Thus, whereas present-day salt marshes produce more organic matter than present-day fresh marshes, this organic matter is mostly flushed to the shelf (where it acts as a nutrient) rather than stored as organic deposits (peats) in the coastal plain.

During rapid sea level rise, when the conditions are optimal for reworking of sands from distributaries into barrier islands, the Ghyben Hertzberg relationship arises (Fig. 4) and causes back barrier marshes to be dominated by fresh-water mires (accommodation space landward of the shoreline). These fresh-water mires retain river-fed recharged groundwater and its nutrients for peat accumulation rather than flushing them to the shelf.

To summarize: during relative sea level rise, accommodation space is landward of the shoreline. Recharging fresh groundwater in the back barrier coastal plain forces marshes to be dominantly fresh-water mires during this period. Mires retain groundwater-fed nutrients and accumulate relatively high quality organic strata. Conversely, during sea level highstand, accommodation space is seaward of the shoreline. Hydrology forces the coastal plain to have more salt marshes, which do not retain nutrients, but instead flush these to the shelf.

2.4. Condensed section

During development of a TST, when accommodation space is landward of backstepping shorelines, the shelf becomes starved of sediment. This process results in increased mineralization of, for example, glauconites, phosphates and siderites on the shelf. The resulting interval is generally called the condensed section (CS) and it is positioned closely on top of a ravinement surface ('transgressive lag' or wave base horizon). The condensed section is the time-equivalent facies of coastal plain peats. Minimal sediment input to the shelf combined with good circulation leads to high levels of bottom water oxygenation. The latter allows abundant bioturbation. Since organic matter preservation is a function of burial rate and biorturbation, the accumulation of organic matter on the shelf decreases during development of a condensed section. Only when water circulation is poor, for instance, due to seasonal stratification, accumulation of organic matter may take place.

On seismic lines, the condensed section is a downlap surface, over which the consecutive highstand parasequences prograde (VanWagoner et al., 1988; but see also Oomkens, 1967). Along major depositional axes, such as large deltaic systems, the first sediments to be deposited on top of the condensed section are prodelta muds. This stratigraphy is very well preserved in the Holocene Rhône delta (Fig. 3).

3. Highstand shelf muds, Mississippi, Rhone, Orinoco and Po deltas

Prodeltaic sediments transfer nutrients (mineral and organic matter) from continent to ocean. During periods of sea level highstand, the shelf functions as a trap for sediments, nutrients and continent-derived organic matter. This trapping mechanism is especially efficient when the shelf is relatively wide and when river waters contain abundant fine-grained sediments and organic matter, a condition most easily achieved during sea level highstand (HST).

Many large rivers experience seasonal changes in runoff that lead to an abundant supply of prodelta muds that are rich in mineral and organic nutrients. Consumption of these materials by organisms causes increase of marine primary production. Subsequent degradation of the dead organic mass may lead to (seasonal) decreases in bottom water oxygenation and to extensive anoxia or dysoxia at the sediment–water interface. This condition of river-induced anoxia is widespread on present-day wide highstand shelves (VanderZwaan, 1999; VanderZwaan and Jorissen, 1991).

Opportunistic and stress-tolerant taxa of foraminifera overtake these oxygen-poor parts of the shelf floor. Specific and characteristic species are found in the direct influence of river-fed waters and nutrients. (Jorissen, 1987; VanderZwaan and Jorissen, 1991). The general fauna pattern is well illustrated in front of both the Po and the Orinoco rivers (Figs. 5 and 6). Here, zones of active mud sedimentation are installed below the outflowing plume of river water which carries suspended sediment and nutrients. In both cases, this plume is deflected by marine currents. The resulting pattern is that zones of organic rich mud are inhabited by opportunistic fauna species closely following the deflected path of river water, which induces the anaerobic zone on the shelf (Figs. 5 and 6).

Experimental work shows that benthic foraminifera are most resistant to the oxygen stress, far more than other macro- and many meiofaunal taxa (e.g., Moodley et al., 1997). The taxa that are abundant in front of major river source points all prefer the raised nutrient levels while being resistant to the oxygen stress (VanderZwaan, 1999).

Similar patterns are seen on the shelves in front of the Po, Orinoco, Rhône and Mississippi deltas. These rivers discharge large amounts of nutrients and organic detritus on the shelf, which is reflected in high organic matter values in shelf. Shelf sediments are finely laminated with little or no bioturbation, indicating oxygen-poor conditions. Sediments also contain abundant pyrite and plant remains. Benthic foraminifera are consistently similar, sometimes even at species level, in both European and American waters (Fig. 6).

The zone below 20 m water depth is most affected by river-induced anoxia, possibly because this is the depth below storm wave base. Here, oxygen cannot be supplied anymore by continuous mixing. Shelf circulation leads to dispersion of fluvial discharge and this leads to a typical distribution of stress-tolerant species. Due to the interaction of excess input of organic detritus and periodic depletion of available oxygen caused by its decomposition, organic matter is readily preserved in these fine-grained sediments. This

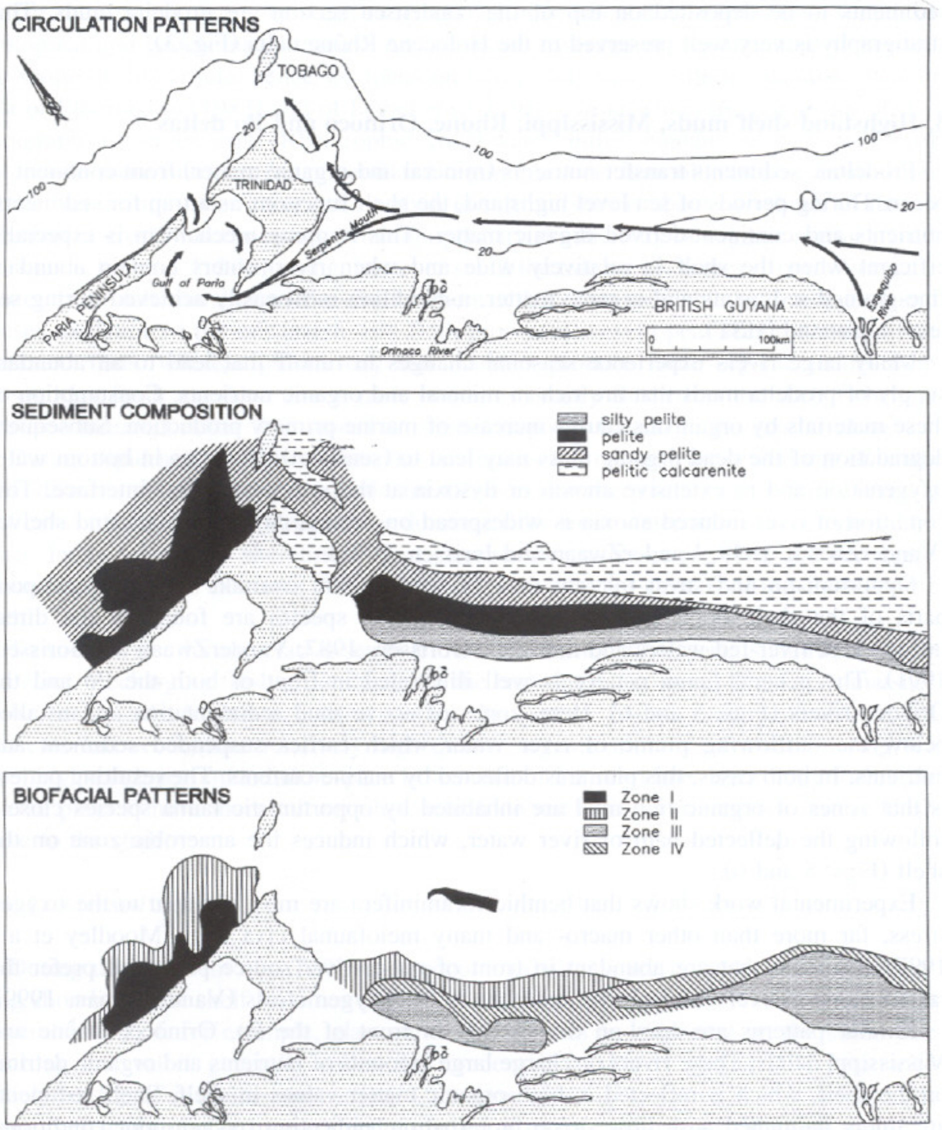

Fig. 5. Present-day circulation patterns, sediment distribution and foraminiferal biofacies on the shelf bordering the Orinoco delta. Modified after VanderZwaan and Jorissen (1991). Fauna patterns closely follow the path of the outflowing river water, which is deflected by strong long-shore currents. These currents transport mud and nutrients further, even as far as the Gulf of Paria. Below their path, a zone of active mud sedimentation is installed. Anaerobic or dysoxic conditions are induced in the zone by the high organic load: highest stress is in zone III, followed by zones IV, I and II.

process is typical and more common on wide shelves than on narrow shelves, which nutrients can quickly bypass. The magnitude of river discharge does not seem to play a

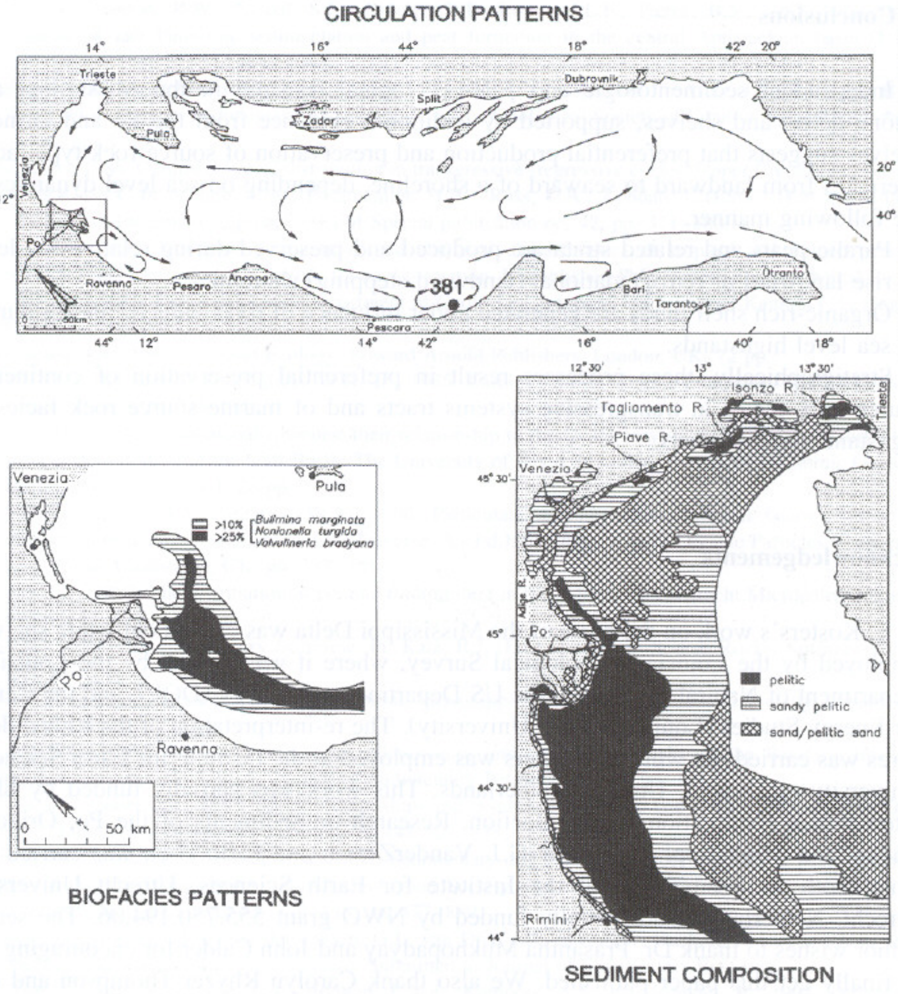

Fig. 6. Present-day circulation patterns, sediment distribution and foraminiferal biofacies in front of the Po delta, Adriatic Sea. Modified after VanderZwaan and Jorissen (1991). Below the outflowing Po waters, forced to flow closely below the Italian coast by the long-shore currents, a belt of organic-rich mud accumulates. This part of the Adriatic Sea is characterized in summer by the occurrence of anoxic or dysoxic conditions. The cumulative distribution of opportunistic species as *B. marginata*, *N. turgida* and *V. bradyana*, closely reflects this zone of stress close to the Po delta.

role. The Orinoco and Mississippi rivers have the highest discharge of the examined shelves, but they do not contain the species that are most stress-tolerant.

The highest probability for development of anoxic conditions occurs during high sea level when shelves are wide and terrigenous load is fine-grained. The typical low faunal diversity and species content is predictable, allowing recognition of such facies in fossil settings, hence leading to recognition of source-rock type intervals.

4. Conclusions

Independent sedimentologic and paleo-ecological research in the Mississippi and Rhône deltas and shelves, supported by additional evidence from the Po and Orinoco shelves suggests that preferential production and preservation of source-rock type facies alternates from landward to seaward of a shoreline, depending on sea level dynamics in the following manner.

- Paralic peats and related strata are produced and preserved during relative sea level rise landward of retrogradational (landward stepping) shorelines.
- Organic-rich shelf muds are generated under influence of river-induced anoxia during sea level highstands.

Stratigraphically, these processes result in preferential preservation of continental source rock facies in transgressive systems tracts and of marine source rock facies in highstand systems tracts.

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