Clastic facies models, a personal perspective

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Facies models evolved from classifications that were mainly descriptive, based on observable, measureable features such as the composition and texture of sedimentary rocks. As our understanding of sedimentary processes expanded, genetic facies models were developed based on the inferred process of formation. Since individual facies cannot be interpreted in isolation, they must be studied with reference to their neighbours, emphasizing the association of facies and sequences, in particular those that coarsen and fine upward. Environmental facies models are based on the interaction of studies on modern environments and ancient rock facies. Earlier facies models tended to invoke intrinsic, autocyclic controls. The advent of sequence stratigraphy led to greater emphasis on the surfaces that separate sequences and to external allocyclic controls. These were, initially, sea-level changes; later, changes in climate, tectonic movements and sediment supply were invoked.

Over time, simple, all embracing models have given way to increasingly complex ones as our knowledge of the variability of nature has increased. Complex though these models are, they are only simplifications of reality. In nature there are no models and the majority of past environments differed in some respect from any modern environment. Each environment and rock sequence is unique.

Key words: Sedimentary facies, process and environmental facies models, sequence stratigraphy.

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The concept of facies, that is a body of rock with specified characteristics, has been used by geologists ever since they recognized that features found in particular rock units could be used to predict the occurrence of coal, oil and mineral ores. The term was introduced by Gressly (1838) who used it to embrace all the lithological and palaeontological aspects of a stratigraphic unit.

Since that time the term has been the subject of considerable debate and its meaning has been changed, especially in North America (Moore 1949; Teichert 1958; Weller 1960; Krumbein & Sloss 1963). For example, Moore (1949) defined facies as "any areally restricted part of a formation". This is not the way it is used in Europe or by anybody today.

Over the past 30–40 years the term facies has generally been used in the original Gressly sense for a distinctive body of rock that formed under certain conditions of sedimentation, reflecting a particular process, set of conditions, or environment. It should differ from those bodies of rock above, below and laterally adjacent. It may be a single bed or group of similar beds. A facies may be subdivided into subfacies or grouped into associations of facies (facies associations). Where sedimentary rocks can be handled at outcrop or in cores, a facies can be defined on the basis of colour, bedding, composition, texture, fossils and sedimentary structures. If the biological content of the rock is its dominant aspect, then it should be called a biofacies, an ichnofacies being distinguished by its suite of trace fossils. If fossils are absent or of little consequence and emphasis is to be placed on the physical and chemical characteristics of the rock, then it should be called a lithofacies. Where definition depends on features seen in thin section, as is often the case with carbonates, the term microfacies is used.

Models are idealized simplifications set up to aid our understanding of complex natural phenomena and processes. They have been extensively used in the interpretation of sedimentary rock facies.

The manner in which facies models should be used has been the subject of considerable debate (Middleton 1973; Anderton 1985; Walker 1979, 1984; Walker & James 1992; Reading 1978, 1986, 1987, 1996; Miall 1999). They are, however, essentially links between

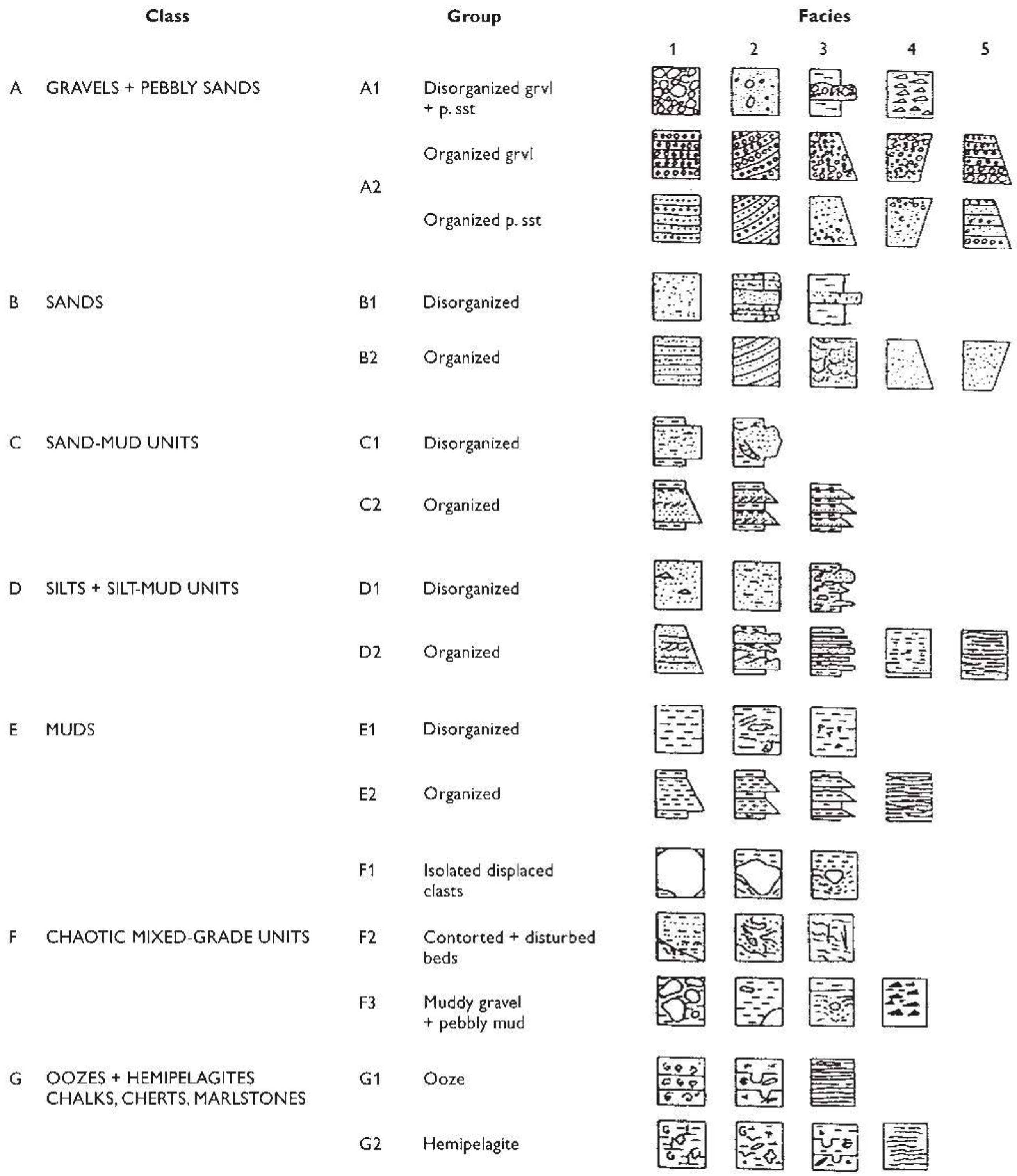


Fig. 1. A descriptive classification for facies recognized in the deep sea (from Stow, 1985). The facies classes are distinguished on the basis of grain size (Classes A-E), internal organization (Class F) and composition (Class G). Facies groups are distinguished mainly on the basis of internal organization and texture. Individual facies (subgroups 1-5) are based on internal structures, bed thickness and composition. Although the classification is designed for deep water sediments, any individual subfacies could also be deposited in shallow water, alluvial or lacustrine environments.

the more descriptive facies classifications and more interpretative models. They are used to interpret facies distributions, both lateral and vertical (through sequence analysis) to predict where as yet undiscovered facies may be found and to indicate the environment, the tectonics, sea-level position and climate of the time.

The earlier facies models were essentially descriptive classifications, based on observable and measureable features, but, as time went by, and our understanding of process and of environment increased, so the word facies came to be used in more genetic senses, that is for the product of a process by which the rock was thought to have formed or the environment in which it was deposited. Although all these senses interlock, it is necessary to be clear of the sense in which the term facies or facies model is being used, in an objectively defined descriptive sense, as an interpretation of the generating process or as an interpretation of the environment in which it was deposited. In addition models have now been extended to those driven by external controls such as changes in sea level, climate, tectonics and the type of sediment supplied to the system.

The creation of facies models and their popularity depends on a number of factors. It may be an individual such as Kuenen who, in the 1950's, initiated, drove and popularized a model for a problem that was awaiting a solution at that time. New techniques and data, unobtainable earlier, enable us to test previously untestable theoretical possibilities or show aspects of the past and present world that could never have been imagined before. 2-D, 3-D and 4-D seismic data have and still are completely transforming ideas and models, especially on and within continental margins and coasts. Economic necessity has always driven geological research from the days when stratigraphy was first used by William Smith, in the early 19th century, to correlate strata cut for the construction of canals, through the facies studies of Shell in the 1960's to improve reservoir models, to the necessity, in recent years for Exxon to correlate unconformities detected in their seismic sections across continental margins.

This paper takes selected examples from deep water, deltaic and fluvial environments to show how ideas and knowledge have evolved over the past 50 years.

Descriptive Classifications

One of the most popular classifications was that of Mutti & Ricci Lucchi (1972) for deep water facies. This lithofacies model (Fig. 1) has continued with slight modifications (Stow 1985; Pickering et al. 1986) to the present day. It was based on observations based on outcrops of ancient facies at a time when it was virtually impossible to obtain cores from modern deep sea sediments. In contrast, outcrops in sections hundreds of metres long could be observed and meticulously measured, even though their mode of emplacement, as well as their environment of deposition, could only be inferred.

Deep water facies were divided into 7 classes, 15 groups and 59 individual facies. The 7 classes were distinguished on the basis of grain size (e.g. gravels

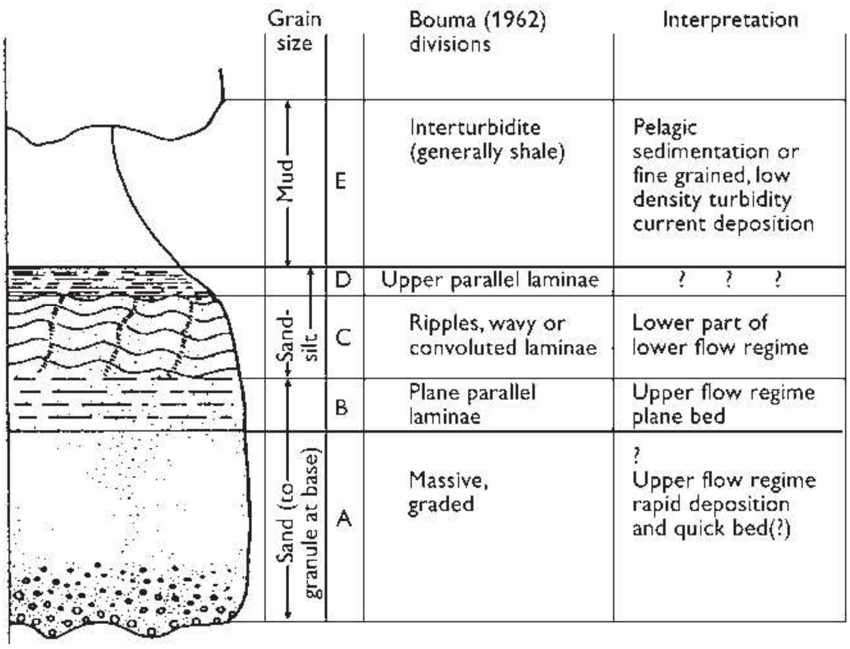


Fig. 2. The sequence of structural divisions in a turbidite bed as described by Bouma (1962) and interpreted as a process facies model by Harms & Fahnestock (1965) and Walker (1965) in terms of flow regimes.

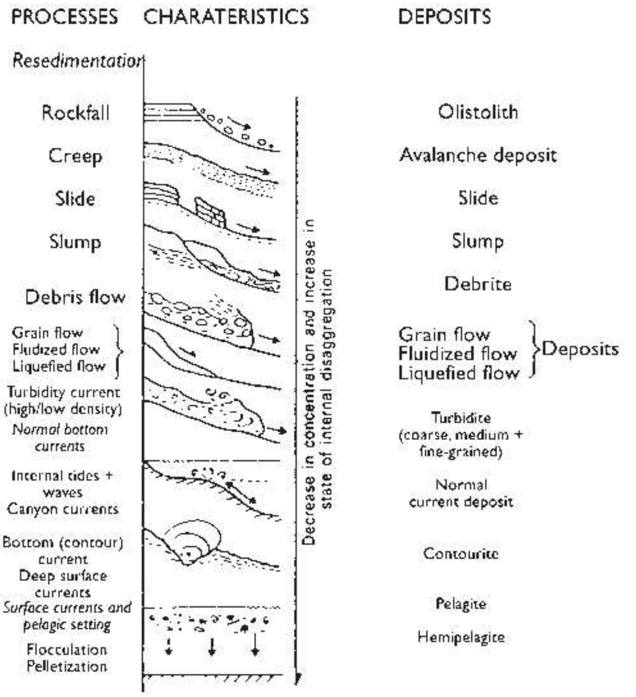


Fig. 3. The full range of process facies models of transport and deposition in the deep sea showing the link between the deposit and inferred process (Stow 1985).

and sands) internal organization (chaotic deposits) and composition (biogenic oozes). The 15 groups were distinguished mainly on the organization of their internal structures and textures. 'Disorganized' facies groups lacked clear stratification and included both structureless gravels, massive sands and bioturbated, massive silty muds and muds. 'Organized' facies groups included those with marked grading, regular lamination, cross-lamination and ripples. The 59 individual facies sub-groups were further subdivided, separated according to their textures, internal structures, composition and bed thickness.

A comparable facies scheme for alluvial facies, that has been extensively applied, is that of Miall (1977). It contains three major grain-size classes, gravel, sand and fines (G,S,F), each of which may be further subdivided according to texture and style of bedding and lamination (e.g. m, massive; t, trough-cross-bedding; p, planar, i.e. tabular, cross-bedding; r, rippled; h, horizontal laminated).

These very detailed and complex facies schemes are invaluable in giving a rigorous objective record of the rocks and enabling different geologists to produce consistent results; they are essential for core analysis in large organizations such as oil companies; and they also force the observer to look at every aspect of the lithology. However, they are time consuming and can become unwieldy. They usually have to be simplified and modified to take account of the time available for the study and the objective of the exercise.

Process facies models

Facies models based on the inferred process by which sediment is considered to have formed generally have the suffix '-ite'. The turbidite model (Fig. 2) is the classic process facies model, the importance of which cannot be exaggerated. It lead, over the next half century to the blooming of process sedimentology, that is the combination of observations in modern environments, of laboratory experiments and meticulous observations on ancient exposed rocks and in cores, within a framework, from the 1960's onwards, of physical parameters.

Though the term turbidite was not then used, the model began in 1950 with the papers of Kuenen (1950), Kuenen & Migliorini (1950) in the Italian Apennines and Natland & Kuenen (1951) in the Ventura Basin of California. At that time there was a major dilemma with the interpretation of flysch, that is the alternations of apparently shallow water sandstones and deep water shales deposited in what were inferred to be synorogenic basins of mountain chains. These alternations were interpreted as having been deposited in very rapidly fluctuating water depths, because the sandstones, thought at that time to be always indicators of shallow water and containing shallow water fossils, were interbedded with shales containing deep-water pelagic fossils. The theory that turbidity currents could carry sands laden with shallow water shells solved a dilemma that numerous geologists in Britain, Poland, the Netherlands and the eastern USA had been attempting to solve.

The term 'turbidite' was introduced in the literature by Kuenen (1957) to solve a major problem of nomenclature that had arisen because of the failure to separate descriptive from genetic facies. This was the use of the word 'greywacke', that is sandstones with a high content of matrix. In the 1950's it had been realized that many greywackes had been deposited by turbidity currents and it had become common to use the term 'greywacke facies' for the deposits of a turbidity current, partly because of the belief, at that time, that mud was an essential component for the formation of a turbidity current. However, as it became apparent that in many greywackes, the mud matrix was the result of the diagenetic alteration of unstable Fe-Mg minerals, it was realized that not all greywackes were formed by turbidity currents. In addition, the deposits of a turbidity current do not always have the high matrix content diagnostic of a greywacke. With the introduction of the word 'turbidite' (Kuenen 1957) for any sandstone thought to have been formed by a turbidity current, the term greywacke could be restricted to a sandstone with a well-defined composition, regardless of whether the high matrix content was the result of deposition from a turbidity current or of diagenesis (Cummins 1962).

Codification of turbidites was achieved by Bouma (1962) whose field measurements quantified the range and variety of turbidite facies. Bouma's study was still essentially descriptive (Fig. 2). Harms & Fahnestock (1965) and Walker (1965), on the other hand, used the expanding understanding of the physics of sedimentation to explain sedimentary structures and their arrangement in terms of flow regimes, that are an indication of the depth and velocity of flows.

The turbidite model is only one of an increasing number of models for deep-water mass-gravity flows (Fig. 3). Soon after its arrival, it was realized that (1) turbidity currents could be of low density as well as of high density as Kuenen had thought, and (2) grain flows (e.g. Stauffer (1967) (with grain-to-grain interactions), liquefied flows (where grains settle downwards, displacing fluid upwards) and fluidized flows (where fluid moves upwards) may produce their own suite of sedimentary structures. In addition, coarser material than sand can be transported into deep water by sudden falls of rock, by slumping, by sliding and by slurry-like debris flows that yield a facies known as a debrite. Thus parallel process models have been developed for coarse-grained (conglomeratic) turbidites (Lowe 1982). Since the processes of transport and deposition can never be known with surety, and since post-depositional modifications can add to or obliterate depositional structures, debate continues fiercely to this day as to how deep water facies were deposited and should be categorized (e.g. Kneller 1995; Shanmugam 2000). Massive sandstones, for example, though generally thought to have been formed by high density turbidity currents, are argued by Shanmugam (2000) to have formed as sandy debris flows and should therefore be debrites, not turbidites.

Alongside models for coarser grained deep sea sediment facies parallel models were developed for fine-grained (mud-rich) turbidites (Stow & Shanmugam 1980).

From quite early days of the turbidite paradigm, there were those who were not prepared to accept that all deep water sands were the product of catastrophic slumps and turbidity currents. During the 1960's it was gradually discovered that oceans were not just rather stagnant bodies of water where deposition below wave base was confined to continuous pelagic settling interrupted by rare catastrophic slumps and turbidity flows. As it became possible to measure mass water flows in the ocean it was realized (e.g. Heezen et al. 1966) that the oceans contained an enormous range of semi-permanent currents which are the deep-water expression of oceanic thermohaline circulation. Since many of these currents, especially in the Atlantic, parallel the contours on the continental slope and rise these currents are known as contour currents and the facies are termed contourites. The composition of clastic contourites ranges from fine terrigenous sand through silt to clay, but also may contain biogenic sediment. When biogenic sediment predominates these biogenic contourites are often indistinguishable from pelagites, formed of sediment generated in the open sea and composed of biogenic material diluted by a proportion (< 25%) of non-biogenic components such as red clays. Hemipelagites are pelagic sediments mixed with silt- and clay-sized particles, derived from a neighbouring land margin.

Extensive facies models have been developed for contourites (summarized in Stow et al. 1996), based on studies of Tertiary to Recent contourite drifts in present-day oceans. The difficulty has been to identify their counterparts in ancient sediments. Few have been identified with certainty. In spite of this, in recent years a case has been made by Shanmugam et al. (1993), studying cores from petroleum reservoirs, for contourites playing a more significant role in deep sea facies in the Gulf of Mexico and the North Sea.

In shallow seas and coastal waters, the earliest process facies models were developed from studies of the effects of tidal currents. Such tidal facies models dominated sedimentological interpretations from the mid-1960's into the 1970's. Models for both estuaries and open shallow seas were developed by researchers in western Europe and north east USA studying the Bay of Fundy, Dutch, French and English estuaries and the shelf sediments of the North Sea. The Haringvliet Estuary of the Rhine delta, for example, was the site for the earliest interpretation of sedimentary structures in terms of flow regimes, as well as the concept of lateral accretion as a cause of a laterally extensive sharp-based fining upward sequence (Oomkens & Terwindt 1960).

The rise and fall of tides either twice daily (semi-diurnal) or daily gives rise to powerful tidal currents that not only alternate with quiet, slack periods but may reverse direction over the same spot at frequent, predictable intervals. The facies gives a distinctive pattern of cross beds, sometimes bipolar, formed during the ebb and flood current stages and mud drapes deposited from fallout in the intervening slack stages. Very sophisticated models have been developed for

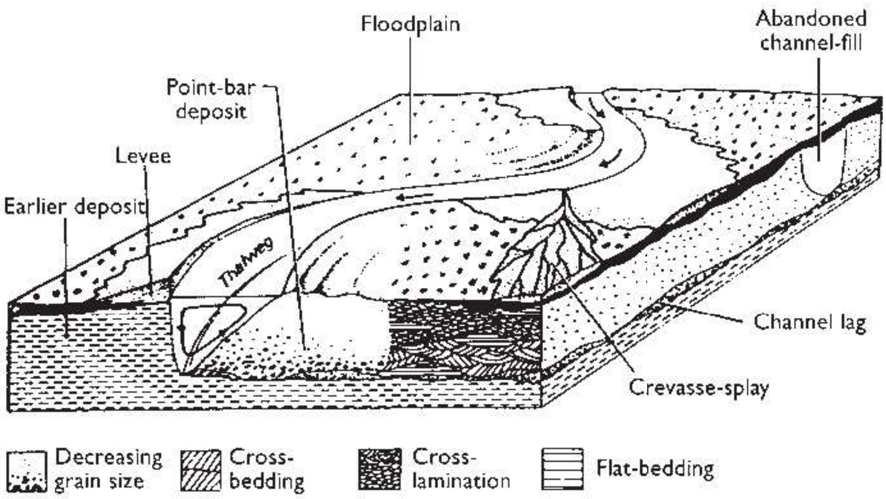


Fig. 4. The classic interpretation of a fining upward sequence as a laterally migrating point bar (after Allen 1964, 1970). The facies model linked process with a specific environment and showed how the vertical superposition of facies could be the result of deposition on a laterally migrating point bar. Notice the crevasse splay deposited during catastrophic flood events that forms a graded bed, sometimes difficult to distinguish from a fining upward sequence.

these tidalites (de Boer et al. 1988), neap-spring cycles being recognized in ancient sediments by the recognition of tidal rhythmites.

Since it was tidal processes, particularly in estuaries and tide-dominated seas that were first documented, the importance of storms was little stressed, except for the effects of hurricanes in the Gulf of Mexico and even hurricanes were thought to have little long term effect on the sedimentary record since they appeared to produce beds only a few centimetres thick and these were rapidly homogeneized by bioturbation. German workers, it is true, (e.g. Reineck and Singh 1972) were conscious of the effects of storms from an early date. However, it was really only the work of Swift (1969) working on the eastern North American shelf, where tidal currents are negligible, that popularized to the Anglo-American world, in a series of papers in the early 1970's, the storm versus fairweather model. This gave rise, in turn, to tempestite models (e.g. Aigner & Reineck 1982) that showed mainly sharp-based graded, thick sandy or bioclastic facies passing seawards into thin muddy distal facies. These graded, sharp-based sandstones have often been confused in the rock record with graded turbidites because the sequence of sedimentary structures is very similar. They can however, be distinguished by the presence of wave ripples indicating they were formed above wave base, or by the trace fossil assemblage.

Environmental facies models

As has already been indicated, important though an interpretation of the formative process is, the same process or different processes that produce a similar facies may occur in more than one, quite dissimilar, environment. A graded sandstone may be a turbidite, a tempestite or formed by a flash flood of a river. A poorly sorted matrix-supported conglomerate may be a debrite, formed by a debris flow or a tillite formed by glacial action. Even a rootlet bed, whilst it does indicate it was deposited very close to or just above water level, does not tell us whether it was formed in a backswamp, on an alluvial fan or river levee. Only the context in which we find the bed tells us the environment or even the process by which it formed. Individual facies, taken in isolation, have their limitations.

Facies have therefore to be interpreted by reference to their neighbours and are consequently grouped into facies associations that are thought to be genetically or environmentally related (Collinson 1969). An association provides additional evidence and so makes interpretation of the environment easier than treating each facies in isolation, particularly in the elimination of alternative interpretations.

In some successions the facies within a succession are interbedded randomly. In others, the facies may lie one above another in a preferred order with predictable upward and downward changes, such as progressive coarsening or fining upward. The importance of facies sequences has long been recognized, at least since Walther's Law of Facies (quoted in Middleton 1973). This states that "only those facies and facies areas can be superimposed, without a break, that can be observed beside each other at the present time". This concept has been taken to indicate that facies occurring in a conformable vertical sequence were formed in laterally adjacent environments and that facies in vertical contact must be the product of geographically neighbouring environments.

However, Walther's Law only applies to successions without breaks. A break in the succession marked either by an erosive contact, or simply a hiatus in deposition, may represent the passage of any number of environments whose products, if they were deposited, were subsequently removed. Some breaks in the succession are essentially autocyclic, that is they reflect natural processes such as the switching of a delta or the lateral migration and avulsion of a river channel. Other breaks, generally more laterally extensive, may be the result of allocyclic controls, external to the local environment due to tectonic movements or changes in climate, sediment supply or sea level. Earlier facies modellers tended to emphasize the gradual sequential essentially autocyclic changes of facies. As we shall see, sequence stratigraphers, on the other hand, stress the breaks or boundaries between sequences, thought to be due to allocyclic controls.

Models based on modern environments were initiated by Fisk (1944) on the Mississippi River, by Fisk et al. (1954) on the Mississippi Delta, Oomkens & Terwindt (1960) on the Haringvliet estuary of the Rhine, and by Glennie (1970) on desert environments. It is significant that the principal purpose of all these studies was to aid in the exploration and production of oil and gas.

These early environmental models were created with limited understanding of the physical processes involved. This changed with the explosion of process sedimentology, particularly with the appearance in 1965 of the classic SEPM Special Publication edited by Middleton (1965) and Allen's (1968) in depth study of the physical processes that formed sedimentary structures. From then on, it was possible to develop environmental models based on measurement of outcrops, particularly sequences and cycles in ancient rocks, to interpret sedimentary structures in terms of physical processes and compare such structures and the composition of sedimentary rocks with comparable features in modern sediments.

The best known and most influential studies on fluvial sediments were those of Allen (1964, 1965a, 1970) who published a series of papers on the fining upward cycles of the alluvial Old Red Sandstone of England and Wales interpreting them as a consequence of lateral migration of point bars in meandering rivers that periodically switched their course (Fig. 4). The full cycle consisted of a sharp, channelled base overlain by an intraformational conglomerate of caliche fragments that passed gradually upwards through parallel-bedded, cross-bedded, cross-laminated sandstones to siltstones capped by a calcrete soil bed. The meandering river model was used extensively by workers all over the world, sometimes to the detriment of alternative explanations for such fining upward cycles, demonstrating the danger of a single, simple model becoming too fashionable. One alternative model, particularly suitable for sediments deposited in semi-arid climates, is that the cycles are the result of ephemeral rivers that flowed for limited periods of time, the channelling and deposition of sandstones occurring during the wet (pluvial) periods, with flows diminishing as rainfall is reduced. Another explanation for many of the smaller cycles is that they were caused by flash floods of very limited duration that can deposit graded beds of some thickness.

Models for a wider spectrum of alluvial deposits were gradually developed over many years by Schumm (1972) who separated alluvial systems into streams dominated by bedload, by mixed load and by suspended load sediments, relating grain size to river sinuosity. Distinctive facies models were created for braided and meandering rivers. Orton & Reading (1993) added gravel-rich alluvial fans to the spectrum that went from alluvial fans through braidplains to the finer grained, low gradient meandering river systems.

Although from the 1930's onwards extensive studies had been made on the deltaic cyclothems of the Carboniferous of the USA and western Europe, these were undertaken with little understanding of modern environments, and little use being made of sedimentary structures, except as palaeocurrent indicators. The abundance of petroleum reservoirs in such deltaic deposits led in the 1960's and 1970's to investigations of other deltas such as the Rhône (Oomkens 1970), Niger (Allen 1965b; Oomkens 1974), Ganges/Brahmaputra (Coleman & Wright 1975), Mahakam (Allen et al. 1979) and Ebro (Maldonado 1975). These studies demonstrated that delta shape and sediment accumulation patterns, especially reservoir sand bodies, varied substantially according to the dominant processes of sedimentation. Where river discharge was high relative to reworking processes in the basin, as in the Mississippi, elongate sand-filled channels ran out into the basin. Where wave action was high, extensive beach/barrier sands form, as in the Rhône. Where tidal range was high, tidal currents are effective well up into the delta plain, as in the Ganges/Brahmaputra or Niger. These variations were encapsulated in the now classical delta model of Galloway (1975) who positioned, on a triangular diagram, each delta, according to whether it is fluvial-, tidal- or wave-dominated or mixtures of more than one process.

To this range of delta models, Orton & Reading (1993) added coarse-grained 'fan deltas' and braidplain deltas, emphasizing the importance of sediment supply to delta systems and of the need to differentiate the dominant grain size in the construction of delta models. The effectiveness of tidal rise and fall, of tidal currents and wave and storm action depends on the grain size of the sediment. A range of deltaic and other coastal systems is now recognized, differentiated not only by the grain size but also by the scales of the system and their slope gradients. Small scale coarse-grained 'fan deltas' supplied directly from the land by catastrophic flood events are relatively unaffected by tides, waves and storms because of the steep gradients of their surfaces. Such systems are very different from the large scale low gradient finer-grained river deltas such as the Mississippi.

In the decade that followed the discovery of turbidity currents as a means of delivering sands to deep water, all environmental models for ancient turbidites assumed, without any doubts, that they had been deposited on flat basin plains, like those of the present day Atlantic Ocean. Palaeocurrent measurements were taken in abundance and generally showed that turbidity currents flowed parallel to the basin axes. Debates were concentrated on whether fill was longitudinal, from one end of the basin, or whether it was by lateral currents that had been deflected along the basin axis (Kuenen 1958). Research on modern deep sea clastic sediments then swung away from the Atlantic to continental margin basins on the Pacific coast of North America. Here Gorsline & Emery (1959) delineated the three principal environments of deep water deposition that we now recognize, basin floor, submarine fan and slope apron, emphasis changing from basin floor to the submarine fan as the principal deep sea facies model, almost to the exclusion of the once exclusive basin plain.

Although the study of modern submarine fans was important to the development and understanding of submarine fans, earlier models were driven primarily by the study of ancient rock sequences such as those in the English Pennines (Walker 1966) and Italian Apennines (Mutti & Ricci Lucchi 1972). The reason for the models being driven by ancient rocks, rather than environmental studies, was because, whilst the shape of modern submarine fans could be roughly outlined (e.g. Normark 1970), it was not possible to determine the nature of the sedimentary fill other than in the top few decimetres. On land, however, whilst the shapes of submarine fans and channels were only rarely exposed, vertical sections, kilometres in length could be measured. These models culminated in the single fan model of Walker (1978) that was widely used in the next decade. On a picture of an idealized submarine fan were placed the predicted facies so that those working on outcrops or with cores could interpret each facies as having formed on a particular part of the fan. Not only were individual facies used, but also sequences; fining/thinning upwards sequences were interpreted as channel fills and coarsening/thickening upwards sequences as prograding lobes.

Valuable though such a model is in relating facies, process and environment into one conceptual model, and popular though it was with petroleum companies and many others, the obvious inadequacy of such a simplistic facies model led to an increasing dissatisfaction with the single fan model to explain all deep water sedimentary facies. Normark (1978) had divided fans into those that were coarse-grained, fed from a submarine canyon and those that were fine-grained, fed from deltas. Chan & Dott (1983), working on outcrops of the Eocene Tyee Formation, chal-

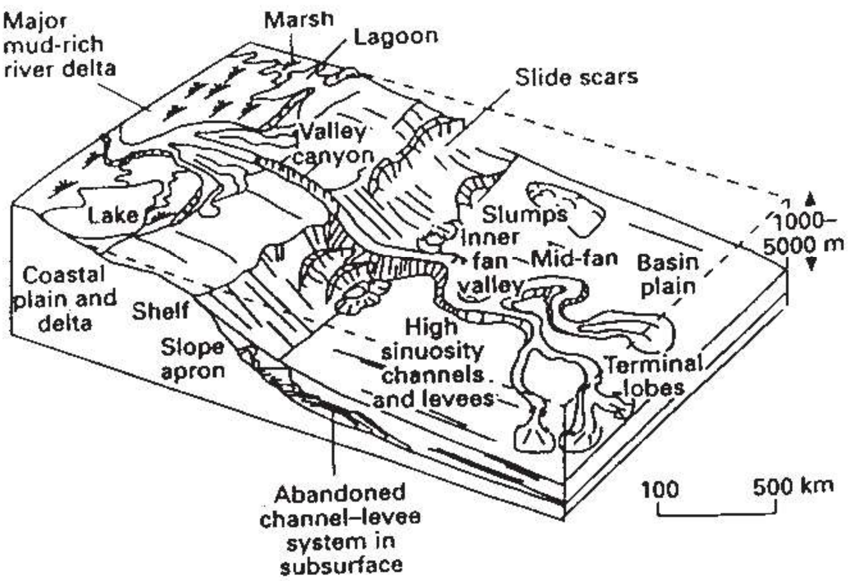
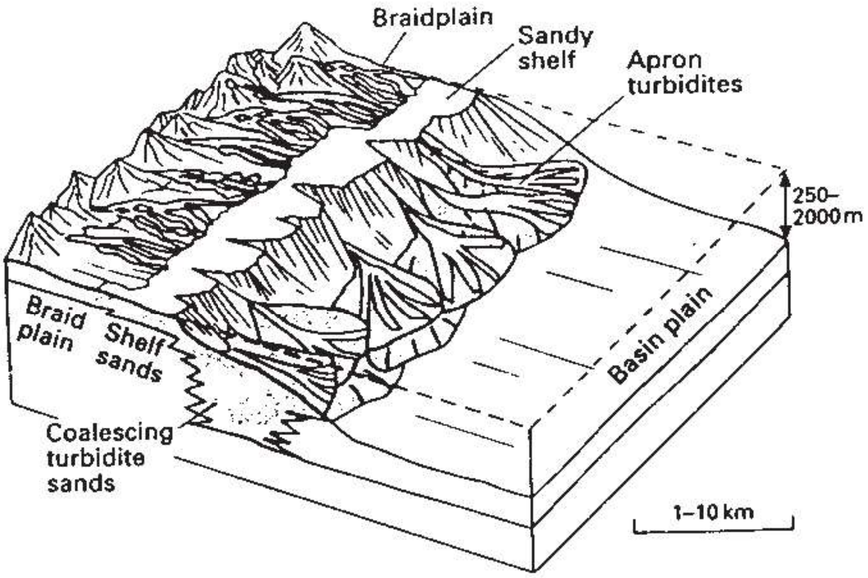


Fig. 5. Environmental facies model for a mud-rich submarine fan, based on the very large, delta-fed fans such as the Mississippi. Rare major events, probably slumps, initiate very large turbidity currents that travel far into the basin (Reading and Richards 1994)

Fig. 6. Environmental facies model for a sand-rich slope-apron showing multiple sourced coalescing fans fed from a mountainous, probably tectonically active, hinterland. A narrow shelf reworks the sediment that is transported by relatively inefficient turbidity currents less than 10 km into the basin (Reading and Richards 1994).



lenged the assumption that they were fed from a single point source, also emphasizing the importance of delta-fed, multiple sourced 'fans'. Mutti (1985), in his summary paper based on the Hecho Group turbidites of the Pyrenean Basin, replaced the term 'fan' by 'turbidite system', developing the important concept of efficient (mud-rich) versus inefficient (sand-rich) systems.

Subsequently there has been an explosion of knowledge on deep water systems. This was a consequence of our increasing knowledge of modern environments and the subsurface, rather than on ancient rock outcrops. It is due to a combination of an increasing number of cores in oceanic sediments, seismic profiling and the discovery and exploitation of deep water petroleum reservoirs in the North Sea, the Gulf of Mexico and the margins of the South Atlantic. Because seismic profiling is much easier in deep water than in shallow water, or on land, models for deep water sediments are now derived more than any other facies models from studies of modern seas and continental margins.

Such studies led to many subdivisions of "fans" based on differences in sediment grain size, efficiency of the transporting turbidity currents, the nature of the feeder system or even the plate tectonic background.

Reading & Richards (1994) distinguished 12 facies models for base-of-slope depositional systems, i.e. submarine fans and slope aprons. The basin floor environment was omitted. They showed that separate models need to be created, distinguished by the volume and calibre (grain size) of sediment supply and the nature of the supplying system whether it is a single point source, a multiple source or a linear slope apron (Figs. 5, 6). Unlike previous authors, they included coarse-grained, gravel-rich "fan delta" systems in their classification.

Thus the prime control for deep water systems is sediment supply. This includes the composition of the sediment, the volume, rate and frequency at which it is made available for deposition, and the number and position of input points. On the basis of grain size, there are mud-rich (Fig. 5), mud/sand-rich, sand-rich (Fig. 6) and gravel-rich systems. As grain size increases, so does slope gradient, flow frequency, impersistence of channel systems and the tendency for channels to migrate. As grain size diminishes, there is an increase in the size of the source area, the size of the depositional system, the downcurrent length, the persistence of flows, fan channels, the size of the channel-levee systems and the tendency to meander and for major slumps and sheet sands to reach the lower fan and basin plain.

Feeder systems can be separated into point-source submarine fans (Fig. 5), multiple-source submarine ramps and linear-source slope aprons (Fig. 6). Point-source submarine fans are characterized by large stable and organized channel-levee systems. Multiple source systems, generally fed by switching deltas, have less organized sequences. Linear source slope aprons have a random pattern of sedimentation and a very low length: width ratio.

Placing particular examples into such rigid classes is not without its dangers. There is a gradational continuum between the classes with some systems falling between two classes. Systems may also change rapidly from one class to another and back again as the ultimate controlling factors such as sediment supply, sea level and subsidence rates alter.

In the end the actual facies distribution that is encountered is a consequence of many local factors that operate primarily within the basin itself. These factors include the shape and size of the basin, the depth of water, basin salinity, organic and hemipelagic supply, semi-permanent ocean bottom (contour) currents, erosional and depositional features of the sediments, synsedimentary tectonics, diapiric movements especially of salt, sand and mud, and differential compaction.

Allocyclic sequence stratigraphic models

The idea that facies models may be the result of external forces has never been absent from the minds of sedimentologists. Prior to the onset of the era of process sedimentology in the 1960's such factors predominated as explanations for facies changes. Tectonic movements were commonly thought to be the driving force, leading, for example, to the distinction between such tectofacies as syn-orogenic flysch and post-orogenic molasse in the Alps and the differentiation of major lithofacies into orthoquartzites, graywackes and arkoses by Krumbein & Sloss (1963).

Nevertheless, the idea that such external factors could be the driving force behind facies models was greatly underplayed in the 1960's and 1970's era of process, internally driven models.

The new "Sequence Stratigraphic" approach, often thought of as a revolution in the Earth Sciences, began with the publication of the now classic American Association of Petroleum Geologists Memoir 26 (Payton 1977). Significantly it was neither sedimentologists nor stratigraphers who initiated the revolution in the Earth Sciences, but petroleum seismic interpreters. As techniques of seismic acquisition and processing improved, they differentiated a number of seismic facies based on reflection configuration, continuity, amplitude, frequency and interval velocity, together with the external form of the unit. Unlike outcrop facies analysis, where the shape of the unit is usually difficult to ascertain, the two- and three-dimensional external form of the seismic facies unit is an essential element in subsurface seismic facies analysis. Shapes include sheets, wedges, banks, topographic buildups and channel fills. Such seismic facies were a major factor in the creation of the deep water environmental facies models discussed in the previous section.

However, what led to a revolution was the emphasis on surfaces and breaks in sedimentation, as petroleum geologists transformed seismic stratigraphy (Payton 1977) into sequence stratigraphy (e.g. Wilgus et al. 1988). Sequence stratigraphy is the analysis of genetically related depositional units within a chronostratigraphic framework. The roots of the ideas go back several decades to the two main schools of North American outcrop and subsurface geologists. The main difference between the schools is in the position of the boundaries between which the sequences are defined, and the emphasis made on the principal control on sequence changes.

The Gulf Coast School, based in Texas and Louisiana, developed a model for 'genetic stratigraphic sequences' (Galloway 1989) bounded by marine flooding surfaces that are easy to correlate in logs and at

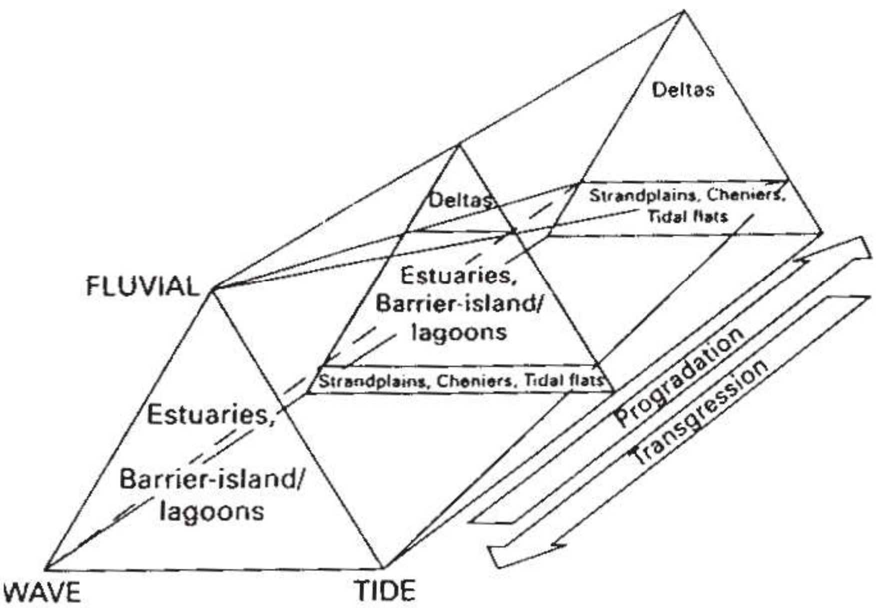


Fig.7. The classic Galloway (1975) delta triangular environmental facies model, based on the dominant process, fluvial supply, waves or tides, is expanded to take into account relative sea-level changes (based on Dalrymple et al. 1992).

outcrop especially when biostratigraphic data are available. They were working mainly in the subsurface over large areas with little or no outcrop, but extensive coverage of rather poor quality, rare cores and abundant electric logs, allowing extensive isopach and isolith maps to be constructed. There was little tectonic deformation and environmental facies models were developed without the attention paid to detailed processes that traditional facies modellers had had to do. Their models were particularly suitable for large regions of substantial but steady subsidence and a high influx of sediment, variations in clastic sediment supply being the principal control on facies patterns and changes.

The Cratonic/North Western/Exxon School was developed initially by Sloss (1963) and revived many years later by the Exxon Group of seismic interpreters, a significant factor being that the leading exponent of the Exxon Group, Peter Vail, had been a student at North Western University. Their depositional sequence model took its sequence boundaries at unconformity surfaces and their supposed correlative conformities. It originated on the central, stable, cratonic shield region of the USA where similar lithofacies, separated by unconformities, could be traced hundreds, if not thousands of kilometres with little change of facies. The Exxon Production Research (EPR) Group developed their depositional sequence model after examination of many seismic sections across passive continental margins around the world. At first control was considered to be almost exclusively eustatic sea-level change, and process sedimentology, even lithofacies, played only a small part in interpretation. Later, changing subsidence rates and sediment influx were included and the methodology and ideas were applied to onshore outcrop geology. Facies patterns, though, were fitted into models of sequence stratigraphy (Wilgus et al. 1988) that were largely based on theoretical concepts rather than a careful analysis of the sedimentary facies.

The depositional sequence model predicted a lithological succession that resulted from variations of sea level divided into a lowstand, a transgressive and highstand systems tract, separated by and including surfaces that include not only the sequence boundaries marking each major lowstand but within the transgressive systems tract an initial flooding surface followed by a transgressive surface and ravinement surface demonstrating the multitude of erosion processes occurring during transgression and a maximum flooding surface (the sequence boundary of Galloway) marking the extreme limit of sea-level rise. Within the major systems tracts there may be a multitude of parasequences and sets of parasequences that may themselves prograde, aggrade or retrograde. Such parasequences are comparable to the process/environmental autocyclic sequences of process sedimentologists, though the latter include a much wider range of environments than the limited shoreline-related parasequences of the sequence stratigraphers.

As with all fundamental and original models in geology, especially those based on data, such as seismic profiles, not previously available, new insights have been given to facies modelling. Surfaces, previously largely ignored by outcrop geologists, partly because they are frequently poorly exposed, are now examined with care, and many more gaps in the sedimentary succession are recognized, recorded and interpreted.

Though successful attempts have been made to show the effect of sea-level change on deep water and fluvial systems, the greatest impact on facies modelling has been on coastal systems because they are more directly affected by sea-level changes, even quite small ones.

The earlier models (Galloway 1975) reflecting the balance between tidal, wave and storm action and the influence of the grain size of sediment supply (Orton & Reading 1993) are not abandoned but have now been expanded to show the effects of rises and falls of sea level (Boyd et al. 1992) (Fig. 7). Regressive coasts are characterized by deltas, fed by rivers, by strandplains fed by longshore and coastal current drift, where wave action is relatively powerful and by prograding tidal flats where tidal action predominates. Transgressive coasts are characterized by barrier island-lagoonal systems where wave power is strong and by estuaries where tidal action is significant.

20 years ago estuaries were hardly ever invoked as a model for the interpretation of ancient sedimentary facies by sedimentologists, in spite of their obvious presence along the coasts around western Europe and eastern USA. This was changed by the discovery and emphasis given to the sequence boundary in the Exxon sequence stratigraphic model. It was shown that in many coastal sequences there were deeply incised valleys that had eroded substantial thicknesses of the underlying sediment column (Dalrymple et al. 1994). Cut during the lowstand when rivers reach out to the shelf, as sea level rises estuaries are filled by a complex pattern of sand and mud packets, broken by several recognizable surfaces, a transgressive surface, a maximum flooding surface and local ravinement surfaces caused by tidal or wave action (Zaitlin et al. 1994) (Fig. 8).

The nature of the estuarine fill depends on whether tidal action predominates, filling the estuary with tidal sand bars, tidal channel sands, or tidal flats, or was dominated by waves so that the central estuarine basin was protected from the sea by a barrier. Thus proc-

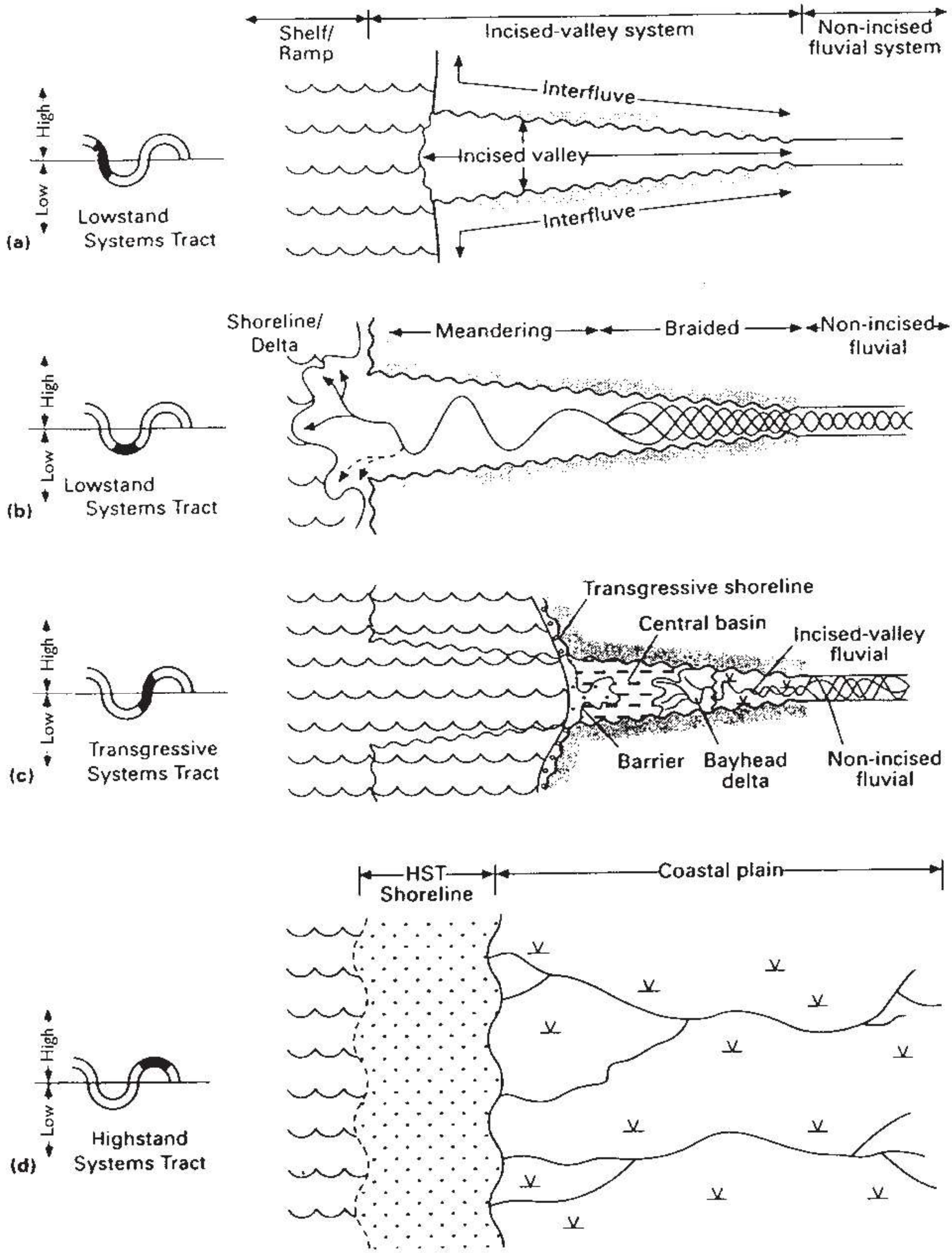


Fig.8. Allocyclic, sequence stratigraphic model driven by an idealized sea-level curve and showing the evolution of an incised-valley system over one complete sea-level cycle. (a) Lowstand time; incision of the valley. (b) Lowstand time; extension of fluvial-deltaic system to shelf edge. (c) during transgression a classic wave-dominated estuarine system develops. (d) during highstand the coastal plain and shoreline prograde beyond the margin of the buried, incised system (modified after Zaitlin et al. 1994)

ess/environmental facies models have to be included within those driven by sequence stratigraphic concepts.

Conclusions

There is a range of different types of facies model, descriptive lithofacies classifications, those that are based on process and those that profess to show the environment of deposition. In addition, there are models driven by considerations of external controls such as changes in sea level, climate, tectonics and the type of sediment supply.

Facies models have been created for many different reasons, to bring coherence to a mass of apparently random complex data and to select features from those data that are considered the most important. Such selection emphasizes data that can be easily measured, understood and interpreted. For example, sedimentary structures were first properly recorded when they could be explained in terms of the physical processes that had transported and deposited the sediments. On the other hand, observers tend to ignore what they cannot explain.

Single, simple models, while useful in teaching, and inevitable at early stages of understanding, are dangerous if applied too literally in the interpretation of facies patterns. As time goes by and knowledge increases, simple models give way to more complex multiple models. Such multiple models are required to isolate the interrelated range of controls that give rise to the actual facies pattern, each of which is unique, similar though it may be in some respects to other facies patterns.

Many successful models are driven by individuals such as Kuenen, who travelled the world with a solution to a problem many people had already perceived. More often it is the effort put in to solve an economic problem such as the determination of the shape, size and distribution of sand bodies, or the correlation of seismic sections around the world's oceans. Limitations of models are the result of the restricted experience of individuals and research groups and their geographical location, models having been dominated by studies in the Californian Borderlands, the Gulf of Mexico, the coasts of eastern USA and western Europe.

With easy air travel these days, this is less and less a limitation. As knowledge and new data about the world are increased, fresh models will have to be constantly created.

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