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Transgressive deposits: a review of their variability

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Abstract

Transgressive deposits accumulate with rising relative sea level during the landward migration of a coastline. Particularly at short time scales (e.g., 4th- to 6th-order cycles), transgressive deposits can be recognised through the evidence of a gradual or irregular landward shift of facies, or an upward deepening of facies that culminates in a surface or zone of maximum flooding. During transgression, the coastline moves landwards and the shelf area enlarges. This is accompanied by a tendency to have more sediment trapped in the alluvial and coastal plain environments, a reduced sediment influx to the basin, and cannibalization (through ravinement) of previously deposited sediments, including those deposited in the early stages of transgression. The resultant deposits can be fully marine, estuarine/lagoonal or fluvial, and can include other facies such as coal and eolian deposits with a variability driven by changes in rate of sea-level rise, sediment supply, textural character of the sediments, shelf gradient or basin physiography.

Transgression may be continuous or punctuated, the latter occurring by alternation of coastal retrogradation and regression despite a longer term, landward-stepping of the shorezone. This commonly results in shoreface retreat, barrier in-place drowning, or a variety of transgressive parasequences whose character depends on the balance between sediment supply and accommodation creation. Any classification effort based on driving force or sedimentary processes tends to be overidealised. We therefore propose a classification based on the recognition of distinctive surfaces (wave and tidal ravinement surfaces, transgressive surface) within the transgressive lithosome.

Transgressive scenarios are presented from different settings. Five types of transgressive lithosome, with variable thickness, lateral extent and internal architecture are discussed. (1) Transgressive deposits developed *below the lowest ravinement surface* (termed T-A) are commonly coal bearing (back-barrier) and alluvial. They accumulate in low-gradient settings where there is divergence between the ravinement trajectory and the surface being transgressed. (2) Transgressive deposits developed *above the tidal but below the wave ravinement surface* (T-B) accumulate where tidal processes dominate over storm-wave processes. Here too there is, at least locally, a slight landward divergence between the two surface types, allowing the development of sandy estuarine lithosomes. The wave ravinement surface may be absent in the innermost part of transects or if the deposits represent purely tide-dominated high-energy settings (that are not dealt with in detail in this paper). (3) Transgressive deposits developed *above the wave ravinement surface in low-gradient settings* (T-C). Such deposits derive from shoreface erosion or from longshore drift. They are usually very thin, but thicken where the transgression was punctuated by regressive pulses or where offshore sand ridges form. (4) Transgressive deposits developed *above the wave ravinement surface in high-gradient high-sediment supply settings* (T-D). In this setting (commonly fault-bounded terraces, valley walls, or simply steep slopes), the

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transgressive deposits can be much thicker because all eroded and newly supplied sediment is deposited locally. (5) Transgressive deposits *without evidence of ravinement surfaces* (T-E). These can be characteristic of low-energy settings that are typically mud-dominated.

Keywords: transgressive deposits; wave ravinement surface; tidal ravinement surface; transgressive surface; classification

1. Introduction

Transgressive deposits may be identified at different spatial or time scales, and it is difficult to discuss them in general terms. Indeed, at longer time scales (e.g., 3rd-order cycles), transgressive deposits can be fully marine, shallow-water, estuarine, fluvial or paleosol in nature and are represented by a broad range of lithologies. However, particularly at short time scales (e.g., 4th- to 6th-order cycles, that are the main focus of this paper), it is possible to define transgressive deposits sensu strictu as those having originated at or near the shoreline, partly or largely in response to rising relative sea level and landward migration of the shoreline.

Transgressive deposits are of interest to both academic and applied research. Within transgressive successions, for example, transgressive sands are commonly more mature both texturally and mineralogically than regressive sands, and therefore in many cases make excellent reservoirs (e.g., Devine, 1991; Snedden and Dalrymple, 1999; Posamentier, 2002). They are commonly very thin, because of the rapid transit that transgressive shorelines make over low-lying coastal plains. In a number of well-documented cases, however, transgressive sands can reach up to a few tens of metres in thickness (e.g., Tye et al., 1993; Ravnås and Steel, 1998; Steel et al., 2000). Fine-grained lithologies are also common within transgressive successions, where they can act as hydrocarbon sources and seals and have significant impact for reservoir characterization, e.g. for the distribution and nature of low-permeability intervals or barriers to fluid flow (Olsen, 1998). These considerations provided the motivation for reviewing the documented, the likely and the possible variation of thickness, extent and architecture of transgressive deposits, particularly their thickness in ancient and modern successions. The ultimate reason to have documentation of this variability is to improve our analytical or predictive ability for such deposits in areas of poor-quality and/or limited data coverage.

The variability of transgressive deposits, driven by numerous factors influencing shoreline migration, is high not only for deposits emplaced during transgression under different conditions (different rate of transgression, geological setting, sedimentary basin), but also for coeval deposits over relatively small distances within the same sedimentary basin (Heward, 1981). Subtle changes in one or a combination of the controlling factors can substantially modify the nature of transgressive deposits. However, almost any effort at classifying transgressive deposits based on the driving factors is likely to be overidealised. In order to overcome this problem, a physical approach, based on the recognition of characteristic features of the transgressive deposits is proposed. Distinct surfaces within the transgressive lithosome mark significant events during the transgression, and form the framework of the resulting stratal architecture. Emphasis on the relevance of stratigraphic surfaces within the rock record is not new in geological literature (e.g., Levorsen, 1931; Twenhofel, 1936; Krumbein, 1942; Sloss, 1963), and has been pointed out particularly in works dealing with seismic and sequence stratigraphy (e.g., Vail et al., 1977; Van Wagoner et al., 1988, 1990). We analyse in detail the stratigraphic surfaces and other relevant elements within transgressive lithosomes.

2. Key features of transgressive deposits

Transgressive deposits accumulate during the landward movement of a coastline. This implies a necessary rise in relative sea level, unless some very unusual situations are invoked, such as significant erosion or subsidence of the land area at a time of slowly falling sea level and minimal sediment input

(Curray, 1964). There are two main criteria for identifying transgressive deposits:

(1) Evidence of a systematic or irregular movement of the shoreline towards the land, causing an overall landward shift of facies. This could be visible in large outcrops or from high-resolution seismic profiles and would be evident from an overall retrogradational stacking pattern of units in correlated well-logs, seismic lines and outcrops (e.g. Van Wagoner et al., 1990). Punctuated landward-stepping geometries are an important diagnostic stratigraphic architecture at both the facies succession and parasequence scales (Galloway, 1998). Punctuation of long-term transgression by repeated short-term regressions is due to the common tendency for sediment-supply rates to outmatch, for short periods, accommodation increase rates.

(2) Evidence of a general or abrupt upward-deepening of facies, culminating in a level of deepest or most offshore facies, commonly termed the maximum flooding zone or surface (MFS). This key surface is detectable in outcrops and cores and forms a downlap surface for the overlying regressive deposits. In gamma-ray and spontaneous-potential well logs, the fining-upward character of transgressive deposits shows a characteristic bell shape. Near the base of many transgressive deposits, one or more important surfaces are present (transgressive surface, tidal and/or wave ravinement surface), in cases where the transgressing shoreface was one of high or intermediate energy, with possible presence of carbonate cement and pebble or shell lags. In many cases, these are the most prominent surfaces visible in outcrops, and as such are important elements in the analysis of sedimentary successions. However, since sediment supply may be laterally variable in a basin, or the underlying sequence boundary created significant topography, lateral tracing of such surfaces is not straightforward, and requires a good knowledge of the basin. Sometimes these surfaces are offset successively landwards, particularly where the transgressive deposits are thick or where transgressive sands show a stratigraphic “rise” with a steep landward trajectory.

2.1. Recent vs. ancient transgressive deposits

As in the case of comparison between ancient and modern deepwater deposits (Mutti and Normark, 1987; Piper et al., 1999), a bias arises from the comparison of ancient and recent transgressive deposits, because of the differences in methodology of study and resultant data sets. Ancient transgressive successions are well studied in sand-dominated outcrops of limited lateral extent that provide good local documentation of key surfaces; recent and modern transgressive systems, on the other hand, are better imaged and sampled spatially, commonly in mud-dominated environments (e.g., Bergman and Snedden, 1999).

Research on transgressive deposits of the last sea-level cycle has a clear advantage with knowledge of eustatic sea-level behaviour and oceanographic or paleoceanographic data, providing detailed information about depositional processes and relationships to present-day physiography. Recent transgressive deposits can be age-dated, putting a strict constraint on the stratigraphic setting and allowing a demonstration of synchroneity of different accumulations within a basin. High-resolution seismic data allow extensive mapping of key surfaces. However, it is difficult to characterise these surfaces from only scattered sediment cores. An additional bias is the dominance of studies of modern transgressive deposits in areas of relatively high relief (e.g., U.S., Canadian and Australian east coasts): there are relatively few studies in coastal-plain areas that are better analogues for many ancient basins.

Another difference between studies of recent and ancient transgressive successions is that the time interval that they encompass may correspond to dissimilar conditions in Earth history or vary by orders of magnitude. Late Quaternary transgressive deposits may represent an unusual record of high-frequency and high-amplitude sea-level oscillations driven by glacioeustasy. The resulting rapid, relative sea-level rises could represent a bias when comparing with the record of geologic times devoid of glaciations (e.g., the Cretaceous). Transgressive deposits emplaced during the last relative sea-level rise represent a very short time interval, but nevertheless reflect also changes in sediment supply and oceanographic regime driven by short-term climatic oscillations. The observation of transgressive shelf sediments on modern shelves is also influenced by the present highstand condition, while comparable ancient deposits represent only the preserved portions of transgressive systems that underwent following sea level fall. In ancient successions, transgressive deposits tend to encompass longer time intervals and allow less stratigraphic resolution, because the depositional record is likely to be less complete. Despite differences of preservation potential, diagenesis, compaction, and successive reworking, ancient and recent transgressive deposits represent complementary datasets.

3. Conceptual aspects of transgression

3.1. Shoreline trajectory

The concept of transgression is well expressed in terms of shoreline trajectory, because of the variable paths that the shoreline may take. The shoreline trajectory is the "cross-sectional shoreline migration path along the depositional dip" in response to changes in relative sea level, sediment supply and basin physiography (Helland-Hansen and Gjelberg, 1994). The shoreline, as used here, is similar to the "depositional shoreline-break" (Posamentier and Vail, 1988), although the level of these two features may be offset (Helland-Hansen and Martinsen, 1996). Transgression occurs when the shoreline trajectory has a direction between 90° (upwards) and 180° (landwards; Fig. 1A). Theoretically, it is possible for the shoreline to have a "negative", transgressive trajectory (180–270°), when significant erosion or subsidence of the land area occurs at a time of slowly falling sea level and minimal sediment input (Curray, 1964); however, this situation seems only of theoretical interest, and it is difficult if not impossible to prove it from the rock record.

There are three scenarios for transgressive shoreline trajectories (Helland-Hansen and Gjelberg, 1994; Fig. 1B):

(1) The shoreline trajectory coincides exactly with, or is at a lower angle than, the older surface being transgressed, and few or no transgressive deposits can be accommodated. This situation is favoured by high rates of relative sea-level rise, a low-gradient transgressed topography, and negligible sediment supply to the shorezone ("nonaccretionary transgression" in Fig. 1B). Of course in a larger context (e.g., in a longer time period or considering a more extended area), deposition may occur somewhere, for example basinwards, where sediments eroded at the shoreline may accumulate.

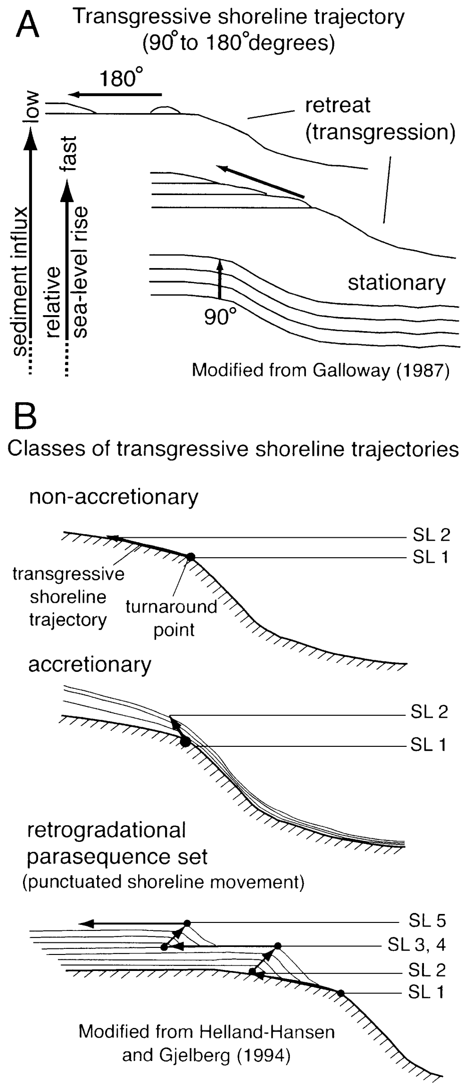


Fig. 1. (A) Transgressive shoreline trajectories comprised between 90°, upwards, and 180°, landwards. (B) Three classes of transgressive shoreline trajectories. The shoreline trajectory is the "cross-sectional shoreline migration path along the depositional dip" in response to changes in relative sea level, sediment supply and basin physiography (Helland-Hansen and Gjelberg, 1994). SL = sea level.

(2) The shoreline trajectory diverges upwards from (i.e. is slightly steeper than) the transgressed topography, and transgressive deposits accumulate, if high sediment supply from behind the shoreface

is provided ("accretionary transgression" in Fig. 1B).

(3) The shoreline trajectory has a complex "zigzag" pattern, if transgression occurs with punctuated shoreline movement, albeit moving overall landwards. In this case, there are short intervals of regression during overall transgression ("retrogradational parasequence set" in Fig. 1B) whether caused by autocyclic shifting during retreat (Muto and Steel, 2000) or by independent changes in accommodation or sediment supply during retreat. This situation is common, because it is likely that all transgressions have at least some "punctuation" in their history. This would happen when the shoreline trajectory is not parallel to the original land surface for one of four reasons: (a) the depth of transgressive erosion changes due to changes in, for example, wave energy; (b) the rate of sediment supply changes because of changes in climate in the hinterland; (c) the original land surface did not slope linearly towards the sea; and/or (d) the rate of relative sea-level rise changes.

It should be noted that in order to get net deposition during transgression it is sufficient for the shoreline trajectory to have been steeper than the original topography only at one time, not continuously, during the entire transgression (Dalrymple, personal communication). A brief period of "accretionary" transgression, followed by a change to "nonaccretionary" transgression (Fig. 1B) will leave a stratigraphic record. The same, but opposite, concept applies to situations of net transgressive erosion. Only if the transgression is "nonaccretionary" throughout its entire history will there be no deposit.

The concept of shoreline trajectory may be applied directly in cases where it is possible to follow the path of the shoreline through time, as on extensive outcrops or high-resolution seismic data. However, it remains a conceptual tool for emphasizing the range of scenarios of transgressive deposits rather than an effective basis for their classification. Fig. 2 illustrates a classic example of a transgressive shoreline trajectory, where shoreline retreat is interrupted by short periods of accelerated relative sea-level rise leading to barrier overstep (Fig. 2A), or stillstand, when barrier progradation and accumulation of locally thicker transgressive deposits occur (Fig. 2B).

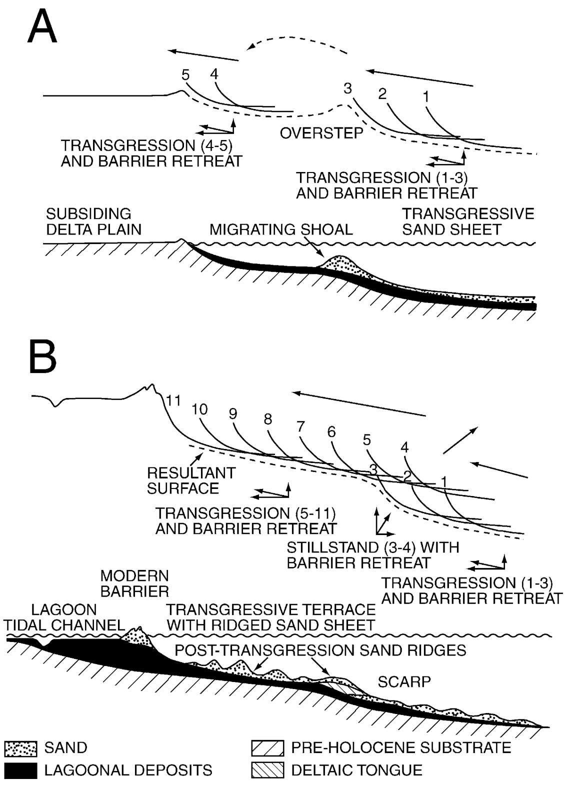


Fig. 2. (A) Diagram illustrating successive shoreface profiles in the case of barrier overstep (Swift, 1975a). (B) Diagram showing the shoreface profile at various positions during shoreface retreat interrupted by a progradation episode. Note the thick wedge of back-barrier (lagoonal) sediments below the ravinement surface (labeled as "resultant surface") and the site of sand accumulation above the ravinement surface during upward accretion and little horizontal retreat (Swift, 1975a).

3.2. Regime model and some implications

The dynamics of shoreline displacement and the resulting architecture and thickness of transgressive deposits are strongly dependent on the rate of sediment influx relative to the rate of sea-level change, shelf gradient (or, more generally, basin physiography) and spatial distribution of energy. Most of these factors have been combined in the regime model (Thorne and Swift, 1991), where the depositional regime (¥) is expressed as the ratio of combined accommodation variables [R (rate of relative base level rise) and D (rate of sediment transport)] to combined supply variables [Q (rate of sediment supply) and *M* (textural composition of the sediment)]. Some implications on these parameters deserve a brief discussion.

The rate of sediment transport (*D*) has a significant effect during transgression. The focusing effect of currents (storm-driven, thermohaline or tidal in origin) against coastal promontories or morphologic barriers may result in regions of either erosion or enhanced accumulation of sediment. In general, both sediment supply and oceanographic regime affect the internal geometry of depositional sequences on very short time intervals (decades to millennia), even during cycles that are primarily driven by sea-level oscillations (Thorne and Swift, 1991). Furthermore, during transgression the oceanographic regime itself is likely to change because of the effects of basin widening and increased wind fetch (especially in epicontinental basins; Correggiari et al., 1996b), varying configuration of the coastline with an increased number of embayments, possible changes in current pattern and strength, and differing interaction between waves, the seafloor and the coastline. Also the tidal regime may be highly influenced by basin/shelf widening (e.g., Howarth, 1982; Reynaud et al., 1999a). Some of these changes have been documented for late Quaternary deposits, where the importance of the above hydrodynamic factors has been stressed (e.g. Harris et al., 1996; Berné et al., 1998; Liu et al., 2002). It could be difficult to demonstrate the same for ancient successions, although it is possible to have evidence that this is the case, as when wave/storm-dominated marine sediments are overlain abruptly by tide-dominated marine—not estuarine—deposits (Willis and Gabel, 2001).

The rate of sediment supply (*Q*) is the main parameter in the supply term, and includes fluctuations that depend on climatic change in the catchment area of the supplying rivers, changes in the pattern of longshore currents, and physical characteristics of the receiving basin. In many simulation models, transgressions and regressions are interpreted as resulting from the combination of eustatic change and constant subsidence, assuming a constant sediment supply (e.g., Heller et al., 2001). Rhythmic fluctuations in sediment supply deriving either from short time-scale tectonic or climatic causes can, however, alter substantially the stacking pattern within depositional sequences (Schlager, 1993).

The sediment character (*M*) depends on the source area, but it is also a function of sediment partitioning occurring from source to basin areas. This is the case of a transgressive lag that results from the action of waves during transgression and produces a winnowing of fine sediment transported alongshore by coastal currents (e.g., Harris et al., 1996), or basinwards (as in the case of part of the outflow of the Yellow River; Alexander et al., 1991).

3.3. Autoretreat

Muto and Steel (1992, 1997) highlighted the inbuilt and inevitable tendency for regressive shorelines to turn around to transgression without the imposition of any change in rates of accommodation creation or sediment supply. This phenomenon was termed autoretreat (Muto and Steel, 1992), and is operative during the regression of coastlines under conditions of even a slight rising relative sea level. In such circumstances, the coastline turns around from regression to transgression after a surprisingly short period, without any decrease in the rate of sediment supply or increase in the rate of relative sea-level rise. Autoretreat is caused by the inability of the sediment supply to fill the ever-increasing area behind the regressive/aggrading shoreline, without some exceptional supply increase. This concept also cautions against automatic use of changes in supply or relative sea-level rise to explain shoreline trajectory changes from regression to transgression.

3.4. Inherited physiography

The inherited physiography of a basin reflects the depositional geometry of older deposits and their history of erosion, burial and compaction. Although many authors have pointed out the importance of this parameter (Abbott, 1985; Belknap and Kraft, 1985; Demarest and Leatherman, 1985; Ross et al., 1995; Helland-Hansen and Martinsen, 1996; Talling, 1998), not enough emphasis has been put on it as one of the main factors that acts at the same rank as the regime parameters in controlling sedimentary architecture. The role of inherited physiography is illustrated here for transgressive deposits in terms of its gradient and its roughness.

The *gradient* of continental shelves (or of inundated alluvial plains) may be low (say <0.001) or high (>0.001; this value is arbitrary and corresponds to creation of 1 m of accommodation over 1 km, with an angle of 0.057°). Miall (1991) reported slope values for 10 modern shelves ranging between 0.00023 and 0.0095. During transgression across a high-gradient topography, the landward movement of the shoreline is relatively slow and the process of ravinement (erosion by wave action) at the shoreface has more time to rework and redeposit sediments. This results in shoreface retreat, formation of a ravinement surface, and possibly relatively thick transgressive deposits above the ravinement surface (a "continuous" transgression is more likely, see Fig. 3). Furthermore, during a relatively slow transgression, there could be a tendency to trap only the coarser sediment fraction in channel axes along the coast, while the finer fraction bypasses to the shelf (Swift, 1976; Kidwell, 1989). An equal rise in relative sea level in a low-gradient setting causes a more rapid landward shift of the shoreline and a much wider transgressed area. This, in turn, causes sediments to be more widely dispersed and the resultant deposits to be thin. This situation is also more prone to in-place drowning of the shoreface, if the rate of relative sea-level rise is sufficiently high (Sanders and Kumar, 1975; Fig. 4A). Transgression across a low coastal gradient will also affect developing estuaries, causing them to be longer and possibly increasing the area affected by tidal processes and their absolute intensity (Dalrymple et al., 1992). A larger estuary has a larger tidal prism than a smaller estuary for the same tidal range, and this in turns leads to stronger tidal currents, because of the fixed period of the tidal cycle.

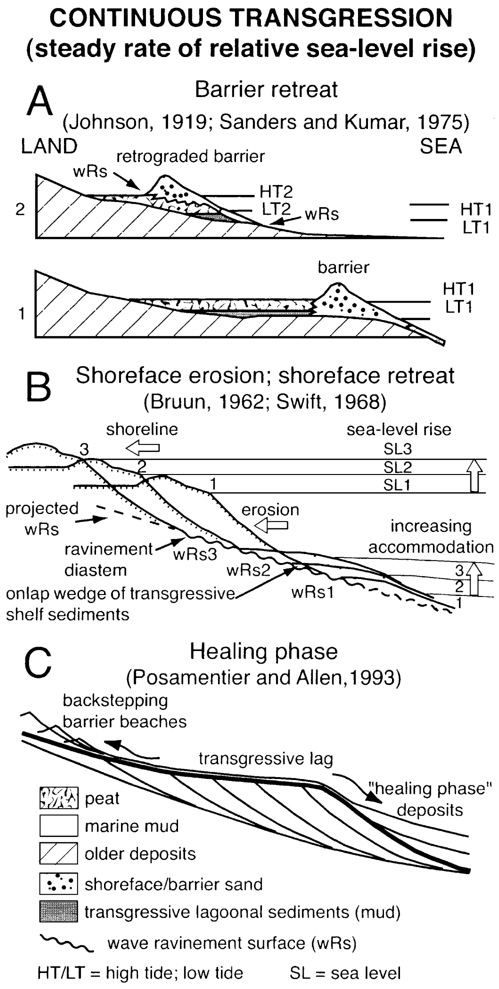
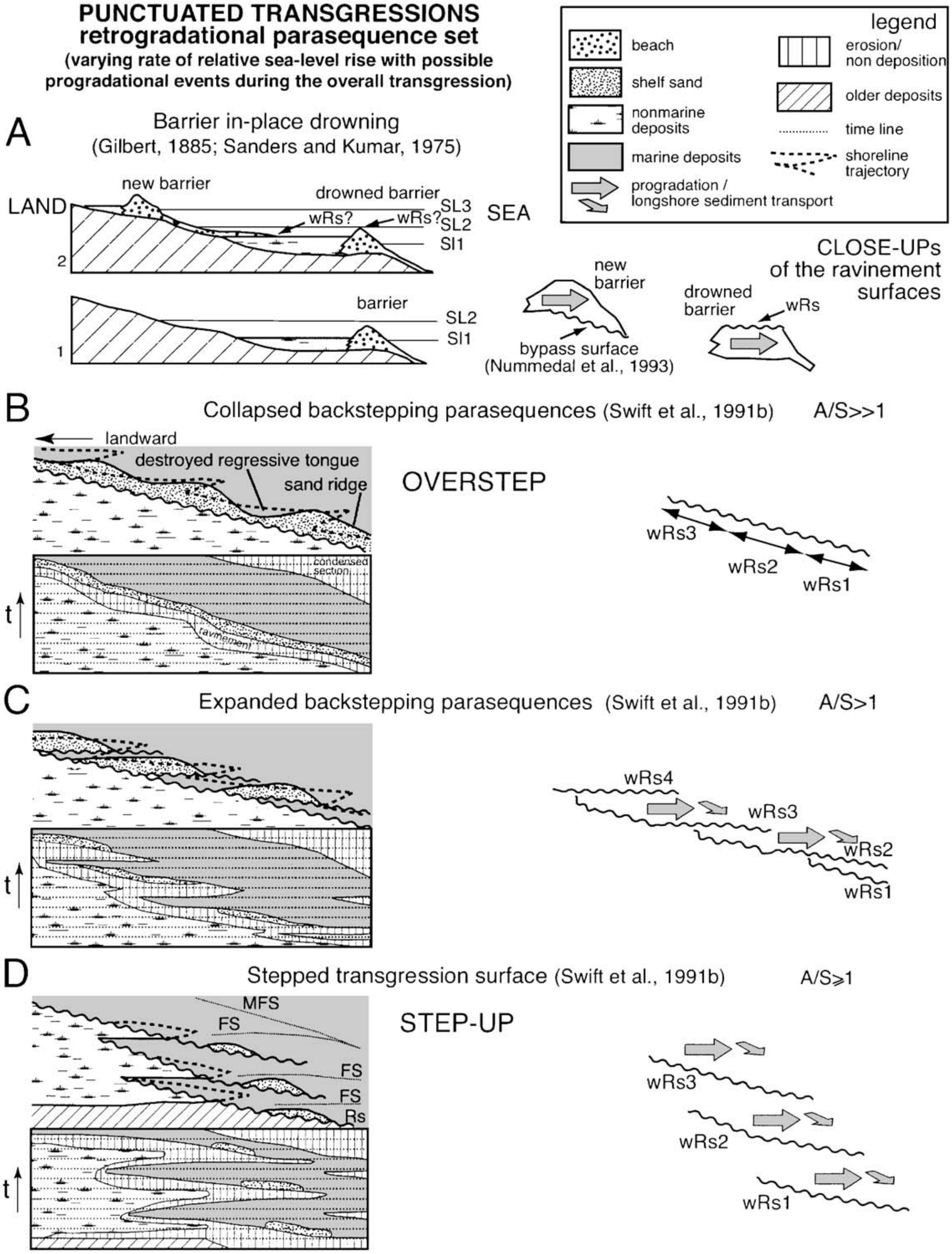


Fig. 3. Schematic inner-shelf to shoreface sections illustrating stratigraphic response to continuous transgression. (A) *Barrier retreat* is caused by wave erosion (ravinement) during relative sea level rise in environments where barrier–lagoon systems are present (Sanders and Kumar, 1975). (B) Similarly, *shoreface erosion* or *shoreface retreat* assumes an adjustment profile of the shoreface during transgression in accordance with the Bruun rule (Bruun, 1962; Swift, 1968). (C) *Healing phase* deposits form when sediment eroded during ravinement is transported beyond the shelf edge (Posamentier and Allen, 1993).

The *roughness* of the inherited physiography is the complex surface pattern resultant from processes preceding transgression, that include the effects of previous relative sea level fluctuations, the duration of relative sea-level lowstands when the surface was subaerially exposed and sculpted by river processes, the nature of the rivers, which in turn is dependant on the climate of the hinterland, and the amount and calibre of the sediment delivered during lowstand. This composite surface (a sequence boundary if there has been a previous sea-level fall) may afterwards be modified and coincide (in some sectors of a transgressed shelf) with the ravinement surface. It is however the physiography of the terrestrial surface preceding transgression (sculpted by incised valleys) that has the greatest influence on the nature of the transgressive coastal system, because most ravinement surfaces have relatively low relief by comparison with the sequence boundary.

The interaction of previous topography and transgressive processes may influence the thickness, pres-


PUNCTUATED TRANSGRESSIONS
retrogradational parasequence set
(varying rate of relative sea-level rise with possible progradational events during the overall transgression)
legend
beach
shelf sand
nonmarine deposits
marine deposits
progradation / longshore sediment transport
erosion/ non deposition
older deposits
time line
shoreline trajectory
A
Barrier in-place drowning
(Gilbert, 1885; Sanders and Kumar, 1975)
new barrier
drowned barrier
LAND
SEA
SL3
SL2
Sl1
wRs?
wRs?
2
barrier
SL2
Sl1
1
CLOSE-UPs of the ravinement surfaces
new barrier
bypass surface (Nummedal et al., 1993)
drowned barrier
wRs
B
Collapsed backstepping parasequences (Swift et al., 1991b)
A/S>>1
landward
destroyed regressive tongue
sand ridge
OVERSTEP
condensed section
ravinement
t
wRs3
wRs2
wRs1
C
Expanded backstepping parasequences (Swift et al., 1991b)
A/S>1
t
wRs4
wRs3
wRs2
wRs1
D
Stepped transgression surface (Swift et al., 1991b)
A/S⩾1
STEP-UP
MFS
FS
FS
FS
Rs
t
wRs3
wRs2
wRs1

ervation potential and degree of tidal influence on transgressive deposits. For example, the inherited roughness derived from the submergence of a coastal sandy lithosome (ridge-and-swale topography) may constitute the focus for the creation of shelf sand ridges through transgressive reworking (McBride and Moslow, 1991; Snedden and Dalrymple, 1999; Snedden et al., 1999). The presence of fault-generated or wave-cut terraces will cause a local surplus of accommodation, resulting in patchy but thick pockets of transgressive deposits (e.g., Hart and Plint, 1993). Previous incised valleys that are incompletely infilled with fluvial sediments will become estuaries, and may become sites of accumulation for coarse transgressive deposits due to reworking in highly energetic tidal inlets. In more general terms (i.e., at various spatial scales), topographically high areas (headlands/interfluves; deltaic headlands, etc.) are very commonly sediment sources (they commonly experience "non-accretionary" transgression), whereas topographically low areas tend to be sediment sinks.

Depending on the physiography of the surface being transgressed and on the effect of shelf widening, tidal processes may become more or less important during transgression. Changes in resonance and increase in the tidal prism may be enhanced by the creation of a more embayed coastal morphology (Mellere and Steel, 1995), by the presence of coupled width and depth decrease in a landward direction within bays and estuaries (Archer et al., 1994) or may occur also under certain geographic configurations in the case of transgression of a flat surface (Dalrymple, personal communication). In some cases, however, irregular estuaries do not promote augmentation of the tidal wave by shoaling and convergence, thereby allowing frictional dissipation to dominate and leading eventually to a landward decrease in tidal influence (Dalrymple et al., 1992). The presence of structural highs (another kind of roughness, albeit at a larger scale), may limit the emplacement of transgressive deposits, but will act as local source of coarse clastics, or may affect the path and locally enhance the velocity of currents, if submerged.

3.5. Stratigraphic response to transgression

Several models have been proposed to explain stratigraphic response to transgression on different coastlines. Continuous and punctuated transgressions represent two end members of such stratigraphic responses (Figs. 3 and 4).

Barrier retreat (Johnson, 1919; Sanders and Kumar, 1975), or *shoreface retreat* (Brunn, 1962; Swift, 1968; Fig. 3A,B), occurs when the base of the shoreface migrates landwards, truncating the pre-existing deposits by wave action and creating a ravinement surface. Coeval transgressive deposits may be preserved below the ravinement surface (paralic deposits on the landward side) and above it (marine deposits onlapping the ravinement surface on the basinward side; Nummedal and Swift, 1987). The ravinement erodes mainly upper and middle shoreface strata, and disperses the eroded sediments both landwards to lagoonal (or estuarine) environments as washover or flood-tidal delta deposits, and to the lowermost shoreface and offshore areas as ebb-tidal deltas and storm beds. The latter forms a transgressive sand that may be sheetlike in places, but may be irregular or with shelf ridges in other places. This sand onlaps the ravinement surface across the shelf, as transgression proceeds. A particular case of transgressive sand sheet is represented by the *healing phase* deposits (Posamentier and Allen, 1993; Fig. 3C), an onlapping wedge or veneer of sediment deposited beyond the shelf break with a sigmoidal shape because of its occurrence on the slope. Shoreface retreat usually occurs with a moderate to low rate of relative sea-level rise, or on high-gradient coasts, because this process needs time to rework and redeposit sediments.

Fig. 4 shows cases of punctuated transgression, with alternating coastal retrogradation and progradation within an overall transgressive trend. *In-place drowning* (Sanders and Kumar, 1975; Fig. 4A) is

Fig. 4. Schematic inner-shelf to shoreface sections illustrating stratigraphic response to discontinuous or punctuated transgression. This includes: (A) *in-place drowning* (Gilbert, 1885; Sanders and Kumar, 1975) and a suite of conditions with an increasing role of sediment supply during transgression, such as (B) *collapsed backstepping parasequences*, (C) *expanded backstepping parasequences*, and (D) *stepped transgression surface* (modified from Swift et al., 1991a,b). Chronostratigraphic charts and close-ups help in the interpretation of the ravinement surfaces (Nummedal et al., 1993). SL = sea level; wRs = wave ravinement surface; FS = flooding surface; MFS = maximum flooding surface; ¥ = *A*/*S* = accommodation/supply ratio as defined in Thorne and Swift, 1991.

characterised by vertical accretion of barrier–lagoon systems that are eventually submerged by an increased rate of relative sea-level rise or a reduction in sediment supply. The paralic deposits may be totally preserved or only slightly reworked below the ravinement surface. This process is typical of low-gradient settings undergoing a stepwise retreat of the coast, allowing barrier drowning during intervals of accelerated relative sea-level rise. A similar situation occurs on the abandoned lobes of the Mississippi delta, where barrier islands essentially "drown in place", but then slowly migrate landwards because of storm reworking (*transgressive submergence*; Penland et al., 1988).

Landward barrier migration has been described in terms of *barrier overstep* and *barrier step-up*, both producing a shoreface erosion surface with an overlying thin sand sheet or storm-ridge sand sheet, depending on the abundance of sand and shoreline history (Swift et al., 1991b; Fig. 4B–D). Barrier overstep and barrier step-up could represent a suite of punctuated transgressive processes with overall increase of sediment supply and temporary regression of the coastline (Figs. 4 and 5B). Swift et al.'s (1991b) *collapsed backstepping parasequences*, similar to classic shoreface ravinement, are formed by a high rate of transgression with water deepening leading to a fining-upward shelf succession ($A/S \gg 1$). In this case, the relatively low sediment supply favours the formation of a physically continuous ravinement surface: in close-up view, this surface is labeled with three different arbitrary names to emphasise its composite and diachronous nature (wRs1 to wRs3; Fig. 4B). With increasing sediment supply ($A/S > 1$), transgression may lead to *expanded back-stepping parasequences*. These could be interpreted as overlying a master ravinement surface with "onlapping" minor ravinement surfaces (Fig. 4C), but it is more likely that the ravinement surfaces are arranged in a step-up manner, with concave-up surfaces progressively eroding landwards and slightly offset upwards (close-up, Fig. 4C). The deposits on top of each ravinement surface are apparently disconnected from any landward source, and so may derive from a longshore sediment source or derive from land, but their landward termination has been eroded by successive ravinement, as in many of the Cardium Formation examples (e.g., Bergman and Walker, 1987). In the case where sediment supply temporarily overbalances the rate of relative sea-level rise, *a stepped transgressive surface* (Swift et al., 1991b; Fig. 4D) or a ravinement cluster (Siggerud and Steel, 1999) may result from a landward and upward-offset series of ravinement surfaces, each separated by brief progradational pulses of sediment derived from land or from lateral sources.

At the landward termination of the wave ravinement surface, where the turnaround from transgression to regression is located, high sediment supply causes this surface to rise with the aggradation of coastal plain deposits before the system starts to prograde. With any resumption of transgression due to lowered sediment supply, a new wave ravinement surface may be created. This pattern may be repeated if there is an overall relative sea-level rise with superimposed fluctuations in sediment supply, creating a succession with interfingering marine and nonmarine deposits, organised as a series of backstepping parasequences (Siggerud and Steel, 1999). In this case, the slightly offset (landwards) stacking of successive ravinement surfaces produce a significant aggradation of the transgressive tract (Olsen et al., 1999; Siggerud and Steel, 1999; Fig. 4C,D).

Various theoretical cases of transgression are summarised in Fig. 5. Curray (1964) plotted "relative sea level" [eustasy and tectonic subsidence/uplift] against the "rate of net deposition" [rate of sediment supply and oceanographic conditions] to show when transgressions and regressions occur. Only the transgressive part of the diagram is reproduced in Fig. 5A as it was in the original paper, showing four fields corresponding to different transgressive conditions. Some of the terms used by Curray (1964), however, are contradictory or unclear and will not be further used in this paper. For example, *discontinuous depositional transgression* is probably the more questionable field of Curray's representation, since the diagram's variables do not permit distinction between continuous and discontinuous transgression (where transgression is defined as landward movement of the shoreline): the preserved deposits might more likely be discontinuous in the field noted, but different conditions might occur such as thin veneers of sand, discontinuous shelf deposits, or a stepwise migration of the shoreline in response to the inability of deposition to keep pace with relative sea-level rise. Curray (1964) defined the other fields of his diagram as follows: *erosional*

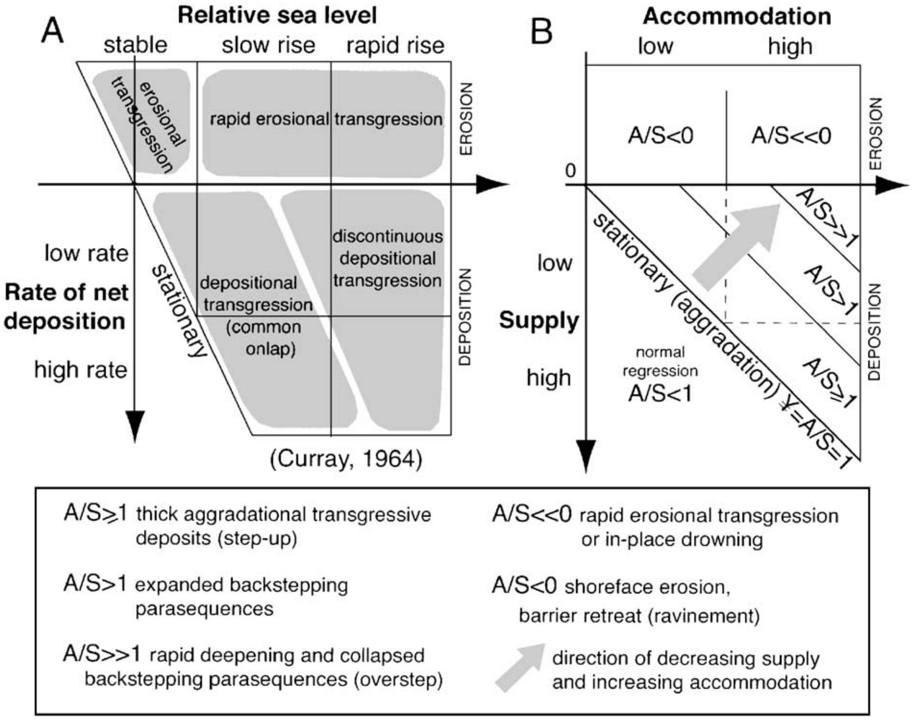


Fig. 5. (A) Transgressive part of the transgression–regression diagram of Curray (1964). (B) Revised version of the diagram. Depositional regime ¥ (as defined by Thorne and Swift, 1991) is expressed as the accommodation–supply ratio (*A*/*S*). See text for discussion.

transgression occurs with relatively stable relative sea level and low net deposition, with negative net deposition due to wave erosion; *rapid erosional transgression* promotes in-place drowning and "overstep" successions, where the former subaerial unconformity is directly overlain by open marine deposits of the late stages of transgression; and *depositional transgression* occurs when subsidence dominates over deposition.

Fig. 5B is an attempt to describe the transgressive processes reported in Figs. 3 and 4 based on the use of accommodation and supply (*A* and *S*, as defined in the regime model; Thorne and Swift, 1991). Other differences with Curray's (1964) diagram (Fig. 5A) are the inclusion of oceanographic conditions in the accommodation term, and the explicit definition of the diagonal line separating transgression from regression. At any point in the diagram in Fig. 5B, we assume $A>0$, whereas $S>0$ corresponds to "deposition" area and $S<0$ to "erosion" area. Erosional transgression is interpreted here (Fig. 5B) as caused by wave or tidal ravinement during relative sea-level rise, with reworking of ancient sediments and deposition above the ravinement surface. The thickness of transgressive deposits depends on the interplay of *A* and *S*, and in particular is maximum if the *A*/*S* ratio is close to 1. Since it is hard to have a perfect balance of *A* and *S* (Muto and Steel, 1997), the *A*/*S* ratio will fluctuate with time (i.e., the transgression could be punctuated), and the labeled fields of the diagram indicate only a time-averaged result. For example, during transgression sediment supply cannot keep pace steadily with increasing accommodation; therefore, it would be possible to develop transgressive deposits in the lower right part of sector labeled as $A/S \geq 1$ (Fig. 5B) only for short time intervals, followed by a resumed transgression as soon as sediment supply decreases.

At any point within the *A*–*S* plot there is only one value of *A*/*S*, thus the cases reported in Figs. 3 and 4 may be represented in Fig. 5B as "historical mapping" of sedimentary systems in the *A*–*S* space, in a way similar to the use of the Curray (1964) diagram by Boyd et al. (1992; their Fig. 7). The instantaneous position representing the evolution of sedimentary systems may at times fall in the regressive field, and at other times in the transgressive field. Therefore, the three diagrams in Fig. 4B–D represent different trajectories of temporally varying conditions—the trajectories of points plotted in the A–S space. For example, "collapsed backstepping parasequences" would plot as the oscillation between two points, one in the transgression field ($A/S<0$ or $A/S\gg1$), and one just barely into the depositional regression field. In order to display the development of a "stepped transgression surface" (Fig. 4D), conditions must have fluctuated between a location where $A/S>1$ (for each transgression) and $A/S<1$ (for each regressive pulse). It is possible to use the diagram in Fig. 5B to play "thought exercises" by trying different locations for the two end points of the oscillation, for example by changing only S (i.e., crossing the $A/S=1$ line vertically), versus changing only A (i.e., crossing $A/S=1$ line horizontally), and then attempting to predict the resulting stratigraphy.

3.6. Preservation potential

During transgression, the coastline moves landwards and the shelf area enlarges. This is accompanied by a tendency to have more sediment trapped in the alluvial and coastal plain environments, a reduced sediment influx to the basin, and cannibalization (through ravinement) of previously deposited sediments, including those deposited in the early stages of transgression. The preservation of transgressive deposits landward of the shoreline depends on the amount of erosion by ravinement, thus it is tied to the extent and steepness of the ravinement surface. Continuous but relatively condensed transgressive deposits are present in a basin in areas seawards (and deeper) than the effect of erosion by tides and waves during transgression. At the shoreface, the maximum preservation potential of transgressive deposits occurs where the trajectory of the ravinement surface is steeper, close to the transgression-to-regression turnaround point.

In many cases, the geometry of transgressive deposits reflects the underlying topography: the thickest, most complex and complete transgressive sequences are preserved in topographic hollows of the underlying surface (e.g. within valleys and on the downthrown sides of growth faults), submerged possibly during stepwise retreat (Heward, 1981). Belknap and Kraft (1981) showed that transgressive deposits are well preserved within incised valleys, where an idealised valley-fill succession consists from bottom to top of fluvial, upper bay marsh/bayhead delta, lower bay tidal inlet/flood-tidal delta, and offshore marine units. The spatial relationships (e.g., the position of local divergence) between the sequence boundary and the overlying wave ravinement surface determine the degree of preservation of transgressive deposits (Belknap and Kraft, 1985). Estuaries act as a sink for sediment of both terrestrial and marine origin, along a coastline, and their deposits have high preservation potential because of their location within paleovalleys (Dalrymple et al., 1992; Zaitlin et al., 1994). On the contrary, there is a tendency for the lack of preservation of transgressive deposits on headlands/interfluves. This could be envisaged also with the concept of shoreline trajectory: it is easier to get an upward trajectory relative to a valley bottom than to a topographically high interfluve. Where barrier–lagoon systems are transgressed, the most likely deposits to be preserved are those of the tidal inlets and flood-tidal deltas, because they are deposited in relatively deep water, and therefore are less likely to be reached by the erosional wave action (ravinement).

4. Variability of transgressive deposits

There are no "typical" transgressive deposits, as such, though some of the end members of the spectrum have been described (e.g. Demarest and Kraft, 1987; Reinson, 1992). Transgressing coastlines may be "embayed" (if they consist of a valley or an estuary and show river influence and deposits), or outside a valley (i.e., on an interfluve, where they appear as sea cliffs or barrier–lagoons without river influence and deposits; Dalrymple et al., 1992; Boyd et al., 1992). During overall transgression, high sediment supply or low rates of relative sea-level rise can cause the coastline to be periodically regressive in character, with deltaic or strandplain shoreline lithosomes alternating with estuarine and lagoonal/barrier deposits.

On modern continental margins, examples of transgressive deposits emplaced during the late-Quaternary sea-level rise include incised-valley fills (Anderson et al., 1996), starved marine mud drapes (Trincardi and Field, 1991), drowned barrier islands (Penland et al., 1988; Snedden et al., 1994), reworked dune fields (Ikehara and Kinoshita, 1994; Correggiari et al., 1996b), thick muddy strata (Cattaneo and Trincardi, 1999), and even active growth of deep sea fans with turbiditic sedimentation during transgression (e.g., Weber et al., 1997). During the last transgression in the coastal area of Papua, coastal currents caused sediment accumulation to be found in elongated areas shifted laterally from the axis of the underlying incised valleys (Harris et al., 1996). In the case of the Canterbury Plains shorezone in New Zealand and in many other places, erosion and retrogradation of the coastline is occurring during present sea-level highstand, due to relatively low sediment supply, extreme wave energy and efficient longshore sediment transport; the retreat of wave-cut cliffs also causes some fluvial incision in the lower reaches of rivers (Leckie, 1994). The next section shows how transgressive deposits vary both along dip-oriented and strike-oriented transects of a basin.

4.1. Dip variability of transgressive deposits

The most unambiguous signatures of transgressive processes are present in coastal and shallow-marine settings, where there is a record of a shift in the position of the shoreline with evident changes in facies, flooding surfaces and possible associated erosion. Transgressions, however, affect sedimentation both landwards of the shorezone and seawards out onto the shelf and beyond. A stratigraphic cross section through a transgressive tract, showing the main operative processes, facies and surfaces, for a coastal plain-shelf transect, was given by Kidwell (1989) (Fig. 6A). Fig. 6B shows an idealised transect with the main environments, the extent of relevant stratigraphic surfaces (Galloway, 1998), and the typical value of slope at different locations along the transect (Cant, 1991). Cross and Lessenger's (1998) scheme of a transgressive systems tract emphasises the variable partitioning of sediment volumes and the differences in process and in grain-size trends across the transect (Fig. 6C), but perhaps underestimates the tendency to preserve thick transgressive estuarine deposits on the shelf (e.g., within valleys) and at the shelf edge, for example after a fall of relative sea level of sufficient duration to allow the formation of a deeply sculpted sequence boundary (e.g. Reynaud et al., 1999b; Steel et al., 2000).

The effect of relative sea-level change on *fluvial/alluvial deposits* is still debated and the distinction between the effects of allocyclic and autocyclic mechanisms is yet poorly understood. However, the seaward reaches of coastal plains are certainly sensitive to sea-level changes (e.g. Siggerud and Steel, 1999), with more complex responses than a simple change in the rate of incision, including changes in channel pattern, width, depth and roughness (Schumm, 1993; Wescott, 1993; Shanley and McCabe, 1994). Both tidal currents and brackish-water can extend tens of kilometres upstream in modern fluvial–estuarine systems; a distance up to 100–150 km of tidal influence in valley fills was documented in ancient successions (e.g., Archer et al., 1994). In addition, during periods of transgression when the shoreline retrogrades tens of kilometres, the above responses will influence areas 100 km or more landwards of the previous coastal zone. This is usually manifest from brackish-water trace fossils and other tidal indicators within otherwise thoroughly fluvial successions (e.g. Shanley et al., 1992; McLaurin and Steel, 2000).

In *coastal plains and paralic environments*, two main types of transgressive systems are present: estuaries in transgressed deltaic or valley areas, and barrier–lagoon systems in transgressed strandplains. *Estuaries* develop at the regressive-to-transgressive turnaround and migrate landwards as transgression proceeds, generally with a simple overall landward translation of facies belts (Dalrymple et al., 1992; Fig. 7A). A dip-oriented cross section (from Allen and Posamentier, 1993; Fig. 7B) shows that both the wave and the tidal ravinement surfaces move landwards, but are formed in different parts of the estuary (Figs. 7 and 8). The infill of esturies is complex because of the interaction of marine (waves and tides) and fluvial processes. However, there is a high degree of organization with the development of a tripartite zonation, particularly in wave-dominated estuaries: coarse sediments accumulate in the outer wave-dominated and in the inner river-dominated areas (though the former may be poorly preserved), whereas fine sediments are present in the "central basin" (Dalrymple et al., 1992). Transgressive–regressive estuary-infill cycles are typical of a cycle

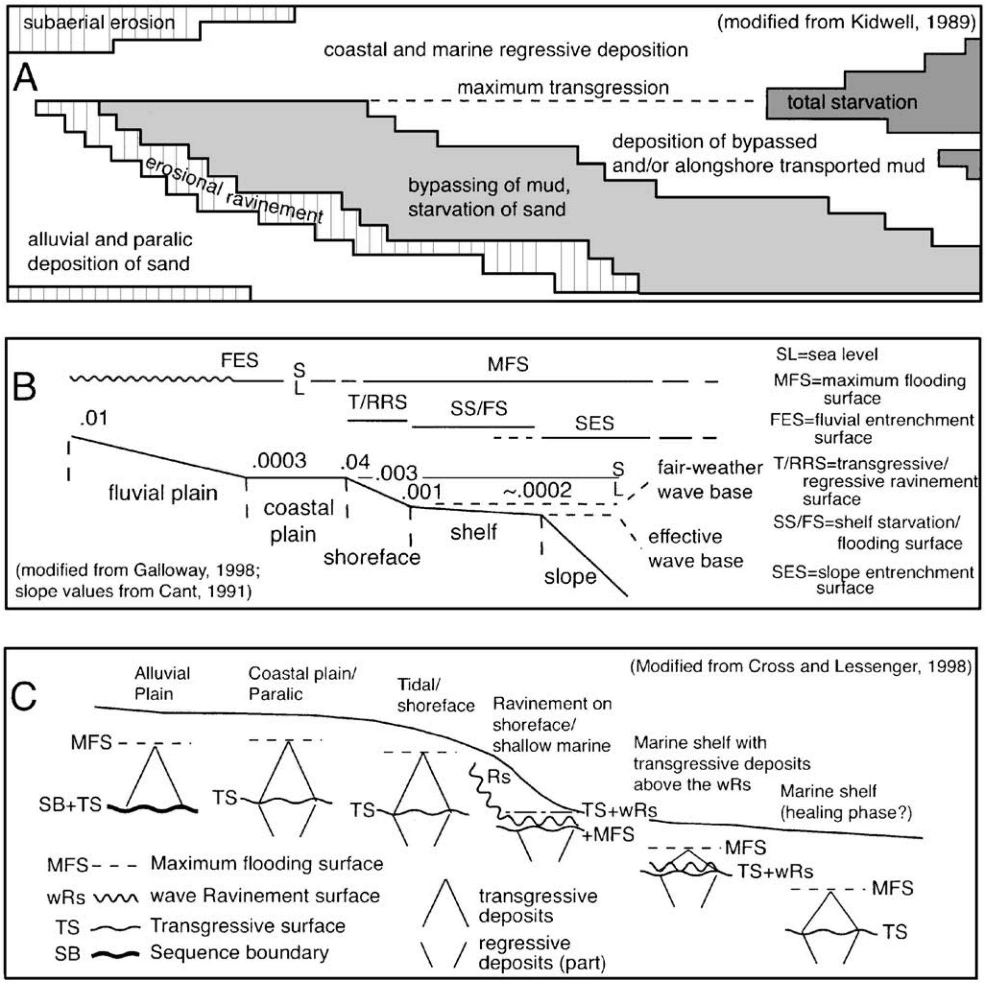


Fig. 6. (A) Landward migration of processes during a transgression in an idealized dip-oriented transect. Time is the vertical axis (from Kidwell, 1989). (B) Idealized transect from nonmarine to slope environments with the extent of the main stratigraphic surfaces (modified from Galloway, 1998), and average slope values (from Cant, 1991). (C) Idealised dip-oriented section of transgressive deposits, indicating the relative thickness of regressive and transgressive deposits of a sedimentary cycle; note that the section seawards of the shoreface is on an interfluve, not in a valley (modified from Cross and Lessenger, 1998).

of relative sea-level fall and rise, and usually constitute a thick estuarine lithosome with high preservation potential. In transgressive *barrier–lagoon systems*, transgressive sands form *above* the wave ravinement surface, producing an erosively based, upward deepening shelf sand as the common transgressive signature, with the barrier largely cannibalized. However, as in the case of estuaries, a thick succession of transgressive deposits exists *below* the landward-rising wave ravinement surface, because of greatly increased accommodation space behind the barrier.

In *shelf* settings, sequence-stratigraphic models consider the depositional sequences as composed of transgressive and highstand deposits, with lowstand deposits typically restricted or absent (e.g. Baum and Vail, 1988). At certain positions over the shelf, locally thick transgressive deposits may form (e.g., ridges of various types as well as cape and estuary-mouth retreat massifs; Swift, 1975b). These deposits may derive

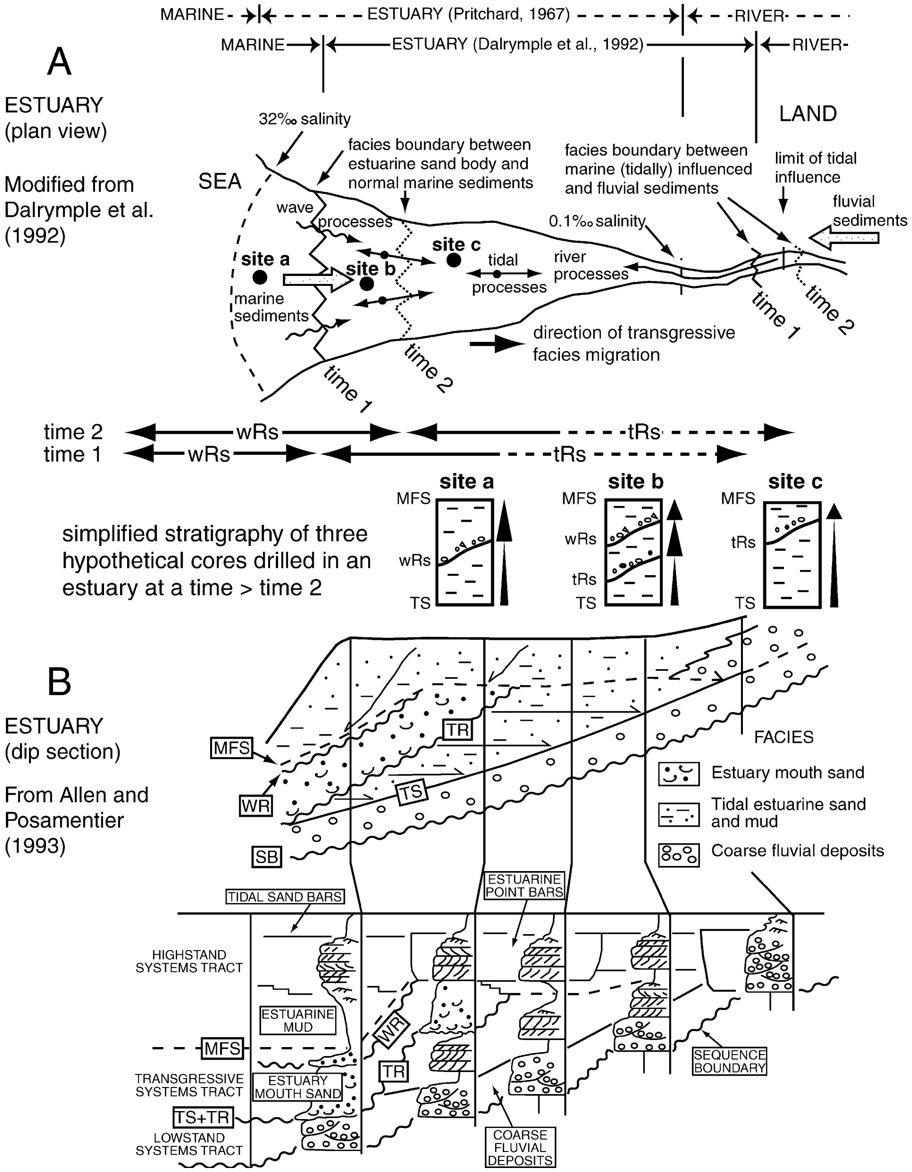


Fig. 7. (A) Schematic representation of the definitions of estuary in plan view according to Pritchard (1967) (dashed lines) and Dalrymple et al. (1992) (solid lines), and the generalized pattern of net, bed-material transport. The facies boundary marking the landward end of the estuary as defined here almost always lies landward of the 0.1% salinity value, but the facies boundary at the outer end may lie either landward (as shown here) or seaward of the limit of normal-marine salinity (32 ‰). The possible evolution of the estuary during transgression from time 1 to time 2 (dotted line) is shown by the extent of tidal (tRs) and wave (wRs) ravinement surfaces and the simplified stratigraphy of three hypothetical cores at sites a, b, and c. (B) Schematic stratigraphic and facies model of a mixed wave- and macrotidally influenced incised-valley fill, based on the Gironde estuary. The lowstand and transgressive systems tracts are readily identifiable, but in certain parts of the valley fill it is difficult to distinguish between the transgressive and early highstand systems tracts and to identify the maximum flooding surface (MFS). The transgressive surface (TS), the wave and the tidal ravinement surfaces (here, WR and TR, respectively) will be regionally continuous and readily identifiable on well logs and cores in a section orthogonal to the shore, except when the wave ravinement surface directly overlies estuary-mouth sands. These surfaces help to identify: (a) tidal-flat and sand-flat deposits above the TS, (b) erosive tidal-channel infills above the tRs, and (c) a thinner wave-reworked lithesome above the wRs. The wRs and tRs have different extents in the strike direction: the wRs is continuous, whereas the tRs is restricted in its lateral extent to areas where tidal channels occur, e.g. tidal inlets and/or estuary mouths.

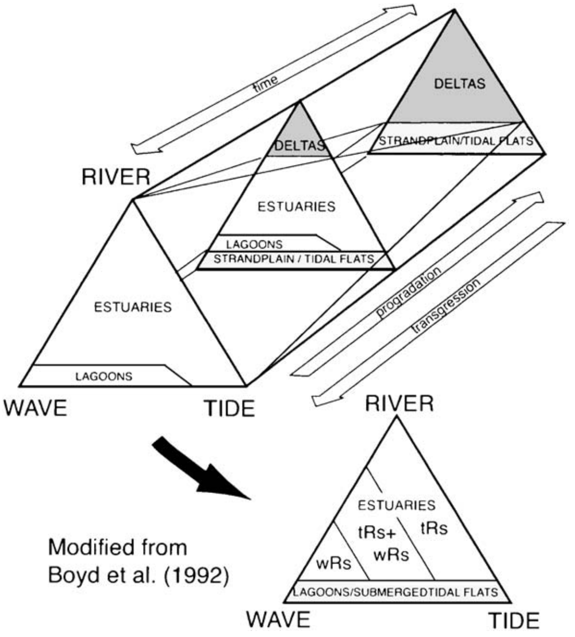


Fig. 8. Evolutionary classification of coastal environment from Boyd et al. (1992). Transgressions are shown by movement toward the front of the prism. The front triangle has been modified to show the occurrence of wave and/or tidal ravinement surfaces as driven by the dominant environmental factors.

from barrier–lagoon systems drowned by rapid sea-level rise (Sanders and Kumar, 1975), partially or totally reworked into attached shoreline bars or sand ridges (McBride and Moslow, 1991; Dalrymple and Hoogendoorn, 1997).

The *deepest parts* of a depositional system are affected by relative sea-level change only indirectly by its control on sediment supply. Nevertheless, this control is particularly important during sea-level low-stand when deeper-water slopes are able to accrete (Morton and Suter, 1996; Plink-Bjorklund and Steel 2002).

4.2. Strike variability of transgressive deposits

The strike variability of a depositional system depends on local subsidence trends, location of sediment sources, current paths and sediment routes, and variations in coastal morphology. Point-source deltas, incised valleys and estuaries, for example, characterise short segments of the coastline, resulting in small-scale strike variability (e.g., Fig. 9). Other environments like line-sourced deltas or wave-dominated strandplains may show relatively little variability over larger distances and build laterally continuous transgressive bodies (Martinsen and Helland-Hansen, 1995).

Basin deepening and transgression do not necessarily coincide in time along every part of a basin margin (Helland-Hansen and Gjelberg, 1994; Posamentier and Allen, 1999). Transgressive deposits with different expressions in terms of presence or absence of ravinement surfaces and facies (continental, estuarine or marine) can be laterally equivalent. The shoreline can have a trajectory parallel to the original land surface, but can lie either above it (in which case terrestrial, estuarine and/or lagoonal deposits are preserved), or below it (in which case the ravinement surface is coincident with the sequence boundary). In fact, these different scenarios commonly exist side by side along a transgressive coast, the former situation occurring in valleys, leading to the preservation of estuarine deposits, and the latter on erosional “headlands” (i.e., interfluves). In cases where relative sea level falls below the shelf edge before transgression, thick successions of both lowstand and transgressive deposits are present within the seaward portion of valleys incised into the earlier shelf (e.g. Reynaud et al., 1999b). In the interfluve areas, the sequence boundary may coincide with the transgressive surface and it is commonly overlain by lag deposits reworked during the initial transgression.

4.3. Transgressive reservoirs

The variability of transgressive shorelines causes problems in reservoir correlation both downdip and along strike (e.g., Hamilton, 1995). However, the lateral variability in thickness of transgressive deposits enhances the likelihood of stratigraphic trap, and transgressive muds and shales may naturally act as both seal and source rock (e.g., Devine, 1991; Snedden and Dalrymple, 1999; Posamentier, 2002). Transgressive sands may onlap structural highs and be sealed by transgressive offshore muds; in some cases, they may become concentrated on topographical/structural highs, as illustrated by the present-day example of Sable Island, with subaerial and subtidal portions (Dalrymple and Hoogendoorn, 1997). Trans-

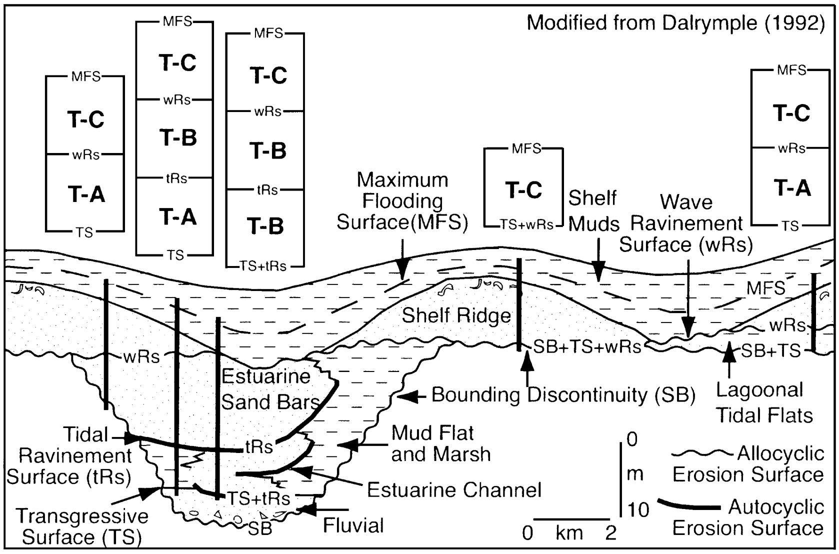


Fig. 9. Hypothetical coast-parallel section showing the stratigraphy of a transgressive systems tract in a tide-dominated setting, assuming complete preservation of estuarine deposits (Dalrymple, 1992). Five schematic stratigraphic columns emphasize the position of key surfaces for transgressive deposits following the criteria illustrated in Section 6 and in Fig. 11.

gressive sands, where present, may be good reservoirs especially in their intermediate parts: at the base they are commonly too rich in carbonate cement, whereas towards the top the presence of intervening silt and clay decreases porosity (Abbott, 1985).

5. Elements in transgressive deposits

5.1. Surfaces

5.1.1. Flooding surface

Marine flooding surface (Table 1) is the general term used for a surface "that separates younger from older strata, across which there is evidence of an abrupt increase in water depth" (Van Wagoner et al., 1988). The definition changed later into "flooding surface" to include also lacustrine environments (Van Wagoner, 1995). In spite of the word flooding implying inundation of previously dry areas, the term is also used where there is evidence of deepening (Bhattacharya, 1993). Typically, a flooding surface (FS) is the boundary of a parasequence (Van Wagoner et al., 1990). Different kinds of flooding surfaces may be recognised in a succession: Bhattacharya (1993) recognised a hierarchy of minor, major and maximum flooding surfaces, based on their lateral extent.

Confusion may arise from other uses of this term in the literature. Van Wagoner et al. (1988) suggested that the deepening associated with a flooding surface may be accompanied by minor submarine erosion. In such cases, however, it is more common to refer to a *ravinement surface* or a *transgressive surface of erosion* (Bhattacharya, 1993). Abbott (1998) used the term *local flooding surface* implying offshore erosion, albeit to a lesser degree than during ravinement. It is difficult to quantify how much erosion may be associated to an FS. We consider the term "flooding surface" as a general term, and "ravinement surface" (see below) as one variety of flooding surface with associated significant erosion (Stamp, 1921).

5.1.2. Maximum flooding surface

Many problems with nomenclature arise from homonymy or synonymy, and the terms used to address key surfaces in the rock record are no exception. In the case of the *maximum flooding surface* (MFS), for example, authors used the same term to address a surface recognised based on different criteria, or gave different names to the same surface. Two

Table 1
Main characters of the surfaces below, within or above transgressive deposits

Flooding surface (FS)

Terminology. Generic term. Different FSs exist according to their lateral extent and position within a sequence. An example is the MFS (see below).

Process. Abrupt increase in water depth with no (or minor) erosion associated. Sedimentation style above and below it may thus be different.

Depositional environment. Any environment which can be submerged by marine or lacustrine waters, or within marine and lacustrine environments showing evidence of water deepening. Some authors use it in fluvial settings, where muddy distal coastal-plain deposits abruptly overlie more proximal alluvium.

Extent and preservation potential. The FS may be of local or regional extent. In shallow marine environments where parasequences were first defined (Van Wagoner et al., 1988), it commonly but not always represents the only record associated with water deepening.

Chronologic character. Considered synchronous, although it presents a minor diachroneity (younger landwards) as inundation or water deepening advances. If it coincides with SB, TS or Rs it is diachronous.

Sequence stratigraphy. The FS is the bounding surface of parasequences (Van Wagoner et al. 1990).

Diagnostic features. Presence of marine facies on top of nonmarine successions, or evidence of an abrupt water deepening above shallow-water deposits (abrupt deepening in facies associations). It may be associated to shell beds above or below it.

May coincide with... if... With SB or TS if it marks the first significant deepening episode in a sequence. With MFS if it marks the peak transgression within a sequence.

Maximum flooding surface (MFS)

Terminology. Also termed downlap surface or maximum transgressive surface if emphasis is on its geometric character. It represents the time of maximum water depth in a vertical succession, and may be more a zone than a surface, when its position is fuzzy.

Process. Minimized sediment input at peak transgression in the basin, shelf and shoreface. This may correspond to a major change in the style of deposition above and below it.

Depositional environment. The surface or zone of maximum flooding may be found in all environments from deep basin to continental. In continental environments, it can be traced within lagoonal deposits, tidal flat-central basin deposits in the case of estuaries, and also into fluvial environments (Dalrymple et al. 1992).

Extent and preservation potential. The MFS is one of the most extensive surfaces in the rock record and it is likely to be preserved along most of its extent (Galloway 1998; Posamentier and Allen 1999). It extends from the deep basin to the shoreface, and may be correlated into continental deposits.

Chronologic character. Since MFS refers to the time of maximum flooding within a basin, it is a synchronous surface, and it marks the time of turnaround from transgressive to regressive strata or of maximum relative water depth in a vertical succession.

Sequence stratigraphy. At the top of transgressive, upward-deepening deposits of the transgressive systems tract.

Diagnostic features. Change in geometry from retrogradational (below) to progradational strata with downlap terminations (above). It may be associated with a condensed section showing reduced oxygen values, high organic matter content, high concentration of platinum elements (iridium), presence of authigenic minerals (e.g., glauconite, phosphate, siderite), high gamma-ray counts, abundant and diverse plankton, microfauna and/or planktic foraminifera, low concentration of benthic foraminifera, association with burrowed, bored, or slightly lithified intervals.

May coincide with... if... With the underlying Rs or Rs + TS in case of starvation during transgression. With SB (+ TS + Rs) if no deposits of the previous relative sea-level lowstand are present.

Wave ravinement surface (wRs)

Terminology. Ravinement is the erosional process caused by wave impact on the shoreface.

Process. Erosion of the shoreface by wave action causing shoreface retreat.

Depositional environment. Due to the originating process, wRs is restricted to shallow marine areas above fair-weather wave base. Above it there may be only few cm of sand, passing upwards to shalier intervals; in some cases there may be ridges and shoal-retreat massifs many meters thick (Snedden and Dalrlymple 1999). Below it the paralic deposits may include peats, lagoonal muds, washover and flood-tidal delta sandstones (Reinson 1992).

Table 1 (*continued*)

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Extent and preservation potential. The wRs extends from the fair-weather wave base at the lowstand position to the upper shoreface at the time of maximum transgression (highstand). It migrates landwards during transgression eroding large sectors of the shelf, and passes basinwards to an FS without associated erosion. It is usually preserved, because sealed by marine deposits.

Chronologic character. Typically diachronous surface with coeval continental or estuarine (below) and marine (above) sediments deposited at its landward and seaward positions, respectively.

Sequence stratigraphy. At the base of or within the transgressive systems tract.

Diagnostic features. The wRs can be identified by its morphology (erosion surface and associated lag) and by the facies that underlie and overlie it (Walker 1992). It represents an erosional contact between nonmarine (below) and marine (above) deposits, with possible presence of a transgressive lag. Above a wRs, in general, there is evidence of water deepening and a fining-upward trend in lithology.

May coincide with... if.... With TS if no paralic transgressive deposits are present or preserved (e.g., in interfluve areas). With TS + SB especially on the inner shelf where lowstand deposits are absent or when the ravinement removes any underlying transgressive coastal plain or back-barrier deposits.

Tidal ravinement surface (tRs)

Terminology. Termed tidal ravinement surface because of the landward-migrating, channel-generated tidal erosion during transgression.

Process. Erosion by tidal currents encroaching landwards and gaining strength with the onset of transgression.

Depositional environment. The tRs is restricted to estuarine coastal areas, i.e., to former coastal plains being transgressed. tRs is particularly pronounced at the bottom of tidal inlets, where it may be overlain by high-energy inlet sands (Demarest and Kraft 1987; Reinson 1992), or tidal channels, possibly associated with angular shale clasts of large dimensions coming from the erosion of tidal flats or bay deposits.

Extent and preservation potential. The tRs may extend over long distances up-dip a tidal inlet incision, from the deepest areas that experienced tide currents in early transgression to the landward limit of tidal influence in late transgression. It is usually of limited lateral (strike-oriented) extent, if confined within a previous incised valley (or tidal inlets) and this increases its preservation potential, preventing erosion by the ensuing wRs.

Chronologic character. Landward-migrating diachronous surface that incises into alluvial or estuarine deposits and is overlain by tide-influenced deposits.

Sequence stratigraphy. At the base of or within the transgressive systems tract. It is below wRs, if wRs is present.

Diagnostic features. Presence of tide-influenced deposits above the erosional surface, with angular clay chips, double mud drapes, sigmoidal lamination, and/or presence of brackish or mixed faunas and trace fossils. A tRs can be recognized because the transgressive deposits on top of it show evidence of tidal influence.

May coincide with... if... With underlying TS if no paralic transgressive deposits are deposited or preserved below it. With TS + SB in the same conditions as the wRs.

Transgressive surface (TS)

Terminology. First surface associated with evidence of shoreline turnaround from regressive to transgressive status. It may also be defined based on the abrupt increase in marine influence across it.

Process. First significant deepening episode within a sequence.

(*continued on next page*)

Table 1 (*continued*)

Transgressive surface (TS)

Depositional environment. The TS may be on top of inundated continental deposits; in marine environments it records water deepening. The TS may separate marginal-marine sediments below from nearshore-marine facies above, or terrigenous to less terrigenous sediments on the outer shelf and slope (Haq et al. 1988). In an estuary, the TS may record an abrupt facies change from fluvial deposits to finer tidal-estuarine muddy sands with onlap terminations (Allen and Posamentier 1993).

Extent and preservation potential. The TS is restricted to the area landwards of most regressive nearshore-sand deposits in the lowstand wedge (Loutit et al., 1988). In the marine portion of a basin, it is present as a conformable transgressive surface. A correlative surface to the TS may correspond in nonmarine areas to a change in the stacking pattern of fluvial deposits becoming more aggradational, or to an increase in tidal influence (e.g., Pedersen and Steel 1999).

Chronologic character. Synchronous surface at the time of regressive-to-transgressive turnaround if defined geometrically, or highly diachronous (younger landwards) if defined based on the first increase in water depth in a vertical succession.

Sequence stratigraphy. At the base of the transgressive systems tract.

Diagnostic features. Change in stratal geometry from progradational (below) to retrogradational (above), deepening in facies associations, and/or change in benthic associations. The TS may be associated with a distinct lithologic change that makes it one of the most prominent surfaces visible on outcrops, especially when coincident with Rs and marked by the presence of a transgressive lag (e.g., Siggerud et al. 2000), but also in areas where sediment supply is dominated by silt and clay. In this case, it could be placed at the base of an interval of increased clay and organic matter content (Embry 1995).

May coincide with... if... In most cases the TS passes landwards (or laterally from the center to the edges of the valleys) to the Rs, which then merges with the sequence boundary. It coincides with MFS if areas where transgressive deposits are nonexistent, not preserved, or below the resolution of the investigation tools (Suter et al 1987; Nummedal and Swift 1987; Abbott 1998).

main criteria have been used in the definition of key surfaces in marine rock successions: one based on the geometry of stratal stacking patterns (termed “type A” surfaces; Catuneanu et al., 1998), the other based on the water depth changes across the surface (“type B” surfaces).

In a geometric sense, the MFS forms at the turnaround between transgressive (landward stepping, retrograding) and regressive (seaward stepping, prograding) strata (Posamentier et al., 1988; Galloway, 1989). It corresponds to the downlap surface at the top of the transgressive systems tract on seismic profiles (Van Wagoner et al., 1988), termed *surface of maximum transgression* in Helland-Hansen and Gjelberg (1994). The MFS has also been described in terms of a deepening in facies association, as any generic flooding surface, but with greater lateral extent visible on regional studies (Walker, 1992). In this sense, the MFS corresponds to the time of maximum water depth in a basin and consequently, with some approximation, to the maximum landward position of the shoreline. This condition has direct impact on sediment-supply rate, creating in large areas of a basin a condensed horizon (*surface of maximum starvation* in Baum and Vail, 1988), with possible concentration of fossils, phosphatic or glauconitic materials (Table 1). In spite of these different definitions, all distinguishing criteria (stratal downlap geometry, maximum water depth, maximum landward position of the shoreline and sediment condensation; see also Pemberton et al., 1992) yield approximately the same surface. It is known, for example, that condensed sections occur at downlap surfaces. At high-enough temporal resolution, the various definitions do not yield precisely the same chronostratigraphic surface; this is especially the case of the difference between times of maximum transgression and maximum water depth (e.g., Jervey, 1988; Carter et al., 1998).

The choice of one criterion depends on the data available and on the position of the succession analysed within a basin. With seismic lines, for example, the MFS is characterised as a time line corresponding to the downlap surface (Table 1). With cores or outcrops of limited extent, it is found at the position of maximum deepening in facies and faunal associations, but in this case the MFS represents a point in time which is difficult to identify precisely (e.g., within a muddy interval) without the help of paleontological studies, and therefore can be referred to as a maximum flooding zone. In this case, it may be slightly diachronous (younger basinwards), because the relative duration of sediment starvation increases basinwards (Jervey, 1988; Loutit et al., 1988). The MFS is usually a conformable surface, but it could become unconformable in areas where submarine erosion occurs (Thorne and Swift, 1991).

5.1.3. Wave ravinement surface

The concept of a *ravinement surface* was first described and defined by Stamp (1921), who noted that, commonly, the first stage in the landward movement of a transgressing sea is marked by a coarse, conglomeratic deposit of coastal origin created by the action of waves. The transgressive *wave ravinement surface* (wRs) is an erosional surface created and driven by wave erosion on the shoreface and by the rising sea level, causing reworking of both older and newly deposited sediment on the shoreface (Swift, 1968). The expression *transgressive surface of erosion* (Walker, 1992) appears to be synonymous with wRs in its initial use, but as a general term it could include all types of ravinement surfaces, both wave and tidal. Faunal evidence shows that the "basal conglomerate" of transgressive deposits immediately overlying the wRs is not coeval throughout a basin (it becomes younger in a landward direction; Jervey, 1988) and is overlain by deeper water sediments. The wRs is by definition a diachronous surface, because shoreface erosion is limited to a small area at any one time, and thus represents a relatively short and local interruption in sedimentation (diastem).

The wRs needs high to moderate wave energy to be significant (i.e., to be associated with substantial erosion) and is present only where wave erosion is important. The wRs, for the rapid rates at which physical processes such as waves operate, usually forms in open-coast marine environments, thus resulting in a physically continuous, although diachronous, surface (Fig. 4). A wave ravinement surface can also form inside open lagoons, marine embayments or estuaries large enough to have appreciable wave action (e.g., below the wave-generated cliffs along the margins of Chesapeake Bay or the Bay of Fundy; Dalrymple, personal communication).

The wRs is commonly a relatively flat, terraced surface (even if in some cases it has some relief; e.g., Bergman and Walker, 1987) rising towards the margin of the basin (Nummedal and Swift, 1987). The updip extent of a wRs depends mainly on the gradient of the transgressed surface, on the amplitude of the relative sea-level rise, and on the rate of sediment supply behind the shoreline. The steepest angle of the wRs is reached at its landward termination, where the turnaround from transgression to regression is located. The erosive depth of the ravinement commonly is in the order of 10 m, roughly corresponding to fairweather wave base (several cases are reported in Saito, 1994). Based on a model for exceptionally high storm waves offshore Japan, Sunamura (1987) reported a theoretical maximum depth of erosion of 40 m and evidence of possible erosion by storm waves 30 m deep. Recent literature (Nummedal and Swift, 1987; Thorne and Swift, 1991; Helland-Hansen and Gjelberg, 1994; Siggerud and Steel, 1999) has emphasised the importance of recognising the transgressive nature of thick back-barrier and coastal-plain deposits stored below the wRs during shoreline retreat, especially during intervals of high accommodation and sediment supply (Fig. 10).

5.1.4. Tidal ravinement surface

By analogy with the wRs formed by shoreface retreat (Stamp, 1921; Swift, 1968), the erosional surface termed the *tidal ravinement surface* (tRs) (Swift, 1968; Allen and Posamentier, 1993) results from the landward migration of the zone of maximum tidal energy. In wave-dominated estuaries the tRs, although restricted to the thalweg of an inlet (the estuary mouth), to tidal distributary channels or to tidal channels in the flood-tidal delta, can be sub-regionally continuous in the distal part of the valley fill, because of the progressive landward migration of the inlet during transgression (Allen and Posamentier, 1993; Zaitlin et al., 1994). In tide-dominated estuaries, the tRs records the landward migration of tidal channels, but may be of greater extent, as in the case of the modern southern North Sea and also the post-glacial Celtic Sea, where tidal erosion occurs over a large area between tidal sand ridges (Reynaud et al., 1999a).

Fig. 7 illustrates the distribution of wRS and tRs within an estuary represented in plan view or in dip section (Fig. 7A and B, respectively). In embayed coastlines, thick lithosomes of tidally influenced sand, generated mainly from tidal channels and tidal sandbar complexes, lie above the tidal ravinement surface

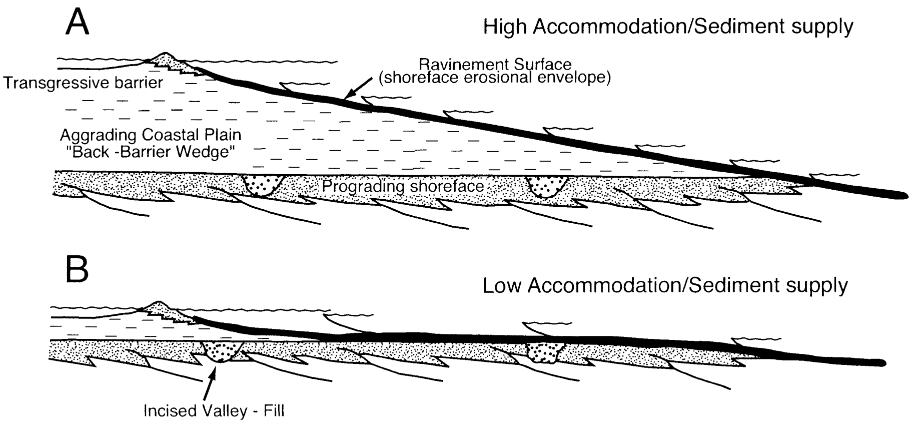


Fig. 10. Variable development and preservation of aggradational coastal-plain and valley-fill deposits behind a transgressing shoreline. High rates of subsidence and sediment supply favour development of a thick "back-barrier wedge", whereas low rates of subsidence and sediment supply result in preservation of valley fill deposits but little or no preservation of transgressive coastal-plain deposits (based on Thorne and Swift, 1991).

and below the wave ravinement surface, where the latter is present. In these situations, three categories of transgressive lithosomes, two ravinement surfaces and a basal transgressive surface can be present, all included within the transgressive systems tract. This is illustrated in Fig. 7B, from the Gironde estuary, where these three surfaces penetrate successively shorter distances landwards during transgression, prior to the shoreline turnaround into a regressive mode (highstand).

5.1.5. Ambiguous or missing ravinement surfaces

The absence of a wRs or tRs at the base, top or within transgressive deposits indicates in general that the transgressing shoreline environment, at that particular transect, was characterised by a low-energy regime, without significant waves or tides in the shorezone. Furthermore, ravinement processes may be limited only to: (1) certain sectors along the basin margin, and (2) certain depth ranges of a transgressed shelf. The first case is a consequence of the strike variability of the coastline (e.g., coastal sectors protected from wave action show little evidence of wave ravinement). The second case happens because the energy regime of the margin may vary during transgression, leaving behind a bathymetry-controlled patchy distribution of ravinement surfaces (e.g., during periods of rapid sea-level rise, there is less time for the ravinement process to operate, and this would result in less detectable ravinement erosion over rapidly submerged areas).

In estuaries, wave and tidal ravinement surface pairs may not always be found above each other. The wRs will not exist in the most inland parts of the estuary at the transgressive limit, or in cases where the embayed coastal morphology prevents the development of waves. The tRs may be absent in areas within the estuary which are lateral to the strongest tidal currents. If these areas are also protected from waves, then the resulting transgressive deposits may lack of any ravinement surface, otherwise they may show only a wRs on top of estuarine facies.

The dominance of fine-grained lithologies is another factor potentially preventing the formation or the detection of ravinement surfaces. Cohesive muds may resist the erosional action of tidal currents or waves. Furthermore, in fine-grained lithologies it can be difficult to notice evidence of erosional ravinement, and also shell beds, if present, tend to be patchy. If a ravinement surface occurs within a muddy succession, the only way to detect it could be through the observation of different trace-fossil assemblages above and below it; for example, trace fossils may help differentiate between muddy estuarine deposits below and shelf mudstones above (MacEachern and Pemberton, 1994).

5.1.6. Transgressive surface

As in the case of the MFS, it is possible to define the *transgressive surface* (TS) based on different criteria: its geometric character or the abrupt change in water depth occurring across it. The TS, as defined originally by Exxon workers, is referred to as the first significant marine flooding surface across the shelf at the top of the lowstand systems tract (Van Wagoner et al., 1988, 1990), or the first flooding surface marking the beginning of more rapid sea level advance over the shelf (Haq et al., 1988). Based on stratal geometry, Embry (1993, 1995) defined the TS as a conformable surface which separates maximum regressive strata from subsequent transgressive strata, and named it the transgressive surface or *maximum regressive turnaround surface*, a term equivalent to the *surface of maximum regression* of Helland-Hansen and Gjelberg (1994). In more basinwards areas, the TS corresponds to the *correlative transgressive surface* (CTS; Catuneanu et al., 1998). Van Wagoner et al. (1990) used "transgressive surface" also as a generic term (as we would do with "flooding surface"), pointing out that several "transgressive surfaces" may be present within a sequence, and all may potentially be confused in regional correlations, because transgressions and regressions are strongly controlled by sediment supply. Van Wagoner et al. (1990) named the two major "transgressive surfaces" in a stratigraphic sequence as the "first transgressive surface" (upper boundary of the lowstand systems tract) and the "maximum flooding surface" (associated with the condensed section at the transgressive–regressive turnaround).

Some contradictions arise from the above definitions. The geometric TS ("type A"; Catuneanu et al., 1998) is a time line in a depositional dip section and separates prograding (coarsening-upward) from overlying retrograding (fining-upward) geometries, encompassing the time of turnaround from a progradational to a retrogradational coastline system (Thorne and Swift, 1991). However, this defines the TS over a limited extent in the dip direction, because deposition is restricted to areas near the lowstand shoreline. Thus, in this sense the TS would not exist as a discrete surface in updip areas, but would be collapsed into the sequence boundary. Furthermore, the geometric TS may be diachronous in a strike direction, because transgression may begin later in areas of high sediment supply. This diachroneity is considered by some to be minor in relation to the duration of the base level rise–fall cycle (Embry, 1995). In the definition based on facies deepening or beginning of marine influence on inundated areas, the TS is formed at the time when water depth is at its shallowest ("type B"; Catuneanu et al., 1998). In this case, however, the TS is the first significant flooding surface (sensu Van Wagoner et al., 1988) and is a facies contact in the broad sense. It must therefore be diachronous, reflecting the landward migration of the shoreline and becoming younger landwards.

5.1.7. Sequence boundary

It is beyond the scope of this paper to address all the problems involved in the definition of a sequence boundary (SB), including the ambiguities in terminology (see, for example Friedman and Sanders, 2000). For a general review of the main models (Exxon model, T-R sequences, genetic stratigraphy, allostratigraphy, forced regression model, etc.) we refer to the existing literature (e.g., Nystuen, 1998; Posamentier and Allen, 1999). However, it is necessary to point out that transgressive deposits on continental shelves lie on older deposits, often with no sedimentary record corresponding to times of relative sea-level lowstands. Therefore, at the base of transgressive deposits there may be a complex polygenetic surface originated from subaerial erosion during times of relative sea-level lowstand (a sequence boundary) and subsequent reworking during the ensuing transgression. In this case, the last imprint tends to influence the nature of the surface (e.g. a tidal or a wave ravinement surface), but the same surface must be considered also as a sequence boundary (Fig. 9).

5.2. Other elements in transgressive deposits

5.2.1. Lithologic changes

On the large scale, transgressive deposits tend to become finer grained upwards, reflecting a general deepening upward trend. This helps their identification in outcrops, cores and well logs (Abbott, 1985). It is also likely that during a transgression the basin becomes progressively starved of terrigenous components, thus increasing in cosmogenic, volcanogenic and authigenic components (Baum and Vail, 1988). The presence of abundant calcareous cement derived from diagenetic dissolution of shell beds is also common. One of the more characteristic lithologic features is, however, the presence of a transgressive lag, resulting from sediment starvation of the shelf (Swift, 1976) or condensation due to dynamic bypass (Kidwell, 1989).

Transgressive lags (excluding sand ridges or shoal-retreat massifs) are deposits characterised as thin (0.5–2 m) conglomeratic, glauconitic or fossiliferous beds at the base of a shallow marine unit (Kidwell, 1989), usually associated with an underlying Rs. Van Wagoner et al. (1990) defined a transgressive lag as a thin, relatively coarse-grained deposit composed of shells, shell fragments, clay rip-up clasts, calcareous nodules, siliciclastic gravel or pebbles concentrated on top of the transgressive surface on the inner to outer shelf by shoreface erosion of the underlying strata. Transgressive lags or shell beds may be laterally associated with erosional surfaces, condensed deposits and extensive sands associated with burrowed firm ground, due to the spatial mosaic of sedimentary regimes active during transgressions (Kidwell, 1989). Transgressive lags and other kind of lags (e.g. not deriving from erosion of older strata below transgressive deposits, but from winnowing of coeval material by storms in correspondence to flooding surfaces) are rarely associated with flooding surfaces not coincident with sequence boundaries, according to Van Wagoner et al. (1990). Other authors instead find a systematic association between shell beds and parasequence-scale flooding surfaces not necessarily associated to sequence boundaries (Kidwell, 1989; Banerjee and Kidwell, 1991). Carbonate beds of either bioclastic (Monstad, 2000; Steel et al., 2000) or nonbioclastic (Dalrymple, personal communication) origin, reflecting sediment starvation during transgression, sometimes rest on flooding surfaces within transgressive tracts or sporadically throughout the upward-fining transgressive interval that separates parasequences.

Thin geochemical lag deposits with accumulation of sedimentary phosphorite, pyrite or glaucony may be related with transgressions (Loutit et al., 1988). The presence of glauconite, an authigenic mineral formed in outer shelf to slope environments, has long been coupled with low sedimentation rates and considered a good indicator of transgressions. However, its presence is diagnostic of transgressive conditions only if accompanied by observations on its distribution within the sediment (layered or scattered), its degree of maturity, and its origin (autochthonous or allochthonous; Amorosi, 1995, 1997; Harris and Whiting, 2000). A nonselective distribution of glaucony of the same maturity in homogeneous lithologies probably reflects autochthonous deposition, whereas vertical grading or concentration in laminae of glaucony grains with different degrees of roundness and maturity indicates allochthonous deposition (Amorosi, 1997). A distinctive feature of transgressive deposits is an upward increase in autochthonous and more mature glaucony, culminating in the condensed section.

5.2.2. Shell beds

Shell beds (with shell as biomineralised invertebrate remains ≥ 2 mm in size) are dense concentrations of shelly fossils also referred to as coquinas, lumachelles, shell gravels and bioclastic calcirudites, and may form transgressive lags, where shell supply is abundant (Kidwell, 1991) and/or detrital sediment supply is low (Heward, 1981). They may record processes of varying duration: sudden mass-mortality events or prolonged transgressions. Kidwell (1991) recognised four broad types of shell beds. *Event concentrations* (1) reflect rapid accumulation at the scale of a single lamina or bed. The accretion or amalgamation of several events may result in the deposition of either thick *multiple-event concentrations* (2) or thin *hiatal concentrations* (3). These latter deposits are typical of low net sedimentation rates with concentration of broadly contemporaneous shells in starved basin margins, open shelves and distal basins, and may result from a transgression. *Lag concentrations* (4) are usually thin (<1 m) and reflect episodes of erosion of older deposits with a residual concentration of old and broken fossils, especially in shallow-marine environments. Lag concentrations may be associated with a ravinement surface, and in case of a rapid transgression tend to form continuous tabular bodies. Any transgressive shell lag may be colonised by marine benthos creating complex assemblages of noncoeval fossils.

5.2.3. Trace fossils

Vertical ichnological succession is analogous to facies succession in the interpretation of paleoenvironments. Trace fossils are sensitive environmental indicators, and may herald the onset of marine influence in sediments, especially on top of nonmarine successions. Trace fossils may aid in locating a surface, for example, when their succession is interrupted, or where abrupt changes in abundance and/or diversity of traces are found. Such surfaces are erosional discontinuities (e.g. Rs), nondepositional hiatuses with minor or no erosion associated (e.g. some flooding surfaces), or depositional discontinuities (e.g. condensed sections, some marine flooding surfaces, and MFS; Pemberton et al., 1992). Trace fossils emplaced across a sequence boundary or a transgressive surface are typically vertically extensive, sharp-walled, may be passively infilled with coarse sediment, and may be dominated by surface-controlled ichnofacies (e.g. *Glossifungites*, *Teredolites* or *Trypanites*; Savrda, 1995), which mark a time gap between the original deposition of a unit and a later superposition of post-depositional traces (Pemberton and MacEachern, 1995).

The concept of ichnofacies cannot alone explain the stratigraphic significance of a surface and must be integrated with sedimentologic, stratigraphic, and paleontologic observations, partially included in the ichnofabric concept (see also MacEachern and Pemberton, 1994; Zaitlin et al., 1994). Ichnofabric allows the recognition of surfaces within stratigraphic successions through an environmental change linked to the process of surface formation. For example, flooding surfaces bounding parasequences may be recognised with the evidence of abrupt relative deepening and landward shift in facies and ichnofabric; the transgressive surface may be recognised by the presence of marine trace fossils superimposed on a nonmarine substratum testifying to a change in salinity accompanying the transgression, but prior to the arrival of the wRs at the same site (e.g. Siggerud and Steel, 1999).

6. Scenarios for transgressive deposits

6.1. A classification of transgressive deposits

Given the complexity of transgressive processes and deposits, a classification based on distinctive physical elements could be useful. The recognition of the elements reviewed here may result in a more predictive tool than the use of stacking pattern of parasequences, as suggested, for example, by Martinsen and Helland-Hansen (1995). Because any transgressive transect will consist of some segments where there is sediment accumulation and others where there is erosion, it is appropriate to discuss transgressive scenarios for arbitrary segments of the transect rather than for a complete transect. The gradient of the pre-existing topography is a critical parameter, especially for its control on the thickness of transgressive deposits, and for this reason it is used in the proposed classification (Fig. 11):

T-A—transgressive deposits *below the lowest Rs*
T-B—transgressive deposits *above the tRs but below the wRs*
T-C—transgressive deposits *above the wRs, in low-gradient settings*
  T-C1—simple transgressive lags
  T-C2—landward-stepping regressive parasequences
  T-C3—shelf sand ridges and shoal retreat massifs
T-D—transgressive deposits *above the wRs, in high-gradient, high-sediment supply settings*
T-E—transgressive deposits *without evidence of ravinement surfaces*.

During prolonged transgression, deposits tend to accumulate both *below* (T-A) and *above* (T-C, T-D) the Rs (Fig. 3). The preserved thickness of each of these classes of deposit appears to be *greatest*: (1) for T-A deposits, where the Rs trajectory diverges significantly, at some point during transgression, from the topographic surface being transgressed, but the latter retains a low angle; and (2) for T-C and T-D deposits, where both the topographic surface and the Rs have a relatively steep slope (more than a few degrees in the case of T-D deposits).

Only some of all the possible combinations of transgressive deposits in Fig. 11 seem to be common in the stratigraphic record. Nummedal and Swift (1987) represented six vertical successions of transgressive deposits encompassing the most common facies successions of transgressive deposits from Holocene examples of the US coast (Fig. 12). These models show highly variable lithologies (e.g., fining- and coarsening-upward trends) and facies associations that may be best understood with reference to the associated bounding surfaces. The four environments represented in Fig. 13 (A to C, different types of estuaries; D, interfluves between estuaries) migrate landwards during transgression (Demarest and Kraft, 1987; Reinson, 1992). The discrimination between different situations may be difficult also here: spit systems migrating laterally into the mouth of large estuaries may produce similar vertical sequences to tidal inlets (Demarest and Kraft, 1987). Again we argue that the differing transgressive deposits will be best disentangled with reference to the associated key surfaces as indicated (see also Fig. 9). Fig. 14 represents the above classes of transgressive deposits in some end member cases.

6.1.1. T-A—transgressive deposits below the lowest ravinement surface

Transgressive deposits emplaced in alluvial plain, coastal plain, lagoonal, and backshore environments may accumulate and be preserved below the Rs where the wave (or tidal) ravinement trajectory is steeper than (or diverges upwards from) the pre-existent topography. This preferential storage of sediment happens because of the time it takes for transgression to occur, underlining also the diachronous nature of the Rs (Nummedal and Swift, 1987).

Theoretically, class T-A deposits may develop both in low- and high-gradient settings. However, the preservation of deposits below the Rs requires a relatively steep shoreline trajectory deriving from a high sediment supply to the area behind the shoreline (Fig. 10). It is unlikely to have thick transgressive deposits below the Rs (class T-A) in high-gradient settings, because the erosional ravinement is active for a prolonged period in a restricted area, and the transgressive paralic deposits are likely to be eroded unless high sediment supply causes the Rs to be even steeper than the transgressed surface. In low-gradient settings, it is well documented that back-barrier and coastal-plain deposits are likely to aggrade during shoreline turnaround and transgression, sometimes resulting in thick and abundant coals below the Rs (e.g. Ryer, 1981; Cross, 1988).

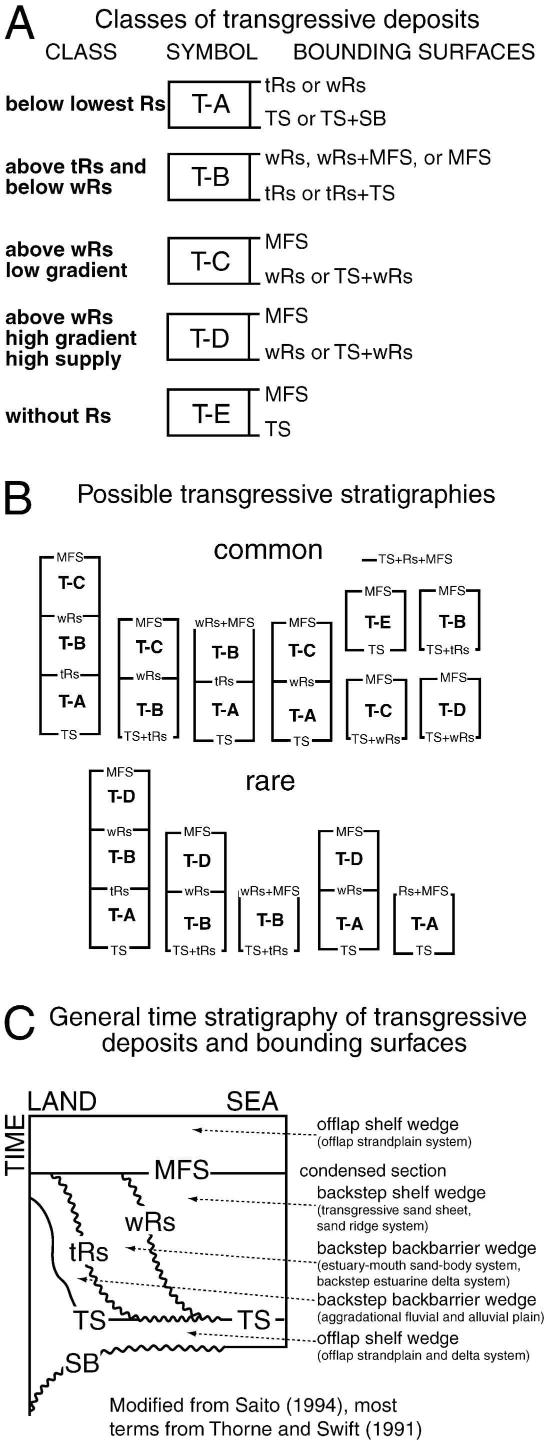


Fig. 11. Classification of transgressive deposits adopted in this paper. All possible combinations of transgressive stratigraphies are summarised, showing cases either common or rare in the rock record. A general time stratigraphy of transgressive deposits and bounding surfaces helps visualise the relative positions of the surfaces.

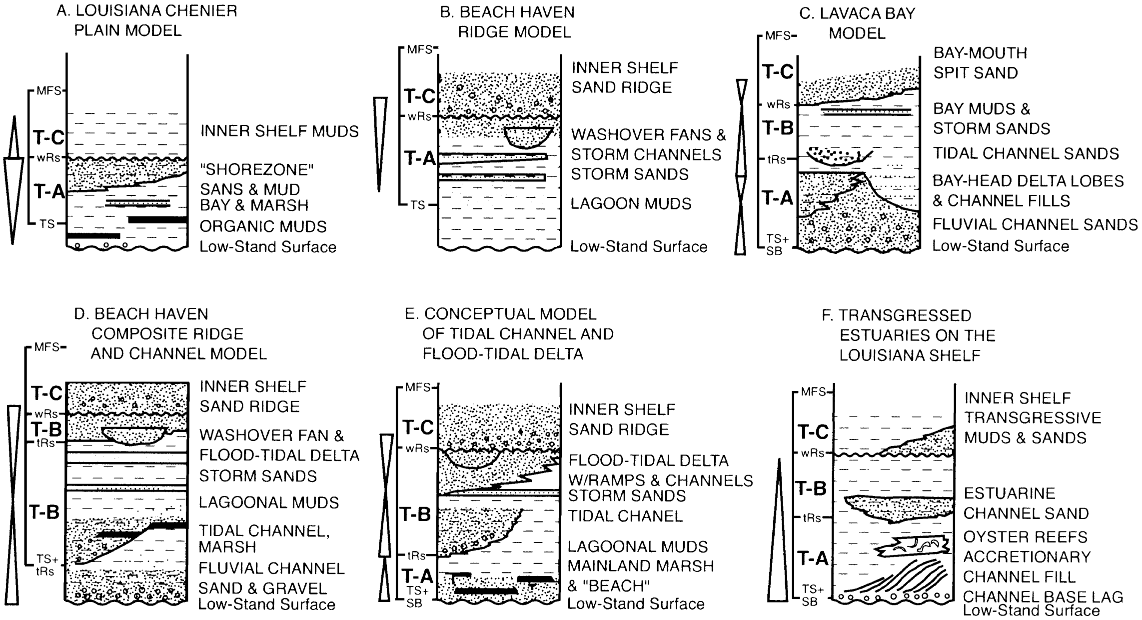
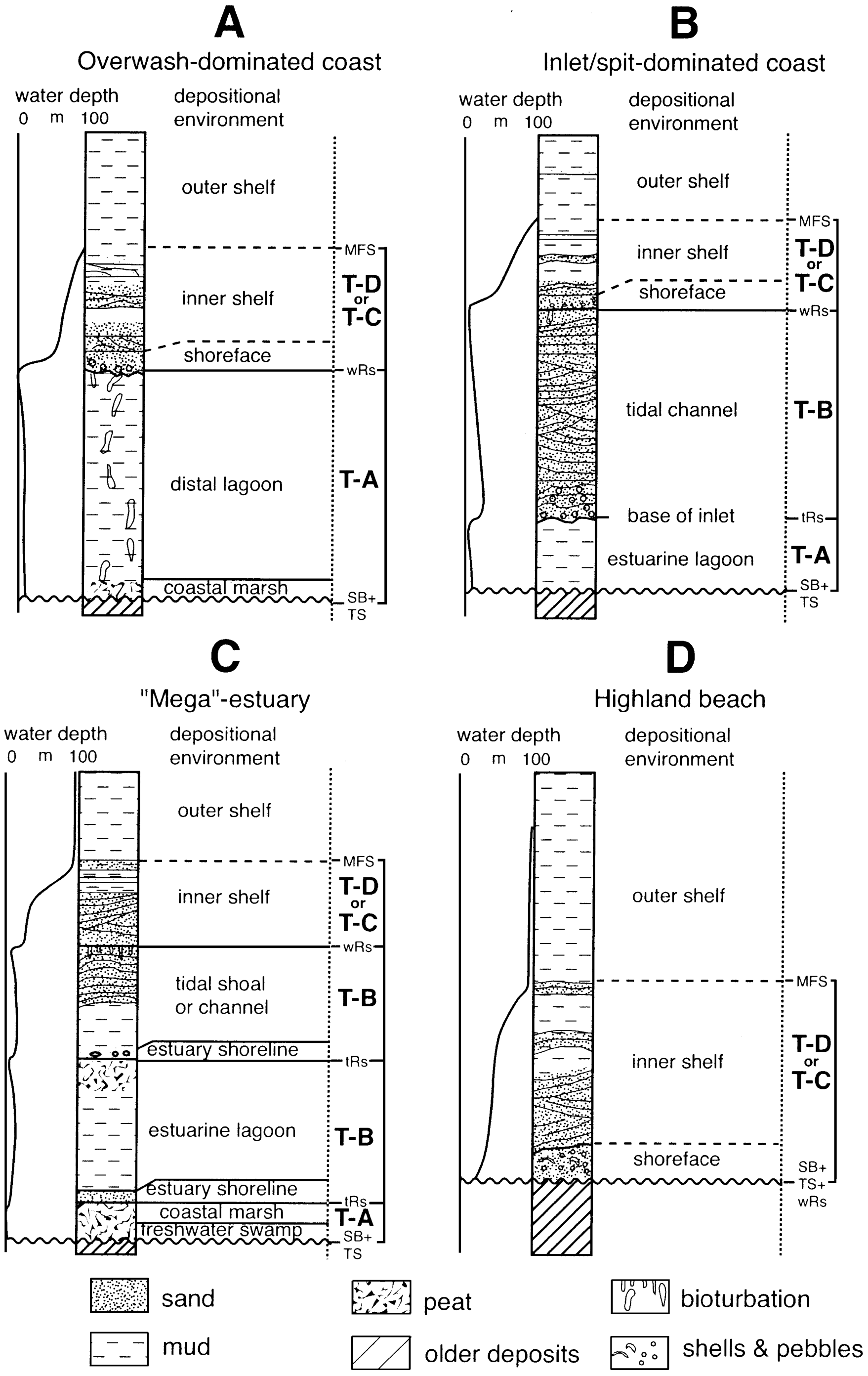


Fig. 12. Generalized representations of stratigraphic columns from Holocene marginal marine settings in the US showing different transgressive stratigraphies (Nummedal and Swift, 1987). On the left of each column, a scheme emphasises the position of key surfaces and classes of transgressive deposits as defined in Fig. 11.

6.1.1.1. El Marcet (Eocene), Sant Llorenc del Munt, SE Ebro Basin. Back-barrier, coal-bearing successions are well-known examples of the T-A scenario, but examples involving coastal alluvium are less commonly documented. An example of the development and preservation of coastal alluvium below a rising ravinement trajectory is well illustrated from the El Marcet data set in Fig. 15 (Steel et al., 2000). The landward-rising (and punctuated) series of ravinement surfaces has a combined erosional and interfingering contact with a time-equivalent nonmarine succession. Detailed correlation shows that individual transgressive episodes at the shoreline are time equivalent with upward-fining fluvial successions on the coastal plain, whereas the incision below an individual alluvial succession correlates with regression at the shoreline (Fig. 15). The overall "transgressive" nature of the alluvial package is confirmed by the younger alluvial units being increasingly marine/brackish influenced. Fig. 15 also illustrates the differing partitioning of alluvial and marine sediment facies during the transgressive–regressive phases of the El Marcet system. Fluvial deposits within the transgressive systems tract are thickly stacked, and increase in their thickness landwards at the expense of the overlying, landward-thinning regressive tract, though of course both of these tracts will eventually thin towards the source area. In the overlying regressive systems tract, the sediment has all bypassed the coastal plain, and has been stored and transported into a widely developed shoreface–slope system.

6.1.1.2. Tarbert Formation (Middle Jurassic), Hild Area, northern North sea. The Tarbert Formation (Hild Area) in the northern North Sea is another example, showing back-barrier (coaly facies) "transgressive" accumulations time-equivalent with sea-level rise at the coastzone (Ravnås and Steel, 1998). The Hild–South Alwyn architectural panel (Fig. 16) for the Tarbert Formation shows five marine transgressive episodes (five high-frequency sequences) fingering into the nonmarine Ness Formation. Because the erosive ravinement surfaces have a "rising" landward trajectory, each of them preserves a thick wedge of coal-bearing, back-barrier



Modified from Demarest and Kraft (1987) and Reinson (1992).

Fig. 13. Vertical successions produced by transgression of different types of coastal environments (modified from Demarest and Kraft, 1987; Reinson, 1992). On the right of each column is the position of key surfaces and classes of transgressive deposits as defined in Fig. 11.

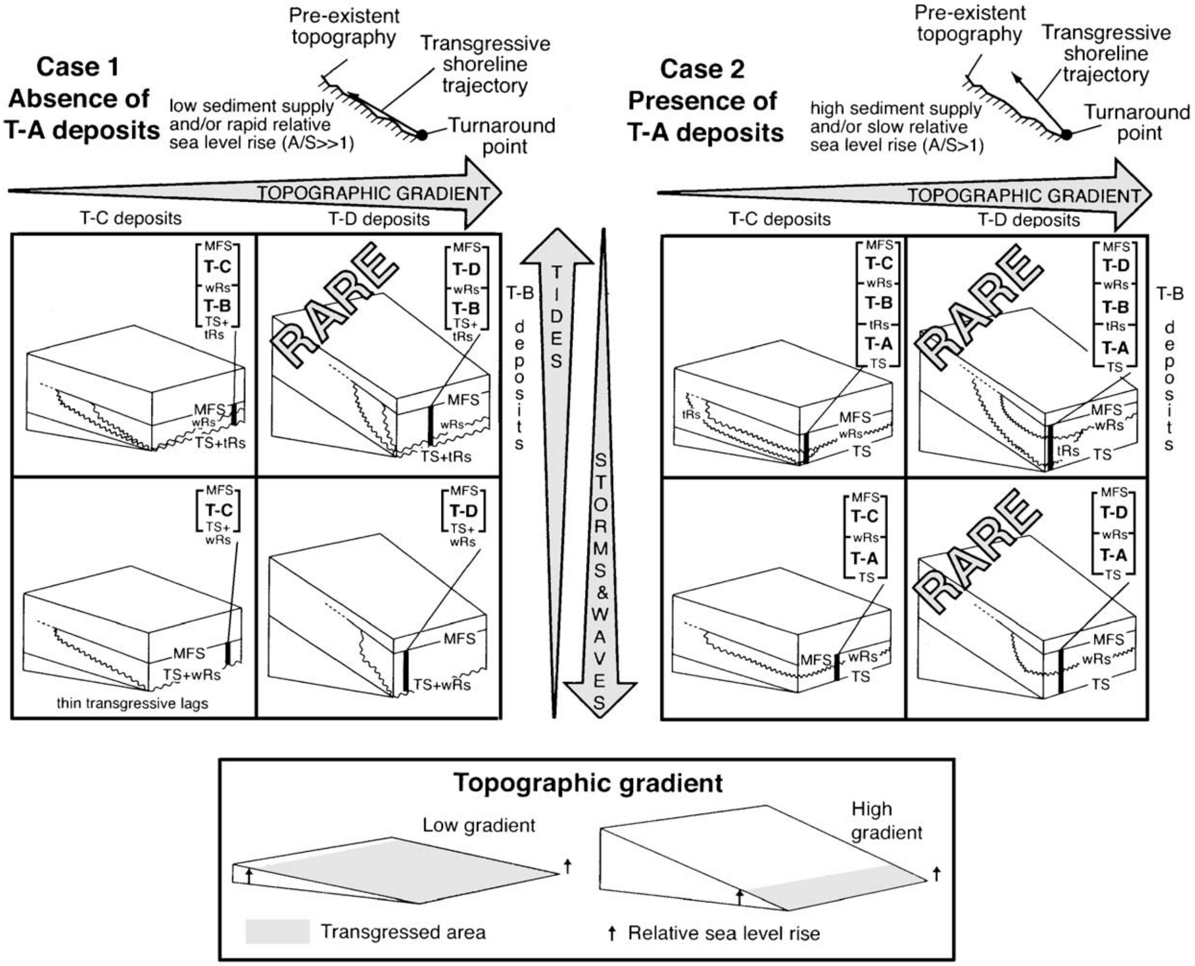


Fig. 14. Distribution of some classes of transgressive deposits (as defined in Fig. 11), based on topographic gradient and dominant process. A first-order distinction is based on the behavior of the shoreline (i.e., ravinement) trajectory: if it coincides with or is directed underneath the transgressed topography, then class T-A deposits will be absent or present only in topographic hollows (e.g., valleys; this possibility, not represented, is an effect of topographic "roughness"). As soon as the shoreline trajectory tends to diverge upwards from the pre-existing topography, then there will develop transgressive deposits below the lowest Rs (class T-A). The topographic gradient controls the area available for transgressive deposition and the resulting potential thickness of the deposits: for comparable sediment supply, on high-gradient settings the transgressive deposits tend to aggrade on a smaller area, whereas on low-gradient settings sediments may be distributed in larger areas and tend to build thin deposits, unless a rapid rise in relative sea level causes the drowning of a sand barrier. The dominant processes (tides versus waves and storms) determine the occurrence of different surfaces within transgressive deposits.

deposits. Each transgressive tract thus consists of a basal coal-bearing unit plus the overlying Rs and its capping sandstone carpet, giving the transgressive systems tracts thicknesses of up to 25 m; overlying each transgressive tract comes a regressive strandplain or deltaic package, the highstand systems tract for each of the five high-frequency sequences (Fig. 16). Offshore marine shales and siltstones are present only in the basinal reaches of each cycle, associated with the maximum flooding surfaces. Note that although the Tarbert Formation is overall transgressive, i.e. does have an overall, rising landward trajectory, the most marked landward stepping is seen at the basal and uppermost sequences in this

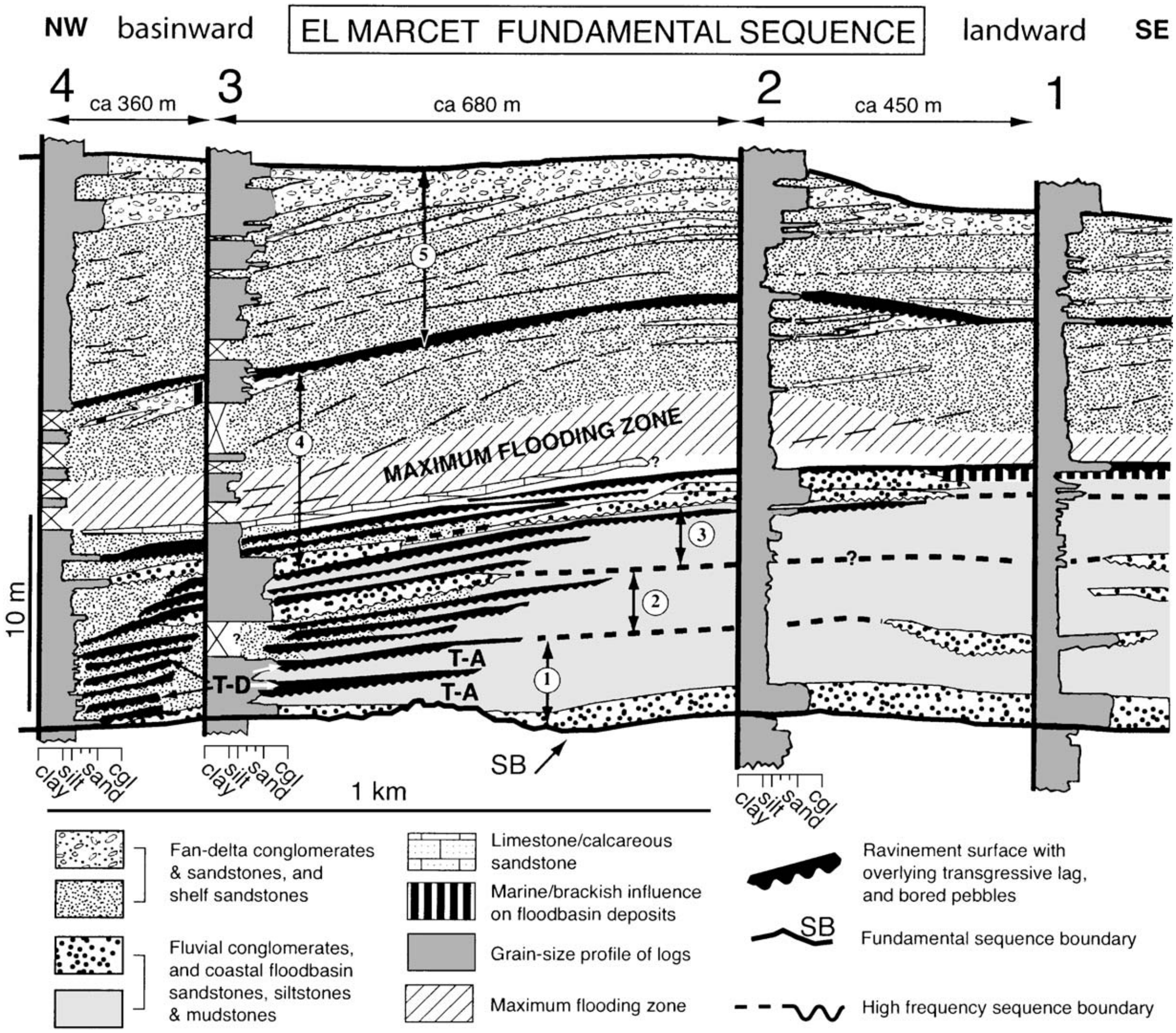


Fig. 15. El Marcet Unit, Sant Llorenc del Munt, SE Ebro Basin, Spain. The sub-units (1–5) have a slight landward-stepping stacking pattern in the lower half of the sequence, and a basinward stepping in the upper half. Note the series of stacked and rapidly rising (landwards) ravinement surfaces separating nonmarine (to right) from marine deposits (to left) within a thick transgressive systems tract. The middle part of the sequence shows the greatest degree of open-marine influence and is termed the maximum flooding zone (Steel et al., 2000).

succession (Fig. 16); sequences 2–4 have an aggradational stacking pattern.

6.1.2. T-B—transgressive deposits above the tidal but below the wave ravinement surface

Transgressive sand lithosomes accumulate below the wRs but above a tRs in some estuarine environments. This situation is most common where a transgressive shorezone is back-filling a coastline which is irregular and incised after a previous fall of sea level. The coastline irregularity, combined with an increased tidal prism generated by the rising and backward moving shorezone, probably tends to cause enhancement of tidal currents in the newly created estuaries (Mellere and Steel, 1995). The landward translation of tidal channels causes significant incision within the estuary (tidal ravinement). There is good preservation potential of the relatively

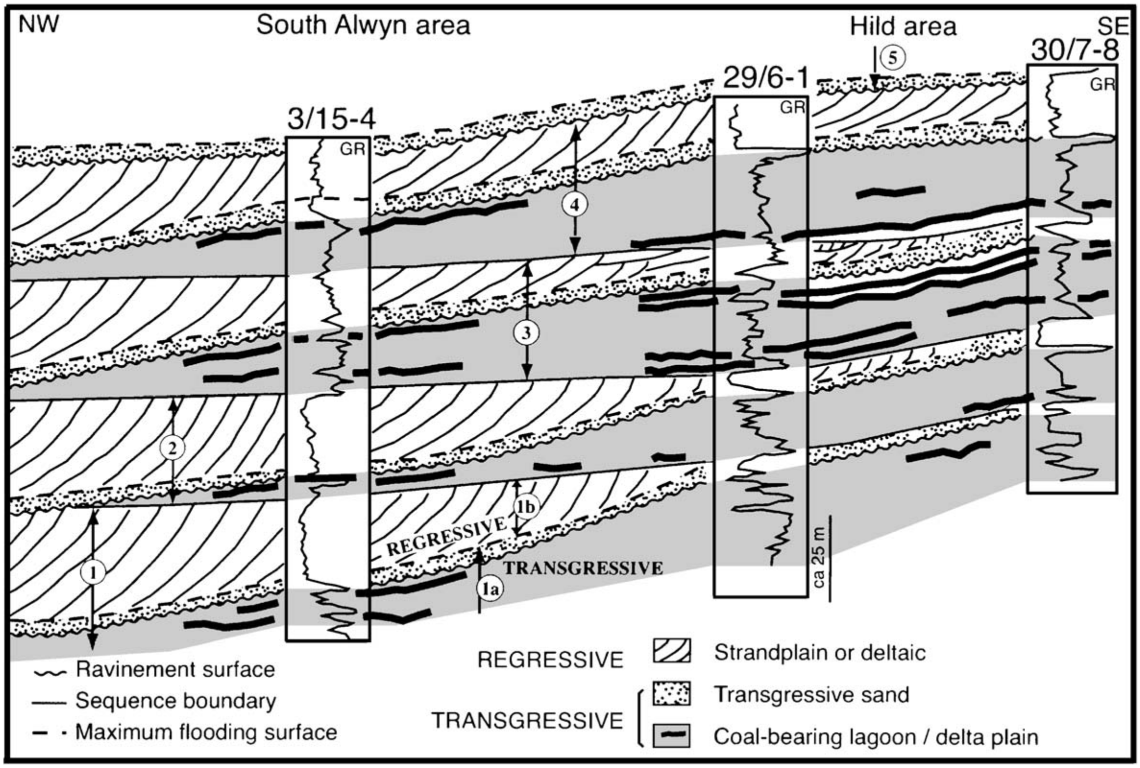


Fig. 16. Tarbert Formation in the Hild–South Alwyn area of the Viking Graben in northern North Sea. Each wave ravinement surface in the five sequences rises landwards (to right) and preserves a thickening wedge of transgressive back-barrier deposits below. The transgressive sands average 5 m in thickness (modified from Ravnås and Steel, 1998).

coarse-grained channel and tidal sand-bar complexes that backfill this topography as already shown in Fig. 7.

6.1.2.1. Dunlin Group (Lower Jurassic), northern North sea. Examples of transgressive deposits of this sort are well seen within Dunlin Group strata of the northern North Sea, within the reservoir sandstones of the Cook Formation (Marjanac, 1995; Marjanac and Steel, 1997). Because of its low gradient and epicontinental setting, the Dunlin Group basin was highly sensitive to even modest changes in relative sea level. The clean Cook sandstones usually are present above sharp erosion surfaces of regional extent and with considerable incision (Fig. 17). The sandstones lie above a tRs and below the wRs (Fig. 18). The tRs is commonly separated from the sequence boundary (SB) by thin tidal-flat deposits (Fig. 18). Lateral correlation of Cook Sandstones across the northern North Sea shows that the transgressive estuarine sandstones lie on a regionally developed valley system which evolved during phases of fall in relative sea level.

6.1.3. T-C—transgressive deposits above the wave ravinement surface, low-gradient settings

The most common low-gradient transgressive deposits are thin lag deposits overlying the TS or wRs, usually showing a clear deepening-upward trend to shelf siltstones and shales. Sometimes such deposits are very thin or absent, with only a sudden facies deepening above the wave ravinement surface. In some cases shelf sand ridges and shoal retreat massifs may form as a result of erosion and subsequent reworking of sand-prone deltaic and/or coastal plain deposits. The interplay of sediment supply and

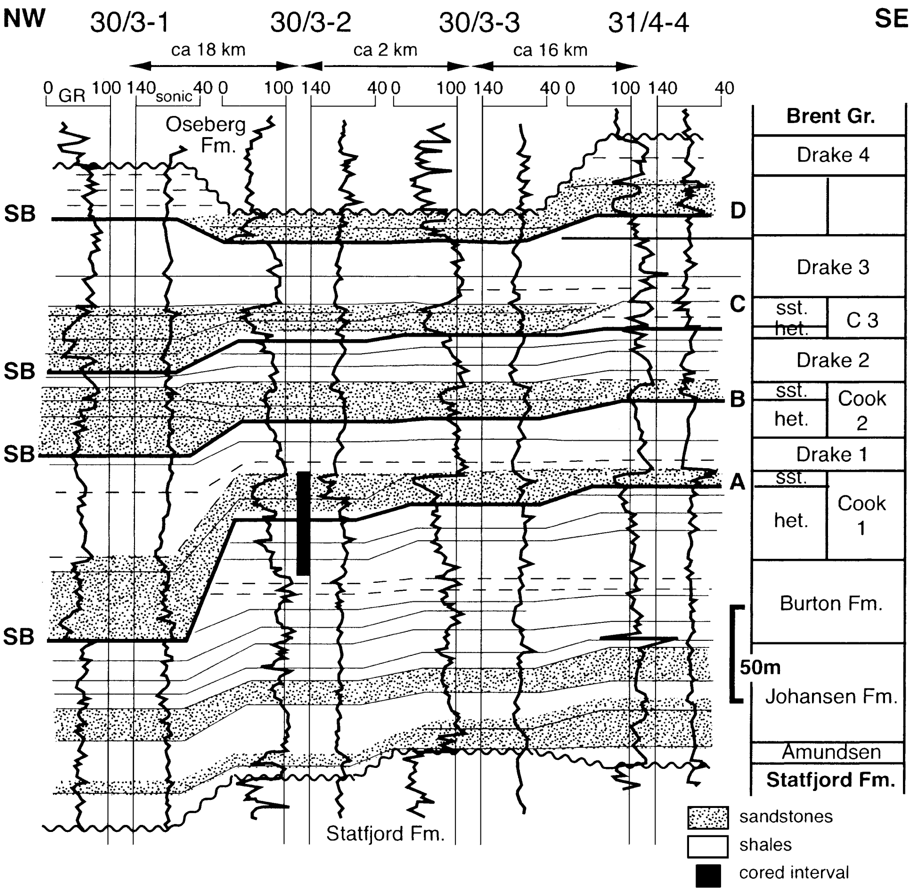


Fig. 17. Dip-oriented cross section (36 km long) showing Lower Jurassic Cook Fm. estuarine sandstone units developed above sub-regional incision surfaces in the Huldra-brage area of northern North Sea. Cored interval (black) shown in Fig. 18 (Marjanac and Steel, 1997).

accommodation determines which of the following transgressive scenarios result.

6.1.4. T-C1—simple transgressive lags

Simple transgressive lags are thin (usually less than 50 cm), relatively coarse-grained beds that contain pebbles, shell fragments, intraclasts or other clasts. They are commonly bioturbated, if immediately overlain by deeper water shales, or are overlain by hummocky cross-stratified/rippled finer sandstones before grading up to shales. Such lags tend to erosively overlie shallower or more proximal facies. Simple transgressive lags are common in the geological literature (e.g., Riemersma and Chan, 1991; Trincardi and Field, 1991).

6.1.5. T-C2—landward-stepping parasequences

6.1.5.1. Mjølner Sand (Kimmeridgian), Central Graben, North Sea. A common variant of the above simple transgressive lag occurs where low-gradient transgressive events are punctuated by small-scale, regressive shoreface tongues (parasequences). The transgressive systems tract is produced by the overall landward-stepping of the regressive parasequences. The Mjølner Sand (Kimmeridgian), in the Central Graben of the North Sea near the Norwegian–Danish sector boundary, provides a good example. Fig. 19 shows the transgressive systems tract overlain by highstand prograding clinoforms. The transgressive sands attain a thickness of some 80

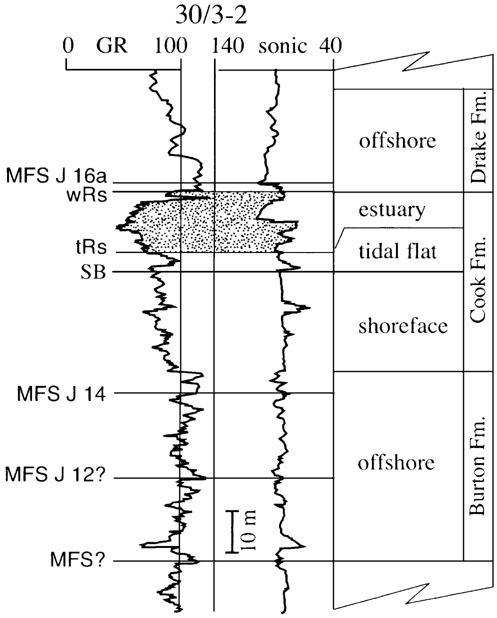


Fig. 18. Well log 30/3-2 from the northern North Sea, Norwegian sector, through part of the Lower Jurassic succession (see location in Fig. 17). Environmental interpretations based on core study (Marjanac and Steel, 1997). Note the thick estuarine sandstone unit between the wave and tidal ravinement surfaces (wRs and tRs). MFS = maximum flooding surface.

m in the middle reaches of the stratigraphic panel, and thin both basinwards and landwards (Fig. 19). The thick development of sand in the middle zones is caused by the development of slightly active tectonic terraces between the platform and the basin, allowing trapping and preservation in the narrow terraced zone.

6.1.6. T-C3—shelf sand ridges and shoal retreat massifs

Shelf sand ridges are one of the more important transgressive sand accumulations on shelves. They result from the transgressive reworking of older sand-rich systems, mainly lowstand deltas or shorefaces, that prograded far out on the shelf during the immediately previous regressive half-cycle. Shelf sand ridges and shoal retreat massifs are relatively common on many modern continental shelves, have an elongated shape and lengths of the order of 10 km. They may have formed as a result of a variety of processes including wave action (e.g., Fig. 2; Swift, 1975a), tidal currents and shelf currents (Posamentier, 2002). It is not clear if it possible to differentiate sand-ridge types based on the controlling parameters (e.g., tide- and storm-generated sand ridges; Swift, 1975b). Recent studies on the internal geometry of shelf sand bodies showed an evolution from tide-dominated to wave-dominated sedimentation (Snedden et al., 1994; Reynaud et al., 1999a). The combination of long-term (eustatic) and short-term (hydrodynamic) factors is a possible explanation for the morphology and internal stratigraphy of sand ridges (e.g., Snedden et al., 1994). The interaction between flow and an initial bathymetric irregularity (typically sandy coastal deposits reworked as relative sea level rises) may form ridges both in tide- and wave-dominated shelf regimes (Evans et al., 1985; Snedden and Dalrymple, 1999).

An example of shelf sand ridge is shown in Fig. 9. Offshore shelf-sand ridges of considerable thickness can accumulate above a wave ravinement surface in low-gradient setting. A modern example of smaller-scale but genetically comparable deposits (subaqueous dunes) was described in the northern Adriatic shelf, where drowned transgressive coastal deposits have been totally reworked into sand dunes (column 4, Fig. 20; Correggiari et al., 1996b).

6.1.7. T-D—transgressive deposits above the wave ravinement surface, high-gradient, high-sediment supply settings

This category of transgressive deposits has not been well documented previously in the literature, at least where the sands are thickly developed. The high-gradient, high-sediment supply and the effect that this has on the transgressive deposits can dominate the entire system, or can be visible only locally. The diagnostic and critical features in this type of system, reflecting the high sediment supply and proximity to active source areas, are the coarse-grained nature of the deposits (commonly derived from fan deltas), the highly aggradational character of the stacking in successive "parasequences", and the occurrence of multiple wave ravinement surfaces separating thin regressive pulses (reflecting a high rate of supply of sediment from land). Transgression across such high gradient slopes, despite relatively high rates of sediment supply, has been documented from the SE margin of the Ebro Basin (see papers in Marzo and Steel,

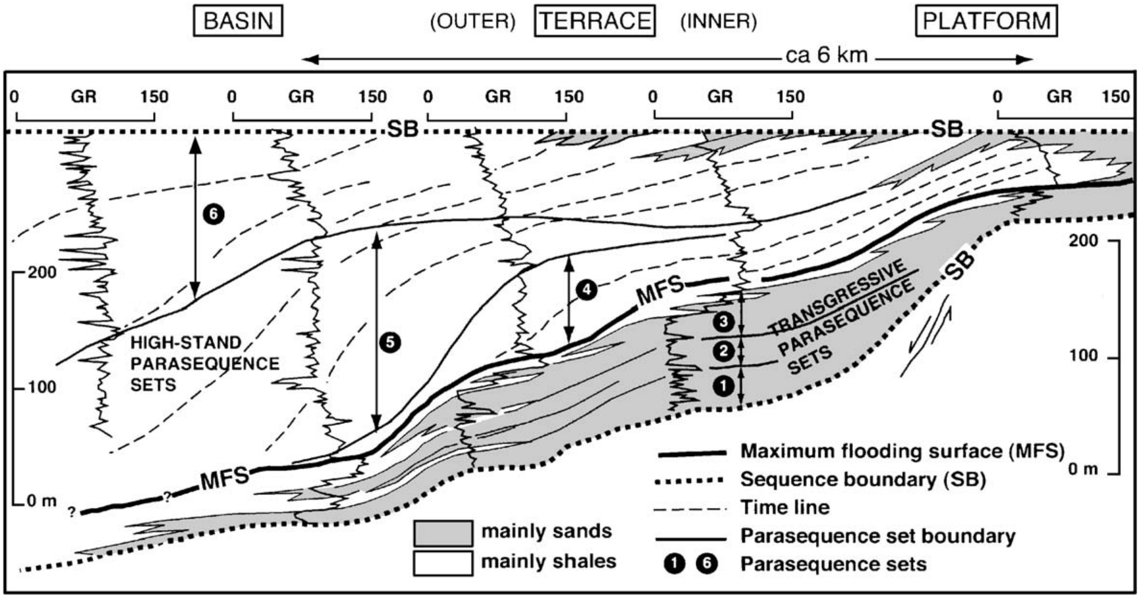


Fig. 19. Development of a thick, landward-stepping series of transgressive parasequence sets in the transgressive systems tract of an Upper Jurassic sequence, Central Graben on Norwegian–Danish border. The great thickness of the TST relates to accumulation on fault-generated terraces between platform and basin.

2000). Fig. 15 from this margin, already used above to illustrate transgressive deposits below the Rs (T-A), shows well also the characteristics of transgressive deposits of Type T-D. An unusual feature of these deposits is the occurrence of bored-pebble pavements on each of the ravinements surfaces. Clusters of up to 20 such surfaces with bored-pebble horizons occur within a 20-m-thick transgressive tract (see Siggerud et al., 2000, for details).

6.1.8. T-E—transgressive deposits without evidence of ravinement surfaces

As pointed out above, wave and tidal ravinement surfaces need a relatively high level of basinal energy to develop. The ravinement surfaces may be absent in low-energy basins or in some areas of higher-energy basins that are protected from wave and tide action. An example could be represented by the Irish Valley Member of the Upper Devonian Catskill Formation (Walker and Harms, 1971). In these cases, the transgressive deposits may be more difficult to identify. The basal transgressive surface, if not coincident with a previous subaerial unconformity, may be lithologically less evident. The support from paleontologic data may be crucial to interpret properly the transgressive nature of such deposits.

6.2. The case of late quaternary transgressive deposits in the Adriatic Sea (Italy)

Transgressive deposits of the last sea level cycle (ca.16 to 5.5 kyr BP) have been studied and correlated along the Italian side of the epicontinental Adriatic Sea from Venice to the Gargano promontory (Fig. 20). High-resolution seismic lines coupled with sedimentological, micropaleontological, and tephrochronological analysis of sediment cores and numerous ^{14}C dates provided a refined chronostratigraphic framework at basin scale. Precise physical correlations allowed the comparison of distinct transgressive records created in different areas of the basin in response to key parameters such as topographic gradients, supply regimes, and oceanographic processes (Trincardi et al., 1994; Correggiari et al., 1996a,b; Cattaneo and Trincardi, 1999).

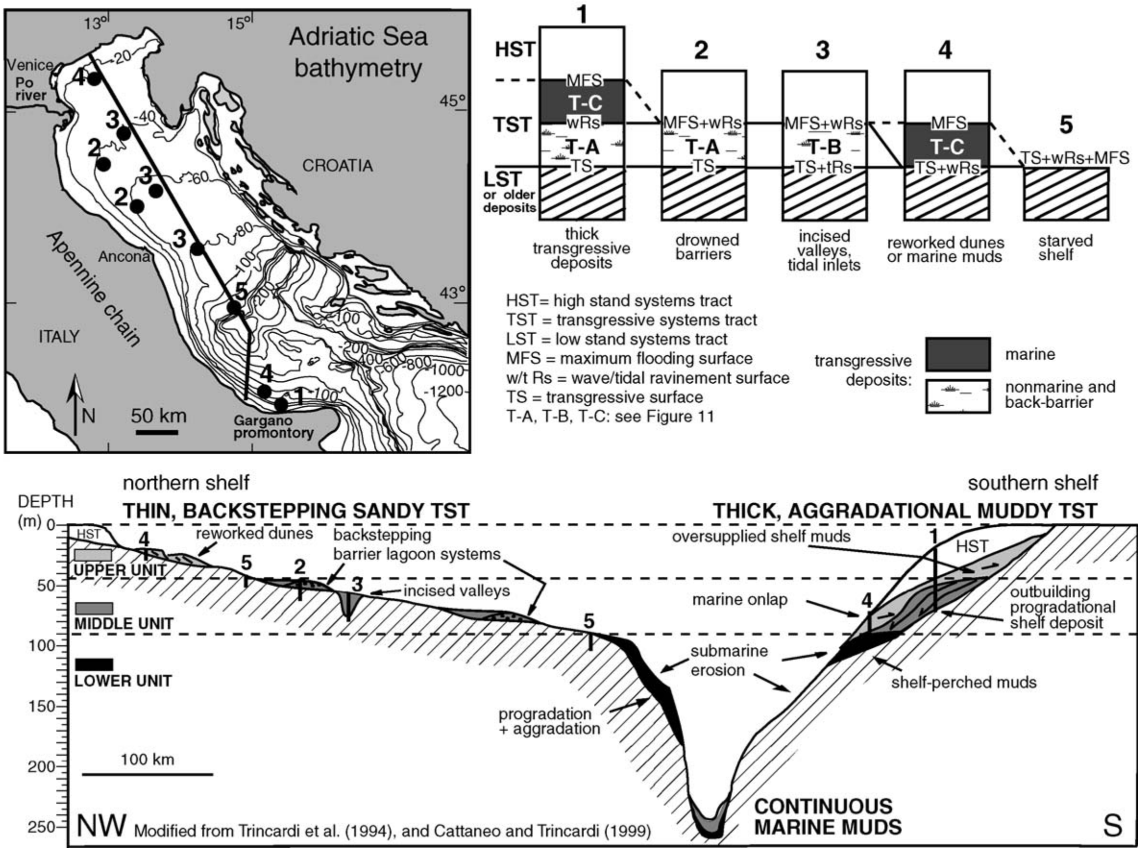


Fig. 20. Bathymetry of the Adriatic Sea with location of five idealized stratigraphic columns and a schematic cross section. The five columns show the variability of transgressive deposits and of their main bounding surfaces (MFS = maximum flooding surface; Rs = ravinement surface; TS = transgressive surface; from Trincardi et al., 1994). The cross section shows the sediment architecture of coeval transgressive deposits in different sectors of the basin (from Cattaneo and Trincardi, 1999). See text for details.

The Adriatic Sea is characterised by a low-gradient shelf in the north and a steeper shelf on the southwestern side, separated by a 260-m-deep remnant basin, with one main sediment source (the Po river; Fig. 20) and a counter-clockwise cyclonic circulation with a wave-dominated microtidal regime (Trincardi et al., 1994). During the late-glacial to early-Holocene transgression, a glacio-eustatic, non-steady sea-level rise of ca. 120 m caused substantial basin widening accompanied by changes in energy regimes across the basin. This trend was further complicated by repeated pulses in sediment supply (possibly controlled by high-frequency climatic changes) to create a complex transgressive succession.

Across the low-gradient northern shelf, the stepwise, high-amplitude relative sea-level rise favoured the deposition and in-place drowning of different generations of transgressive barrier–lagoon systems. Where present, the paralic transgressive deposits rest on a TS and are topped by a wRs (columns 1 and 2; Fig. 20). In areas of intense wave action, the continental record has been totally reworked resulting in accumulation of marine transgressive deposits above the wRs (column 4; Fig. 20). The rapidly transgressed, sediment-starved areas of the shelf between the drowned barrier–lagoon systems show a thin transgressive lag where the wRs virtually coincides with the MFS (column 5; Fig. 20). Locally, on the northern shelf, incised valleys that originated during previous relative sea-level lowstand show transgressive estuarine backfill resting on top of an erosional surface (a sequence boundary coincident with a TS and tRs) and capped by a wRs that coincides with the MFS (column 3; Fig. 20; Correggiari et al., 1996b); similar incised valleys away from sediment transport routes (i.e., closer to the Croatian coast) are erosional features with scarce or absent sediment infill (column 5; Fig. 20).

The southwestern Adriatic shelf shows a steeper topographic gradient, has areas of local uplift and higher sediment supply, and is characterised by the deposition of the thickest transgressive succession (up to 25 m; Cattaneo and Trincardi, 1999). This is composed of marine muds and/or storm-dominated shelf deposits above the wRs (column 4; Fig. 20), or, in more landward positions, of possibly nonmarine deposits below, and marine muds above, a wRs (column 1; Fig. 20; the nonmarine deposits however have not been sampled due to their depth in the sediment column exceeding the sampling capabilities of conventional piston coring). Within an overall package of transgressive muddy deposits, a slightly sandier shelf sandbody with a progradational geometry stands out (cross section; Fig. 20). This unit was probably emplaced during slower rates of relative sea-level rise or stillstand driven by paleoclimatic changes (Cattaneo and Trincardi, 1999). A wRs is locally visible at the top of the progradational unit, as a result of resumed transgression, especially in areas close to topographic highs that may have enhanced wave action. However, the wRs is not always detectable, especially in sectors of the basin with a more embayed topography. There, thick muddy transgressive marine deposits rest on a TS and are topped by a MFS. In the 250-m-deep basin, continuous marine sedimentation took place during transgression, whereas along the basin margins the transgressive deposits show an onlapping, “healing-phase” geometry on top of older sediments at depths exceeding 100 m.

7. Conclusions

The study of a series of transgressive systems tracts has highlighted the variability in thickness, lateral dimensions, and internal architecture of transgressive deposits. Five main types of transgressive deposits are described:

T-A—transgressive deposits developed *below the lowest ravinement surface*. These are not only commonly coal-bearing deposits, but also include significant coastal alluvial successions. They develop and are preserved in low-gradient settings, usually where there is divergence between the ravinement trajectory and the topographic surface being transgressed, or in the case of barrier in-place drowning. Care should be taken to correctly correlate these coal-bearing strata to the transgressive part of sequence, if useful predictions are to be made.

T-B—transgressive deposits (commonly much more sand-prone than (T-A) above), developed and preserved *above the tidal ravinement surface but below the wave ravinement surface*. These deposits are widespread in tide-dominated settings, and develop also in environments where tidal processes locally dominate over wave/storm processes, and as a result are limited areally within the depositional transect. The local separation or slight divergence between tidal and wave ravinement surfaces allows estuarine sandbodies to develop. Maximum flooding surfaces should be used as a horizontal datum in correlation of these deposits, otherwise the estuarine sands do not exhibit the full basal relief. The above wave ravinement surface may be absent in the most landward positions of a depositional transect, or in cases where the deposits represent high-energy settings that are purely tide-dominated.

T-C—transgressive deposits developed *above the wave ravinement surface in low-gradient settings*. These deposits are derived from shoreface erosional (and newly supplied sediment) products during transgression. They are usually thin (less than 1 m thick), but can cumulatively be thicker if transgression is punctuated with repeated regressive parasequences. Shelf sand ridges of considerable thickness (up to 20 m) may accumulate in this transgressive setting, and would be included in this category of transgressive deposits.

T-D—transgressive deposits developed *above the wave ravinement surface in high-gradient, high-sediment supply settings*. In this setting, coarse-grained transgressive lithosomes can aggradationally develop (up to a few tens of metres thick), because all the eroded and newly supplied sediment is redeposited fairly locally above a high-gradient wave ravinement or cluster of ravinements. These lithosomes tend to be narrow ($<2-3$ km) but are extensive along strike.

T-E—transgressive deposits *without evidence of ravinement surfaces*. These deposits are characteristic of low-energy coastlines, and are typically developed in mud-dominated successions.

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