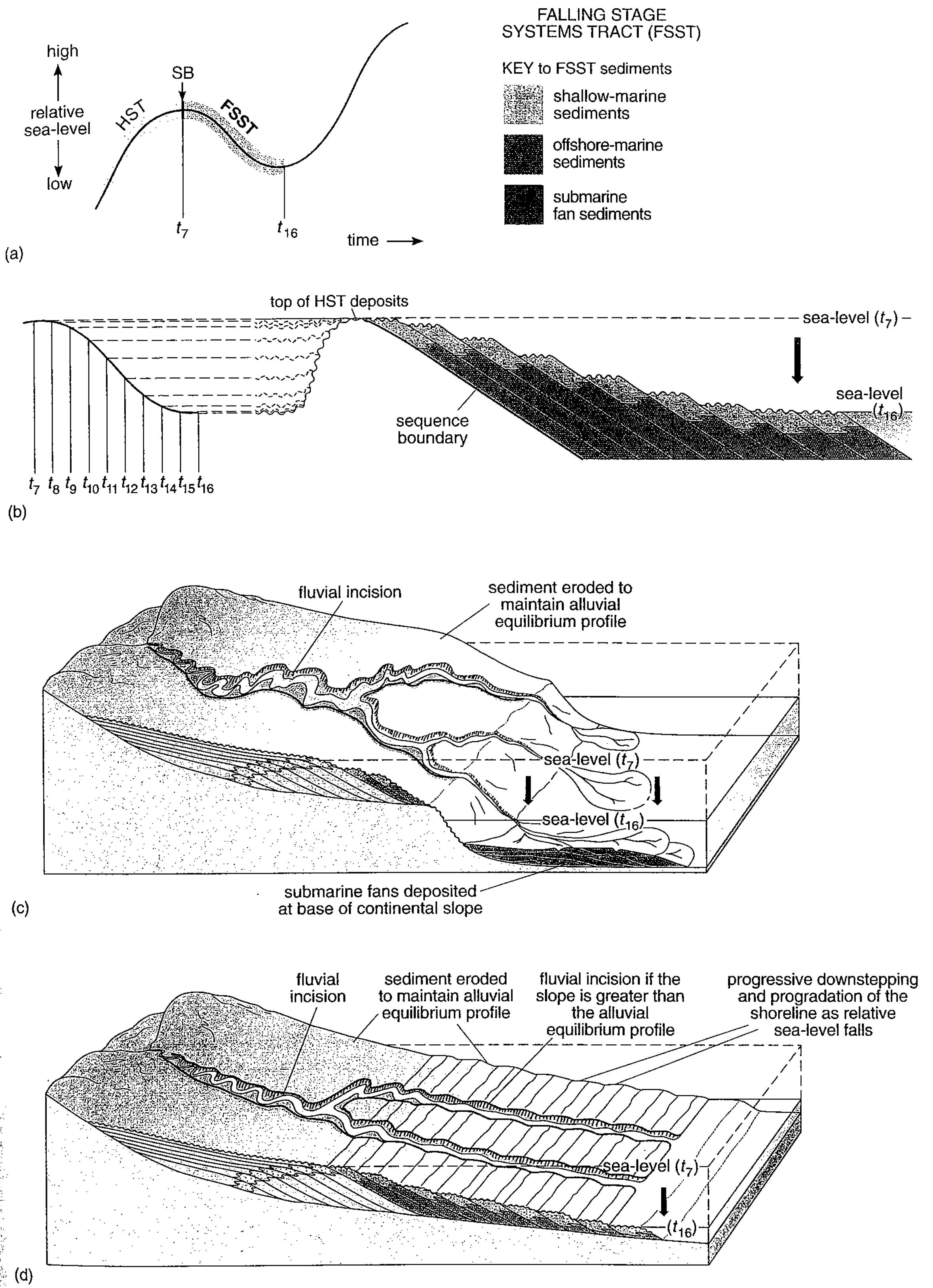
Surfaces that correlate laterally with unconformities, but are not themselves unconformities, are termed *correlative conformities* (Figure 4.11). These can be difficult to identify because there is often no distinct change in facies. For instance, if the water depth at a particular point along the marine depositional profile suddenly changes from 100 m to 90 m (i.e. all below storm wave-base) where mud is being deposited, there is unlikely to be a pronounced change in the composition of the muds above and below the correlative conformity but the features preserved depend on the particular sedimentary system. As the correlative conformity is traced further landward, or into areas of lower subsidence, it may exhibit a slight change in facies either side of the surface (e.g. siltstones gradationally overlying mudstones, or a more subtle change from organic-rich mudstones to organic-poor silty mudstones). The correlative conformity is important for dating the sequence boundary. It lies at the base of any sediments deposited during falling relative sea-level and represents the time at which relative sea-level started to fall.

During a regression, as opposed to a forced regression illustrated here, the sequence boundary would form during the temporary decrease in the *rate* of relative sea-level rise or the stillstand that occurs between the decreasing rate of relative sea-level rise when the highstand systems tract is deposited and the increasing rate of relative sea-level rise when the overlying lowstand systems tract is deposited (see p.77). The sequence boundary in this case would be at the surface where the facies belts reach their most proximal position and the minimal erosion results in the unconformity part being absent or poorly developed.

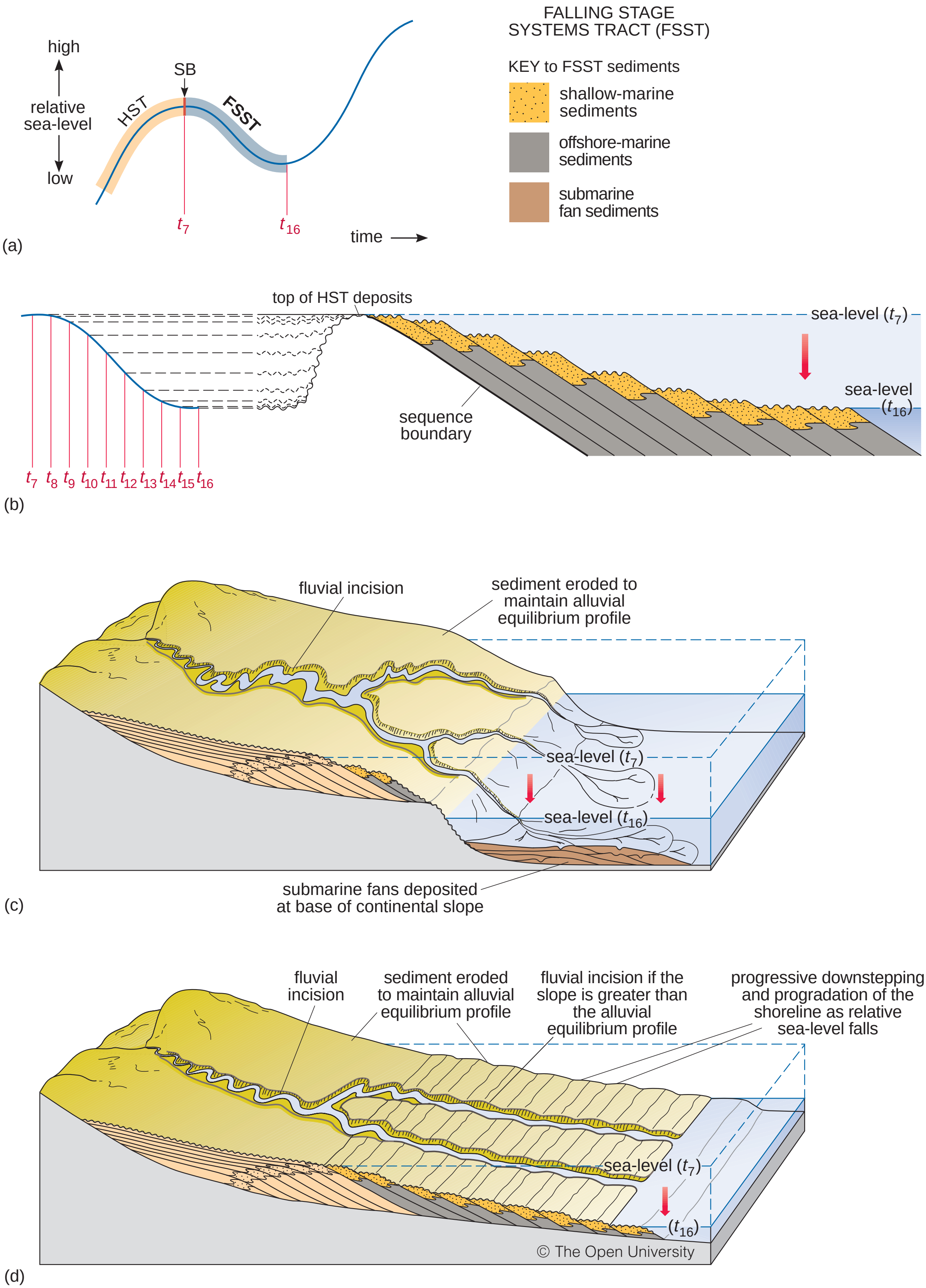
The falling stage systems tract (FSST)

The combined effect of relative sea-level fall and hence increased erosion will be to: (i) increase supply of siliciclastics or reworked carbonates into the sea; and (ii) move all the facies belts in a distal direction (i.e. progradation) and, topographically, down the depositional profile (i.e. the shoreline will be at a lower height than in each previous time step (Figure 4.12)). Thus, foreshore sediments may be found unconformably overlying, for instance, offshore transition zone sediments. For siliciclastic environments, sediment will mainly be sourced from rivers that are incising and transporting sediment into the sea in response to the fall in relative sea-level. Carbonate sediments will be produced *in situ* at a lower position on the depositional profile, or derived from erosion of previously deposited carbonates, and under appropriate conditions, downstepping reefs will track falling sea-level (Chapters 12 and 13). Sediment deposited during falling relative sea-level is termed the *falling stage systems tract* (FSST) (Figure 4.12).

Figure 4.12 (opposite) Features of the falling stage systems tract (FSST). (a) Interval on the theoretical relative sea-level curve shown in Figure 4.8 during which the FSST is deposited. (b) Detail of the relative sea-level curve (in blue) and the FSST sediments deposited. The curve spans a phase of increasing and then decreasing rate of relative sea-level fall (i.e. a slow, then rapid, and finally a slow decrease in the amount of accommodation space). The relative sea-level curve is divided into equal time units (red lines t_7, t_8 etc.). Dashed horizontal black lines in the middle indicate the amount of accommodation space lost during each time step in the relative sea-level fall and hence the potential depth down to which fluvial valleys might incise. The right-hand part shows sediments deposited for each of the equal time intervals assuming a constant rate of sediment supply, that sediment continues to be deposited, and that the depositional profile is gently sloping. The decrease in accommodation space in proximal areas results in a progradational parasequence set. Sediments deposited over the time interval between maximum and minimum relative sea-levels form the FSST. The tops of the previously deposited parasequences in the FSST are eroded as relative sea-level continues to fall. (c) Geometry and features of the FSST along a margin with a shelf break. In this case, the first two parasequences of the FSST are deposited on the continental shelf as downstepping parasequences (t_7–t_8 and t_8–t_9). It is assumed that in this case after t_9 relative sea-level fell below the shelf break and therefore that all further sediment was transported down the steep continental slope into the deep sea where it was deposited as submarine fans on the basin floor. (d) Geometry and features of the FSST along a ramp margin showing the deposition of an attached FSST. (c) and (d) are not to scale and show a slightly greater relative sea-level fall than (a) and (b) in order to show all the features.



high
relative sea-level
low
SB
HST
FSST
t_7
t_{16}
time
(a)
FALLING STAGE SYSTEMS TRACT (FSST)
KEY to FSST sediments
shallow-marine sediments
offshore-marine sediments
submarine fan sediments
top of HST deposits
sea-level (t_7)
sea-level (t_{16})
sequence boundary
t_7 t_8 t_9 t_{10} t_{11} t_{12} t_{13} t_{14} t_{15} t_{16}
(b)
fluvial incision
sediment eroded to maintain alluvial equilibrium profile
sea-level (t_7)
sea-level (t_{16})
submarine fans deposited at base of continental slope
(c)
fluvial incision
sediment eroded to maintain alluvial equilibrium profile
fluvial incision if the slope is greater than the alluvial equilibrium profile
progressive downstepping and progradation of the shoreline as relative sea-level falls
sea-level (t_7)
(t_{16})
(d)


FALLING STAGE SYSTEMS TRACT (FSST)
KEY to FSST sediments
shallow-marine sediments
offshore-marine sediments
submarine fan sediments
high
relative sea-level
low
SB
HST
FSST
t_7
t_{16}
time
(a)
top of HST deposits
sea-level (t_7)
sea-level (t_{16})
sequence boundary
t_7 t_8 t_9 t_{10} t_{11} t_{12} t_{13} t_{14} t_{15} t_{16}
(b)
fluvial incision
sediment eroded to maintain alluvial equilibrium profile
sea-level (t_7)
sea-level (t_{16})
submarine fans deposited at base of continental slope
(c)
fluvial incision
sediment eroded to maintain alluvial equilibrium profile
fluvial incision if the slope is greater than the alluvial equilibrium profile
progressive downstepping and progradation of the shoreline as relative sea-level falls
sea-level (t_7)
(t_{16})
© The Open University
(d)

The preservation, geometry and lateral position of the FSST is variable, depending on the shape of the depositional profile, the magnitude and rate of the relative sea-level fall, the rate of sediment supply and the changes of sedimentary process that occur as relative sea-level falls and a larger area is subaerially exposed (Figure 4.13). For shelf-break margins, if the HST sediments have not filled all the space available on the continental shelf, downstepping parasequences will be deposited as shown for the first two parasequences t_7–t_9 in Figure 4.12c. However, when relative sea-level falls below the shelf edge the relatively steep depositional profile results in sediment from the incised river valleys accumulating at the base of the continental slope as submarine fans (Figure 4.12c, t_9–t_{16}). In contrast, for a ramp type margin, with its much more shallow gradient, the effect of a similar magnitude sea-level fall can be much more dramatic. On ramp type margins, the whole depositional system can be forced basinward by as much as several kilometres (Figure 4.13a) because the amount of nearby accommodation space lost compared to the total amount of accommodation space available is much greater than on the shelf break margins (Figure 4.14). Because of this wide potential geographical separation of the HST and FSST, many sediments deposited during forced regression on ramp margins have probably gone unrecognized. The relative sea-level fall can alternatively result in the deposition of parasequences all along the depositional profile distal from the last highstand shoreline, each one progressively downstepping as relative sea-level falls (Figures 4.12b,d and 4.13b,c).

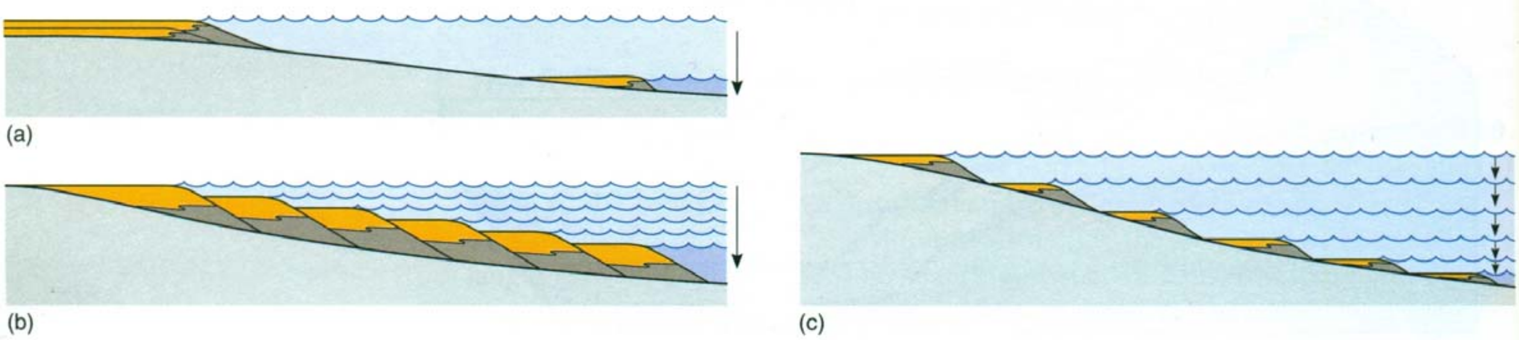


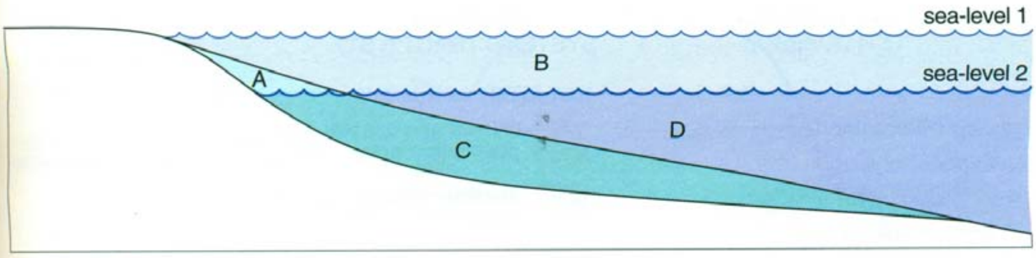
Figure 4.13 Different types of FSST. The parasequences shown on the left are older than those shown on the right of each profile. (a) A detached systems tract. (b) An attached FSST. (c) Another type of detached FSST. Arrows show relative sea-level falls. See text for further explanation. *(Posamentier and Morris, 2000.)*

❍ Figure 4.13b and c shows two possible scenarios for a ramp of the same dip. Which part of the Figure represents a higher sediment supply or a slower rate of relative sea-level fall?

● Figure 4.13b represents a higher rate of sediment supply or a slower rate of relative sea-level fall because the parasequences gradationally downstep whereas in Figure 4.13c the distance that each parasequence downsteps is much greater, resulting in each one being isolated from the next.

The parasequences shown in Figure 4.13a and c are sometimes called stranded parasequences or a *detached* FSST because the shoreline in each case is separated from the previous one. In contrast, the parasequences in Figure 4.13b make up an *attached* FSST.

In situations where, during the forced regression, sediment supply is low to moderate, or the rate of relative sea-level fall is particularly high, or there is continued erosion along the depositional profile to the lowest sea-level, a FSST will not be preserved. The lack of a FSST is quite common in the geological record. In situations where there is a regression rather than a forced regression, there will *never* be a FSST, because this systems tract is solely a consequence of forced regression.



$$\frac{A+B}{C+D} \ll \frac{B}{D}$$

Figure 4.14 Sketch to show that the proportion of coastal accommodation space lost during a relative sea-level fall is much greater for a ramp type margin than a shelf break margin. A–D are volumes of water. A + B = volume of water lost after the relative sea-level fall on a shelf break margin; C + D = volume of water remaining after the relative sea-level fall on a shelf break margin; B = volume of water lost after the relative sea-level fall on a ramp type margin; D = volume of water remaining on a ramp type margin after the relative sea-level fall.

The lowstand systems tract (LST)

At time t_{16} on the theoretical sea-level curve (Figure 4.8), relative sea-level fall reaches its minimum and accommodation space is neither being created nor destroyed. But, by t_{17}, a small amount of accommodation space has been created; this allows the shoreline to start building upwards from its lowest position. Progradational marine sediments will be deposited and the fluvial system will cease to incise (Figure 4.15a,b overleaf). This process will continue until there is a much more pronounced increase in the amount of accommodation space which for the theoretical curve shown in Figures 4.8a,b and 4.15 (overleaf) is at t_{21}. The package of sediment deposited between the minimum relative sea-level and the pronounced increase in accommodation space is termed the *lowstand systems tract* (LST); this is composed of progradational to aggradational parasequence sets. In the case of the shelf break margin, the LST may comprise one or more submarine fans deposited on the shelf slope on top of the recently formed slope of the FSST submarine fans. These slope fans may be overlain by one or more progradational parasequences as the shoreline progrades again over the top of the gently dipping slope fan (Figure 4.15c). For ramp type margins, progradational to aggradational parasequences will build up above the last FSST shoreline (Figure 4.15b,d).

The transgressive surface (TS)

As relative sea-level begins to rise at a significant pace, it will reach a point where the long-term rate of creation of accommodation space is greater than the rate of sediment supply and there will be a transgression. The locus of sedimentation will be shifted in a landward direction and there will be deposition of a retrogradational parasequence or parasequence set (the transgressive systems tract, see p.80). The base of these retrogradational parasequences marks the *transgressive surface* (TS). In the scenario that we have used, this will start to form at t_{21} (Figure 4.16a overleaf). The transgressive surface is often particularly well developed in the coastal environments of the shoreface and foreshore where the rise in relative sea-level results in minor erosion and reworking of the sediments from increased wave-, tide-, and storm-induced activity resulting in the formation of a minor unconformity (see erosion surface at t_{21} marked on Figure 4.11c,e). In the proximal (i.e. landward) areas, the transgressive surface may be marked by marine sediments overlying non-marine sediments (Figure 4.16).

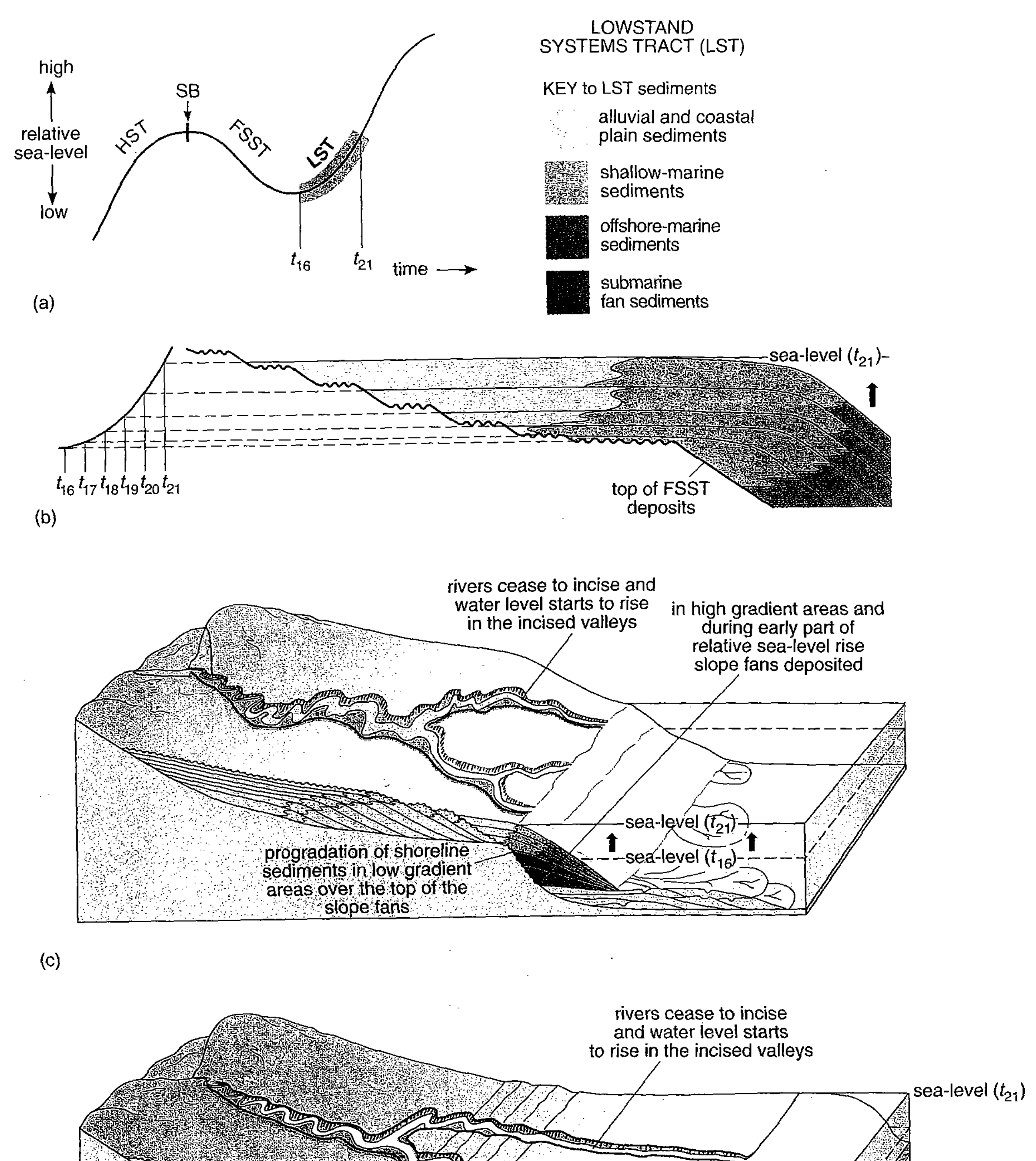
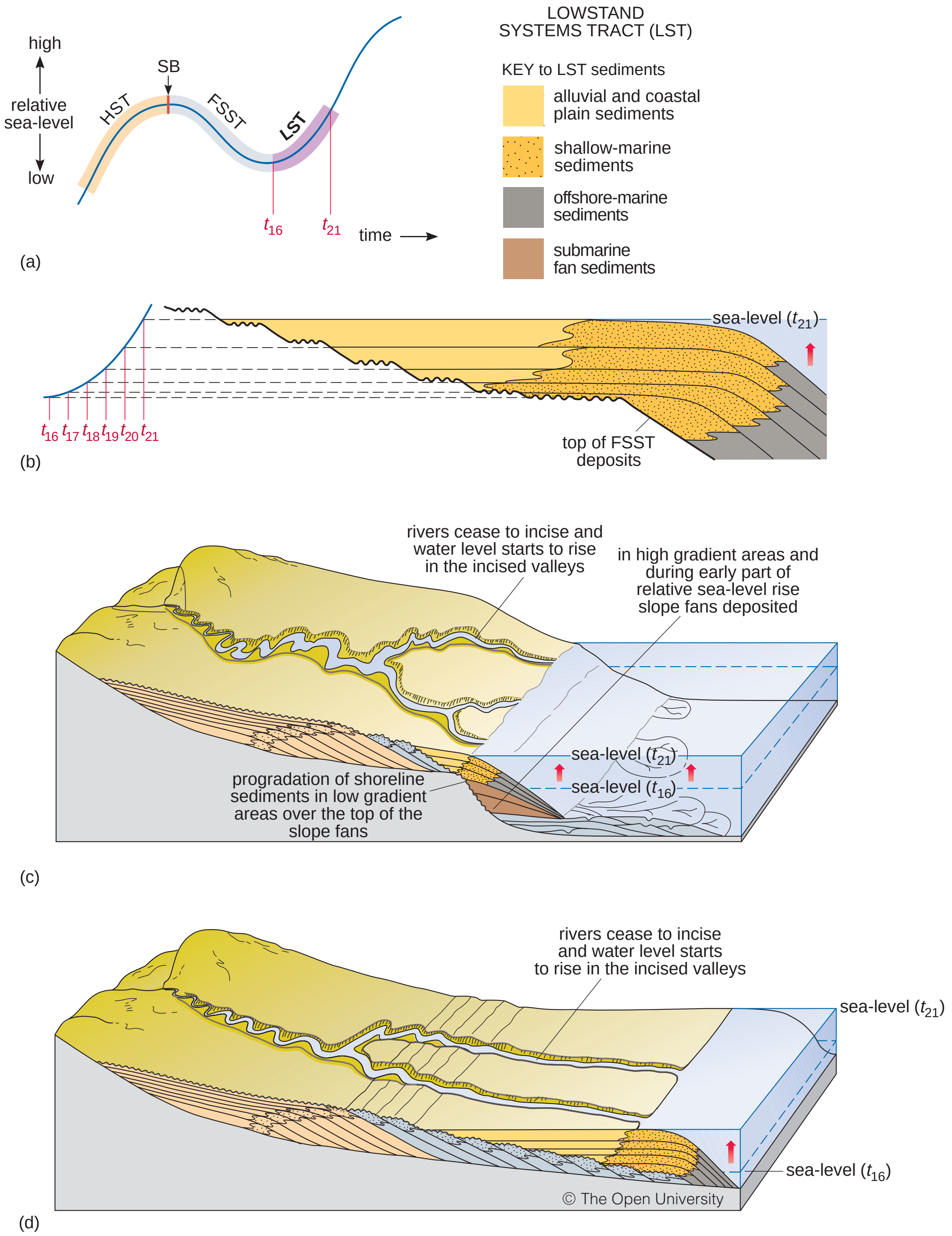


Figure 4.15 Features of the lowstand systems tract (LST). (a) Interval on the theoretical relative sea-level curve shown in Figure 4.8, during which the LST is deposited. (b) Detail of the relative sea-level curve (in blue) and the LST sediments deposited. The curve is over a phase of slowly rising relative sea-level (i.e. an increase in the rate of creation of accommodation space). The relative sea-level curve is divided into equal time units (red lines t_{16}, t_{17} etc.). Dashed horizontal black lines in the middle indicate the amount of accommodation space created during each time step in the relative sea-level rise. The right-hand part shows sediments deposited for each of the equal time intervals assuming a constant rate of sediment supply and that the depositional profile is gently sloping. The sediments deposited over the time interval between the minimum relative sea-level and the more pronounced increase in sea-level form the LST. (c) Geometry and features of the LST along a margin with a shelf break. Initially, submarine slope fans may be deposited (shown as t_{16}–t_{18}) until the gradient is low enough and sea-level is high enough that the shoreline can prograde out into the basin (t_{18}–t_{21}) and coastline sediments can be deposited. (d) Geometry and features of the LST along a ramp margin. (c) and (d) are not to scale.



high
relative sea-level
low
SB
HST
FSST
LST
t_{16}
t_{21}
time
(a)
LOWSTAND SYSTEMS TRACT (LST)
KEY to LST sediments
alluvial and coastal plain sediments
shallow-marine sediments
offshore-marine sediments
submarine fan sediments
sea-level (t_{21})
t_{16} t_{17} t_{18} t_{19} t_{20} t_{21}
top of FSST deposits
(b)
rivers cease to incise and water level starts to rise in the incised valleys
in high gradient areas and during early part of relative sea-level rise slope fans deposited
sea-level (t_{21})
sea-level (t_{16})
progradation of shoreline sediments in low gradient areas over the top of the slope fans
(c)
rivers cease to incise and water level starts to rise in the incised valleys
sea-level (t_{21})
sea-level (t_{16})
© The Open University
(d)

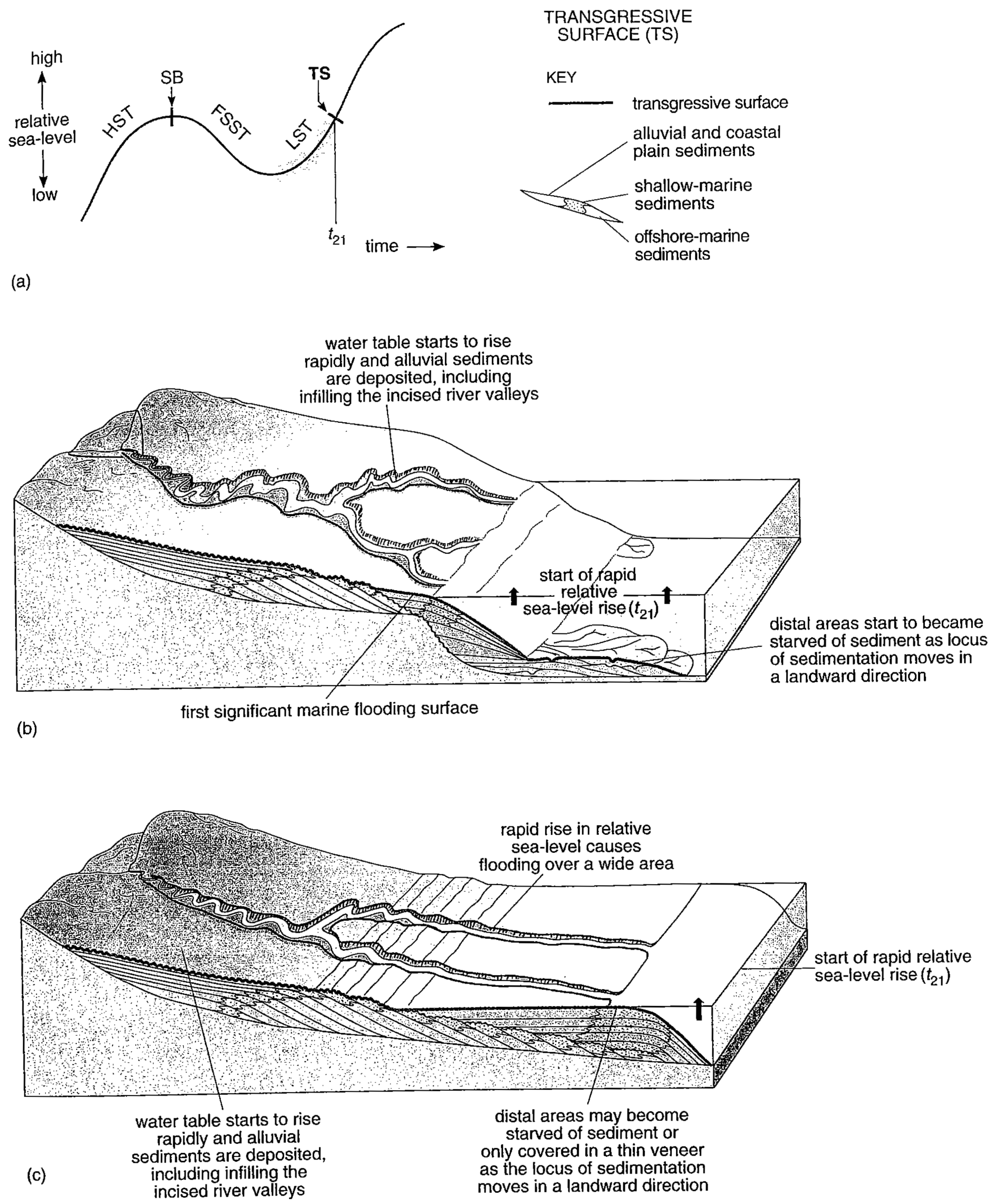
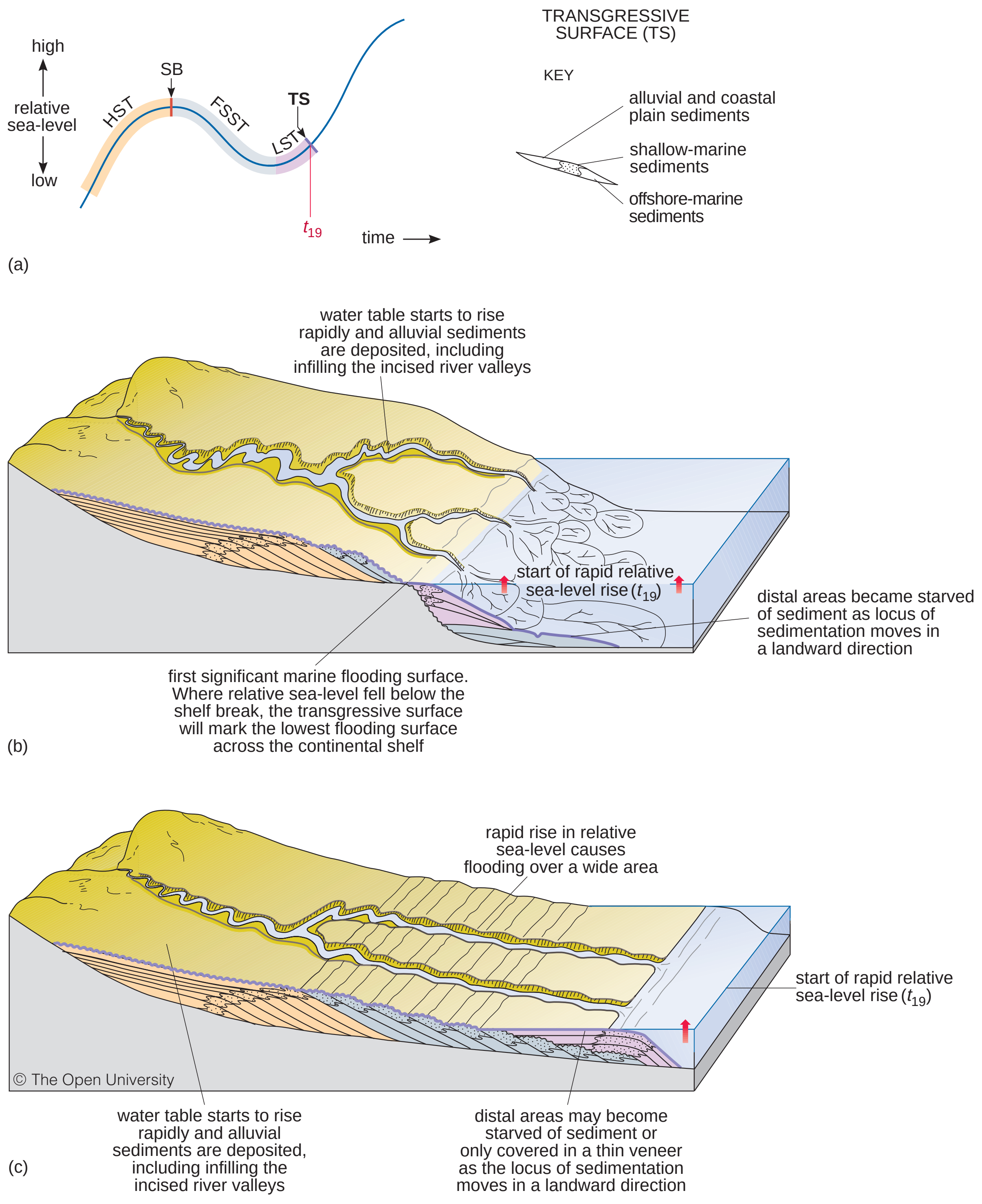


Figure 4.16 The geometry and features of the transgressive surface (TS). (a) Position on the theoretical relative sea-level curve where the transgressive surface starts to form. (b) Geometry and features of the transgressive surface along a shelf break margin. (c) Geometry and features of the transgressive surface along a ramp margin. (b) and (c) not to scale.



high
relative
sea-level
low
SB
HST
FSST
TS
LST
t_{19}
time
(a)
TRANSGRESSIVE
SURFACE (TS)
KEY
alluvial and coastal
plain sediments
shallow-marine
sediments
offshore-marine
sediments
water table starts to rise
rapidly and alluvial sediments
are deposited, including
infilling the incised river valleys
start of rapid relative
sea-level rise (t_{19})
distal areas became starved
of sediment as locus of
sedimentation moves in
a landward direction
first significant marine flooding surface.
Where relative sea-level fell below the
shelf break, the transgressive surface
will mark the lowest flooding surface
across the continental shelf
(b)
rapid rise in relative
sea-level causes
flooding over a wide area
start of rapid relative
sea-level rise (t_{19})
© The Open University
water table starts to rise
rapidly and alluvial
sediments are deposited,
including infilling the
incised river valleys
distal areas may become
starved of sediment or
only covered in a thin veneer
as the locus of sedimentation
moves in a landward direction
(c)

The transgressive systems tract (TST)

The sediments immediately overlying the transgressive surface form the *transgressive systems tract* (TST) and are all deposited during the interval when the rate of increase in accommodation space is greater than the rate of sediment supply (in this case, t_{21}–t_{23}, Figure 4.17). Note that more sediment is usually deposited in proximal areas than distal areas during this period because the locus of sedimentation has been moved in a proximal direction (Figure 4.17b–d). The facies belts and parasequences of the TST will retrograde; retrograding parasequences are diagnostic of the TST in most siliciclastic and some carbonate environments. In the case of carbonate depositional environments, transgression often results in large shallow-marine areas being flooded and made available for colonization by carbonate-producing communities such as coral reefs. This can lead to an *increase* in the rate of carbonate production and deposition which will result in aggradational or even progradational parasequence stacking patterns (see Chapters 11 and 12). Transgression of the sea will lead to infilling of the incised valleys created during falling relative sea-level.

Variations in sediment supply, the rate of relative sea-level rise and the exact nature of the depositional profile determine the type of deposits in the TST and its timing. During transgression, siliciclastic sediment supply tends to be lower than at other times because sediment is trapped in proximal areas and there is no incision. If sediment supply is low, the TST may be thin or even absent, or comprise reworked sediments rich in fossils. Over continental shelves or in shallow seas, such as those that existed for much of the Mesozoic, deposition of organic carbon-rich mudrocks was common and these deposits are often interpreted to represent TSTs. This is because relative sea-level rise is thought to have led to increased organic productivity as more nutrients were available from the newly flooded area. The earliest time the TST can stop forming is at the maximum rate of relative sea-level rise (t_{22}) but because sediment supply is here assumed to be constant and we have a sinusoidal curve, the top and bottom of the TST will be symmetrical about t_{22}.

The maximum flooding surface (MFS)

As the rate of relative sea-level rise increases, distal parts of the depositional profile may be completely, or almost completely, starved of siliciclastic sediment, because the locus of sedimentation has moved so far landward that no, or very little, sediment reaches the deeper parts of the basin (Figure 4.18 overleaf). This starvation reaches its most landward position between the maximum rate of relative sea-level rise and the maximum sea-level (t_{22} and t_{29} respectively on our theoretical relative sea-level curve), depending on the particular conditions. In this case, it occurs at t_{23}. Sediment starvation in the distal area will continue longer than in the proximal area (pink area on Figure 4.18c and e). The low sediment supply results in formation of a condensed bed; such beds are often highly fossiliferous as there is less sediment to 'dilute' the fossils which continue to be deposited on the sea-floor. The fossils' preservation potential is increased by the likelihood of cementation and precipitation of authigenic minerals like phosphate, as sedimentation rate decreases. The top of the condensed section and/or submarine unconformity is termed the *maximum flooding surface* (MFS) (Figure 4.18). In proximal areas, the MFS is associated with the most landward position of the shoreline and the most extensive marine sediments (e.g. thin brackish or marine sediments in deltaic successions). Marine sediments are often deposited in proximal areas which have previously been entirely non-marine. In addition, flooding of more proximal areas will cause the most pronounced rise in the water table, affecting deserts and causing further realignment in the depositional profile of alluvial systems. If deltas are present, the

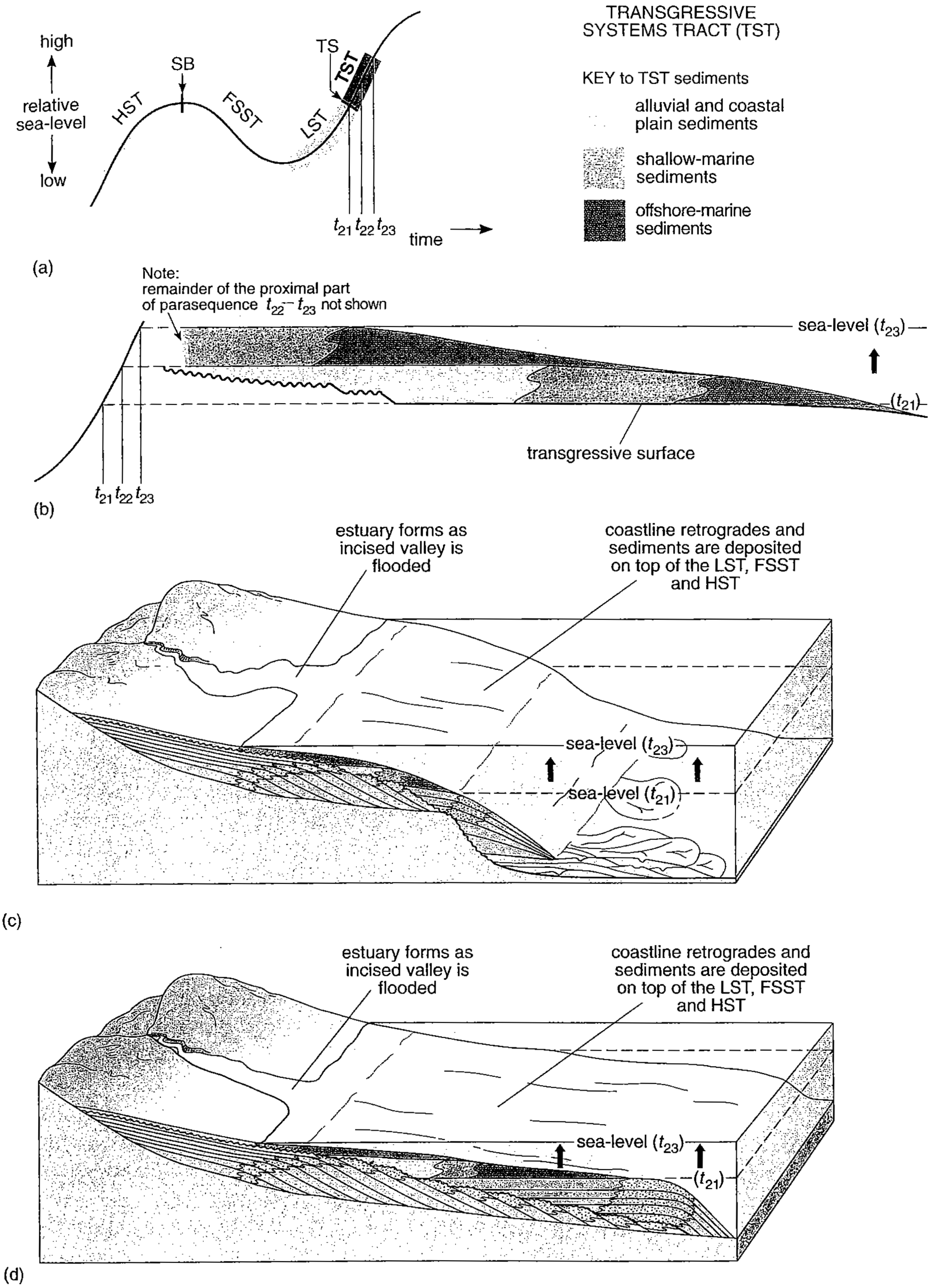
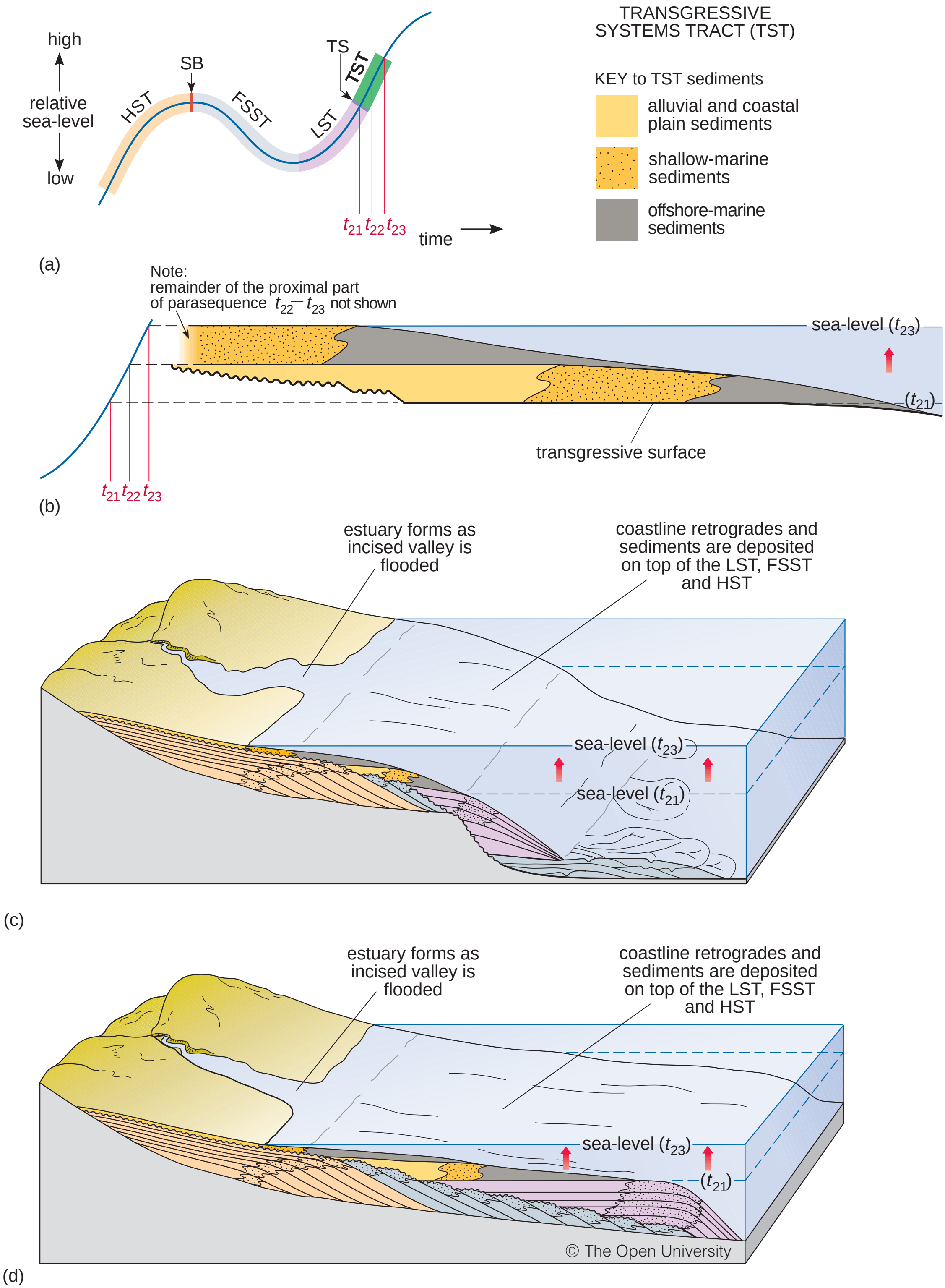
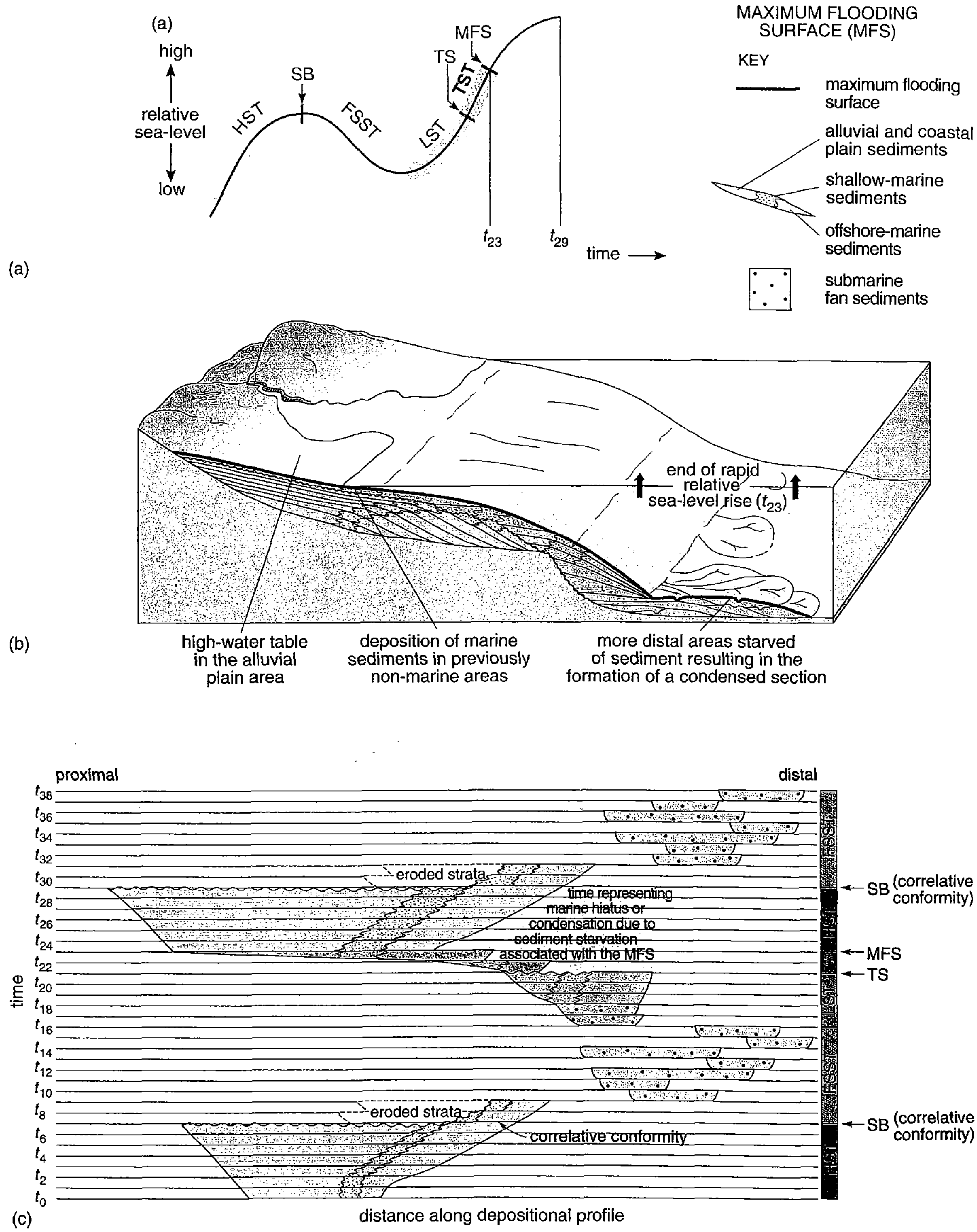


Figure 4.17 Features of the transgressive systems tract (TST). (a) Interval on the theoretical relative sea-level curve shown in Figure 4.8 during which the TST is deposited. (b) Detail of the relative sea-level curve (blue) and TST sediments deposited. The curve spans a phase where increase in the rate of relative sea-level rise is greater than the rate of sediment supply. The relative sea-level curve is divided into equal time units (red lines t_{20}, t_{21} etc.). Dashed horizontal black lines in the middle indicate the amount of accommodation space created during each time step in the relative sea-level rise. The right-hand part shows sediments deposited for each of the equal time intervals assuming a constant rate of sediment supply. These parasequences show a retrogradational pattern. Sediments deposited over the time interval between pronounced increase in the rate of creation of accommodation space and maximum rate of relative sea-level rise form the TST. (c) Geometry and features of the TST along a margin with a shelf break. (d) Geometry and features of the TST along a ramp margin. (c) and (d) not to scale.

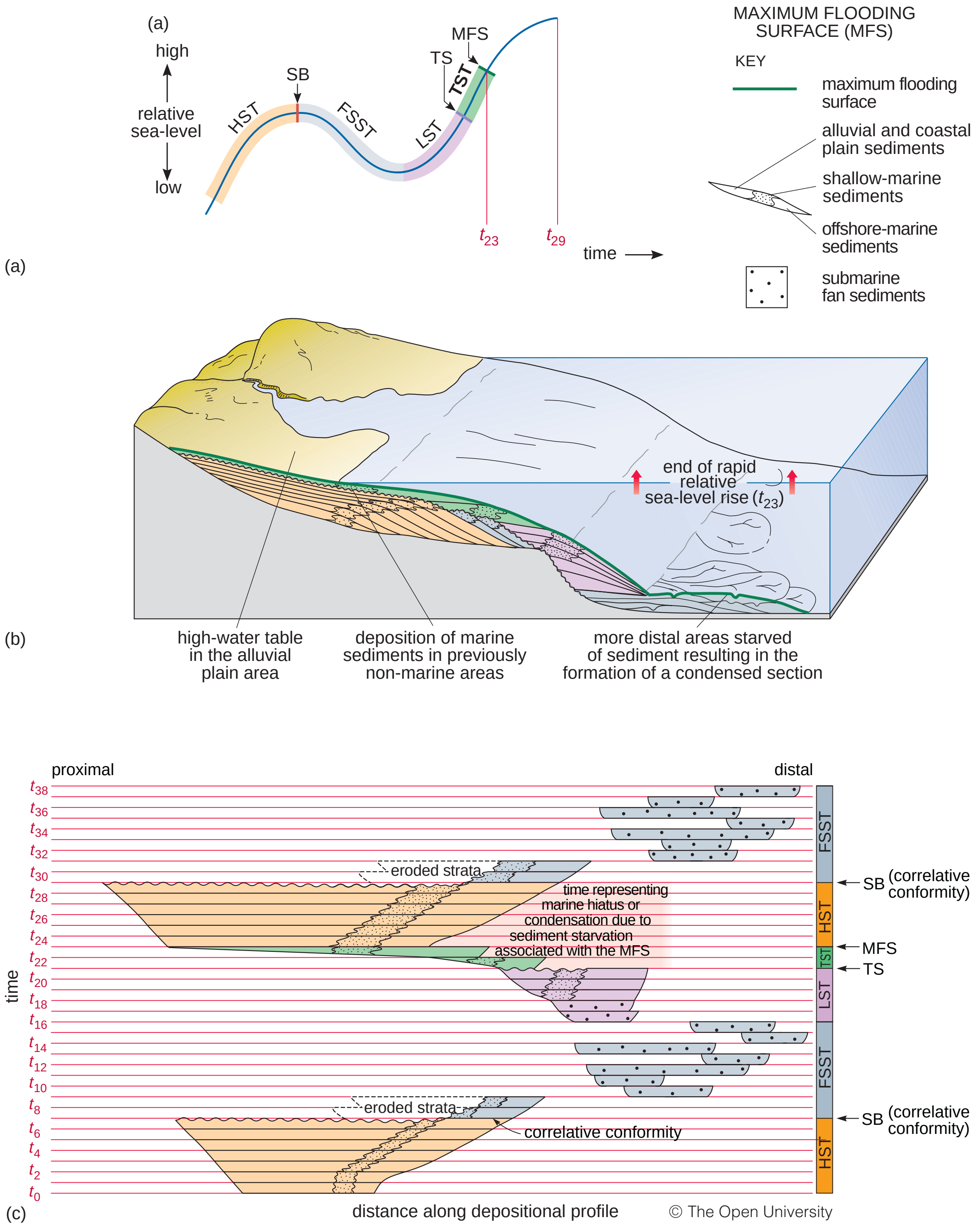


TRANSGRESSIVE SYSTEMS TRACT (TST)
high
relative sea-level
low
HST
SB
FSST
LST
TS
TST
t21 t22 t23
time
KEY to TST sediments
alluvial and coastal plain sediments
shallow-marine sediments
offshore-marine sediments
(a)
Note: remainder of the proximal part of parasequence t22–t23 not shown
sea-level (t23)
(t21)
transgressive surface
t21 t22 t23
(b)
estuary forms as incised valley is flooded
coastline retrogrades and sediments are deposited on top of the LST, FSST and HST
sea-level (t23)
sea-level (t21)
(c)
estuary forms as incised valley is flooded
coastline retrogrades and sediments are deposited on top of the LST, FSST and HST
sea-level (t23)
(t21)
© The Open University
(d)



rise in the water table, due to maximum flooding, will increase the occurrence of swamps, flooding of floodplains and avulsion* of distributary channels. This often leads to the formation and preservation of peat in proximal areas because the waterlogged conditions promote anoxia, thus reducing the chance of the organic matter being oxidized. The next river avulsion or relative sea-level fall will deposit siliciclastic sediments on the peat and following burial this will become preserved as coal.

* Lateral displacement of stream/river from its main channel into a new course on the floodplain.



(a)
high
relative sea-level
low
SB
HST
FSST
LST
TS
TST
MFS
t_{23}
t_{29}
time
MAXIMUM FLOODING SURFACE (MFS)
KEY
maximum flooding surface
alluvial and coastal plain sediments
shallow-marine sediments
offshore-marine sediments
submarine fan sediments
(a)
end of rapid relative sea-level rise (t_{23})
high-water table in the alluvial plain area
deposition of marine sediments in previously non-marine areas
more distal areas starved of sediment resulting in the formation of a condensed section
(b)
proximal
distal
t_{38}
t_{36}
t_{34}
t_{32}
t_{30}
t_{28}
t_{26}
t_{24}
t_{22}
t_{20}
t_{18}
t_{16}
t_{14}
t_{12}
t_{10}
t_{8}
t_{6}
t_{4}
t_{2}
t_{0}
time
eroded strata
time representing marine hiatus or condensation due to sediment starvation associated with the MFS
eroded strata
correlative conformity
FSST
HST
TST
LST
FSST
HST
SB (correlative conformity)
MFS
TS
SB (correlative conformity)
(c)
distance along depositional profile
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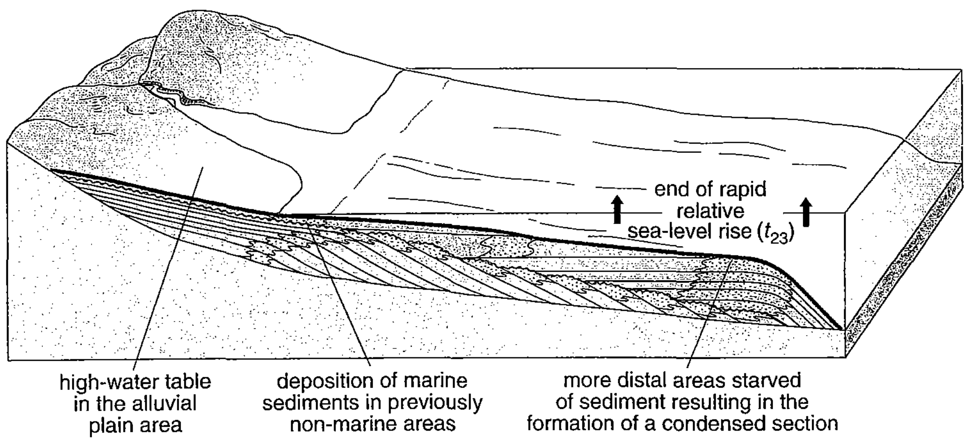


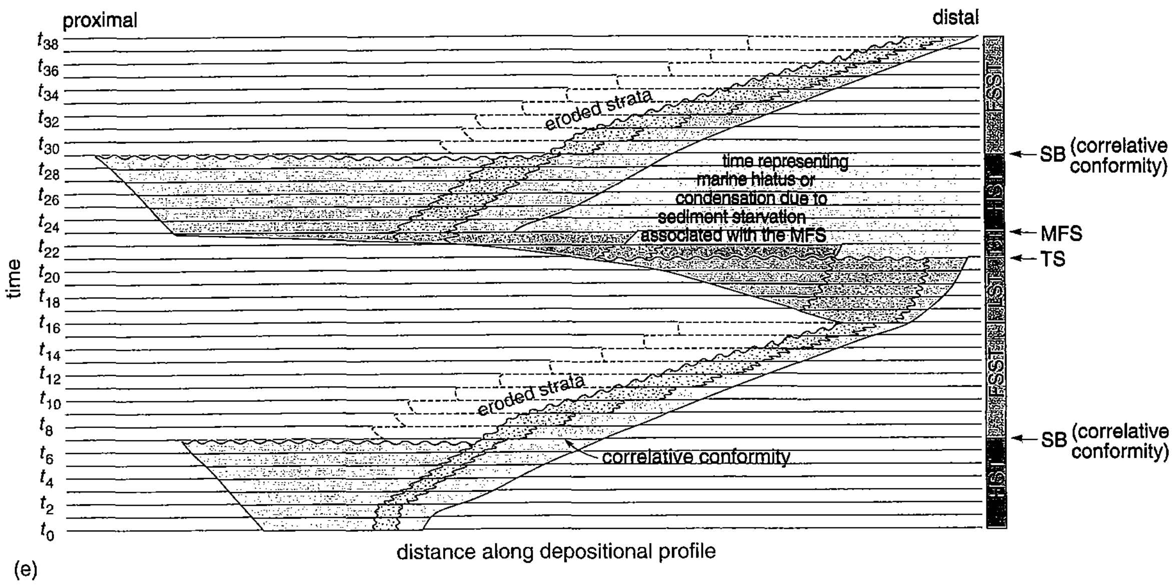
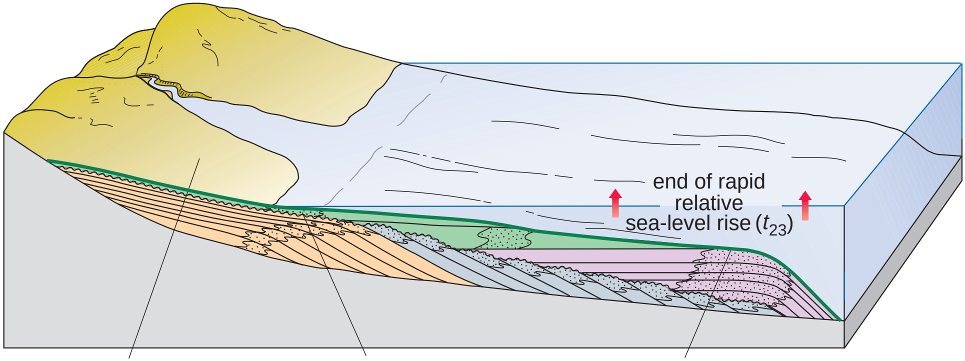


Figure 4.18 Features of the maximum flooding surface (MFS). (a) Position (t_{23}) on the theoretical relative sea-level curve shown in Figure 4.8 where the maximum flooding surface forms in this case. The exact position of the MFS depends on the balance between the rate of relative sea-level rise and rate of sediment supply. (b) Geometry and features of the maximum flooding surface along a margin with a shelf break. (b and d) Sediments that may be deposited simultaneously with formation of the maximum flooding surface are not shown. (c) Chronostratigraphical diagram from t_0–t_{38} to show the time represented by the maximum flooding surface and condensed section (shaded pink). (d) Geometry and features of the maximum flooding surface along a ramp margin. (e) Chronostratigraphical diagram from t_0–t_{38} showing similar features to (c). Note that for simplicity the hemipelagic and pelagic sediments that will be deposited in the deeper part of the basin are not shown. (b) and (d) not to scale. See text for further explanation.

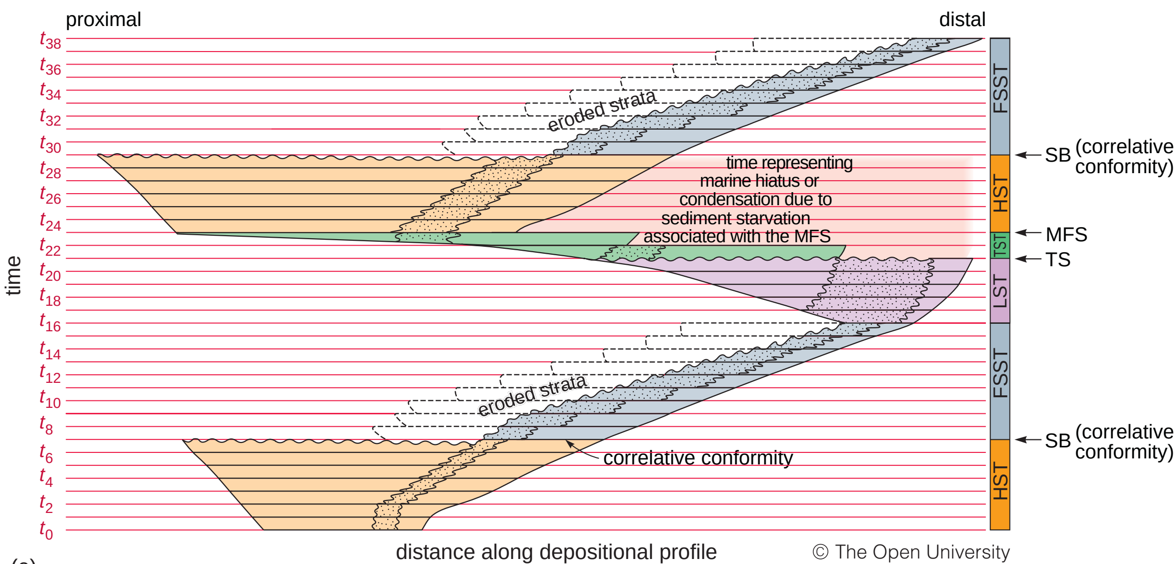
When the long-term rate of increase in accommodation space is again balanced or exceeded by the rate of sediment supply, in this case at t_{23}, then the next highstand system tract will be deposited. The earliest this can start to happen is just after the maximum rate of relative sea-level rise and the latest is at maximum relative sea-level (t_{22} and t_{29} respectively in this case).

The cycle will then repeat itself again. The package of sediment between two successive sequence boundaries forms a *depositional sequence* (or commonly just a '*sequence*'). The sequence stratigraphy model presented here is the most current at the time of writing. A brief summary of how the model has been updated and variations on it are discussed in Box 4.1 (p.86).



end of rapid relative sea-level rise (t_{23})
high-water table in the alluvial plain area
deposition of marine sediments in previously non-marine areas
more distal areas starved of sediment resulting in the formation of a condensed section

(d)



proximal
distal
time
t_{38}
t_{36}
t_{34}
t_{32}
t_{30}
t_{28}
t_{26}
t_{24}
t_{22}
t_{20}
t_{18}
t_{16}
t_{14}
t_{12}
t_{10}
t_8
t_6
t_4
t_2
t_0
eroded strata
time representing marine hiatus or condensation due to sediment starvation associated with the MFS
eroded strata
correlative conformity
FSST
HST
TST
LST
FSST
HST
SB (correlative conformity)
MFS
TS
SB (correlative conformity)
distance along depositional profile

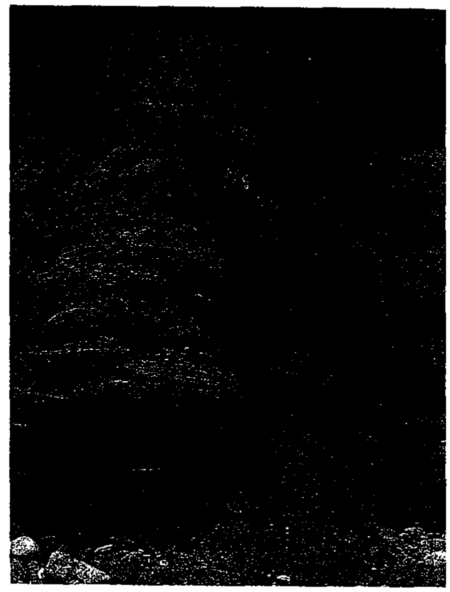
(e)

4.3.2 Field examples of key surfaces and systems tracts

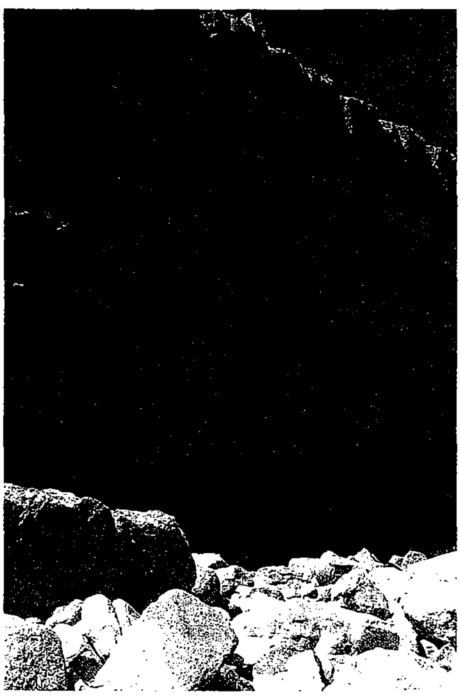
Figure 4.19 shows photographs of several features of depositional sequences in the field from a variety of depositional settings in southern England.

- ❍ Assuming that Figure 4.19a and b are equivalent in age, and that they were deposited in areas with the same subsidence history, which is the more proximal section and why?
- ● Figure 4.19b is likely to be the more proximal section because at this locality the sequence boundary is marked by a sharp surface (possibly an unconformity) whereas in Figure 4.19a it is a correlative conformity which is always more basinward than the unconformity.

(a) Cliff *c.* 40 m high.



(b) Cliff *c.* 3 m high.



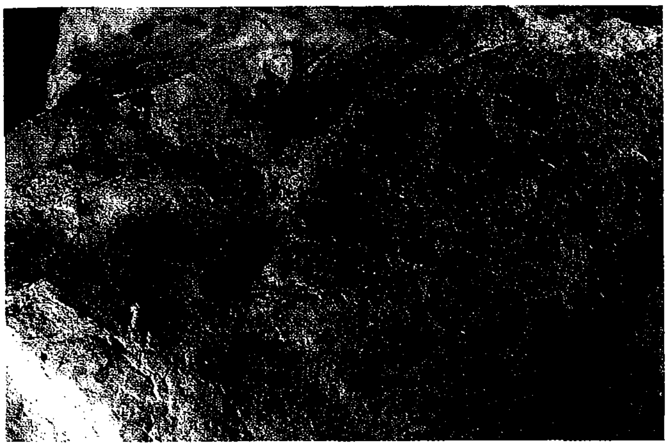
(c) Cliff *c.* 16 m high.

(d) Cliff *c.* 2.5 m high.

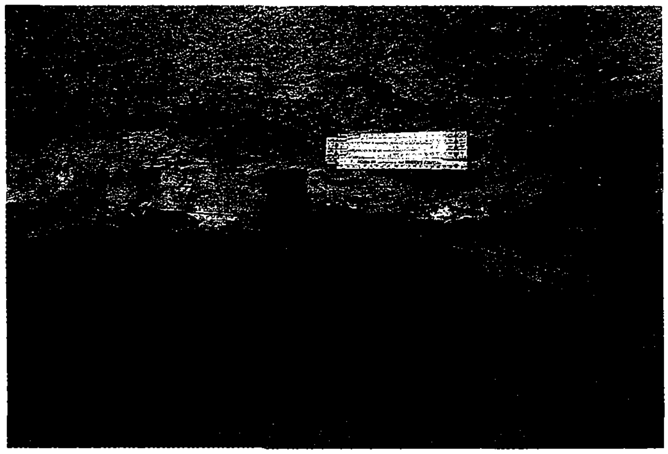
Figure 4.19 Features of depositional sequences. (a) Succession showing upward gradational increase in amount of silt and fine-grained sand interpreted to represent a correlative conformity, Kimmeridgian, Dorset. (b) Sharp surface interpreted as a sequence boundary between open marine mudstones and shallow-marine/estuarine sandstones, Oxfordian, Dorset. (c) Micrites and biomicrites with chert nodules (black) overlain by cross-stratified oosparites (white bed at clifftop) from a carbonate ramp succession. The base of the oosparites is interpreted as a sequence boundary as the ooids were deposited in much shallower water than the biomicrites, Portlandian, Dorset. (d) Intensely bioturbated biomicrites containing a very rich, diverse fauna; interpreted as a condensed TST from a carbonate ramp succession, Portlandian, Dorset.

(e) Ammonite = 40 cm diameter.

(f) Nodule = 8 cm across.



(g) View *c.* 25 cm across.



(h) Ruler = 25 cm length.

Figure 4.19 (continued) (e) An oyster and serpulid encrusted ammonite indicating condensation from the maximum flooding surface at the top of the TST shown in (d), Portlandian, Dorset. (f) A carbonate nodule from within a mudrock succession. The formation of nodules is often related to a pause or decrease in the rate of deposition. These nodules are interpreted to mark a maximum flooding surface, Kimmeridgian, Dorset. (g) Cross-section through a hardground within a chalk succession showing nodules and possibly pebbles coated with the authigenic minerals glauconite (green) and phosphate (yellow). There is intense bioturbation and some of the nodules have also been bored. The top of this bed is interpreted to represent a maximum flooding surface, Cretaceous, Isle of Wight. (h) A shallow-marine shell bed containing a mixture of grains including mudstone pebbles, ooids and quartz sand grains representing the transgressive lag formed during shoreface erosion at the base of a TST, Oxfordian, Dorset. *((a)–(f), (h) Angela Coe, Open University; (g) Simon Grant, British Petroleum.)*

○ What does the evidence in Figure 4.19g indicate about (a) the sedimentation rate and (b) the time represented by the bed?

● (a) The precipitation of authigenic minerals indicates a very low to zero sedimentation rate. (b) The bed probably represents quite a long period of time because of the boring and the intense authigenic mineralization. Also some of the nodules appear to have been rolled around to form pebbles.

○ Figure 4.19d contains a rich and diverse fauna, some of which is broken and reworked and some of which is not. How does this evidence fit in with the interpretation that it is a TST?

● The rich and diverse fauna, both broken and whole, fits with reworking of sediment during transgression when the shells would become broken and there would be a relatively low sediment input as most of the sediment was probably trapped in more proximal areas during relative sea-level rise.

Box 4.1 Controversies in the sequence stratigraphy model

Three systems tracts versus four, Type 1 and Type 2 sequence boundaries

In the original sequence stratigraphical model devised in the late 1970s, and for over a decade after, only three systems tracts were recognized: lowstand, transgressive and highstand systems tracts. The highstand systems tract was interpreted to form between the maximum rate of relative sea-level rise and maximum rate of relative sea-level fall. Thus, the HST included the lower part of the falling stage systems tract where it was preserved. The lowstand systems tract was interpreted to form between the maximum rate of relative sea-level fall and start of the rapid rate of rise (marked by the transgressive surface).

In the earlier versions of the model, two types of sequence boundary were recognized (Types 1 and 2). Type 1 boundaries were interpreted to form when there was a relative sea-level fall (now termed a forced regression) at the depositional-shoreline break*. In the specific case of Type 1 sequence boundaries that formed on shelf break margins, the 'lowstand systems tract' was subdivided into the basin-floor fan (equivalent to the upper part of the falling stage systems tract, Section 4.3.1), slope fan and lowstand wedge (equivalent to the lowstand systems tract, Section 4.3.1). Type 2 boundaries were interpreted to form when there was what is now termed a regression at the depositional-shoreline break. In this case, the lowstand systems tract was referred to as the shelf-margin wedge. Lowermost systems tract was yet another term used all-inclusively to describe the different 'lowstand' deposits.

In the early 1990s, it was noted that the model failed to account properly for sediment packages deposited during relative sea-level fall on a ramp type margin, like those shown in Figure 4.13, and particularly for features of carbonate successions. Thus, the distinction between forced regressions and regressions was noted and received prominence; several researchers then proposed a fourth systems tract to account for sediments interpreted to have been deposited during falling relative sea-level rather than just low sea-level. This systems tract has had various names but is now commonly referred to as the falling stage systems tract. Many examples of falling stage systems tracts, in addition to basin-floor submarine fans, are now recognized; for examples see Sections 6.4, 9.2 and 13.1. Research on other successions together with computer modelling has led to wider acceptance of the falling stage systems tract. However, some authors still divide their sequences deposited during forced regressions into three systems tracts.

* The depositional-shoreline break is the position on the shelf proximal from which the depositional surface is above base level and distal from which the depositional surface is below base level.

Position of the sequence boundary

In the 1970s' to 1980s' model, much emphasis was placed on the fact that the sequence boundary formed at the maximum rate of relative sea-level fall. Though interesting, some of the chronostratigraphical figures from these papers do not show this but do fit well with the model presented in Section 4.3.1. Whilst most researchers now accept the four systems tract model for forced regressions, there is still some controversy as to where the sequence boundary should be placed. The three options are:

(i) At the base of the falling stage systems tract (Section 4.3.1). In this case, the correlative conformity forms at the start of the relative sea-level fall and equates to the start of erosion in the proximal areas and therefore the onset of formation of the unconformity.

(ii) At the top of the falling stage systems tract. In this position, the correlative conformity forms at the absolute low of relative sea-level and is equivalent to the lowest surface of incision in the proximal sections. In this case, the unconformity starts to form before the formation of the correlative conformity. The problem with putting the sequence boundary in this position is that its timing is dependent on the position along the depositional profile, correct distinction between the falling stage and lowstand systems tract, and the sedimentation rate.

(iii) At the maximum rate of relative sea-level fall. In this case, the timing is hard to define in proximal sections because it lies in the middle of the unconformity; however, the maximum rate of relative sea-level fall in some cases equates to the time when there was the most pronounced major basinward shift of facies.

Genetic stratigraphic sequences

An alternative sequence stratigraphical model was proposed by Galloway (1989) in which the maximum flooding surfaces were chosen as the boundaries to the packages of sediment rather than the sequence boundaries. He termed the sediment packages between maximum flooding surfaces 'genetic stratigraphic sequences'. Though this model has raised much discussion because, often, maximum flooding surfaces are prominent and easily correlated over wide areas, the model has not been widely accepted because it results in the unconformity being in the middle of the package. Nor does it give prominence to the only key surface that is independent of sediment supply (i.e. the sequence boundary). For further discussion of this model, see references in the further reading list.

Miall (1997) and Posamentier and Morris (1999) both contain a description of the history of the sequence stratigraphy model and describe most of the controversies.

4.3.3 Natural variability and summary of the features of sequences

The four systems tracts — FSST, LST, TST and HST — are all composed of several co-existing and linked depositional systems or environments ranging from the deep marine to coastal and fluvial systems. Therefore, sequences do not divide the sedimentary record on the basis of different sedimentary systems or facies belts but rather on key surfaces (the sequence boundary, transgressive surface and maximum flooding surface) which each represent a particular time at which *all* the depositional systems change in response to a particular change in the relative sea-level cycle. The exact nature of the systems tracts and key surfaces within the depositional sequence depend upon: (i) the shape of the equilibrium profile of the sedimentary systems; (ii) the rate and amplitude of relative sea-level change; (iii) the sedimentary system present (e.g. delta, strandplain or carbonate ramp); the rate of sediment supply.

Consequently, systems tracts and sequences will vary in thickness, internal character and in the time taken to deposit them, depending on the combined effects of these different factors. Systems tracts may often only be partially preserved or in fact be entirely absent. In these cases, key surfaces become superimposed. Some of the variations in the sequences resulting from the first three points listed above have been introduced earlier in this Chapter and will be covered in the case studies later in the book. Sediment supply is considered in a bit more detail below.

Sediment supply and its control on sequence architecture

If we consider three extreme situations in which sediment supply is either zero, very high, or highly variable, it is not hard to see that the morphology of the systems tracts and sequences in our model will alter dramatically. Quite simply, if there is no sediment supply, there can be no deposition of new sediment, regardless of what relative sea-level is doing. So what will happen during one cycle of relative sea-level rise and fall in a case where sediment supply is zero? As relative sea-level falls, the previous depositional surface will be eroded as the wave-bases are lowered, in addition to the subaerial erosion of newly exposed rock. The eroded products will be deposited on the sequence boundary as the FSST and LST. As relative sea-level rises, marine erosion of the FSST and LST may occur in which case all that will be left is a thin coarse-grained 'lag' deposit representing the TST. The HST will be limited to thin, condensed intervals, formed from whatever debris settled out of the water column. Such conditions will lead to a condensed sequence or simply an unconformity surface.

If sediment supply is very high, accommodation space will quickly be filled, even during the highest rates of relative sea-level rise. This could mean that there is too much sediment entering the basin for aggradation and retrogradation to occur. Thus, rather than the sequence being identifiable on the basis of its progradational, aggradational and retrogradational parasequence stacking patterns, systems tracts would instead only exhibit varying degrees of progradation (Section 13.1 describes an example with no retrogradation).

In general, the rate of siliciclastic sediment supply will drop during a relative sea-level rise, because flooding of the land reduces the potential for subaerial erosion close to the shoreline. Conversely, a relative sea-level fall elevates the land with respect to the sea, exposing areas formerly submerged. The potential for subaerial erosion is therefore enhanced and so is siliciclastic sediment supply. For carbonate environments, the situation can be very different. The production of carbonate in shallow-marine areas can keep pace with relative sea-level rise, and because of the increase in flooded area the supply of carbonate sediment increases. During relative sea-level fall, the carbonate production area often decreases, areas that are subaerially exposed become cemented

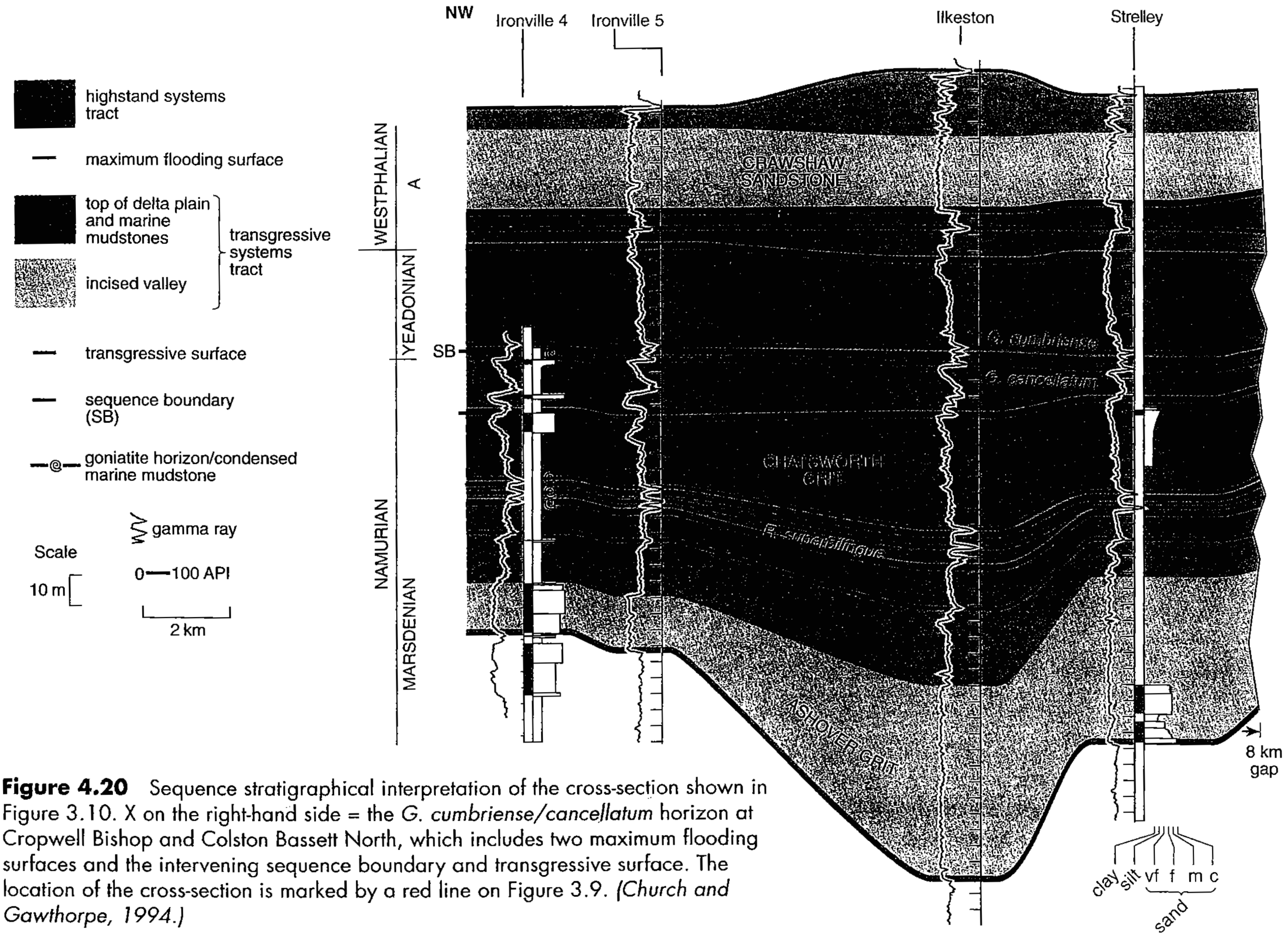


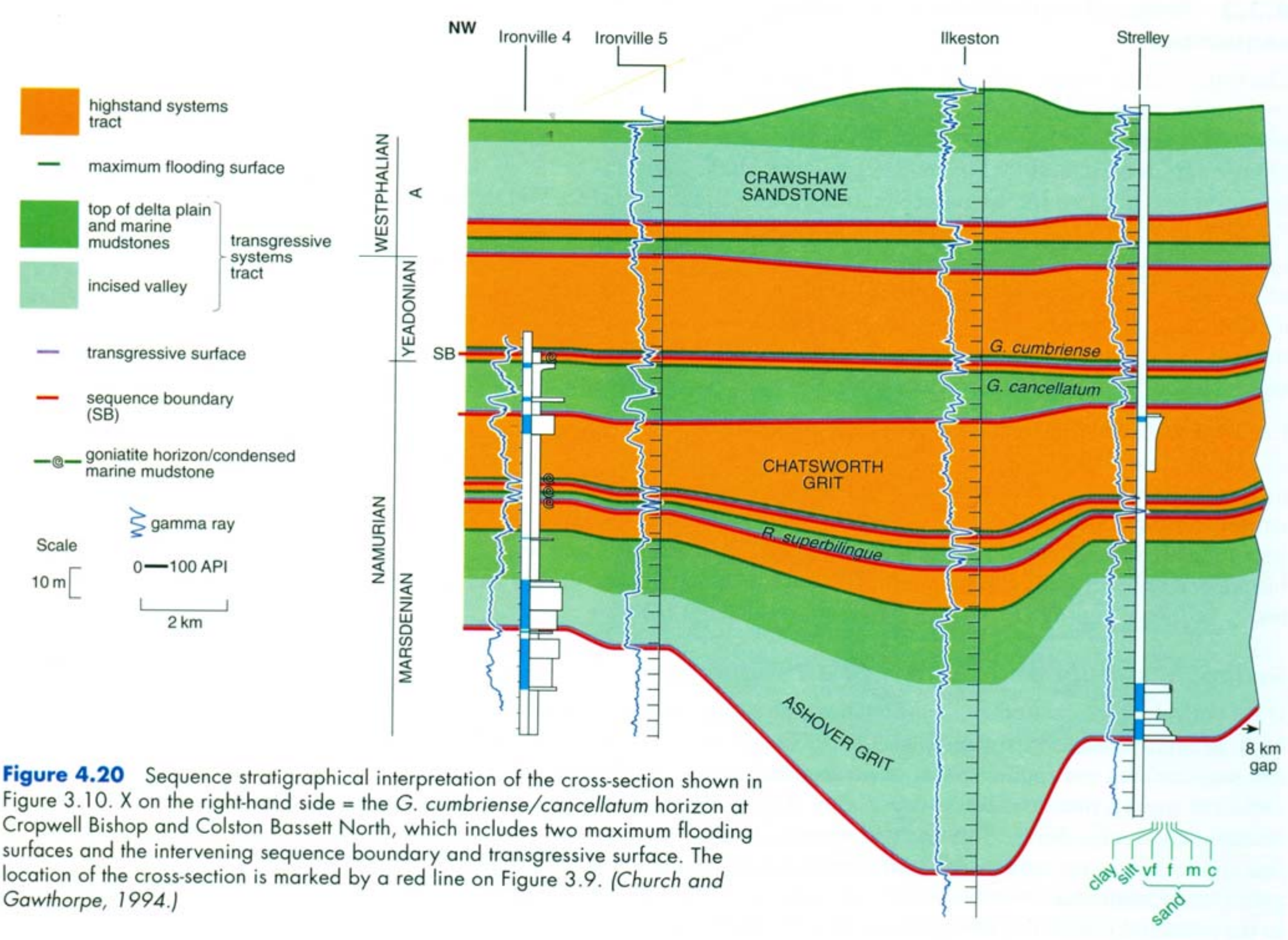
Figure 4.20 Sequence stratigraphical interpretation of the cross-section shown in Figure 3.10. X on the right-hand side = the *G. cumbriense/cancellatum* horizon at Cropwell Bishop and Colston Bassett North, which includes two maximum flooding surfaces and the intervening sequence boundary and transgressive surface. The location of the cross-section is marked by a red line on Figure 3.9. *(Church and Gawthorpe, 1994.)*

and the supply of carbonate sediment decreases. These differences between carbonates and siliciclastics are discussed further in Chapters 11 and 12.

Relative sea-level fluctuations can control the deposition of sediment at two scales; (1) high-frequency fluctuations responsible for the deposition of parasequences, which are superimposed on (2) lower-frequency fluctuations responsible for the deposition of sequences. This may seem complex enough, but in fact even lower-frequency (longer-term) sea-level changes act to modify the way in which sequences stack together. We will consider this in Chapter 5. In Section 4.4, we will reconsider the Carboniferous succession described in Section 3.5 to illustrate some of the many new terms and concepts that have been introduced in this Chapter.

4.4 The Carboniferous example revisited

In Section 3.5, we described sedimentary cycles from the Namurian, formed in a deltaic environment, and concluded that deposition was probably controlled by fluctuations in relative sea-level. You will remember that each cycle is composed of a progradational phase (delta), a transgressive phase (the transition back to delta front and prodelta sediments and the capping by a goniatite-bearing marine mudstone) and some have an erosive phase (incised valleys), most likely caused by a drop in relative sea-level.



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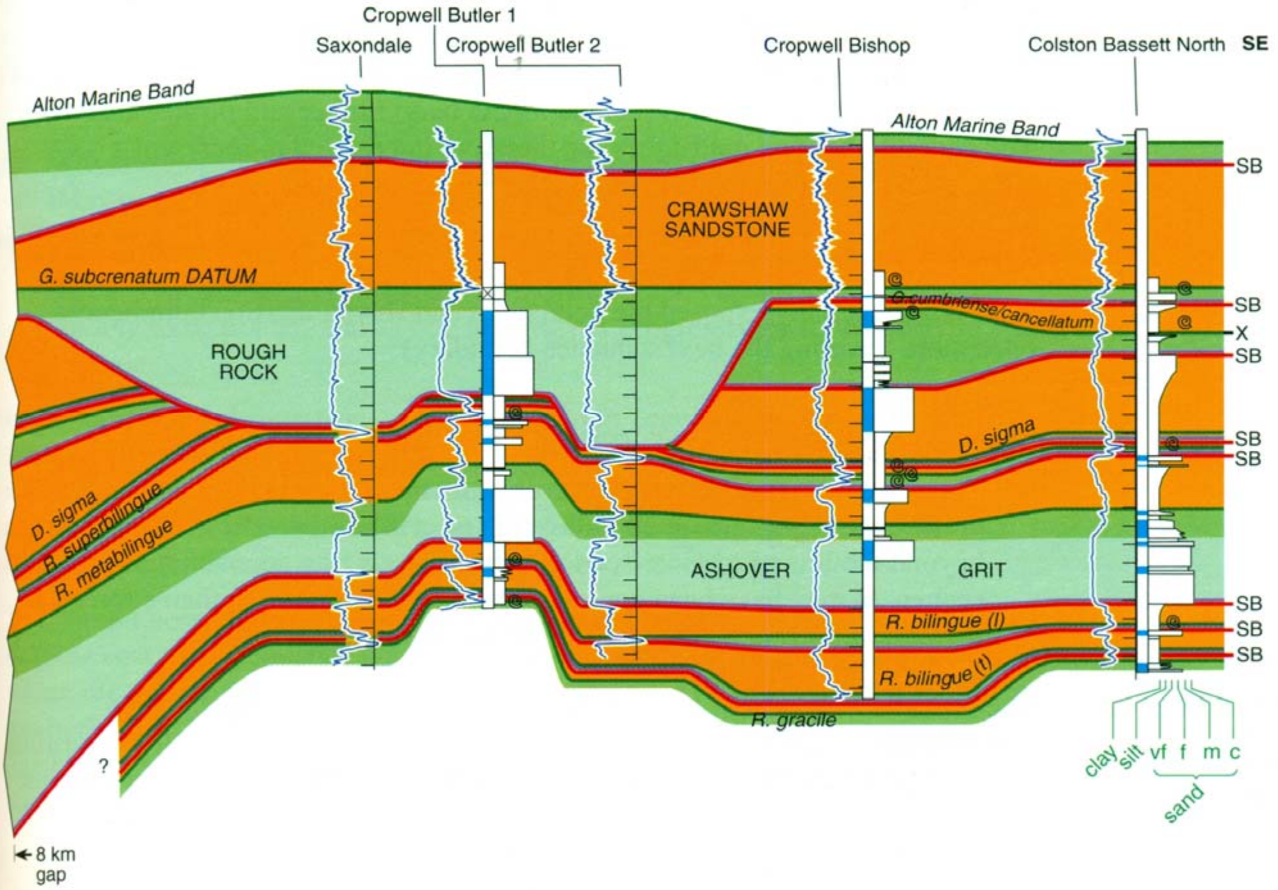

- From what you have learnt in this Chapter, how did the prominent surface that defines the base of the incised valleys form and what surface does it represent?
- The incised valleys were created during a relative sea-level fall, so the base of each valley is interpreted as a sequence boundary.
- During what part of the relative sea-level change were the incised valleys filled with sediment, and to what systems tract would you assign fill?
- The incised valleys were infilled during relative sea-level rise and so most likely belong to the TST.

However, depending on the position of the incised valley and the magnitude of the relative sea-level rise, it is possible that the incised valley fills represent the LST, or even the lower HST. But most incised valley fills found in the geological record are now interpreted to be TSTs.

Figure 4.20 shows one possible sequence stratigraphical interpretation of the data presented in Figure 3.10. Rather unsurprisingly, the goniatite-bearing marine mudstones are also assigned to a TST. However, it is likely that the transgression would not have been an instantaneous event. Periodic flooding of the delta as relative sea-level started to rise, forced rivers to burst their banks (or 'levées'), prior to the final marine inundation and abandonment of the delta. Consequently, the underlying delta plain deposits, at the point where mouth bar/delta front/delta top sandstones show a transition back to prodelta mudstone and delta front sandstone, are also assigned to the TST (Figure 4.20). This is because the increased flooding of the delta would lead to the eventual dominance of muddier facies (seen as the change from yellow below to grey above in Figure 3.10). The gamma-ray log reflects this with progressively higher API values (i.e. the log deflects to the right), so its response can be useful in defining the base of the TST.

The TST terminates with the goniatite-bearing marine mudstones. As explained in Section 4.2.1, these goniatite-bearing mudstones are condensed due to their great distance from any sediment supply. This reflects movement of the point of sediment input into the basin (i.e. the mouth bars) further and further landward. The goniatite-bearing mudstones are therefore interpreted to represent a condensed section associated with the maximum flooding surface.

Overlying the maximum flooding surface, the main phase of delta progradation is interpreted as the HST. This would have continued until the next relative sea-level fall subaerially exposed the delta plain and fluvial incision commenced once more (creating the next sequence boundary).

❍ Why do some cycles have incised valleys, whilst others do not?

● There are two possible reasons for this. It is possible that they all do, but the cross-section in Figure 4.20 fails to intersect all of the valleys, i.e. they lie beyond the line of our intersection. Alternatively, the deposition of some sequences may have been controlled by a regression rather than a forced regression, in which case there would be no fluvial incision.

The identification of sequences with and without incision will help us to determine the magnitude of the relative sea-level curve that controlled deposition during this time. Sediment transported through these eroded valleys and out into the basin would form part of the FSST and LST of a sequence (Figures 4.12, 4.15). Such deposits are not shown in Figure 4.20 because the section is too proximal (i.e. too far to the left of Figures 4.12 and 4.15).

4.5 Lithostratigraphy versus chronostratigraphy, seismic stratigraphy, and the geometry of sequence stratigraphical surfaces

❍ Consider the flooding surfaces between the parasequences marked in Figure 4.18. Are these chronostratigraphical or lithostratigraphical boundaries?

● They are chronostratigraphical boundaries as they mark the time of flooding and cut across different lithologies.

In a progradational parasequence set, the chronostratigraphical flooding surfaces that gently dip in an offshore direction are often referred to as *clinoforms* (Figure 4.21). Clinoforms form as sedimentary systems such as deltas prograde into the basin. During each time interval, sediment is deposited on the delta plain, delta front and prodelta. On a smaller scale, the lateral accretion surfaces in point bars of meandering river systems are a type of clinoform; similarly, the front surface of a subaqueous or subaerial dune as it builds forward to form cross-stratification is also a type of clinoform. Geometrically, clinoforms are inclined surfaces whose dip lessens at their top and base until they run tangential to the horizontal (Figure 4.21).

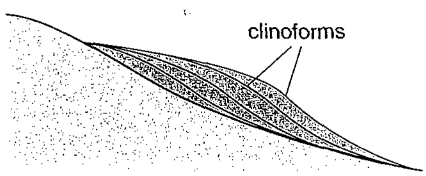

Figure 4.21 Cartoon to show clinoforms.

Clinoforms are widely recognized in seismic reflection studies (Box 4.2) which are used to study sedimentary deposits on a basin-wide scale. These clinoforms often represent the progradation of a coastal succession. The recognition of clinoforms on seismic sections brings us to another important point, in fact one of the major factors that led to the development of sequence stratigraphy in the 1970s and 1980s. This is that seismic reflectors are nearly always *chronostratigraphical* surfaces rather than lithostratigraphical surfaces.

❍ Why are seismic reflectors more likely to be chronostratigraphical than lithostratigraphical surfaces?

● Because the acoustic impedance contrast (Box 4.2) is usually greater across chronostratigraphical compared to lithostratigraphical surfaces, the latter tending to be gradational as one lithology is progressively replaced by another.

For instance, the change from offshore transition zone mudstones to shoreface sandstones is gradational, which leads to no marked impedance contrast, whereas if foreshore sandstones overlie offshore transition zone mudstones due to a relative sea-level fall, the acoustic impedance contrast will be greater and therefore the boundary is likely to be expressed as a seismic reflector.

You should now be able to see how we can take this further; unconformities, such as those that mark sequence boundaries, will show up as seismic discordances where the underlying strata have been partly removed by erosion or no sediment has been deposited. Reflectors within the underlying packages will terminate against the unconformity, and this type of reflector termination is called *erosional truncation* (Figure 4.22).

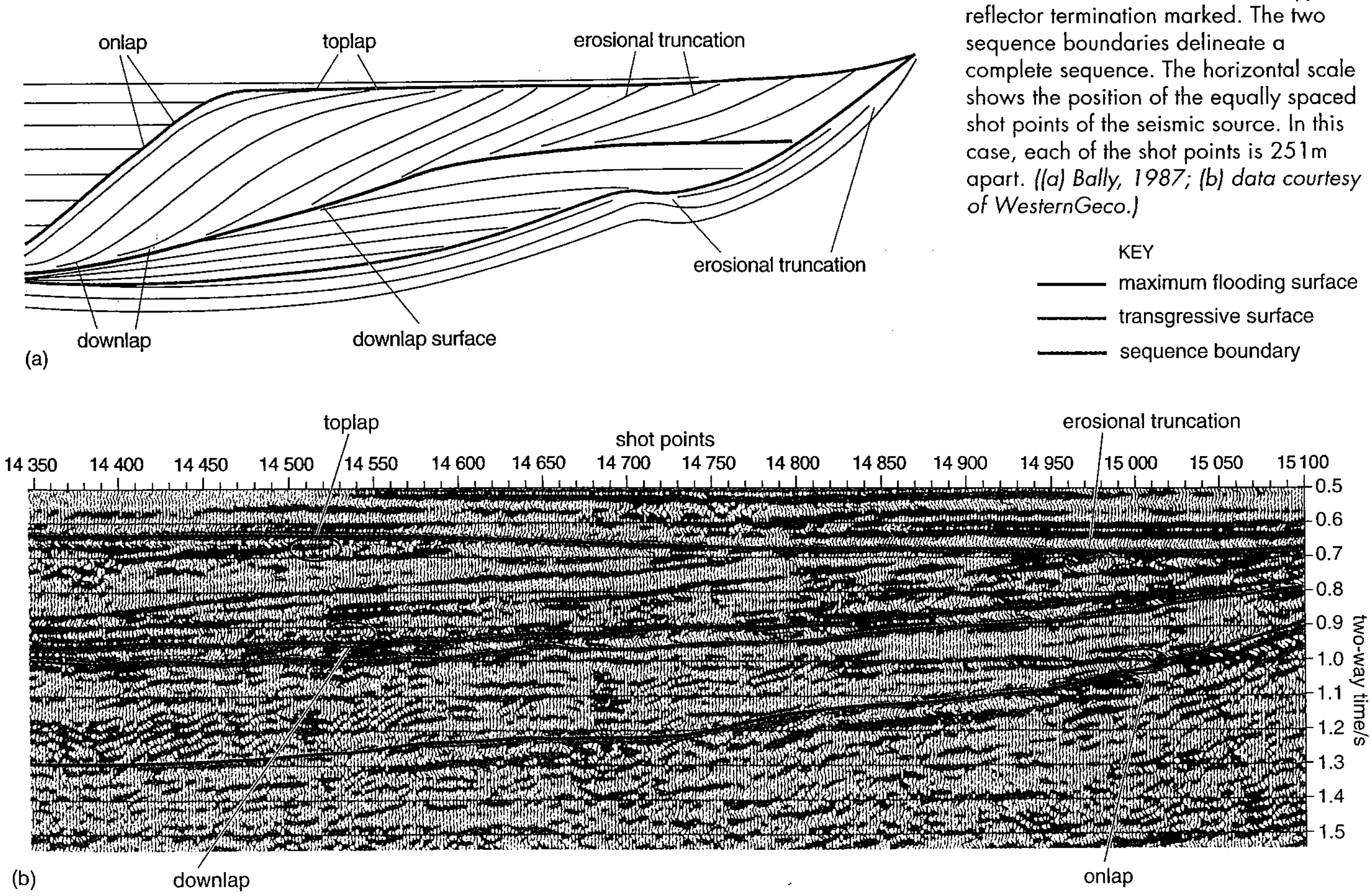

Figure 4.22 (a) Different types of seismic reflector termination. Some of these geometric relationships can also be seen in large exposures and cross-sections. (b) An example of a seismic section with some of the different types of reflector termination marked. The two sequence boundaries delineate a complete sequence. The horizontal scale shows the position of the equally spaced shot points of the seismic source. In this case, each of the shot points is 251 m apart. *((a) Bally, 1987; (b) data courtesy of WesternGeco.)*

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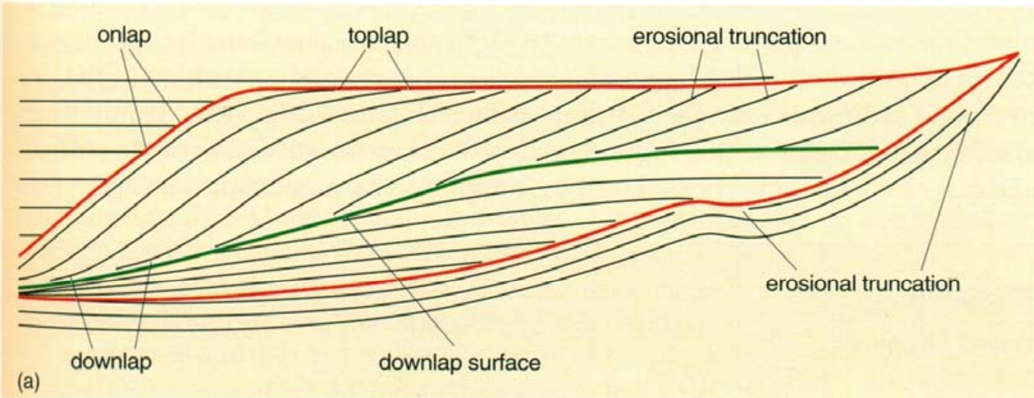

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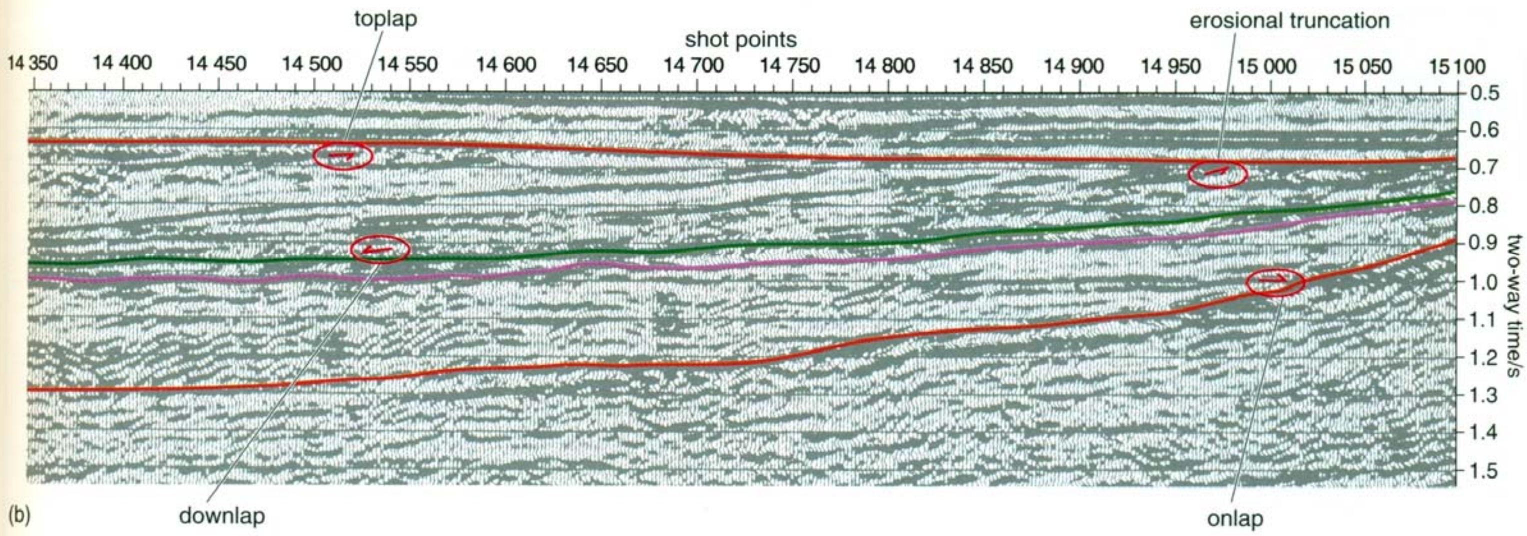
KEY
maximum flooding surface
transgressive surface
sequence boundary



❍ What will happen on the seismic section as a sequence boundary is traced out laterally in a distal direction?

● The seismic reflector will become less well marked because the erosional truncation and change in lithology will gradually become less until the unconformity becomes a correlative conformity.

As a sequence boundary is traced from an unconformity in the proximal sections to a correlative conformity in distal sections, the type of reflector termination underlying the sequence boundary will change from erosional truncation to *toplap* (Figure 4.22). An analogue to this is a perfect set of cross-stratified beds dipping towards the right with the top and bottom of the beds curving to a shallower angle so that they run tangentially to the horizontal. If we now erode the top of the cross-stratified beds along an inclined surface dipping towards the left (Figure 4.23), we are left with erosional truncation on the left-hand side and toplap on the right-hand side. Sediments deposited on top of the erosional truncation surface will show an *onlap* geometry (Figure 4.22).

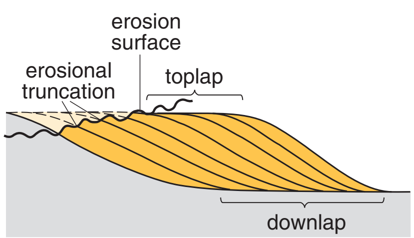


Figure 4.23 Cartoon showing the difference between erosional truncation and toplap.

Maximum flooding surfaces can often be picked out on seismic sections if the overlying HST is composed of clinoforms, the toes of which run tangentially into the maximum flooding surface; this kind of termination is called *downlap* (Figures 4.22 and 4.23).

Thus, the reflector termination characteristics of chronostratigraphical surfaces can be used to delineate key sequence stratigraphical surfaces and hence systems tracts and individual sequences. Most commonly, sequence boundaries are characterized by erosional truncation and toplap below the surface and onlap on top of the surface (Figure 4.22); transgressive surfaces are characterized by onlap; and maximum flooding surfaces are characterized by downlap of the overlying sediments onto the flooding surface (Figure 4.22). These features may also be recognizable within individual exposures, especially large-scale cliffs, and can also sometimes be deduced by compiling many sections.

Box 4.2 Seismic reflection surveying

Seismic reflection surveying is a geophysical technique used by the oil industry and research groups to derive subsurface geological information. It has been used particularly in the study of sedimentary basins, and can be done on land or at sea. Seismic waves are sound waves generated by a seismic source; they then travel through the subsurface, are reflected at geological boundaries within the subsurface and return to the surface where they are recorded. This is shown as wave 1 reflected from reflector 1 (Figure 4.24a). Wave 2 has been both reflected by reflector 2 and refracted (or bent) by reflector 1. Thus, a picture of the subsurface geology can be compiled. The record of ground motion (or pressure variation at sea) with time when plotted on paper is called a seismic trace (Figure 4.24b). The amplitude of a reflection is a measure of the strength of the ground motion, shown by the deviation of the seismic trace. Individual seismic traces are the result of a complex stacking of many seismic traces (the details of which we will not consider here), which act to reduce background noise (e.g., from nearby roads in land surveys or ships in marine surveys). A number of seismic traces displayed side by side form a seismic section (Figures 4.22b, 4.24c,d). This is a representation of a slice of the Earth and is produced by moving the source and detectors along the line of survey. Shots are fired at a regular horizontal distance apart (usually around 25 m). In order to make the reflections more easily visible, the right-hand half of the amplitude of the seismic wave trace is usually coloured black (compare Figure 4.24c with Figure 4.24d).

The horizontal scale of a seismic section is a measure of horizontal distance along the line of survey. The vertical scale is the two-way time of the seismic wave, i.e. the time taken for the wave to travel down into the ground and back up again after reflection.

When interpreting seismic sections, the section is examined for reflection continuity. Continuity is where a reflection on a trace can also be recognized on neighbouring traces, with only small changes in the arrival time. Because half of the seismic trace is coloured black, such continuities appear as black or white lines running across the section (Figure 4.22b: note that in this Figure, the black has been converted to grey so the interpretation can be seen). These continuities are termed reflectors and are generated by interfaces where the density and/or acoustic velocity (speed of sound in the material) of the rock and/or its fluid content changes. The product of the density and sonic velocity of a material is termed its *acoustic impedance*. The interfaces may be bedding planes but may also be fault planes or any other extensive boundary between rock types. In some areas, there may be few or no seismic reflectors because there are no reflecting interfaces; too deep for sufficient seismic energy to reach (seismic energy is attenuated as it travels through the Earth); or a very complex structure.

The fact that the vertical scale is measured in two-way time and not in depth is important because it means that a seismic section is *not* a true geological cross-section through the Earth.

- ❍ What extra information would we need to convert a seismic section into a geological cross-section?
- ● The velocity of each of the rock layers because $v = d/t$ where v = velocity, d = distance and t = time.

As this velocity will vary for each different lithology, this is no easy task. Oil companies need such information because they have to calculate how deep to drill in order to intersect an oil reservoir within a geological structure. Whilst it can be obtained by computer modelling, the only precise way to calculate velocities is to drill a borehole somewhere along the line of the seismic section and then to measure directly the time taken for a sound wave to pass through each of the rock units within the borehole. This gives the time it takes a seismic wave to reach any specified depth in the borehole. Where this depth corresponds to a major change in rock type capable of generating a seismic reflector, we can use this time to locate the corresponding reflector on the seismic section. This is called 'tying the well to the seismic section' and allows information obtained on the various rocks in the borehole to be extrapolated along the seismic section. The configuration, continuity, amplitude, frequency and interval velocity of seismic reflection patterns can be used to predict the lithological content of the subsurface packages (seismic facies analysis).

It should be realized that this is a very simplified explanation of how seismic sections can be used to derive subsurface geological information. In reality, there are other subtle differences that distinguish seismic sections from a geological cross-section and much computer time is required to remove 'artefacts' which are inherent in the acquisition and processing of seismic data. However, there is insufficient space to detail these here.

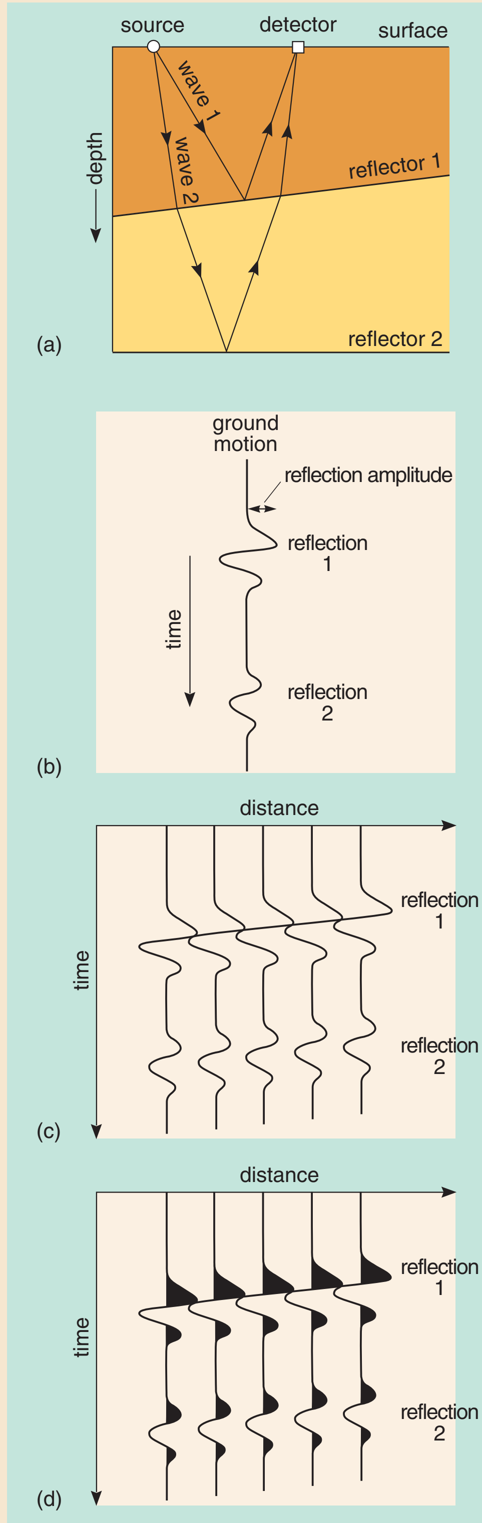


Figure 4.24 Seismic reflection surveying: (a) seismic reflection and refraction; (b) a seismic trace —reflection 1 has a higher amplitude than reflection 2; (c) a diagrammatic seismic section, composed of seismic traces from many shot points; (d) shading of the right-hand half of the wave to make the reflections more easily visible.

4.6 Global sea-level change and eustatic sea-level charts

The previous Sections in this Chapter should give a clear indication that subtle changes in relative sea-level can be detected through analysis of the sedimentary record. However, analysis of single sedimentary successions or even one particular basin does not indicate that the changes in sea-level detected are global in extent. This can only be established by examining the same age successions from a number of sedimentary basins in different tectonic regimes all over the world.

This then raises the problem of stratigraphical correlation of the different sections at the time-resolution of at least the sequence boundaries. Various stratigraphical techniques, but particularly biostratigraphy (Section 2.1.2), have been used extensively to try to test the global correlation of various parts of the stratigraphical record. This has given mixed results; whilst some depositional sequences appear to correlate globally, others do not. However, it is often not clear that the biostratigraphy (or other dating technique) is of sufficient resolution or precision. The breakthroughs in proving the global correlation of the cycles (or not) will probably only come from using an integration of stratigraphical dating techniques. This integration would potentially allow both a higher resolution correlation and the robustness of the correlation to be demonstrated by independent techniques. The other problem with testing the global correlation of sequences is separating out the local effects from the possible global signal. For instance, if a particular area or a whole basin has a very high sediment supply or a complex local tectonic history, then the timing of the individual sequences will be different from a succession with a moderate sediment supply and simple subsidence history.

At the time of the development of the sequence stratigraphy model in the late 1970s, Peter Vail and colleagues from Exxon Production Research, USA and elsewhere, compiled a global sea-level chart for the Mesozoic and Cainozoic, showing (at the resolution of about 1 Ma) how they interpreted global sea-level to have changed through time. Since its first publication (see Payton, 1977), the chart has been revised and republished several times, each version incorporating more data, some of which is from classical exposures around the world. One of the most extensively referenced versions of this chart is the 'Mesozoic–Cenozoic Cycle Chart' * published in 1988 by Haq *et al.* in Wilgus *et al.* These charts have produced much discussion partly because the data that support the interpretations have never been made fully available as they were based largely on confidential seismic sections and because researchers around the world have spent much time comparing particular sections with these 'global' sea-level charts.

The chart's most recent reincarnation (Hardenbol *et al.*, 1998) is slightly more modest because it only claims to be a European sea-level chart. Still, though, a full data set supporting the interpretations has never really been made widely available. It is interesting to note that publication of these sea-level charts was always, at least in part, intended to be provocative, and it certainly has got stratigraphers and sedimentologists discussing whether or not there is a global signal in the stratigraphical record.

However, the global nature of sequence stratigraphical cycles for much of geological time has yet to be proven. Global sea-level changes have really only been proven for the Quaternary and much of the Neogene where the oxygen-isotope record is good and can be directly linked to global sea-level change.

* Cenozoic is the American spelling of Cainozoic.

4.7 Summary

- Parasequences are the smallest bed-scale cycles within sedimentary successions. They comprise shallowing-upward progradational successions and are bounded by flooding surfaces. A flooding surface separates younger from older strata across which there is evidence of an increase in water depth.
- Parasequences stack together in patterns according to the longer-term changes in the balance between the rate of sediment supply and the rate of change of accommodation space (relative sea-level). The stacking pattern may be either progradational (parasequences build in a basinward direction), or aggradational (parasequences remain in the same lateral position), or retrogradational (parasequences build in a landward direction). Groups of parasequences showing the same stacking pattern are termed parasequence sets.
- Depositional sequences or sequences comprise relatively conformable packages of sediment bounded by sequence boundaries.
- The sequence boundary, transgressive surface and maximum flooding surface are all key surfaces associated with depositional sequences.
- Sequences are divided into systems tracts, each of which comprise a linkage of contemporaneous depositional systems or facies belts.
- The features of key surfaces and systems tracts are summarized in Table 4.1 (overleaf).
- The Namurian succession of northern England can be interpreted using the sequence stratigraphy model. Sequence boundaries formed during forced regressions are represented by the base of the incised palaeovalleys, and where fluvial incision has not occurred by subaerial exposure of the delta plain. During the transgression, the incised valleys are infilled and delta front, prodelta and marine mudstones are deposited across the top of the delta plain. Maximum flooding is interpreted to be represented by the goniatite-bearing marine mudstones. The HST is marked by the main phase of delta progradation.
- Seismic reflectors are chronostratigraphical surfaces.
- Sequence stratigraphical analysis of seismic sections is greatly aided by recognition of different types of seismic reflector termination. These include onlap, erosional truncation, downlap and toplap. Similar types of stratal termination and geometries may be recognized in large-scale cross-sections.

Table 4.1 Summary of the features of systems tracts and key surfaces. Note that for simplicity the timing of the systems tracts and key surfaces are given with reference to a relative sea-level cycle assuming that the sedimentation rate is constant but, the same features, except for the FSST, could form due to changes in the sedimentation rate with relative sea-level staying constant. However, in most geological situations these sequence stratigraphical features are a combination of the balance between relative sea-level change and sediment supply.

Key surface or systems tract	Timing within the relative sea-level cycle			Bounding surface		Parasequence stacking pattern and geometry of the key surface	Typical sedimentary features that may develop
	Period	Earliest starting point	Latest end point	Lower	Upper		
Highstand systems tract (HST)	Stable to decreasing rate of relative sea-level rise	Maximum rate of relative sea-level rise	Maximum relative sea-level	MFS	SB	HST comprises aggradational to progradational parasequence sets. It usually downlaps onto the MFS and may onlap onto the SB.	Fairly stable depositional environments; widespread facies belts.
Maximum flooding surface (MFS)	Between maximum rate of relative sea-level rise and maximum relative sea-level	Maximum rate of relative sea-level rise	Maximum relative sea-level	–	–	MFS represents period when distal areas are starved of sediment. The period of starvation will increase in duration in a distal direction. Strata overlying the MFS downlap onto it.	Condensed section; precipitation of authigenic minerals (e.g. phosphate and glauconite); abundant and diverse fauna; deepest-water facies; widest landward extent of marine facies; last significant flooding surface in the sequence.
Transgressive systems tract (TST)	Increasing rate of relative sea-level rise	Pronounced rise in relative sea-level	Maximum rate of relative sea-level rise	TS	MFS	Provided the rate of relative sea-level rise is greater than the supply of sediment, which is often the case, the TST comprises a retrogradational parasequence set.	In many successions, the TST comprises fairly condensed, reworked sediments, with an overall deepening-upward trend. However, for some carbonate successions, it may represent the period of highest sediment productivity. Typically comprises very widespread facies belts.
Transgressive surface (TS)	Start of increased rate of relative sea-level rise	Pronounced rise in relative sea-level	Maximum rate of relative sea-level rise	–	–	TS marks onset of pronounced relative sea-level rise. It is the first significant marine flooding surface. In most siliciclastic and some carbonate successions, it is the base of the first retrogradational parasequence. Usually overlain by onlapping strata, and may be detected by increase in the amount of onlap	Sharp erosion surface in shoreface zone; winnowed lag of fossils and/or clasts; initiation of deepening-upward trend.

Lowstand systems tract (LST)	*Initial* very slow rate of relative sea-level rise or stillstand	Minimum relative sea-level	Pronounced rise in relative sea-level	–	TS	LST comprises progradational to aggradational parasequence sets. The LST will onlap the FSST.	Deposition of sediments on top of the underlying FSST (if present). Similar facies to underlying FSST.
Falling stage systems tract (FSST) *	Falling relative sea-level (forced regression)	Start of relative sea-level fall	Minimum relative sea-level	SB	–	FSST comprises a progradational parasequence set or redeposited sediments.	Deposition of sediments lower down the depositional profile than the same facies belts of the underlying HST. FSST either comprises downstepping parasequences (unattached to attached) or redeposited material below the shelf break.
Sequence boundary (SB)	Falling relative sea-level (forced regression) or inflexion point in the temporary decrease in the rate of relative sea-level rise	Start of relative sea-level fall (forced regressions) or inflexion point in the temporary decrease in the rate of relative sea-level rise	Minimum relative sea-level	–	–	Depositional sequences are bounded by sequence boundaries. SB is an unconformity formed by *subaerial exposure and erosion* in proximal areas (for forced regressions), and/or marine erosion in coastal areas. The unconformity passes into a correlative conformity as it is traced laterally into stratigraphically complete distal sections or areas with a higher subsidence rate. Underneath the sequence boundary there may be erosional truncation of strata due to erosion and strata may onlap onto the sequence boundary.	Unconformity (often marked by a biostratigraphical gap) or its correlative conformity; evidence for *extensive subaerial exposure and/* or erosion; incised valley formation; basinward shift of facies.

* FSSTs are a consequence of forced regressions; they do not form during regressions.

4.8 References

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