'Base profile': a unifying concept in alluvial sequence stratigraphy

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Abstract: The sequence stratigraphy of sedimentary strata is governed by the creation and removal of accommodation space. However, current sequence stratigraphic models do not properly account for changes in accommodation space in the alluvial environment. In order to rectify this, a concept is proposed here called base profile. Base profile can be used to describe and explain the deposition and removal of fluvial sediments analogous to the way the term base level (relative sea-level) is used in the sequence stratigraphic analysis of coastal and marine strata. Base profile is the surface measured relative to a chronostratigraphic datum within a drainage basin to which rivers would regrade were conditions to remain constant. It represents the continental extension of base level. Changes in accommodation space occur if base profile rises or falls as a result of (a) subsidence or uplift, (b) variations in sediment supply, (c) variations in river discharge, (d) eustatic fluctuations, and (e) progradation or retrogradation of the coast. During a rise in base profile, coarse-grained siliciclastic sediment is trapped on the alluvial plain due to fluvial aggradation and mostly only fine-grained sediment will reach the marine environment. A fall in base profile is associated with fluvial degradation and maximum sediment input to the marine environment. Base profile forms a simple basis for describing, correlating and interpreting alluvial strata. Simple models are developed here using base profile which show how different continental and marine processes can lead to the deposition of laterally extensive, coarse-grained fluvial strata.

The correlation and interpretation of marine and coastal sediments have been revolutionized in recent years by the development and widespread application of sequence stratigraphy (e.g. Vail *et al.* 1977; Van Wagoner *et al.* 1988; Posamentier *et al.* 1988; Posamentier & Vail 1988; Galloway 1989; Shanley & McCabe 1991). However, many authors have indicated that there are limitations in using current sequence stratigraphic models to explain the deposition and erosion of sediment by rivers (e.g. Leopold & Bull 1979; Galloway 1989; Miall 1991; Schumm 1993; Wescott 1993; Wright & Marriott 1993; Koss *et al.* 1994; Shanley & McCabe 1994). One of the main problems is that, at present, it is difficult to describe alluvial sediments in sequence stratigraphic terms without first interpreting whether they may, for example, have developed during a rise or a fall in relative sea-level. Even where marine influence is unequivocal, workers often have problems in agreeing whether fluvial deposits should be assigned to lowstand, transgressive or highstand systems tracts (e.g. compare Maynard 1992; Bristow & Maynard 1994; Church & Gawthorpe 1994; Hampson *et al.* 1996).

There are three important reasons why it is essential that sequence stratigraphy can be applied successfully to alluvial sediments. Firstly, fluvial sandstones form excellent hydrocarbon reservoirs and any improvement in their prediction and correlation is of great economic value. Secondly, the deposition and removal of sediment on the alluvial plain directly affects the sediment flux to, and hence the sequence stratigraphy of, coastal and marine deposits. Thirdly, it is preferable if geologists and geomorphologists can describe and interpret alluvial sediments in a consistent way.

The purpose of the first part of this paper is to introduce a new concept that describes the dynamic nature of the drainage basin similar to the way that the concept of base level describes the dynamic nature of the marine basin. The second part of the paper consists of a discussion of some simple models and implications which arise from the new concept.

Terminology

Some confusion has been caused in recent years by different usage of terms such as 'base level' and attempts to introduce new terminology such as 'stream equilibrium profile' (e.g. Posamentier *et al.* 1988). In this paper base level is used to mean relative sea-level. The term stream equilibrium profile is dropped in favour of 'graded profile'. In addition, the term 'drainage basin' refers to all parts of the continent that are drained or traversed by rivers that ultimately deliver water to a similar part of the coast; the network of rivers and streams within a drainage

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basin is known as the 'river system'; the term 'hinterland' refers to the highland or proximal area of the drainage basin from which coarse-grained sediment is supplied; the term 'alluvial plain' indicates all parts of the drainage basin between the hinterland and the coast, be they valleys, floodplains or interfluvial areas; the word 'coast' is used in preference to bayline as the lower limit of alluvial deposits and as the upper limit of paralic and estuarine deposits; and the term 'marine' includes paralic and estuarine environments.

The graded river

An easy way of understanding sedimentary processes in the alluvial environment is by considering the concept of the graded river. A graded river is defined as one in which no significant erosion or deposition occurs along its length that is of permanent effect on the overall profile of the river (Davis 1902; Mackin 1948).

A river reaches the graded state when it is capable over the year or a period of years to transport all parts of the bed-load along all portions of the river at rates equivalent to sediment supply; i.e. the power of a graded river, as determined by the discharge, velocity and the form of the channel, exactly balances the energy required to carry the bed-load. A river is not graded if the power of the river over a period of years is either (a) insufficient to carry all of the bed-load, or (b) greater than is required to carry all of the bed-load. In the case of (a), the floor of the alluvial plain will build upwards (aggrade) as part of the bed-load is left behind; in the case of (b), the river will cut downwards (degrade) because some of the excess power of the river is spent picking up new bed-load material.

The amount of bed-load which a river can carry is determined by the amount and proportion of different grain-sizes present (Mackin 1948). Generally, the greater the amount and/or the proportion of coarser grain-sized material, the greater the power of the river that is required to transport it; i.e. a graded river carrying coarse bed-load will be steeper (i.e. faster flowing), and/or will have greater discharge, and/or will have a more efficient channel form than a similar river carrying finer grained bed-load (see Lane 1955).

Generally the profile of a graded river flattens towards the coast which partially reflects greater efficiencies in channel form and relatively higher discharge rates (Mackin 1948). Thus, a large, slow-moving river can typically transport all the bed-load provided by its faster flowing tributaries. A further reason for this flattening may be that the proportion of coarse grain-sizes in the bed-load decreases with distance from the source of the sediment due to abrasion during transport.

Controls on the graded profile

The overall shape of the graded profile of a river reflects: (i) the length of the river from the watershed to the coast; (ii) the change in elevation along the length of the river; (iii) the amount and variation in discharge; and (iv) the amount and grain-sizes of the sediment.

A river may go out of grade if changes occur in the height and position of the watershed; the height and position of the coast; the slope of the alluvial plain; the amount of water entering the river; and weathering, erosion, vegetation and bed-rock in the sediment source area. These variations in turn simply reflect the effects of subsidence and uplift within the drainage basin, changes in climate and the relative height of sea-level, and sedimentological and geomorphological processes in the hinterland and at the coast.

In order to get back in grade, rivers will tend either to degrade or aggrade. Much of the erosion that results from fluvial degradation will occur during periods when the river is at peak discharge; much of the deposition associated with aggradation will occur when flow begins to wane after periods of peak discharge. Provided that there is sufficient time, most changes in grade along any part of a river will also affect the grade of adjoining tributaries and distributaries by altering the height of the junctions, the velocity of the river and (temporarily) the amount of sediment transported downstream.

Significant changes in the graded profile of a river due to variations in factors such as climate or the height of sea-level, are likely to affect large parts of the drainage basin. Therefore, such changes, which represent periods of aggradation or degradation, may serve as useful correlatable events within alluvial strata. In order to describe and explain these events over geological time, a concept is proposed known as 'base profile'.

Base profile

The sequence stratigraphy of marine strata is greatly influenced by the effects of subsidence and changes in eustatic sea-level. In order to simplify observations and interpretations the concept of base level is used. Base level is the relative height of sea-level above a chronostratigraphic datum (Fig. 1). An increase in the relative height of sea-level (a rise in base level) may be due to subsidence or a eustatic increase in sea-level or a combination of both. Base level

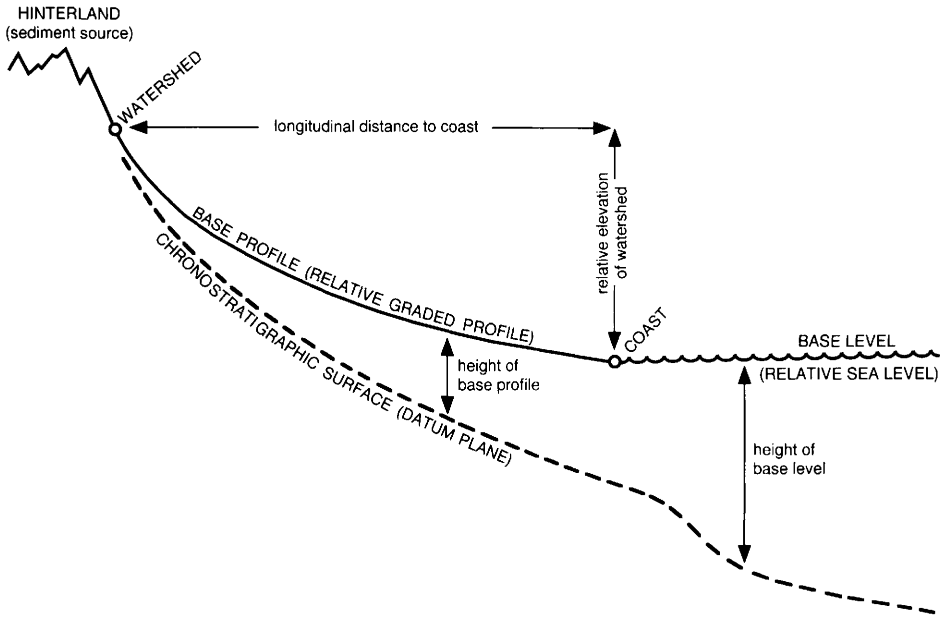

Fig. 1. Diagrammatic cross-section illustrating the concept of base profile (relative graded profile) and its relationship to base level (relative sea-level).

controls accommodation space for coastal and marine sediment as well as the position of the coast. In contrast, accommodation space for alluvial sediment is related to the graded profile of a river. The easiest way of explaining changes in accommodation space in the alluvial environment is by describing them relative to a chronostratigraphic surface or datum similar to the way base level is used in the marine environment (Fig. 1). If the height of the graded profile increases relative to the datum then accommodation space for alluvial sediment is created. If the height of the graded profile decreases relative to the datum then accommodation space is removed. Therefore, a concept of relative graded profile is proposed. Relative graded profile is given the name base profile in this paper in keeping with the name base level. Base profile is defined as the ideal graded profile of a drainage basin at a specific moment in time relative to a chronostratigraphic datum. Rivers will tend to aggrade up to or degrade down to the base profile.

The base profile of a drainage basin intersects sea-level at the coast and it is thus the terrestrial equivalent of base level (Fig. 1). Unlike base level, changes in the height of base profile are related, not only to eustatic sea-level and subsidence, but also to river discharge and hinterland tectonics. Over time, compaction will tend to cause strata to lower in height relative to the original position of any particular base profile. In theory, the effect of compaction should be corrected for; in practice, it can usually be ignored (Quirk 1994).

Shanley & McCabe (1994), in recognizing differences in the definition of base level between different workers and disciplines, coined the term stratigraphic base level to mean a dynamic equilibrium surface that separates erosion from deposition of continental as well as marine strata. Although they do not clearly indicate what the distinction is between stratigraphic base level and terms such as graded profile and stream equilibrium profile, it is different from the concept of base profile for the following reasons.

(i) Base profile constitutes the position of the graded profile relative to a chronostratigraphic datum, stratigraphic base level does not.

(ii) The effect of stratigraphic base level on fluvial architecture is described as different to those of climate, sediment supply and hinterland tectonics (pp 556, 558 and 564 in Shanley & McCabe 1994), whereas base profile includes these effects.

(iii) Stratigraphic base level is synonymous with the groundwater table in aeolian strata (page 553 in Shanley & McCabe 1994), base

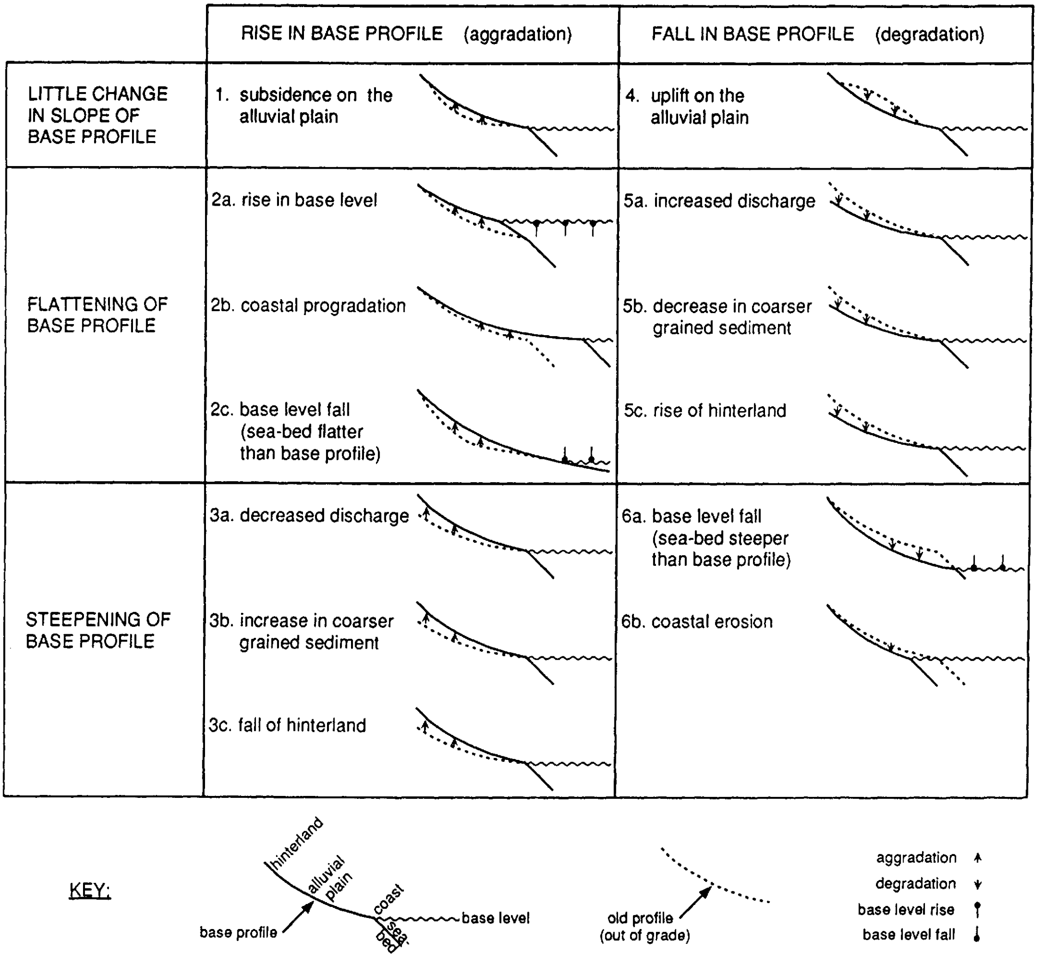

Fig. 2. The causes and effects of changes in base profile within a drainage basin.

profile is meant only to apply to alluvial strata.

To avoid confusion with other definitions, it is thought better to limit the use of base level to meaning relative sea-level.

Controls on base profile

Each portion of a graded river may accommodate a certain range of possible slopes by variations in channel form but it must be in equilibrium with each adjacent upstream and downstream portion of the river system. Therefore, although flexibility exists in the system, at any one time a drainage basin will have one unique base profile which will depend on the following parameters: the elevation of the watershed relative to sea-level; the longitudinal distance from the watershed to the coast; the river discharge; the amount and type of bed-load (coarse-grained) sediment being carried by the rivers; the forms of the river channels.

Base profile may change as a result of these parameters being affected by uplift or subsidence on the continent, a rise or fall in base level, a change in climate, a change in sediment supply, or an increase or decrease in the longitudinal distance to the coast. After a change in base profile, the drainage basin will be out of grade until the rivers have adjusted to the position of the new base profile. However, there is unlikely to be enough time available for the river system to become completely regraded before another change in base profile occurs. In fact, factors such as subsidence will cause base profile to be continually moving; i.e. base profile, similar to base level, is dynamic.

The position of any new base profile may lie above or below the old base profile. The change is described as either a rise in base profile or a fall in base profile (Fig. 2). A rise in base profile means that there is an increase in the height of the ideal graded profile relative to the datum plane. A fall in base profile means that there is a decrease in the height of the ideal graded profile relative to the datum plane. A rise in base profile will tend to lead to the deposition of alluvial sediment (fluvial aggradation) when new accommodation space is created. A fall in base profile will tend to lead to erosion on the alluvial plain (fluvial degradation) when accommodation space is removed.

Rivers can compensate for certain changes in the conditions affecting a drainage basin by changing their channel form (Schumm 1993; Wescott 1993) rather than base profile. However, these changes will not be preserved in the sedimentary record unless a rise in base profile occurs.

Changes in base profile will cause variations in sediment flux to the marine environment as sediment is trapped on, or removed from, the continent by rivers. Not until the alluvial plain has readjusted to the new base profile will the sediment flux fully stabilize; i.e. when the amount of sediment reaching the coast approximately matches the supply of sediment from the hinterland.

Changes in base profile

Three types of changes in base profile can occur:

- where the river aggrades or degrades in order to maintain the original slope of the river (1 and 4 in Fig. 2);
- where the river aggrades or degrades leading to a reduction in the slope of the river (2a–c and 5a–c in Fig. 2);
- where the river aggrades or degrades leading to an increase in the slope of the river (3a–c and 6a–b in Fig. 2).

Rises in base profile which cause a change in the slope of a river will normally be associated with an increase in efficiency in channel form (particularly in the cases of 2a, 2b, 3a, 3b and 3c in Fig. 2). Falls in base profile which cause a change in the slope of a river will normally be associated with a decrease in efficiency in channel form (particularly in the cases of 5a, 5b, 5c, 6a and 6b in Fig. 2).

The main controls on changes in base profile are considered separately in the discussion below although they may well occur in combination with one another. The discussion only considers those changes in base profile that are of sufficient magnitude to affect the sedimentary record over fairly large distances, i.e. those that can be correlated.

Effect of subsidence or uplift within the drainage basin

The simplest change in base profile is that caused by subsidence and uplift on the alluvial plain. In the case of subsidence, a river will build up to the level of the alluvial plain by aggradation in order to maintain grade, i.e. a rise in base profile occurs (1 in Fig. 2). The rate of rise in base profile will correspond to the rate of subsidence. Uplift will cause the opposite effect, namely that rivers will degrade due to a fall in base profile (4 in Fig. 2).

A similar change in base profile occurs towards the hinterland of a drainage basin if it is affected by tilting, mountain building, mountain collapse or isostatic readjustments. A rise in the height of the hinterland will cause an increase in the slope and hence an increase in the velocity of a river. Therefore, rivers will often tend to erode and degrade. This change manifests itself as a fall in base profile (5c in Fig. 2). The new base profile has a slope similar to, or greater than, that of the old graded profile prior to uplift, depending on adjustments in channel form. During the process of regrading, the downstream portions of a river will be affected due to a change in the amount of bed-load being carried by the river. However, these effects will only be temporary, provided that the river has time to adjust to the new base profile. A fall in the height of the hinterland will cause rivers to slow down and coarse-grained material will tend to accumulate (aggrade) until grade is once more re-established. This equates with a rise in base profile (3c in Fig. 2).

Effect of changes in river discharge and sediment supply

A permanent change in discharge relative to the amount of coarse-grained sediment entering a river will tend to cause a change, not only in the position of the base profile, but also ultimately in the slope of the drainage basin. For example, if the amount of coarse-grained sediment decreases, a river has surplus power which will lead to down-cutting and flattening of the profile. The river will continue to flatten and slow down until it is back in grade. This corresponds to a fall in base profile and the effects will be most pronounced towards the hinterland (5b in

Fig. 2). The same effects will be seen where the amount of river discharge increases (5a in Fig. 2).

Where river discharge decreases and/or the amount of bed-load increases, the river will be incapable of carrying the coarser-grained sediment. This will cause material to build up or aggrade in the hinterland until the slope and hence the velocity of the river is again in balance. This represents a rise in base profile, the effect of which decreases to zero at the coast (3a and 3b in Fig. 2). The amount of fine-grained sediment that a river can carry in suspension is almost unlimited (Mackin 1948) and will therefore have little effect on base profile.

Changes in climate will often lead to both a change in river discharge and sediment supply. For instance, a change from humid to semi-arid conditions will tend to cause a decrease in river discharge and an increase in sediment supply (Schumm 1977). In this particular example, both effects will probably combine to produce a rise in base profile (3a + 3b in Fig. 2). However, further discussion of this is beyond the scope of this paper.

Effect of changes in the position of the coast

Coastal progradation will result in a rise in base profile (2b in Fig. 2). This occurs in order that the river or rivers build up sufficient slope to carry the bed-load across the extended part of the alluvial plain. The new slope is generally small because the extended rivers are generally more efficient than higher up on the alluvial plain. Therefore, the amount of rise in base profile on the alluvial plain caused by coastal progradation alone is fairly limited. However, the rate of subsidence within a basin may increase in the direction of progradation, in which case an additional component of rising base profile will become more important as the alluvial plain extends. This effect is equivalent to rising base level which is discussed below.

A fall in base profile will occur if coastal erosion cuts back into the lower end of the drainage basin (6b in Fig. 2). This fall is necessary in order to compensate for the decrease in the length of the river.

Effect of changes in base level

The greatest control on base profile close to the coast will come from changes in base level. A rise in base level will have an analogous effect to that of the tide coming in to an estuary. The river will become sluggish in its lower reaches causing the deposition of the coarsest part of the bed-load. This has the effect of decreasing the slope of the adjacent upstream portion of the river which in turn causes it too to become more sluggish and deposit coarse-grained fluvial material. Thus a chain of fluvial aggradational events, equivalent to a rise in base profile, will work back up the river until grade is re-established (2a in Fig. 2). Koss *et al.* (1994) have elegantly shown in modelling experiments how deposition of this fluvial sediment will occur as a series of backstepping lobes. The new graded portion of the river will have a slightly shallower slope and a more efficient channel form than the old profile but is otherwise similar. The amount of transgression that occurs during a rise in base level depends on the balance between the rate of fluvial aggradation and the rate of change of base level. The exact shape of the new base profile is also dependent on this balance. If the coast retreats past any point on the continent, base level will take over from base profile as the main control on accommodation space and marine strata will overstep alluvial deposits (e.g. (1) in Fig. 3).

The distance inland to which fluvial deposition is affected by base level rise is strongly influenced by the type and relative amount of bed-load sediment transported by the river, the amount of change in slope that variations in channel efficiency can accommodate and the time available between each increment of base level rise. For example, a river which is only carrying fine-grained sediment in suspension will tend to show little change in base profile in response to a rise in base level. Also, if a rise in base level proceeds very rapidly, the rate of fluvial aggradation may be insufficient to prevent the continent from quickly flooding.

A fall in base level may cause either a fall or a rise in base profile, depending on whether the slope of the sea-bed in front of the old river mouth is steeper or flatter than the slope of the new portion of graded river that will flow down it (Miall 1991; Posamentier *et al.* 1992; Wescott 1993; Shanley & McCabe 1994). Usually the sea-bed in front of a major river is steeper than the graded profile (e.g. Nummedal *et al.* 1993), in which case a fall in base level will mean that base profile will also fall and the river will tend to degrade (6a in Fig. 2). In rare cases where the sea-bed is flatter than the graded profile, a rise in base profile will occur due to a fall in base level (2c in Fig. 2). Such a situation may arise in an internal drainage basin where rivers feed into a shallow-bottomed lake or where new rivers develop across a recently exposed continental shelf.

Schumm (1993) and Shanley and McCabe

(1994) have concluded that the effects of a change in base level are unlikely to extend more than a few hundred kilometres inland. The maximum inland position to which the effect of a change in base level extends is where the new base profile intersects the old base profile. The location of this intersection point depends on the change in the height of base level and the slope of the new base profile relative to the old base profile (see (1) in Fig. 3). The slope of the new base profile in turn is related to the changes in channel form that the rivers can accommodate.

Dominance and order of changes in base profile

The causes and effects that lead to changes in base profile have been treated here separately. However, in reality, more than one of these processes is likely to be working at the same time, but at different magnitudes and at different rates. Over the long term, subsidence is likely to be the dominant process that leads to the preservation of thick packages of alluvial sediment, i.e. in an overall sense, base profile will continue to rise at a rate roughly equivalent to the rate of subsidence. Variations in climate, hinterland tectonics and base level may cause higher order rises and falls in base profile which are superimposed on this overall rate. Many of the causes of these high order variations are likely to be cyclical. Thus, in areas of high subsidence, repetitious alluvial sequences might develop, separated by unconformities or periods of slowing down or stillstand in the rate of rise of base profile.

Sequence stratigraphic context

Lateral and vertical extent of alluvial sequences

Changes in base profile may not affect all parts of a single drainage basin. Many changes in base profile will decrease to almost zero before either the hinterland or the coast is reached. This is mainly because variations in channel form can allow a river to accommodate certain changes in slope (Schumm 1993). Also there may not be enough time for distant parts of the drainage basin to react to a change in base profile. Nonetheless, in areas where thick packages of alluvial sediment have been preserved, it should be possible to correlate important changes in base profile for distances of several tens to hundreds of kilometres.

Where a fluvial sand is overlain by a similar fluvial sand, the preserved thickness of the underlying sand (corrected for compaction) gives an approximate measurement of the amount of rise in base profile prior to the deposition of the overlying sand. In contrast, it will usually be difficult to estimate the amount of fall in base profile associated with any particular continental unconformity. In fact, it may be difficult to distinguish unconformities from channel scour features.

Aggradation

A rise in base profile is associated with the accumulation of coarse-grained and associated floodplain sediment on the continent by fluvial aggradation. Fluvial aggradation occurs along portions of the river that have slopes less than the base profile (although the final profile may be steeper than the old base profile). Therefore, coarse-grained sediment cannot easily be transported to the coast until the rivers have been regraded and/or the channel form has become more efficient, i.e. mostly only fine-grained sediment will reach the marine environment via rivers during a rise in base profile. Such fine-grained marine deposits are often equated with transgression (rapid rise in base level). However, Fig. 2 shows that there are other causes of rises in base profile that can trap coarse-grained sediment on the continent (1–3c in Fig. 2), such as a relative decrease in river discharge. Away from a river channel, aggradation of floodplain sediment may accompany a rise in base profile. Some of this material may be removed later due to channel avulsion depending on the rate of aggradation (Bridge & Leeder 1979).

In cases where a rise in base profile is due to a rise in base level (2a in Fig. 2), coarse-grained fluvial strata will tend to backstep as the continent becomes progressively flooded (see Koss *et al.* 1994). This backstepping pattern occurs because successive new base profiles intersect the old profile progressively nearer to the hinterland as the coast retrogrades ((1) in Fig. 3). The youngest fluvial sediments prior to transgression are expected to show a fining- and thinning-upwards trend (e.g. Shanley & McCabe 1991). A condensed sequence and a maximum flooding surface will usually occur above such a fining-upwards package. Inland from the coast, the time of maximum flooding will tend to correspond with the upper part of a coarse-grained fluvial interval (Quirk 1994) and possible tidal influence (Shanley *et al.* 1992).

Fluvial sandstones underlying a flooding surface are often interpreted as representing incised valley fills (e.g. Van Wagoner *et al.* 1990). However, incision (due to a fall in base profile) need not always precede a rise in base profile. Indeed, incision may be absent in areas of high subsidence. Where incision has occurred, aggradational fluvial sandstones will tend to be constrained within the valley unless and until base profile rises above the valley sides. Where incision has not occurred, for example above a type 2 sequence boundary (e.g. Posamentier *et al.* 1988), fluvial sandstones may form amalgamated, sheet-like bodies if the rate of aggradation is low to moderate (see Bridge & Leeder 1979) or the amount of coarse-grained bed-load is high (Quirk 1994). However, transgression will generally proceed at a faster rate over an alluvial plain that has not been incised than along an incised valley with a similar gradient. This is because the products of fluvial aggradation that accompany the rise in base profile are spread over a larger area on a flat plain than in the confines of an incised valley. Also, changes in the slope of the drainage basin are accommodated more easily on a flat plain where lateral changes in channel form are not constrained (Schumm 1993). It is therefore probable that alluvial sequences which do not occur within incised valleys are likely to be thinner but more extensive than their incised counterparts.

Where rises in base profile have occurred due to purely continental processes, such as climate change or tectonics (1, 3a–3c in Fig. 2), then aggradation of coarse-grained sediments will tend to begin upstream and advance downstream. Subtle downlap may occur on the underlying alluvial surface ((3) in Fig. 3) and coarsening- and thickening-upwards alluvial strata are predicted to develop.

Over the long term, degradation will tend to outweigh aggradational processes towards the hinterland and for this reason many effects on base profile due to changes in climate and orogenesis will not be preserved, except in areas of active continental subsidence.

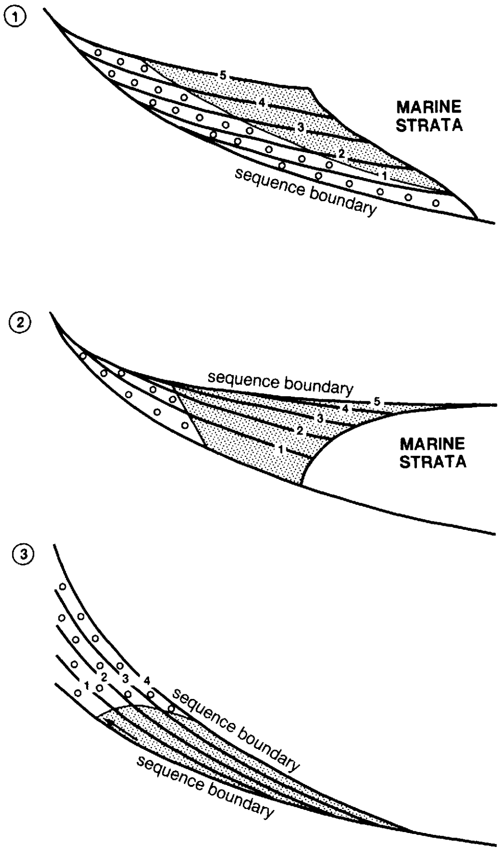

Fig. 3. Idealized cross-sections through alluvial intervals deposited as a result of rising base profile: (1) due to base level rise (transgression); (2) due to highstand progradation; (3) due to continental processes such as decreased discharge, increased coarse-grained sediment supply or subsidence within the hinterland. The hinterland is on the left of each cross-section. Circles represent alluvial deposits associated with braided rivers; dots represent alluvial deposits associated with meandering and low sinuosity rivers; numbered lines indicate the position of successive alluvial surfaces that may or may not have caught up with rising base profile.

Channel form

It is often possible to distinguish at outcrop or in the subsurface between fluvial sediments that were deposited by braided rivers and those that were deposited by meandering or low sinuosity rivers. Braided rivers are more common in areas with high gradients; meandering (high-medium sinuosity) rivers are more common in areas with medium–low gradients; and straight (low sinuosity) rivers are more typical of areas with very low gradients (Allen 1970; Ouchi 1985). Hence, braided rivers are generally found closer to the hinterland, where the slope of the drainage basin is high, and low sinuosity rivers (which may or may not anastomose) on flat coastal plains. Meandering rivers usually occupy the intervening part of the alluvial plain. Channel form is also influenced by discharge and the amount of coarse-grained bed-load. For example, for the same slope braided rivers tend to have higher discharges than meandering rivers (Allen 1970). Therefore, where it is possible to log changes in channel form within fluvial strata, inferences can be made about changes in discharge relative to sediment supply or changes in the slope of the river due to tectonics or base level effects. These inferences may in turn be useful in interpreting what caused the rise in base profile that led to the deposition of fluvial strata in the first place. Thus, continental processes that cause a rise in base profile, such as a decrease in relative discharge or a fall in the height of the hinterland (3a–c in Fig. 2), will lead initially to a decrease in sinuosity or a change from braided to meandering channels as the rivers are forced to become more efficient. However, as fluvial aggradation proceeds, the profile of the drainage basin will gradually steepen ((3) in Fig. 3). Therefore, a change from low sinuosity to high sinuosity channel deposits or from meandering to braided channel deposits is predicted upwards in the sedimentary succession. In contrast, a rise in base profile due to a rise in base level is likely to lead to a different effect, namely a change from high sinuosity to low sinuosity channel deposits or a change from braided to meandering deposits as the profile of the drainage basin gradually flattens upwards with time and the rivers become more efficient ((1) in Fig. 3).

A more general observation can also be made that eustatic changes in sea-level will cause cyclical variations in channel patterns, i.e. a eustatic fall will usually lead to an increase in the graded slope of the lower part of the drainage basin (6a in Fig. 2) and a eustatic rise will usually lead to a decrease in the graded slope (2a in Fig. 2). It is therefore possible to explain why braided fluvial channels are more typical of lowstand and early transgressive systems tracts and meandering and low sinuosity channels are more typical of late transgressive and highstand systems tracts.

Variations in channel form essentially represent an increase or decrease in the efficiency of the river. A river that is confined within an incised valley or flows through resistant material cannot easily change its channel form (Schumm 1993) and the river will consequently show greater susceptibility to changes in base profile than those that are unconfined. It is also difficult for highly braided rivers to become less efficient or very straight rivers to become more efficient.

Other changes in the efficiency of river channels may occur during changes in base profile, such as a change to a smoother or rougher bedform. The reader is referred to Schumm (1977) who discusses in great detail how channel form reacts to changes in water discharge, bed-load and gradient.

Degradation

During a fall in base profile the alluvial plain will be subject to erosion and sediment will by-pass the continent. Fluvial degradation occurs along portions of the river system which, during the process of regrading, have slopes steeper than the base profile. The point where the new profile intersects the old graded profile is called the knick point. The rate that the knick point migrates upstream from the mouth of the river is inversely proportional to the square root of the time since base level was lowered (see Begin 1988). Provided that there is enough time, the products of degradation, in addition to sediment from the hinterland, will be transported to the coast. Hence, unconformities in the alluvial environment will correlate with periods of maximum sediment influx in the marine environment and consequently most marine sands will have no alluvial counterpart of the same age.

Subaerial unconformities are often interpreted as type 1 sequence boundaries indicative of a fall in base level (e.g. Aigner & Bachmann 1992). However, any fall in base profile can produce an erosional surface by fluvial degradation (4–6b in Fig. 2). Whether this unconformity is due to a fall in base level or some other process, such as increased discharge, can, in theory, be assessed by whether the amount of erosion increases or decreases towards the coast.

Much of the erosion associated with a fall in base level tends to be confined to incised valleys, indicating that the rate of fall of base profile was relatively rapid. Outside of such valleys, changes in base profile may be marked by subtle changes within palaeosols rather than fluvial aggradation or degradation (e.g. Wright & Marriot 1993). For example, a wetter palaeosol might develop as the water table rises in association with fluvial aggradation within an adjacent valley. In contrast, a drier palaeosol may form as the water table falls due to valley incision. Where a fall in base profile occurs more slowly, then peneplanation rather than incision may occur.

Any surface that has developed within alluvial strata as a result of a fall in base profile may be regarded as a continental sequence boundary (e.g. Fig. 3).

Edge effects

Where a rise or fall in base profile occurs relatively quickly, the change in base profile towards the edges of the area affected by the change may be in a sense opposite to the change in the main part of the area, i.e. the change in base profile will smooth out the effect rather than wholly counteract it. For example, Nummedal *et al.* (1993) have shown examples of rivers that are aggrading along most of their length due to coastal progradation, the effect of which is apparently compensated by fluvial degradation in the upper reaches of the rivers. Ouchi (1985) has demonstrated that a small amount of aggradation may occur downstream and upstream of an area of significant uplift; similarly, a small amount of degradation may occur at the edges of an area of subsidence. However, these effects are likely to be ephemeral because the area affected by a change in base profile will not remain fixed.

Susceptibility of drainage basin to changes in base profile

Processes of aggradation and degradation in a drainage basin will tend to occur as a series of chain reactions downstream or upstream from the place of maximum incremental change in base profile (Fig. 3). It is therefore unlikely that there will be enough time available between every change in base profile for the drainage basin to completely adjust, particularly in cases where the change in base profile is relatively small. Also in cases such as subsidence or uplift or a rise or a fall in base level (1, 2a, 2c, 3c, 4, 5c and 6a in Fig. 2), base profile is dynamic rather than fixed, i.e. while rivers react the position of base profile continues to change. Although a drainage basin will always attempt to catch up with base profile, it may not be able to before it is overwhelmed by some other event such as marine transgression. Also certain geomorphic thresholds may not be overcome. For example, a fall in base profile may not be sufficient to cause erosion of a resistive bed.

Schumm (1993) has also pointed out that changes in the grade of a drainage basin are partially accommodated by variations in channel form, i.e. a new base profile may contain slopes that are significantly steeper or flatter than the old base profile. Therefore, the difference in the height between the new and the old base profile will decrease almost to zero before the coast or the hinterland is reached. In such cases the new base profile will intersect the old base profile on the alluvial plain. If this intersection point migrates with time, onlap, downlap and toplap patterns may develop within alluvial strata (see Fig. 3).

It is clear, therefore, that a rise in base level will lead to very little, if any, aggradation in the higher reaches of the river system. Similarly, very little fluvial aggradation will occur close to the coast as a result of a relative decrease in discharge. Mature palaeosols may develop in areas of a drainage basin which have not been affected by a change in base profile (see Wright & Marriott 1993).

Local disturbances

Ephemeral features in a river system such as small lakes or waterfalls may lead to localized events of aggradation or degradation unrelated to base profile. If these temporary adjustments are recorded in the sedimentary column then they are unlikely to correlate for distances of more than a few kilometres. The effects of major autocyclical processes, such as stream capture, may be of regional extent but such events will be of random occurrence within any particular sedimentary package.

Intra-continental sequences

Some drainage basins feed large internal lakes rather than oceans. In such cases, base level may be regarded as relative lake level and base profile is the theoretical graded profile between the hinterland and the lake edge. It is therefore possible to correlate and interpret intra-continental sequences using the same criteria as for river systems that supply the sea.

Discussion

Alluvial sequences typically consist of various thicknesses of aggradational fluvial and floodplain deposits separated by unconformities or soils (e.g. Boyd & Diessel 1994). Such sediments record changes in base profile. On the basis of the previous discussion, predictions can be made concerning the nature of intervals associated with different types of alluvial sequences. These are summarized in Table 1 and illustrated in Fig. 3 for three intervals associated with higher order rises in base profile. These intervals can be defined as system tracts on the basis that they consist of a depositional system linked in time and space. Intervals 1 and 2 depicted in Fig. 3 and Table 1 are equivalent to the alluvial parts of transgressive systems tracts and highstand systems tracts, respectively.

Changes in base profile are thought to be cyclical similar to base level. Therefore, a rise in base profile is usually preceded by and/or succeeded by a fall in base profile, except in areas of very high subsidence. Such a fall in base profile will lead to the formation of a continental sequence boundary. Hence, in areas of low–

Table 1. *List of attributes that characterize alluvial intervals (systems tracts) depicted in Fig. 3*

1 Alluvial interval associated with marine transgression	**2** Alluvial interval associated with coastal progradation	**3** Alluvial interval associated with changes in hinterland
base profile backsteps and flattens with time	base profile builds out and flattens with time	base profile steepens with time
interval pinches out towards the hinterland	interval is thin and pinches out towards the hinterland	interval pinches out towards coast
strata at base of interval show onlapping relationship towards the hinterland	strata at top of interval display toplap or are truncated	strata at base of interval show downlapping relationship towards the coast
strata fine and thin upwards	strata thin upwards	strata coarsen and thicken upwards
braided channel deposits tend to occur at base of interval	meandering-low sinuosity channel deposits are most common	braided fluvial deposits tend to occur at top of interval
evidence for increasing marine influence upwards	evidence for decreasing marine influence upwards	little evidence of marine influence
continental sequence boundary at base of interval	continental sequence boundary at top of interval	continental sequence boundary at base and top of interval

moderate subsidence, continental sequence boundaries are predicted to occur at the bases of intervals 1 and 3 in Fig. 3 (Table 1) and to truncate the tops of intervals 2 and 3 in Fig. 3 (Table 1). On this basis, interval 3 represents a complete alluvial sequence which consists of only one systems tract. Intervals 1 and 2 (Fig. 3, Table 1) are likely to occur at the bases and tops of sequences which also contain marine strata; they represent improvements in the treatment of alluvial strata compared to the traditional sequence stratigraphic models of, for example, Posamentier & Vail (1988).

Conclusions

Base profile is defined as the ideal graded profile of a drainage basin at a specific moment in time relative to a chronostratigraphic datum. It can be used to describe changes in accommodation space in the alluvial environment. Rivers will tend to aggrade up to or degrade down to base profile. New accommodation space is created in a drainage basin by a rise in base profile which may be due to one or more of the following reasons: subsidence on the alluvial plain; a decrease in river discharge and/or an increase in the amount of coarse-grained sediment; a decrease in the height of the hinterland; a rise in base level; coastal progradation; a fall in base level across a shallow-bottomed lake or a flat shelf.

Thick packages of alluvial sediment are only likely to be preserved over the long term in areas of active subsidence. However, higher order rises and falls in base profile within such packages may be due to the effects of climate, hinterland tectonics and eustasy. The explanation for any higher order rise in base profile can be assessed by whether the effect decreases or increases towards the hinterland, by whether the sedimentary interval coarsens or fines upwards, by whether there is a change in the form of the fluvial channels, by whether there is marine influence and by the lap-out geometries of the strata.

Continental unconformities, which may be interpreted as sequence boundaries, develop as a result of falls in base profile. Falls in base profile occur not only because of falls in base level but also due to uplift on the continent, due to increased discharge relative to coarse-grained sediment supply and due to the effects of coastal erosion. However, fluvial incision need not necessarily precede fluvial aggradation.

The sediment flux in the marine environment will vary according to changes in the grade of a drainage basin. For example, a rise in base profile caused by changes in the hinterland will cause starvation of coarse-grained sediment in the marine environment, i.e. coarse-grained fluvial sediments will usually correlate with fine-grained marine beds.

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