The large-scale dynamics of grain-size variation in alluvial basins, 2: Application to syntectonic conglomerate

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ABSTRACT

The concept of 'syntectonic' conglomerate is based on the idea that gravel progradation is mainly generated by an increase in tectonic uplift and erosion of a source area with attendant increase in sediment flux supplied to a basin. However, other mechanisms, such as changes in basin subsidence rates, sorting of supplied sediment, and capability of transporting streams, can also lead to progradation and be difficult to distinguish from a syntectonic origin. Here we use our previously developed model to help understand the origin of gravel progradation in three Neogene alluvial basins – the Bermejo Basin of Argentina, the Himalayan Foreland Basin, and the San Pedro Basin of southern Arizona – all of which have available high-resolution magnetostratigraphy. Interpretation of the origin of gravel progradation in these basins begins with calculation of basin equilibrium time, which is the time-scale required for the streams to reach a steady-state profile, assuming constant conditions.

We then compare the time-scale of the observed changes in the basin with the equilibrium time to determine if and how the model can be applied to the stratigraphic record. Most of the changes we have studied occur on time scales longer than the equilibrium time ('slow variations'), in which case the key to interpretation is the relationship between overall grain-size change and sedimentation rate in vertical sections.

Of the three examples studied only one, the Bermejo Basin, is consistent with the traditional model of syntectonic progradation. Overall progradation in the two other basins is most consistent with a long-term reduction in basin subsidence rates. In addition, short-term variation in diffusivity or sediment flux, probably climatically driven, is the most likely control of small-scale progradation of gravel tongues in the San Pedro Basin. These results, along with observations from other basins, suggest that subsidence is clearly an important control on clastic progradation on 'slow' time scales (i.e. generally a million years or more). If subsidence rates are directly linked to tectonic events, then subsidence-driven progradation marks times of tectonic quiescence and is clearly not syntectonic in the traditional sense.

These examples show that the model can be useful in interpreting the rock record, particularly when combined with other traditional basin-analysis techniques. In particular, our results can be used to help discriminate between clastic progradation due to tectonic origin and progradation resulting from other mechanisms in alluvial basins.

1 INTRODUCTION

Although several factors influence the overall development of stratigraphic sequences in alluvial sedimentary basins, the primary controls are essentially four – the rate that sediment is supplied to the basin from various source areas (or sediment flux); the relative abundance of different grain sizes within the supplied sediment; the rate and distribution of subsidence within the basin; and the rate of water supply associated with the fluvial transport systems (Paola *et al.* 1992, hereafter *Part 1*). In addition, changes in sea-level can profoundly affect basin stratigraphy, but these effects diminish upstream of the shoreline (Paola *et al.* 1991). Changes in the balance among these factors control major aspects of basinal stratigraphy, including the degree to which a basin is filled, the distribution of grain-size or major lithofacies boundaries within the basin fill, the stacking patterns of fluvial channel deposits, the geometry of the stratigraphic sequences, and the distribution of major unconformities across a basin (e.g. Sloss 1962; Leeder 1978; Paola 1988; Flemings & Jordan 1990; Part 1).

In our previous paper (Part 1) we developed a simple model for grain-size variation in alluvial sedimentary basins that examines the type, geometry and time-scale of stratigraphic response due to changes in these governing parameters. In this paper we use those model results to interpret the primary cause of gravel progradation in a variety of sedimentary basins based on available field observations. The application of these model results to observed stratigraphic sequences provides useful insights into the origin and interpretation of 'syntectonic' conglomerates.

Ideally, a true test of our model would require detailed measurements of the spatial grain-size pattern coupled with high-resolution chronostratigraphy, as well as independent constraints on the other fundamental variables of the system, especially the diffusivity. We discussed some of what would be involved in generating such a data set in Part 1. It is difficult to place independent constraints on all the possible controlling variables from the stratigraphic record. Instead, this paper focuses on two more tractable questions: are the model results at least broadly consistent with the best-constrained observations currently available, and are they useful in interpreting these data?

2 INTERPRETATION OF 'SYNTECTONIC' CONGLOMERATES

Of the various aspects of sedimentation that can be modelled, gravel progradation is one of the most interesting. Although gravel deposits make up a relatively small fraction of the stratigraphic record, they receive a disproportionate amount of attention. This is because, in part, conglomerates are in many cases well exposed, are amenable to study by many sedimentological techniques, and are often associated with tectonic activity (e.g. Steel *et al.* 1977; Rust & Koster 1984). Traditionally, syntectonic conglomerate is interpreted to result from an increase in sediment flux caused by tectonic uplift and erosion of source areas (e.g. Van Houten 1974; Mayer & Myers 1981). Thus, by analysing and dating syntectonic conglomerate, regional tectonic timing can be established (e.g. Wiltschko & Dorr 1983; Burbank *et al.* 1988 No. 645). In recent years this concept of syntectonic deposition has been challenged by a variety of studies that point out that an increase in sediment supply is not the only possible cause of gravel progradation in sedimentary basins (Sloss 1962; Blair & Bilodeau 1988; Heller *et al.* 1988; Paola 1988; Flemings & Jordan 1989; Paola 1990). Other factors that can lead to gravel progradation include a decrease in basin subsidence rates, an increase in the relative abundance of gravel supplied by the source area, an increase in rainfall and stream discharge (which enhances the ability of a river to transport gravel into a basin), and an increase in rate of relative sea-level fall. Hence interpretation of tectonic timing based on gravel progradation depends on which factor, or combination of factors, exerts dominant controls on the sedimentary systems.

3 AN OVERVIEW OF THE BASIN-FILLING MODEL

The model that we developed in Part 1 couples a linear diffusion equation for sediment dispersal with a simple mass-balance model based on selective deposition for grain-size partitioning and downstream fining. By deriving the diffusion equation from first principles rather than assuming it *a priori* we show that the diffusivity is mainly controlled by the average rate of water supply and the type of streams in the system (braided or single-thread). The four independent governing variables whose influence on basin sedimentation we examine are: input sediment flux, subsidence rate, gravel fraction in the sediment supply, and diffusivity, which is mainly controlled by water supply. The stratigraphic response of the basin to cyclic changes in all of these factors, except gravel fraction, depends on the ratio between the time-scale over which the changes take place and a time constant that is different for each basin. Based on scaling the equations, this characteristic time constant for basin response, which we call the *equilibrium time constant* (T_{eq}) is defined as

$$T_{eq} = L^2/v, \qquad (1)$$

where L is the basin length in the direction of sediment transport and v is the diffusivity, defined as

$$v = \frac{-8\langle q\rangle A\sqrt{C_f}}{C_0(s-1)}, \qquad (2)$$

where $\langle q\rangle$ is the long-term average water supply to the basin, A is a coefficient equal to 0.15 for braided streams and 1.0 for single-thread (meandering) streams, C_f a drag coefficient, for which we assume a value of 0.01, C_0 the sediment concentration in the bed, taken to be 0.6, and s the sediment specific gravity, taken to be 2.67. In physical terms, if a basin is allowed to evolve under constant rate and distribution of subsidence and sediment input, the surface topography (stream profile) will reach steady-state in a time of the order of T_{eq}. For basin-modelling purposes, however, the real importance of the equilibrium time constant is that the form of the basin response is determined by whether the time-scale of the imposed variations T is substantially greater than or less than T_{eq}. There is a continuous variation in the style of response between these two end-member cases, which we refer to as 'slow' and 'rapid' variations, respectively. Although equation (1) provides a precise definition of T_{eq}, this term is nothing more than a scaling parameter that provides a general criterion for distinguishing two broad classes of basin response; therefore its value need not be known precisely. This is fortunate because T_{eq} can, at best, only be approximated, given the large uncertainties in estimating palaeobasin length and palaeodiffusivity. The reader is referred to fig. 6 of Part 1 for a discussion of the sensitivity of the basin response to variation in T_{eq}. Although T_{eq} varies with basin length and diffusivity, equilibrium time would be of the order of 10^6 yr for a basin on the order of 100 km long, with moderate water supply (diffusivity).

The model results are discussed in detail in Part 1, but are briefly summarized here. A gradual increase in the rate of sediment supply (sediment flux), as might occur during an increase in tectonic uplift and erosion of a mountain belt, causes gravel progradation farther into a basin. At the same time, increased sediment flux yields *increased* vertical sediment accumulation rates coeval with gravel progradation. Therefore, a coarsening-upwards trend driven by increased sediment flux will have a positive correlation between grain-size and vertical accumulation rates (figs 2 and 3 of Part 1). We refer to this as 'flux-driven' gravel progradation.

In contrast, a slow reduction in basin subsidence rates leads to a decrease in vertical space produced per unit of time in which sediment can be stored. A reduction in subsidence inhibits the ability of sediment to aggrade, leading to a progradation of gravel farther into the basin. In this case, gravel progrades during a time of *decreasing* vertical sediment-accumulation rates (fig. 3 of Part 1). We refer to this model result as 'subsidence-driven' gravel progradation. If rapid subsidence results from rapid tectonic loading, then 'subsidence-driven' gravel progradation takes place during times of reduced tectonic activity, and these gravels are clearly not 'syntectonic' in origin.

Slow variation in diffusivity (controlled by precipitation and, therefore, average water discharge) has no effect on gravel distribution: although an increase in water supply will tend to transport gravel farther out into the basin, as the basin continues to subside over long time periods the gravel front must migrate back into the proximal basin in order to fill in the hole created by the subsidence. In contrast, rapid change of diffusivity, that is a change over a time period of much less than the T_{eq} for a given basin, produces thin, extensive gravel progradation similar in form to that generated by rapid variation in sediment supply (Part 1). In this case a 'rapid' increase in discharge with no concomitant increase in sediment flux will lead to erosion and reworking of the proximal basin deposits and deposition further out across the basin as the river systems adjust themselves by reducing their gradient. The same effect occurs when sediment flux is reduced relative to the rate of water supply, because in either case what matters is the flux of sediment relative to the flux of water. Notice that, in either of these two cases, 'rapid' variations in the fundamental parameters yield far more asymmetric stratigraphic geometries, greater distance of gravel progradation, and deeper unconformity development, than do 'slow' variations in these same parameters.

3.1 Sea level controls

We have not included changes in sea-level in the modelling so far, although in some situations it is an important control on alluvial sedimentation (e.g. Leopold & Bull 1978; Posamentier & Vail 1988). In the examples studied here, we do not consider sea-level variation an important influence because all sections represent alluvial systems located far upstream from associated shorelines, or were unattached to sea-level. Although fluvial response to sea-level changes is not well studied, these effects very likely decay upstream over a distance that depends on the period of the sea-level change or on the backwater distance of the river (Paola *et al.* 1991), or on the presence of bedrock knickpoints in the stream profile (Posamentier & Vail 1988). In addition, the stratigraphic sections studied would require many tens to many thousands of metres of relative sea-level change over periods of less than a few million years to account for the long-term progradation of gravel. This scale of change, especially the upper values, is difficult if not impossible, to ascribe to sea-level fluctations alone.

4 APPLICATION OF THE MODEL

From the above discussion it is clear that one way to apply and test the model is to compare vertical changes in grain size with sediment-accumulation rates. The model results can be applied to the rock record of sedimentary basins if sufficiently detailed grain-size information and age control are available, as well as enough information to allow calculation of the basin equilibrium time. Unfortunately, relatively few studies contain all of these essential data. Those that exist, to our knowledge, generally utilize magnetostratigraphy to establish age control of sufficient resolution to test the model. Of these we present the results for three examples to illustrate how the model can be used to interpret the cause of clastic progradation. In two of the three examples, calculated sediment accumulation rates have been corrected for differential compaction. Failing to correct for compaction would decrease accumulation rates for mudstones relative to conglomerates, which would tend to favor the 'flux-driven' interpretation for gravel progradation.

In our examples we are trying to determine the driving mechanism for coarsening-upwards sequences. The model results suggest that the expected form of the basin response depends on the time scale of the variation relative to the equilibrium time T_{eq}; thus we must begin by estimating T_{eq}. As discussed above, exact determination of T_{eq} is not required; the degree of sensitivity of the form of the basin response to variation in T_{eq} is discussed in Part 1. If T_{eq} is such that the variation in question is slow, then calculation of vertical sediment accumulation rates within the coarsening-upward sequence can be used to determine whether the dominant control is changes in sediment flux, subsidence or changes in supplied gravel fraction.

4.1 Case 1: Miocene sediments of the Andean foreland

High-resolution magnetostratigraphic studies have been completed in the Neogene deposits of the Bermejo foreland basin in NW Argentina (Jordan *et al.* 1988; Reynolds *et al.* 1990). Thrust faults within the Precordillera have affected both the subsidence and the sediment flux in a stratigraphic section exposed near Las Juntas, at present within the Precordillera thrust belt (Jordan *et al.* 1988). At Las Juntas, a thick (4780 m) sequence (Fig. 1) that coarsens upwards from siltstone and sandstone to conglomerate was deposited between 19 Ma and 10 Ma has been studied and used to determine tectonic timing in the adjacent thrust belt (Reynolds *et al.* 1990).

The equilibrium time for the Bermejo Basin

As we discussed above, we must first estimate the equilibrium time for the basin. Flemings & Jordan (1989) estimated diffusivity in the region for the interval 5 to 0 Ma by empirically fitting observed basin and surface geometry. This estimate of diffusivity is consistent with modern rainfall rates and catchment size and so is assumed to be at least roughly representative of Neogene conditions in this part of the basin. The depositional length (L; distance from mountain front to transverse trunk streams) of this part of the foreland basin for Neogene time is poorly known but ranges between 150 km and 300 km (T. E. Jordan, pers. commn.). Using a value for the basin width of 150 km and the empirically determined diffusivity of 0.02 km^2 yr^{-1}, we calculate an equilibrium time (T_{eq}) of about 1×10^6 yr. Using the maximum basin width of 300 km increases T_{eq} to 4.5×10^6 yr. Assuming that diffusivities estimated for the past 5 Ma are representative of all of Neogene time, then gravel progradation that occurred over times of roughly several million years or more represents deposition over periods longer than the basin equilibrium time.

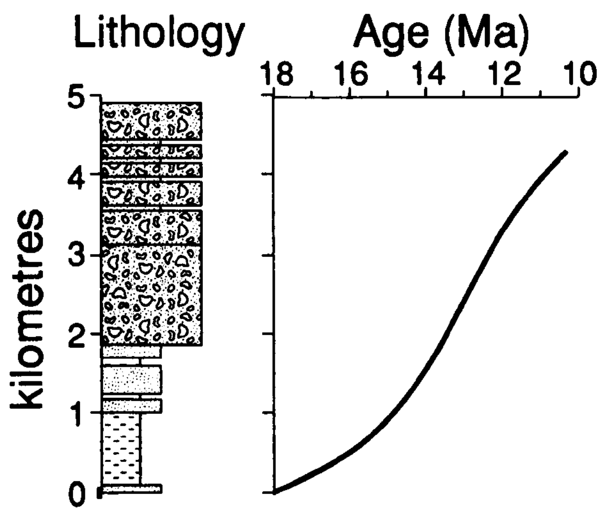

Fig. 1 Generalized lithological section at Las Juntas, Argentina with calculated sediment accumulation rates corrected for compaction. Lithologies are simplified to show dominant intervals of conglomerate, sandstone (stipple) and siltstone/mudstone (dashed). Data from Reynolds *et al.* (1990). Sedimentation rates are constrained by about 30 magnetic polarity reversals.

Results

Long-term vertical sediment-accumulation rates calculated from the magnetostratigraphy by Las Juntas, corrected from compaction, show a period of steady, but small (0.2–1 mm yr^{-1}) increase in sediment-accumulation rate followed by a fairly rapid increase and then a slower decrease upsection, as the section also becomes coarser grained (Fig. 1). The transition from dominantly sandy to dominantly gravelly deposition occurs within, but late in, the period of overall increasing sedimentation rate (Fig. 1). The overall increase in sedimentation rates coincident with progradation of gravel into the area took place over four million years. Since the coarsening-upward sequence (progradation) represents only half of the sedimentary cycle, the other half being the retrogradational phase, the minimum period for a complete cycle consistent with this increase in sedimentation rate is about eight million years. This variation is, therefore, clearly 'slow' compared to the longest reasonable equilibrium time estimated above. The positive correlation between grain-size and vertical sedimentation rate suggests that the observed upward coarsening is flux-driven; the time lag between the increase in sedimentation rate and the coarsening suggests that the gravel front was some distance upstream of the measured section when the sediment flux began to increase. While other controlling factors may have changed as well, the only way the model can generate a positive correlation between accumulation rate and grain-size is if sediment flux was the primary controlling factor that increased during the time of deposition.

The most likely cause for this flux-driven sedimentation is tectonic uplift in the source area, consistent with the interpretation of Reynolds *et al.* (1990) that the gravel progradation is syntectonic. However, we note that uplift is not the only possible explanation for an increase in sediment flux – changes in source-area lithology, precipitation rate, drainage pattern or vegetation type could affect the sediment flux as well. Shorter-term periods of rapid sedimentation superimposed on the long-term accumulation rates that are shown by Reynolds *et al.* (1990) are less well constrained by the data, have time scales close to or less than that of the equilibrium time for the basin and likely represent periods of rapid progradation of the gravel front due to short-term events that generated 'rapid' responses.

4.2 Case 2: Plio-Pleistocene sediments of the Himalayan foreland

Burbank *et al.* (1988) present a superbly documented example of gravel progradation in the Himalayan foreland Basin. A series of magnetostratigraphic sections from the Siwalik Group in the NW Syntaxis of Pakistan were measured at distances of between 65 km and 110 km from the leading edge of the Main Boundary Thrust (Raynolds & Johnson 1985; Burbank *et al.* 1986, 1988). These sections were deposited between 3 Ma and 1 Ma and contain

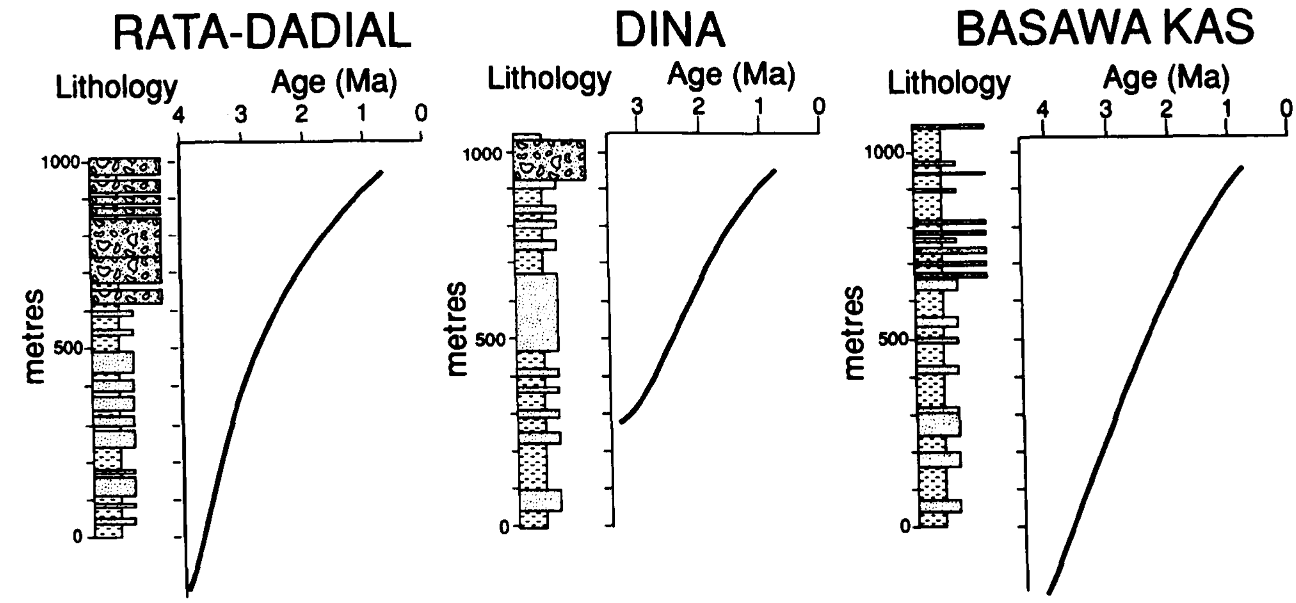

Fig. 2 Generalized lithological sections of the Siwalik Group in the NW Himalaya Foreland showing calculated sediment accumulation rates corrected for compaction. Data from Raynolds & Johnson (1985) and Burbank *et al.* (1988). Symbols as in Fig. 1. The three sections are shown from (left to right) proximal to distal and span a total transverse distance of approximately 40 km. Sedimentation rates constrained by 7–10 magnetic polarity reversals.

coarsening-upward sequences that grade upward from fluvial molasse sandstones into conglomerates (Fig. 2). From these sections Burbank *et al.* (1988) demonstrated that the gravel front prograded from the thrust belt out across the basin at a rate of roughly 30 km Myr^{-1} after an episode of thrusting between 4.5 Ma and 4 Ma. The progradation of the gravel generally coincided with a reduction in accumulation rate over times across the basin. Calculated vertical sediment accumulation rates show a general decrease that takes place at the same time as, or before, the overall grain-sizes increase up into gravels (Fig. 2). As Burbank *et al.* point out, gravel progradation that took place coincident with a reduction in vertical sedimentation rates appears to be a clear example of subsidence-driven progradation as defined in Part 1. This is corroborated by the fact that the lag time between the decrease in local sedimentation rate and the first appearance of the gravel increases down the transport system, consistent with progradation of the gravel front through time. The high resolution of the age data from this system makes it possible to examine the cause of gravel progradation in more detail and compare it with the model results.

In Part 1 we showed that subsidence-driven progradation is strongest if the time scale of variation is long compared to T_{eq}. Thus our interpretation of the progradation as subsidence-driven would be substantially weakened if the time scale of variation were much less than T_{eq}.

The equilibrium time for the Himalayan foreland

Based on the flexural rigidity of the Himalayan lithosphere (5×10^{24} to 10^{25} N·m; Karner & Watts 1983), the approximate length of the foreland basin is 250–300 km. However, throughout the period of time of interest to us, the drainage system comprised a longitudinal trunk river fed by transverse feeder systems. The gravel progradation took place within the transverse river systems, so for L we use the distance from the mountain front to where the river joins the major trunk valley. This distance is considerably less than the entire basin length. We will assume a maximum value of 200 km for the length of the depositional basin, although the true length may have been significantly less (D. W. Burbank, pers. comm.), which would greatly reduce our calculated basin equilibrium time.

To estimate the diffusivity of the fluvial system that fed the basin, we must first decide whether the system was braided or single-thread; this sets the variable A in equation (2). Published observations (Johnson *et al.* 1985) suggest that the streams responsible for the basin-fill deposits were individual sandy channels with mud banks that resulted in fining-upward sequences. However, the coarse gravels that prograde across the basin are described as 'alluvial fan' deposits (Raynolds & Johnson 1985), probably of braided-stream origin (R. G. Raynolds, pers. comm.).

The final element needed to determine the diffusivity of the river system is an estimate of q, the rate of water supply to the basin. In the absence of any better method, we will use the product of rainfall rate and catchment length to constrain q. The catchment length for the Siwalik Group exposed in the Potwar Plateau in the Northwest Syntaxis is not precisely known. On the basis of the composition of the gravels the catchment included at least the Pir Panjal Range, some 150 km distant, and possibly the ancestral drainage headed much farther away in the Great Himalayan Range (D. W. Burbank, pers. comm.). We assume a catchment length of 200 km but will examine the sensitivity of our results to uncertainties in basin and catchment length below.

In the absence of detailed paleoclimate studies in this region, there is no simple way to estimate the rainfall rates in the river catchments during late Pliocene through Pleistocene time. We use the present average rainfall rate in the catchment area upstream of where the gravel data have been obtained. The rainfall during the time period of interest may be somewhat less than today, but a value of ~ 1 m yr^{-1} is consistent with what little is known of the climate during the time of deposition (D. W. Burbank, pers. comm.) and is approximately the present rainfall value.

Using the values above we calculate an equilibrium time of 2×10^6 years for these deposits of the Himalayan foreland using equation (2). Note that any uncertainty in the diffusivity translates linearly into an uncertainty in T_{eq}, but the effect on T_{eq} of uncertainty in depositional length of the basin is doubled because T_{eq} depends on the square of the length. Thus a moderately large uncertainty of 25% in either rainfall or catchment length (for example, if the true catchment length in this area was between 150 km and 250 km) leads to a 25% uncertainty in the calculated T_{eq} which is small (in this example ± 0.5 Myr). In the Himalaya case, our estimate of the catchment length is probably too low; if so, then our estimate of T_{eq} is also too low and thus, our predicted stratigraphic response is somewhat 'slower' than what should actually appear in the rock record. In contrast, an uncertainty of 25% in basin length (L) would lead to 50% uncertainty in T_{eq} – which in this example is still relatively small (± 1.0 Myr) – since we are examining stratigraphic sections that represent several million years of deposition. Fortunately, the depositional length of the basin is usually better constrained because the sedimentary record of the basin fill is preserved. In general, however, an increase in catchment length or decrease in length of the depositional basin would decrease the calcualted equilibrium time.

Results

The observed coarsening-upward and decrease in sedimentation rate took place over about two million years; therefore, the minimum period of a complete cycle corresponding to this change is four million years. This period is significantly longer than the estimated T_{eq} for the basin, so we consider the gravel progradation to be a 'slow' response to changes in the driving controls. Gravel progradation coincident with a reduction in vertical sedimentation rates appears to be a clear example of subsidence-driven progradation, consistent with the interpretation of Burbank *et al.* (1988). This is not to say that other factors were not influencing the progradation of the gravel, only that subsidence is the major control.

An interesting feature of the Himalayan data, stressed by Burbank *et al.* (1988; 1989) is that, assuming that the gravel front began prograding out from the Main Boundary Thrust when the thrust became active at 4–4.5 Ma, then the average migration speed of the front would have had to be 40–70 km Myr^{-1} for the gravel to have reached the proximal edge of the study area by 3 Ma. Thus it would seem that the front migrated most rapidly during the early stages of thrusting, when high subsidence rates might have been expected to pond the gravel near the thrust front (Heller *et al.* 1988). This apparent rapid progradation could have resulted from either of two factors: (1) a change in one of the other controlling parameters that overwhelmed the effect of the increase in subsidence rate, such as an initial increase in sediment flux associated with beginning uplift of the thrust belt, or (2) an early 'rapid' non-equilibrium response that took place as the basin was establishing a new transport system, which occurs over a time-scale less than T_{eq}. In either case, where data are available in the Siwalik Group the progradation is subsidence-driven. This, coupled with the early phase of apparently rapid progradation, suggests that the major control on gravel progradation in this basin changed over time.

4.3 Case 3: Plio-Pleistocene St David Formation of Arizona

A succession of gravel tongues are present in the upper part of the St David Formation of the San Pedro Valley of southern Arizona (Fig. 3; Lindsay *et al.* 1990a, b). These gravel units were likely deposited over very short periods of time, as discussed below, and so probably represent an example of 'rapid' gravel progradation. The St David Formation was deposited between Pliocene and Pleistocene time in an extensional basin about 20 km wide. Age is tightly constrained in the middle to upper members of the St David Formation (3 to 0.6 Ma) by vertebrate faunas (Lindsay *et al.* 1990a) and magnetostratigraphy (Johnson *et al.* 1975). The upper member of the St David Formation consists of 6 or 7 well-defined gravel tongues separated by paleosols that were deposited over a time interval of 0.85 Myr (G. A. Smith, pers. comm.). As opposed to the previous examples, no compaction corrections have been applied to the St David Formation, so that sedimentation rates shown on Fig. 3 are minimum values, especially for the finer-grained rocks. As discussed above, a reduction in sedimentation rate for fine-grained rocks tends to favour the likelihood of sediment-flux driven progradation.

The equilibrium time for the San Pedro Valley

As before, to determine what parameters exerted primary control over the progradation of gravel into the basin, the equilibrium sedimentary response time for the basin must be estimated first. To do this we must estimate diffusivity for the basin, which we again relate to the rate of precipitation in the basin and the catchment length. In this case, the problem of calculating palaeodiffusivity is further complicated by the possibility that variations in past precipitation brought by climate changes may have been the primary driving force for gravel progradation within the formation (Lindsay *et al.* 1990b). It is not clear what precipitation rates were during deposition of the St David Formation. However, at present, the climate is arid and appears to have been generally the same over the last few million years (Melton 1965; Breckenridge 1978). Therefore, for the purposes of scaling we use a value of 200 mm yr^{-1} for average precipitation rate during the period of deposition of the St David Formation. The uncertainty in the estimated equilibrium time is linearly dependent on uncertainty in this parameter.

The gravel deposits of the St David Formation were transported into the San Pedro Valley largely by streams that flowed laterally from the valley margin; these clasts mixed in with the sediments carried by the longitudinal river system that flowed along the valley axis (Gray 1967). The length of the basin (L) at the time of deposition was essentially that of today (Gray 1967), thus the appropriate basin length scale is the present half-width of the basin (10 km). We assume that the same length scale applies to the catchment basin, although the catchment may have been somewhat smaller. Finally, the sedimentology of the gravels (G. A. Smith, pers. comm.) suggests that the braided-river form of the diffusivity is appropriate. Combining these values, we compute a characteristic diffusivity of 2×10^{-4} km^2 yr^{-1}, which gives a response time (T_{eq}) for the basin of 5×10^5 yr. Since at least five thin tongues of gravel have prograded into the basin over a period of 0.85×10^6 yr (Fig. 3) we infer that the equilibrium time is much greater than the average period of each gravel cycle (*c.* 1.3×10^5 yr; G. A. Smith, pers. comm.), so that these are 'rapid' variations. Note that if we have overestimated the palaeo-rainfall rate, this would increase T_{eq} and strengthen our interpretation that these are rapid variations. If we have underestimated the rainfall then T_{eq} would be reduced. It would require an increase in the average paleorainfall rate of about a factor of 3, to 600 mm yr^{-1}, to make the observed cycle period close to the basin equilibrium time.

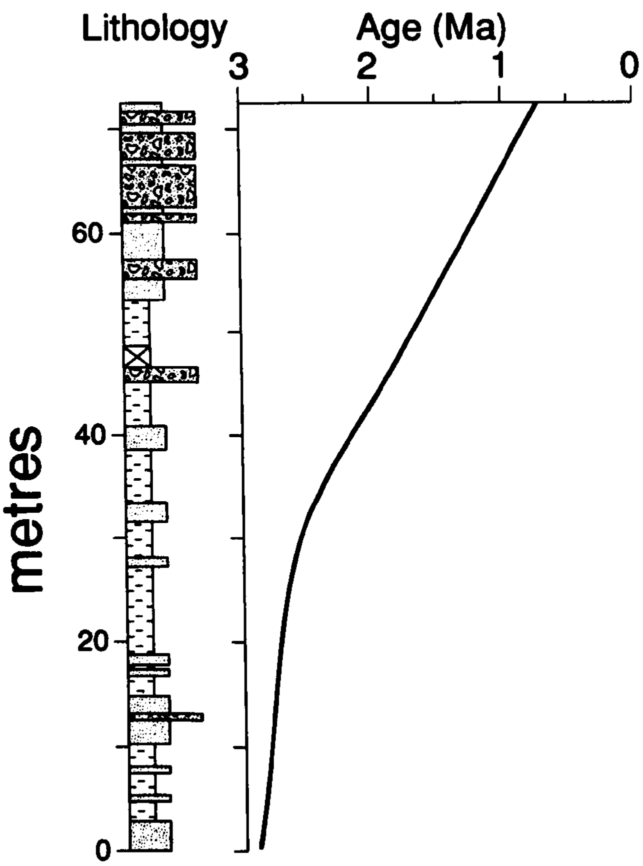

Fig. 3 Generalized lithologic section of the middle and upper St David Formation in the San Pedro Valley of southern Arizona with caculated sediment accumulation rates not corrected for compaction. Data from Lindsay *et al.* (1990a, 1990b) and Johnson *et al.* (1975). Sedimentation rates constrained by 5 magnetic polarity reversals.

Results

Lindsay *et al.* (1990a, b) have stressed that several lines of evidence suggest that the gravel cycles of the upper part of the St David Formation formed during an interval of tectonic quiescence, and thus were probably climatically controlled. In general an interpretation of climate control is consistent with, and is in fact reinforced by, the model results of Part 1. The equilibrium time-scale calculated above suggests that the gravel cycles are too rapid to be subsidence-driven. Our model results suggest that rapid changes in subsidence rates leave little evidence of gravel progradation in the stratigraphic record.

Furthermore, the abrupt change between conglomerates and mudstones seen in the upper part of the St David Formation (Fig. 3) is consistent with the model results for rapid variations in either sediment flux or diffusivity. Gravel progradation forced by short-term changes in these factors is abrupt across most of the basin (see fig. 4 of Part 1). In contrast, with slow variations in these parameters the gravel front migrates slowly and continuously, and vertical change in grain-size at any given location in the basin is predicted to be more gradual.

We note, however, that the overall coarsening of grain-size from the middle to the upper parts of the St David Formation spans an interval of at least 2 million years and involves a decrease in sedimentation rate of about a factor of 2 (Fig. 3). Since the time span involved in the overall coarsening-upwards sequence is long compared to the calculated equilibrium time, it would seem that gravel progradation on the scale of the entire sequence is likely due to a long-term decrease in rate of subsidence across the basin. Even though the section has not been corrected for compaction, any correction would tend to increase sedimentation rates in the finer-grained units, further exaggerating the inverse relationship between grain-size and sedimentation rate shown on Fig. 3. This result is broadly consistent with the interpretation of Lindsay *et al.* (1990b) of tectonic quiescence in the area during deposition of these units, although their interpretation is that tectonic activity stopped well before the initiation of gravel deposition anywhere in the system. This apparent conflict can not be resolved here, but may relate to ongoing, albeit diminishing, regional subsidence despite the absence of local tectonism or, less likely, a more complex interaction due to changes in more than one variable such as a strong increase in relative abundance of gravel coupled with a strong decrease in sediment flux. Nonetheless, the overall upward coarsening in grain size in the unit appears to be most consistent with model results of 'subsidence-driven' progradation, yet the superimposed short term pulses of gravel progradation that comprise the sequence are likely due to rapid changes in either sediment flux, rainfall, or both.

We have generated model simulations using the estimated equilibrium time for the San Pedro Basin (Fig. 4), to determine the relative progradation of the gravel front due to short-term changes in diffusivity superimposed on a long-term decrease in basin subsidence rates. These model results show that a short distance out into the basin the stratigraphic record would show an overall progradation of gravel into the basin that consists of intermittent pulses of gravel progradation associated with the short-term variations. The extent of progradation associated with short-term (rapid) pulses is much greater than that expected for long-term (slow) progradation if the imposed variations are of comparable magnitude. Although sedimentation rates, shown by the distance between successive time lines (Fig. 4), vary during short-term cycles, they decrease upsection overall due to the influence of decreasing subsidence rates.

The model results support the suggestion of Lindsay *et al.* (1990a, 1990b) that the short-term gravel progradation cycles can be explained by climatic change. Climatic change could precipitate these changes by either changing the diffusivity of the stream systems by varying the rate of water supply, and/or by changing the flux of sediment brought to the basin by varying the rate of erosion in the source area. The results of the general model (Part 1) suggest that the sedimentary responses to variations in either sediment or diffusivity are nearly identical, so that independent evidence would be needed to distinguish between them.

5 DISCUSSION

The application of the model developed in Part 1 to a variety of sedimentary basins shows that model results can be used to help interpret the origin and significance of clastic progradation in alluvial sequences. In each of the three case studies examined, application of the model was made possible by the availability of high-resolution, primarily magnetostratigraphic, age control within the sedimentary sequence. The key to interpreting the cause of clastic progradation in a basin is the determination of the 'equilibrium time' in the base (T_{eq}). The equilibrium time, as discussed in Part 1, represents the characteristic response time required for a sedimentary sequence to reach equilibrium in response to a change in one of its controlling parameters. As discussed in Part 1, coarsening-upwards sequences deposited over times much shorter than the equilibrium time tend to record the effects of changes in the sediment surface, while the long-term balance between sedimentation rate and subsidence tends to be the primary cause of coarsening-upward sequences deposited over time periods longer than the equilibrium time. For example, we expect that the present distribution of alluvial fans in Death Valley reflects a combination of the long-term interplay

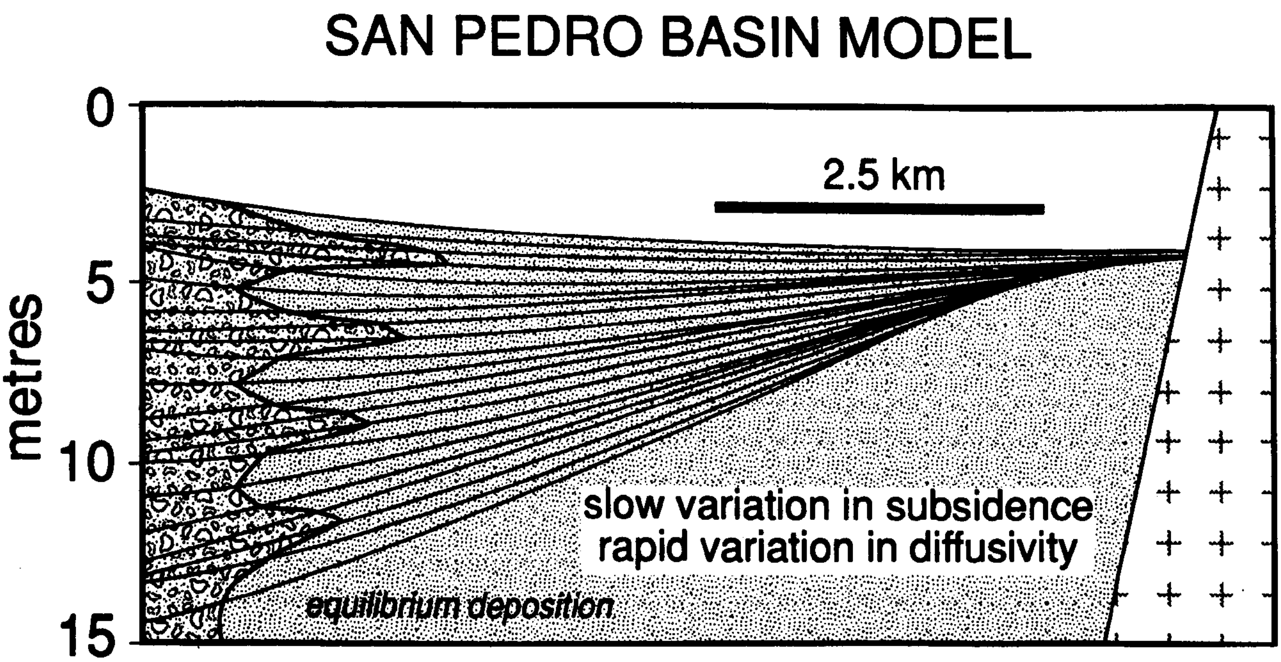

Fig. 4 Model result for gravel progradation into an asymmetric basin undergoing rapid variation in diffusivity superimposed on an overall slow decrease in subsidence rates. Time lines are drawn every 5×10^4 yr. Symbols as in Fig. 1. Sediment derived from the left; subsidence is asymmetric, increasing to the left. Values used for model run are: $T_{eq} = 5 \times 10^5$ yr; $n = 2 \times 10^{-4}$ km^2 yr^{-1}; basin length = 10 km; subsidence rate = average sedimentation rate = 0.03 km^2 Myr^{-1}; gravel fraction = 30% of total sediment supply; capture ratio = 0.9; diffusivity varies by an amplitude of 0.5 and cycles over a time period of 10^5 yr; subsidence varies by an amplitude of 0.8 and cycles over a time period of 2×10^6 yr. See Part 1 for explanation of variables used in the model.

between sediment supply from the flanking ranges and subsidence of the valley floor as well as the recent climatic conditions, especially precipitation rate, in the region.

Of the basins discussed in this paper, only one case, from Las Juntas in the Andean Foreland Basin, shows a positive correlation between grain-size and vertical sedimentation rate, suggesting gravel progradation was driven by an increase in sediment flux. Two of the cases discussed above, the Siwalik Group of the Himalayan Foreland and the long-term coarsening trend of the St David Formation in southern Arizona, show inverse relationships between grain-size and vertical sediment-accumulation rate, indicating gravel progradation due to a long-term decrease in rate of subsidence in the basin. Lastly, the short-term progradation of gravel seen within the upper part of the St David Formation is most likely due to rapid changes in either sediment flux or diffusivity (i.e. water supply in the river systems), either of which is consistent with an interpretation of climatic control.

It is clear from the examples discussed above that (1) more than one primary control can be acting in different parts of a basin at the same time, (2) the dominant control affecting a specific stratigraphic sequence can change through time, and (3) different controls can be at work in the same stratigraphic sequence at the same time but are acting over different time scales. As an example, the St David Formation shows quite clearly that even though the periodic, short-term progradation of gravels in the section likely resulted from non-equilibrium response to changes in sediment flux and/or diffusivity, the overall coarsening upwards of the entire stratigraphic sequence may record a general long-term reduction in subsidence rates over the same time period.

5.1 Tectonic subsidence versus sedimentation rate

The model we have developed includes subsidence as one of four primary controls on gravel progradation. However, in the sedimentary record the only information available is sedimentation rate, which is not necessarily equal to the subsidence rate. Application of our model, however, does not require that the subsidence rate be known independently; the key observation for applying the model is the relationship between sediment-accumulation rates and grain-size trends. Specifically, an inverse relationship between grain-size and vertical sedimentation rate signifies that subsidence exerts the major control on lithofacies distribution. As we pointed out in Part 1, this is true even for basin configurations for which sedimentation rate and subsidence rate are inversely related. In real basins, subsidence can be caused by compaction of underlying sedimentary units, isostatic adjustment to loading by the sediment fill, and tectonic subsidence. There is nothing in the field data that uniquely requires that tectonic subsidence be the cause of changes in vertical accumulation rates. However, for the following reasons, we believe that tectonic subsidence was probably the main cause for major changes in subsidence within the basins studied.

Compaction of underlying sedimentary units can cause basin subsidence without there being a tectonic component. In general these effects are secondary, except in cases where very thick accumulations of sediment occur, such as in passive-margin sequences (Reynolds *et al.* 1991). In the examples discussed here, pre-existing uncompacted sediment thicknesses are generally small and probably not a major contributor to subsidence.

The isostatic effect of sediment loading leads to the subsidence of a basin under the weight of its own sedimentary fill. Local isostatic loading increases subsidence by a factor of about 2.5, but regional isostatic (flexural) effects can greatly increase or decrease this value. These isostatic effects always occur during basin filling, no matter if sedimentation is the result of changes in sediment flux, subsidence or some other cause. Therefore, sediment loading and compaction have real, and in some cases significant (Reynolds *et al.* 1991), effects on subsidence. However, these effects tend to amplify tectonic subsidence and in most cases are second-order controls on the subsidence.

Thus, in the examples discussed here, and as may be generally true for thick accumulations of alluvial sediments over time periods of the order of a few million years or more, tectonics likely exert the major control on basin subsidence.

5.2 Syntectonic versus antitectonic gravel progradation

As discussed earlier, the classical scenario for syntectonic sedimentation is the progradation of gravel into a basin as a result of increased sediment flux due to tectonic uplift and erosion of the source area. However, to the degree that subsidence rates are coupled to tectonic activity, perhaps due to lithospheric flexure adjacent to tectonic loads (Angevine *et al.* 1990), then the progradation of gravel due to a decrease in basin subsidence rates cannot be interpreted as 'syntectonic', but rather as coincident with a time of reduced tectonic activity, i.e. 'antitectonic'. In many cases, a better record of accelerated tectonic activity in subsidence-driven settings is an increase in vertical accumulation rates in the proximal part of the basin.

It is clear that subsidence-driven sedimentation can be a major control on gravel progradation, even in tectonically very active regions. For example, even though the mountains of the Himalaya discharge large volumes of sediment into their associated foreland basin, and this sediment supply is augmented by longitudinal sediment transport systems (Burbank *et al.* 1986), it is still the variations in subsidence rate that apparently exert the major influence on gravel progradation into the basin where data are available. Assuming that subsidence is due to thrust loading along the Main Boundary Thrust, then the prograding gravels record times of relative tectonic quiescence and are not 'syntectonic' in origin.

5.3 Subsidence as a major control on long-term gravel progradation

Two of the three cases described here show that long-term changes in subsidence rate exerted the major control on clastic progradation within the observed stratigraphic sequences. These few examples can be augmented by several others that are suggestive but do not have sufficient data available to analyse the cause of gravel progradation. One such data set comes from the Ridge Basin, a strike-slip-related basin of Miocene to Pliocene age in southern California (Crowell 1974). Magnetostratigraphic study of this basin by Ensley & Verosub (1982) shows an inverse relationship between grain-size and vertical sediment accumulation rates (their fig. 10), consistent with an interpretation that coarse progradation was primarily subsidence driven. Similarly, a study of Plio-Pleistocene deposits of Pine Valley basin, of northeastern Nevada, an asymmetrically-subsiding half graben, shows that gravels have prograded furthest into the basin where subsidence rates have been the slowest (Gordon & Heller in press). Lastly, a recent study of sediment accumulation in the Alberta Foreland Basin of Cretaceous age in western Canada (Underschultz & Erdmer 1991) shows that for most of the basin's history times of most rapid accumulation were also times of relatively fine-grained depostion (their fig. 7). This suggests that either sedimentation rates and rock types were controlled by sequential erosion of very different, but regularly interlayered, source rocks in the adjacent Columbian thrust belt, or, more likely, that subsidence exerted the major control on clastic progradation over a time-scale of a few million years.

If, as more data are obtained, the theory that subsidence exerts the major control on clastic progradation in stratigraphic sections over periods of a few millions of years holds true, then there are important implications for the interpretation of large-scale basin-filling sequences. The most significant is that for stratigraphic sequences of sufficient duration ($> T_{eq}$), changes in subsidence rate dictate the overall stratigraphic response, and therefore, changes in sediment flux are less pronounced over these time periods. This may be because in many basins subsidence occurs as an essentially immediate elastic response to tectonic loading (e.g. Watts & Ryan 1976; Angevine *et al.* 1990). Therefore, to the extent that tectonic growth of mountain belts takes place over periods of a few million years, such as seen in thrust belts (e.g. Wiltschko & Dorr 1983; Burbank & Raynolds 1988), then basin subsidence rates will vary over similar time periods. In contrast, rates of sediment supply may vary over a wide range of time periods, but once mountain belts are uplifted, they tend to maintain themselves as sediment sources over long periods of time as isostatic uplift compensates for erosional loss of mass (Stephenson & Lambeck 1985).

6 CONCLUSIONS

Our primary conclusion is that the theoretical model developed in Part 1 seems to be generally applicable to the stratigraphic record. Specifically we can identify 'slow' versus 'rapid' variations in gravel progradation in a variety of basins using the quantitative criterion developed in our model. The observed form of the basin response is consistent with the model predictions, and in our examples is, for the most part, consistent with the existing interpretations. The key to interpreting the observed gravel progradation is calculation of the basin equilibrium time (T_{eq}), which exerts a major influence on lithostratigraphic response of a basin to changes in the governing extrabasinal controls such as sediment flux, sorting, diffusivity and subsidence.

The concept of 'syntectonic' conglomerate implies that gravel progradation results from an increase in uplift and erosion rates in mountain belts—in our terminology 'sediment-flux-driven' progradation. We have shown that, at least in some cases, the primary driving mechanism can be evaluated, and that significant gravel progradation occurs due to other factors. Assuming that tectonic activity is directly related to subsidence rates, the results of our model should be useful in the interpretation of tectonic timing from the stratigraphic record. Available data from a limited number of basins suggests that subsidence-driven progradation is a major, if not *the* major, cause of gravel progradation within basins over stratigraphic intervals greater than the equilibrium time—for many basins a few million years or more.

Lastly, we hope that the examples presented in this paper make clear the fundamental importance of field data in using and evaluating models such as the one presented in Part 1. In addition, since quantitative models require quantitative data, high-resolution chronostratigraphic studies are of paramount importance to testing and fine tuning this and other theoretical models of basinal and stratigraphic development. The goal of this paper has been to see how the model results compare with observations of deposits in real sedimentary basins, within the limitations of existing data bases. This exercise shows that, for the most part, the existing data produced from qualitatively based studies are insufficient to refine even very simple models such as those we have developed. Clearly there is a strong need for new studies specifically designed around the requirements of model testing and refinement.

The generation of quantitative models to explain aspects of the stratigraphic record is an essential and potentially powerful tool when used in conjunction with other basin-analysis techniques. Models of any kind, quantitative or not, rarely answer fundamental questions by themselves, but, instead, provide a framework through which the geological record can be viewed and interpreted. Given that the stratigraphic record is far too complex to interpret intuitively, one must bring to bear every available means of interpretation. Only by combining the strengths of stratigraphic and sedimentological studies with geophysical analyses and well-grounded modelling approaches can accurate interpretations of the sedimentary record be made. The combination of these techniques along with other independent geological observations can shed light on the relationship between geological controls and the stratigraphic record.

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