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The role of erosion and deposition in the construction of alluvial fan sequences in the Guadix Formation (SE Spain)

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Abstract

A study is made of a Pliocene alluvial fan in the Guadix Basin (Betic Cordillera, Spain). On the basis of the characteristics of the sequences and the position of the Arroyo de Gor section within the fan, a model is proposed to explain the sequential trends, taking into account the importance of the erosional processes associated with lateral displacement according to a pendular pattern of a fluvial system made up of a trunk channel and lateral, secondary channels. Lateral migration of channels in a constant direction is a consequence of the preferential attachment of bars to one bank, as shown by recent systems. Change in the direction of migration is caused when channels reach the basin margin or the opposing slope of an adjoining fan. This can also occur if tilting towards the centre of the basin takes place.

According to this model, a marginal position in a fan would be recognised by a series of fining and thinning upward (FU + ThU) sequences delimited by clear erosion surfaces. The backsets of the bars accumulated in the channels invariably dip towards the centre of the fan. A central position is characterised by a higher number of FU + ThU sequences not reaching completion at the top (and, therefore, with a lower proportion of overbank facies). The backsets dip alternately in opposite directions. This model may also be used for the evolution of the sediment supply/subsidence ratio in a particular zone of a basin.

Introduction

The episodic character of alluvial megasequences has been demonstrated in many cases (e.g. Allen 1974, Steel et al. 1977, Heward 1978, Bluck 1980, Ruegg 1991). The phenomenon is mostly related to climatic or tectonic cyclical variations, but in the analysis of continental basins a factor to be taken into account is that even under ideal conditions for the accumulation of fluvial sediment the dynamics of the rivers causing deposition can set the sediment in movement again, as the fluvial medium constitutes the transference system of materials towards marine, lacustrine or coastal environments (Friend 1989).

This paper emphasises the role of erosional processes as a fundamental factor in developing cyclical repetitions in the stratigraphic record of an alluvial fan. The importance of erosion is illustrated by the Guadix Formation, a Plio-Pleistocene alluvial complex in the Betic Cordillera (southern Spain). A dynamic fan model combining depositional and erosional processes is proposed to interpret the sequences. This model may be usefully applied to other ancient examples and also in economic geological studies.

Geological background

The Guadix Basin is situated in the Betic Cordillera (Spain), one of the mountain chains formed during the closure of the Tethys (Sanz de Galdeano 1990). It is located on the contact between the two main geodynamic domains of the cordillera, traditionally known as the External Zones (representing the deformed South Iberian palaeomargin, e.g. Fallot 1948, García Hernández et al. 1980, Geel et al. 1992, Martín

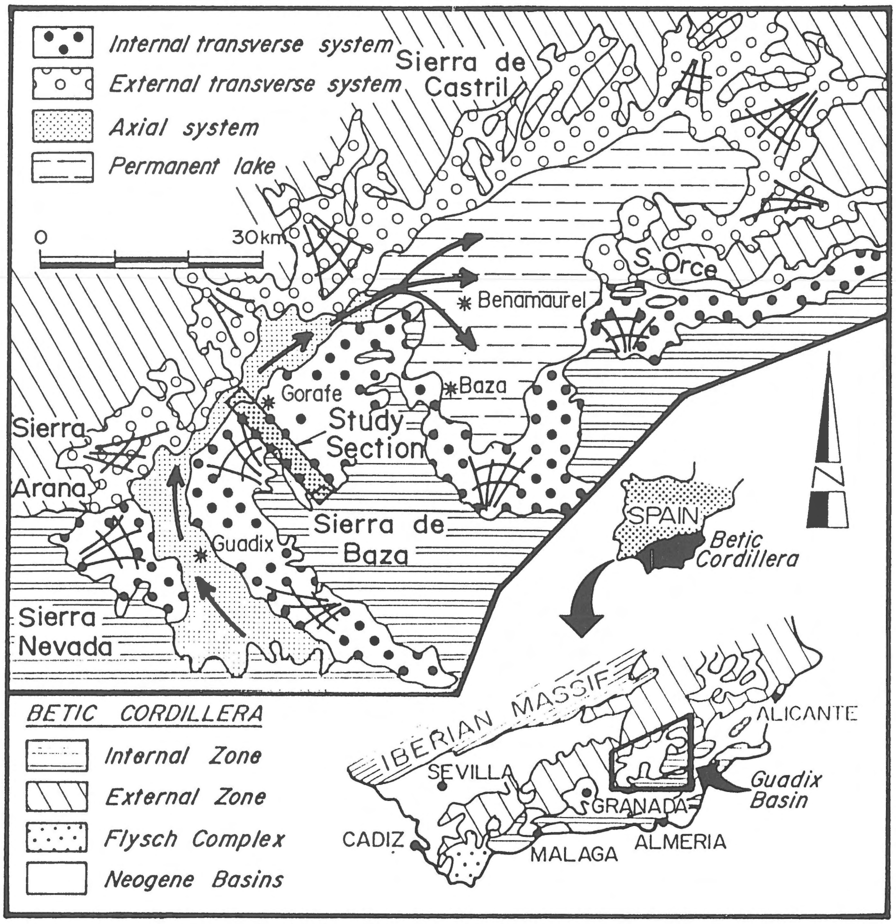

Fig. 1. Geological setting of the Guadix Basin in the Betic Cordillera and palaeogeographic sketch map of the basin for the Pliocene (with location of the Arroyo de Gor section and of major alluvial fans). Arrows indicate the direction of the master drainage (Axial system).

Algarra et al. 1992) and the Internal Zones (resulting from the deformation and emplacement of part of the Alboran domain, Balanyá & García Dueñas 1988) (Fig. 1). The marine infill of the basin started during the Late Miocene (Rodríguez Fernández 1982) and the continental infill began towards the end of the Miocene and continued throughout the Pliocene and Pleistocene (Viseras 1991). The continental infill consists of alluvial sediments, known as the Guadix Formation (Drasche 1879, Vera 1970), and of lacustrine sediments which developed especially in the eastern sector of the basin (Fig. 1). The most recent alluvial unit filling the basin, which appears to overlie the alluvium treated in this paper, corresponds to an extensive braidplain with sedimentary characteristics depicting a strong control by the Late Pliocene and Pleistocene climatic variations. Most of the features of this final unit resemble those described for outwash sandur deposits (Boothroyd & Ashley 1975, Ruegg 1977, Church & Gilbert 1979).

Three synchronous drainage systems can be distinguished in the Guadix Basin on the basis of sedimentological characteristics and the composition of clasts and fine sediments (Viseras & Fernández 1989, Viseras 1991): a longitudinal axial system and two fan systems running transversely to the palaeogeographic axis of the basin. The latter will be referred to as internal and external, respectively, in allusion to their main source areas (Internal and External Zones, respectively, Fig. 1, Viseras & Fernández 1992).

This paper focuses on a Lower Pliocene alluvial fan of the internal transverse system, which crops out extensively throughout the Arroyo de Gor section. These rocks present most of the diagnostic criteria of alluvial fan deposits as given in the classical models (e.g. Bull 1972, Boothroyd & Ashley 1975, Heward 1978, Rust 1978, Nilsen 1982).

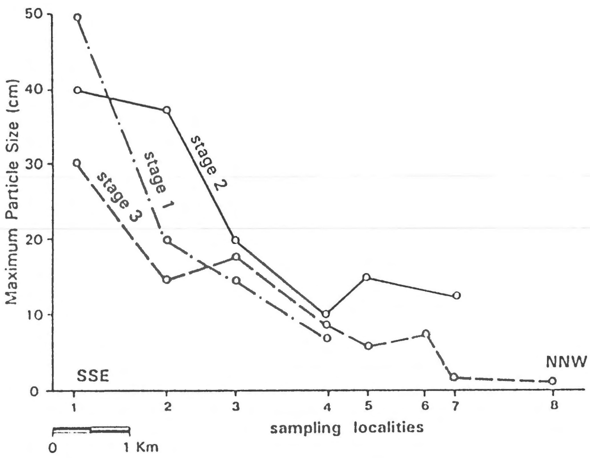

Fig. 2. Maximum Particle Size (MPS) for the three stages of fan growth from a proximal (SSE) to a distal (NNW) position in the Pliocene of the Arroyo de Gor section (sampling localities shown on Fig. 10). The younger the stage, the less steep the gradient of the MPS line. This is related to a progressive increase of the fan radius.

Main characteristics of the alluvial fan analysed

General description

It is not our intention to present a detailed analysis of the sedimentological characteristics of the alluvial fan, as this has been the subject of previous publications (Viseras et al. 1989a, b, 1993, Fernández et al. 1991, Viseras 1991). We describe only its general features, paying particular attention to data relevant to the development of the model.

The Lower Pliocene fan is made up of three stratigraphically superposed units delimited by palaeosol horizons. Previous sedimentological analysis indicates that these units represent three stages of growth of the same fan. It is also found that the fan radius increases progressively from approximately 6 km in stage 1 (lowermost) to around 9 km in stage 3 (uppermost), as it is possible to mark the distal boundary of the fan where it joins the axial system, with clearly different compositional and sedimentological characteristics (Viseras 1991, Viseras & Fernández 1989, 1992).

Throughout the fan development there was a progressive decrease in local subsidence, as indicated by the progressively lesser deformation of the base of the younger units, and by a decrease in sedimentation rate from approximately 3.5 to 1.5 cm/1000 years (Viseras 1991). In addition, alluvial material lying against the substratum of the basin shows a progressive unconformity, which implies that the older beds underwent tilting towards the centre of the basin.

Figure 2 shows the proximal–distal change in maximum particle size (MPS) in the channel deposits for the three growth stages. The general slope of the lines decreases in the more recent stages, suggesting that the rivers had a progressively longer evolution as has been described in other examples (e.g. Boothroyd & Ashley 1975, Bluck 1987, Dawson 1988, Heller & Paola 1992, Paola et al. 1992). This corroborates our interpretation that the fan radius increased through time.

Figure 3 shows the relative proportion of channel deposits to overbank deposits established for each of the three growth stages at five points along the section (sampling stations 1–5 in Fig. 2). In all three levels the proportion of overbank deposits increases towards distal positions. This proportion also rises progressively in the upper levels at the same sampling station. This could either indicate a retrograding of the fan during its growth, or a reduction in radius, both of which are contradicted by the data presented above. The model must explain this apparent contradiction. It must also explain why the maximum particle size does not decrease upward throughout the three levels at each location (Fig. 3), despite the increase in the proportion of overbank facies to channel facies.

Significant features of the alluvial sequences

This section deals with one particular category of sequences out of all the categories established for the internal transverse system fans (Viseras 1991), including the fan outcropping in the Arroyo de Gor section. These sequences have an average thickness of 20–30 m and some distinctive characteristics (Fig. 4). Each growth stage of the fan is made up of three to five sequences.

The sequences are made of two types of components: gravelly channel complexes and overbank complexes.

Gravelly channel complexes

The gravelly channel complexes are bodies made of gravel with a lateral extent of up to 250 m and thicknesses of 75 to 250 cm. They can be classified as sheet bodies (Friend 1983). Their base is erosional and in most cases regularly stepped, indicating growth by a continued westward displacement of the channel (Figs 5, 6). This systematic displacement means that each channel complex is a diachronous unit growing

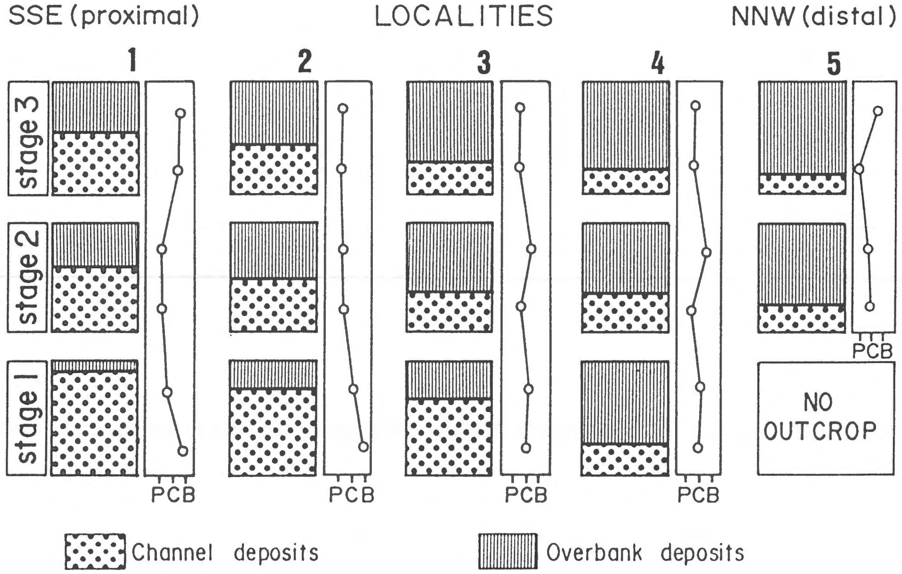

Fig. 3. Ratio of overbank to channel deposits (left-hand columns) for each stage of fan growth at localities 1–5 of Fig. 2. Vertical change in MPS in the gravelly channel complexes (P-pebble, C-cobble, B-boulder) is shown in the columns to the right (sampling localities shown on Fig. 10).

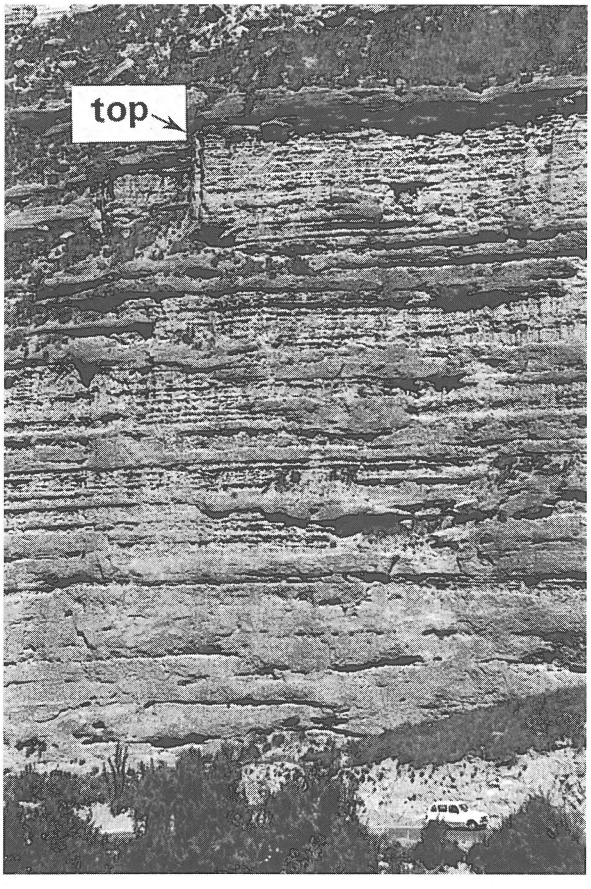

Fig. 4. Fining and thinning upward (FU + ThU) sequence in the Arroyo de Gor section near locality 3, fan growth stage 2 (car for scale).

simultaneously with a diachronous overbank unit (Fig. 6). Moreover, it is remarkable that the orientation of the sole marks at the base of each channel complex undergoes minimal dispersion ($\leq 15°$) throughout the lateral extent (100–250 m) of each outcrop. Campbell (1976) described similar offsets in alluvial fan deposits, although on a larger scale.

Internally, the stepped channel complexes are dominated by cross-bedded gravels invariably dipping 10–15° WSW, and showing clast imbrication upslope on the cross beds (Fig. 6). In contrast, finer sediment (coarse sand to granule) also appears in a lesser proportion, organised in planar cross laminae dipping approximately 30° ENE. Towards the east these finer sediments are occasionally organised in trough cross-lamination. In other examples, the gently dipping cross-bedded gravels have been interpreted as backsets [1] and the planar cross laminae of granules as foresets, corresponding to the heads and tails of bank-attached bars, respectively (Bluck 1976, 1982, Haughton 1989). The coarse sand with trough cross-lamination corresponds to the infill of the slough channel (Fig. 7). In this case, it would represent bars attached to the accreting bank (here the eastern bank) of a channel migrating laterally towards the west. This kind of bars has been referred to in literature as lateral diagonal bars (Bluck

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[1] We use 'backset' as proposed by Bluck (1976). The term has been used also by Postma et al. (1983), Postma (1984) and Postma & Roep (1985) with a different meaning and for a different setting.

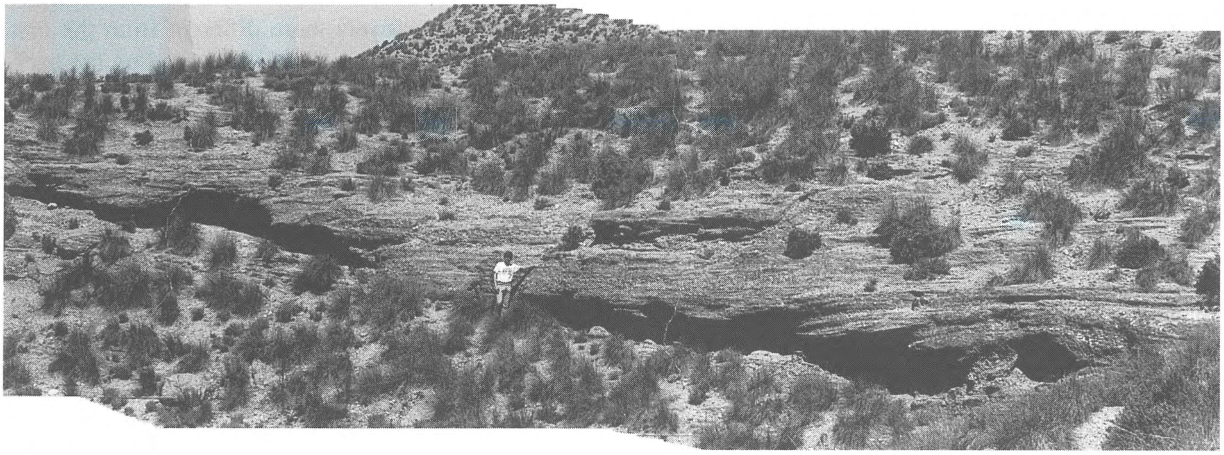

Fig. 5. Field example showing the progressive offset of the gravelly channel complexes in the Arroyo de Gor section, near locality 7, fan growth stage 2 (WSW to the left).

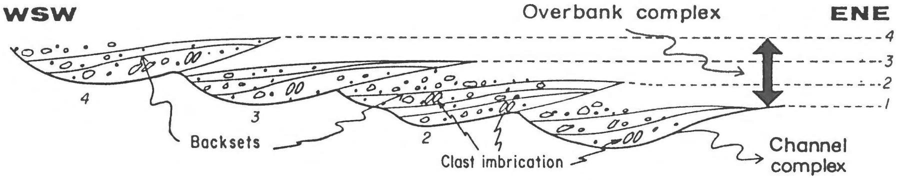

Fig. 6. Schematic diagram showing progressive WSW offset of diachronic channel and overbank complexes like those shown in Fig. 5. The vertical scale is exaggerated.

1979, Church & Gilbert 1979, Forbes 1983, Billi et al. 1987).

Overbank complexes

The overbank complexes are sands or lutites with horizontal lamination or small-scale ripples. Occasionally, intercalations occur of small lenses of granules with a flat base and upward-convex top, not more than 1.5–2 m in lateral extent, and 15–20 cm in maximum thickness; they have been interpreted as crevasse-splays (Viseras 1991, Fernández et al. 1991). In the upper part of the sequences, the overbank complexes usually show root casts indicative of soil development. As already observed (Fig. 6), these complexes grow diachronically together with the gravelly complexes. They represent the flood-plain deposits of the channels.

Sequences made up of these two components begin with an erosion surface on which several gravelly channel complexes are vertically stacked, forming a coarse basal layer up to 3–4 m thick (Fig. 8). Upward in the sequence, the gravelly beds are separated from each other by progressively thicker beds of overbank complexes (Fig. 4). The sequence culminates in a thick (locally up to 5 m) bed of overbank deposits, commonly with palaeosol horizons (Fig. 9). The boundary with the next sequence is another erosional scar irregularly cutting the fine sediment bed (Fig. 8). The lower part of the new sequence is also a multistorey unit made of several gravelly complexes.

Analysis of the maximum particle size shows a gradual upward decrease in the channel complexes of each sequence. Since the gravel beds (formed by accumulation of successive gravelly complexes) become progressively thinner towards the top, the sequences

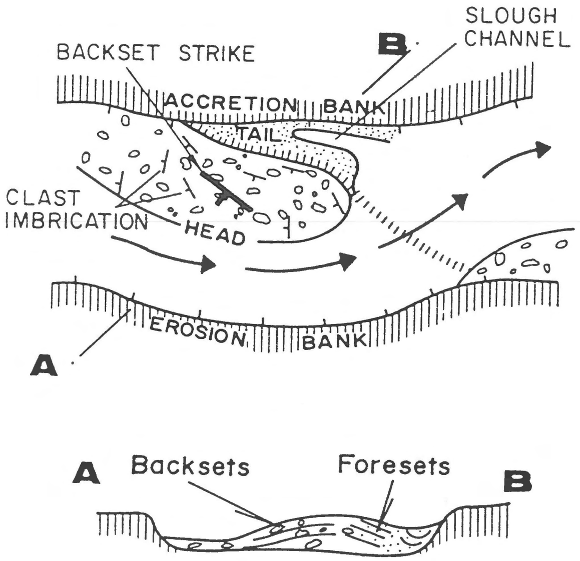

Fig. 7. Relations between the different parts of a lateral bar (after Bluck 1982), with backset and foreset cross-bedding.

can be defined as FU + ThU (fining and thinning upward) sequences (Fig. 4).

Palaeocurrent analysis

Palaeocurrents were analysed at three points in stage 2 along the Arroyo de Gor section. Both sole marks and clast imbrication in the gravelly channel complexes were measured (Fig. 10).

The sole marks (flutes and grooves) present a slight counterclockwise turn in a proximal–distal direction (Fig. 10). Apparently, the Arroyo de Gor crosses the northeastern part of the Pliocene cone, although not exactly at the apex, but rather slightly oblique to the radii of the cone. This agrees with the fact that in the southernmost part of the outcrop, where the Pliocene sediments lie directly on the metamorphic basement, inner fan facies are not well developed (Viseras 1991, Fernández et al. 1991) and are found slightly to the southwest. In addition, north of Gorafe, where the valley widens considerably, the geometry of the top of growth stage 2 can be determined. It is marked by a slightly upward convex soil horizon dipping ENE, which also indicates that the section is located in an eastern part of the Pliocene fan.

In the most proximal zone, imbrication is unimodal and the predominant trend coincides with the results of the sole mark analysis. A bimodal trend becomes clear in more distal zones (Fig. 10). One trend, represented by the larger clasts in the thalweg, has the same direction as the sole marks. The other trend, which becomes progressively more different from the first, corresponds to smaller clasts imbricated on the backsets of the gravelly bars. The coincidence between sole marks and clast imbrication in proximal areas is due to the fact that here the bars are longitudinal or medial (Viseras 1991), so that the backsets strike approximately perpendicularly to the flow and dip upstream. On the other hand, in more distal zones the bars are bank-attached with backsets oblique to the main flow (Fig. 7).

Interpretation and proposed model of sedimentary dynamics

The model proposed here has to explain the following facts: the appearance of a series of FU + ThU cycles such as those in the eastern part of a fan with SE–NW axis; the almost exclusively WSW channel migration, based on offset of the bases of the gravel beds; and the preservation of only the backsets and foresets of bars attached to the eastern bank of the channels. Also, the model has to explain why the proportion of overbank deposits increases relative to channel deposits when the fan had a larger radius (later stages of growth), even though there is no clear reduction in maximum particle size.

The accumulation of a bar against a channel bank implies local erosion of the opposite bank, if the cross-section of the channel is to remain approximately constant. Therefore, if bank-attached bars develop preferentially on one bank of a channel, the channel tends to migrate laterally towards the opposite side (Amundson & Hendry 1989, Todd & Went 1989, Viseras et al. 1989a). The bars attached to the bank towards which migration occurs are eliminated by channel erosion. On entering a sedimentary basin, a channel can thus migrate in a constant direction, creating a fan-shaped surface (e.g. Thorrarinson 1956, Gole & Chitale 1966, Bluck 1976, 1979, 1980, Wells & Dorr 1987). A well known case is the Kosi River (India), which in 230 years has gradually migrated from east to west on a fan over 125 km wide (Gole & Chitale 1966).

The Guadix Formation requires a model similar to that of some present-day braided channel systems. In these systems two zones can be distinguished, one of higher channel density, actually constituting a trunk channel, and another of lower density consisting of interconnected channels linked to the trunk channel and

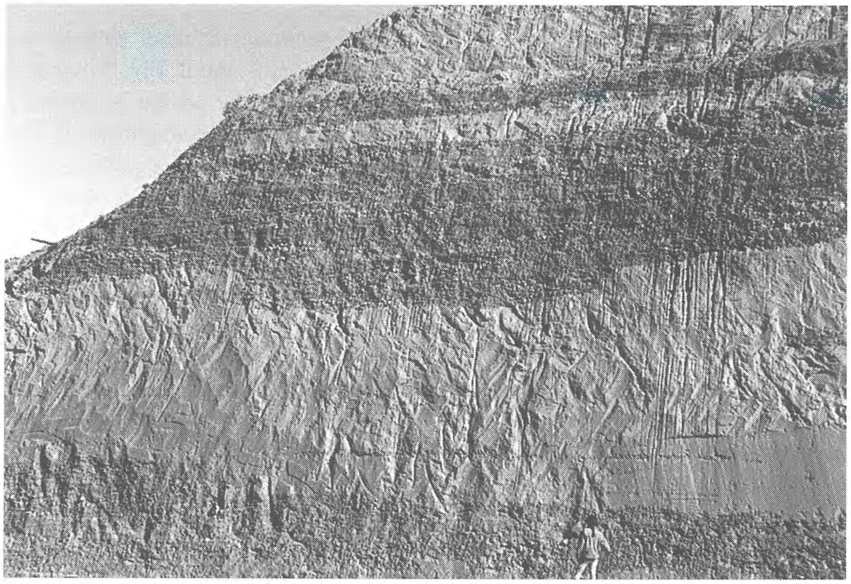

Fig. 8. Erosion scar cutting the fine sediments of an overbank sequence. Notice the stepped base of the channel complex and the constant dip of backsets towards the left (WSW) (human figure for scale).

known as secondary channels or anabranches (Jackson 1834) (Fig. 11). Wide flood-plain areas are situated on both sides of the channel system.

In the course of lateral migration, such a channel system would first cause a coarsening and thickening upward sequence (CU + TkU), as a result of deposition by the trunk channel preceded by the secondary channels. A fining and thinning upward (FU + ThU) sequence would then follow (Figs 11, 12), due to withdrawal of the trunk channel and subsequent deposition by the secondary channels on the other side. Finally, fine flood-plain sediments would be deposited during periods of overbank flooding of the now distant channels (Fig. 12).

Nevertheless, the erosional processes associated with the migration of the channel system (particularly the trunk channel, due to its larger size) are not restricted to the elimination of bars on the erosion bank. They also affect the CU + TkU sequence deposited before the trunk channel reaches a given point. It is a continuous process in which each secondary channel first eliminates the deposits accumulated on its erosion bank and part of the older flood-plain deposits. The CU + TkU sequence is therefore never well developed. The trunk channel erodes the relatively thin bed of remaining deposits of the preceding secondary channels. Thus, without having to suggest a major phase of erosion, only the FU + ThU sequences are preserved as the result of the withdrawal of the channel system. The bases of

Fig. 9. Root casts related to palaeosol development on the overbank deposits of the upper part of a FU + ThU sequence in the Arroyo de Gor section (locality 6, fan growth stage 3).

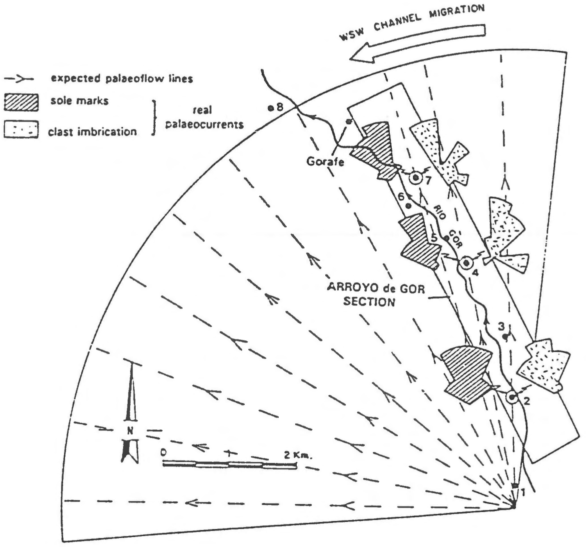

Fig. 10. Reconstruction of the location of the Pliocene alluvial fan after the counterclockwise turn, based on sole mark palaeocurrent directions in fan growth stage 2 (1–8, sampling localities of Figs 2, 3).

these sequences are characterised by a marked erosion surface representing the elimination of the preceding CU + TkU sequence.

Near the edge of the fan formed by the channel system, the FU + ThU sequence formed by passage of the system towards that edge would be eliminated by channel migration in the opposite direction, since not enough time would be available for the sequence to be overlain and protected by overbank deposits. However, the younger FU + ThU sequence, formed by channel migration back towards the centre of the fan, is buried under a thick bed of fine deposits resulting from the numerous inundations in the time that the channel system requires to reach the other side of the fan and return to this position. Only the flood-plain deposits would then be eliminated, and possibly also the uppermost part of the FU + ThU sequence beneath. So, in a marginal position of the fan the main record would be that of the FU + ThU sequences formed by passage of the channel system towards the centre of the fan.

Figure 13 is a schematic illustration of the effects of the model on hypothetical columns in a central and a marginal position of a fan. For each position, the left column shows the complete sequence without the effects of erosion. The resulting sequence shows what is actually preserved. The sequences are shown to the left or right of a central line, according to whether they represent channel system movement to the left (sequences A and B, Fig. 13) or to the right (sequences C and D). The letters A and C refer to sequences formed during approach of the stream system (CU + TkU sequences); they will be eliminated by the erosion caused by their own secondary channels and the trunk channels at the base of B and D (FU + ThU), which represent withdrawal of the system from the point analysed.

Thus, in the marginal column, A_1 will be eroded by its secondary channels and the trunk channel at the base of B_1. The upper part of B_1 is a thick bed of fine deposits, which will partly be eliminated together with C_1, because of the trunk channel at the base of D_1. The latter channel does not erode B_1 completely, so this sequence is preserved. D_1 is eroded by the secondary channels of A_2 and the basal erosion of B_2, as not enough time passes for D_1 to be covered by a thick bed of overbank facies. The erosion preceding B_2 eliminates A_2. B_2 is preserved by the same mechanism as B_1. The final result is that two FU + ThU sequences (B_1 and B_2) are preserved at this marginal position, both of which show backsets dipping to the left.

In a central position the time interval between successive passages of the channel system has an intermediate value. Each FU + ThU sequence has therefore upper fine deposits only partially protecting the sequence from erosion due to the next passage of the channels in the opposite direction. Thus, in the central column of Fig. 13, A_1 is eliminated by the base of B_1. The erosion resulting from the passage of the channels preceding D_1 eliminated both C_1 and a considerable part of B_1. Therefore, the complete B_1 sequence at a marginal position records the same time interval as the sequences B_1 and D_1 in the central core, that are both incomplete at the top and have backsets of the bars dipping in opposite directions. In addition, a smaller proportion of overbank facies appears in the central column.

For the Guadix Formation the mechanism proposed above explains why FU + ThU sequences with backsets dipping WSW are present in the Arroyo de Gor section, located near the northeast margin of a fan. It is the result of the selective preservation of deposits reflecting migration phases of the channel system towards the western margin of the fan. This model nonetheless requires a mechanism causing a channel that is continuously being displaced in one direction (by preferential accumulation of bars on the opposite bank) to change this trend sharply, thus giving rise to the pendular pattern allowing overall development of the sequences.

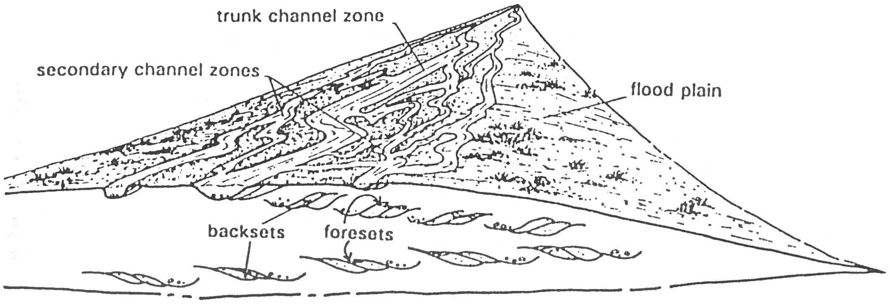

Fig. 11. Schematic diagram showing different parts of the channel network. The vertical scale is exaggerated.

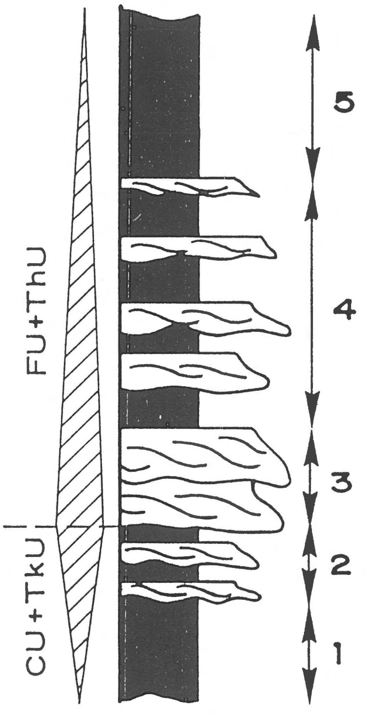

Fig. 12. Theoretical CU + TkU and FU + TkU sequences resulting from passage of the channel network over a given location, with complete preservation. 1, Flood plain distant from channels. 2, Pre-trunk secondary channels. 3, Trunk channel. 4, Post-trunk secondary channels. 5, Flood plain distant from channels. Backset bedding is represented.

On the basis of the data available for the Guadix Formation, we propose two possible mechanisms that not necessarily exclude each other:

(1) A channel system with lateral displacement and a single entry point into the basin will eventually reach the basin edge (Fig. 14A). At this point the erosion bank becomes more insurmountable than the accretion bank. Bars begin thus to accumulate on the basin margin and a systematic displacement of the system in the opposite direction begins. If the sediment supply solidus subsidence ratio increases, the fans will gradually become larger until they grow together (Fig. 14B). Each fan has thus the same effect on adjoining fans as the basin margin. In this way, narrower (lower sweep angle A_s) fans of larger radius are formed.

(2) Transformation of a broad fan with almost 180° sweep angle to a narrower fan with larger radius can also result from a tilting towards the centre of the basin. The lateral displacement of the channels is thus limited to a narrower band, whose width depends on the gradient caused by the tilting.

As already mentioned, the sector of the basin containing the fan under discussion underwent a progressive decrease in subsidence rate throughout the Early Pliocene. In addition, the progressive unconformity in the alluvial sediments demonstrates synsedimentary tilting during the early growth of the fan. As a consequence of both processes, the radius of the fan increased from about 6 km to 9 km and the sweep angle decreased between growth stages 1 and 3. The younger stages in the Arroyo de Gor section represent therefore increasingly marginal parts of the fan (Fig. 15). In the context of the proposed model, this explains the progressive increase in overbank deposits relative to channel deposits in younger stages, without reduction in particle size.

Conclusions and significance of proposed model

On the basis of the specific characteristics of the sequences, the palaeocurrent analysis and a compari-

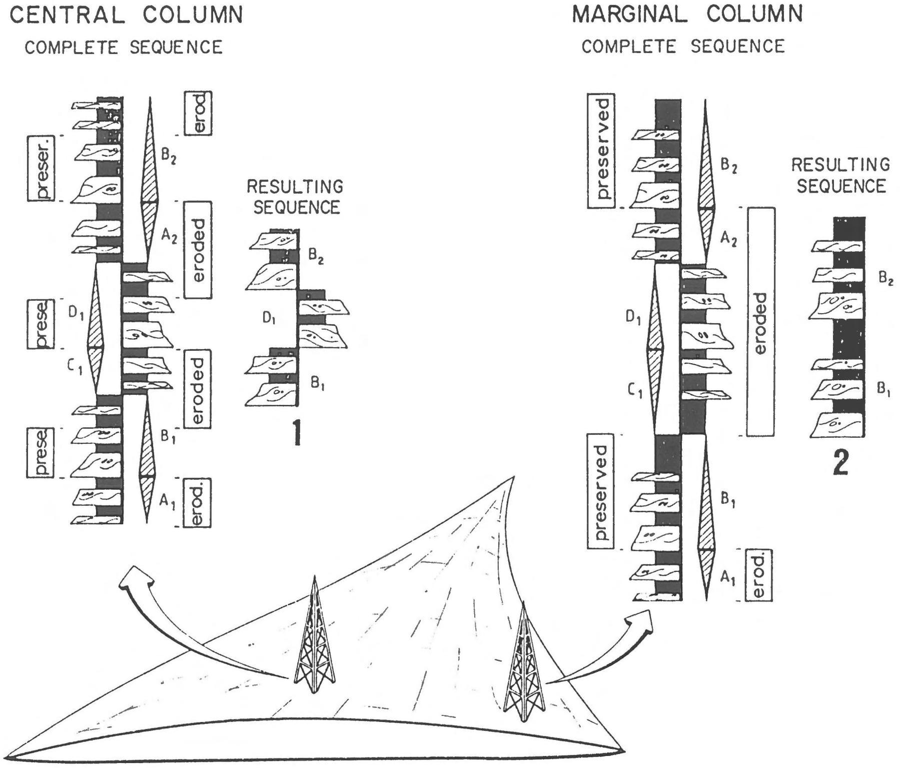

Fig. 13. Complete theoretical sequences and real records considering erosion linked to channel network migration. 1, A central position in the fan can be recognised by a high number of not very thick FU + ThU sequences, scarcity of overbank sediments, and backsets alternately dipping in opposite directions. 2, A marginal position is characterised by fewer but thicker FU + ThU sequences, higher proportion of overbank fines, and backsets dipping invariably towards the centre of the fan.

son among successive stages of a Lower Pliocene alluvial fan in the Arroyo de Gor section (Guadix Basin), along with previous analyses of facies and architectural elements (Fernández et al. 1991, Viseras 1991), a model of sedimentary dynamics in alluvial fans is proposed. The model invokes a trunk channel with a series of secondary channels on either side, all of which migrate laterally in a pendular movement, describing a fan-shaped surface. The lateral migration of all the channels is caused by the greater accumulation of bank-attached bars on one of the banks (accretion bank). The change in direction of migration, resulting in the pendular pattern, takes place when the channels reach a point where the gradient makes the erosion bank more insurmountable than the accretion bank. This point can be either the basin margin itself or the edge of an adjoining fan. The same process can be caused by a tilting of the fan towards the centre of the basin.

This model implies that erosional processes linked to the displacement of the channel system are of great importance in the characteristics of the resulting depositional sequences. The model can therefore help to solve several problems in ancient alluvial basins:

(1) The general location of a fan can be reconstructed by analysing the sequences in a single sector of the fan. A position close to the margin can be recognised by a series of FU + ThU sequences with relatively thick overbank deposits towards the top and with backsets dipping invariably towards the centre of the fan. The latter are recognisable by their slight inclination upstream or towards the channel, by imbricated clasts upslope and dipping in the opposite direction in comparison with the foresets (which have a finer grain-size). On the other hand, a central position can be recognised by a larger number of FU + ThU sequences that are incomplete at the top and have backsets dipping alternately in opposite directions. The proportion of coarse facies is thus higher in a central position, so that the model could be useful when prospect-

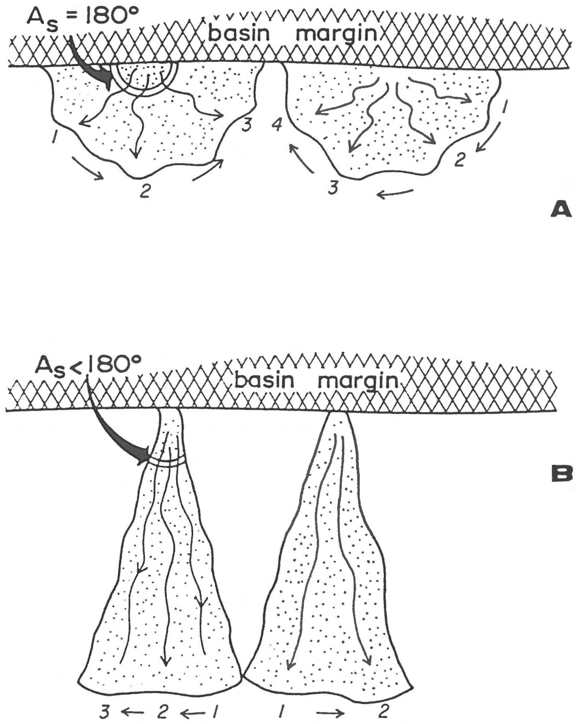

Fig. 14. Possibilities of change in channel migration direction. If the sediment supply is constant and the subsidence decreases or the bottom is tilted basinward the sweep angle (A_s) decreases and the radius of the fan increases (from A to B). 1–4 represent successive positions of the same channel.

ing for highly porous facies in economic geological studies.

(2) The analysis of the changes in shape of superposed fans or successive growth stages of the same fan (inferred by the number of FU + ThU sequences, the orientation of the backsets, and the proportion of overbank facies) can provide valuable indirect information on the evolution of the basin sector in which the fan developed. Evolution towards fans with greater radius and lower sweep angle, such as inferred for the example analysed here, is consistent with a constant increase in the sediment supply/subsidence ratio throughout the Early Pliocene.

Acknowledgements

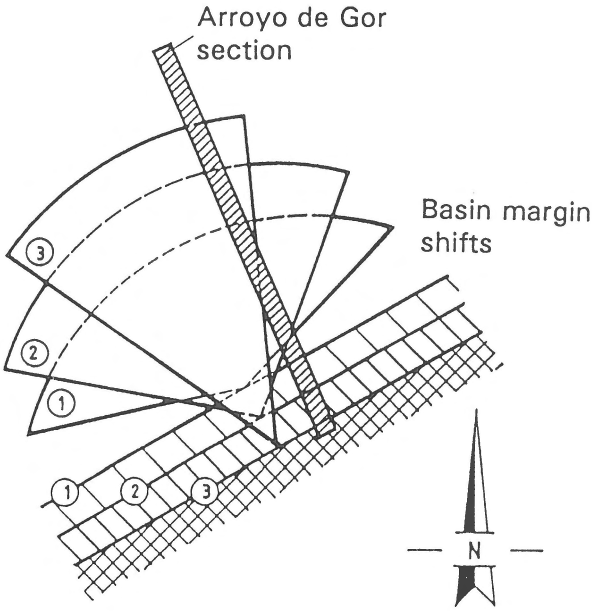

Fig. 15. The Arroyo de Gor section shows a more marginal position of the fan for progressively younger stages (1–3) as a consequence of a changing fan shape.

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